# Polyphase directional detection for power system protection

Nyun-Fook, Chin

*Award date:*
1994

*Awarding institution:*
University of Bath

# POLYPHASE DIRECTIONAL DETECTION

# FOR

# POWER SYSTEM PROTECTION

submitted by Nyun-Fook, Chin
for the degree of PhD
of the University of Bath
1994

This thesis is dedicated to my parents

and to my wife Jennifer,

daughter Louise and son Kendrick

for their understanding and sacrifice

in supporting

my venture into this project

at the expense of not being able to enjoy week-end

and holiday family get together

**Summary**

The basis of a new approach in determining the direction of a fault point based on a polyphase consideration is developed from an examination of the principle of operation of the electromechanical polyphase directional relay used on distribution systems. The new approach is based on an examination of the symmetrical components, the positive and the negative phase sequence components, of voltages and currents generated at the relaying point to derive the direction information of a fault point.

The angular displacement between the corresponding phase sequence voltage and current phasors, after the necessary phase shift, is examined whether it is within $\pm 90^0$ to define forward faults or outside this range to indicate reverse faults. Results of the steady-state fault analyses of typical distribution systems to test the response of the new technique are presented. These confirm the validity of the new principle of directional detection which has better performance than the established directional relays used on distribution systems.

The envisaged performance of the new method of detecting fault direction under transient conditions generated on the occurrence of system disturbances is discussed. The conclusion is that power system transients do not affect the criterion adopted in the new approach to determine the correct fault direction.

The possibility of greatly improved performance in traditional method of detecting direction emerges together with a new scope for application to areas that are not possible previously. These new applications, on the assumption of the new technique being implemented into an

operational hardware, are outlined. These focus mainly on the protection of plant items of ac generators and motors.

The project concludes with a recommendation for further work to develop the new basis into an operational protection relay with a consideration of the transient performance prior to implementing the new principle of detecting direction.

**Acknowledgement**

It is impossible to complete this project without the kind assistance and encouragement given to me by my friends, colleagues and my family. This space does not allow me to acknowledge everyone individually. However, I like to specially express my sincere thanks to the followings:

Professor A T Johns, as my supervisor of this work, for his expertise advice and encouragement.

Mr E P Walker, as my industrial supervisor, for his valuable advice and comments on the work.

Mr J R Rathbone for assisting in obtaining information for my references and providing advice on language matters.

Mr K Y Fung, Senior Protection Engineer of China Light & Power Company, Hong Kong, for providing system data to enable this investigation based on actual system.

Dr K M Ko for assisting in the modifications of the fault analysis programme.

Miss Alice Cheng, my Secretary, for assisting the typing of this thesis and for patience and tolerance to my constant demand for changes and to look after the day-to-day work at the same time.

I also wish to thank GEC ALSTHOM T&D Protection & Control Limited for its financial sponsorship to enable me to enrol for this course and to take on this project.

Finally, I like to thank my wife Jennifer for her patience and understanding during my absence from home spending late nights and weekends in the office.

## CONTENTS

## CHAPTER 6 PROPOSED NEW APPROACH TO POLYPHASE DIRECTIONAL DETECTION

# CHAPTER ONE

## INTRODUCTION

### 1.1 Introduction

Research work on power system protection tends to concentrate on high voltage systems biasing towards the transmission area. This is particularly so with the present use of digital techniques to implement traditional functions with added facilities to improve performance levels and in the search for new principles of operation to solve difficult problem areas in power system protection.

A practical illustration of the former is the digital implementation of Kirchhoff's current law in differential feeder protection schemes. In this case one of the most common and well tried principles of operation has been implemented digitally in hardware and accompanying software techniques have been used to avoid the need for synchronization of signal sampling [2.10]. This enhances the cost-performance level of current differential protection schemes such as phase segregated comparison.

The field of distance protection has also seen a tremendous amount of research work being performed. Recent work [1.12, 1.14, 1.15, 1.16, 1.18, 1.23, 1.24] concentrates on the development of algorithms for implementation using microprocessors in digital distance relaying. In addition to improvements in speed and accuracy, work is being done on adaptive aspects of distance relaying [1.14, 1.15, 1.18] in order to generate distance relay characteristics that are adapted to the dynamic behaviour of the primary system. These again are targeted at the protection of transmission systems.

The latest trend is to provide records of primary system disturbances whilst the protection functions are being performed [2.18, 2.19, 2.20] and there is also growing interest in the coordination of protection with control functions through suitable communication media [2.21, 2.22]. This is made possible by the use of digital techniques in the design of both protection and control equipment and is driven by the need to improve cost and efficiency of operation.

Another area of research interest in the protection of transmission networks is the use of superimposed components [1.20] in directional elements for directional comparison schemes. This use of superimposed components has also been implemented in phase comparison schemes in the People's of Republic of China [1.22].

A relatively small amount of research work has been performed in protection functions for distribution systems. One area is in the design of current-operated relays for traditional overcurrent and earthfault protection.

Electromechanical relay designs, using induction discs, have been well proven and established. The introduction of transistors and integrated circuits saw the development of solid-state equivalents of this type of current-operated relay. These equivalents, when introduced into the market, have not been able to compete on economical grounds with electromechanical designs. This was followed by the investigation of digital implementations using microprocessors and the associated memory chips. With the processor which has memory and analogue-to-digital convertor on the same chip, the cost of digital designs became economically viable.

Early work on conventional overcurrent and earthfault protection concentrated on a digital implementation of current detection and measurement using different software techniques. The result was commercially available digital current-operated relays in the late 1970's for overcurrent and earthfault protection schemes [2.11]. It was also the first time where a given hardware provided a selection of operating characteristics by calling up the stored software algorithms in the hardware memory bank. This resulted in better accuracy and repeatability, but more significantly it has provided engineers with much needed application flexibility. Application engineers do not need to be concerned with the selection of relay operating characteristics at the project inception stage when detailed information about the system is not available. The selection can be carried out at the commissioning stage of the project.

More recent developments in this area have been the addition of extra facilities in the same protection relay. These include:

- measurement functions such as calculations of active and reactive power, voltage, current and power factor.

- control functions such as load shedding, issue of trip signal on request from a central station and automatic reclose signal to circuit breakers.

- communication functions, such as remote access of information stored in the relays and change of set parameters.

The latest area of interest is in the adaptability of protection both in transmission [1.14, 1.15] and distribution system protection [1.17]. The protection relays installed on the system are designed to adjust in sympathy with changing power system conditions in order to provide optimal performance. In the study of adaptability of distribution system protection [1.17] computer overcurrent relaying concepts are used. These are microprocessor-based designs, together with communication facilities, to continuously monitor and analyze various feeder currents and voltages from which the relay characteristics are adjusted automatically to provide faster and improved protection. In addition, economic viability aspects are being investigated to enhance the chances of applying state-of-the-art technology in hardware to implement the new concepts [1.25].

However, there is still an area that has not been examined - the area of response of current-operated relays used as current-level detectors with or without time delay of the definite or inverse time type. These relays do not have a defined area of response of the primary system within which they operate when a fault occurs.

Conventional overcurrent and earthfault protection for power supply systems, using current-operated relays, relies on the detection of currents in excess of pre-determined settings. Their areas of response, in which the occurrence of primary system faults will result in secondary fault currents flowing in excess of their settings, are not well defined. It is therefore difficult to achieve selective tripping of circuit breakers to isolate the minimum number of faulty circuits and/or items of plant.

The process of coordinating this type of relay involves selecting suitable settings to meet their fundamental functions under the requirements of sensitivity, selectivity, reliability and speed. These requirements must be satisfied for a variety of system operating conditions and configurations, such that different faults can be detected by the appropriate relays with those closest to the fault points having the priority of operation. This approach, based on the topology of the network and assumed operating conditions, may result in degradation of performance of the overall system protection if there are significant operational configuration changes. Work has been carried out to computerise this process [1.7] using various simulation and modelling techniques. The latest work uses expert systems to carry out coordination studies [1.13]. Little or no work has been done on the actual relay design or on improving operating principles to achieve improved selectivity.

There are a number of methods that can be applied to improve the discriminative feature of a protective scheme and these depend on the degree of sophistication and the related cost involved. One method is to make use of a primary equipment arrangement employing current transformers to form a well defined zone and connected in a differential mode. Current-operated relays are arranged to measure differential current and operate when the differential current exceeds the relay setting due to faults inside the zone defined by the current transformer placement. This is illustrated in Figure 1.1.

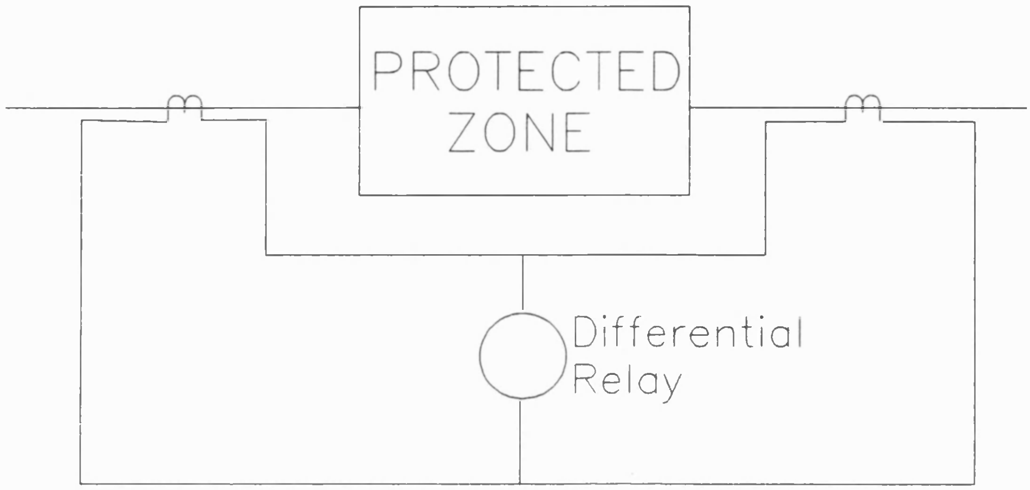



Figure 1.1 Unit Protection

This method provides absolute selectivity, when the current transformers are specified correctly, because the scheme responds only to faults within a well defined zone. This type of scheme is generally known as a unit scheme or unit protection, a typical example of which is current differential protection [3.8].

For non-unit schemes of protection, selectivity is relative because discrimination is governed by the grading of different zone settings, all of which may respond to a particular fault on the system.

Current-operated relays used in general overcurrent and earthfault protection cannot provide absolute selectivity. The level of selectivity depends on the current or/and the time settings of all similar relays on the system and the ability to maintain satisfactory operation under different system operating conditions and configurations.

For overcurrent and earthfault protection based on current level detections, which is generally the main protection for lower voltage distribution systems, the most cost-effective method of improving the performance level in selective operation is to build in control to the current level detection.

This control restricts the response of the relays to faults occurring on certain portions of the system.

Figure 1.2 illustrates the need to provide restriction on the response of current-operated relays installed on the various feeders of a distribution system.

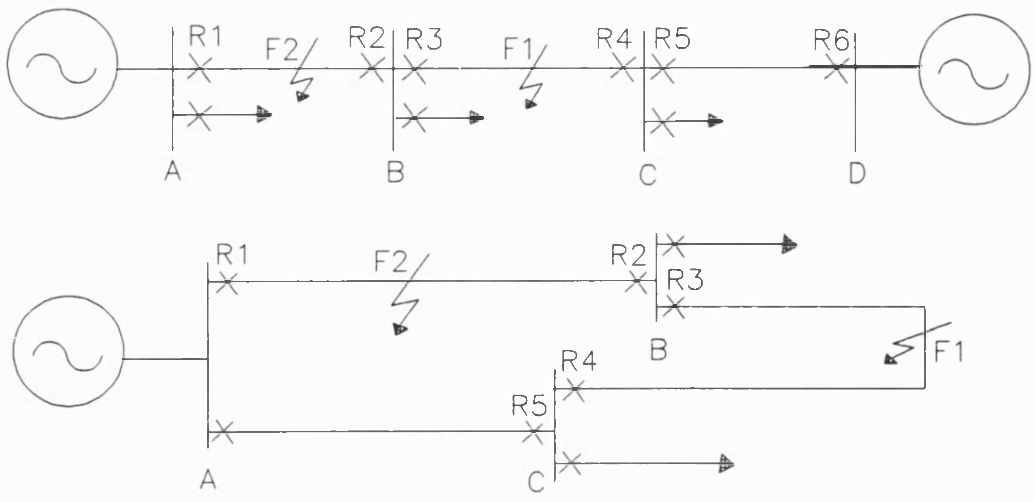



Figure 1.2 The Need to provide Response Restriction on Current-operated Relays.

For a fault at point $F_1$ relays $R_3$ and $R_4$ must operate first to isolate the fault without interrupting the supply to the distribution points B and C. Whilst the reliability of supply to consumers is greatly improved, demands are made on the performance of the protection relays to ensure that only relays $R_3$ and $R_4$ are responsive to the fault. This leads to the following issues to be considered to ensure satisfactory operation under all conditions.

(i) For relays protecting a given section, such as BC, each relay, say $R_3$ must remain stable to a remote-end fault beyond the remote-end relay $R_4$ with maximum fault current flowing. It must also be stable for an immediate reverse fault behind its location.

(ii) A relay protecting a given section must coordinate with, in addition to the relay at the opposite end of the section, all other relays on other circuits connected to the same busbar.

(iii) Without additional means it is not possible to ensure that only relays $R_3$ and $R_4$ operate for a fault at $F_1$. For this condition the operating time of $R_3$ must be shorter than that of $R_2$, but for a fault at $F_2$ the operating time of $R_3$ must be longer than that of $R_2$. These two contradicting requirements cannot readily be met.

The above three issues are all concerned with the undesirable ability of current-operated relays to respond to reverse faults i.e., faults that are "behind" the relays, away from the protected section. If this ability is removed, making the relays only responsive to faults on the protected section concerned, the above problems would not occur.

Figure 1.3 shows another common problem. For the fault shown, the current flowing through the healthy circuit is detected by the current-operated relays on the two incoming feeders. The normal discrimination requirements between the high voltage side and the low voltage side relays and protective devices on the low voltage outgoing circuits necessitates the same current and time delay settings on the low voltage relays. The fault indicated would cause the two low voltage relays, detecting the same current, to operate and trip the supply to the distribution boards.

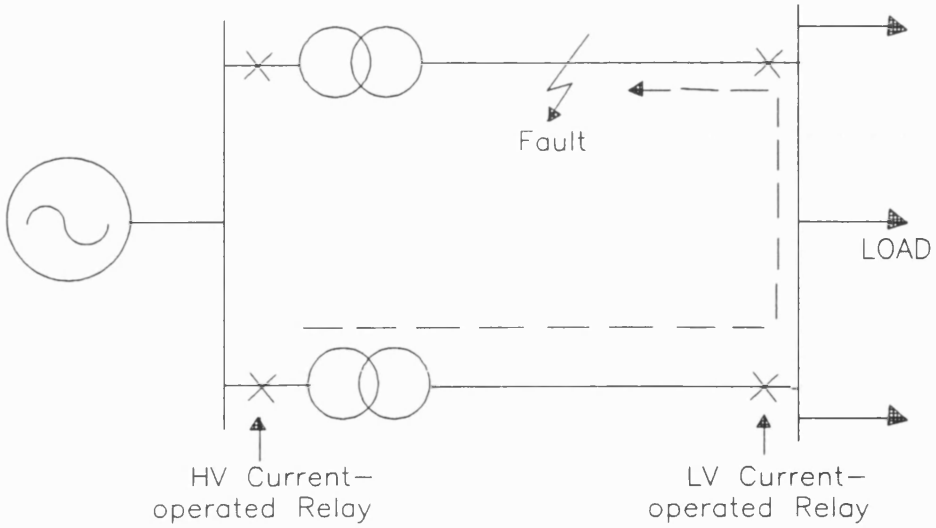



Figure 1.3 Unnecessary Tripping of Healthy Feeder due to lack of Response Control of Current-operated Relays.

If the low voltage current-operated relays can be restricted in their operation such that they only respond to current flowing in the direction of the power transformers, the above problem would not occur. Only the relay detecting current flowing into the power transformer (in this case the relay on the faulted circuit), will respond to the fault condition and isolate the fault.

This control on current-operated relays would restrict the relay operation for primary system faults occurring in one of the two possible directions, being referred to as forward for operation or reverse for restraint with respect to the relay location. These are illustrated in Figure 1.4. This control function is performed by directional relays.

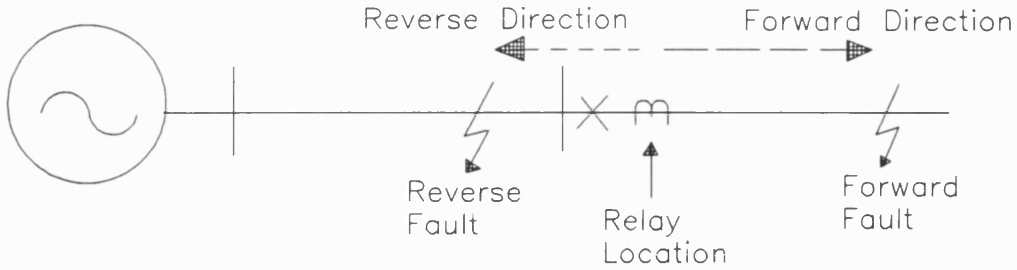



Figure 1.4 Illustration of Directions and Fault Types with reference to Relay Location.

Directional relays are used extensively to recognize the difference between current supplied in the forward or reverse directions.

Directional control of current-operated relays has been implemented by electromechanical means since the early days and this was followed by the development of solid-state equipment with added customer-selectable operating characteristics [2.6].

The directional control elements are either of single-phase or polyphase designs with the latter mostly based on electromechanical technology. Though commercially available three-phase solid-state types exist they are essentially single-phase elements housed together in a single case [2.6] with a common output. There are the truly solid-state polyphase directional relays based on the use of phase sequence quantities but their application is restricted [2.1].

Hitherto, work has been carried out [1.3, 1.4] to investigate the performance limits of directional relays used for overcurrent and earthfault protection. The design and principle of operation of these relays has already been fixed. No attempt has been made to examine alternative methods to overcome the limitations of these existing relays. For single phase relays, work by Sonnemann [1.4] has already exhausted all the possibilities of improving further the directional detection capabilities of existing relays. Other methods of directional detection have been investigated and implemented [1.8, 1.20, 2.14, 2.22, 2.23], but they are for transmission system protection rather than for distribution system overcurrent and earthfault protection.

The purpose of this project is to investigate the possibility of a new directional detection method to provide the basis for further development of a digital polyphase directional relay. It is unlikely, for distribution systems, that single phase consideration will yield possible alternatives and this project is therefore based on a consideration of polyphase types. The aim is to improve the performance of existing polyphase directional detection which are mainly based on electromechanical designs. The performance of polyphase directional relays has hitherto been compromised by the lack of sensitivity to earth faults, especially in the presence of heavy load current which has in turn resulted in application restrictions. The fault current must be high compared with load current, e.g. 3 times the load current as the minimum [2.3]. Other polyphase directional relays [2.1] have application limitations in that they can only be applied to cover phase faults.

The present investigation is aimed at examining the principle of operation of polyphase electromechanical directional relays from which a new approach on polyphase basis is proposed to detect direction of a fault point from a study of the symmetrical components of voltages and currents generated at the relaying point. The operating characteristic is structured to match the fault profile for forward fault operation and also for reverse fault restraint.

The objective is to derive a new method that is superior over the established methods either on single or polyphase basis and to be able to provide a phase selection capability within the new approach. This will overcome the limitation of polyphase relaying in its inability to identify the faulted phase(s) and should provide a very cost-effective design.

The main application areas targeted are the distribution systems where current-operated relays are extensively used. It is, however, envisaged that it should be applicable to the protection of transmission systems and individual plant items. It is proposed that the new directional detection technique be considered for eventual application together with conventional current-operated relays to form directional overcurrent and earthfault protection schemes. The performance level sought shall therefore be at least that of existing directional overcurrent and earthfault protection relays.

The proposed new polyphase directional detection approach will be examined for other applications with any modification or additional work where necessary.

The objectives are divided into the following sections:

(i) To examine the various possible means of detecting the direction of current flow with reference to a polarising voltage.

(ii) To decide, from (i) above, on a method with optimal performance against the stated requirements. This will be based on steady-state studies.

(iii) To carry out fault analyses to generate the required voltage and current signals to test the proposed method of directional detection.

(iv) To examine the possible applications of the new relay.

(v) To propose further work to implement the new method of directional detection in commercially available hardware.

## 1.2 Structure of the Thesis

This investigation is divided into the following sections:

The fundamental operation of directional relays used on distribution systems for current-operated relays is examined in Chapter 2 followed by brief descriptions of the various methods of directional detection.

A survey of existing directional relays, again used for current-operated relays in service, is made in Chapter 3 to highlight the application of various methods that are possible to derive the direction of faults with respect to the relay location. This survey includes both electromechanical and solid-state designs together with a brief look at the latest digital directional elements.

The performance of all existing directional relays is examined in Chapter 4 to highlight their weaknesses in their applications to particular systems.

The performance requirements of directional relays are then stated in Chapter 5, as the terms of reference for a new directional element, together with the targeted application areas in distribution systems.

Chapter 6 examines the fundamentals of directional detection leading to a proposal for a new approach to directional detection on a polyphase basis for power system protection. The new approach employs symmetrical components of voltages and currents to derive the fault point direction information with reference to the relay location.

Chapter 7 provides the analyses of power system faults to test the validity of the new proposed directional detection method when subjected to single-phase-to-earth, phase-to-phase, clear of or to earth and three phase fault types. The results are to prove that under different power distribution system configurations and operating conditions the symmetrical components of voltages and currents generated at the relaying point provide correct information to determine the direction of fault points. The results are presented for 33kV resistance-earthed and 11kV solidly-earthed distribution systems with plain- and also transformer-feeder arrangements.

The envisaged performance of the new method under transient power system conditions is also discussed.

Chapter 8 presents the possible application areas of the proposed new polyphase directional detection method highlighting the benefits of the new approach.

Chapters 9 and 10 conclude the thesis and provide recommendations for further work, leading to realisation of the new method into hardware for real time testing and service experience.

# CHAPTER TWO

# DIRECTIONAL RELAYS

## 2.1 Introduction

The application of directional relays has an important role in power system protection scheme designs. In high voltage network protection, directional detection forms the nucleus of many schemes such as directional comparison schemes [1.8, 3.8, 3.9] for protection of extra high and high voltage transmission systems. The operation of this type of scheme depends on the comparison of the direction of fault power at the two ends of the protected line by the operation/non-operation of directional relays at the two ends. The directional relays are arranged to "look" into the protected line such that internal faults will produce operations of both directional relays whilst external faults can only be "seen" by one directional relay. The comparison process is assisted by the use of a signalling channel transmitting a blocking signal if the faults are external.

On distribution systems directional relays provide an economical means of upgrading the performance of current-operated relays by providing increased selectivity, though still limited, without the need for extensive co-ordination with each other by different operating levels and operating times.

## 2.2 Principle of Operation of a Directional Relay:

The direction of a point can only be established with reference to another point. In power system protection the direction of a fault point always makes reference to the relay location point. This direction is either forward for operation or reverse for restraint.

At the relay location point, in order to determine whether a fault has occurred in the forward or reverse direction, two signals are required by a directional relay which then compares these to make a decision. These two signals are the operating and the reference or polarising signals. The polarising signal maintains the same polarity when a forward or a reverse fault occurs but the operating signal changes in polarity for these two fault conditions providing the differentiation.

For conventional overcurrent and earthfault protection using current detectors, the current signal from the power system is used as the operating quantity. A directional relay used to control a current detector to form directional overcurrent and earthfault protection, therefore, uses the same operating current signal and requires an additional polarising signal. The power system voltage becomes the natural choice as the polarising signal.

For an alternating current system, the position of a fault point with respect to a relaying point can be determined by examining the phase relationship between the polarising voltage and operating current phasors.

The basis for differentiating the direction of a fault with respect to the relay location is the fact that for a forward fault the angular displacement between the operating current and the polarising voltage is different compared with that for a reverse fault. It is necessary to determine the boundary limits between the two variations of angular displacement between the two fault conditions to enable positive detection of forward or reverse faults.

It is assumed that current flowing from the busbar to the protected circuit is positive and that from the protected circuit to the busbar is negative with reference to a fixed relay location.

As shown in Figure 2.1 consider relay R protecting the line section AB:

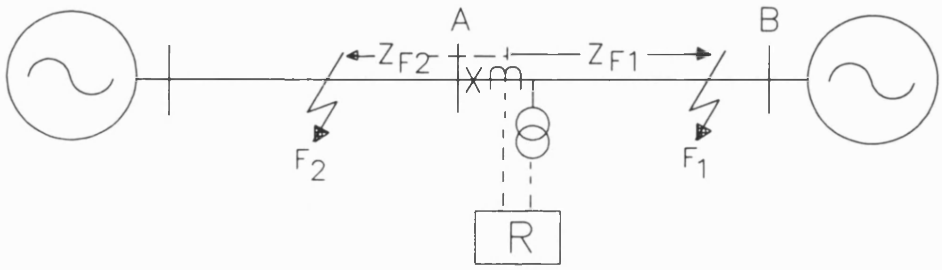



Figure 2.1 Principle of Operation of a Directional Relay.

Consider a fault at $F_1$ with fault impedance $Z_{F1}$ from the relay location to the fault point. With a fault current $I_{F1}$ flowing to the fault "seen" by the relay the voltage measured by the relay is:

$$V_{F1} = I_{F1}\, Z_{F1} \qquad \text{........2.01}$$

The angular displacement $\Theta_{F1}$ between $V_{F1}$ and $I_{F1}$ is the impedance angle of $Z_{F1}$ :

$$\angle \frac{V_{F1}}{I_{F1}} = \theta_{F1} = \angle Z_{F1} \qquad \text{........2.02}$$

The range of variation of the angular displacement between the voltage and current signals for this forward fault condition is therefore limited to:

$$\theta_{F1} = \angle Z_{F1} = 0° \ to \ 90° \qquad \text{........2.03}$$

When a fault occurs at F2, a reverse fault for relay R, the voltage it "sees" with a fault current $I_{F2}$ flowing is given by:

$$V_{F2} = -\, I_{F2}\, Z_{F2} \qquad \text{........2.04}$$

The minus (-) sign denotes the opposite direction of current flow adopted by the relay for operation.

The angular displacement $\Theta_{F2}$ between the voltage and the current signals "seen" by the relay for this reverse fault condition is given by:

$$\angle \frac{V_{F2}}{I_{F2}} = \theta_{F2} = \angle Z_{F2} + 180° \qquad \text{........2.05}$$

The range of variation of the angular displacement between the voltage and the current signals for this reverse fault condition is therefore given by:

$$\begin{aligned} \theta_{F2} &= \angle Z_{F2} + 180° \\ &= 180° \ to \ 270° \end{aligned} \qquad \text{........2.06}$$

From equations 2.03 and 2.06 it can be concluded that:

- for a forward fault the angular displacement between the voltage and the current signals is that the current signal lags the voltage signal by 0° to 90°.

- for a reverse fault the angular displacement between the voltage and the current signals is that the current signal lags the voltage signal by 180° to 270°.

The phasor diagrams showing the positions of the voltage and current phasors for these two fault positions are shown in Figure 2.2.

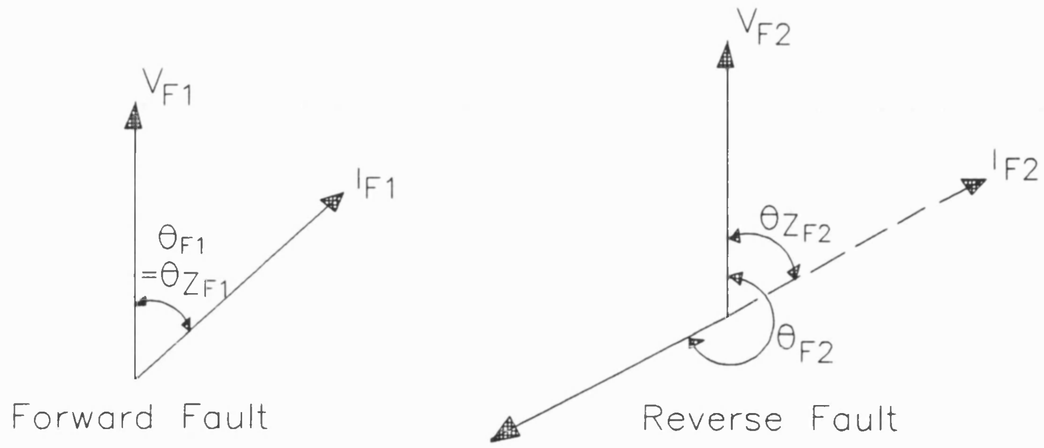



Figure 2.2 Angular Displacement between the Voltage and Current Phasors for Forward and Reverse Fault Conditions.

By comparing the phase displacement between the voltage and the current signals it is, therefore, possible to establish the direction of a fault point with reference to the relay location.

Alternatively, the power flowing in the protected circuit can be examined. Inherently the flow of power in an electric circuit is directional on the basis of:

$$Power = V.I.\ Cos\ \theta \qquad \text{........2.07}$$

where V = voltage

I = current

$\Theta$ = angle between V and I.

The sign of the power value depends on the value of the angle $\Theta$. For positive power flow, determined by the values of $\Theta$, it can be defined for $-90^\circ \leq \Theta \leq +90^\circ$ as the forward or operating direction and for negative power flow as the reverse or restraint direction.

The above two methods, though common in determining the direction of the current signal with respect to the voltage signal, differ according to the application areas concerned.

The use of active power measurement, hereinafter called a power relay, is generally employed under steady-state conditions with significant amount of active power flow in the primary circuit. This technique is not reliable under fault conditions when the fault current is mainly or wholly reactive, or the actual power flow is very small towards the limit of the operating level of the equipment.

The use of phase angle information between two selected signals, hereinafter called a directional relay, has been successfully applied in power system protection to detect direction of current flow under fault conditions.

In order to cover all possible types of faults, to operate in cases of forward faults and to remain stable for reverse faults, it is important to select the two most suitable signals, the operating and the polarising quantities and the angular range of measurement between them.

From the definition above, it can be seen that with a fixed reference (or polarising signal) there is a difference between the sign of the current signal for forward and reverse faults. It is important, therefore, that the polarising signal chosen should remain unchanged in polarity for both forward and reverse faults.

A pure phase-comparison process would be adequate to determine the direction of current flow. The criterion for success of this approach is that all types of faults occurring in the forward direction result in the phase relationship falling within the designed boundaries of operation. Conversely, the phase between the operating and polarising signals resulting from any faults on the system in the reverse direction should not encroach onto the range of operation, which would otherwise result in wrong detection of direction.

The use of voltage as the polarising signal leads to the design of a voltage polarised directional relay. There are many combinations of voltages to form the polarising signal, leading to a number of relay connections defined as the angle between the relay operating current and its polarising voltage at primary system unity power factor. The most common types of relay connections are 30-degree, 60-degree and 90-degree or quadrature connections. The input voltage and current signals to each of these connection types on a single-phase basis are shown in Table 2.1 [3.8, 3.9].

Table 2.1 Different Connections of Single-phase Voltage Polarised Directional Relays with the associated Input Signals:

| Connections | Input Signals | | |
|---|---|---|---|
| | A-Phase Relays | B-Phase Relays | C-Phase Relays |
| 30° | $I_A$ $V_{AC}$ | $I_B$ $V_{BA}$ | $I_C$ $V_{CB}$ |
| 60° | $I_{AB}$ $V_{AC}$ | $I_{BC}$ $V_{BA}$ | $I_{CA}$ $V_{CB}$ |
| 60° | $I_A$ $-V_C$ | $I_B$ $-V_A$ | $I_C$ $-V_B$ |
| 90° | $I_A$ $V_{BC}$ | $I_B$ $V_{CA}$ | $I_C$ $V_{AB}$ |

It is well established [1.4, 3.8, 3.9] that the 90-degree or quadrature connection is the best for use with phase overcurrent protection.

For directional earthfault protection the directional element, in addition to using voltage as the polarising signal, can also use a current signal leading to a current polarised directional earthfault relay. It is also possible to use a combination of voltage and current to form a dual polarised directional earthfault relay.

For earthfault protection, the zero phase sequence current is used as the operating signal and the most convenient polarising signal is, therefore, the zero phase sequence voltage and the zero phase sequence current [3.8].

The objectives of selecting the correct operating current and polarising voltage are to ensure that under all fault conditions:

(i) that the magnitudes of the voltage and current signals are sufficient to meet the threshold of operation of the detectors.

(ii) the angular displacements between these two signals are within the boundaries defined for forward fault operation or reverse fault restraint.

Figure 2.3 illustrates the $30^0$ connection selecting the voltage $V_{AC}$ and the current $I_A$ as the input signals for the A-phase directional relay on single-phase basis.

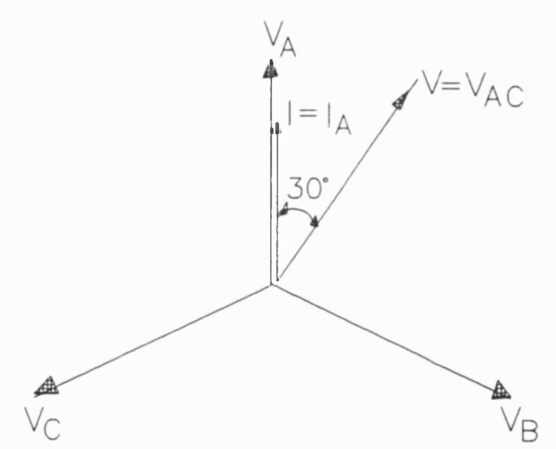



Figure 2.3 Typical Input Voltage and Current Phasors for 30-degree Connection of a Directional Relay.

For the 90° connection where the polarising voltage is in quadrature with the operating current under unity power factor conditions, the A-phase relay, again on single phase basis, uses the current $I_A$ as the operating signal and the voltage $V_{BC}$ as the polarising signal. The phasor diagram is shown in Figure 2.4.

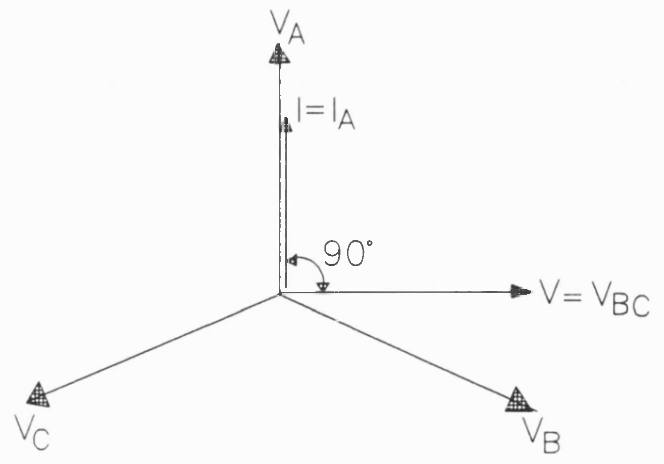



Figure 2.4 Typical Input Voltage and Current Phasors for 90-degree Connection of a Directional Relay.

When the appropriate input voltage and current signals have been selected for a given design it is necessary that under forward fault conditions the angular displacement between the two input signals is within the boundaries of operation of the design. To check this requirement consider a 3-phase fault and the A-phase relay with a $90^0$ connection. The relay input signals are $I_A$ for the operating current and $V_{BC}$ for the polarising voltage. The phasor diagram is shown in Figure 2.5.

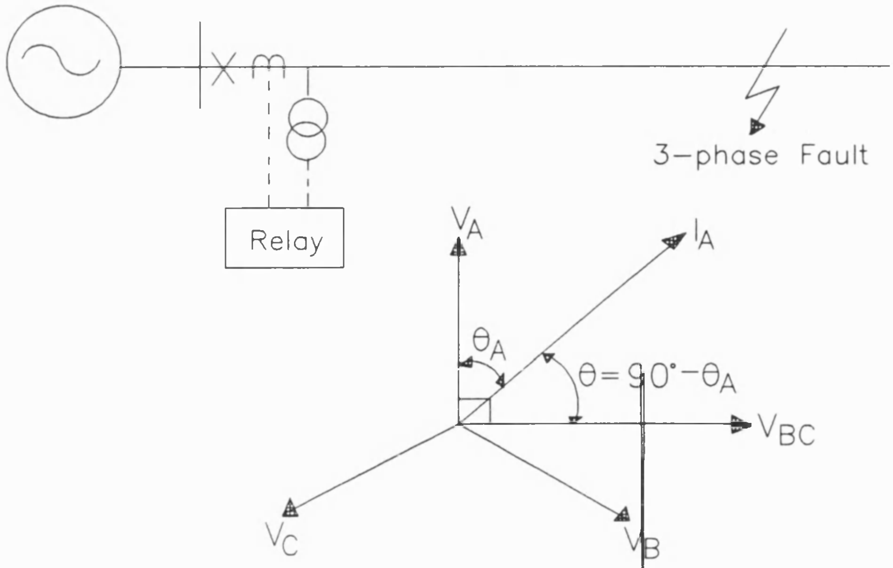



Figure 2.5 Phase Displacement between the Input Voltage and Current for a 90-degree Connection Directional Relay under a 3-phase Fault Condition.

For a 3-phase fault the angular displacement $\Theta$ between the input signals V and I is given by:

$$\theta = 90^{\circ} - \theta_A \qquad \text{........2.08}$$

where $\Theta_A$ is the argument of the fault impedance between the relaying point and the fault point.

$\Theta_A$ varies from approximately zero for close-up arcing faults to 90° for remote faults with negligible fault resistance. This gives a range of variation of $\Theta$:

$$\theta = 0^{\circ} \ to \ 90^{\circ} \qquad \text{........2.09}$$

If the boundaries of operation for this relay are 90° ≥ Θ ≥ 0°, the directional relay is then able to determine the direction of the fault point correctly.

Consider the case of a phase-phase fault involving the B and C phases and the B-phase relay, again with a $90^0$ connection. The relay input signals are $I_B$ for the operating current and $V_{CA}$ for the polarising voltage. The phasor diagram is shown in Figure 2.6.

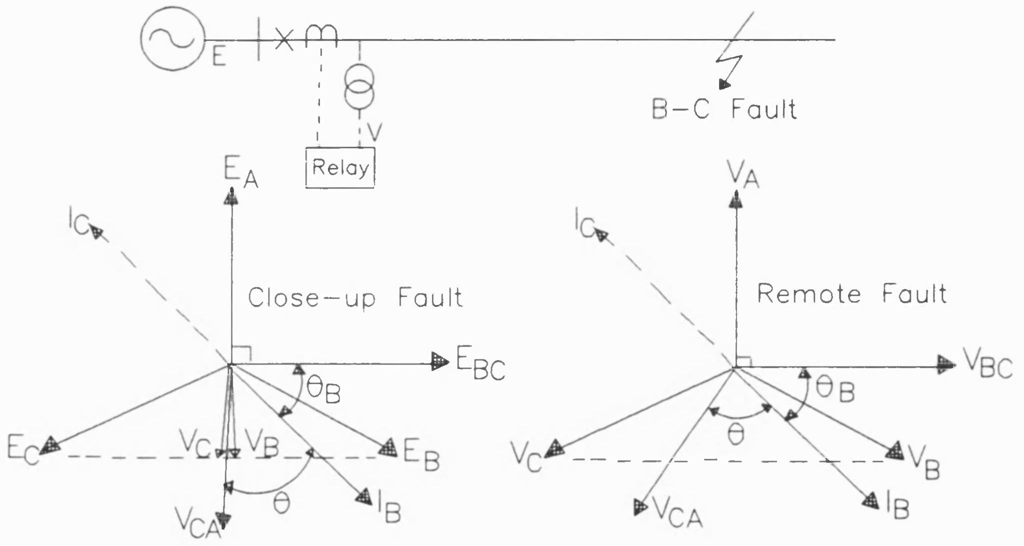



Figure 2.6 Phase Displacement between the Input Voltage and Current for a 90−degree Connection Directional Relay under a Phase−phase Fault Condition.

For close-up faults the phase displacement Θ between the input voltage $V_{CA}$ and the input current $I_B$ is given by:

$$\theta \approx 90° - \theta_B \qquad \text{........2.10}$$

where $\Theta_B$ is the angle associated with the impedance consisting of the source impedance and fault resistance.

The range of variation of this impedance angle $\Theta_B$ is:

$$\theta_B = 0° \ to \ 90° \qquad \text{........2.11}$$

This provides the limits to the variation of the phase displacement $\Theta$ as:

$$0° \leq \theta \leq 90° \qquad \text{........2.12}$$

For forward faults, remote from the relay location, the voltage drop across the source impedance is small. The phase displacement $\Theta$ between the input voltage $V_{CA}$ and the input current $I_B$ is then given by:

$$\theta \approx 120° - \theta_B \qquad \text{........2.13}$$

This gives the limits to the variation of the phase displacement $\Theta$ for this fault condition:

$$30° \leq \theta \leq 120° \qquad \text{........2.14}$$

If the boundary of operation for this relay is $90° \geq \Theta \geq 0°$, based on the 3-phase fault consideration above, the relay may not be able to operate for all the remote forward faults involving the B and C phases.

The above examples illustrate how the range of phase displacement between the two input signals under different fault conditions varies according to the connection of the relay. It is thus necessary to define clearly the boundaries of operation in terms of angular range within which the phase displacement between the operating current and polarising voltage, for the forward fault condition considered, falls.

The boundaries of operation are defined by the maximum torque angle of the relay. This is defined as the angle by which the operating current applied to the relay must be displaced from the polarising voltage to produce maximum torque. This terminology has been derived from the electromechanical design of directional relays. For solid state relay designs, it has been referred to as the relay characteristic angle. The boundary of operation is then $\pm$ 90° on either side of the maximum torque angle position. A typical example, for a 90° connection, is +45° maximum torque angle. This is illustrated in Figure 2.7 for the A-phase relay based on a single phase design using the A-phase current ($I_A$) and B-C-phase voltage ($V_{BC}$) as the input signals.

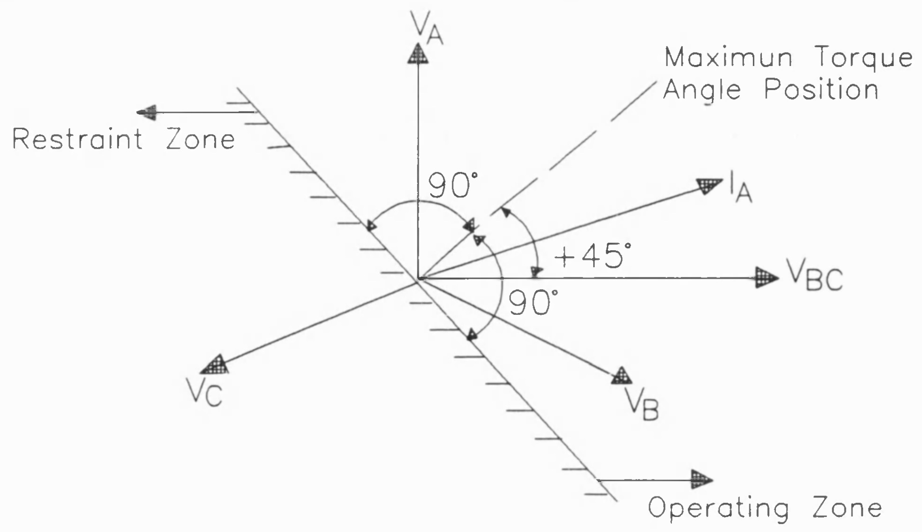



Figure 2.7 Boundries of Operation defined by the Maximum Torque Angle for a 90-degree Connection Directional Relay.

The directional relay is now fully defined with both the connection and maximum torque angle stated and provides clearly defined boundaries of operation. For a correctly designed directional relay, the range of variation of the angular displacement between the selected operating current signal and the polarising voltage signal should be within these boundaries of operation for all forward fault types and under any operating conditions. Conversely for reverse faults, the angular displacement between the two input signals should never fall within the operating range.

## 2.3 Different Methods of Directional Detection

Section 2.1 outlined one method of determining fault direction with reference to the relay location. This method, dependent on the angular displacement between an operating current signal and a polarising voltage signal, is the most common form of directional detection method used in relays applied to distribution system protection.

There are a number of directional elements being employed in practical applications using different principles of operation. These include:

(i) "Product" type directional relays based on the effect of mixing voltage and a current signals that depend on the magnitudes of the signals and their angular displacement.

(ii) Phase-angle-measurement directional relays based on the value of angular displacement between a chosen voltage and an appropriate current signal or between two compensated voltage signals. The measurement process is substantially independent of the magnitudes of the input signals.

(iii) Directional-impedance type directional relays based on the comparison of a combination of voltage and current signals against a polarising voltage signal.

(iv) Phase-compensated type directional relays based on phase comparison between two of three compensated phase voltages.

(v) Travelling-wave-phenomenon type directional relays based on an observation of the change in travelling voltage and current wave polarities due to the occurrence of a disturbance on the power system.

(vi) Superimposed-signal type directional relays, based on a comparison of the superimposed voltage and current signals generated under fault conditions.

### 2.3.1 "Product" type of Directional Relays

The first generation of directional relay was based on this principle of operation. The design, based on electromechanical techniques and employed mainly for the directional control of overcurrent and earthfault protection relays, uses "product" measurement to achieve the phase-comparison process between the input operating current and the polarising voltage. This responds to the product of voltage and current and the cosine function in terms of the phase angle between these two quantities and other intentional phase shifts.

The basic design consists of a mechanically moving element operating on the interaction between the polarising circuit flux and the operating circuit flux. The design is arranged in such a way that contact-closing torque is produced for forward faults whilst reverse faults will result in contact-opening or restraint torque.

Figure 2.8 shows an electromechanically designed directional relay. Two circuits, one voltage and the other current with voltage being used as the polarising signal, generate fluxes that act on the moving element at the centre.

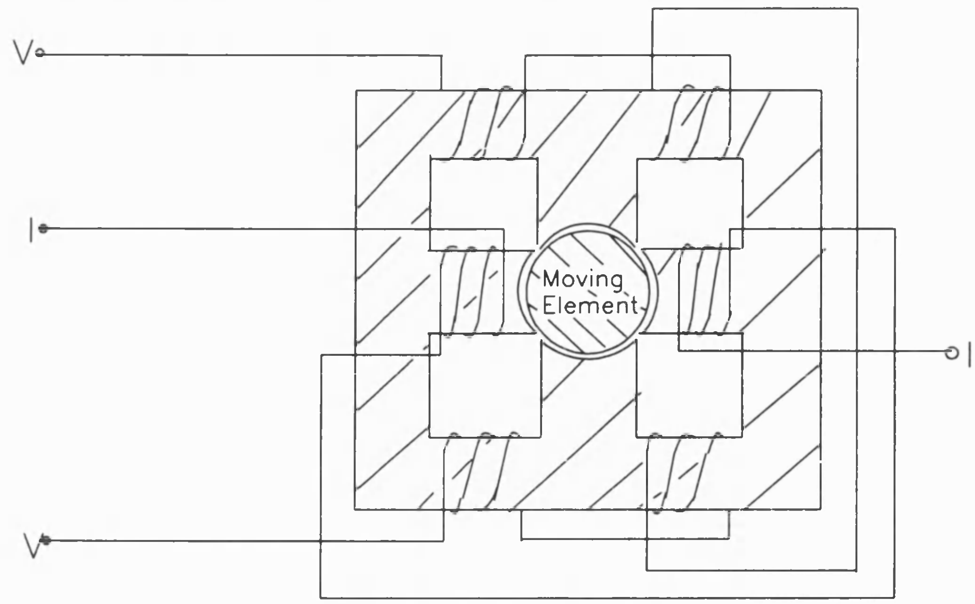



Figure 2.8 Electromechanical Directional Relay.

The phasor diagram is shown in Figure 2.9 with the fluxes generated by the voltage and current signals.

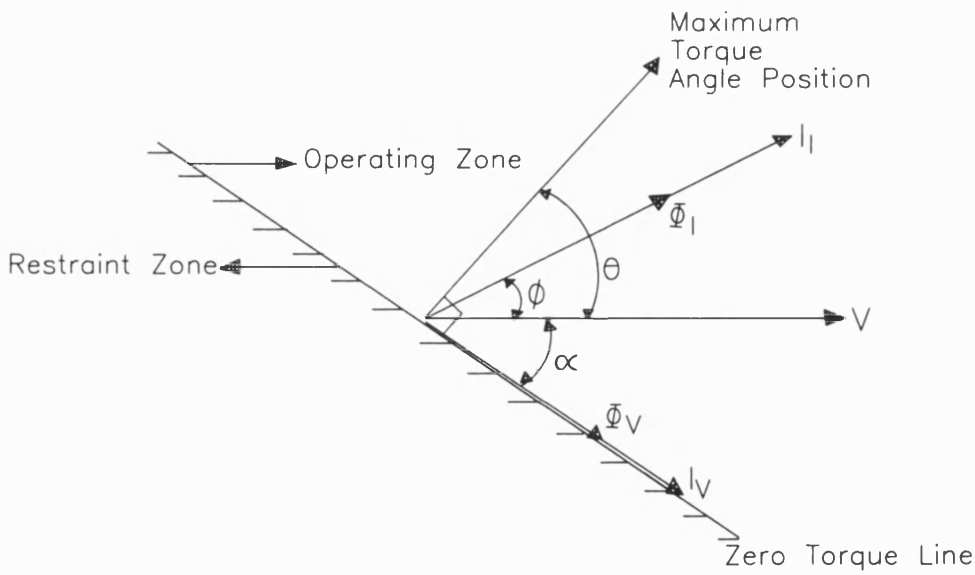



Figure 2.9 Phasor Diagram of the Input Voltage and Current and the Fluxes generated for an Electromechanical Directional Relay.

The flow of currents in the two circuits ($I_V$ in the voltage circuit and $I_I$ in the current circuit), generates two fluxes, $\Phi_V$ and $\Phi_I$ respectively. The electrical torque generated by the interaction of these two fluxes to drive the moving element is proportional to the magnitude of the two fluxes and the sine function of the angular displacement between them. This is given by:

$$Torque \propto \Phi_V \, \Phi_I \, Sin\ (\phi + \alpha) \qquad \text{.......2.15}$$

The flux produced is directly proportional to the respective voltage or current magnitude. Hence:

$$Torque \propto |V| \ |I| \ Sin\ (\phi + \alpha) \qquad \text{.......2.16}$$

The torque produced for a given voltage and current is maximum when $\phi + \alpha = 90°$. With the voltage signal, and hence the voltage flux $\Phi_V$ as the reference, a maximum torque position of the current flux phasor $\Phi_I$ can be defined as a perpendicular line to the phasor $\Phi_V$. This is the maximum torque angle line along which the current phasor $I_I$ and hence the current flux $\Phi_I$ will generate maximum torque to drive the moving element. If this maximum torque angle line is at an angle $\Theta$ from the voltage phasor V, the angle $\Theta$ is defined as the maximum torque angle.

From Figure 2.9 it can be seen that:

$$\phi + \alpha = 90° - (\theta - \phi) \qquad \text{.......2.17}$$

Hence the torque produced becomes:

$$\begin{aligned} Torque &\propto |V| \; |I| \; Sin \; (90° - (\theta - \phi)) \\ &\propto |V| \; |I| \; Cos \; (\theta - \phi) \end{aligned}$$

.........2.18

The torque produced is maximum when $\phi = \Theta$, i.e. when the current phasor is displaced from the voltage phasor by the maximum torque angle value.

This product type directional relay therefore operates on the interaction or "product" of the three quantities - voltage, current and the cosine function of their angular displacement and any additional phase shift. The torque produced becomes negative if the angular displacement falls outside the range of angles, in this case ± 90° from the maximum torque angle line. A zero torque line can then be drawn as shown in Figure 2.9, one side of which is for operation i.e., the forward direction, and the other side for restraint or reverse direction.

Figure 2.9 shows the operating zone with no minimum limit to the operating current. In practice a certain amount of operating current is required and this current is minimum when its phasor is in phase with the maximum torque angle line position. This is shown in Figure 2.10.

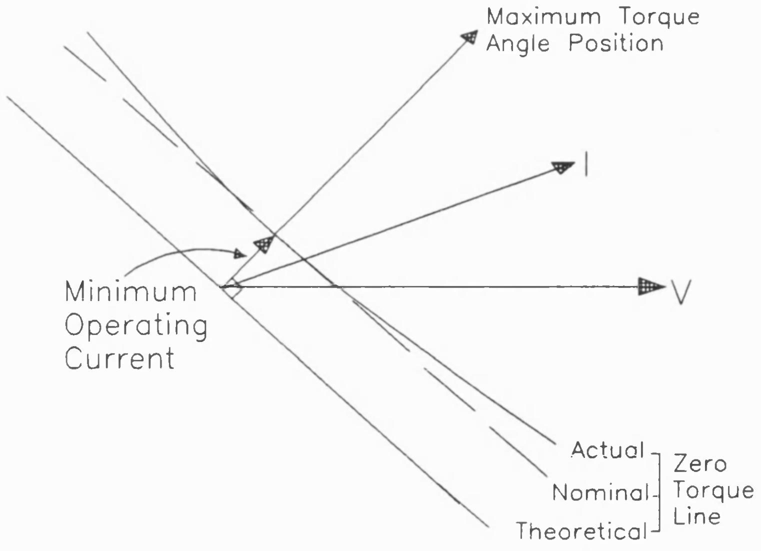



Figure 2.10 Operating Characteristic of Practical Electromechanical Directional Relay.

It can be seen that away from the maximum torque angle position, the amount of current required increases.

### 2.3.2 Phase-angle-measurement type of Directional Relays

This is a modified form of the "product" type of directional relay. In this case, the direction of a fault is wholly determined by examining the angular displacement between the operating current signal and the polarising voltage signal. The magnitude of the two signals, apart from meeting the minimum operating threshold of the equipment, does not come into the directional decision process.

This type of directional relay [1.5] is made possible by solid-state electronic designs where maximum sensitivity can be achieved. The phase angle measurement process can be made independent of the magnitude of the two signals once the signal strength exceeds the equipment operating threshold. The threshold level is so small that the directional detection process is considered practically independent of the signal magnitudes.

For this type of directional relay, the basic principle of operation remains the same by examining the phase displacement of the operating current phasor in relation to the polarising voltage phasor to determine the direction of fault. In this case, there is no mechanical torque produced for operation. Hence, there is no maximum torque angle and instead, the relay characteristic angle is defined. This is the position of the operating current phasor with reference to the polarising voltage phasor for maximum sensitivity under which condition the relay will have the fastest operating speed. Figure 2.11 shows the operating characteristic of this type of directional relay.

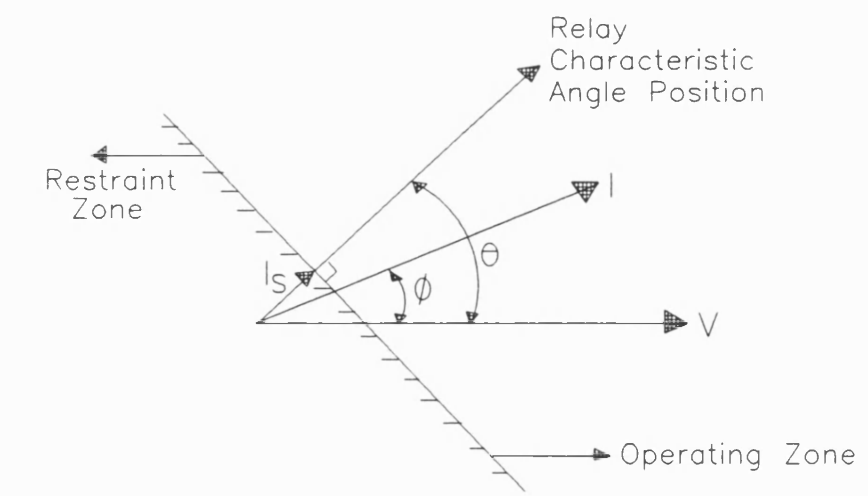



Figure 2.11 Operating Characteristic of Phase−angle−measurement type Directional Relay.

With the polarising voltage signal V greater than the designed threshold, the operating equation is:

$$I \, Cos \, (\phi - \theta) \geq I_s \qquad \text{........2.19}$$

which is independent of the polarising voltage signal magnitude, where $I_s$ is the minimum setting current.

The operating current also increases with its phase displacement related to the polarising voltage moving away from the relay characteristic angle position.

### 2.3.3 Directional-impedance type of Directional Relays

The use of directional impedance relays as directional elements has been well established. They have the added advantage of having a well defined area of response or reach. This reach is set in terms of the impedance value of the protected circuit beyond which the relay will not respond.

Directional impedance relays form the basis of the most popular form of protection for high voltage transmission and subtransmission networks and are commonly known as distance protection. Much research has been done into this particular form of power system protection from the initial electromechanical design, through to the first generation of solid-state relays, to the present day fully digital methods.

The most common form of directional impedance relays are the Mho relays as shown in Figure 2.12. Plotted on the impedance plane its characteristic shows a well defined area of operation inside the circle at a setting equivalent to Z ohms of the protected line. The characteristic passes through the origin, which is the relay location, indicating the directionalisation of the relay operating for forward faults on the protected line up to the reach point.

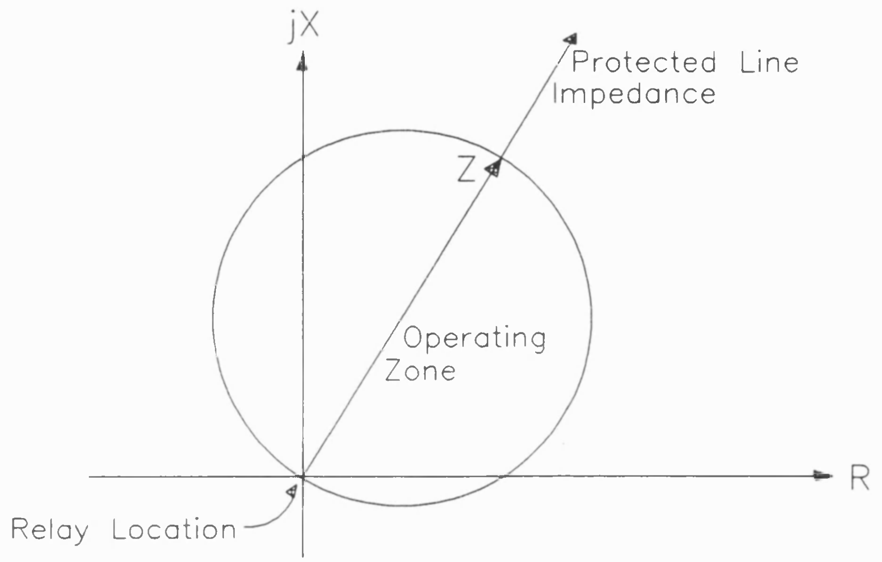



Figure 2.12 Mho type Directional Impedance Relay Characteristic.

Early efforts have been put into improving directional sensitivity without maloperation for faults with very low fault voltage especially in the reverse direction. Other work included ways to overcome one of the biggest limitations of impedance relays i.e., the limit on the amount of fault resistance coverage because of limits imposed by the load impedance. This led to the development of the cross-polarised characteristic which provides better directional sensitivity with increased fault resistance coverage without load encroachment. This is shown in Figure 2.13 for different source impedance values.

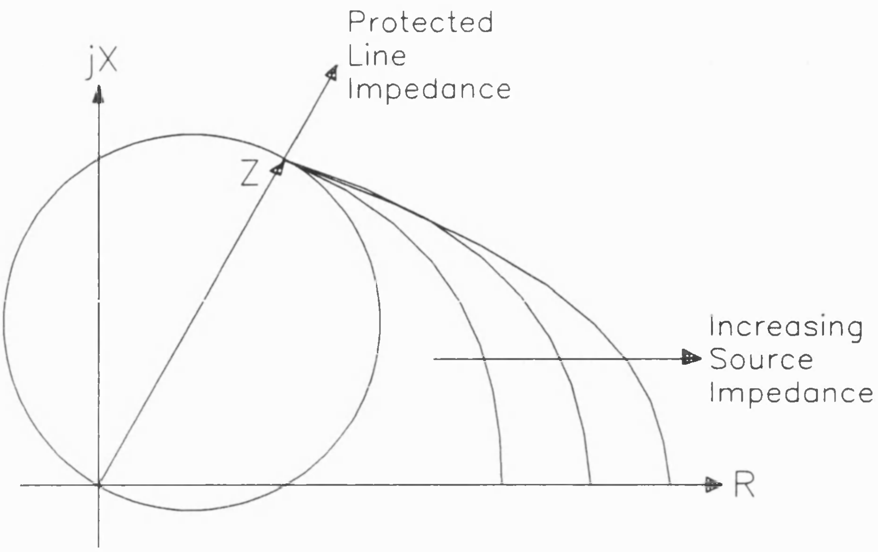



Figure 2.13 Cross-polarised Mho Directional Impedance Relay Characteristic.

This dependence on source impedance for increased fault resistance coverage generally limits its application to short lines.

An alternative was put forward based on a polygonal or quadrilateral characteristic with a directional line passing through the relay location on the impedance plane. This is illustrated in Figure 2.14.

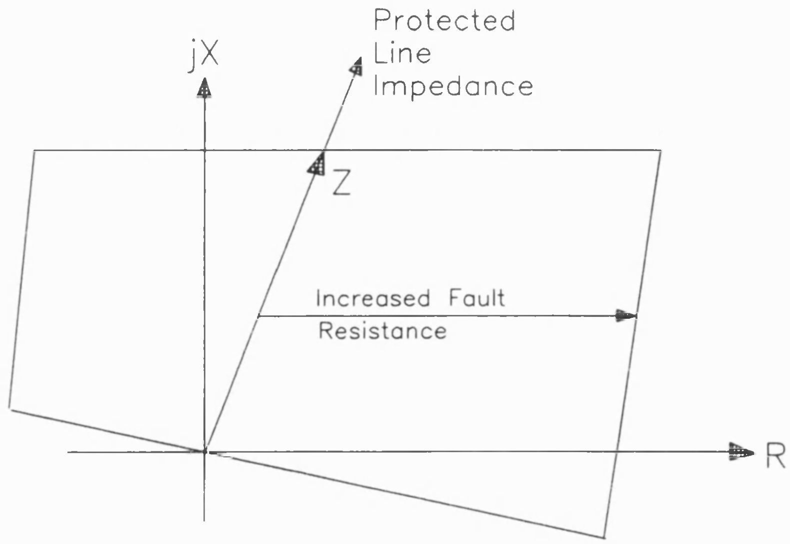



Figure 2.14 Quadrilateral type Directional Impedance Relay Characteristic.

However, early designs suffered from the problem of accuracy control at the reach point and also from achieving uniform speed within the whole of the operating zone. This was mainly due to the use of multi-input comparators.

The latest use of fully numerical methods has enabled successful generation of quadrilateral characteristics with good directional properties and an adaptive reactance characteristic to overcome traditional problems associated with such characteristics. This included tilting of the reactance lines to match the pre-fault loading conditions [1.24] and special trip logic controls to overcome overreaching due to double-phase-to-earth fault with significant fault resistance.

Directional impedance relays illustrate the derivative form of phase comparison between signals. Consider the case of the self-polarised mho characteristic, as shown in Figure 2.12; the characteristic is generated by measuring the angle between a composite operating signal V-IZ and the polarising signal V as shown Figure 2.15.

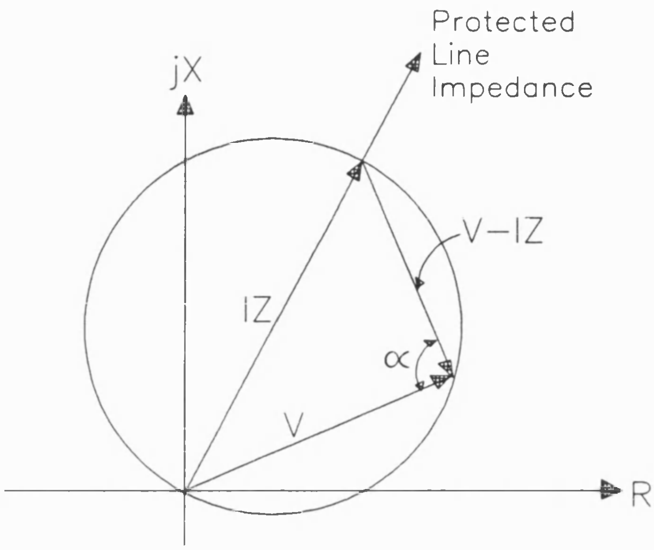



Figure 2.15 Generation of a Self−polarised Mho type Directional Impedance Characteristic.

For operation, the criterion is :

$$270° > \alpha > 90° \qquad \text{..........2.20}$$

This is the region inside the circle.

Instead of measuring the actual angle, the same result can be obtained by shifting the V signal through - 90° to provide the polarising signal and then examine the relative phase of the V-IZ signal (whether leading or lagging), as shown in Figure 2.16. External faults for no operation result in the composite operating signal V-IZ leading the polarising signal $V_{pol}$ whilst internal faults for operation result in V-IZ lagging $V_{pol}$.

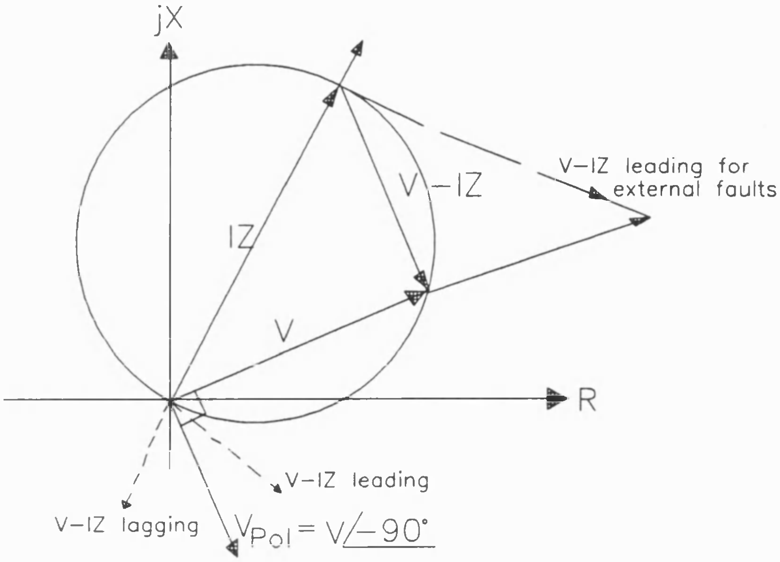


Figure 2.16 Generation of a Mho type Directional Impedance Relay Characteristic by Examining the Phase Relationship between the Operating and Polarising Signals.

This method was introduced in the 1980 [1.12] to provide high speed of operation with immunity against electrical interferences.

The use of directional impedance elements has been very successful and has been implemented in the application of various protection schemes such as directional comparison schemes over a suitable signalling channel. One of the limits, however, is the amount of fault resistance detectable by such elements. Therefore, directional earthfault schemes using zero phase sequence voltage and current signals to generate another form of directional relay are required. The directional relay used in this type of scheme is based on either the 'product' type or the phase-angle-measurement type that can operate down to very low fault current and can, therefore, detect much higher fault resistances.

### 2.3.4 Phase-Compensator type Directional Relays

A derivative of the directional impedance relay is the phase-compensator type directional relay [1.8]. This is based on a phase comparison between two of the three compensated phase voltages defined as:

$$V_{cA} = V_A - (I_A + K_O I_O) K Z_L \qquad \text{..........2.21}$$

$$V_{cB} = V_B - (I_B + K_O I_O) K Z_L \qquad \text{..........2.22}$$

$$V_{cC} = V_C - (I_C + K_O I_O) K Z_L \qquad \text{..........2.23}$$

where $K_O$ is the zero phase sequence compensating factor, K (a constant greater than unity) and $Z_L$ (the positive phase sequence impedance of the protected line).

Three comparators are set up to compare:

$$V_{cA} \sim V_{cB}$$

$$V_{cB} \sim V_{cC}$$

$$V_{cC} \sim V_{cA}$$

If $V_{cA}$ leads $V_{cB}$, $V_{cB}$ leads $V_{cC}$ or $V_{cC}$ leads $V_{cA}$ by an angle $\Theta$ then an output to indicate forward direction will be produced when:

$$180° \leq \Theta \leq 360° \qquad \text{.................2.24}$$

or $$210° \leq \Theta \leq 390° \qquad \text{................2.25}$$

This operating range is illustrated in Figure 2.17 for the comparison between $V_{cA}$ and $V_{cB}$ assuming $V_{cB}$ rotates about a fixed $V_{cA}$.

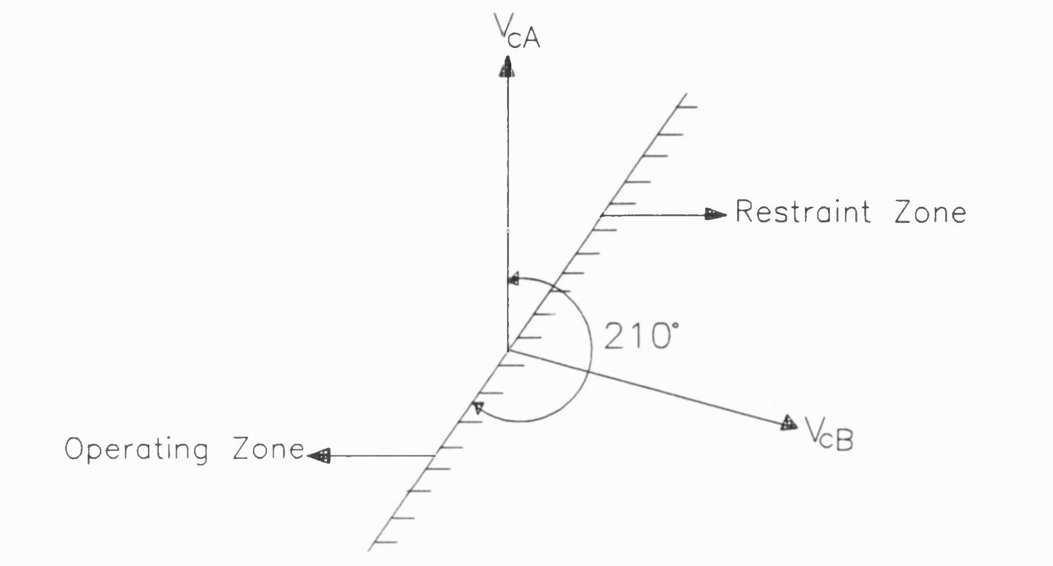



Figure 2.17 Operating Characteristic of a Phase-compensator type Directional Relay.

Figure 2.18 shows the phase relationship between the compensated voltages for a B-C phase-phase fault to illustrate the principle of operation.

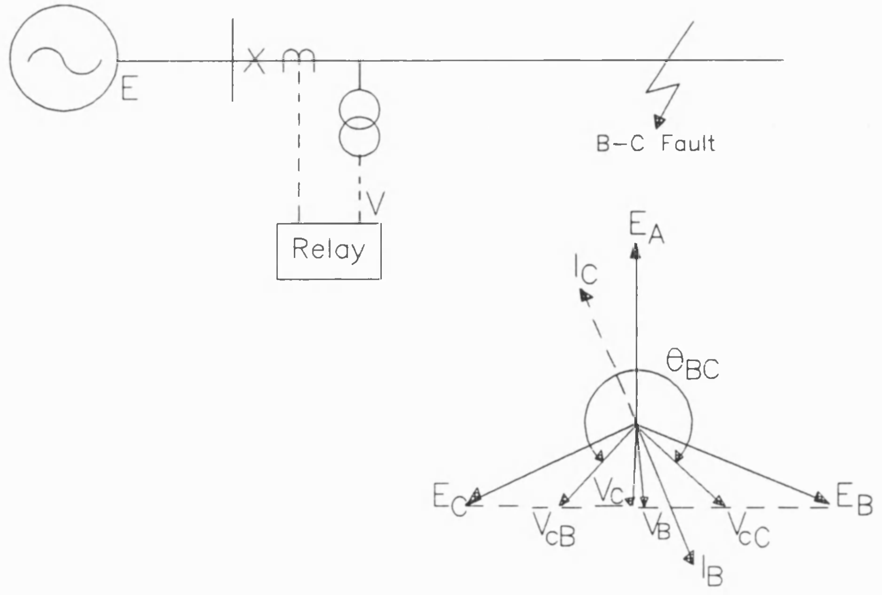



Figure 2.18 Compensated Voltages derived for a B–C Phase–phase Fault and the Comparison Angle.

This phase-compensator type directional relay has been shown [1.8] to operate satisfactorily with good directionality, under power swing and two-phase operation conditions.

### 2.3.5 Directional Relays based on Travelling Wave Phenomenon

The operating speed of directional impedance relays is limited to about one cycle operating time though half cycle operating time is possible with some present day commercially available directional impedance relays [1.12, 1.24]. To improve the speed further, directional detection has to be based on other principles of operation. This involves the use of travelling-wave related phenomenon direction detection principle.

The use of travelling wave polarities at the relay location to determine the direction of a fault point in relation to the relay location forms the basis of a directional wave detector.

From superposition theory, a faulted power supply system consists of an unfaulted part or the normal system and a superimposed component as shown in Figure 2.19.

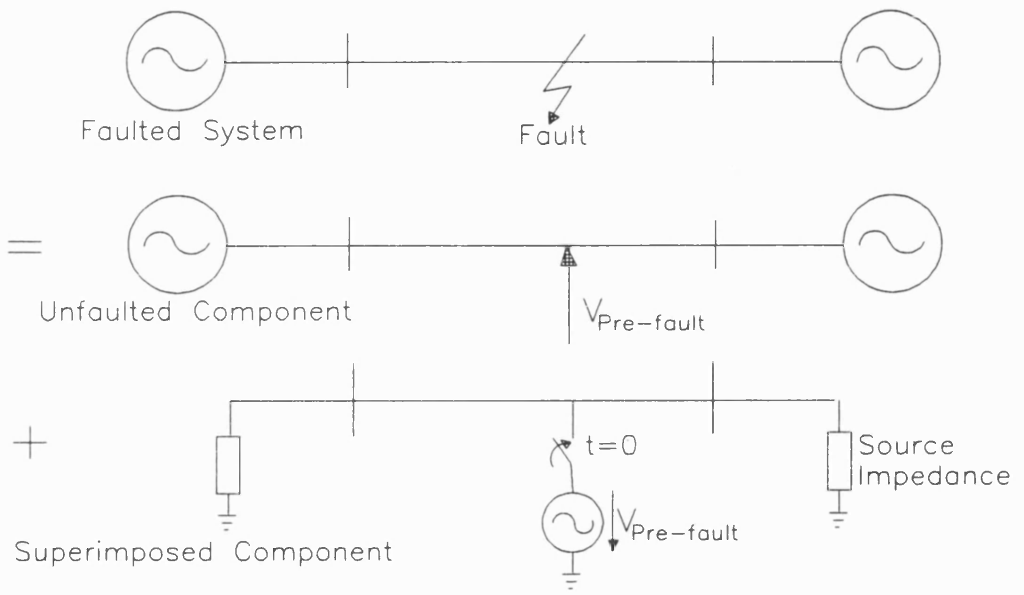



Figure 2.19 Superimposed Component in a Faulted System.

The superimposed component is produced by a fictitious voltage source applied to the fault point at the instant of fault inception with the two sources represented by the equivalent source impedances. The fictitious source has voltages on the faulted phases equal in magnitude and opposite in sign to the pre-fault voltages at the fault point.

The application of the fictitious source at the fault point causes voltage and current travelling waves to move from the fault point towards the two line-end terminals as shown in Figure 2.20. Positive current is defined at the relay location as a current flowing from the busbar to the line.

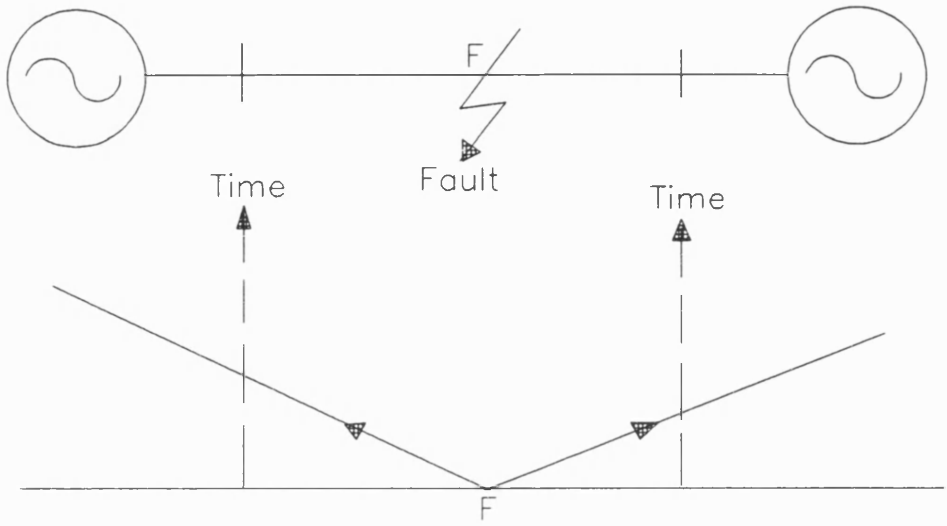



Figure 2.20 Generation and Propagation of Travelling Waves.

If the pre-fault voltage is positive, the fictitious source causes negative voltage waves to propagate towards the two line-end terminals but the current waves are positive since the source causes currents to flow from the two line ends to the faulted point. If the pre-fault voltage is negative, the current and voltage waves change in polarity. These are shown in Figure 2.21.

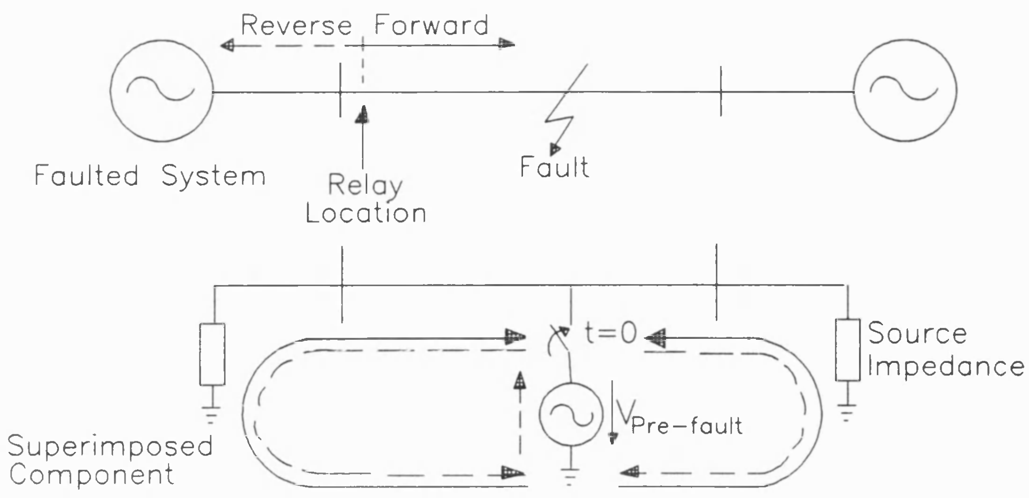



Figure 2.21 Polarity of the Travelling Waves generated under a Forward Fault Condition.

For a forward fault the voltage and current waves therefore have opposite polarity at the relay location.

In the case of a reverse fault, the fictitious source at the fault point causes the voltage and current waves to have the same polarity at the relay location as shown in Figure 2.22.

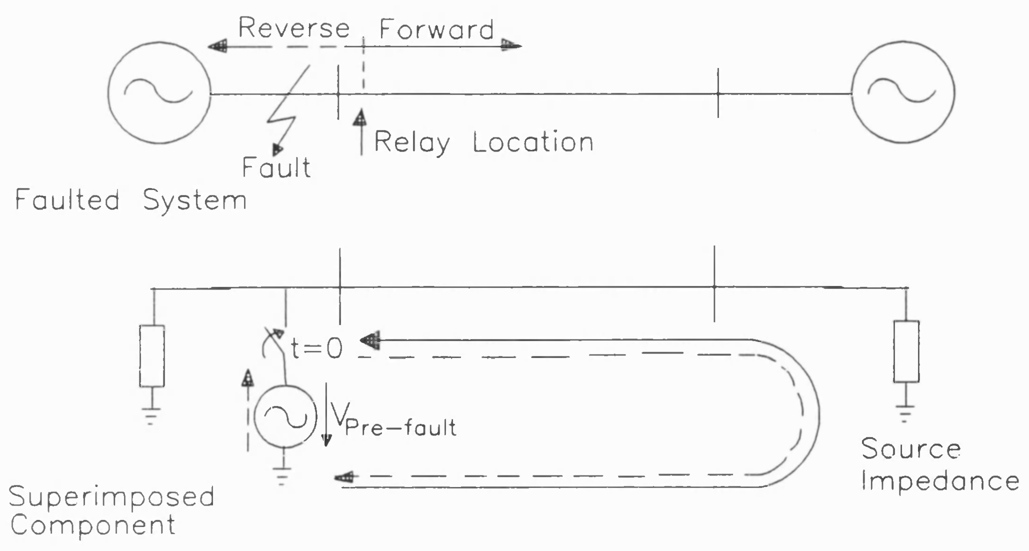



Figure 2.22 Polarity of the Travelling Waves generated under a Reverse Fault Condition.

From the principles outlined above, it can thus be concluded that in the case of a forward fault both line ends will experience voltage and current travelling waves of different polarities whilst for a reverse fault the two waves have the same polarity. These can be [3.7] determined by a travelling wave polarity detector as shown in Figure 2.23.

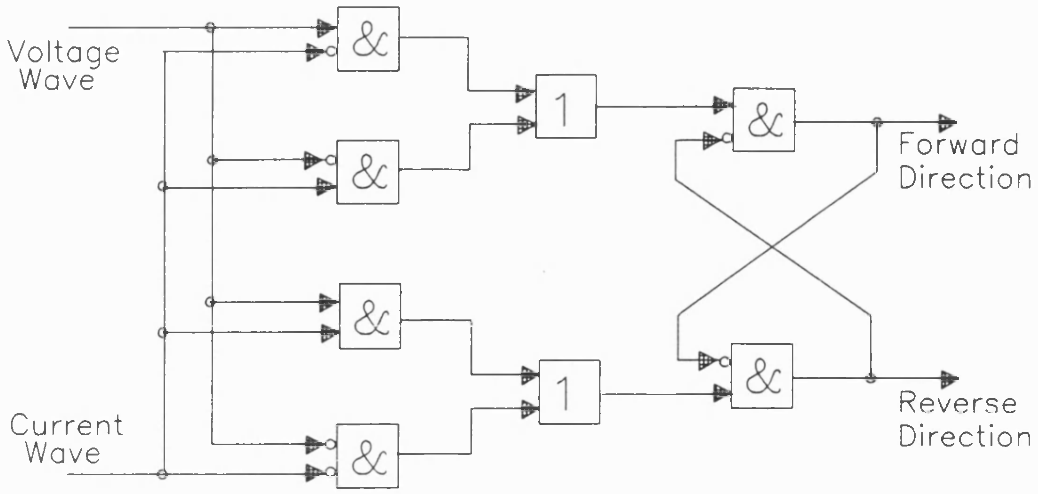



Figure 2.23 A Travelling Wave Polarity Detector.

For a forward fault, assuming the input voltage wave is positive whilst the current wave is negative, Figure 2.24 shows the output from the polarity detector indicating the occurrence of a forward fault.

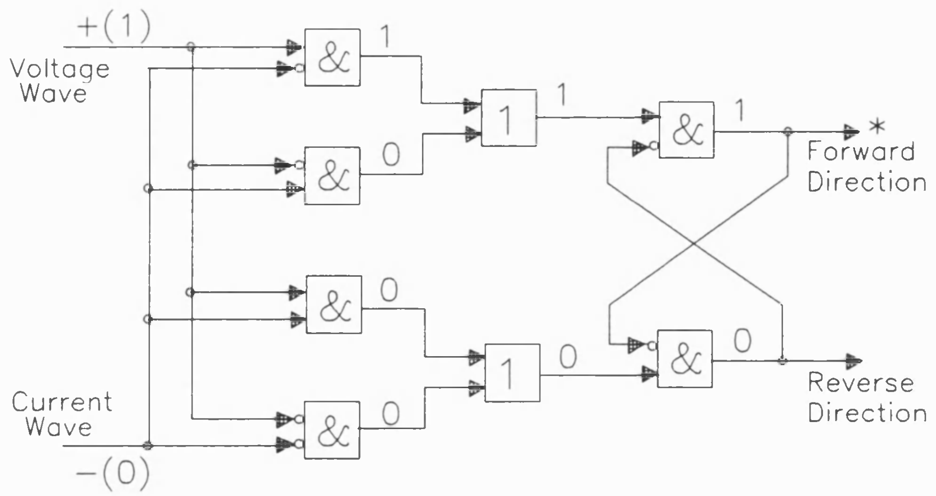



Figure 2.24 Output from the Travelling Wave Polarity Detector for Forward Faults.

For a reverse fault, assuming both the voltage and current waves are positive in polarity, the output from the polarity detector indicates a reverse fault direction as shown in Figure 2.25.

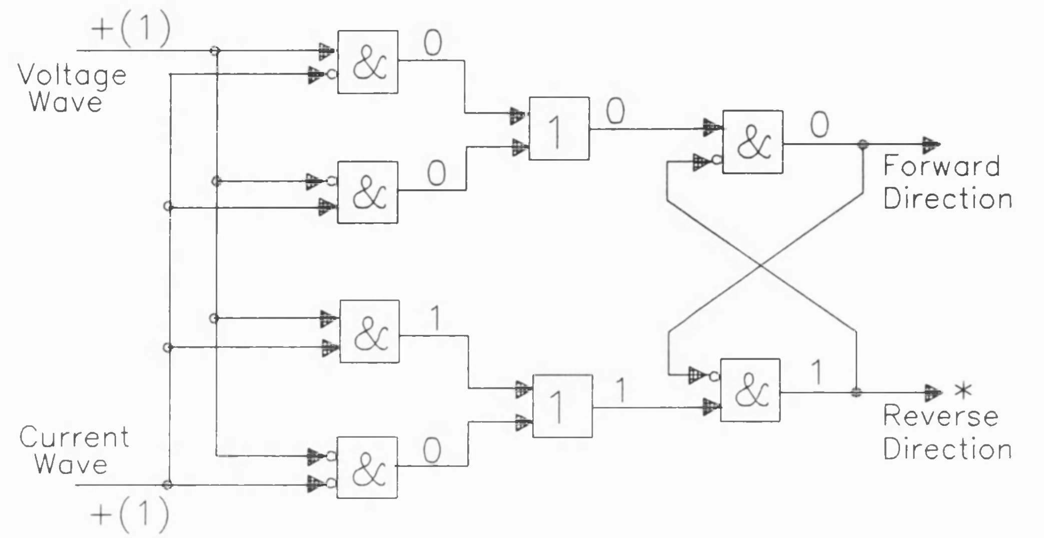



Figure 2.25 Output from the Travelling Wave Polarity Detector for Reverse Faults.

### 2.3.6 Directional Relays based on Superimposed Components

This type of directional relay [1.20, 2.14. 2.22] examines the changes in the voltage and the current signals at the relay location during the occurrence of a fault on the system. The superimposed components of the voltage and the current signals are employed in this directional detection process.

From the superimposed component of the system shown in Figure 2.19, the superimposed voltage $\Delta v$ and current $\Delta i$ signals (illustrated in Figure 2.26 for positive pre-fault voltage under forward fault condition) have the following relationship:

$$\Delta i = -\frac{\Delta v}{Z_S}$$

$$= -\frac{\Delta v}{|Z_S|} \angle -\theta_{ZS} \qquad \text{..........2.26}$$

where $Z_S$ is the source impedance with an angle $\Theta_{ZS}$.

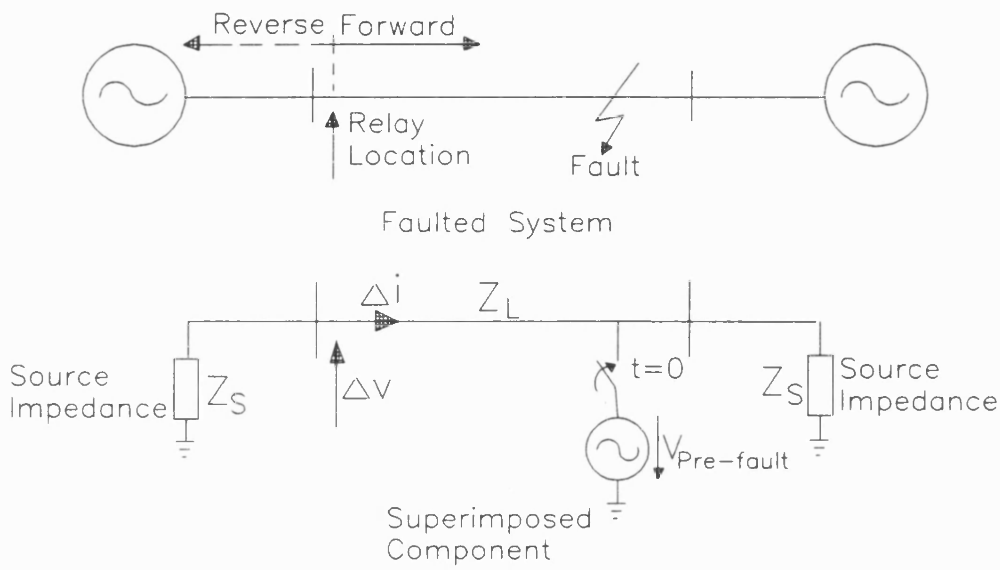



Figure 2.26 Superimposed Voltage and Current Components in a Faulted System for Forward Faults.

For a reverse fault, shown in Figure 2.27 the relationship between the two superimposed components is:

$$\Delta i = +\frac{\Delta v}{Z_S + Z_L}$$

$$= +\frac{\Delta v}{|Z_S + Z_L|} \angle -\theta_{ZS+ZL} \qquad \text{........2.27}$$

where $Z_L$ is the protected line impedance and $\Theta_{ZS+ZL}$ is the angle associated with the apparent source impedance for a reverse fault.

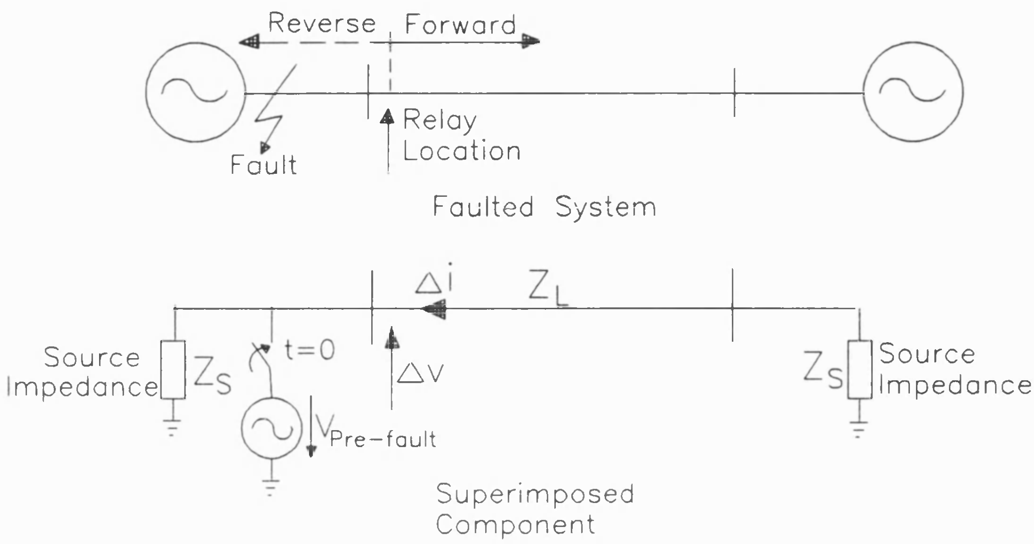



Figure 2.27 Superimposed Voltage and Current Components in a Faulted System for Reverse Faults.

The difference in polarity between the forward and reverse fault relationship shown in equations 2.26 and 2.27 thus provides a basis for directional detection. The process involves a comparison of the two signals, superimposed current $\Delta i$ and the superimposed voltage $\Delta v$ delayed by an angle equal to the angle of the apparent source impedance. Forward fault conditions are indicated by opposite polarity of the two signals, whilst like polarity indicates a reverse fault condition.

# CHAPTER THREE

# SURVEY OF EXISTING DIRECTIONAL RELAYS FOR USE WITH OVERCURRENT AND EARTHFAULT PROTECTION SCHEMES

## 3.1 Introduction

Existing directional relays for use with overcurrent and earthfault protection schemes consist of single-phase and polyphase types each of which can be of electromechanical or solid-state design. The solid-state design can be further classified into analogue or digital versions depending on whether analogue circuits or microprocessors with numerical techniques are used to implement the directional detection process.

Most of the directional elements used are based on the "product" type principle of operation using a polarising voltage and an operating current signals. Phase sequence components of voltages and currents are used in some designs (mainly the zero and negative phase sequence components) to determine fault direction based on either the "product" type or the phase-angle-measurement type of principle of operation.

## 3.2 Single-phase Directional Relays

Single-phase type of directional relays are generally designed for voltage polarisation. Relays with different maximum torque angles or relay characteristic angles are used to control the overcurrent and earthfault protection relays for different system configurations and system earthing arrangements. Different applications require different operating characteristics and the correct types have to be chosen for a particular application. Examples [3.8] of these are different leading maximum torque angles for directional overcurrent protection of plain- or transformer-feeders and various lagging maximum torque angles for directional earthfault protection applied to systems with different earthing arrangements.

For earthfault protection application the polarising signal input of some relays has two circuits to accept two polarising signals. These relays are dual-polarised with both voltage and current signals, each having different maximum torque or relay characteristic angles with reference to the operating current signal. The purpose of using these two polarising signals is to provide reference for the directional detection process, in case one signal is below the equipment threshold of operation.

For relays employing phase sequence components of voltages and currents the same principle of operation applies. The directional detection decision is based on the angular displacement between the voltage and current of the chosen phase sequence being within set limits. The most common type is the directional relay for earth faults using zero phase sequence components of voltage and current to determine the direction of faults. The zero phase sequence components are extracted by the connections of the instrument transformers before feeding to the directional relay.

There are basically five types [3.8, 3.9] of single-phase directional relays for overcurrent protection based on different connections. Each type of connection may have a selection of maximum torque angles or relay characteristic angles to suit different applications. It has been recognized [1.4, 3.8, 3.9] that the 90° connection is the best of the five in performance and has been adopted by most manufacturers [2.5, 2.6, 2.7, 2.13].

Single-phase directional relays for earthfault protection have only one design using the zero phase sequence voltage and current to determine the fault direction.

### 3.2.1 Electromechanical Design Type

The electromechanical design of a single-phase directional relay operates on the voltage-ampere "product" principle in which a contact-closing torque is produced acting on a moving element by the interaction of the voltage and current signals electromagnetically.

The moving element driven by the torque produced takes the form of an induction "cup" [2.7, 2.12, 2.13, 2.17]. The "cup" unit has a very low inertia and provides high speed of operation. Figure 3.1 shows the construction of a single-phase induction "cup" directional relay.

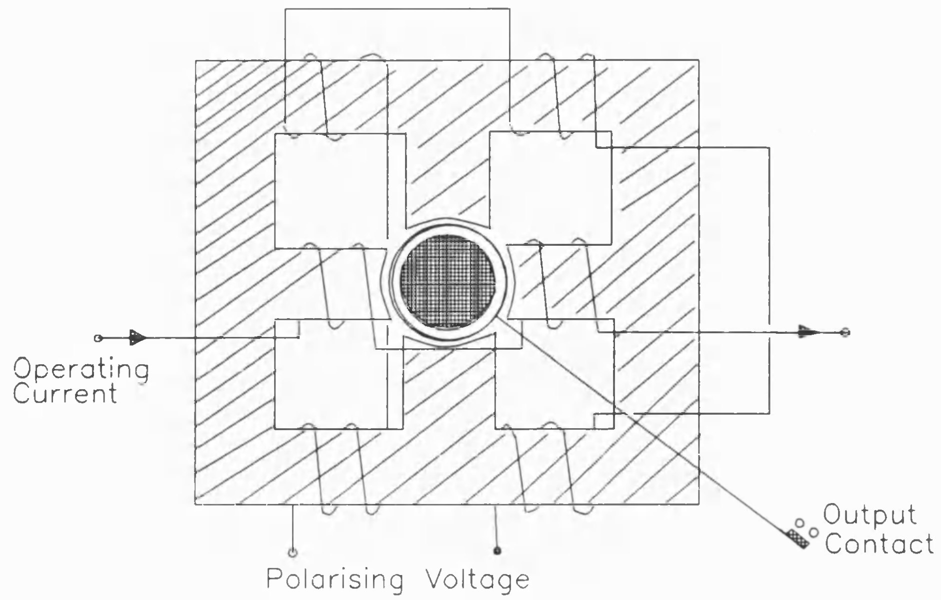


Figure 3.1 Construction of a Single-phase Induction Cup Directional Relay.

This type of directional relay uses the 90° or quadrature connection. Positive contact-closing torque is produced when the angular displacement between the two signals is within a defined range corresponding to a forward fault profile. A minimum level of polarising voltage and operating current signals is required to ensure positive operation. Details of the analysis of the principle of operation is shown in Appendix 11.3.

Instead of using an induction "cup" element based on phase comparison, polarity detectors such as polarised relays with rectifier bridges are also used [3.7, 3.11] based on an amplitude comparison of the two signals. This is shown in Figure 3.2.

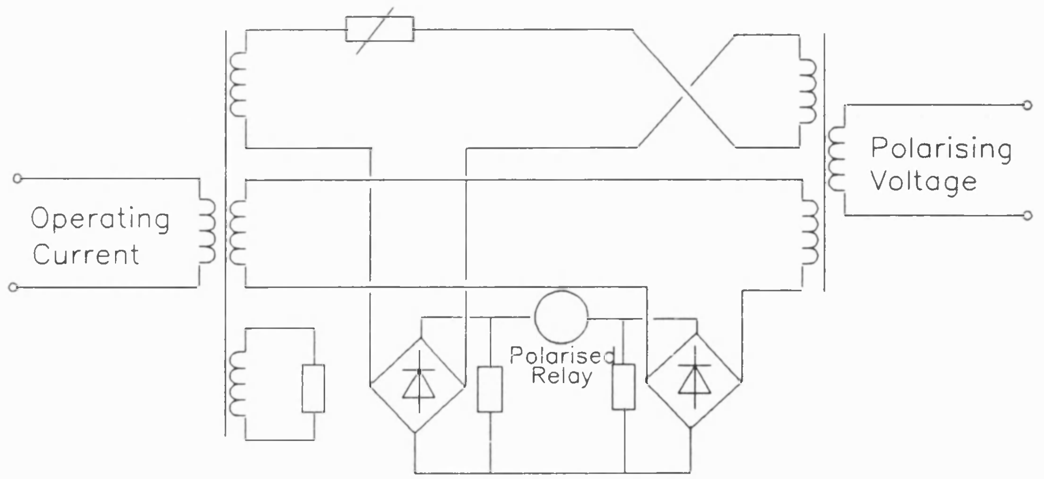



Figure 3.2 Construction of a Rectifier–Bridge/ Polarity–Detector type Directional Relay.

The direction information is extracted from a comparison of the polarities of the selected polarising and operating signals. The output of the comparison depends on the angular displacement between the two signals. Details of the analysis of the principle of operation is shown in Appendix 11.6.

### 3.2.2 Solid-state Design Type

Solid-state single-phase directional relays were introduced in the 1960's to improve the sensitivity and the operating speed. Most of the design of solid-state directional relays have been based on the analogue techniques. The most recent equipment uses digital techniques based on microprocessor technology.

The first generation of solid-state directional relays [2.16] used rectifier-bridge phase comparator and transistor design. The direction information is extracted from a measurement of the phase angle between the polarising voltage and the operating current signals. The solid-state design uses the same connections and maximum torque angles (relay characteristic angles) adopted in the electromechanical design.

#### 3.2.2.1 Analogue Design

The early generation of solid-state analogue design using discrete electronic components was merely an implementation of the electromechanical concept using mostly the phase-angle measurement technique to determine relay operation for forward faults or restraint for reverse faults. This gave some improvement in the sensitivity in terms of both threshold of operation and operating range. The basic circuit is shown in Figure 3.3.

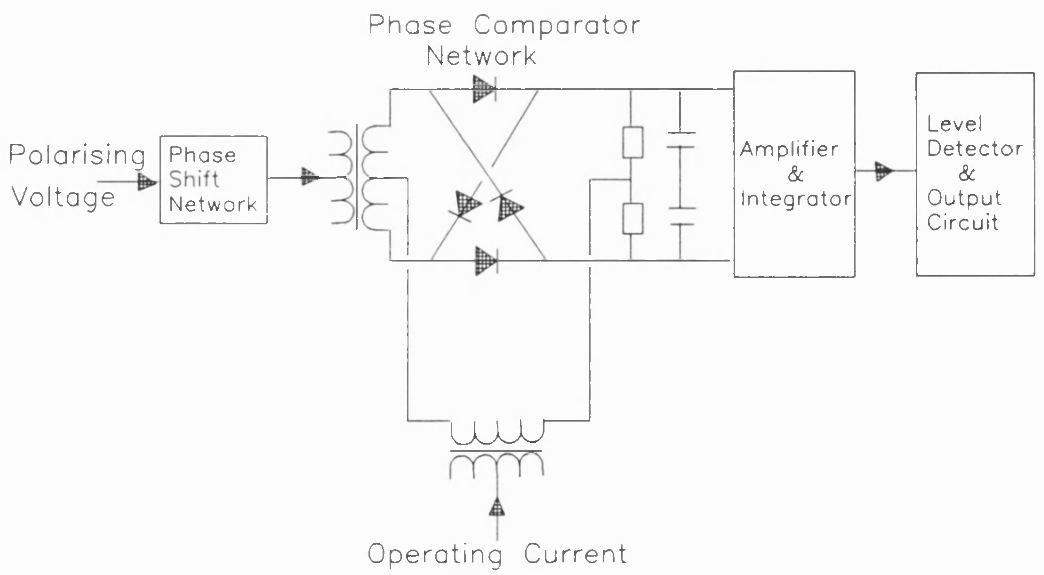



Figure 3.3 Basic Circuit of a Single-phase Solid-state Analogue Directional Relay.

A later design using integrated circuits improves the performance further [2.6]. The application flexibility is also enhanced in that the same relay unit is provided with multiple relay characteristic angle selection to enable the same unit for application as directional overcurrent or earthfault protection for different primary system configurations with different earthing arrangements of the system neutrals. This facility for multiple angle selection is implemented as shown in Figure 3.4.

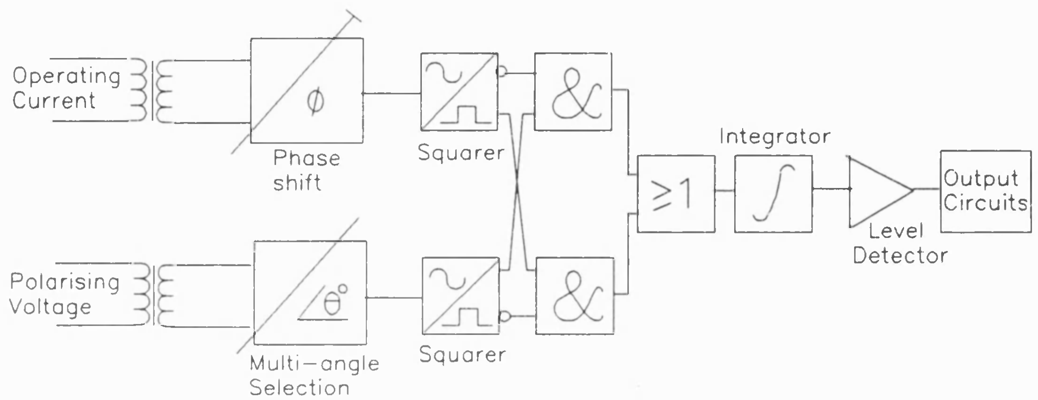



Figure 3.4 Basic Circuit of a Single-phase Solid-state Directional Relay using Integrated Circuits and providing Multi-characteristic-angle Selection.

### 3.2.2.2 Digital Design

Digital techniques have not introduced any fundamental changes in the principle of operation of directional relays. Single-phase digital directional relays for overcurrent and earthfault protection [2.18, 2.21] still use the phase-angle measurement between a polarising and an operating signals to determine the fault direction. There is no change in the signal selection and the operating angular range. However, there is further improvement in the operating range with further increase in sensitivity. The resolution in relay characteristic angle selection and also the range are much better and wider. It is also possible to programme the forward or reverse direction of the directional element without changing the external connections from the voltage and current transducers.

## 3.3 Polyphase Directional Relays

Though it is less common, polyphase directional relays are also available which have some advantages compared with the single-phase design. One obvious advantage is the cost of equipment with one three-phase unit compared with three single-phase units. There are some situations where polyphase directional relays are more suitable. These are discussed in Chapter 4.

There are four types of polyphase directional relays:

- Electromechanical type with a single moving element.

- Electromechanical type with three single-phase elements operating on one common shaft and operating a single set of output contacts.

- Solid-state type with three single-phase elements electronically separate but housed in one single relay case.

- Electromechanical or solid-state type based on phase sequence voltages and currents.

### 3.3.1 Electromechanical Design Type

Polyphase directional relays based on the electromechanical design techniques are either of the induction cylinder or "cup" unit [1.1, 2.7, 2.13] or the induction loop type [1.27, 2.12]. The induction cup type is a true polyphase design in that the various voltage and current signals are arranged to react with each other. The basic construction is shown in Figure 3.5.

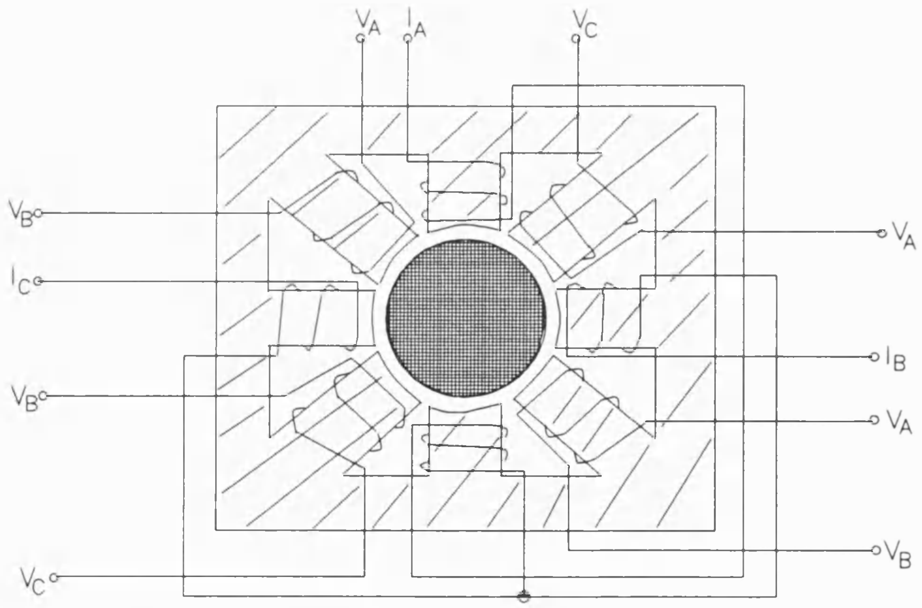


Figure 3.5 Construction of a Polyphase Electromechanical Induction Cup Directional Relay.

The induction loop type is not a true polyphase design in that three separate single-phase elements are used to act on a common shaft to provide the driving torque to cause the output contact to close for forward fault operation. This is illustrated in Figure 3.6 [2.12].

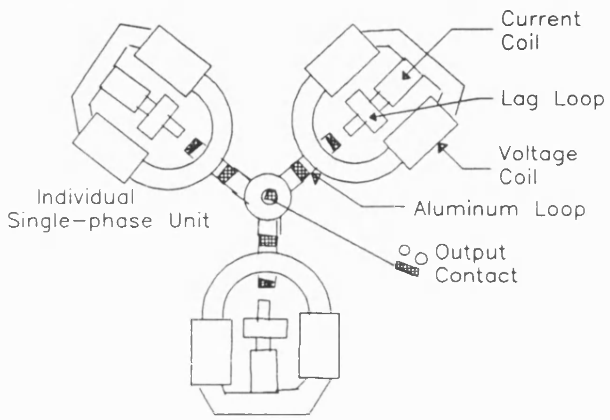



Figure 3.6 Construction of a Polyphase Electromechanical Induction Loop Directional Relay.

There is also a third type of electromechanical polyphase directional relay using phase sequence voltages and currents implemented on the "product' principle of operation. In this case, contact-closing torque is produced by the interaction of the fluxes generated by the phase sequence voltages and currents [2.13]. This is shown in Figure 3.7. for a design using the negative phase sequence components of voltage and current.

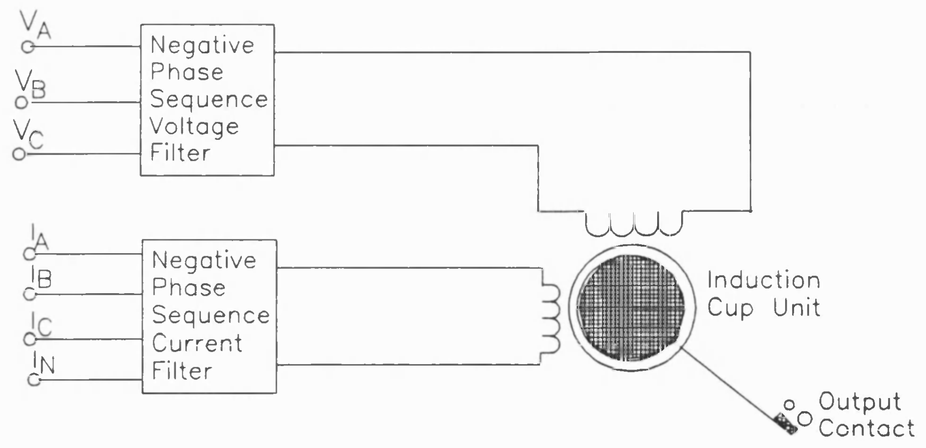



Figure 3.7 Construction of a Polyphase Electromechanical Induction Cup Directional Relay using Negative Phase Sequence Voltage & Current.

Alternatively, the direction is determined by the angular displacement between the two phase sequence signals using rectifier bridges and polarised relays [3.7, 3.11]. This is illustrated in Figure 3.8 for a polyphase directional relay based on the negative phase sequence components of voltage and current.

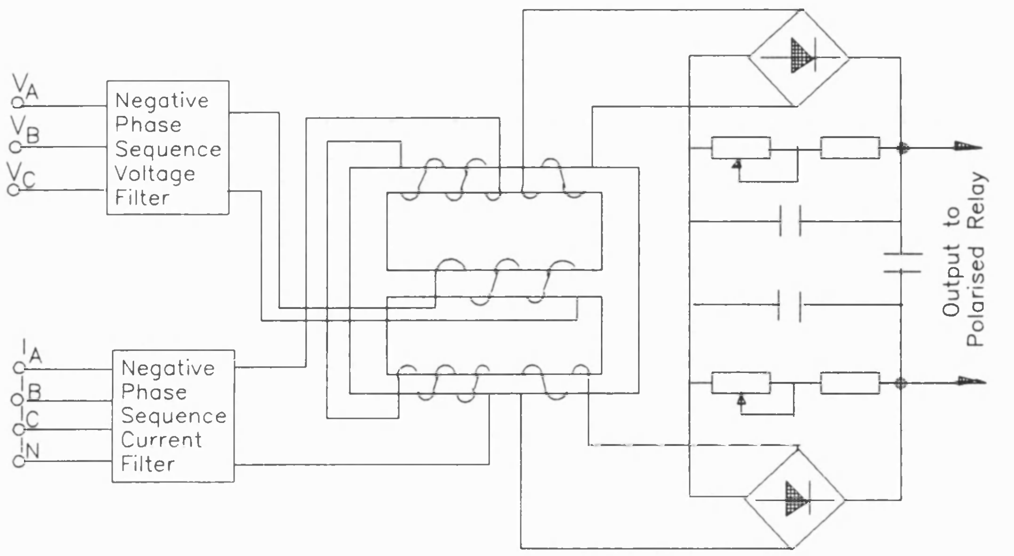


Figure 3.8 Rectifier Bridge type Polyphase Directional Relay using Negative Phase Sequence Voltage & Current.

### 3.3.2 Solid-state Design Type

There are two types of solid-state polyphase directional relays using either analogue or digital design. The first type consists of three single-phase directional units, each with separate outputs but housed in a single case with a common or individual power supplies [2.6, 2.24]. There is no solid-state equivalent of the electromechanical polyphase directional relay based on the "product" principle of operation.

The second type of solid-state polyphase directional relay uses phase sequence components extracted from the three phase system to derive the directional information of faults. The phase sequence components are either of the positive [2.1] or negative phase sequence [2.25].

### 3.3.2.1 Analogue Design

The relay consists of three single-phase directional units each with a separate output but housed in a single relay case with a common or individual power supplies for the electronic circuitry [2.6, 2.24]. The principle of operation is identical to the single-phase design. The basic circuit is shown in Figure 3.9.

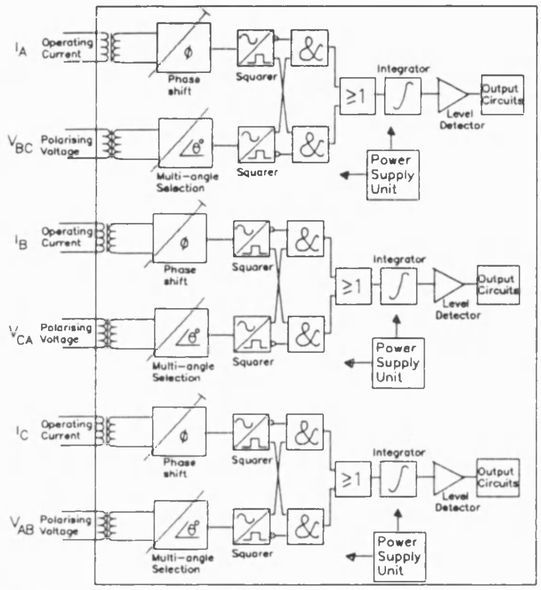


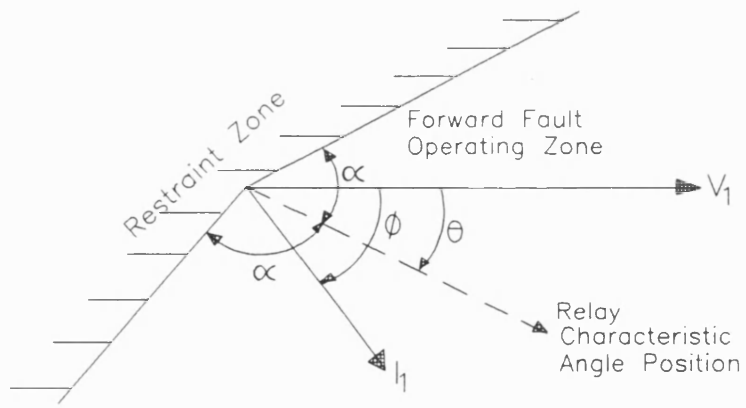

Figure 3.9 Basic Circuit of a Polyphase Solid-state Directional Relay with three Single-phase Units in a Common Relay Case.

### 3.3.2.2. Digital Design

The digital design of a polyphase directional relay for distribution system protection is again based on the single-phase concept. However, in this case the ability to multiplex signals and the power of single microprocessor have enabled a single unit to carry out a polyphase directional detection process. Fundamentally, the principle of operation is still based on an examination of a single polarising voltage and an operating current identical to the known single-phase design.

The three-element or some times four-element (three for phase and one for earth faults) digital polyphase directional relay uses only one microprocessor [2.18]. The signals associated with individual phase element are examined sequentially.

The other digital design of a polyphase directional relay uses phase sequence components [2.1] to derive the direction information. The operating characteristic of a relay using positive phase sequence components of voltage and current is shown in Figure 3.10.




α = Operating zone adjustment.
Ø = Phase angle between the positive phase sequence voltage & current for forward faults.
θ = Relay characteristic angle adjustment.

Figure 3.10 Operating Characteristic of a Polyphase Directional Relay using Positive Phase Sequence Voltage and Current.

The relay characteristic angle and the operating boundaries are adjustable to meet different applications.

# CHAPTER FOUR

## REVIEW OF PERFORMANCE OF EXISTING DIRECTIONAL RELAYS

### 4.1 Introduction

Existing directional relays used to directionalise current-operated relays for either overcurrent or earthfault protection of power systems have some limitations either in the equipment design or the principle of operation. For distribution systems the "product" type or phase-angle-measurement type are generally used whilst for transmission systems directional relays based on directional impedance measurement, travelling waves or superimposed components are mainly used. To cover high-resistance earth faults in transmission system protection schemes, additional phase-angle-measurement type directional relays, based on detection of either zero or negative phase sequence components of voltage and current and using solid-state designs, are employed to supplement the main scheme.

This Chapter highlights the deficiency in performance and problems in the applications of existing directional relays are outlined to serve as the basis for improvement by the proposed new method of directional detection. Since the prime objective of this project is to investigate directional detection methods for distribution systems, using current-operated relays, this Chapter concentrates on directional relays used for this area of power system protection.

The deficiency is investigated first on the basis of the hardware implementation, followed by an examination of the various principles of operation.

## 4.2 Electromechanical Design Type

Electromechanical designs of directional relays require a finite amount of energy to operate. This results in the boundary of operation being displaced from the origin as shown in Figure 4.1 to represent the minimum operating current required at the rated polarising signal level.

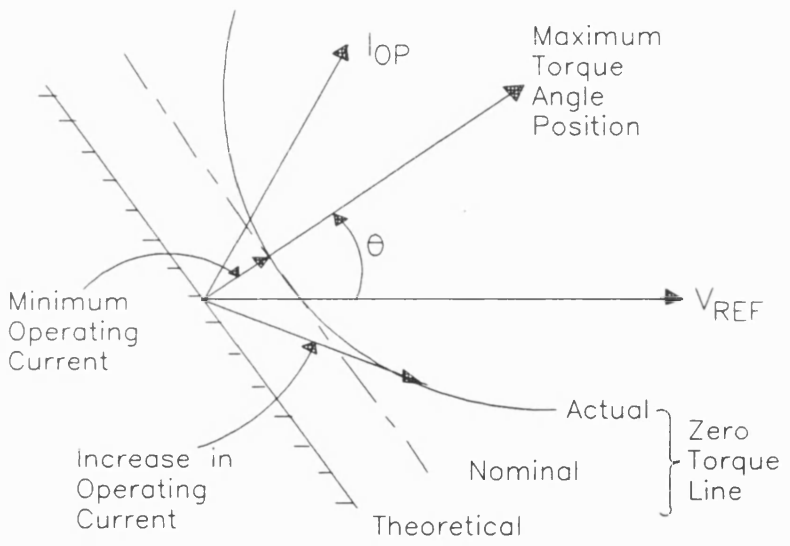



Figure 4.1 Displacement of the Operating Characteristic due to required Finite Amount Of Input Signal Magnitudes

At other levels of polarising signal, the corresponding operating current also increases. The variation of the operating current, with different levels of polarising voltage, is shown in Figure 4.2.

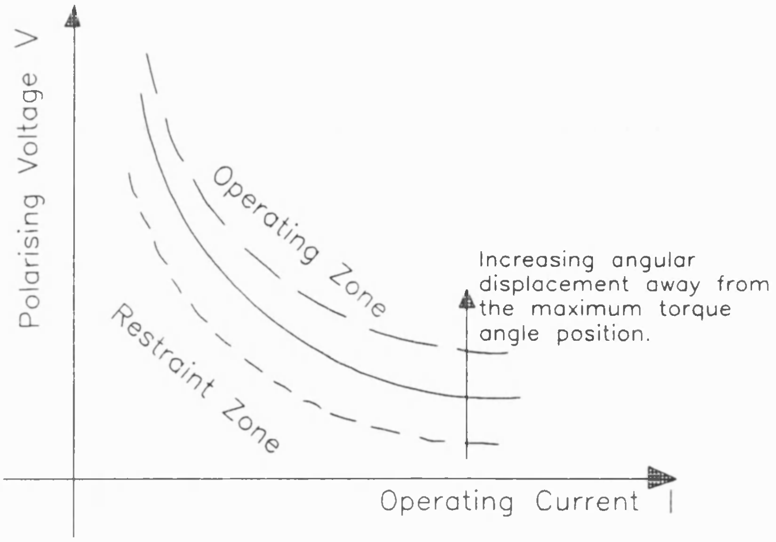



Figure 4.2 Relationship between Operating Current and Polarising Voltage of an Electromechanical Directional Relay.

Generally, electromechanical designs are less sensitive requiring higher minimum levels of polarising voltage and operating current to ensure positive identification of fault direction.

Figure 4.2 also shows the "product" relationship between the operating current and the polarising voltage. It should be noted that as the operating current increases saturation of the magnetic circuit will occur. The flux generated by this increasing operating current signal will reach the maximum possible value. This gives rise to the minimum polarising voltage value. At a given value of polarising voltage there is a corresponding range of operating current for claimed performance. It can be seen that as the angular displacement between the two signals moves away from the maximum torque angle position, the signal levels required for operation increase. Typically [2.7], at the maximum torque angle position and at 1% nominal polarising voltage, the operating current range is 1 to 15 times the rated current. At 3%

polarising voltage the operating current range is 0.4 to 40 times the rated current.

The need for a minimum polarising voltage level creates a possible dead zone in the forward direction or an indeterminate zone in the reverse direction for close-up three-phase faults.

In a 'product' type of design, the input energy/operating time characteristic usually follows an inverse time curve, i.e. the higher the input energising signals, the faster the operation. The speed is, therefore, compromised by sensitivity for a given amount of available primary energy. This is also affected by the input signals being off angle i.e. the angle of displacement does not coincide with the designed maximum torque angle of the relay. The larger the displacement from the maximum torque angle position, the longer the operating time for a given magnitude of input signals. Figure 4.3 illustrates the results obtained from an existing directional relay [2.6].

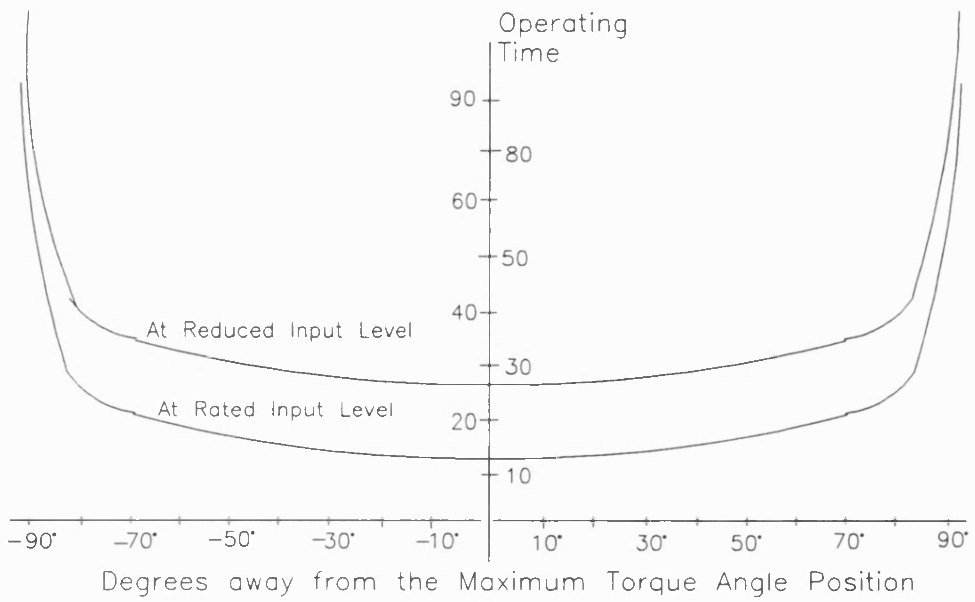



Figure 4.3 Operating Time Characteristic of a "Product" type Directional Relay.

The sensitivity of a 'product' type of design is also affected by the amount of angular displacement of the input signals from the designed maximum torque angle position. Maximum sensitivity is achieved when the displacement is coincidental with the maximum torque angle position. An electromechanical design of directional relay, which has a typical maximum directional sensitivity of 1% of nominal polarising signal with rated operating signal, requires 3% of nominal polarising signal when the operating signal is reduced to 40% of rated value. All these figures are quoted at maximum torque angle [2.7]. When the phase displacement between the polarising and operating signals is away from the maximum torque angle position, the sensitivity is reduced, requiring a higher level of operating signal for a given polarising signal level and this operating signal level increases with reduction in the polarising signal level.

The directional range, i.e. the angular displacement of the operating signal from the maximum torque angle position, within which is considered the operating zone or forward direction, is influenced by the magnitude of the input quantities. This is illustrated in Figures 4.4 [2.7].

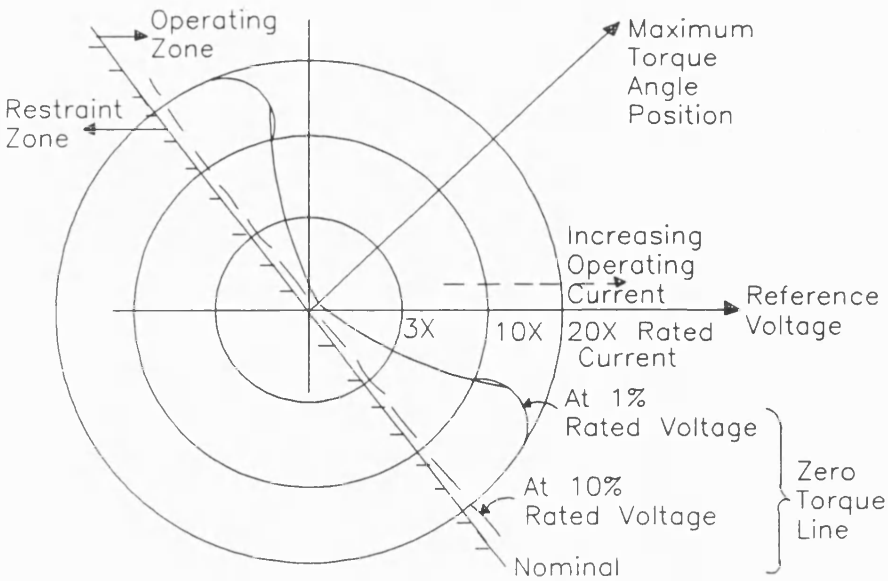



Figure 4.4 Operating Characteristic of a "Product" Type Directional Relay at Different Input Signal Levels.

In the electromechanical design of directional relays, there are a number of torque components [3.3] being produced, as shown in Appendix 11.2, by the interaction of the applied voltage and current signals on the moving element (or elements) and the basic mechanical design:

(i) Torque due to voltage signal alone or $(\text{voltage})^2$ - voltage component

(ii) Torque due to current signal alone or $(\text{current})^2$ - current component

(iii) Torque due to "product" of voltage and current signals - "product" component

(iv) Torque due to the mechanical control spring

It is impossible to design, electrically, the directional relays to operate wholly on the torque due to the "product" of the input voltage and current signals. The imperfect symmetry of the moving element and the magnetic core [2.3] creates torque components due to either the polarising or the operating signal alone. The effect of these other torque components due to voltage and current signal individually can only be minimised, but cannot be eliminated completely.

These other components of torque are only balanced out by mechanical adjustment, which is personal-skill dependent and is susceptible to mechanical disturbances in the handling process [2.17]. This provides a potential for maloperation, on loss of polarising voltage, due to voltage transformer supply failure or close-up reverse three-phase faults, with a voltage level falling below the minimum value.

An alternative design to the induction "cup" is the use of induction loops [1.27]. This provides a similar performance level to the cup unit. In this design the directional relay is not a true polyphase element. Three single-phase elements are coupled together mechanically via a common shaft driven by three induction loops.

## 4.3 Solid-State Design Type

The solid-state design of directional relays improves several aspects of performance compared to the equivalent electromechanical design. Solid-state relays are less susceptible to mechanical disturbance. They are more sensitive, requiring only very low signal levels to make a directional decision, with the directional range less affected by the variation in the signal levels. The sensitivity is also less affected by the off-angle characteristic of the input polarising and operating signals, when their angular displacement is away from the relay characteristic angle position. The operating speed is also more uniform over the operating angular range and the signal level variation.

The first generation of solid-state directional relays using a discrete transistor design only had marginal increase in sensitivity (e.g. operating down to 3% of rated operating signal) but considerable increase in the directional range [2.16]. The use of integrated circuits in the design of the current range of solid-state directional relays improves the overall performance further, in terms of sensitivity and directional range.

Figure 4.5 shows the operating characteristic of a solid-state analogue design of directional relay [2.6] as the equivalent to an electromechanical design, whose operating characteristic is shown in Figure 4.4, illustrating the improvements achieved.

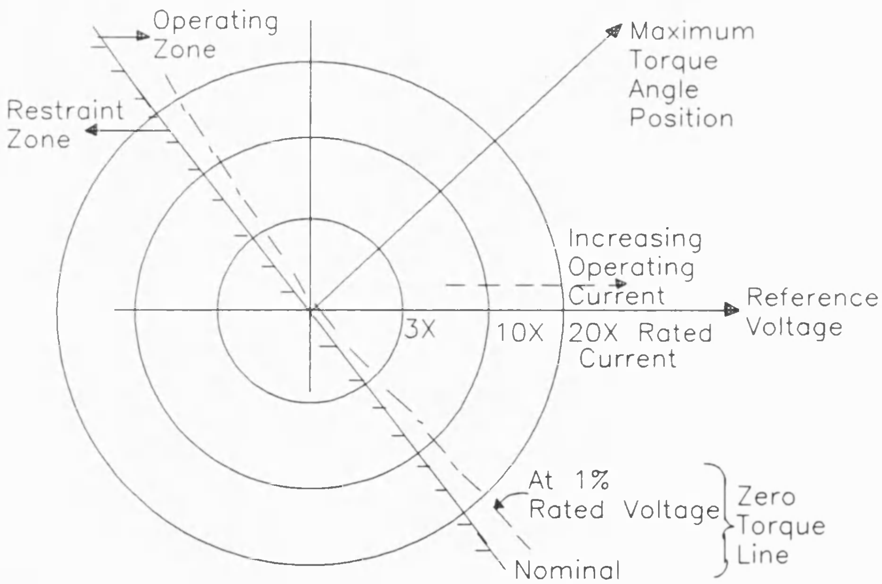



Figure 4.5 Operating Characteristic of an Equivalent Solid-state Design to the Electromechanical Directional Relay shown in Figure 4.4.

The latest design of solid-state digital directional relays, using numerical techniques, reduces the required signal levels for correct directional detection even further, down to 0.5% of rated polarising signal. The directional range is also improved, to approach the theoretical limits of $\pm 90^\circ$ on either side of the relay characteristic angle [2.18].

Figure 4.6 shows the operating characteristic of the latest digital directional relay [2.18]. The $\pm 90^\circ$ on either side of the adjustable relay characteristic angle is maintained down to the minimum polarising signal level of 0.5% of rated value. This directional relay is applicable to different systems and to both overcurrent and earthfault protection schemes, by the adjustment on the relay characteristic angle.

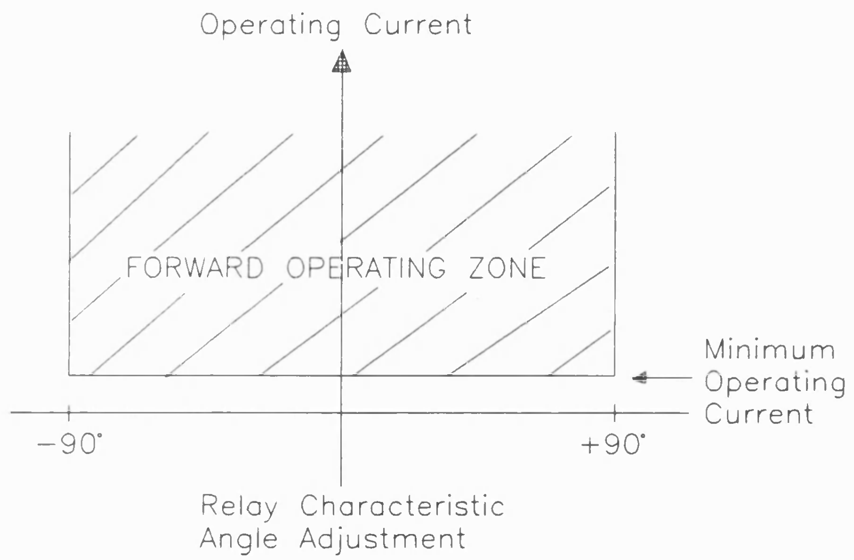



Figure 4.6 Operating Characteristic of a Digital Directional Relay for any Polarising Voltage levels above the Threshold of Operation.

For three-phase faults, where there is a total collapse of the relay input voltage, digital directional relays are designed with memory feature [2.1] to provide an infinite directional sensitivity.

## 4.4 Single-phase Directional Relays

There are five types of directional element connections, as illustrated in Chapter 3, that have been used for many years. These connections are derived by the selection of input voltages and currents to give the desired maximum torque angle position and the operating angular range to match, as near as possible, the fault profiles. A study of these connections [1.4, 3.8, 3.9] reveals that none of these is perfect. All directional relays, using one of these connections, operate incorrectly under some fault conditions which are different for each connection. However, the probability of such fault conditions producing incorrect operation of directional relays is low.

The voltage-polarised standard 90° connection is best suited to directionalise overcurrent protection relays [3.8, 3.9] and it has been the standard design, used by most protection relay manufacturers, for this application. To directionalise current-operated earth fault relays, voltage or voltage/current polarised directional relays are used. These directional relays use zero phase sequence voltage and current as the input signals.

The 90° connection type of directional relay is affected by the following operating conditions:

(i) Sound-phase currents due to single-phase-to-earth faults on multiple-earthed systems.

(ii) Partial loss of voltage transformer supply.

(iii) Faults on star-delta power transformers.

(iv) Non-symmetrical zero phase sequence impedances of parallel feeders.

The single-phase directional relays used for earthfault protection schemes are influenced by the following conditions:

(i) Availability of a zero phase sequence polarising signal.

(ii) Effect of zero phase sequence mutual coupling between parallel circuits.

### 4.4.1 Maloperation on Sound-phase Currents on Multiple-earthed Systems

For multiple-earthed systems, a single-phase-to-earth fault will result in the flow of zero phase sequence current in the sound phases. It is possible for a single phase directional relay, with the 90° connection and connected to the sound phases, to maloperate. This is illustrated in Figure 4.7. Consider the directional relay "67" at location C "looking" into the protected section CD and assume an A-phase-to-earth fault at point F on the adjacent section AB, close to the end B.

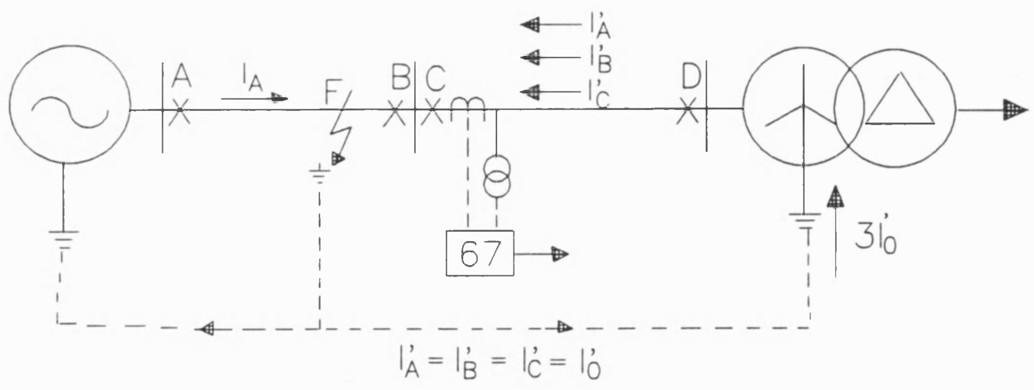



Figure 4.7 The Effect of Sound-phase Current on a Single-phase Directional Relay for Earth Faults on Multiple-earthed Systems.

The earthfault current flows through the faulted point and returns via the two earthing paths (the power transformer star winding earthing point and the source earthing point). The two sound-phase currents are $I'_B$ and $I'_C$ flowing through the directional relay "67" under consideration.

For this system, assuming only a large source available as shown, the voltages appearing at the terminals of the directional relay at location C, are:

$$V_A = 0$$

$$V_B = E_B$$

$$V_C = E_C$$

Assuming all the line impedances are pure reactance, the phasor diagram of the relay input voltage and current signals is shown in Figure 4.8.

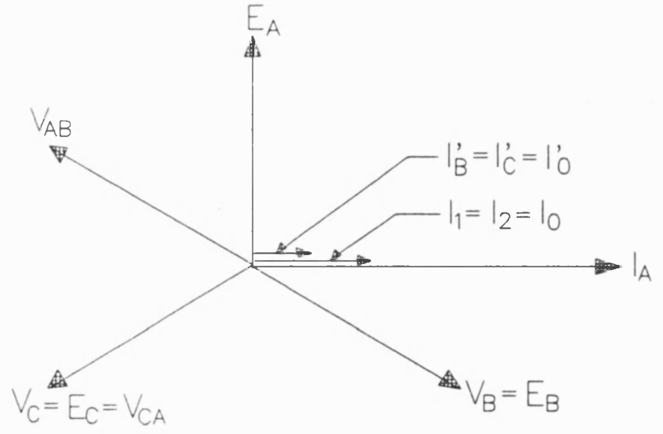



Figure 4.8 Phasor Diagram of the Input Voltage and Current Signals to the Single-phase Directional Relays "67" shown in Figure 4.7.

From the phasor diagram it can be seen that current $I'_B$ is lagging $V_{CA}$ (these are the input signals to the B-phase relay) by 210° and current $I'_C$ lagging $V_{AB}$ (these are the input signals to the C-phase relay) by 150°

If the directional relays used have a maximum torque angle of +45°, the two relays connected to the sound phases at location B will not operate but at location C, because of the reverse connection of the current transformers, the currents presented to the two directional relays connected to the sound phases are 180° out of phase. These fall into the operating zone of the sound-phase-connected relays at location C, causing the two sound-phase-connected relays to maloperate. These are shown in Figures 4.9 and 4.10 for the phase B and C respectively.

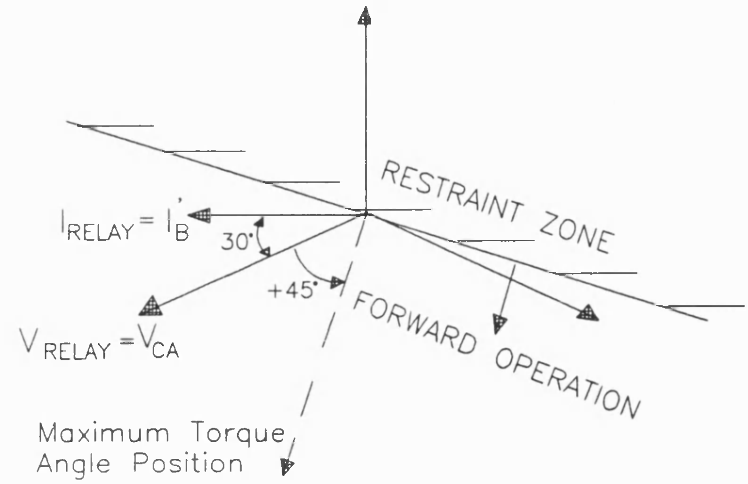



Figure 4.9 Phasor Diagram of the B–phase Relay Input Voltage and Current and its Operating Characteristic showing the Maloperation of this Relay.

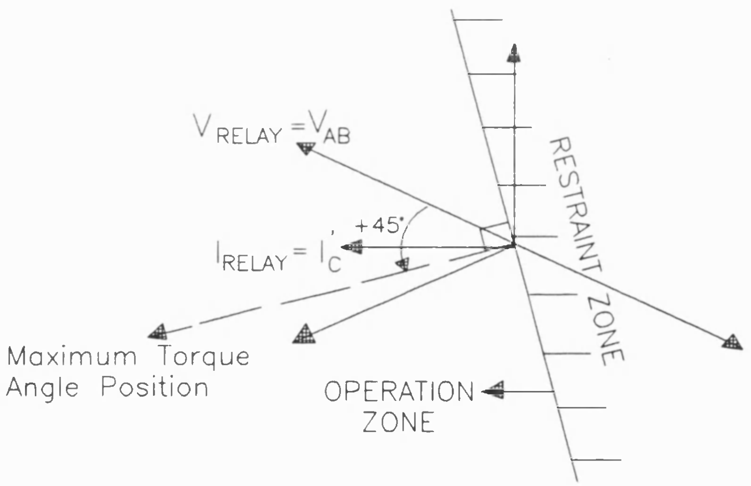



Figure 4.10 Phasor Diagram of the C–phase Relay Input Voltage and Current and its Operating Characteristic showing the Maloperation of this Relay.

### 4.4.2. Maloperation on Loss of Voltage Transformer Supply

Normally the loss of the polarising voltage signal to a directional relay does not cause maloperation of the relays. However, a partial loss of the voltage transformer supply to directional relays may cause maloperation due to changes in the composition of the polarising voltage and the presence of load current.

Figure 4.11 shows a system with line section AB and load current flowing from A to B.

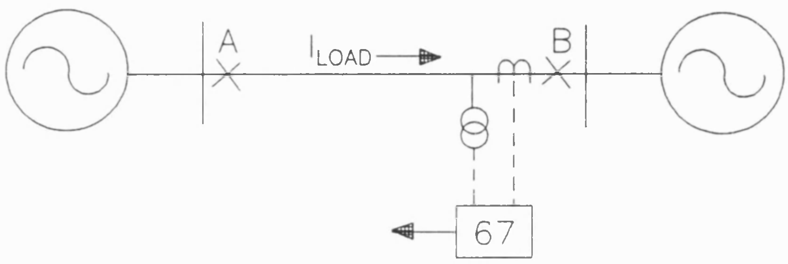



Figure 4.11 System Conditions for possible Maloperation of Single-phase Directional Relays on Partial Failure of the Voltage Transformer Supply.

Consider the directional relays "67" at end B; when there is an open circuit to the C phase of the voltage transformer supply the A-phase directional relay may maloperate. This can be illustrated by examining the phasor diagrams as shown in Figures 4.12 and 4.13.

Assume a load power factor of 0.95, corresponding to a load impedance angle of 18°. Relay "67" remains stable under this load transfer condition, where the load current is in opposition to the forward direction of the relay.

Let the voltage transformer secondary loads across C-A phases ($Z_{CA}$) and across B-C phases ($Z_{BC}$) have equal impedance angles.

On failure of the C-phase supply e.g., blowing of the C-phase fuse, the voltage across $Z_{BC}$ is part of $V_{BA}$. The various voltage and current phasors are shown in Figure 4.12.

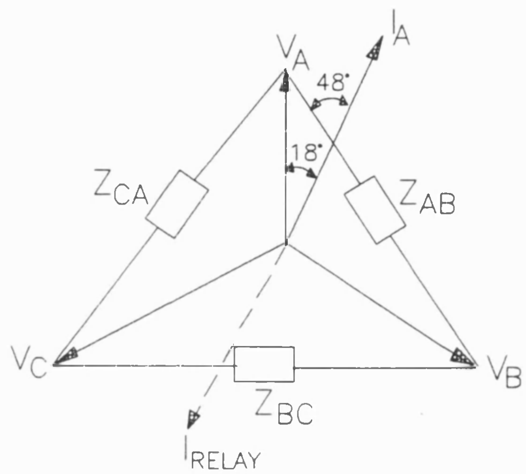



Figure 4.12 Phasor Diagram of the System Voltages and Load Current related to the Voltage Transformer Supply Secondary Load.

Therefore for the A-phase directional relay:

| | |
|---|---|
| Relay current $= -I_A$ | the load current is in opposition to the relay forward direction. |
| Relay voltage $= V_{BC}$ | |
| $= V_{BA}$ | on failure of C-phase supply |

The relay input voltage and current phasors are shown in Figure 4.13, together with the operating boundaries of the relay with a +30° maximum torque angle.

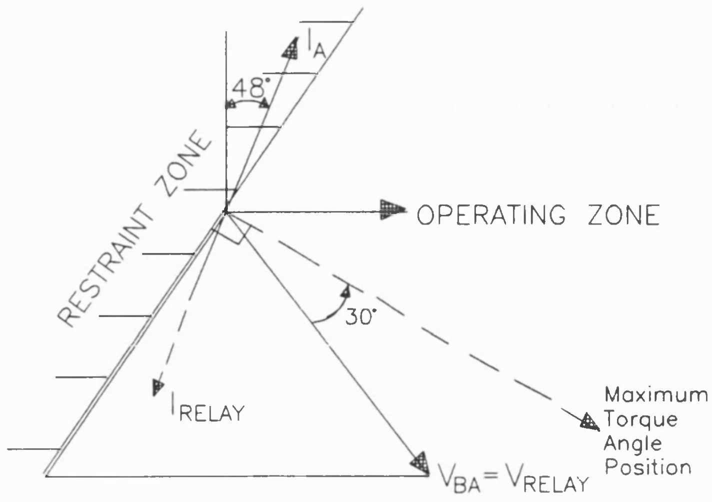



Figure 4.13 Phasor Diagram of the A-phase Relay Input Voltage and Current and the Relay Operating Boundaries.

This shows that the A-phase directional relay could maloperate, as the angular displacement between the polarising voltage and the operating current is within the operating zone of the relay.

If the relay maximum torque angle is +45° or the system load power factor is lower than 0.866 (i.e. a load impedance angle of 30°), no maloperation would occur as the angular displacement between the two relay input signals is outside the operating zone of the relay.

A 60°-connected directional relay does not exhibit this problem but it has more other shortcomings [1.4, 3.8] compared with the 90° connection.

### 4.4.3 Maloperation on Star-delta Power Transformer Faults

Phase-to-phase faults on one side of a star-delta power transformer produce the 2-1-1 current distribution on the three phases of the other side of the transformer. This is shown in Figure 4.14 for a star-delta (Yd11) transformer with an A-B fault on the delta side.

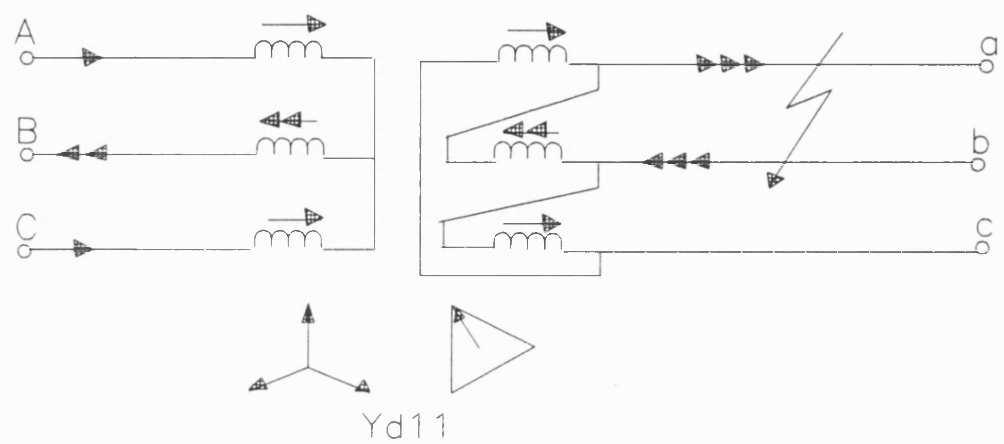



Figure 4.14 Current Distribution in a Star/Delta Transformer for a Phase-phase Fault on One Side.

In this case the current distribution on the star side is two units on the B phase and one unit each on the A and C phases.

The phasor diagrams indicating the phase relationship between the various phase sequence components of currents are shown in Figure 4.15 for both the delta- and star-side currents. The transformation ratio of the power transformer is assumed to be unity.

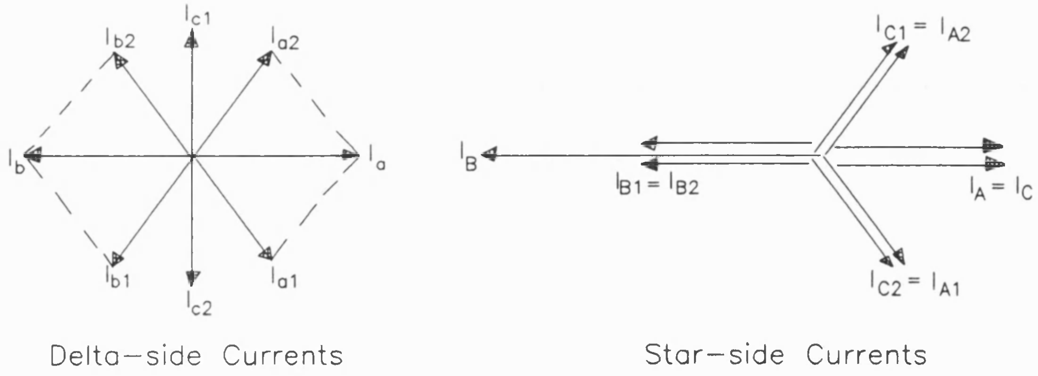



Figure 4.15 Phasor Diagram of the Phase Sequence Currents on the Two Sides of a Yd11 Power Transformer for a Phase–phase Fault on the Delta Side.

Consider the directional relays "67" at the two locations of a supply system shown in Figure 4.16; these are arranged to "look" into the two protected feeders AB and BC as indicated.

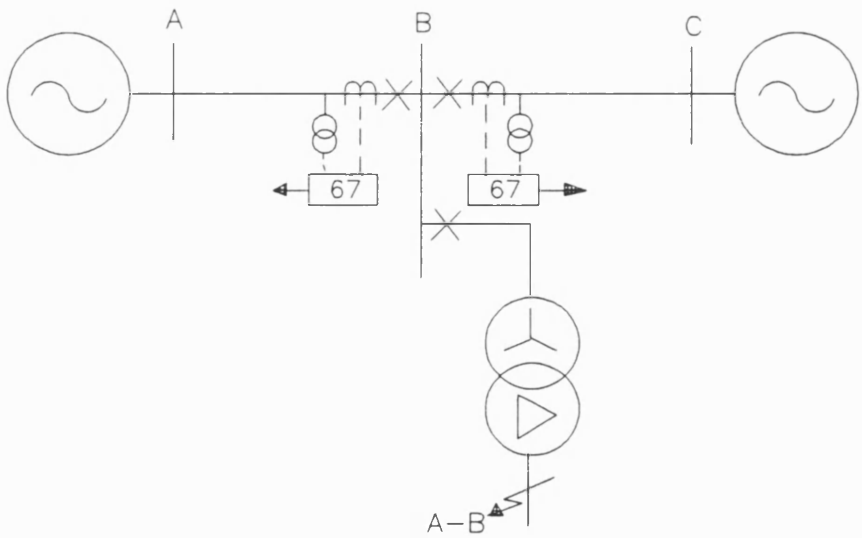



Figure 4.16 The Effect of Star/delta Transformer Faults on the Performance of Single–phase Directional Relays.

Consider an A-B phase fault on the delta side of the transformer; assuming the source impedance at the supply busbar B is much smaller than the transformer impedance, the voltages at the star side of the transformer would remain substantially symmetrical for the A-B fault condition on the delta side. The two directional relays are therefore supplied with balanced voltages. The phasor diagrams for the various voltages and currents, on both sides of the transformer, are shown in Figure 4.17.

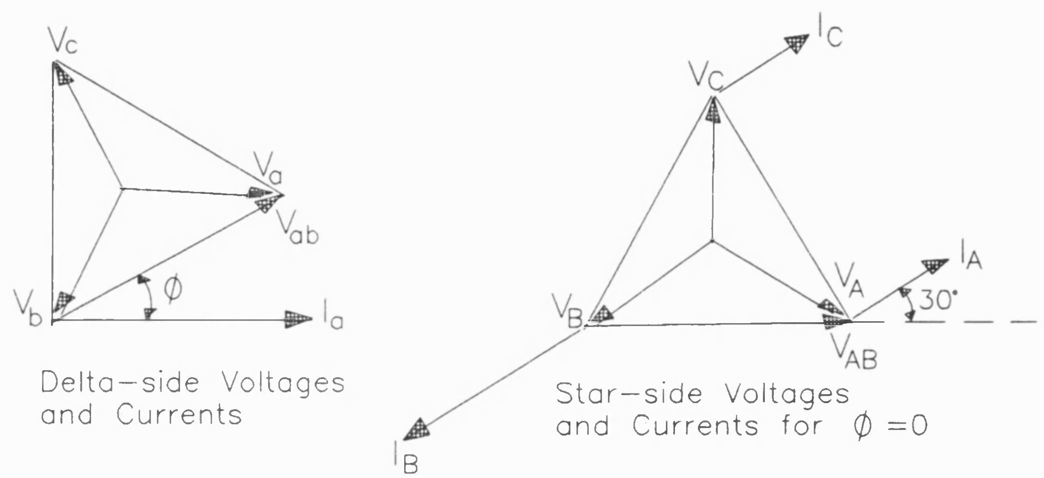



Figure 4.17 Phasor Diagram of the Voltages and Currents on both sides of the Transformer for the A-B Phase Fault shown in Figure 4.16.

If the fault impedance angle $\phi$ between the driving voltage $V_{AB}$ and the fault current $I_A$ on the delta side is zero, the star-side current phasors are as shown with the B-phase current phasor $I_B$ in phase with the voltage $V_B$.

Consider the A-phase directional relays at substation B protecting the two feeders AB and BC; the input signals are:

Relay current = $-I_A$ the fault current is in opposition to the relay forward direction.

Relay voltage = $V_{BC}$

The operating zone of the relay is shown in Figure 4.18 for a relay with +30° maximum torque angle.

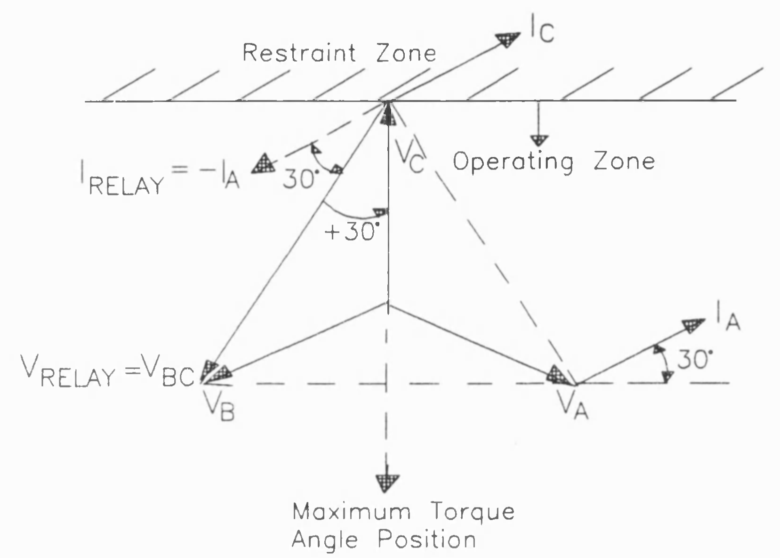



Figure 4.18 Operating Characteristic of the A-phase Directional Relay for an A-B Phase Fault on the Delta Side of the Transformer shown in Figure 4.16.

This shows that the relay operating current is within the operating characteristic of the relay causing it to maloperate. In this case the fault impedance angle $\phi$ for the fault on the delta side is assumed to be 0°. If the range of $\phi$ is considered as 0° to 90°, the range of angle between the relay current $-I_A$ and the relay voltage $V_{BC}$ is 30° to 120°. The maloperation region is when the angle is within the range 30° to 60° as illustrated in Figure 4.18. This corresponds to a range of 0° to 30° for the fault impedance angle $\phi$ on the delta side of the transformer. This is more likely to occur on cables or for arcing faults where the arc resistance predominates the fault impedance.

Similar conclusions can be drawn for the behaviour of the single-phase directional relays on the other two phases.

### 4.4.4 Maloperation on Radial Parallel Feeders with Non-symmetrical Zero-phase-sequence Impedances

One of the common applications of directional relays is on radial parallel feeders in order to avoid tripping out the healthy feeder with a fault on the other feeder. The directional relays are arranged to look into the feeders. These are shown in Figure 4.19.

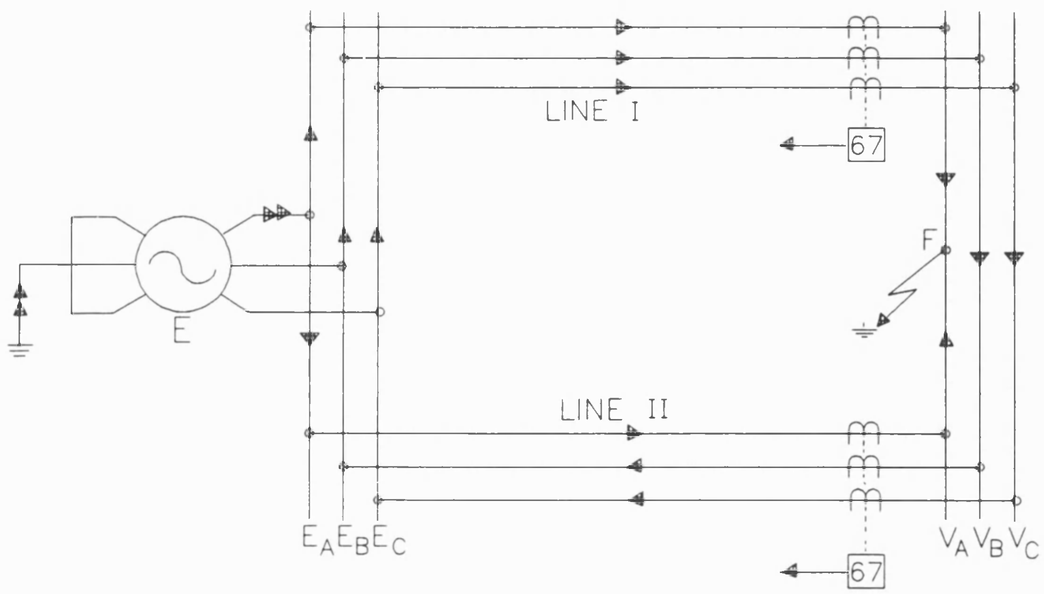


Figure 4.19 Single−phase Directional Relays applied to Radial Parallel Feeders.

For a single-phase-to-earth fault at point F as shown it is possible that the single-phase 90°-connected directional relays on the healthy phases of one of the feeders will maloperate if the two feeders do not have symmetrical zero phase sequence impedances. The directional relays on the faulted phase of the two feeders behave correctly.

From fault analysis using symmetrical components, assume the positive and negative phase sequence impedances of the two feeders are identical but not the zero phase sequence impedances, the followings apply:

At fault point:

$$I_1 = I_2 = I_0$$

At the two relaying points:

$$I_{1(I)} = I_{2(I)} \qquad \text{for Line I}$$

$$I_{1(II)} = I_{2(II)} \qquad \text{for Line II}$$

and $$I_{1(I)} = I_{1(II)} = I_{2(I)} = I_{2(II)} = I_{1R}$$

where $I_{1R}$ is the current seen by the relay.

$$I_{0(I)} \neq I_{0(II)}$$

The sound-phase currents at the two relaying points are given by:

for Line I $$I_{B(I)} = I_{0(I)} - I_{1R}$$

$$I_{C(I)} = I_{0(I)} - I_{1R}$$

for Line II $$I_{B(II)} = I_{0(II)} - I_{1R}$$

$$I_{C(II)} = I_{0(II)} - I_{1R}$$

Figure 4.20 shows the phasor diagrams of the voltage and current (in secondary terms and with the relay direction looking into the protected feeders) input signals to all the three single-phase 90°-connected directional relays with +45° maximum torque angle.

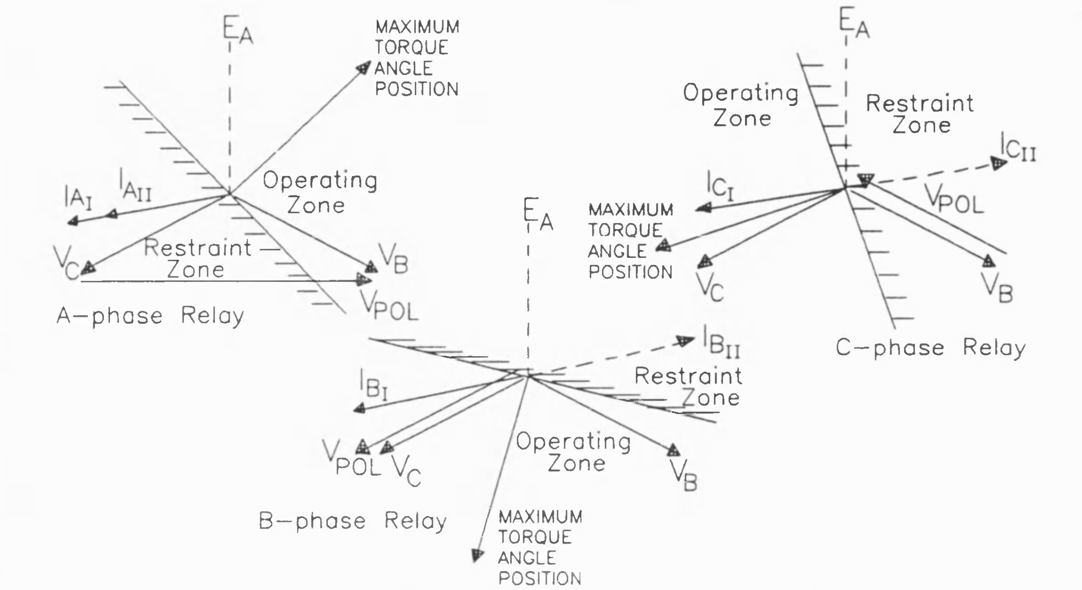



Figure 4.20 Phasor Diagrams of the Input Voltage and Current Signals to Single−phase 90°−connected Directional Relays on Parallel Feeders for Reverse Earth Faults.

It can be seen that the two sound-phase directional relays on one of the two feeders (Line I) could maloperate under this reverse single-phase-to-earth-fault condition.

### 4.4.5 Directional Relays for Earthfault Detection

This type of single phase directional relay, to determine the direction of earth faults, derives the directional information from a comparison of the zero phase sequence voltage as the polarising source and the zero phase sequence current as the operating signal. In some applications, the dual-polarised directional relay is also used which requires a suitable zero phase sequence current source as the additional polarising signal to the relay.

There are a number of problems in using zero phase sequence quantities to detect the direction of earth faults.

#### 4.4.5.1 Availability of Zero Phase Sequence Polarising Signals

One main problem of applying single-phase directional relays for earth faults, using zero phase sequence components, is the availability of suitable zero phase sequence polarising signals. Zero phase sequence voltage can only be reproduced by using three single phase voltage transformers or the three-phase type with five-limb construction. No zero phase sequence voltage is available at the secondary of a line-to-line connected voltage transformer and zero phase sequence voltage polarising is impossible with delta or open-delta-connected voltage transformers. The secondary windings have to be connected in a broken delta formation. These are illustrated in Figure 4.21.

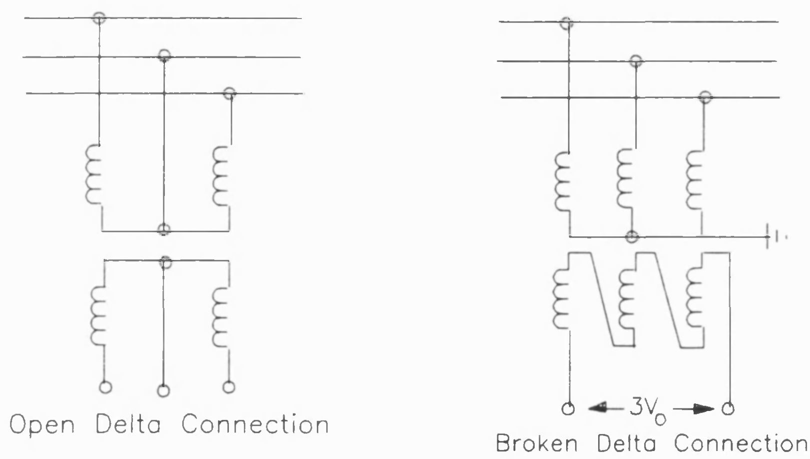



Figure 4.21 Zero Phase Sequence Voltage Source.

Zero phase sequence current polarising requires a suitable zero phase sequence current source. The basic requirement is that the current signal must not change in polarity when the fault direction changes between forward and reverse directions. The most common source is from the earthing path of a star-connected power transformer bank that also has a delta winding. Figure 4.22 shows the various suitable and also unsuitable sources of zero phase sequence current for polarising a directional relay using zero phase sequence quantities [1.33, 3.8, 3.9].

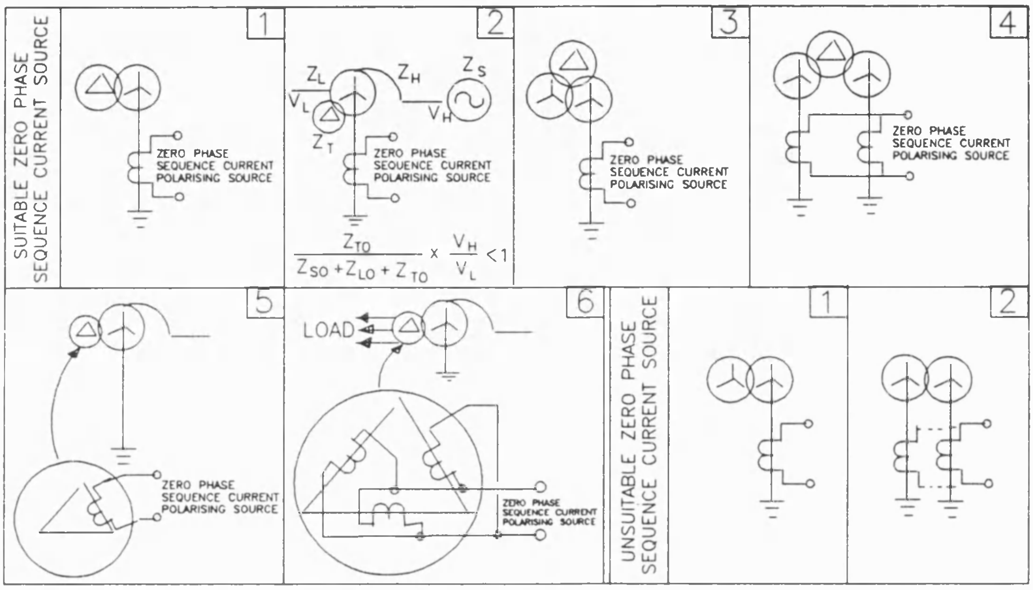



Figure 4.22 Zero Phase Sequence Current Polarising Sources.

#### 4.4.5.2 Mutual Coupling between Parallel Lines

For overhead lines supported on the same tower or on adjacent towers in the same right-of-way there is mutual inductive coupling between them that presents some problems to directional relays that employ zero phase sequence components of voltage and current to determine fault direction. The positive and negative phase sequence coupling is usually very small and is neglected whilst the zero phase sequence coupling can be very strong and its effect degrades the performance of such type of directional relays.

There are two common types of configuration where this zero phase sequence mutual coupling effect needs to be investigated:

(i) Parallel lines with common positive and zero phase sequence sources.

(ii) Parallel lines with common positive phase sequence sources but isolated zero phase sequence sources.

These are shown in Figure 4.23

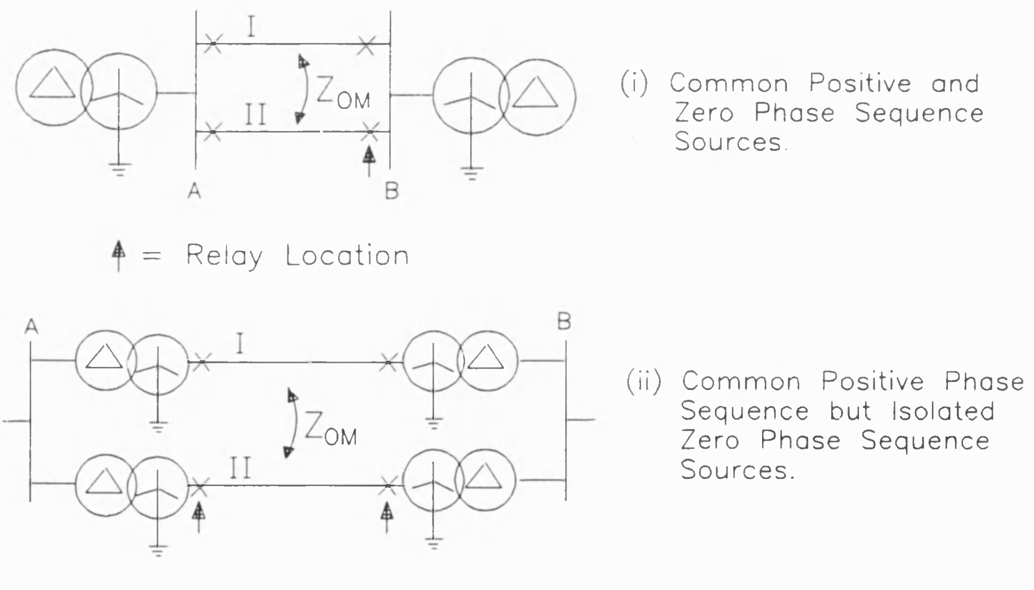



Figure 4.23 Mutual Coupling between Parallel Lines.

The zero phase sequence networks of these two systems are shown in Figure 4.24.

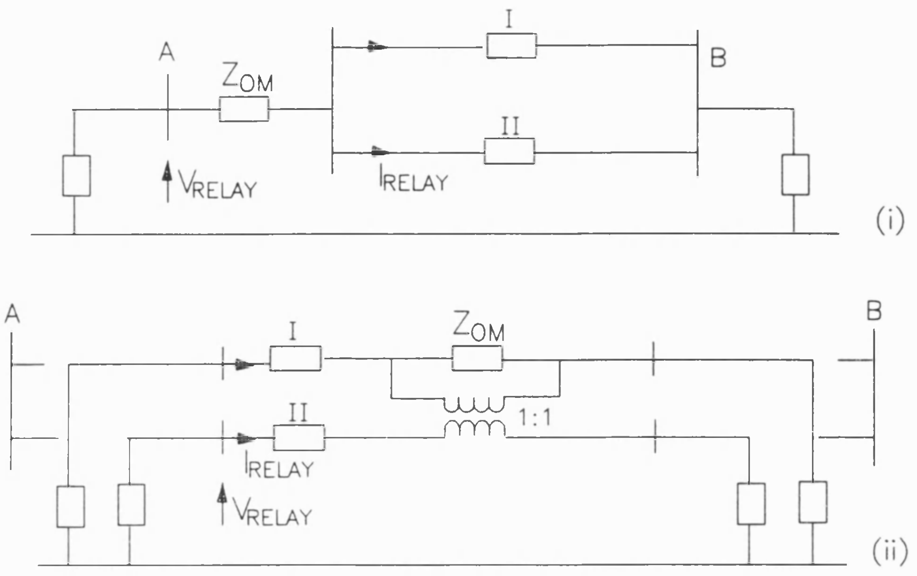



Figure 4.24 Zero Phase Sequence Networks of the Systems shown in Figure 4.23.

For system (i) zero phase sequence current always flows up the neutral independent of fault positions and system operation conditions. There is no problem with conventional single-phase directional relays using zero phase sequence quantities to determine fault direction.

A possible problem may exist when the circuit breaker at one line end is open and a fault occurs near this line end. This is illustrated in Figure 4.25 where the circuit breaker of line I at B is open and an earth fault occurs as shown.

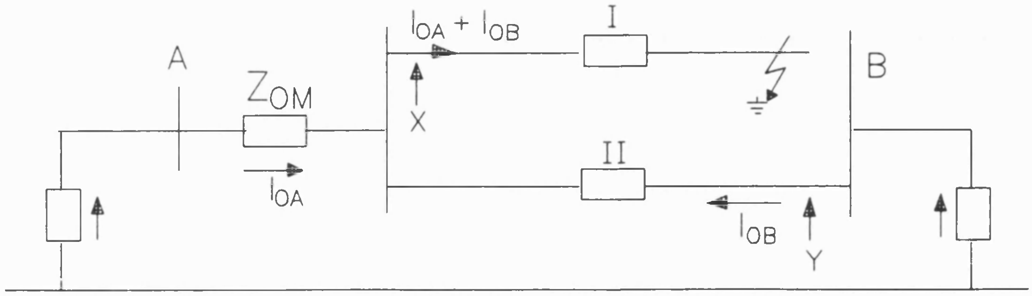



Figure 4.25 The Effect of different Zero Phase Sequence Currents 'seen' by Relays at different Locations.

For product-type directional relays using zero phase sequence current as both polarising and operating signals it is possible that $I_{OA}$ ($I_{OA}$ + $I_{OB}$) at relay location X is less than $(I_{OB})^2$ at relay location Y. The directional relay at Y will therefore operate faster. The coordination between the operation of these two directional earthfault protection relays has to depend on the operating speed of the associated current-level detectors.

For system (ii) an earth fault near one line end at point F as shown in Figure 4.26 is "seen" by the single-phase directional relays based on zero phase sequence components of voltage and current at the two ends of the healthy line to be an internal fault.

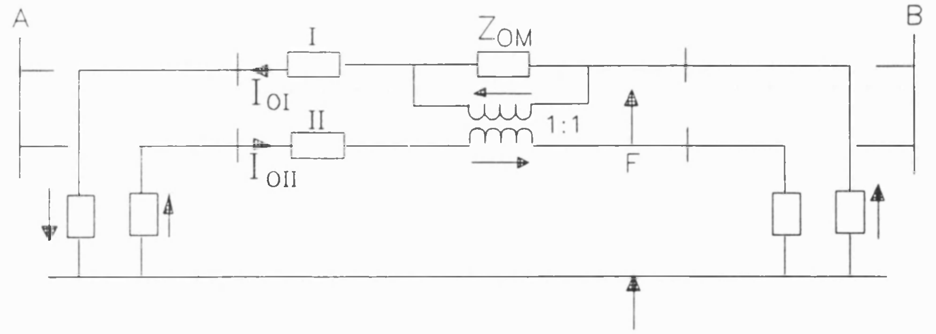



Figure 4.26 Maloperation of Zero Phase Sequence Directional Relays due to Mutual Coupling between Parallel Lines on Systems with Isolated Zero Phase Sequence Sources.

The zero phase sequence component of the fault current $I_{OII}$ flowing in the faulted line induces a current $I_{OI}$ in the healthy line through the zone phase sequence mutual coupling $Z_{OM}$. This induced current $I_{OI}$ is flowing up the neutral at one end and down the neutral at the other end. With the operating currents at the two line ends flowing into and away from the protected line respectively the two directional relays both detect the presence of an internal fault. The healthy line will be tripped incorrectly if the two directional relays are linked by a signalling channel to form a directional comparison scheme; or proper coordination between the operating times of the current detectors associated with both the healthy and fault lines earth fault protection relays is not implemented.

## 4.5 Polyphase Directional Relays

Instead of using single-phase directional relays it is advantageous in some applications, to use one polyphase directional relay to control the 3-phase overcurrent and earthfault current detectors. Apart from cost saving in using a polyphase unit compared with multiple single-phase units, there are applications where polyphase relays are more suitable and less problematic.

The application of polyphase relays is significant on systems with multiple earthing where it is possible for heavy current to flow in all three phases during a single-phase-to-earth fault, with the result that certain single-phase directional relays may trip incorrectly [1.1, 3.7, 3.8, 3.9]. The polyphase relay offers the best solution.

There are a number of deficiencies in the performance of existing polyphase directional relays depending on the design.

### 4.5.1 Effect of Load Current

The successful application of polyphase directional relays depends on the flow of sufficient fault current even in the presence of heavy load transfer. This is to ensure that the load current flow will not prevent the relay from responding correctly to the occurrence of a fault. This situation is illustrated in Figure 4.27.

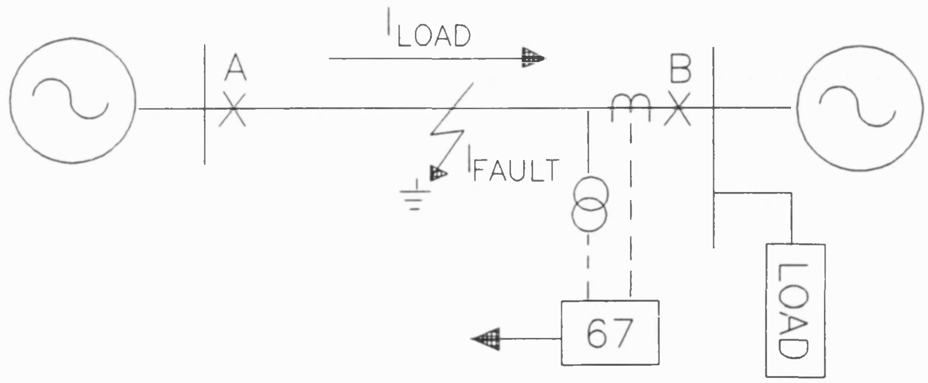



Figure 4.27 The Effect of Load Transfer on a Polyphase Directional Relay Performance in the Presence of a Single-phase-to-earth Fault.

Significant load flow is maintained across feeder AB with a single-phase-to-earth fault on the feeder. With the direction of load transfer shown, the directional relay at end B is subjected to the effect of load current flowing in opposition to the fault current. The fault current component must predominate to ensure correct directional detection by the relay at end B.

An existing polyphase directional relay [2.3] specifies that single-phase-to-earth fault current must be greater than three times the maximum load current to ensure correct detection of direction when an earth fault occurs in the presence of heavy load transfer. If this condition cannot be met a separate directional relay for earth faults is required to supplement the polyphase unit.

This requirement of minimum fault current limits the application of a polyphase directional relay to only the protection of effectively earthed systems, having the necessary minimum fault levels under minimum generation conditions.

### 4.5.2 Phase Selection

All the true polyphase directional relays currently available do not have phase selection capability. This deficiency does not, however, affect the direction detection process and hence the operation of directional overcurrent and earthfault protection. It limits the application scope mainly from the operation point of view. Operators are not able to determine the faulted phase(s) to enable speedy fault repairs and restoration of power supply. Phase selection capability also enables the application of the polyphase directional relays to transmission system protection where single-phase tripping and auto-reclose facilities are required to maintain system stability.

### 4.5.3 Directional Detection based on Phase Sequence Quantities

There are two types of polyphase directional relay available based on the use of negative phase sequence quantities [2.13] or positive phase sequence quantities [2.1]. Both types have limitations in their applications because of deficiency in performance.

#### 4.5.3.1 Using Negative Phase Sequence Quantities

One of the major shortcomings of polyphase directional relays, using negative phase sequence components of voltage and current, is the inability to detect balanced three-phase faults. There is no negative phase sequence component generated under such fault conditions to enable relay operation.

In practice, the detection of balanced three-phase faults is based on the assumption that such faults always start as unbalanced faults for about one cycle [3.7]. During this brief transition time the negative phase sequence directional relays are able to operate. This requires high speed of operation for the directional relays. The rectifier-bridge type is designed for this application.

In Chapter 3 and illustrated in Figure 3.8, the basic design is not able to meet the high speed requirement because of the need to delay the phase sequence filter output to allow the filter to settle during the initial fault inception period. In addition, there is also a need to smooth the output from the rectifier bridge to prevent chattering of the output relay.

In order to reduce the response time, three phase negative phase sequence components of voltage and current are generated. Figure 4.28 shows the generation of three phase negative phase sequence output from the three phase input signals.

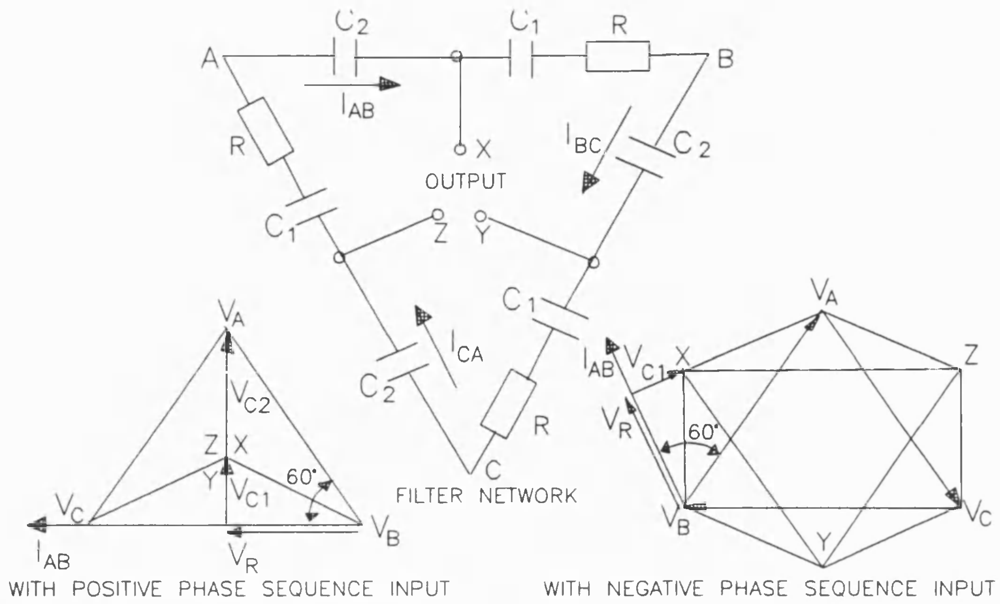



Figure 4.28 Generation of Three-phase Negative Phase Sequence Output.

This improved design [3.7] does not require a delay in the filter output nor smoothing at the output of the rectifier bridges. Three-phase rectifier bridges are used in the improved design. The speed of operation is increased to about 0.5 - 0.75 cycles. Hence, the required transition time for balanced three-phase faults to develop from the initial unbalanced faults is about 0.5 cycle to allow the improved negative phase sequence directional relay to operate. This design has been in successful service in the People's Republic of China, applied to a directional comparison blocking scheme on high voltage transmission lines.

The second problem with directional relays based on the negative phase sequence voltage and current is the maloperation caused by unbalanced operation of the primary systems generating negative phase sequence components of voltage and current. This occurs when single-phase tripping and auto-reclose facilities are used or when there is broken conductor on the protected feeder. The former is associated with transmission systems.

The other type of negative phase sequence directional relay, using an induction "cup", is not designed to cover all types of fault. Instead, it is mainly used [2.13] as the directional control element for the current-operated unit on distribution system earthfault protection schemes. The directional unit operates from the negative phase sequence components whilst the separate current detector operates from the zero phase sequence component making it applicable to earthfault protection only.

The detection of earth fault direction using negative phase sequence components of voltage and current is applicable in many cases where zero phase sequence directional sensing is impossible. Figure 4.29 illustrates such cases where negative phase sequence directional relays are advantageous because of the non-availability of a suitable zero phase sequence polarising voltage or current source.

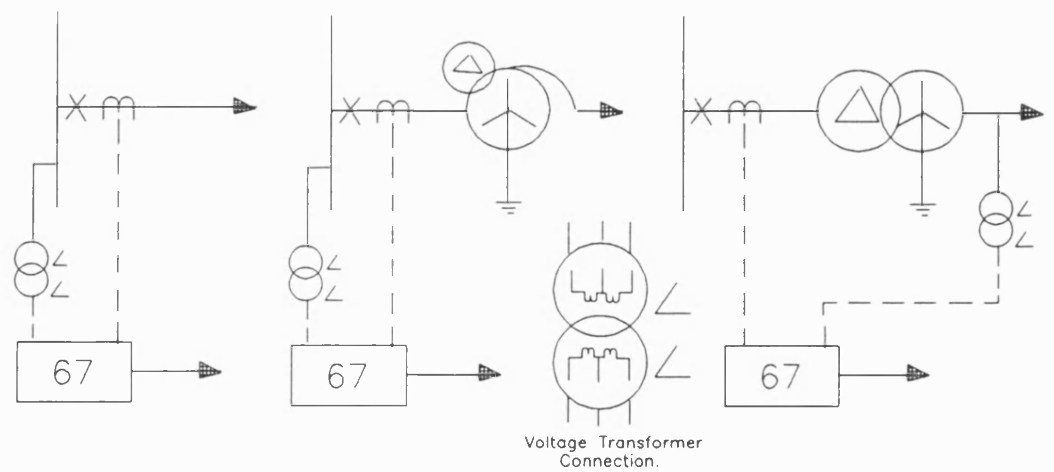



Figure 4.29 Examples of Non-availability of Suitable Zero Phase Sequence Voltage or Current Polarising Sources.

In addition, the problem of zero phase sequence mutual coupling effect between parallel lines as detailed in Section 4.4.5.2 does not exist when negative phase sequence components are used.

### 4.5.3.2 Using Positive Phase Sequence Quantities

Though the positive phase sequence components of voltage and current are present in all types of fault the use of the angular displacement between them to determine the fault direction is limited and affected by the pre-fault system conditions and load transfer during the fault period.

The directional relay [2.1] based on the measurement of the angle between the positive phase sequence voltage and current is designed for use with overcurrent protection to detect phase faults only. The relay is not recommended to directionalise earthfault protection relays. However, it incorporates a memory feature to provide infinite directional sensitivity for close-up three-phase balanced faults using the pre-fault voltage to maintain a reference for the direction detection process.

## 4.6 Other Problems associated with Existing Directional Relays

Existing directional relays exhibit some problems when they are applied to some systems and are subjected to some operating conditions. Compromises are made by using complementary facilities or accepting the risk of occurrence of those problems.

### 4.6.1 Total Collapse of Relay Voltage

Directional relays require a polarising source to determine the direction of faults. Nearly all existing designs of directional relay require a minimum value of polarising source. In the case of electromechanical relays, the minimum required values range from 1% to 3% of rated value [2.7] whilst solid-state designs need only about 1% [2.6] to ensure satisfactory direction detection. The latest range of digital directional relays [2.18] reduces this requirement to 0.5%. It is, however, still not possible to operate the relay down to zero polarising voltage to cover solid three-phase close-up faults. One relay [2.1] uses prefault voltage as a form of memory voltage to help the direction detection process on the total collapse of relay polarising signal. However, this has not been widely implemented and it is accepted that relays will fail in total collapse of polarising source or their operation is indeterminate. The risk is limited by virtue of the fact that a three-phase fault, with all the phases shorted together simultaneously, rarely occurs. It has been assumed that three-phase faults generally evolve from unbalanced faults involving one or more phases initially.

### 4.6.2 Transformer Energisation on Multiple-earthed Systems

On multiple-earthed systems, for a feeder supplying an in-zone transformer with earthed primary winding it is possible to obtain zero phase sequence current flowing when the transformer is energised. This is shown in Figure 4.30.

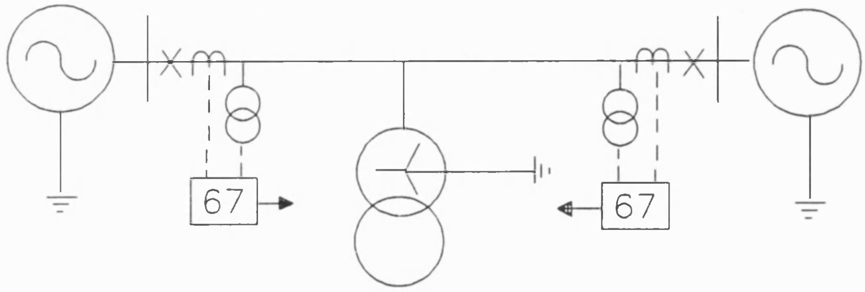



Figure 4.30 In–zone Transformer with Earthed Primary on a Multiple–earthed System.

It has been thought that a directional earthfault relay based on zero phase sequence quantities at the two ends of the feeder will maloperate. On this basis a feature has been incorporated [2.26] to detect the transformer energisation condition by examining the inrush current waveform and to inhibit the directional relays. This feature is not available in other relays and is applied to transmission line protection.

### 4.6.3 Directionalised Instantaneous Overcurrent Protection

It has always been difficult to provide directional relay for instantaneous current detectors because of the difference in operating and resetting times between the directional element and the current level detectors. A difficult example is shown in Figure 4.31 where there is pre-fault load current flowing into the protected feeder and a subsequent reverse fault occurred behind the relay location.

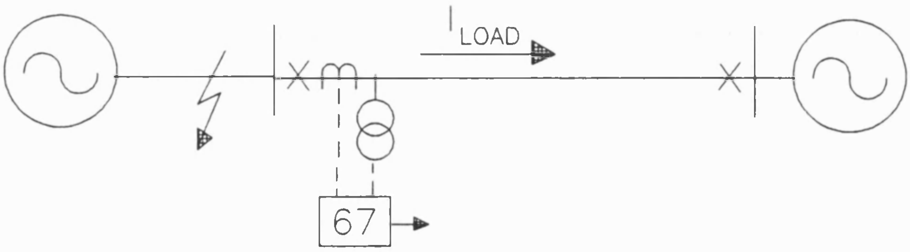



Figure 4.31 Response of Instantaneous Directional Overcurrent Protection Relay with Pre-fault Forward Load Current Flow and Reverse Fault.

The directional element detects correct direction during the pre-fault load flow period. It has to restrain when the reverse fault occurs. This necessitates the direction detection process to reset faster than the current level detection to inhibit the current detection operation. When fast current detectors are used it is not always possible to effect the inhibition resulting in maloperation.

The solution has been to slow down the speed of the current measurement process to allow a complete resetting of the directional unit i.e., to enable the directional unit to re-establish the correct direction of the fault.

# CHAPTER FIVE

# PERFORMANCE REQUIREMENTS OF A DIRECTIONAL RELAY

## 5.1 Introduction

Directional relays are required to maintain an output continuously whilst they are in service. They are dynamic devices making decision in a transient period. The decision is reflected in the output which can be in either operation or restraint state and must be adaptive to the primary system conditions to change the state accordingly and dynamically. It is this dynamic nature of their operation that directional relays are designed with considerable emphasis on various behaviour characteristics to increase the security level.

Chapter 4 highlighted the deficiency of existing directional relays applied to distribution system overcurrent and earthfault protection schemes using current-operated relays. This project is to investigate a new polyphase directional detection method with one of the aims to address this deficiency. This Chapter is to explain the requirements of a directional relay and to state the specifications that are desirable from the proposed new directional detection method taking into account the inadequate performance level of existing relays. The scope of application remains primarily for distribution system overcurrent and earthfault protection schemes.

## 5.2 Forward Fault Operation

The primary role of a directional relay is to be able to operate for all forward faults under different operating conditions and different system configurations with acceptable sensitivity and speed.

The first requirement is, therefore, that a directional relay must not be restricted in its application by primary system operation or configuration.

For overcurrent and earthfault protection using current-operated relays the operating current sensitivity is significant only for earthfault protection as short circuit conditions generally produce more-than-adequate fault current to operate overcurrent detectors. To cover earthfault conditions there are generally two types of current-operated earthfault protection relays, one with standard setting ranges, typically 10-40% of the circuit rating and the other with sensitive setting that can provide settings as low as 0.5% [3.8, 3.9]. The latter is generally applied to high impedance earthed systems or completely isolated systems where an earthfault produces limited earthfault current or results in the flow of only unbalanced capacitive currents. To directionalise such sensitive current-operated earthfault protection relays it is essential that the directional elements should also have similar level of current sensitivity. With present technology sensitivity is not an issue as there are relays now available that can operate down to 0.2% of rated current [2.18]. Any further increase in sensitivity is not desirable as any noise may cause maloperation. This noise may include spill current produced by current transformer errors.

The directional sensitivity in terms of minimum polarising signal level should be infinity, i.e., the proposed new directional detection method should be capable of operating down to zero fault voltage for all types of faults.

The process of directionalising current-operated relays involves some form of control on the current level detection in a sequential arrangement. The directional element must operate first to enable the current level measurement process. This sequential arrangement of operation is necessary to overcome transient problem to maintain stability when current flow directions change with the types of operating conditions as detailed in Chapter 4. It is, therefore, important that the speed of operation of the direction detection process is as high as possible to reduce the delay in the current level measurement process.

The followings are the specific considerations to ensure satisfactory operation of the proposed new polyphase directional detection method for forward faults.

### 5.2.1 Responses to Power System Faults

It is important that the proposed new method should respond to all faults in the forward direction limited only by its threshold of operation and not by the fault types. There should not be any blind spot(s) in the forward direction where faults are not detected due to shortcomings in the operating principle. The primary system configuration must not impose any constraint on the application of the new method.

### 5.2.2 Threshold of Operation

Every power system protection device requires high sensitivity. This necessity is to ensure reliable operation under all system operating conditions. The operating threshold of a directional relay must therefore be lower than the minimum available energising signal(s) with sufficient margin to cover equipment and data tolerance and to ensure the desired speed of operation. This requirement is particularly onerous for earthfault detection with high impedance earthed or isolated neutral systems where earthfault current is limited to very low value or restricted to just unbalanced capacitive current in the case of isolated neutral systems.

For directional overcurrent and earthfault protection the directional detection must be more sensitive than the current level measurement process.

### 5.2.3 Operating Speed

As with all power system protection devices the faster the operating speed, with no unacceptable compromises in sensitivity, dependability and security, the better the device. For directional overcurrent and earthfault protection the whole operation process consists of the directional detection followed by current-level comparison against a pre-set value. The directional element controls the current-level detector. It is, therefore, necessary to limit the directional detection time to avoid contributing significantly to the overall operating time of the protection. The new directional detection method must have the fastest possible operating speed.

### 5.2.4 Directional Sensitivity

The directional detection process requires a finite level of the input signals to enable reliable decision on the direction of faults with particular emphasis on the reference signal. The target should be infinite directional sensitivity, i.e., the directional relay should be capable of operating down to zero fault voltage when the voltage signal is used as the polarising source. This will require a careful selection of the polarising voltage incorporating, where necessary, some form of memory of the pre-fault voltage.

### 5.2.5 Operating Zone

A directional relay having the capability to respond to faults must be able to discriminate between operation for forward faults and restraint for reverse faults. The operating zone in terms of angular range for operation must not be compromised by the variation in the magnitudes of input signals and in the angular displacement changes between them within the operating range.

### 5.2.6 Phase Selection Capability

Polyphase devices are, without additional means, generally not capable of providing faulted phase(s) identification information. It is important and an added advantage to have faulted phase(s) identification capability in addition to being able to determine fault direction. This provides primary system fault-finding and post-fault analysis of the system and protection device performance. It also enables consideration for application to transmission system protection where phase selection facility is required for single-phase tripping and auto-reclosing.

### 5.2.7 Operating Characteristics

Figures 5.1 to 5.3 show a comparison of the various operating characteristics of existing directional relays and those that are desirable from the new method of detecting direction.

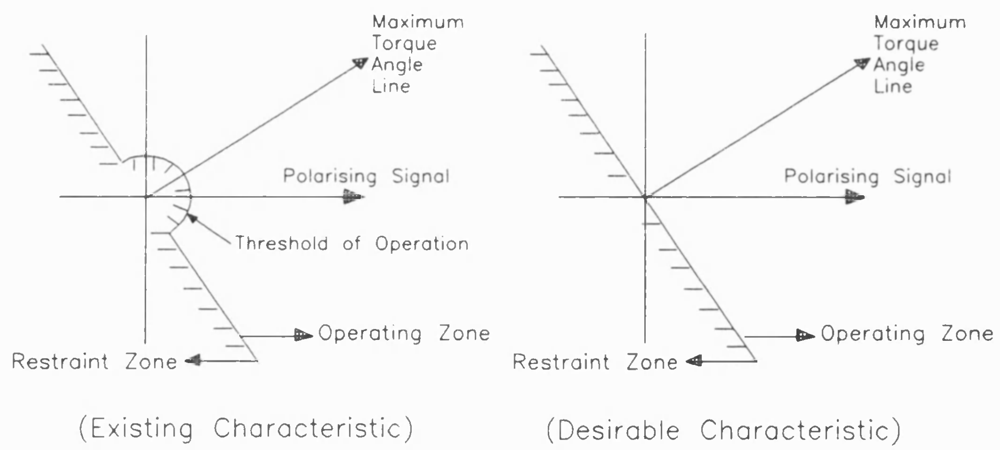



Figure 5.1 A Comparison of the Existing and Desirable Operating Characteristics on the Threshold of Operation of the Polarising Signal.

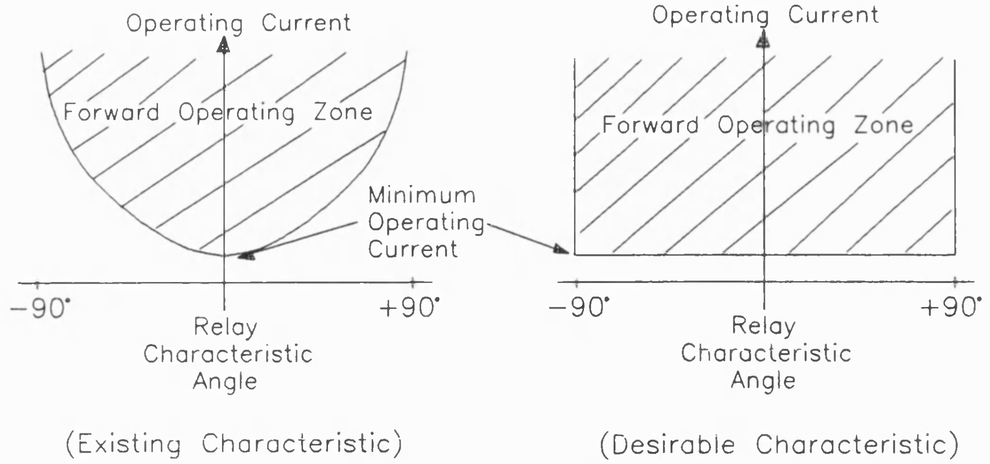



Figure 5.2 A Comparison of the Existing and Desirable Operating Characteristics on the Directional Range at Minimum Operating Current Condition.

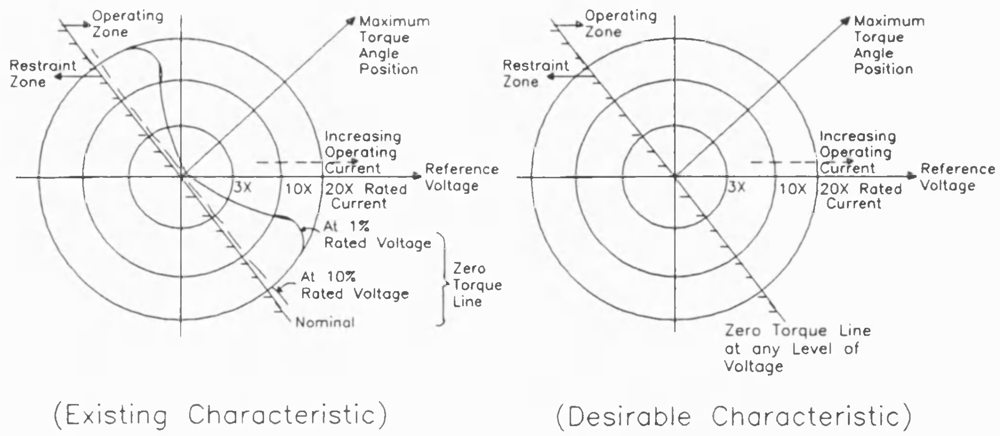



Figure 5.3 A Comparison of the Existing and Desirable Operating Characteristics on the Directional Range at Minimum Polarising Voltage Condition.

It can be seen that the new desirable operating characteristics aim to improve:

- the sensitivity without any blind spot(s) where the new method would fail to detect due to threshold of operation.

- the effect of the variation in the angular displacement between the operating and polarising signals away from the relay characteristic angle.

- the effect of the variation of input parameters on the directional range of the new method.

## 5.3 Reverse Fault Restraint

The other role of a directional relay is not to operate for reverse load transfer or reverse faults under all operating conditions and for different system configurations. This is one of the most important requirements of the new directional detection method. In addition, the dynamic nature of a directional relay's operation makes it necessary to consider increasing the security level to ensure that its operation is not influenced by other factors not related to the actual directional detection process.

There are a few areas that need addressing with reference to security of operation for directional relays to ensure that they provide restraint output for non-genuine fault conditions even under abnormal operating environment. These should also apply to the new directional detection method.

### 5.3.1 Stability against Loss of Reference Signal

A directional relay makes its decision based on a comparison of two signals, an operating signal against a reference signal. The loss of the reference signal makes definition of direction indeterminate, hence the requirement of stability for loss of the reference source in that the directional relay must not provide a forward fault operation output. This condition may be caused by the supply voltage transformer failure.

### 5.3.2 Stability against Loss of Operating Signal

It is equally important that the loss of the operating signal does not cause an output from the direction detection process. This condition may be caused by problem(s) in the current transformer supply circuits.

## 5.4 Effects of the Electrical Operating Environment

It is not uncommon that a given design of equipment has restriction in its application imposed by its operating environment. An example of a directional relay having such a restriction is an electromechanical polyphase directional relay [2.3] that cannot be applied to a resistance-earthed system where an earth fault results in limited current flow. For the proposed new directional detection method its operation should not be influenced or affected significantly by its operating environment. There are conditions that affect existing directional relays and which require a review with the proposed new method.

### 5.4.1 Primary System Normal Loading Conditions

Generally, existing directional relays respond to normal load current that flows in the same direction as their operating direction. Though this behaviour does not normally hinder the overall performance when this type of directional element is used in directional overcurrent schemes, it is sometimes advantageous to have the directional relay restrained from operation under this condition. This feature enables the application of directional overcurrent relays to systems where the minimum fault current may be lower than the maximum load current. The restraint feature permits the setting of the current level detector to be lower than the maximum load current.

This restraint feature is generally obtained with an additional signal from the system voltage [2.12, 2.25, 2.30]. The voltage signal is used to provide a restraint torque in the electromechanical directional relays where a driving torque is produced by the operating current and polarising voltage. The normal voltage level under loading and even power swing conditions will inhibit the directional relay from operation. This feature will help in maintaining or improving the dynamic stability of a directional instantaneous overcurrent when there is a reverse fault following the pre-fault forward load flow condition. It is, therefore, advantageous that the new directional detection method incorporates or possesses similar feature.

### 5.4.2 Primary System Pre-fault Load Current

As explained in Chapter 4 one of the most difficult operating conditions under which reliable operation of a polyphase directional relay is required is that when a fault is coupled by load transfer in the affected circuit. This is of special importance for a directional detection relay which uses signals that are influenced by any load current flow. It is, therefore, a requirement that pre-fault load current flow should not affect the proposed directional detection method.

### 5.4.3 Primary System Configuration

One configuration of the primary system that can create problem for some directional relays is when there are a number of feeders running alongside each other producing mutual coupling effects between them. The new directional detection method should not be affected by this mutual coupling effect.

The earthing method of the primary system neutrals should also not impose restriction on the application of the new method of detecting direction. For resistance-earthed systems the earthfault current is limited which may not be sufficient to enable the operation of the directional detection process. The problem of multiple-earthed systems also needs to be investigated as such systems, on the occurence of earth faults, produce multiple paths for the flow of zero phase sequence current giving rise to the flow of sound-phase current. The proposed directional detection method should be applicable to both these types of systems to include also isolated systems.

## 5.5 Specifications of a Directional Detection Method

The required specifications of the proposed new directional detection method may be stated as follows.

The directional detection method shall be capable of operation for all forward faults with the following performance:

- Maximum sensitivity with operating current down to 0.2% or lower, of the rated current to cover high resistance faults.

- The sensitivity shall not be influenced by any pre-fault load current flow.

- Infinite directional sensitivity operating down to zero fault voltage for all types of faults.

- Possession of phase selection capability.

- Maximum operating speed down to 1 to 1½ cycles of operating time.

- Directional range is to be independent of the input signal levels above minimum required level.

- Directional range is to be independent of angular displacement between the input signals within the limiting values.

- Applicable to all primary system configurations with different earthing arrangement of the system neutrals or isolated systems.

- Independent of mutual coupling between parallel circuits.

- Capable of operating correctly on unbalanced systems.

The directional detection method shall restrain for all reverse faults and remain stable for the following conditions:

- The presence of only one input, either the operating or polarising signal.

- Normal loading condition with load current flowing in either direction.

- 3-phase close-up reverse faults down to zero fault voltage.

- Failure of the voltage transformer supply.

# CHAPTER SIX

# PROPOSED NEW APPROACH TO POLYPHASE DIRECTIONAL DETECTION

## 6.1 Introduction

Chapter 2 outlines the principle of operation of directional relays and the different methods of detecting the direction of a fault point in relation to a relay location, either in the forward or reverse directions.

Chapter 4 provides a review of performance of various existing directional relays. It indicates that there is a need to investigate an alternative method of detecting fault direction on a polyphase basis for use with overcurrent and earthfault protection applied to distribution systems. The method should also be capable of being employed in the design of directional relays that form the nucleus of schemes based on directional comparison principle of operation for transmission systems and other plant item protection. Polyphase directional detection performance should be designed so as not to be restricted by primary system operating conditions, such as fault current level compared with pre-fault load current [2.3], or primary system configuration such as system earthing methods.

The basis of the new approach is an examination of the angular displacement between an operating signal and a reference or polarising signal. Hitherto, directional relays based on this concept, either single or polyphase elements of the electromechanical or solid-state design, have the limitations detailed in Chapter 4. However, these limitations arise mainly because of the constraint imposed on the input signal selection. The selection is limited to the different combination of the system voltages and currents. Internal phase shifts in the design of the relays provide a certain degree of improvement to the performance by attempting to match the relay operating characteristic to the fault profile of the protected circuit.

To meet the performance requirements, as stated in Chapter 5, it is proposed that the symmetrical components of voltages and currents be examined to derive directional information as the basis for the new approach to directional detection on a polyphase basis.

On a three-phase system a short circuit on a feeder will result in positive-phase-sequence power flowing towards the fault whilst negative-phase-sequence and zero-phase-sequence power, with one or both produced by the fault, flowing away from the fault. However, the relative magnitude of the positive-, negative- and zero-phase-sequence power that flows through the relay location is dependent on the type of fault, the division of power of each phase sequence from the two line ends and the fault position from the relaying point. The magnitudes of the various sequence components, though varying in proportion, do not affect the direction of flow of each component as stated.

Any one of the phase sequence components of the power or combination of two or three of them may be used to provide directional information. Similarly, the product of the voltage and current of a given phase sequence or a combination of different products of other phase sequences should also provide a means to detect the direction of the fault.

Appendices 11.4 and 11.5 show the make-up of the input signals to a directional relay to operate for forward faults. The input power to the relay consists of all or a combination of the phase sequence components depending on the input signals employed.

Different combinations of phase sequence volt-ampere components can be obtained dependent on the voltages and currents chosen as inputs to the directional detector, i.e., dependent on the different connections, as defined in Chapter 2, of the directional elements. It is not necessary that all input combinations of voltages and currents will produce all the phase sequence components.

In the electromechanical design of a polyphase directional relay, the production of contact-closing torque to drive a moving element on detection of forward faults is based on the interaction of fluxes generated by the voltage and current signals as detailed in Chapter 2. The performance depends on the selection of voltages and currents applied to the relay and the arrangement of the interaction, by design of physical layout of the voltage and current coils and accurate mechanical settings, of their resultant fluxes. As shown in Appendix 11.2 there are also fluxes generated by current or voltage signal alone if symmetry is not provided in the structure of the moving element. These fluxes generate torque components that can only be cancelled out by accurate mechanical adjustment [2.3, 2.17]. A typical arrangement [1.1] of the voltage and current coils for a polyphase directional relay and the signals to the individual coils are shown in Figure 6.1. The moving element, in the form of an inverted aluminum "cup", is mounted in the centre and is free to rotate about a vertical axis [2.7, 3.0, 3.9].

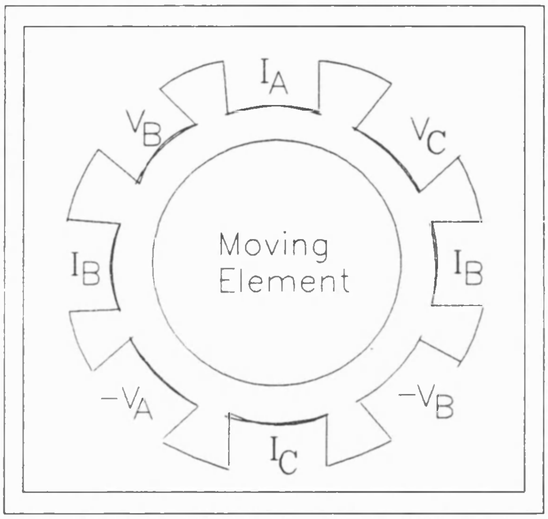



Figure 6.1 A Typical Arrangement of the Voltage and Current Coils of a Polyphase Electromechanical Directional Relay with Quadrature Connection.

It should be noted that only interaction between adjacent pairs of voltage and current signals are considered. The interaction between alternate pairs of voltage and current signals is arranged such that the various components of torque produced balance out substantially to zero with more accurate balancing by mechanical setting of the moving element assembly [1.1, 2.17].

The resultant torque produced on the moving element by the interaction of adjacent pairs of voltages and currents is therefore proportional to [1.1, 1.2]:

$$\mathbb{R}\ (V_{BC}\bar{I}_A + V_{CA}\bar{I}_B + V_{AB}\bar{I}_C)$$

There are three torque components, each being generated by the three volt-ampere products. The individual component, whether it is positive to drive the moving element to close the output contact or negative to restrain operation, is dependent on the angular displacement between the voltage and current signals concerned. The resultant torque then determines the output contact status, closed for forward faults (provided both the voltage and current magnitudes are above the threshold of operation) and open for reverse faults.

Appendix 11.2 shows that the product of two sinusoidal functions does not produce harmonically varying components. Instead, a constant output, in this case the production of a driving torque results, which has a fixed magnitude for given values of voltage and current in rms terms and for a given phase displacement between them. This constant contact-closing torque, therefore, provides the basis for a positive indication of the direction of a fault point. The direction can be defined, by the selection of suitable operating current(s) and polarising voltage(s) and the limits on the phase displacement between them for operation. This selection of input quantities and the limits imposed on the phase displacement between them for operation to define forward direction must ensure that under no circumstances will a reverse fault produce a condition that matches the operating criteria defined.

The proposed new method of detecting direction employs an approach similar to the design of the electromechanical polyphase directional relay. Instead of examining the "product" of the input signals, which is dependent on both magnitude and phase displacement of the signals, the "product" of the voltage and current signals is examined for the resulting angular displacement between them with additional phase shifts as necessary. The resulting angular displacement, if it falls within set limits for operation, defines a forward direction to the fault point.

## 6.2 New Approach to Polyphase Directional Detection

In the electromechanical directional relay design, the torque produced between two actuating signals, say currents $I_x$ and $I_y$ to drive the moving element, is given by Appendix 11.2:

$$Torque = K \times |I_x| \times |I_y| \times Sin\ \alpha \qquad .....6.01$$

where $\alpha$ is the angular displacement between the fluxes generated by the two actuating signals applied to the relay. If a symmetrical structure for the moving element is used, the angle $\alpha$ is also equal to the displacement between the two actuating signals [3.3].

If one of the fluxes is displaced from its corresponding actuating signal by a phase angle $\beta$ e.g. when this actuating signal is a voltage V, the associated flux-generating current will be displaced, and the other is a current I so that the torque produced is given by:

$$Torque = K \times |V| \times |I| \times Sin\ (\beta + \phi) \qquad \ldots\ldots\ldots 6.02$$

Figure 6.2 shows the actuating signal phasors V and I and the positions of the associated fluxes.

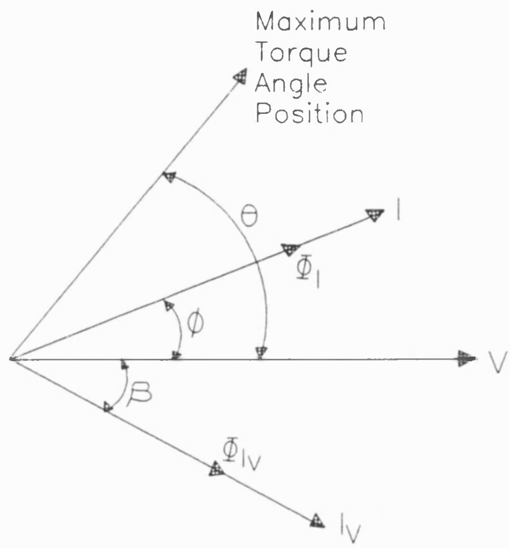



Figure 6.2 Phasor Diagram showing the Positions of the Actuating Signals and the Fluxes generated with the various Phase Displacements.

From the actual application point of view it is more practical to relate the torque magnitude to the actuating signals and the displacement between them rather than depending on the value of $\beta$ which is product design dependent. It is also necessary to define the most sensitive area of the relay operating zone, by creating a maximum torque angle $\Theta$, to match the fault profile.

The torque produced is a maximum when Sin $(\beta+\phi)$ = 1 or when $\beta+\phi=90°$, creating the maximum torque angle position.

From Figure 6.2 the torque produced can be expressed as:

$$
\begin{aligned}
Torque &= K \times |V| \times |I| \times Sin\ (\beta+\phi) \\
&= K \times |V| \times |I| \times Sin\ [90^\circ-(\theta-\phi)] \\
&= K \times |V| \times |I| \times Cos\ (\phi-\theta)
\end{aligned}
$$

........6.03

The selection of the actuating voltage may involve phase shifting a known voltage and in general, the torque developed can be expressed as:

$$Torque = K \times |V| \times |I| \times Cos\ (\phi \pm \lambda \pm \theta)$$

........6.04

where $\lambda$ is the intentional phase shift given to the polarising voltage V and $\Theta$ the maximum torque angle.

In most directional relay designs to date based on the "product" or phase-angle-measurement type [2.6, 2.7, 2.9, 2.13, 2.16], the value of $\lambda$ is fixed and is entirely decided from the selection of the appropriate polarising voltage(s) that provides the inherent phase shift from the reference phase for the operating current(s). As an example, the A-phase directional relay with 90° connection uses the A-phase current and BC-phase voltage with the latter providing an inherent 90° phase shift compared to the use of A-phase current and also A-phase voltage as shown in Figure 6.3.

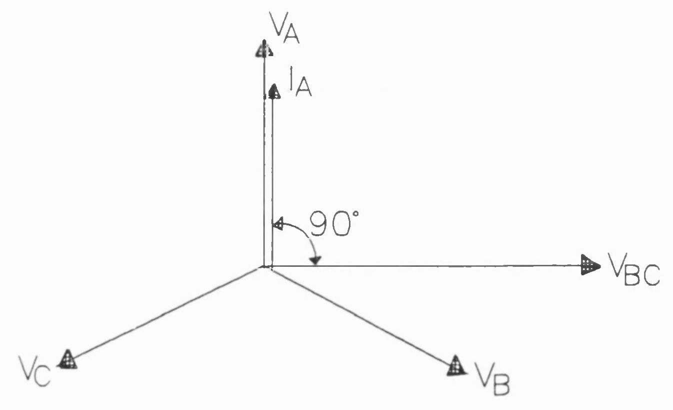



Figure 6.3 Inherent Phase Shift provided by Selection of Different Input Voltage $V_{BC}$ instead of $V_A$ for the A–phase Directional Relay.

Figure 6.4 shows the fluxes generated and the angular displacement between the input signals. The result is that the torque produced is dependent on the product of voltage V and current I and the final angular displacement between them.

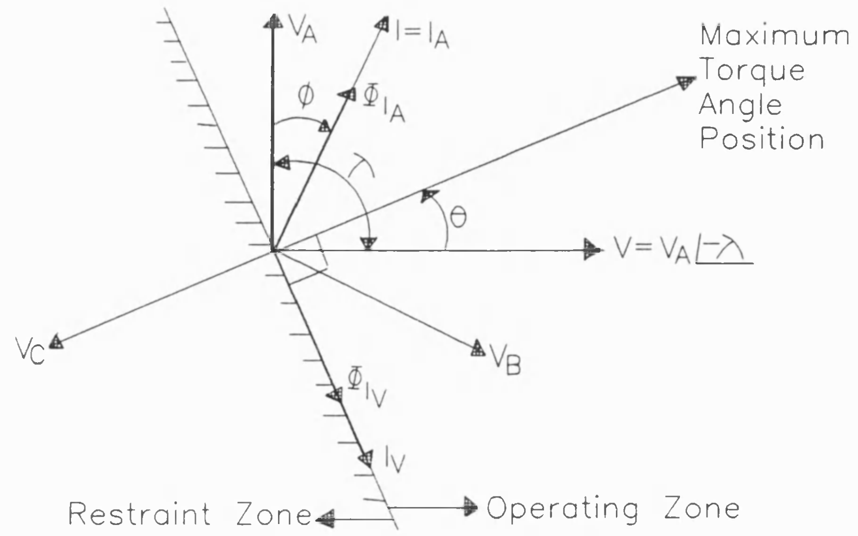



Figure 6.4 Phasor Diagram of Input Voltage and Current showing the Inherent Phase Displacement and the Intentional Phase Shift together with the Maximum Torque Angle Position.

The voltage V applied to the relay is obtained by phase shifting the system voltage $V_A$. Internally, the circuit design ensures that the resulting current from the voltage signal lags the voltage by a certain angle such that when the system current vector I applied to the relay lags the system voltage by the same angle, maximum torque is produced. The position of this particular current vector I with reference to the phase shifted voltage V, shown as angle $\Theta$, defines the maximum torque angle position. An operating zone is generated which is $\pm 90^\circ$ on either side of the maximum torque angle position.

The phase displacement, as shown in Figure 6.4, between the two fluxes due to the voltage and current is given by $90^\circ + \lambda - \Theta - \phi$ or $90^\circ - (\phi - \lambda + \Theta)$.

$$\therefore \; Torque = K \times |V| \times |I| \times Sin\,[90° - (\phi - \lambda + \theta)]$$

$$= K \times |V| \times |I| \times Cos\,(\phi - \lambda + \theta) \qquad ......6.05$$

This shows that the torque is positive, for forward fault operation when:

$$Cos\,(\phi - \lambda + \theta) \geq 0$$

$$or \quad -90° \leq (\phi - \lambda + \theta) \leq +90° \qquad ......6.06$$

The new approach uses a similar principle of examining the "product" of voltage and current and cosine function of the phase displacement angle between them. Forward direction is defined by a positive value of the "product". This necessitates that the cosine term must be positive or the resulting angle within the cosine function must be within $\pm 90^0$. The new approach examines only the angular displacement between the voltage and current signals chosen as inputs and with any necessary phase shift to define operation for forward and reverse faults if the resulting angle is within or outside a defined range respectively. The magnitudes of the input signals do not play a part in the directional detection process. The investigation shall be on the selection of the input signals, the variation of the angular displacement and the definition of an operating range.

The selection of an operating current and a polarising voltage provides information on the inherent phase displacement between the signals corresponding to the value of $\lambda$. The values of $\lambda$ and $\Theta$, caused by the choice of the polarising voltage and internal phase shift in the design of actual directional relays, can be considered, taking into account of their polarity, as the total required intentional phase shift. This phase shift ensures that for the set limits of $\pm 90°$ for forward fault operation, the resultant phase displacement between the operating current(s) and polarising voltage(s) for all types of forward faults falls within these set limits.

This investigation determines the optimal value of the effective intentional phase shift to be applied to the chosen operating current(s) and polarising voltage(s), so that the overall angular displacement is within the $\pm 90°$ limits for all types of forward faults and outside this range for all types of reverse faults. Alternatively, other more suitable limits may have to be defined to improve the selectivity performance.

Instead of examining the absolute voltage(s) and current(s) their symmetrical components shall be employed. The torque produced to drive the moving element in an electromechanical directional relay and being proportional to volt-ampere products can be expressed [1.1, 1.2] in terms of the "products" of the individual symmetrical components of voltages and currents. These are illustrated in Appendices 11.3 and 11.4.

For a 90° connection the torque produced by the interaction of the polarising voltage $V_{BC}$ and the operating current $I_A$ for the A-phase relay is given by:

$$Torque \propto \mathbb{R}\ (K_1 V_1 \bar{I}_1 + K_2 V_2 \bar{I}_2)$$

$K_1$ and $K_2$ are fixed for a given design and may be complex. The zero phase sequence component is not present in this particular selection of voltages and currents applied to the relay.

In general, it can be stated that the torque produced is due to the active components of the various phase sequence power acting on the moving element(s) to cause the output contact(s) to close or open dependent on the occurrence of forward or reverse faults. These active components are dependent on:

$$Torque \propto \mathbb{R}\ (K_1 V_1 \bar{I}_1 + K_2 V_2 \bar{I}_2 + K_0 V_0 \bar{I}_0)$$

The individual torque components expressed in terms of the phase sequence components of the voltages and currents are, whether they are positive or negative, dependent on the angular displacement between the voltage and current of the respective phase sequence components.

In order to optimise the performance, a maximum torque angle $\Theta$ is added to modify the expression for the active power above. This is an attempt to ensure that when the majority, if not all, of forward faults occur, maximum contact-closing torque or maximum sensitivity is produced in the relay.

In addition, it is also an attempt to limit the response of the relay to $\pm 90°$ on either side of the maximum torque angle position for the operating current vector corresponding to all forward-fault conditions.

The new expression is therefore:

$$Torque \propto \mathbb{R}\ (K_1V_1\bar{I}_1\ \angle\pm\theta_1 + K_2V_2\bar{I}_2\ \angle\pm\theta_2 + K_0V_0\bar{I}_0\angle\pm\theta_0)$$

In order to make use of all the three components to indicate the direction of a fault and to maximise sensitivity it is desirable that $\Theta_1$, $\Theta_2$ and $\Theta_0$ should be selected to make the negative and zero phase sequence components in antiphase to the positive phase sequence component so that the signs of all the three sequences of power are the same.

The selection of input current(s) and voltage(s) from which the symmetrical components are derived provides the phase shift $\lambda$ to the polarising signal.

The final expression for the torque produced is therefore given by:

$$Torque \propto \mathbb{R}\ (K_1V_1\bar{I}_1\ \angle(\pm\theta_1\pm\lambda_1) + K_2V_2\bar{I}_2\ \angle(\pm\theta_2\pm\lambda_2) + K_0V_0\bar{I}_0\angle(\pm\theta_0\pm\lambda_0)$$

For a given design of an electromechanical directional relay, it is not possible to change the influence of each phase sequence component separately by giving different weighting factors. The values of $K_1$, $K_2$ and $K_0$ are fixed for a given design of relay and are dependent on the selection of input signals and the physical design such as the moving element assembly including any control spring or plate [2.3, 2.7]. Solid-state designs merely provide a direct equivalent using the same input signals but examine only the phase displacement when the signals are above the thresholds of operation.

Different weighting factors are required to meet the different requirements for different fault types. The effect of this constraint of fixed weighting factors is reflected in the lack of sensitivity to detect earth faults as discussed in Chapter 4 for polyphase directional relays [2.3].

### 6.2.1 Use of Symmetrical Components to detect Fault Direction

Instead of examining the summation of volt-ampere product of the three-phase voltages and currents for a polyphase directional relay to determine the direction of a fault with respect to the relay location it is proposed to examine the symmetrical components of voltages and currents directly to provide a direction-detection decision process.

The objective is to examine the phase relationship between the phase sequence components (in a suitable combination) of the voltages and currents from which to determine the fault direction with respect to the relay location.

Kimbark [1.2], in an analysis of an electromechanical polyphase directional relay, presented the various possibilities of connections. For the quadrature connections, only the positive and negative phase sequence components are present and the following relationships between the two phase sequence components of voltages and currents can be established for the chosen input voltages and currents to generate the required driving torque:

1. $(V_A I_{CB} + V_B I_{AC} + V_C I_{BA}) = 3\sqrt{3}(V_1 I_1 \angle 270° + V_2 I_2 \angle 90°)$ .........6.07

$$2.\ (V_{CB}I_A + V_{AC}I_B + V_{BA}I_C) = 3\sqrt{3}(V_1I_1\angle 90° + V_2I_2\angle 270°) \qquad .........6.08$$

$$3.\ (V_{CB}I_{BA} - V_{BA}I_{CB}) = 3\sqrt{3}(V_1I_1\angle 270° + V_2I_2\angle 90°) \qquad .........6.09$$

The 90° and 270° phase shifts are introduced because of the connections i.e., the use of different voltages and currents applied to the directional relay. These angles correspond to the angle λ mentioned in section 6.2.

For the 60° connection of a polyphase directional relay the input voltages and currents used by McConnell [1.1] are as follow and expressed in terms of the phase sequence components:

$$I_A\{(-2V_C)+(V_A+V_B)\}+I_B\{(-2V_A)+(V_B+V_C)\}+I_C\{(-2V_B)+(V_C+V_A)\}$$
$$= 9(V_1I_1\angle 120° + V_2I_2\angle 240°) \qquad ........6.10$$

Again, the performance of this 60° -connected directional relay can be evaluated by examining the volt-ampere products of the two phase sequence components of voltages and currents. The polarity of the torque components still depends on the resultant phase displacement between the phase sequence voltages and currents.

The above analysis shows that it is possible to employ symmetrical components directly to derive the direction information of the fault point.

Analyses of other connections, such as the 30° connection will [1.2] similarly show other combinations of the various phase sequence components.

The traditional connections introducing inherent phase shifts have limited ranges of angles to modify the volt-ampere products because of the number of possible voltages and currents available to the directional relays without artificial phase shifts. The situation is improved with the introduction of a maximum torque angle to pre-define the operating range of the relay. The proposed new approach of using directly the phase sequence components will have unlimited ranges of angles in the manipulation of the phase sequence quantities introducing phase shifts to arrive at the optimal combination.

The basis is to extract the required phase sequence components from the input voltages and currents after which these components are conditioned before being examined to derive the direction information.

To improve the performance in terms of sensitivity, overcoming the main limitation of electromechanical design, different weighting factors will be examined for the different phase sequence quantities.

One criticism against the use of polyphase directional relays is the loss of phase selection capability to identify the faulted phase(s). Other means have to be designed where faulted phase(s) identification is required in the fault detection process. For current-operated relays with directional control the phase selection function relies on the operation of the current level detectors associated with each phase. This is possible except in the case of only a single current level detector being used with multiplexed 3-phase input currents.

The availability of the phase sequence components enables [1.11] the identification of faulted phase(s). Mouton and Souillard have shown, as given in Appendix 11.7, a method of phase selection using symmetrical components. Commercially available protection [2.4] and fault location [2.34] equipment has also applied this principle of phase selection.

It is envisaged that the new approach of polyphase directional detection without the loss of phase selection capability will significantly improve the cost effectiveness and performance of protection schemes using this type of element.

#### 6.2.1.1 Choice of Phase Sequence Components

The presence of a particular phase sequence component depends on the type of fault. Positive phase sequence current is always available for all kinds of faults. Negative phase sequence current is available for all but 3-phase faults. Zero phase sequence current is available only in earth faults.

It appears, therefore, that if one single sequence component were to be selected to represent the three phase currents, the positive phase sequence component network would suffice. In practice, this is not the case as in many, if not most of the applications, there is a need to consider the presence of load current during the fault. It must be recognized that the positive phase sequence component consists of two parts, the load current and the fault current.

For a single-phase-to-earth fault on a feeder, the positive phase sequence component of fault current at both ends will be in phase as "seen" by the relay system. However, any load flow across the feeder during the fault will produce a positive phase sequence component of load current at one end that is 180° out of phase with that at the other end. The phase position of the load component relative to fault component depends on such factors as the direction of the load current flow, power factor of the load and the phase angles of the system impedances. The phase position of the net (load plus fault) positive phase sequence current entering one end of the line relative to that entering the other end will depend on these same factors plus the relative magnitudes of the fault and load components of current.

The flow of through load current during a fault can, therefore, lead to a wrong direction conclusion if only positive phase sequence components of voltage and current are used. An example is the occurrence of a high resistance single-phase-to-earth fault on a feeder with load transfer through the feeder.

In general, the larger the fault current and the less the load current the more reliable is the operation of a directional relay based on pure positive phase sequence components. Heavier line loadings and lower fault currents will make the directional decision more difficult to conclude.

Significant negative phase sequence current is present only during faults. It is present in all but balanced three-phase faults and there is no significant negative sequence component of load current. Pure negative phase sequence quantities appear ideal for the design of a directional relay except that it will not operate for balanced three-phase faults. Similar comments may be made regarding pure zero phase sequence current with the additional limitation that it will not operate for phase-to-phase faults. Thus, there does not appear to be one single phase sequence component that could be used to meet all the performance requirements.

There are a number of different approaches that are possible by mixing different phase sequence components in a given proportion to form a composite signal. However, there are two main questions to be resolved, i.e.:

1. Which phase sequence components should be mixed together to form a composite signal?

2. What percentage of the full magnitude of each phase sequence component should be used?

The selection of phase sequence components and weighting factors should take into account the following:

- The application rules should be simple enough to make the application practical and applicable to systems for which the end product is intended.

- The aim should be to use the least number of phase sequence components to achieve the desired performance.

- Load current effect must be minimised. This means the negative phase sequence and/or the zero phase sequence components should have a greater weighting factor compared to the positive phase sequence component.

The above considerations mean the best overall results would be obtained from using a combination of the positive and negative phase sequence components with the latter dominant over the former to give higher sensitivity to earth fault detection.

Without the inclusion of the zero phase sequence component the task of evaluating the overall performance would be simpler. This is mainly due to the current distribution in the zero phase sequence network being generally quite different from that in the positive and negative phase sequence networks, where the current distributions are approximately the same. For any given fault on a feeder the ratio of the positive phase sequence component to negative phase sequence component of the fault current at any terminal is the same as at any other terminal of that feeder. This, however, is not necessarily true of the ratio of positive or negative phase sequence component to the zero phase sequence component.

It has also been recognized [1.4] that the 60° and the 90° connections of directional relays provide the best options to fit the majority areas of applications. These two types of connections result in contribution in the directional detection process only from the positive and negative phase sequence components.

It is, therefore, proposed that only the positive and negative phase sequence components are employed in the new approach to a polyphase directional detection method.

#### 6.2.1.2 Combination of Phase Sequence Components

There are two approaches to make use of the symmetrical components of voltages and currents in order to examine the angular displacement between them to determine the fault direction.

One method is based on forming two composite signals separately (one for voltage and the other for current) to represent their respective primary phase information. The direction of the fault is determined by examining the angular relationship between these composite voltage and current signals.

The other approach is to examine the limits of angular relationship between the individual phase sequence voltage and current for different fault conditions and then to combine the limits to define forward and reverse directions with suitable weighting factors in deriving the combination.

### 6.2.2 Use of Composite Signals

The chosen symmetrical components of voltages and currents can be combined in a given proportion, both magnitude and angle, to form two composite signals of voltage and current from which fault point direction information can be derived. It is, however, important that a fixed reference is used for both the composite voltage and current so that a true comparison between them can be made to obtain meaningful phase difference information and hence the direction of a fault point.

#### 6.2.2.1 Composite Current Signal

Extensive work has been carried out on the derivation of an optimal composite current signal to represent faithfully the primary current phase information for use in power line carrier phase comparison schemes [2.2]. A composite current signal is also used in current differential protection schemes [2.15].

The composite current signal $I_m$ can be represented by:

$$I_m = n\, I_1 + m\, I_2 + p\, I_0 \qquad \text{..........6.11}$$

where m, n and p are constants that may be complex.

This signal represents, for any combination of load and fault currents, the phase angle of the primary current with respect to some convenient reference.

Work by Adamson and Talkhan [1.26] concluded that the optimal signal combination is:

$$I_m = m\ I_2 + n\ I_1 \qquad \text{......6.12}$$

where m is variable between 5 to 20, and n = -1.0

The negative phase sequence component has been given a much higher weighting factor to maintain high sensitivity for earth faults in the presence of full load current, especially under minimum fault level conditions.

For phase comparison schemes involving only the current signal, details of the reference point for the phase information of the current are not important provided the two line-end currents use the same reference.

However, for detection of current flow direction at only one relay location the reference has to be established locally.

#### 6.2.2.2 Composite Voltage Signal

To provide locally at the relaying point a known reference quantity to the composite current signal to establish fault direction a composite voltage also has to be derived to satisfy the following requirements:

(i) Representation of the primary phase voltage.

(ii) Provision of an optimal polarising signal for the directional decision making process.

The composite voltage signal can again be a combination of the various phase sequence voltages as:

$$V_m = w\,V_1 + x\,V_2 + y\,V_0 \qquad \text{.........6.13}$$

where w, x and y are constants that may be complex.

Three-phase power or volt-ampere product is a function of the symmetrical components of voltages and currents of the same phase sequence. There is no "cross coupling" [3.6] of power or volt-ampere product, for example, from negative or positive phase sequence current reacting with the zero phase sequence voltage.

It has been decided that the operating composite current signal should consist of only the positive and negative phase sequence components. The composite voltage signal has to be made up of similar components to enable determination of the angular displacement between corresponding symmetrical components. Therefore:

$$V_m = w\,V_1 + x\,V_2 \qquad \text{..........6.14}$$

The consideration for the proportions of the two components differs from that of the composite current signal. In this case, the important requirement is the need to provide sufficient polarising signal to enable the determination of fault direction. To meet this need it is advisable to provide a greater weighting factor for the negative phase sequence component in order to provide the necessary boost in cases of low negative phase sequence source impedance producing low negative phase sequence voltage at the relaying point.

### 6.2.2.3 Directional Decision

The directional decision is based on the angular information of a complex function derived from the composite voltage and current signals. A composite function can thus be formulated by comparing the two composite signals:

$$F_m = \frac{V_m}{I_m} = \frac{w\,V_1 + x\,V_2}{n\,I_1 + m\,I_2} \qquad \text{........6.15}$$

$$F_m = |F_m| \angle\theta_m \qquad \text{.........6.16}$$

For operation defining forward faults the angular displacement limits have to be set such that:

$$-90° \leq \theta_m \leq +90° \qquad \text{........6.17}$$

or other suitable ranges.

To ensure that for all types of forward faults the resultant angular displacement $\Theta_m$ is within the set limits, suitable values for the four constants, w, x, m and n (which are interdependent) have to be determined. There will thus be a large number of possibilities of combinations in the comparison of $V_m$ and $I_m$. The effectiveness of this comparison may be considered on the basis of the angular threshold boundaries dividing forward and reverse faults. The range of $\Theta_m$ should, therefore, be well defined and distinct for forward and reverse faults to give maximum discrimination.

In the absence of an ideal comparison process it has to resolve itself into an optimization of the choice of the constants w, x, m and n in conjunction with a practicably realizable boundary characteristic in order to afford maximum selectivity in forward and reverse direction definition.

Simplifying the expression still leaves the requirement of two constants to be determined to limit the angular displacement to be within a defined range for all forward faults:

$$F_m = \frac{K_V V_1 + V_2}{K_I I_1 + I_2} \qquad \text{........6.18}$$

$$Or \quad F_m = \frac{V_1 + K_v V_2}{I_1 + K_I I_2} \qquad \text{........6.19}$$

with the constants K's $\geq$ 1.0 in equation 6.19 to give higher weighting factor to the negative phase sequence component.

In this approach $F_m$ has to be evaluated as a complete function. The individual voltage and current signals cannot be examined independently. Optimization of the two signals separately to represent the primary system conditions does not necessarily lead to a suitable comparison between these two signals to enable derivation of the fault direction information.

### 6.2.3 Use of a Combined Function

Alternatively, the angular displacement can be examined by considering the individual phase sequence components separately. The combined effect is then optimized to ensure that all forward faults will produce angular displacement within a defined range.

A combined function is thus defined as:

$$F_C = K_{C1}\frac{V_1}{I_1} + K_{C2}\frac{V_2}{I_2} \qquad \text{........6.20}$$

where $K_{C1}$ *and* $K_{C2}$ are constants that may be complex.

$$F_C = |F_C| \angle\theta_c \qquad \text{..........6.21}$$

For operation defining forward faults the boundary values of the angular displacement $\Theta_C$ again have to be defined.

The above approach means that in order to ensure all forward faults will produce the angular displacement within a stated operating range the displacement of the negative phase sequence component and that of the positive phase sequence component must be within the same range. On this basis it is possible to consider separately, if necessary, the two phase sequence components to suit any particular application environment in deriving directional information. This approach is also easier to handle because of the known normal limits for the negative phase sequence quantities [3.7] independent of the pre-fault loading conditions.

When the angular displacement of the combined function is established by optimizing the angles associated with the $K_C$'s, different weighting factors can then be applied using different magnitudes to consider the sensitivity aspect of the directional detection. It has, therefore, been decided that this will be the approach for this investigation into a new proposal for directional detection on a polyphase basis. The objective is to determine suitable values for $K_{C1}$ and $K_{C2}$ such that for forward faults $\Theta_c$ is within a well defined range of angular displacement values and is outside this range for reverse faults.

McConnell [1.1] in his design of a polyphase directional relay found that the contact-closing torque to drive the moving element for forward faults due to the various phase sequence components are:

$$\left.\begin{aligned} \text{Torque}_1 &\propto \text{Cos}\,(\phi_1 - 60° + \Theta) \\ \text{Torque}_2 &\propto \text{Cos}\,(\phi_2 + 60° + \Theta) \end{aligned}\right\} \text{ for } 60° \text{ connection}$$

and

$$\left.\begin{aligned}\text{Torque}_1 &\propto \text{Cos}\,(\phi_1 - 90° + \Theta) \\ \text{Torque}_2 &\propto \text{Cos}\,(\phi_2 + 90° + \Theta)\end{aligned}\right\} \text{ for } 90° \text{ connection}$$

The two components (positive and negative phase sequences) of torque must be such that they act together in the same sense, on a common moving element, producing positive operation for forward faults and restraint for reverse faults.

The $\pm$ 60° or $\pm$ 90° shifts are produced by the use of different voltages and currents to generate the required fluxes for the electromechanical motion to achieve the desired effect of operation for forward faults and restraint for reverse faults.

The introduction of the maximum torque angle $\Theta$ provides, not only the most sensitive detection area of the relay to correspond to the most concentrated area of forward fault occurrence, but to restrict the response of the relay by limiting the angular displacement of the operating current to $\pm$ 90° from the position of the maximum torque angle.

The different phase shifts for the positive and negative phase sequence components imply that the maximum torque angle has to be different for the two components. However, for a given electromechanical design it is not possible to provide different maximum torque angles for the two different phase sequence components. The choice of a single value is therefore, a compromise between sensitivity, ability to operate for forward faults, selectivity and ability to restrain for reverse faults.

The combined effect of the inherent phase shift due to connection of a polarising voltage signal and the purposely introduced maximum torque angle leads to the production of positive contact-closing torque. The combination produces the desired effect of operation for forward faults and restraint for reverse faults.

The approach of using symmetrical components directly extracted from the input voltage and current signals enables the introduction of a single phase shift, associated with $K_{C1}$ and $K_{C2}$, of any values to the phase sequence components. This will provide optimization of the required angular phase shift separately to the two phase sequence components. The contribution from the two phase sequence components can also be made different by using different magnitudes for $K_{C1}$ and $K_{C2}$, thus providing greater sensitivity for earth faults.

Following the approach of an operating range for the angular displacement to be $\pm$ 90° on either side of the maximum torque angle position, it is proposed that the limits for $\Theta_C$ shall be $\pm$ 90° for operation for forward faults in deriving the values of $K_{C1}$ and $K_{C2}$.

Hence:

$$F_C = K_{C1}\frac{V_1}{I_1} + K_{C2}\frac{V_2}{I_2} \qquad \text{.........6.22}$$

$$= |F_C| \angle \theta_C \qquad \text{.........6.23}$$

For forward faults:

$$-90° \le \theta_c \le +90° \qquad \text{........6.24}$$

For reverse faults:

$$-90° \ge \theta_c \ge +90° \qquad \text{.........6.25}$$

These angular limits provide a very simple method to check whether the displacement is within the range by amplitude comparison [3.2]. Consider the positive phase sequence component:

$$F_{C1} = \frac{K_{C1} V_1}{I_1} \qquad \text{.........6.26}$$

$$= |F_{C1}| \angle F_{C1} \qquad \text{.........6.27}$$

If $-90° \le \angle F_{C1} \le +90°$

$$|K_{C1} V_1 + I_1| \ge |K_{C1} V_1 - I_1| \qquad \text{........6.28}$$

This is illustrated in Figure 6.5

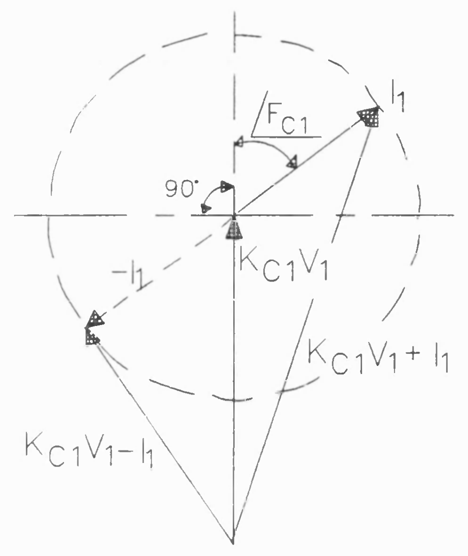



Figure 6.5 Amplitude Comparison to determine ±90° limits between Two Signals.

It is, therefore, possible to check the angular displacement against the ±90° limits and obtain an indication of forward or reverse direction, without the need to determine the actual values. This will help in the realization of the idea in the design of an actual product, especially by digital techniques, comparing the sum and the difference of two corresponding samples of voltage and current.

Before proposing values for $K_{C1}$ and $K_{C2}$ the angular displacement between the voltage and current for the two phase sequence quantities should be examined separately during forward and reverse fault conditions to establish the inherent limits produced.

### 6.2.3.1 Presentation of the Operating Characteristic of Directional Relays

The operating characteristic of the proposed method of directional detection is to be presented in a polar plane. The basic impedance plane or R-X plane shall be adopted but presented in polar form in terms of degrees of phase shift or angular displacement as shown in Figure 6.6. The following conventions are used:

| | | |
|---|---|---|
| Inductive impedance angle | $\angle Z$ | = positive angle |
| Current lagging voltage angle | $\angle(\frac{V}{I})$ | = positive angle |
| Lagging angle phase shift | | = positive angle |

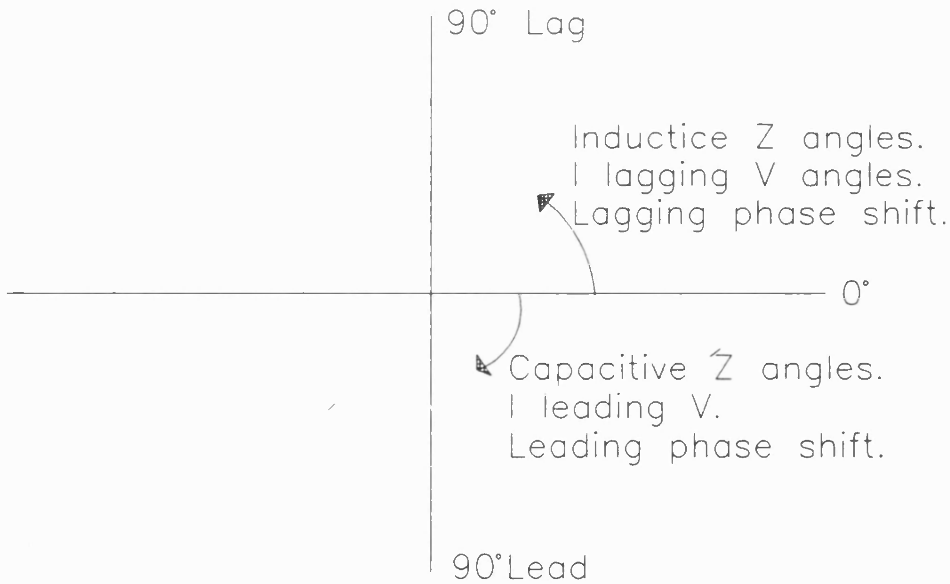



Figure 6.6 Polar Plane for Presentation of Direction Detection Operating Characteristic.

#### 6.2.3.2 Presentation of Traditional Directional Relay Operating Characteristics to Negative Phase Sequence Quantities

It has been established [1.1, 1.3] that the torque developed to drive the moving element of an electromechanical "product"-type directional relay consists of components that are proportional to the phase sequence components of voltages and currents:

$$Torque_1 \propto |V_1| \times |I_1| \times Cos\ (\phi_1 - 60° + \theta) \qquad \textit{for } 60° \textit{ connection}$$

$$or \propto |V_1| \times |I_1| \times Cos\ (\phi_1 - 90° + \theta) \qquad \textit{for } 90° \textit{ connection}$$

$$Torque_2 \propto |V_2| \times |I_2| \times Cos\ (\phi_2 + 60° + \theta) \qquad \textit{for } 60° \textit{ connection}$$

$$or \propto |V_2| \times |I_2| \times Cos\ (\phi_2 + 90° + \theta) \qquad \textit{for } 90° \textit{ connection}$$

Consider the case of the 90° connection and the negative phase sequence component:

$$Torque_2 = K \times |V_2| \times |I_2| \times Cos(\phi_2 + 90° + \theta) \qquad ......6.29$$

For maximum torque angle $\Theta = +45°$, torque$_2$ is maximum when:

$$Cos\ (\phi_2 + 90° + \Theta) = 1$$

$$or\ \phi_2 + 90° + 45° = 0°$$

$$\therefore\ \phi_2 = -135° \quad \text{i.e. a leading angle}$$

Under the most sensitive condition of the directional relay, the negative phase sequence current $I_2$ leads the corresponding voltage $V_2$ by 135°. Since this is the maximum torque angle position, the operating zone is ± 90° on either side of this position. This can be presented in the polar plane as shown in Figure 6.7. There is no consideration for the threshold of operation of the energising quantities.

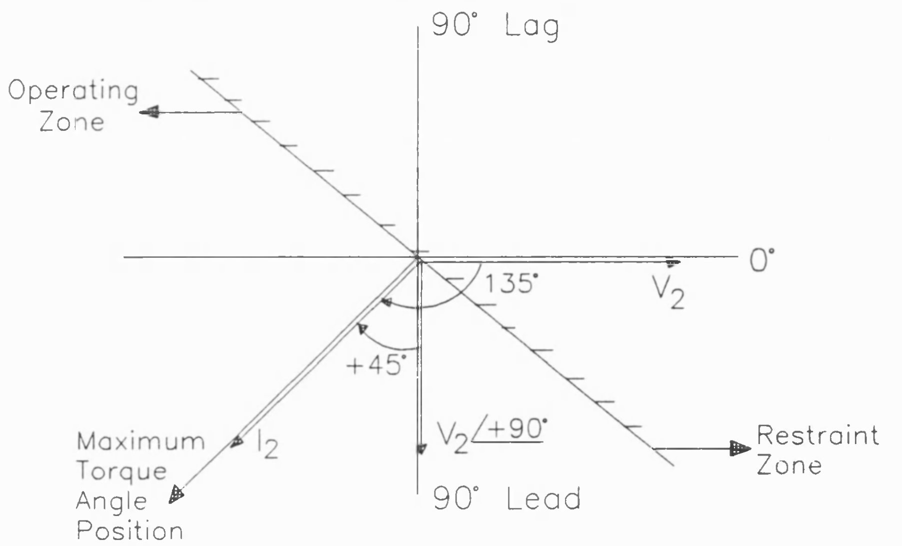



Figure 6.7 Operating Zone of an Electromechanical Product–type Directional Relay due to Negative Phase Sequence Components of Voltage and Current plotted on a Polar Plane.

Figure 6.7 shows the operating zone of the relay to negative phase sequence actuating signals. The limits of operation can be compared against fault occurrence area to check the selectivity of the relay.

### 6.2.3.3 Presentation of Traditional Directional Relay Operating Characteristics to Positive Phase Sequence Quantities

The component of the torque developed to drive the moving element of an electromechanical "product" -type directional relay and which is proportional to the positive phase sequence quantities is:

$$Torque_1 \propto |V_1| \times |I_1| \times Cos\ (\phi_1 - 60° + \theta) \qquad \textit{for } 60° \textit{ connection}$$
$$or \propto |V_1| \times |I_1| \times Cos\ (\phi_1 - 90° + \theta) \qquad \textit{for } 90° \textit{ connection}$$

Consider the case of the 90° connection:

$$Torque_1 = K \times |V_1| \times |I_1| \times Cos(\phi_1 - 90° + \theta)$$

.........6.30

For maximum torque angle $\Theta = +45°$, torque$_1$ is maximum when:

$$Cos\ (\phi_1 - 90° + \Theta) = 1$$

$$\text{or } \phi_1 - 90° + 45° = 0°$$

$$\therefore \phi_1 = 45° \quad \text{i.e. a lagging angle}$$

The operating characteristic is shown in Figure 6.8 with the operating zone at $\pm 90°$ on either side of the maximum torque angle position.

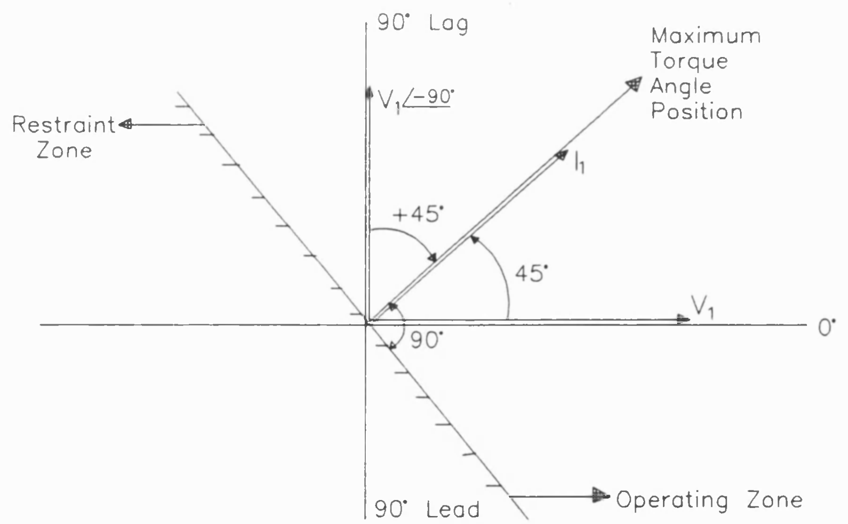



Figure 6.8 Operating Zone of an Electromechanical Product-type Directional Relay due to Positive Phase Sequence Components of Voltage and Current plotted on a Polar Plane.

From Figures 6.7 and 6.8, it can be seen that the response of the directional relay to negative phase sequence quantities is in opposition to the response to positive phase sequence quantities. This illustrates the point stated earlier, that positive phase sequence power flows towards a fault whilst the negative phase sequence power flows away from the fault and a directional relay designed to operate for forward faults must respond in accordance to these different flow directions.

### 6.2.3.4 Limits of Angular Displacement between Negative Phase Sequence Voltage and Current for Forward and Reverse Faults

Consider the network shown in Figure 6.9. Assume two directional relays "looking into" the protected feeder AB and an unbalanced fault occurring at point F external to the feeder.

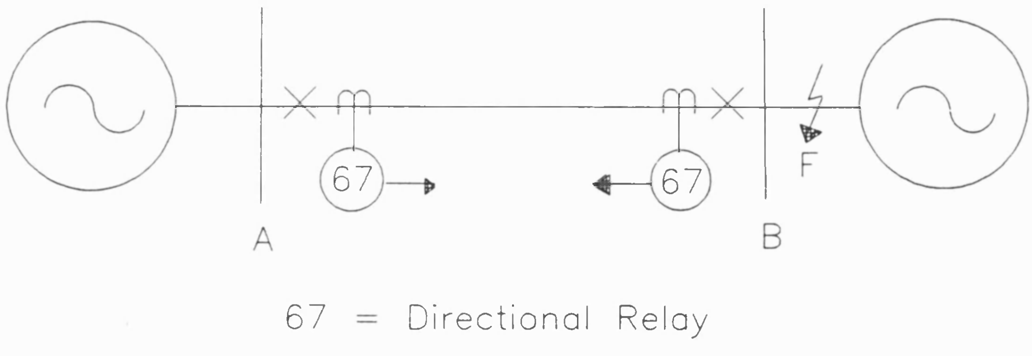



Figure 6.9 A double-end-fed System with Directional Relays at both Ends.

The negative phase sequence network of the system is as shown in Figure 6.10.

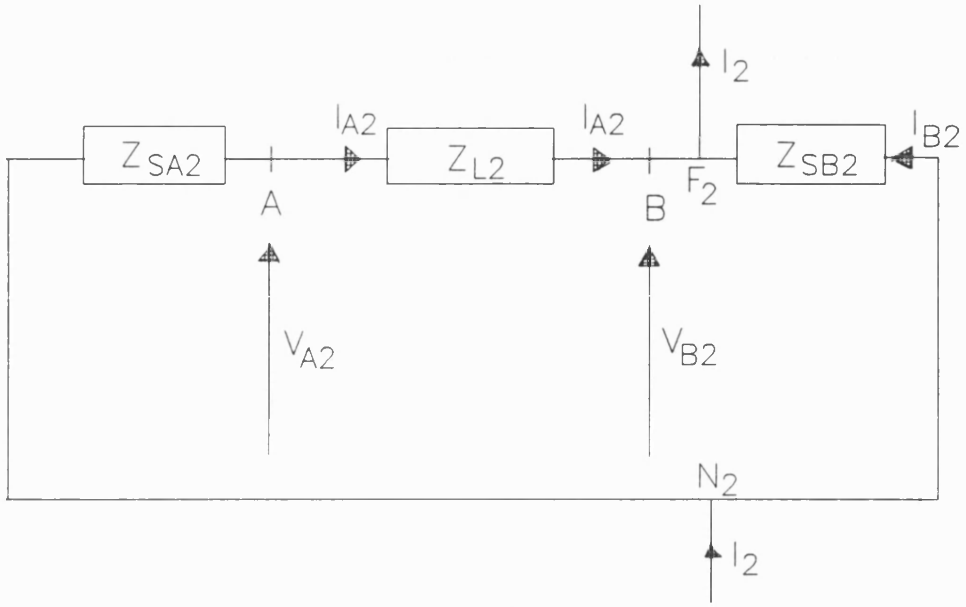



Figure 6.10 The Negative Phase Sequence Network of the System shown in Figure 6.9

At relaying point A:

$$V_{A2} = -I_{A2} \times Z_{SA2}$$

$$\frac{V_{A2}}{I_{A2}} = -Z_{SA2} \qquad \text{........6.31}$$

At relaying point B:

$$V_{B2} = -I_{A2} \times (Z_{SA2} + Z_{L2})$$

Relay B is arranged to "look into" feeder AB, the current it "sees" is therefore in the opposite direction to that flowing towards the fault at F.

$$\text{Therefore } V_{B2} = I_{A2} \times (Z_{SA2} + Z_{L2})$$

$$\frac{V_{B2}}{I_{A2}} = (Z_{SA2} + Z_{L2}) \qquad \text{.........6.32}$$

Consider Figure 6.9 again; if for an external fault at F:

$\Theta_A$ = angular displacement of $\frac{V_{A2}}{I_{A2}}$ at relaying point A

$\Theta_B$ = angular displacement of $\frac{V_{B2}}{I_{A2}}$ at relaying point B

and

$\Theta_{SA2}$ = negative phase sequence source impedance angle at A

$\Theta_{L2}$ = negative phase sequence line impedance angle

then

$$\theta_A = \angle(Z_{SA2}) + 180° \qquad \text{........6.33}$$

$$\theta_B = \angle(Z_{SA2} + Z_{L2}) \qquad \text{........6.34}$$

The values of $\Theta_{SA2}$ and $\Theta_{L2}$ are:

| | |
|---|---|
| $0^\circ \leq \Theta_{SA2} \leq 90^\circ$ | the limiting values for inductive sources. |
| or $45^\circ \leq \Theta_{SA2} \leq 90^\circ$ | for practical systems. |
| $0^\circ \leq \Theta_{L2} \leq 90^\circ$ | the limiting values for inductive lines. |
| or $30^\circ \leq \Theta_{L2} \leq 90^\circ$ | for practical feeders [3.9]. |

This gives the limits of angular displacement between the negative phase sequence voltage and current at the two relay locations A and B as shown in Figure 6.11:

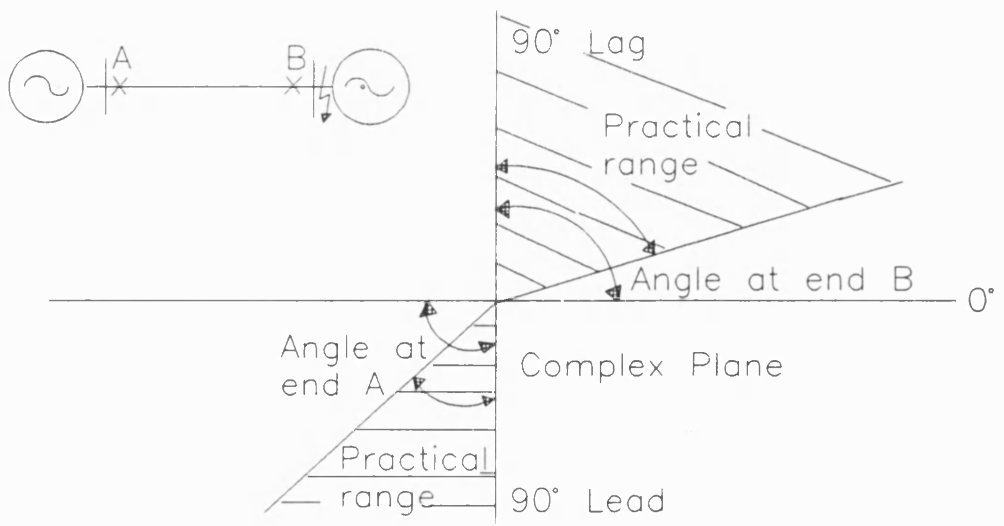



Figure 6.11 Variation of the Angular Displacement between Negative Phase Sequence Voltage and Current at the two ends of a line for an external fault at one end of the line.

$\Theta_A$ = +180° to +270° the limiting values.

or = +225° to +270° the practical range.

$\Theta_B$ = 0° to +90° the limiting values.

or = +30° to +90° the practical range.

This shows that for a forward fault the angular displacement between $V_2$ and $I_2$ is purely determined by the source impedance angle behind the relay shifted by 180°. For a reverse fault the angular displacement between $V_2$ and $I_2$ is the angular displacement of the combined impedance of source at the remote end of the protected feeder and the protected feeder itself. It can, therefore, be stated that the angular displacement between negative phase sequence voltage $V_2$ and current $I_2$ has the following limiting values:

For a forward fault "seen" by a directional relay at A, the angular displacement is:

+180° to +270°

For a reverse fault "seen" by a directional relay at B, the angular displacement is:

0° to +90°

In practice the ranges are smaller but they provide the limiting values for consideration.

Figure 6.12 shows the range of angular displacement between the negative phase sequence voltage and current for both forward and reverse faults "seen" by the two directional relays at A and B.

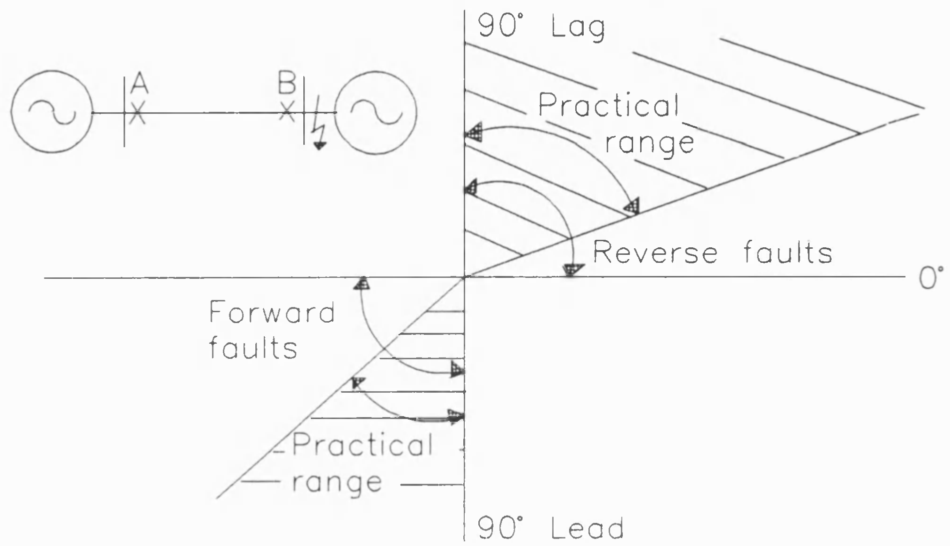



Figure 6.12 Range of Phase Displacement between Negative Phase Sequence Voltage and Current for Forward and Reverse Faults.

**6.2.3.5 Value of the Constant $K_{C2}$ - Angle**

Though the limits of angular displacement, as demonstrated, between the negative phase sequence voltage and current are within a defined range, a fixed value for the angle associated with $K_{C2}$ has to be established so that for all forward faults:

$$-90° \leq \angle(K_{C2}\frac{V_2}{I_2}) \leq +90° \qquad .......6.35$$

$$\angle(K_{C2}\frac{V_2}{I_2}) = \angle(K_{C2}) + \angle(\frac{V_2}{I_2})$$

$$= \angle(K_{C2}) + \phi_2$$

From the earlier analysis, the values of $\phi_2$, the angular displacement limits between the negative phase sequence voltage and current are:

$$+180° \leq \phi_2 \leq +270° \textit{ for forward faults} \qquad ......6.36$$

$$0° \leq \phi_2 \leq +90° \textit{ for reverse faults} \qquad ......6.37$$

To meet the requirement of:

$$-90° \leq \angle(K_{C2}\frac{V_2}{I_2}) \leq +90° \textit{ for forward faults} \qquad ......6.38$$

the angle $\angle(K_{C2})$ associated with $K_{C2}$ for forward faults must be such that:

$$-90° \leq [\angle(K_{C2}) + \phi_2] \leq +90° \qquad ......6.39$$

Figure 6.13 shows the angular displacement between $V_2$ and $I_2$ for forward faults and the area within which the angle must lie to ensure operation within $\pm$ 90°.

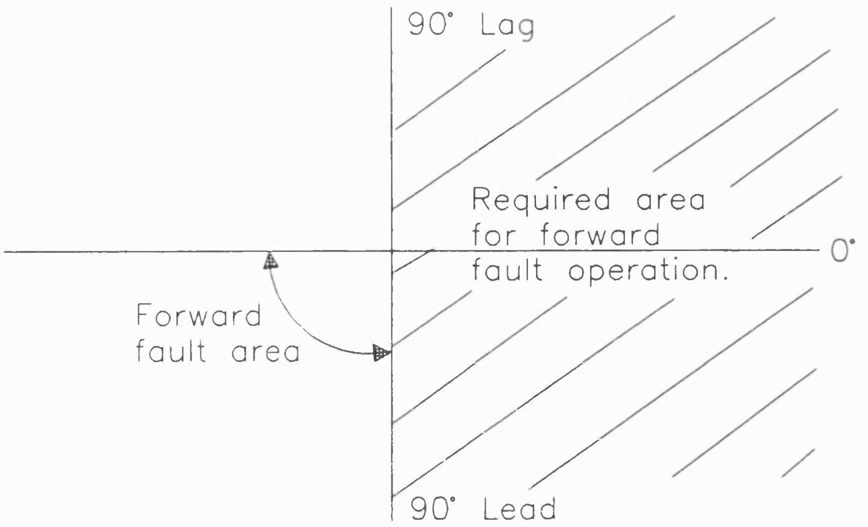



Figure 6.13 Phase Displacement between Negative Phase Sequence Voltage and Current for Forward Faults and the Required Area it has to lie to be within the Defined Operation Limits.

It can be seen that the most appropriate position, with the forward fault area occupying only 90° spread, is to shift this forward fault area to be centred around the 0° axis. The limits of the new forward fault area is then $\pm 45°$. This requires the $K_{C2}$ to provide a lagging angular phase shift of 135°, i.e., $\angle(K_{C2}) = +135°$

The new forward fault area is shown in Figure 6.14.

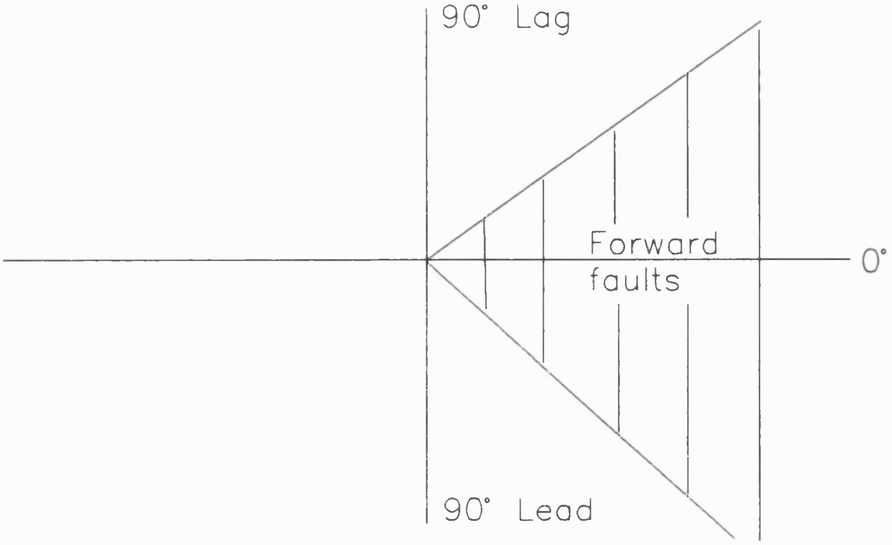



Figure 6.14 Range of ($K_{C2} * V_2/I_2$) Angle for Forward Faults with $K_{C2}$ providing 135 degrees Lagging Phase shift.

It should be noted that the source impedance associated with the negative phase sequence network has been assumed to have a range of 0° to 90°. In practice the value is likely to be between 45° to 90°. This means that with this practical range of the negative phase sequence source impedance angle the angular displacement between negative phase sequence voltage $V_2$ and current $I_2$ is within the range -135° to -90°. The angle associated with $K_{C2}\frac{V_2}{I_2}$ for a lagging angular phase shift of 135° introduced by $K_{C2}$ is 0° to +45° as shown in Figure 6.15.

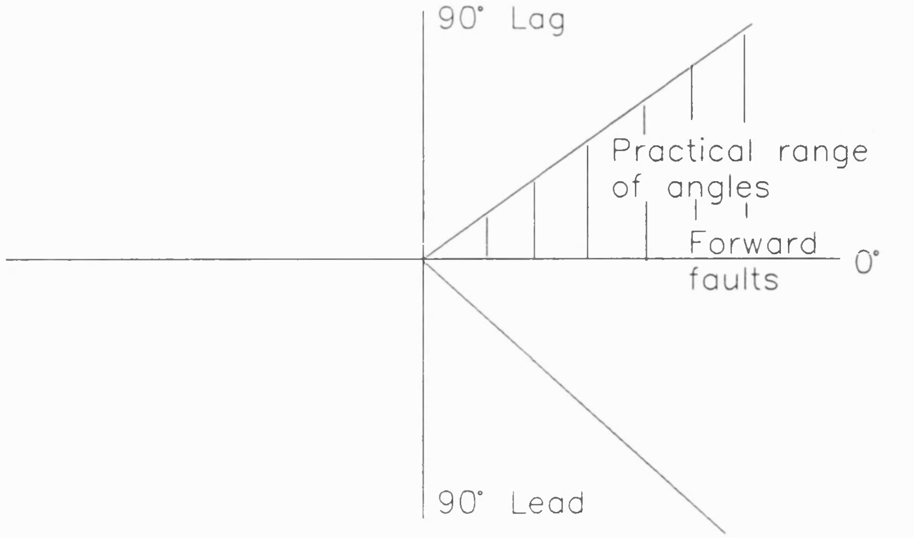



Figure 6.15 Range of ( $K_{C2} * V_2/I_2$ ) Angle for Forward Faults with $K_{C2}$ providing 135 degrees Lagging Phase shift with Practical Range of Negative Phase Sequence Source Impedance Angle.

For reverse faults the spread of angular displacement between negative phase sequence voltage $V_2$ and current $I_2$ is 0° to +90° with the negative phase sequence source and line impedance angles assumed to have minimum values of 0° and maximum values of 90°. This is shown in Figure 6.16 together with the desired area within which the range of angles should lie.

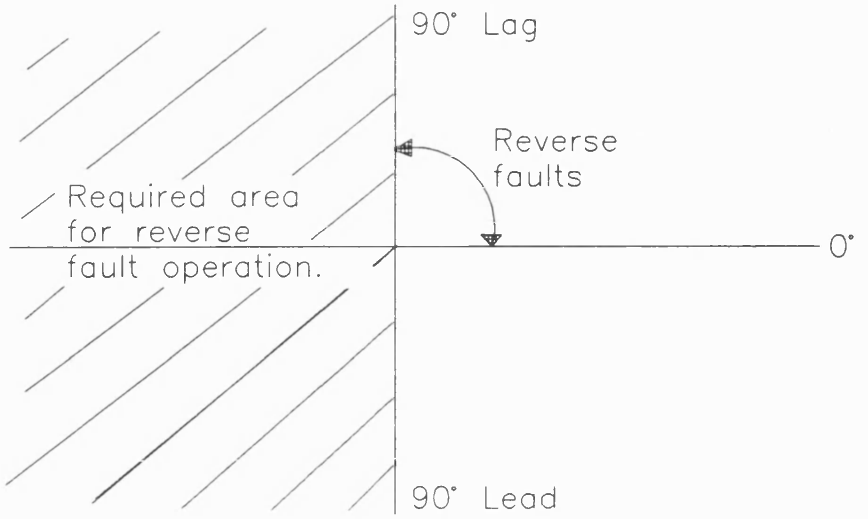



Figure 6.16 Phase Displacement between Negative Phase Sequence Voltage and Current for Reverse Faults and the Required Area it has to lie to be within the Defined Operation Limits.

With $K_{C2}$ introducing a 135° lagging angular phase shift the spread of the angle associated with $K_{C2}\dfrac{V_2}{I_2}$ is +135° to +225°. This is illustrated in Figure 6.17.

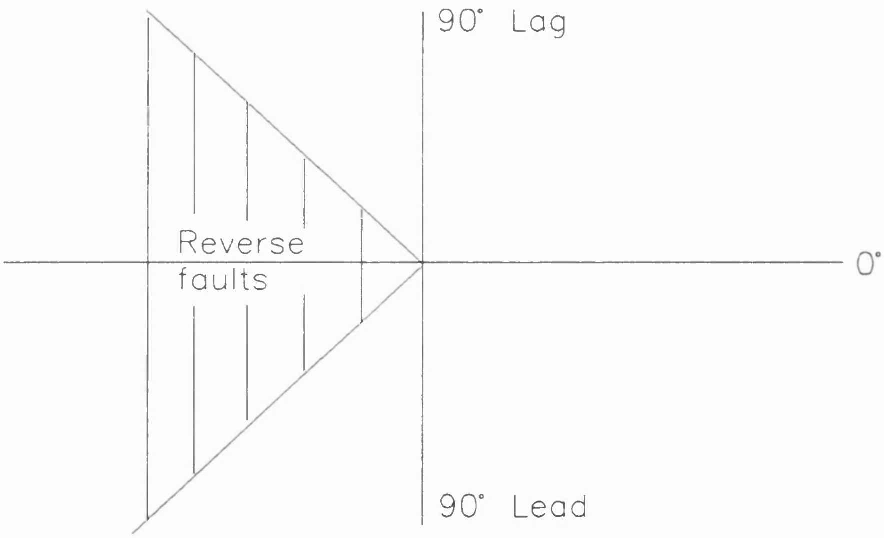



Figure 6.17 Range of $(K_{C2} * V_2/I_2)$ Angle for Reverse Faults with $K_{C2}$ providing 135 degrees Lagging Phase shift.

The minimum practical values for the negative phase sequence source and line impedance angles are likely to be about 45° and 30° respectively. The spread of the angle associated with $K_{C2}\frac{V_2}{I_2}$ for reverse faults is, therefore, +165° to +225°. This is shown in Figure 6.18.

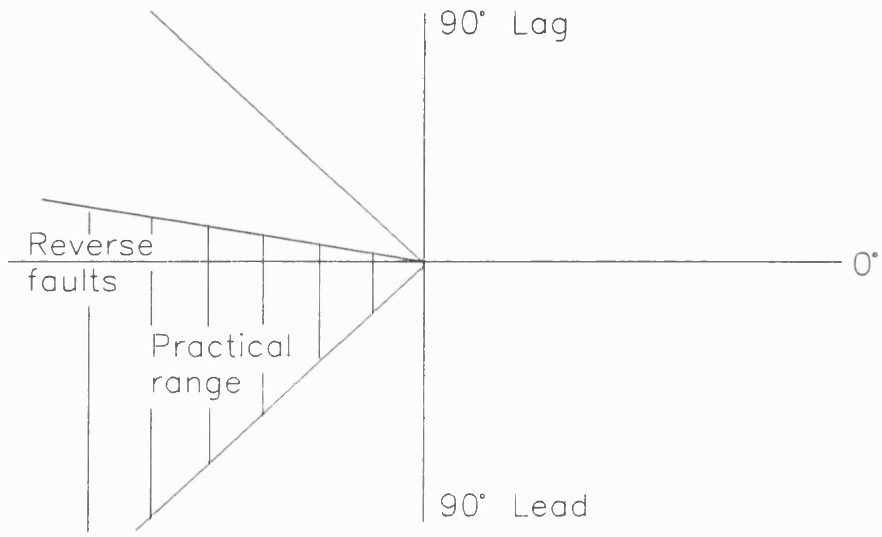



Figure 6.18 Range of ($K_{C2}*V_2/I_2$) Angle for Reverse Faults with $K_{C2}$ providing 135 degrees Lagging Phase shift.

The limiting range of angles associated with $K_{C2}\frac{V_2}{I_2}$ for both forward and reverse faults and their practical values are shown in Figure 6.19.

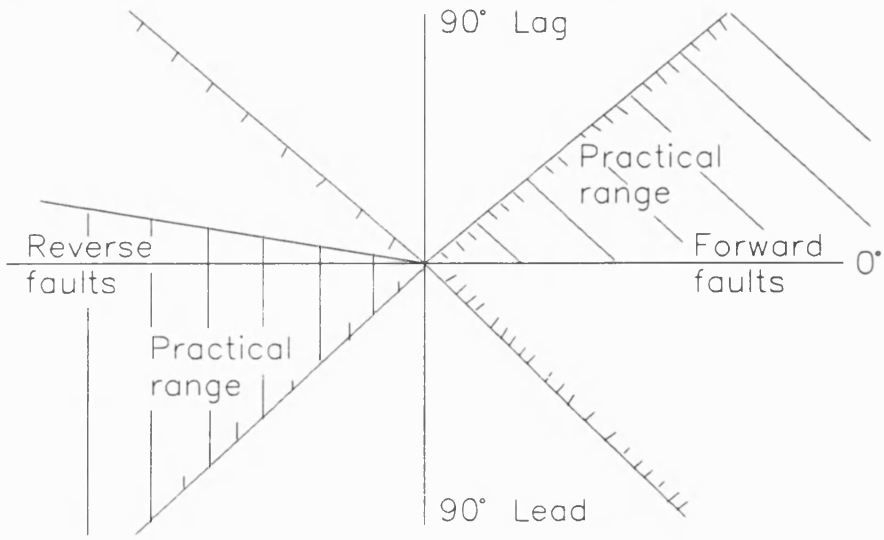



Figure 6.19 Range of $(K_{C2} * V_2/I_2)$ Angle for Forward and Reverse Faults with $K_{C2}$ providing 135 degrees Lagging Phase Shift for Practical Systems.

This shows that there is over 90° separation between forward and reverse faults which provides a very good discrimination margin. Under fault conditions directional relays based on negative phase sequence quantities are very dependable in operation and are widely used in some countries [3.7, 3.11].

#### 6.2.3.6 Angular Displacement between Positive Phase Sequence Voltage and Current for Forward and Reverse Faults

The objective in this case is to determine $K_{C1}$ so that the spread of the angle associated with $K_{C1}\frac{V_1}{I_1}$ is within $\pm 90°$ for all forward faults.

For the positive phase sequence voltage and current the angular displacement between them is not obvious and depends on dynamically changing quantities such as the source voltage, the direction of load current flow, power factor of the load and phase angles of the system impedances.

Consider the system shown in Figure 6.20 with a fault occurring at point F:

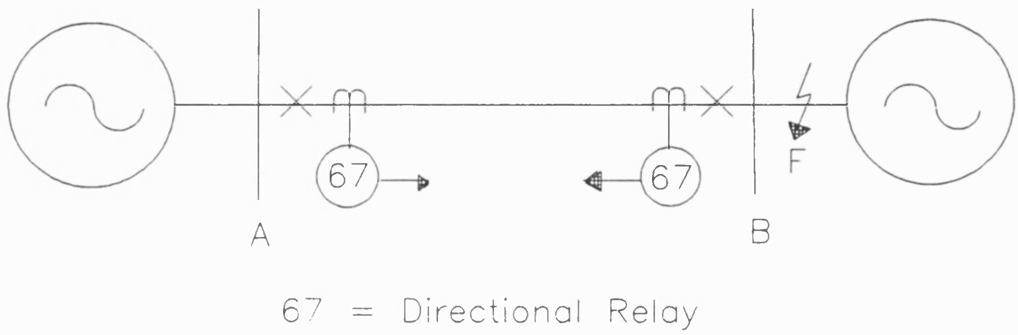



Figure 6.20 A double-end-fed System with Directional Relays at both Ends.

The positive phase sequence network of the system is shown in Figure 6.21.

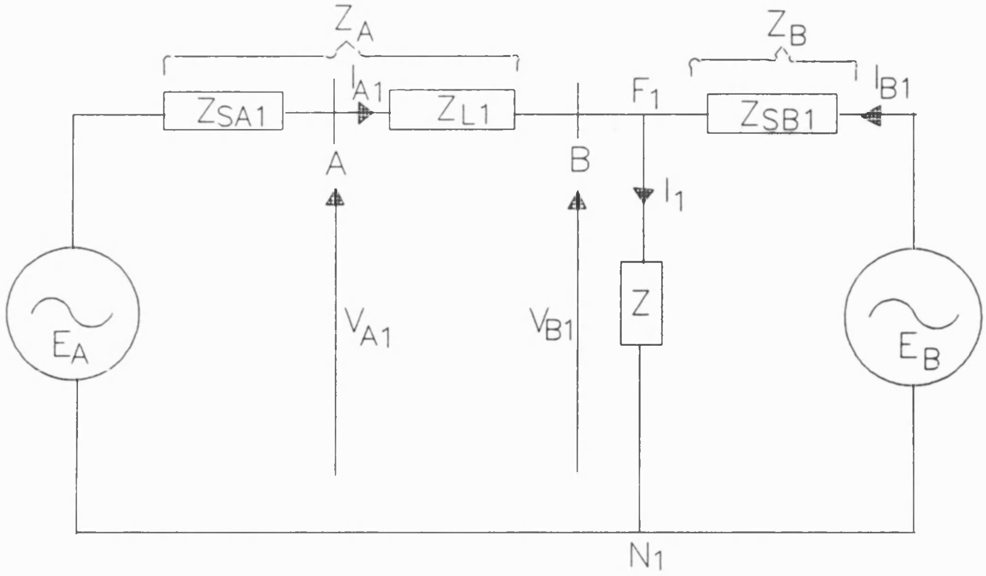



Figure 6.21 Positive Phase Sequence Network of the System shown in Figure 6.20.

This positive phase sequence network is applicable to all types of shunt faults assuming complete transposition of the line section AB and neglecting shunt capacitance. Shunt impedance Z is a variable impedance whose composition depends on the type of fault:

$$Z = 0 \text{ or } R_F \qquad \textit{for 3-phase-earth faults} \qquad \text{........6.40}$$

$$\text{or} \quad = Z_2+Z_0+3R_F \qquad \textit{for single-phase-earth faults} \qquad \text{........6.41}$$

$$\text{or} \quad = Z_2+R_F \qquad \textit{for phase-phase faults} \qquad \text{........6.42}$$

$$\text{or} \quad = Z_2 \| (Z_0+3R_F) \qquad \textit{for phase-phase-earth faults} \qquad \text{........6.43}$$

These different combinations are illustrated in Figure 6.22 which are fault-type dependent.

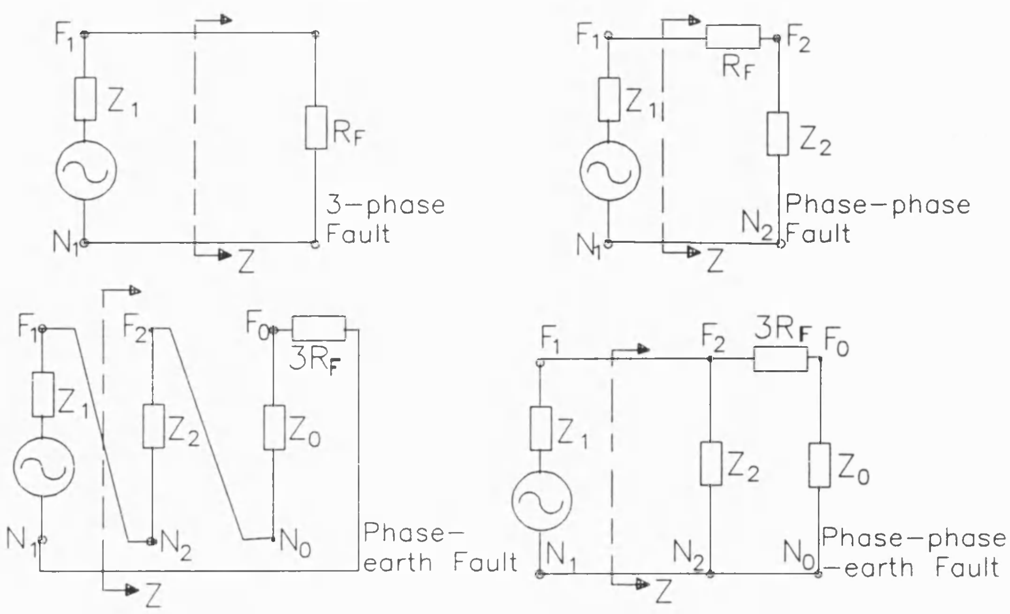



Figure 6.22 Composition of Shunt Impedance Z for Various Types of Faults

To determine the limits of the angular displacement between positive phase sequence voltage and current the ranges of angles associated with the various impedances have to be estimated.

The effect of pre-fault loading is to be neglected initially to obtain an estimate of the range with a more realistic determination taking account of pre-fault loading.

### 6.2.3.6.1 Angle associated with the Variable Shunt Impedance Z

The angle associated with the variable shunt impedance Z depends on:

- types of fault defining the composition of Z
- system earthing affecting the zero phase sequence impedance
- fault resistance compared with the phase sequence components

Considering the individual components that make up the variable shunt impedance Z, the spread of their angles are:

$\angle R_F$ or $\angle 3R_F = 0°$

$\angle Z_2 = 45°$ to $90°$

$\angle Z_0 = 0°$ to $90°$ depending on the system earthing arrangement

For 3-phase-earth faults from equation 6.40:

$Z = 0$ for zero fault resistance

$= R_F$ for a given fault resistance $R_F$

$\therefore \quad \angle Z = 0°$

For single-phase-earth faults from equation 6.41:

$$Z = Z_2 + Z_0 + 3R_F$$

$$\therefore \quad \angle Z = \angle(Z_2 + Z_0 + 3R_F)$$

$= 0°$ to $90°$ depending on system earthing arrangement and fault resistance value $R_F$ compared with the phase sequence impedances.

For phase-phase faults from equation 6.42:

$$Z = Z_2 + R_F$$

$$\therefore \quad \angle Z = \angle(Z_2 + R_F)$$

$= 0°$ to $90°$ depending on the fault resistance value $R_F$ compared with the negative phase sequence impedance $Z_2$.

For phase-phase-earth faults from equation 6.43:

$$Z = Z_2 \| (Z_0 + 3R_F)$$

$$= \frac{Z_2\ (Z_0 + 3R_F)}{Z_2 + Z_0 + 3R_F}$$

$$\therefore \quad \angle Z = \angle Z_2 + \angle(Z_0 + 3R_F) - \angle(Z_2 + Z_0 + 3R_F)$$

$$\left.\begin{array}{l} \angle(Z_0 + 3R_F) = 0^\circ \text{ to } 90^\circ \\ \angle(Z_2 + Z_0 + 3R_F) = 0^\circ \text{ to } 90^\circ \end{array}\right\} \begin{array}{l} \text{depending on the system earthing and} \\ \text{value of fault resistance } R_F \text{ compared} \\ \text{with the phase sequence impedances} \end{array}$$

Taking the limits of the three components independently as the basis, the range of angles associated with the variable shunt impedance Z is given by:

$$\angle Z = \angle Z_2 + \angle(Z_0 + 3R_F) - \angle(Z_2 + Z_0 + 3R_F)$$

$$\text{Minimum } \angle Z = 45^\circ + 0^\circ - 90^\circ$$

$$= -45^\circ$$

$$\text{Maximum } \angle Z = 90^\circ + 90^\circ - 0^\circ$$

$$= +180^\circ$$

It appears, therefore, that the range of angles associated with the variable shunt impedance Z is:

$\angle Z = -45^\circ$ to $+180^\circ$ depending on system earthing and value of fault resistance $R_F$ compared with the phase sequence impedances.

In practice the above limiting cases do not occur at the same time. Consider the case of resistance-earthed systems or the case of high resistance faults on solidly-earthed systems such that $R_F >> Z_o$ and $R_F >> Z_2$:

$$\angle(Z_o + 3R_F) \longrightarrow 0°$$

and also $$\angle(Z_2 + Z_0 + 3R_F) \longrightarrow 0°$$

$$\therefore \angle Z \text{ is determined by } \angle Z_2$$

$$\text{and } \angle Z = 45° \text{ to } 90°$$

For low resistance faults such that $R_F << Z_o$ and $R_F << Z_2$ consider solidly-earthed systems:

$$\angle(Z_o + 3R_F) \longrightarrow 90°$$

$$\angle(Z_2 + Z_0 + 3R_F) \longrightarrow 90°$$

$$\therefore \angle Z = \angle Z_2 + \angle(Z_0 + 3R_F) - \angle(Z_2 + Z_0 + 3R_F) \longrightarrow 45° \text{ to } 90°$$

With all the shunt fault types considered the angle associated with the variable shunt impedance is, therefore:

$$\angle Z = 0° \text{ to } +90°$$

#### 6.2.3.6.2 Limits of Angular Displacement without considering Pre-fault Load Current Flow

Neglecting, at the moment, the pre-fault load current through the relay locations the positive phase sequence component of the fault current at the fault point can readily be established using the pre-fault voltage $V_{p.f.}$ at the fault point as shown in Appendix 11.8. The positive phase sequence network shown in Figure 6.21 can be re-drawn as shown in Figure 6.23 using the pre-fault voltage $V_{p.f.}$ at the fault point between F and N to calculate the positive phase sequence component of the fault current.

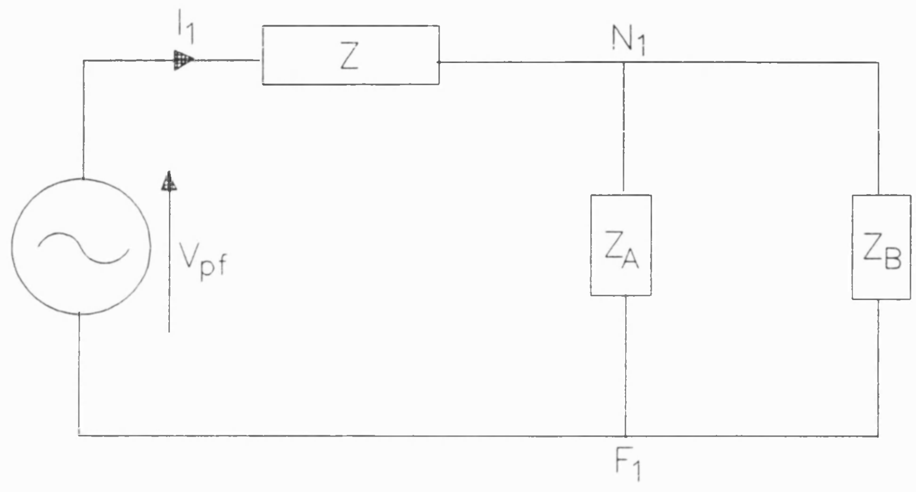



Figure 6.23 Positive Phase Sequence Network using Pre-fault Voltage.

The positive phase sequence component of the fault current at the fault point is given by:

$$I_1 = \frac{V_{p.f.}}{Z + \frac{Z_A Z_B}{Z_A + Z_B}} \qquad \text{..........6.44}$$

Without considering the load current component through the relay locations at A and B the components of current due to actual fault current $I_1$ through these two locations can be determined. The phase displacement between the positive phase sequence voltage $V_1$ and current $I_1$ at the two relaying locations A and B for a fault at point F on the system can then be established.

With reference to Figure 6.21 and Figure 6.23 consider the directional relay at A:

$$I_{A1} = I_1 \times \frac{Z_B}{Z_A + Z_B}$$

$$V_{A1} = I_{A1}Z_{L1} + I_1Z$$

$$= I_1 \times \frac{Z_B}{Z_A+Z_B} \times Z_{L1} + I_1 \times Z$$

$$= I_1 \left[\frac{Z_B \times Z_{L1}}{Z_A + Z_B} + Z\right]$$

$$therefore\ \frac{V_{A1}}{I_{A1}} = \frac{\left[\frac{Z_B \times Z_{L1}}{Z_A + Z_B} + Z\right]}{\frac{Z_B}{Z_A + Z_B}}$$

$$= \frac{Z_BZ_{L1} + Z(Z_A + Z_B)}{Z_B}$$

$$= Z_{L1} + Z + \frac{Z_A}{Z_B} \times Z \quad .............6.45$$

Consider the directional relay at B:

$$V_{B1} = I_1 \times Z$$

$$I_{A1} = I_1 \times \frac{Z_B}{Z_A + Z_B}$$

$$\therefore \frac{V_{B1}}{I_{A1}} = \frac{Z(Z_A + Z_B)}{Z_B}$$

$$= Z + \frac{Z_A}{Z_B} \times Z \qquad \text{......6.46}$$

Since the directional relay at B is arranged to "look" into the protected line section AB the current into the relay is reversed. Therefore the relay at B should "see":

$$\frac{V_{B1}}{-I_{A1}} = -[Z + \frac{Z_A}{Z_B} \times Z] \qquad \text{......6.47}$$

Without taking into account the load current contribution to the total relay current it can be seen that the phase displacement between the positive phase sequence voltage and current depends only on the angles associated with the various impedances. As expected, it is not influenced by the source emf's and the phase difference between them.

The angle between the positive phase sequence voltage and current for both forward and reverse faults can be established:

For forward fault "seen" by relay at location A from equation 6.45:

$$\frac{V_{A1}}{I_{A1}} = Z_{L1} + Z + \frac{Z_A}{Z_B} \times Z \qquad \text{.......6.48}$$

For reverse fault "seen" by relay at location B from equation 6.47:

$$\frac{V_{B1}}{-I_{A1}} = -[Z + \frac{Z_A}{Z_B} \times Z] \qquad \text{......6.49}$$

The range of angles associated with the individual impedances are:

$$\begin{aligned}
\angle Z_{L1} &= 0° \; to \; +90° \quad \textit{the limiting values} \\
or &= +30° \; to \; +90° \quad \textit{for practical feeders} \\
\angle Z_A &= \angle(Z_{SA1} + Z_{L1}) \\
&= 0° \; to \; +90° \quad \textit{the limiting values} \\
or &= +30° \; to \; +90° \quad \textit{for practical feeders and sources} \\
\angle Z_B &= \angle Z_{SB1} \\
&= 0° \; to \; +90° \quad \textit{the limiting values} \\
&= +45° \; to \; +90° \quad \textit{for practical systems} \\
\angle \frac{Z_A}{Z_B} &= \angle Z_A - \angle Z_B
\end{aligned}$$

For homogeneous systems $\angle Z_A = \angle Z_B$, *hence* $\angle(\frac{Z_A}{Z_B}) = 0°$

For a non-homogeneous system the angles associated with the two impedances $Z_A$ and $Z_B$ are not necessarily identical. Taking into account the ranges of $\angle Z_A$ and $\angle Z_B$ and the assumption that, for a given system and a line under consideration, it is unlikely that the magnitudes of $\angle Z_A$ and $\angle Z_B$ are in the opposite extremes, i.e. one angle is at the lowest value whilst the other is at the highest value, the range of $\angle \frac{Z_A}{Z_B}$ is taken to be -30° to +30° for practical systems. It should be noted that for distribution systems arranged in a closed or open ring configuration with only one source as shown in Figure 6.24, the angular displacement should be very small due to the different impedance characteristics of the various sections making up the feeder ring.

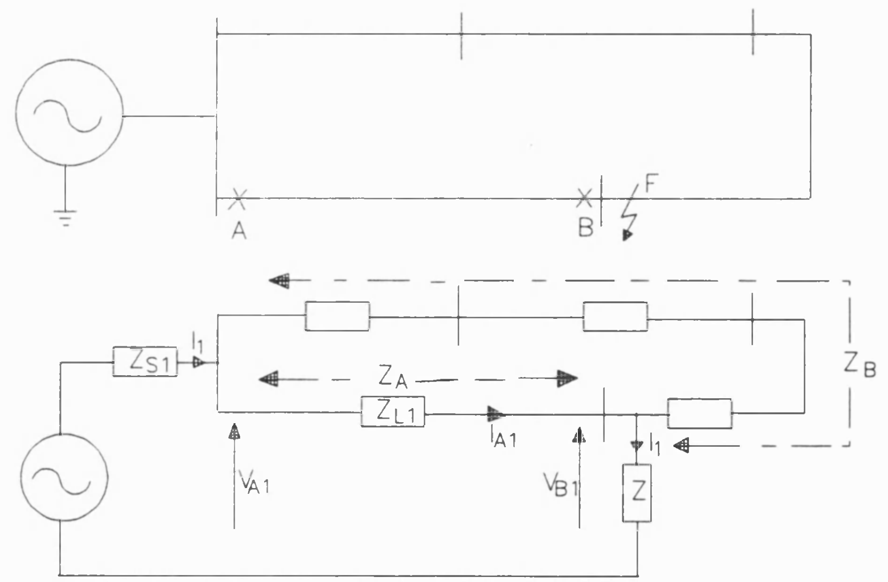



Figure 6.24 A Distribution System arranged in a Ring with a Single Source and its Equivalent Positive Phase Sequence Network for a Fault at point F.

The angular displacement between positive phase sequence voltage and current for forward and reverse faults can now be established as before.

For forward faults from equation 6.48:

$$\frac{V_{A1}}{I_{A1}} = Z_{L1} + Z + \frac{Z_A}{Z_B} \times Z$$

$$\angle\frac{V_{A1}}{I_{A1}} = \angle(Z_{L1} + Z + \frac{Z_A}{Z_B} \times Z)$$

$$\angle Z_{L1} = +30° \ to \ +90°$$

$$\angle Z = 0° \ to \ +90°$$

$$\angle\frac{Z_A}{Z_B} = -30° \ to \ +30°$$

$$therefore \ \angle(\frac{Z_A}{Z_B} \times Z) = -30° \ to \ +120°$$

$$Hence \ \angle\frac{V_{A1}}{I_{A1}} = -30° \ to \ +120°$$

For reverse faults from equation 6.49:

$$\frac{V_{B1}}{-I_{A1}} = -\left[Z + \frac{Z_A}{Z_B} \times Z\right]$$

$$\angle\frac{V_{B1}}{-I_{A1}} = +180° + (-30° \textit{ to } +120°)$$

$$= +150° \textit{ to } +300°$$

Figure 6.25 shows the angular displacement ranges between the positive phase sequence voltage and current for forward and reverse faults.

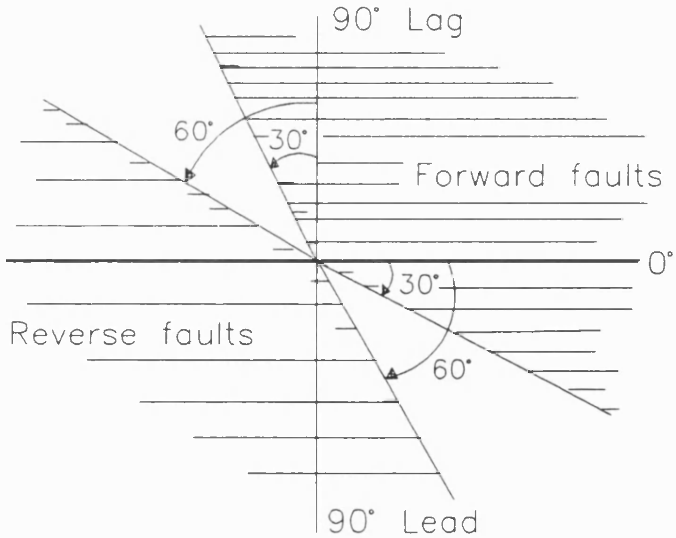



Figure 6.25 Angular Displacement between Positive Phase Sequence Voltage and Current for Forward and Reverse Faults without considering Pre-fault Load Current.

#### 6.2.3.6.3 Limits of Angular Displacement with consideration for Pre-fault Load Current Flow

Now consider the effect of the pre-fault load current and refer to Figure 6.21 again.

For a forward fault at relay location A:

$$V_{A1} = I_{A1}Z_{L1} + I_1 Z$$

$$\frac{V_{A1}}{I_{A1}} = Z_{L1} + \frac{I_{A1} + I_{B1}}{I_{A1}}.Z$$

$$= Z_{L1} + Z + \frac{I_{B1}}{I_{A1}}.Z \qquad \text{.......6.50}$$

For a reverse fault at relay location B:

$$V_{B1} = I_1 \times Z$$

$$= (I_{A1} + I_{B1})Z$$

$$\frac{V_{B1}}{-I_{A1}} = -[Z + \frac{I_{B1}}{I_{A1}}Z] \qquad \text{.....6.51}$$

From the above it can be seen that the ratio of the positive phase sequence voltage and current and the associated angular displacement is influenced by the ratio of the two currents fed from the two line-end sources. This latter ratio, considering both magnitude and phase displacement, depends on the pre-fault conditions of the system.

The pre-fault loading is governed by the source emf's $E_A$ and $E_B$ and the phase displacement between them.

### 6.2.3.6.4 Ratio of the two Components of Current $I_{B1}$ and $I_{A1}$ fed from the two Line-end Sources

Consider the positive phase sequence network shown in Figure 6.21 and redrawn as in Figure 6.26.

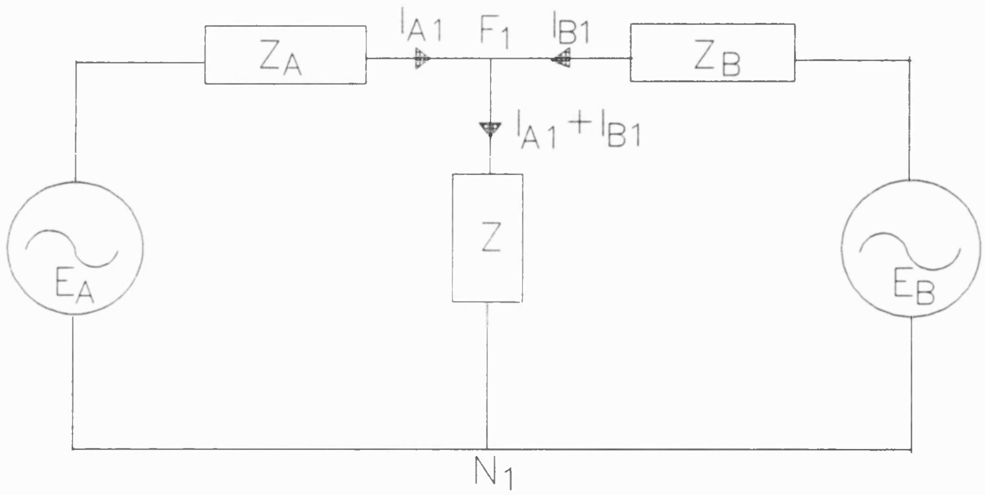



Figure 6.26 Equivalent Positive Phase Sequence for a Double-end fed System for different Fault Conditions.

$$E_A = I_{A1}Z_A + (I_{A1}+I_{B1})Z$$

$$E_B = I_{B1}Z_B + (I_{A1}+I_{B1})Z$$

$$\frac{E_A}{E_B} = \frac{I_{A1}(Z_A+Z)+I_{B1}Z}{I_{A1}Z+I_{B1}(Z_B+Z)}$$

$$= \frac{\frac{I_{A1}}{I_{B1}}(Z_A + Z)+Z}{\frac{I_{A1}}{I_{B1}}Z + (Z_B+Z)}$$

$$\frac{E_A}{E_B}\left[\frac{I_{A1}}{I_{B1}}Z+(Z_B+Z)\right] = \frac{I_{A1}}{I_{B1}}(Z_A+Z)+Z$$

$$\frac{I_{A1}}{I_{B1}}\left[\frac{E_A}{E_B}Z-(Z_A+Z)\right] = Z-\frac{E_A}{E_B}(Z_B+Z)$$

$$\textit{therefore} \quad \frac{I_{A1}}{I_{B1}} = \frac{-\frac{E_A}{E_B}(Z_B+Z)+Z}{\frac{E_A}{E_B}Z-(Z_A+Z)}$$

$$= \frac{-\frac{E_A}{E_B}\left(\frac{Z_B+Z}{Z}\right)+1}{\frac{E_A}{E_B}-\left(\frac{Z_A+Z}{Z}\right)}$$

$$\textit{or} \quad \frac{I_{B1}}{I_{A1}} = \frac{\frac{E_A}{E_B}-\left(\frac{Z_A+Z}{Z}\right)}{-\frac{E_A}{E_B}\left(\frac{Z_B+Z}{Z}\right)+1} \qquad \text{......6.52}$$

This ratio $\frac{I_{B1}}{I_{A1}}$ of two complex variables gives rise [3.2] to orthogonal circular loci, the diameters of which are dependent on the ratio of magnitudes of the driving emf's for one set of circles and on the phase difference between them for the other set of circles.

In general:

$$\frac{I_{B1}}{I_{A1}} = \frac{K_1 \frac{E_A}{E_B} + K_2}{K_3 \frac{E_A}{E_B} + K_4}$$

$$\left|\frac{I_{B1}}{I_{A1}}\right| \angle \frac{I_{B1}}{I_{A1}} = \frac{K_1 \left|\frac{E_A}{E_B}\right| \angle\delta + K_2}{K_3 \left|\frac{E_A}{E_B}\right| \angle\delta + K_4} \qquad \text{........6.53}$$

The poles of the orthogonal circles are given by $\frac{K_1}{K_3}$ *and* $\frac{K_2}{K_4}$ . All the circles will pass through these poles.

For the system shown in Figure 6.26

$$K_1 = 1$$
$$K_2 = -\frac{Z_A + Z}{Z}$$
$$K_3 = -\frac{Z_B + Z}{Z}$$
$$K_4 = 1$$

Within the practical limits of the difference in magnitudes of the two emf's, say 0.8

to 1.2 and a range of variation of the phase difference it is possible to establish a practical range of phase difference between the two components of fault currents fed from the two line-end sources for a given system.

It should be noted that for distribution systems as stated in Section 6.2.3.6.2 and shown in Figure 6.24, there is only one common source supplying to a given feeder but via two routes. This makes the angular displacement between the two components of currents fed from the two line ends very small since the pre-fault load current is small compared with the fault component. This angular displacement depends mainly on the ratio of the two impedances on either side of the fault point. These two impedances may consist of sections of the feeder ring. This is shown in Figure 6.27.

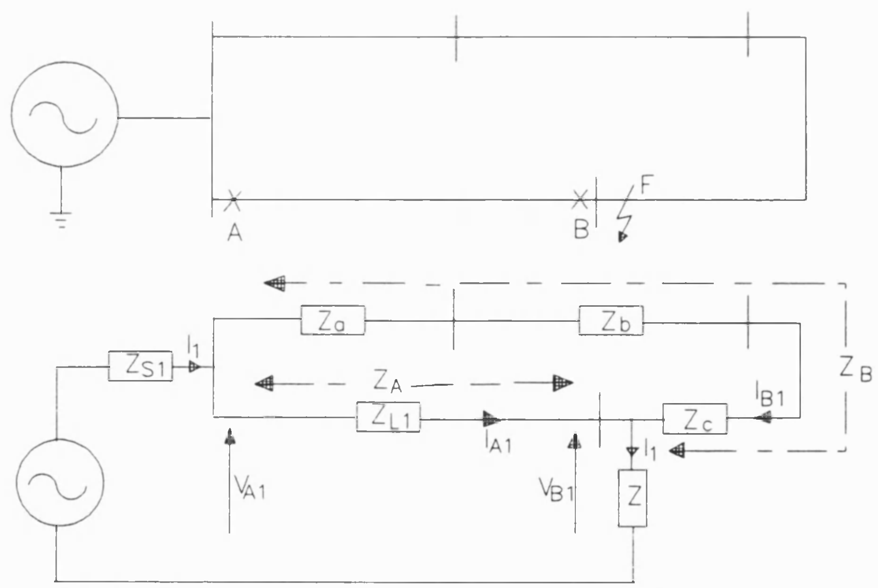



Figure 6.27 A Distribution Ring System with a Single Source and its Equivalent Positive Phase Sequence Network for a Fault at point F.

In this case the impedance $Z_A$ consists of only the protected line impedance $Z_{L1}$ whilst impedance $Z_B$ consists of the positive phase sequence impedances of the three sections of the ring $Z_a$, $Z_b$ and $Z_c$. Neglecting the effect of load currents tapped at the various busbar sections:

$$I_{A1} = I_1 \times \frac{Z_B}{Z_A + Z_B}$$

$$I_{B1} = I_1 \times \frac{Z_A}{Z_A + Z_B}$$

$$\textit{therefore} \quad \frac{I_{B1}}{I_{A1}} = \frac{Z_A}{Z_B}$$

Under this condition the angular displacement between the positive phase sequence voltage and current at the two relay locations can be shown to be independent of the ratio of the two components $I_{A1}$ and $I_{B1}$ of fault currents fed from the two line ends to the fault.

Consider the directional relay at A:

$$I_{A1} = I_1 \times \frac{Z_B}{Z_A + Z_B}$$

$$V_{A1} = Z_{L1}I_{A1} + I_1 Z$$

$$= Z_{L1} [I_1 \times \frac{Z_B}{Z_A + Z_B}] + I_1 Z$$

$$= I_1[\frac{Z_{L1}Z_B}{Z_A + Z_B} + Z]$$

$$\textit{therefore } \frac{V_{A1}}{I_{A1}} = \frac{Z_{L1}Z_B + Z(Z_A+Z_B)}{Z_B}$$

$$= Z_{L1} + Z + \frac{Z_A}{Z_B}Z \qquad \text{.........6.54}$$

Similarly, for the directional relay at B:

$$\frac{V_{B1}}{-I_{A1}} = - \frac{I_1 Z}{I_1 \times \frac{Z_B}{Z_A + Z_B}}$$

$$= - [Z + \frac{Z_A}{Z_B}Z] \qquad \text{........6.55}$$

Therefore, neglecting the pre-fault loading the angular displacement between the positive phase sequence voltage and current for both forward and reverse faults for a distribution ring system with a single source depends only on the various impedances of the system. For high resistance faults or high impedance earthed systems the same effect, as discussed earlier, will occur in that the ratio of the two components of currents $I_{A1}$ and $I_{B1}$ will have an influence in the final angular displacement between positive phase sequence voltage and current.

For this analysis, taking into account cases of two different sources at the two line ends and to establish the limits of angular displacement between the positive phase sequence voltage and current at a given location, a range of $\pm 45°$ shall be taken for the phase difference between the two components of currents. This will allow for the pre-fault loading effect on the angular displacement between the positive phase sequence voltage and current.

### 6.2.3.6.5 Limits of Angular Displacement between Positive Phase Sequence Voltage and Current for Forward and Reverse Faults

Consider the system shown in Figure 6.21 again. At the two relaying locations the fault at F presents a forward fault to the directional relay at A and a reverse fault to the directional relay at B.

For relay A, the ratio of positive phase sequence voltage and current for forward fault, shown earlier in equation 6.50, is:

$$\frac{V_{A1}}{I_{A1}} = Z_{L1} + Z + \frac{I_{B1}}{I_{A1}} \times Z$$

For relay B, the ratio for reverse faults, as "seen" by the relay and from equation 6.51, is:

$$\frac{V_{B1}}{-I_{A1}} = -\left[Z + \frac{I_{B1}}{I_{A1}} \times Z\right]$$

The angles associated with $\frac{V_{A1}}{I_{A1}}$ *and* $\frac{V_{B1}}{-I_{A1}}$ are dependent on the angles associated with the positive phase sequence impedance of the line $Z_{L1}$, the fault-type-dependent variable shunt impedance Z and the ratio of the fault currents fed from the two line-end sources.

The angle associated with the line impedance $Z_{L1}$ has a practical range of:

$$\angle Z_{L1} = 30° \textit{ to } 90°$$

The angle associated with the ratio of currents $\frac{I_{B1}}{I_{A1}}$, as discussed in Section 6.2.3.6.4, has a practical range of:

$$\angle\frac{I_{B1}}{I_{A1}} = -45° \textit{ to } +45°$$

The angle associated with the variable shunt impedance Z has a practical range of:

$$\angle Z = 0° \textit{ to } +90°$$

The angle associated with $(\frac{I_{B1}}{I_{A1}} \times Z)$ is thus given by:

$$\angle(\frac{I_{B1}}{I_{A1}} \times Z) = \angle\frac{I_{B1}}{I_A} + \angle Z$$

$$= (-45° \; to \; +45°) + (0° \; to \; +90°)$$

$$= -45° \; to \; +135°$$

The range of angular displacement between positive phase sequence voltage and current for forward and reverse faults taking into account the effect of pre-fault loading conditions can now be determined.

For forward faults:

$$\angle\frac{V_{A1}}{I_{A1}} = \angle(Z_{L1} + Z + \frac{I_{B1}}{I_{A1}}Z)$$

$$= -45° + 135°$$

For reverse faults:

$$\angle\frac{V_{B1}}{-I_{A1}} = \angle[-(Z + \frac{I_{B1}}{I_{A1}}Z)]$$

$$= 180° + \angle(Z + \frac{I_{B1}}{I_{A1}}Z)$$

$$= 180° + (-45° to + 135°)$$

$$= 135° \; to \; 315°$$

This is shown in Figure 6.28.

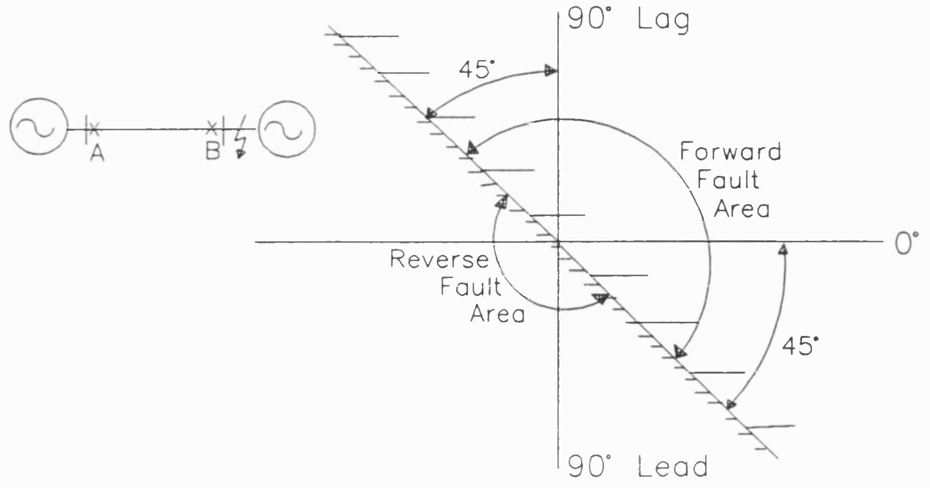



Figure 6.28 Range of Phase Displacement between Positive Phase Sequence Voltage and Current for Forward and Reverse Faults.

### 6.2.3.6.6 Value of Constant $K_{C1}$ - Angle

Figure 6.29 shows the range of angular displacement between the positive phase sequence voltage and current for forward faults and the required range using the constant $K_{C1}$ to provide the phase shift.

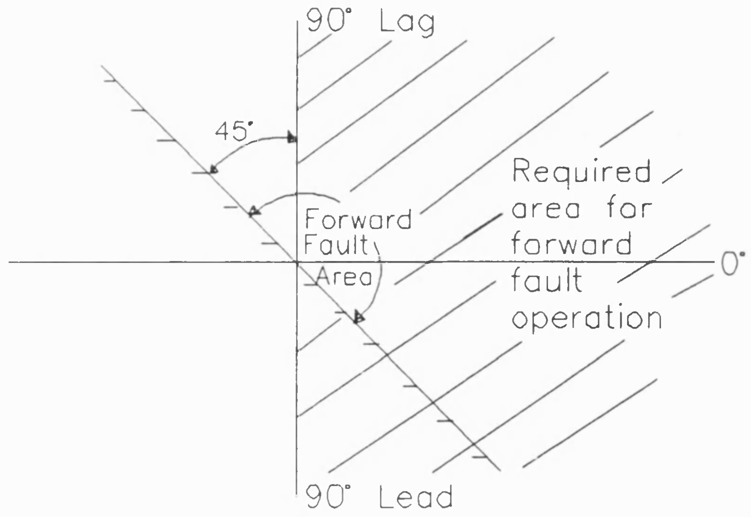



Figure 6.29 Phase Displacement between Positive Phase Sequence Voltage and Current for Forward Faults and the Required Area it has to lie within the Defined Operation Limits.

This shows that the phase shift required and provided by $K_{C1}$ must be 45° leading.

Figure 6.30 shows the range of angular displacement for reverse faults and the range after being phase shifted by a leading angle of 45° via the constant $K_{C1}$.

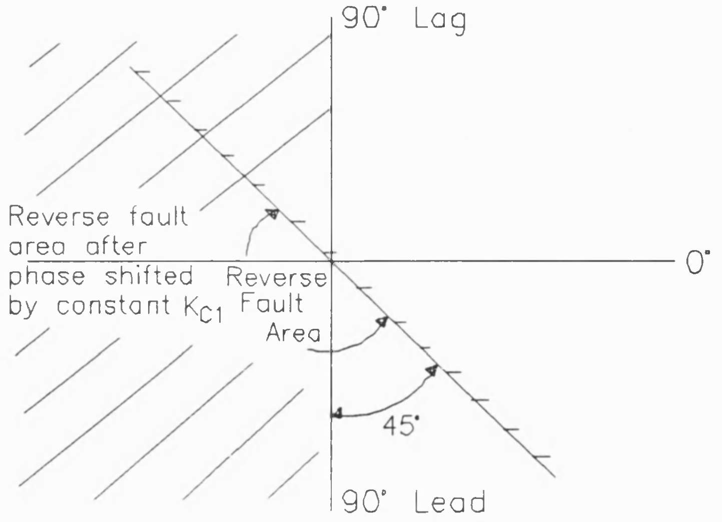



Figure 6.30 Phase Displacement between Positive Phase Sequence Voltage and Current for Reverse Faults and after Phase-shifted by the Constant $K_{C1}$.

The ranges of angular displacement for the positive phase sequence component of the combined function $K_{C1}\dfrac{V_1}{I_1}$ for forward and reverse faults are shown in Figure 6.31.

These new ranges meet the requirements of:

For forward faults:

$$-90° \leq K_{C1}\frac{V_1}{I_1} \leq +90° \qquad .......6.56$$

For reverse faults:

$$-90° \geq K_{C1}\frac{V_1}{I_1} \geq +90° \qquad ........6.57$$

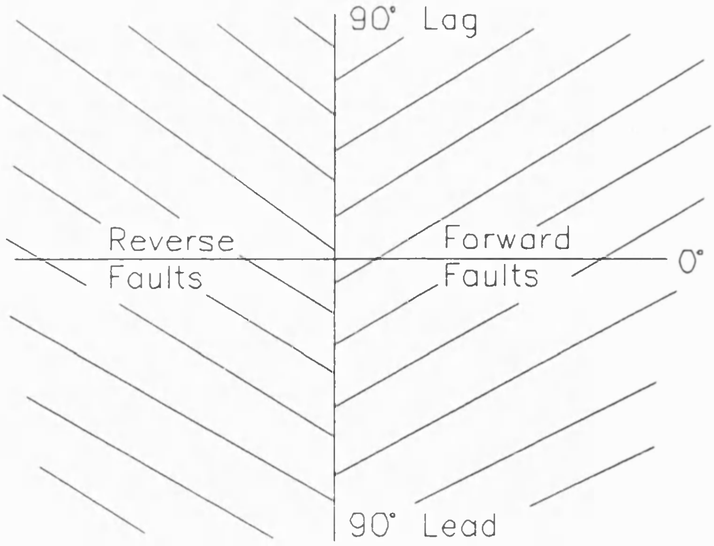



Figure 6.31 Range of $(K_{C1} * V_1/I_1)$ Angle for Forward and Reverse Faults with $K_{C1}$ providing 45 degrees Leading Phase Shift.

### 6.2.3.7 Values of the Constants $K_{C1}$ and $K_{C2}$ - Magnitudes

The magnitudes of $K_{C1}$ and $K_{C2}$ must ensure that under all fault conditions the signals are sufficient to enable a reliable decision on the directional detection process, especially for close-up faults towards the relay location.

$K_{C1}$ determines the directional sensitivity for balanced 3-phase faults. Commercially available modern static directional relays generally [2.5, 2.6] have a typical directional sensitivity of 1% of rated input voltage without purposely amplifying the input signal before the directional detection process, i.e. with $K_{C1} = 1$. It is proposed that $K_{C1}$ be set to unity and rely on other means, such as the use of memory voltage, in the implementation of actual relay design to provide unlimited directional sensitivity for close-up 3-phase faults.

The magnitude of $K_{C2}$ in relation to $K_{C1}$ is primarily determined by the requirement of sensitivity for earth faults, especially high resistance earth faults in the presence of high load transfer.

As discussed in Section 6.2.1.1, because of load current being positive phase sequence current as well, any load current flow across a feeder with an internal fault on it will influence the angular displacement between the positive phase sequence voltage and current with the latter consisting of both load and fault components. This will introduce error in the direction detection process for the particular fault point. The higher the load transfer with less fault component, e.g. high resistance faults with heavy load transfer, the less reliable is the direction detection process based on pure positive phase sequence component. Under this condition it is necessary that the negative phase sequence component is used to ensure correct direction is detected. The limiting case is when the total effect of the positive and negative phase sequence components of the fault current just balance out the effect of the positive phase sequence load current.

Consider the case of a single phase to earth fault on a feeder with simultaneous load transfer across it:

Load current $= I_L$

Combination of positive and negative phase sequence components of fault current $= I_1 + N\, I_2$

At the limiting condition:

$$I_L = I_1 + N\, I_2 \qquad \text{.......6.58}$$

For single phase to earth faults the two components of current are equal at the fault point and is ⅓ of the fault current.

At the relay location:

$$I_1 \approx I_2 \approx \frac{1}{3}\, I_f$$

where $I_f$ is the total fault current through the relay location.

Therefore

$$I_L \approx \frac{1}{3}\, I_f\,(1 + N)$$

$$or \quad I_f \approx \frac{3 I_L}{1 + N} \qquad \text{........6.59}$$

If the required fault sensitivity is 15% of rated current with a load transfer of rated value:

$$0.15 \approx \frac{3 \times 1}{1 + N}$$

$$N \approx 19$$

The weighting factor for the negative phase sequence component is about 20 to maintain normal fault sensitivity in the presence of load transfer. Similar values are also used in phase comparison scheme design [2.2].

It is therefore proposed that a factor of 20 is used for the magnitude of $K_{C2}$.

### 6.2.3.8 The Combined Function

The combined function proposed previously:

$$F_C = K_{C1}\frac{V_1}{I_1} + K_{C2}\frac{V_2}{I_2}$$

can now be defined:

$$F_C = 1\angle\underline{-45°}\left(\frac{V_1}{I_1}\right) + 20\angle\underline{+135°}\left(\frac{V_2}{I_2}\right)$$

$$\theta_C = \angle F_C$$

......6.60

For forward faults:

$$-90° \leq \theta_C \leq +90°$$ .......6.61

For reverse faults:

$$-90° \geq \theta_C \geq +90°$$ ......6.62

### 6.2.3.9 Faults on Non-reference Phases

For the extraction of the symmetrical components the A phase has been chosen as the reference phase.

The combined function $F_C$ given by

$$F_C = K_{C1}\frac{V_1}{I_1} + K_{C2}\frac{V_2}{I_2}$$

should, therefore, only be valid for the reference phases which are phase A for single-phase-to-earth fault and phases B and C for phase-to-phase or phase-to-phase-to-earth faults.

For faults involving other phases, it is necessary to consider the 120° or 240° phase shifts in a manner appropriate to the fault conditions.

Consider the symmetrical components of voltage and current separately.

For A-E phase-to-earth, B-C phase-to-phase and B-C-E phase-to-phase-to-earth faults:

Symmetrical components of voltages = $V_1$, $V_2$

Symmetrical components of currents = $I_1$, $I_2$

For B-E phase-to-earth, C-A phase-to-phase and C-A-E phase-to-phase-to-earth faults:

Symmetrical components of voltages = $aV_1$, $a^2V_2$

Symmetrical components of currents = $aI_1$, $a^2I_2$

For C-E phase-to-earth, A-B phase-to-phase and A-B-E phase-to-phase-to-earth faults:

Symmetrical components of voltages = $a^2V_1$, $aV_2$

Symmetrical components of currents = $a^2I_1$, $aI_2$

Though it can be seen that the 120° or 240° phase shifts are necessary for faults on the non-reference phases in considering the symmetrical components this necessity is cancelled out when the combined function

$$F_C = K_{C1}\frac{V_1}{I_1} + K_{C2}\frac{V_2}{I_2}$$

is considered consisting of a ratio of the two corresponding phase sequence components of voltages and currents. Therefore, the combined function should also be valid for all types of faults.

CHAPTER SEVEN

# TESTING OF THE VALIDITY OF THE PROPOSED NEW POLYPHASE DIRECTIONAL DETECTION METHOD

## 7.1 Introduction

To test the validity of the proposed basis of detecting fault direction steady-state fault analyses are carried out to generate the required voltage and current data at the relaying point. These data in the form of phase sequence components of voltage and current are used to form the combined function detailed in Chapter 6 from which the angular limits of the function are checked. The fault analysis programme is based on Fortran 77 run on personal computers. The results are presented in graphic form by using a separate proprietary software programme to confirm the validity of the proposed approach to detect direction of fault points by examining the resulting angle $\theta_C$ associated with the combined function $F_C$.

The envisaged performance of the new method under power system transient conditions is discussed.

## 7.2 Fault Analysis Programme

The fault analysis programme used is the MCZ0912A [3.12] developed by GEC ALSTHOM T&D Protection & Control Limited to study fault-generated voltages and currents as inputs to various relay simulation programmes for relay performance evaluation. The programme calculates the symmetrical components of currents and voltages and their respective phase and line values at specified relay locations in a 3-phase power system operating under steady-state pre-fault and/or fault conditions.

The programme solves for all possible combinations of loading conditions, shunt fault types and fault locations with the studied system assumed to be fully symmetrical. The voltage and current values can be obtained at any specified relay locations for any specified fault points. The values can be specified to be the relevant phase sequence components and/or phase quantities.

## 7.3 Characteristic-plotting and Graphic-presentation Programme

The graph plotting facilities of the Lotus 1-2-3 programme [3.13] developed by Lotus Development Corporation is used to present the various data and studies results graphically. The values of the combined function in terms of both magnitude and phase angle obtained for different system configurations with different pre-fault conditions and under various fault conditions are used as input to this Lotus 1-2-3 programme to provide graphic presentation of the studies results.

## 7.4 Networks chosen for the Studies

The following distribution networks taken from China Light & Power Company Limited [2.29] of Hong Kong are used to generate the required voltage and current signals to check the validity of the proposal to detect fault directions. These are shown in Figures 7.1 and 7.2 for plain- and transformer-feeder systems respectively.

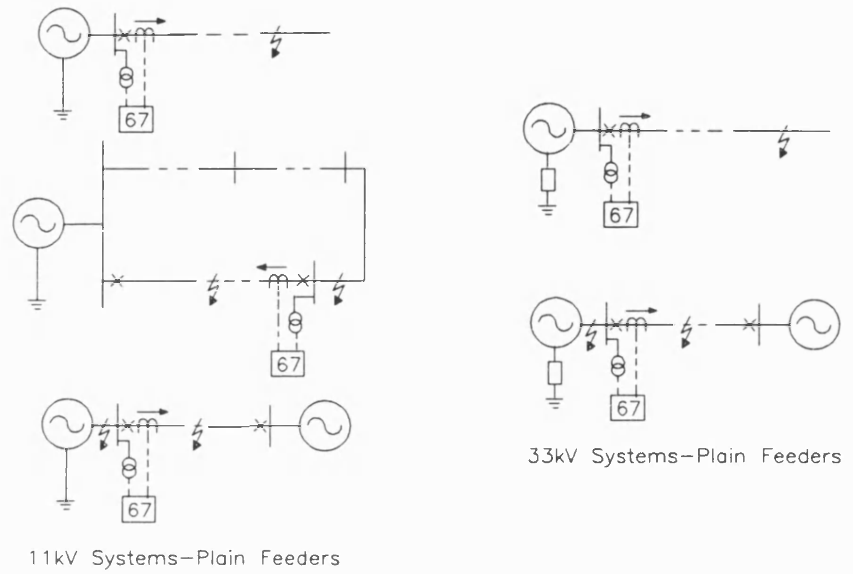



Figure 7.1 Solidly–earthed 11kV and Resistance–earthed 33kV Plain–feeder Systems chosen for the Studies.

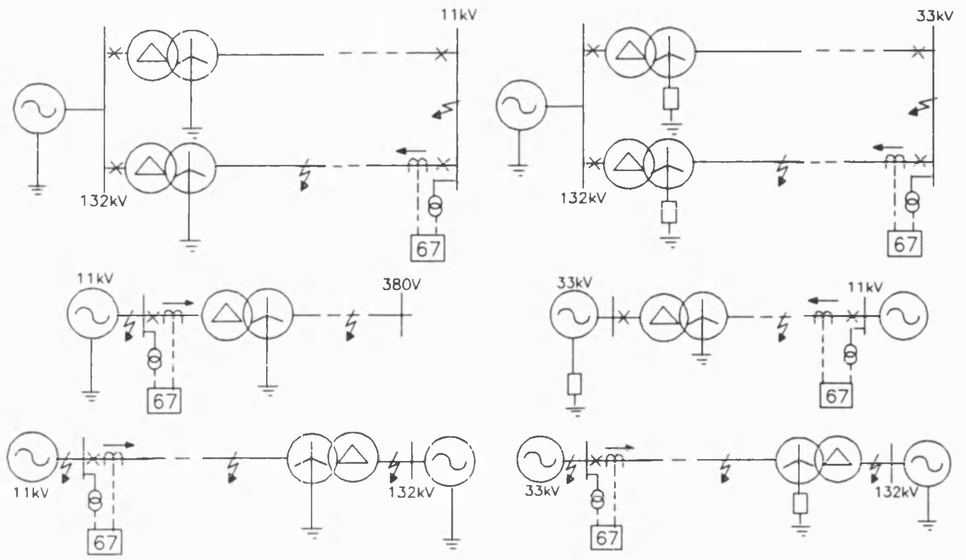



Figure 7.2 Solidly–earthed 11kV and Resistance–earthed 33kV Transformer–feeder Systems chosen for the Studies

The plain-feeder systems enable an investigation into the fundamental basis of the proposed new method of detecting fault direction, i.e., to prove the validity of the method without the effect of other influencing factors such as phase shift introduced by power transformers and multiple zero phase sequence current sources on multiple-earthed systems.

The influence of primary system earthing methods and arrangements on the new directional detection method is nil because of the non-employment of the zero phase sequence components of voltage and current.

The effect of phase shift caused by power transformers from one voltage level system to another can be investigated by the transformer-feeder systems shown in Figure 7.2. This should prove the effectiveness of the new method, which is based on a measure of the angular displacement between two signals, when the primary systems introduce angular phase shift to the voltage and current phasors.

## 7.5 Network Data for the Studies

For the networks chosen for the studies as shown in Figures 7.1 and 7.2 the values [2.29] of the various components making up the networks are given below.

### 7.5.1 132kV Systems

Maximum fault level = 6000 MVA

Source impedance = j2.904Ω at 132kV

= j0.182Ω at 33kV

= j0.020Ω at 11kV

Minimum fault level = 1000 MVA

Source impedance = j17.424Ω at 132kV

= j1.089Ω at 33kV

= j0.121Ω at 11kV

132/33kV transformers:

Rating = 80 MVA

Impedance = 0.061 + j2.178 Ω at 33kV

132/11kV transformers:

Rating = 35 MVA

Impedance = 0.021 + j0.918 Ω at 11kV

### 7.5.2 33kV Systems

Maximum fault level = 1500 MVA

Source impedance = j0.726Ω at 33kV

= 0.081Ω at 11kV

Minimum fault level = 200 MVA

Source impedance = j5.445Ω at 33kV

= 0.605Ω at 11kV

Neutral earthing resistor = 23.8Ω

33/11kV transformer:

Rating = 35 MVA

Impedance = 0.142 + j3.709 Ω at 33kV

= 0.16 + j0.412 Ω at 11kV

Feeders:

Underground cables 20 MVA 349A 6.4km $Z_1 = 0.168 + j0.238$ Ω/km

$Z_0 = 0.799 + j0.647$ Ω/km

Overhead lines 17 MVA 297A 10.7km $Z_1 = 0.204 + j0.336$ Ω/km

$Z_0 = 0.539 + j0.947$ Ω/km

### 7.5.3 11kV Systems

Maximum fault level = 350 MVA

Source impedance = j0.346Ω at 11kV

Minimum fault level = 70 MVA

Source impedance = j1.729Ω at 11kV

Solidly-earthed

11kV/380V transformers:

Rating = 1.5 MVA

Impedances = 5.3%

= j4.275 Ω at 11kV

Feeders:

Underground cables 7 MVA 370A 2km $Z_1 = 0.120 + j0.076$ Ω/km

$Z_0 = 1.685 + j0.097$ Ω/km

Overhead lines 3.8 MVA 200A 10km $Z_1 = 0.550 + j0.355$ Ω/km

$Z_0 = 0.938 + j1.346$ Ω/km

### 7.5.4 380V Low Voltage Systems

Underground cables 800 mm² $Z_1 = 0.028 + j0.085$ Ω/km at 380V

1000A 0.5km $= 23.463 + j71.226$ Ω/km at 11kV

$Z_0 = 0.154 + j0.167$ Ω/km at 380V

$= 129.044 + j139.938$ Ω/km at 11kV

## 7.6 Studies Results

The results of the investigation on the responses of the proposed new directional detection method based on the 33KV and 11KV distribution systems shown in Figures 7.1 and 7.2 are presented in the following sections. The different system configurations are studied for different fault types. The effects of fault levels, fault positions, pre-fault load levels where applicable and fault resistances for each configuration are examined and presented. The studies start from analysing a basic system of a single source feeding an overhead line and then an underground cable feeder to examining the various common forms of distribution system arrangements.

The results take the form of a directional angle $\theta_C$ defined by the combined function $F_C$:

$$F_C = 1\angle\underline{-45°}(\frac{V_1}{I_1}) + 20\angle\underline{+135°}(\frac{V_2}{I_2})$$

$$\theta_C = \angle F_C$$

The values of $\theta_C$ for different fault levels, fault positions, pre-fault load currents and fault resistances are obtained to compare with the limits of $\pm 90^0$ for operation for forward faults as given by:

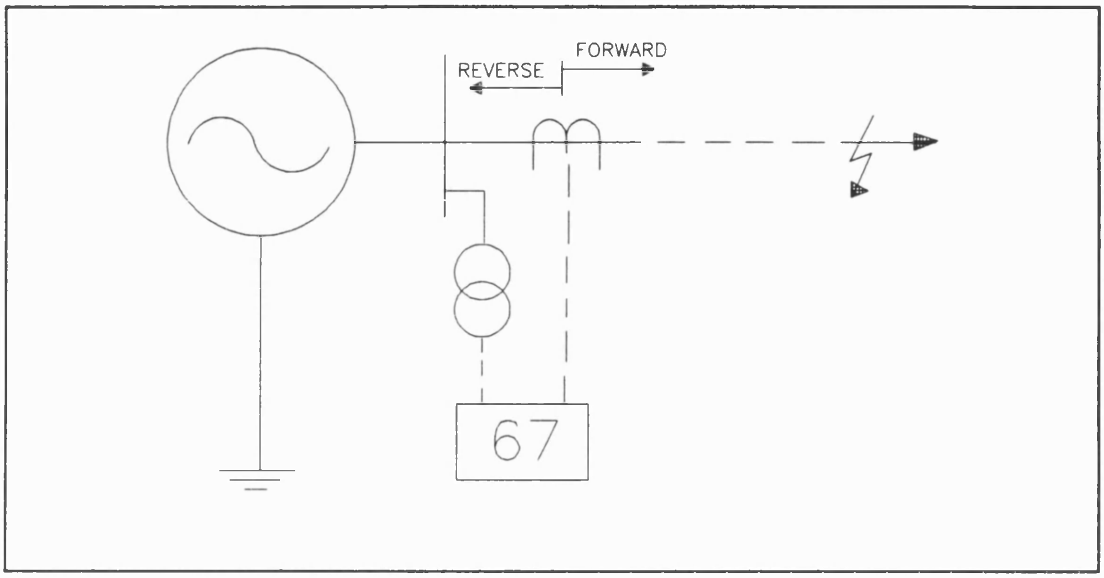
$$-90° \leq \theta_C \leq +90°$$

### 7.6.1 Plain-feeder Systems

These systems provide the basic platform to test the validity of the proposed new directional detection method. Its responses to the variation of the fault levels, fault positions, pre-fault load levels and fault resistances are presented.

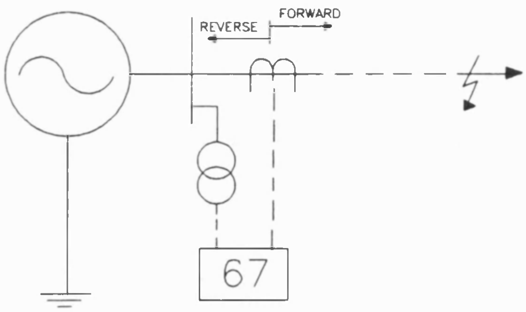
### 7.6.1.1 11kV Single Source System of either Overhead Line or Underground Cable Feeder

The system is shown below:




A directional relay 67 is arranged to protect a feeder of an 11kV distribution system with a single source of supply.

The directional angles $\theta_C$ for various fault types on the feeder under maximum and minimum fault levels and their variations with fault point positions and fault resistances are presented in Figures 7.6.1.1.1 to 7.6.1.1.24 with the directional relay arranged to "see" the faults as being either in the forward or reverse direction. The results for faults on both overhead line and underground cable feeders are presented.




11kV Overhead Line System

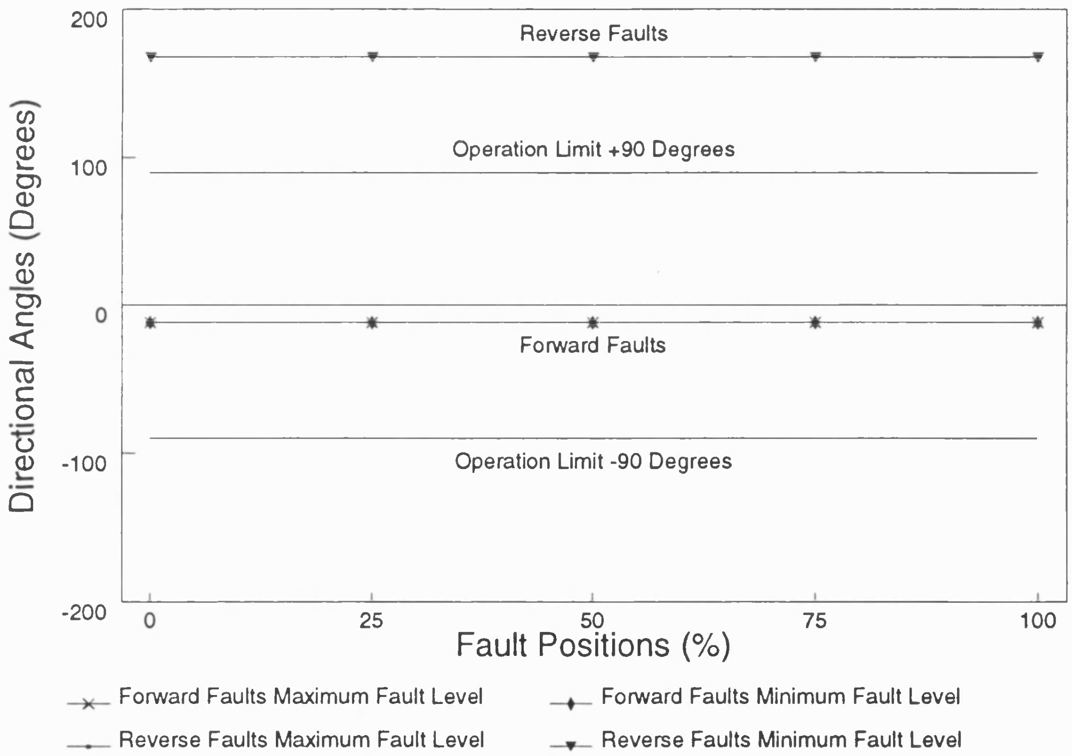
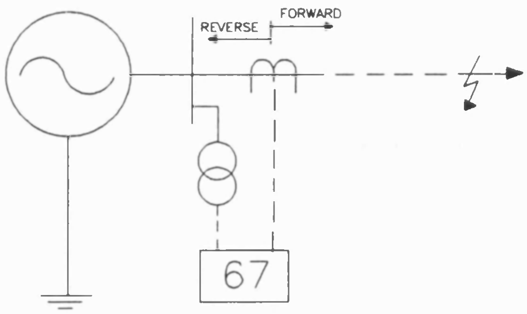



Figure 7.6.1.1.1 Variations of Directional Angle $\theta_C$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for 3-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11kV Overhead Line System

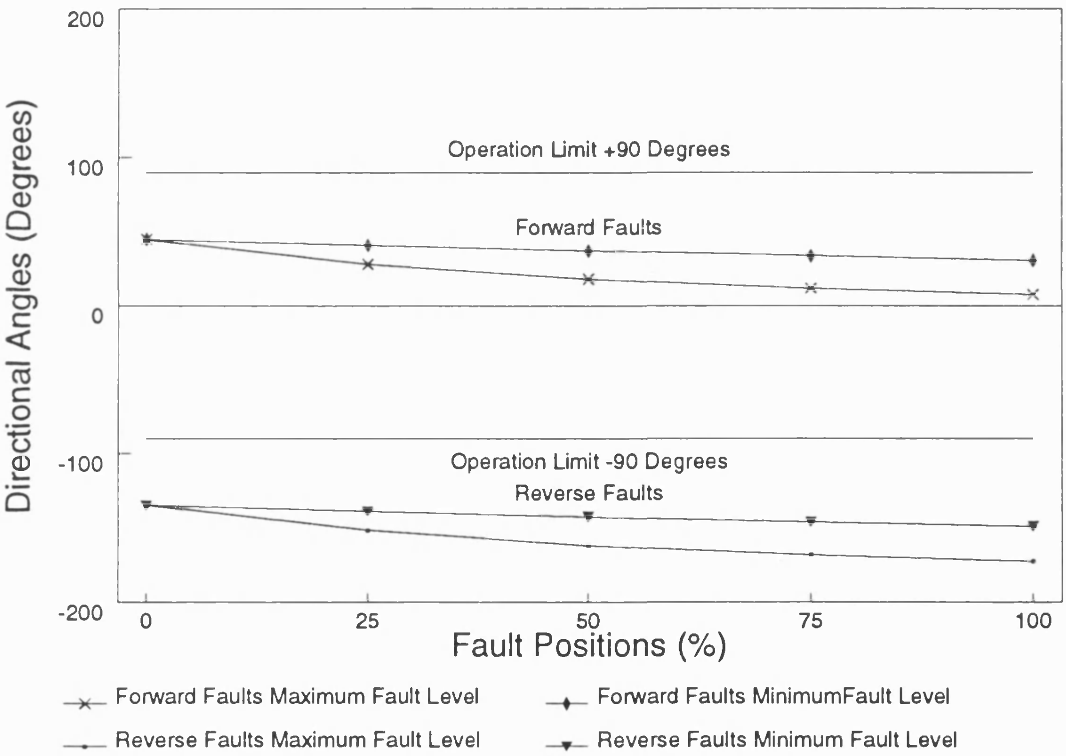
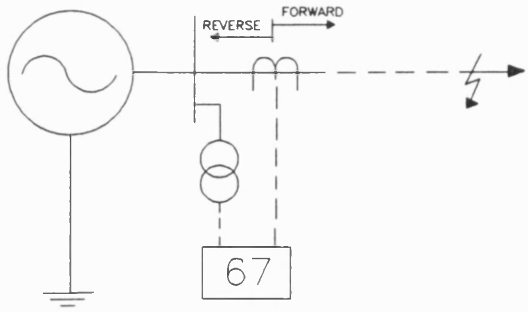



Figure 7.6.1.1.2 Variations of Directional Angle $\theta_c$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for Phase-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11kV Overhead Line System

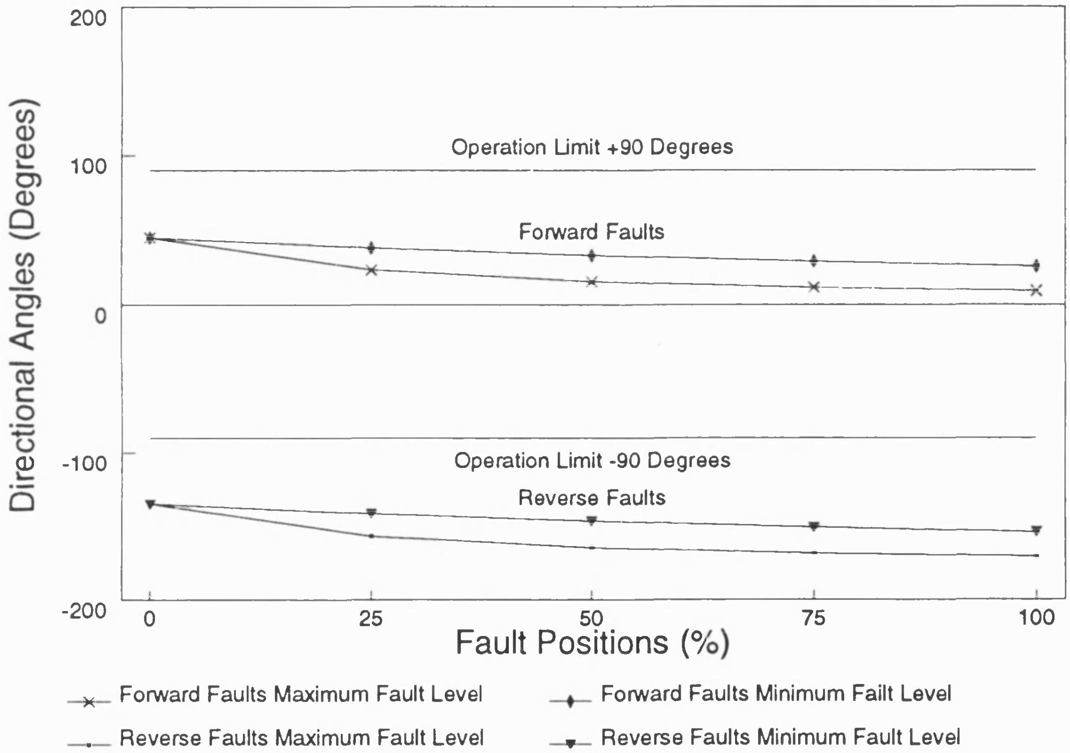
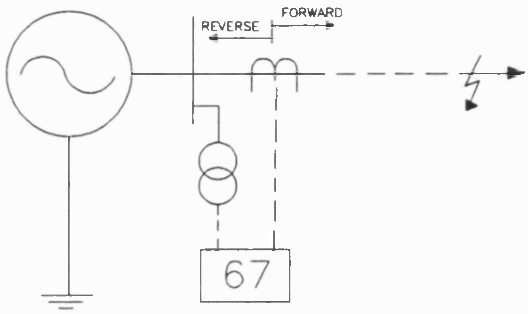



Figure 7.6.1.1.3 Variations of Directional Angle $\theta_C$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for Single-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11kV Overhead Line System

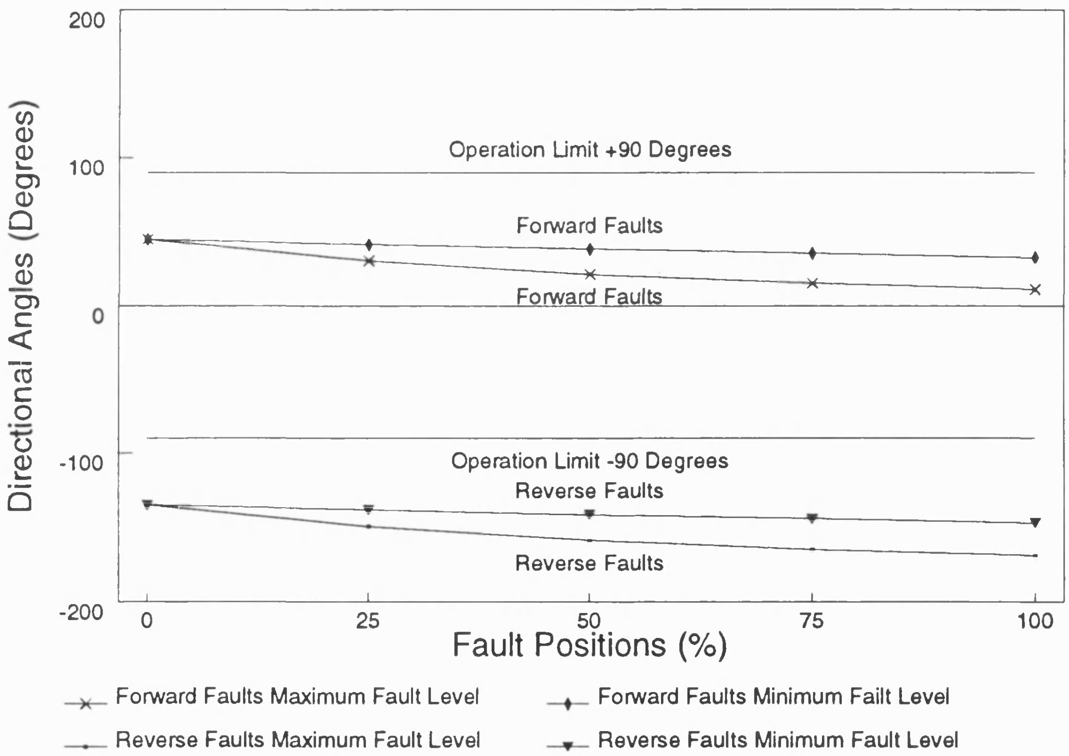
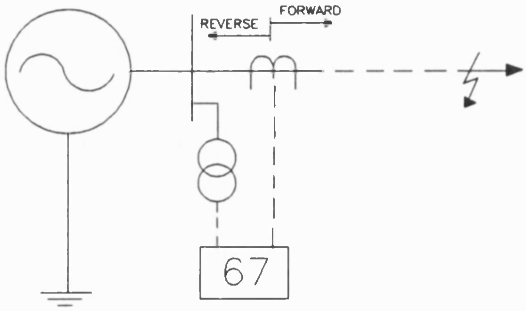



Figure 7.6.1.1.4 Variations of Directional Angle $\theta_C$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for Phase-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11kV Overhead Line System

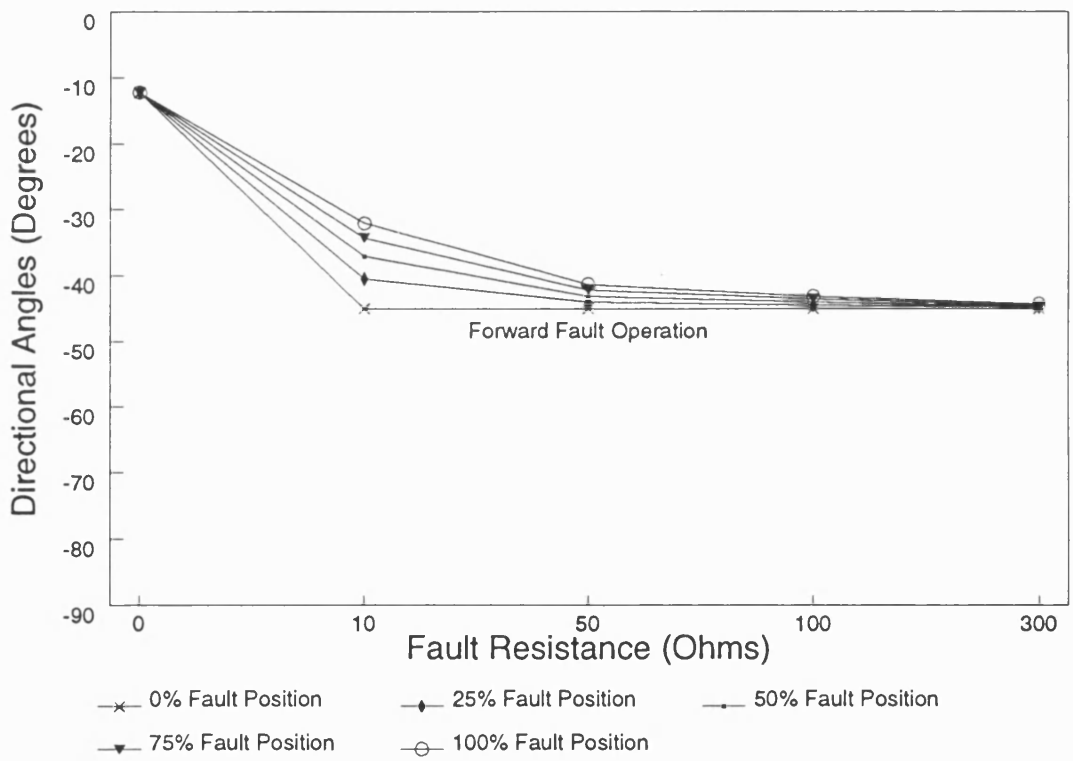
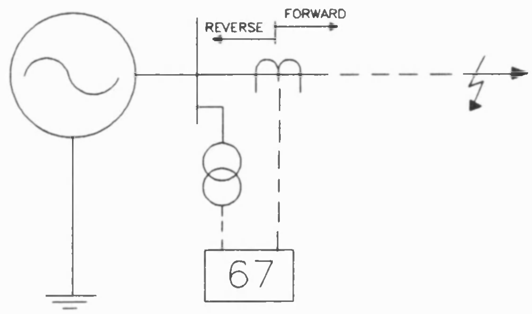



Figure 7.6.1.1.5 Variations of Directional Angle $\theta_C$ for Forward 3-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Overhead Line System

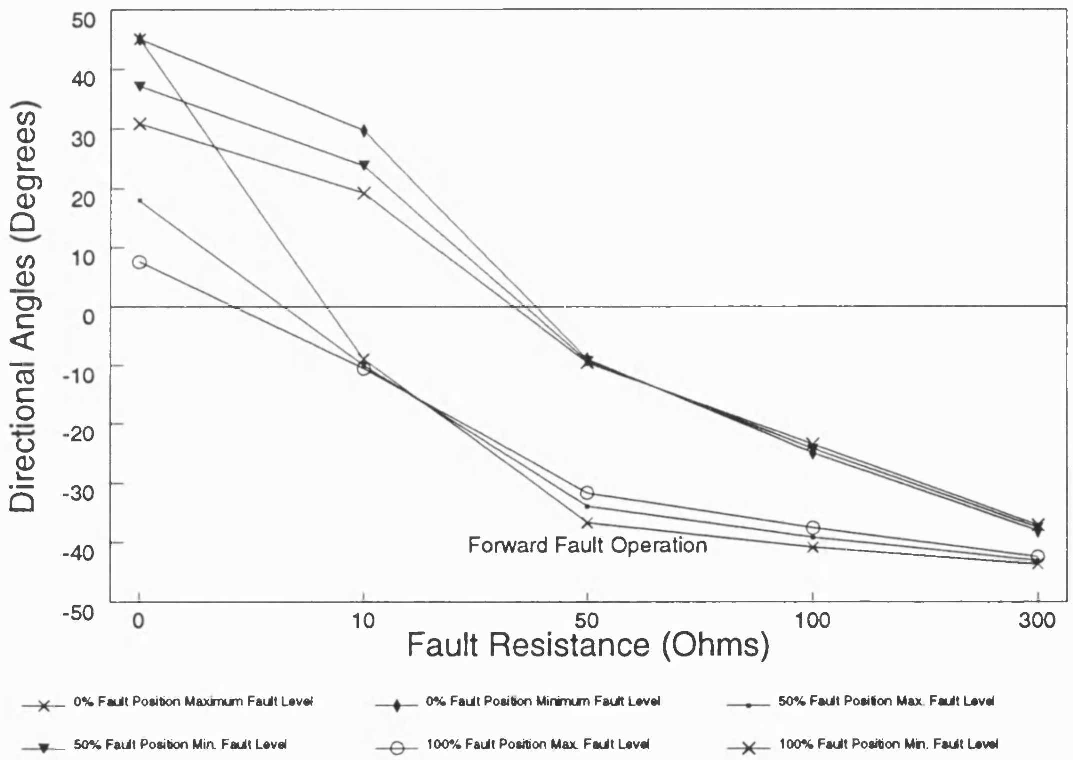
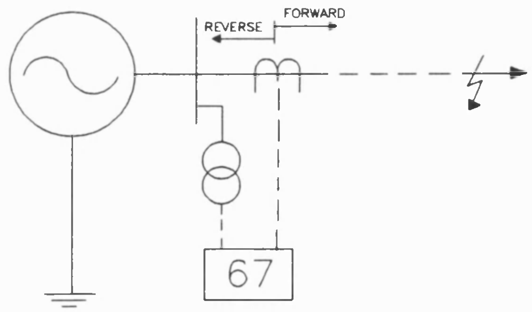



Figure 7.6.1.1.6 Variations of Directional Angle $\theta_C$ for Forward Phase-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Overhead Line System

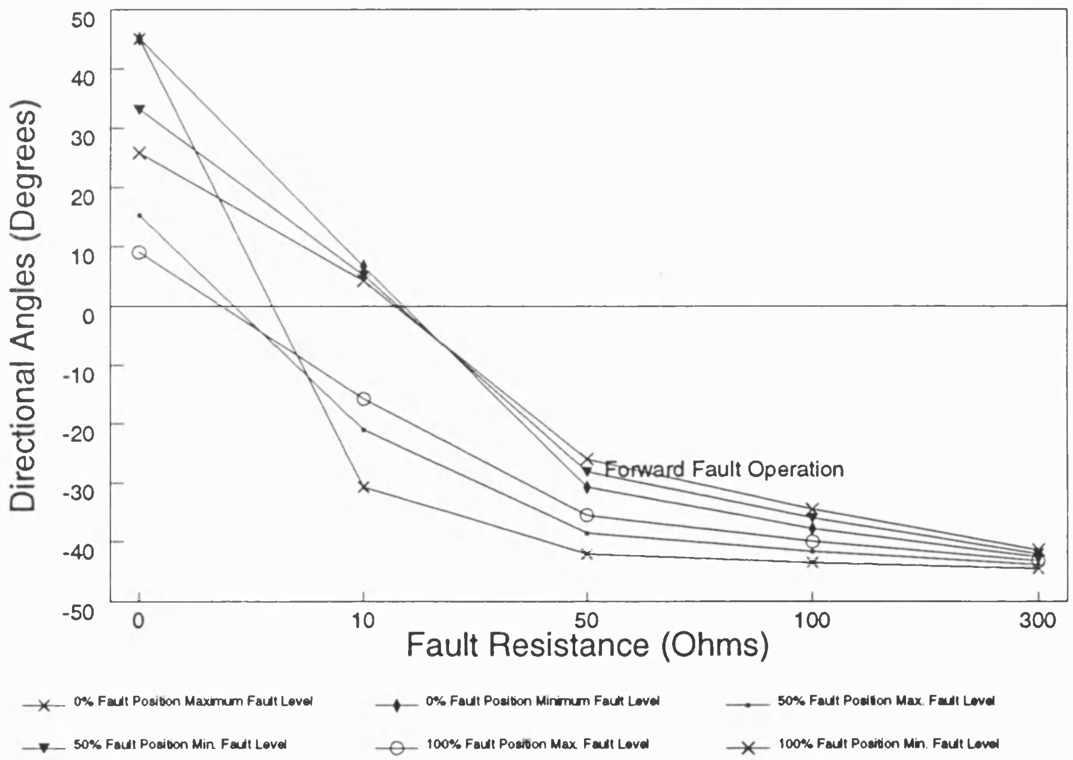
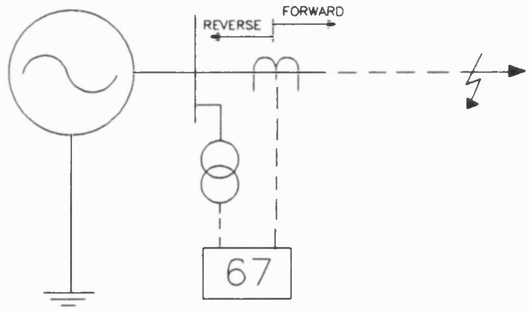



Figure 7.6.1.1.7 Variations of Directional Angle $\theta_C$ for Forward Single-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Overhead Line System

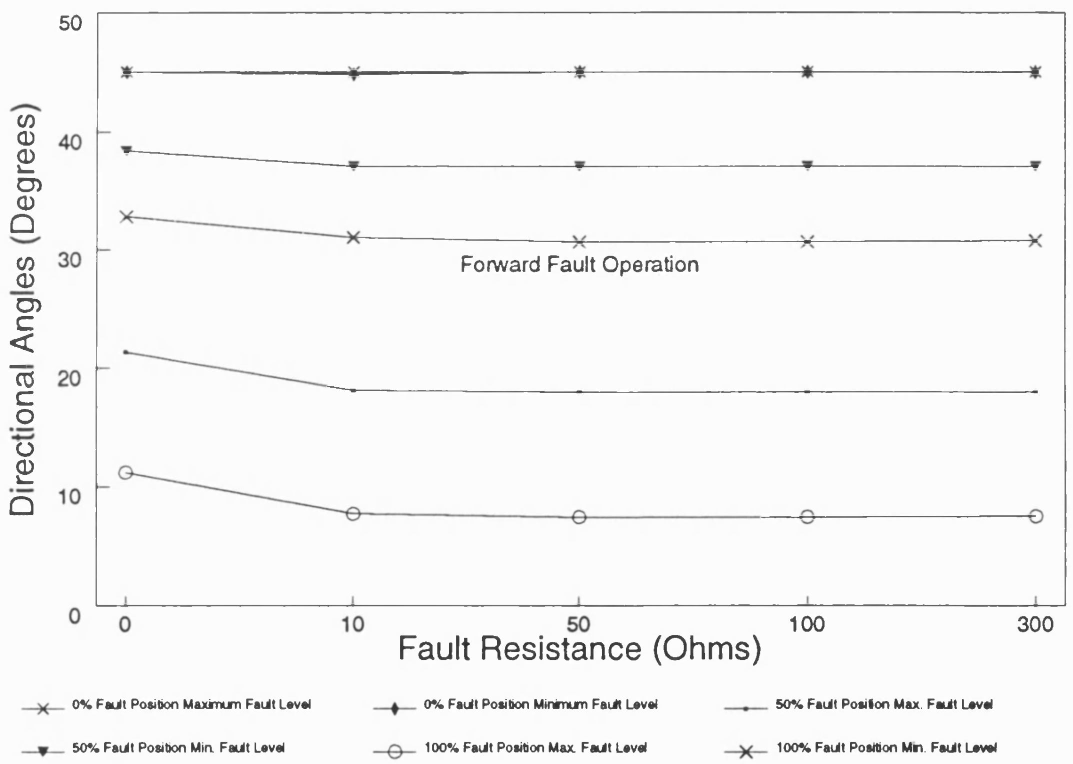
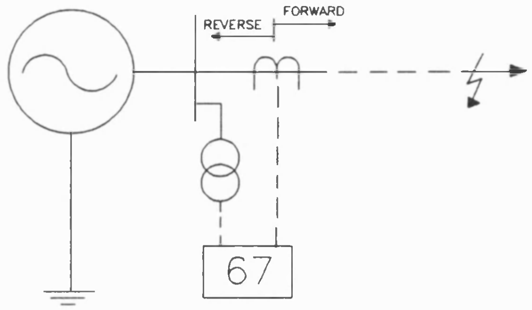



Figure 7.6.1.1.8 Variations of Directional Angle $\theta_C$ for Forward Phase-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Overhead Line System

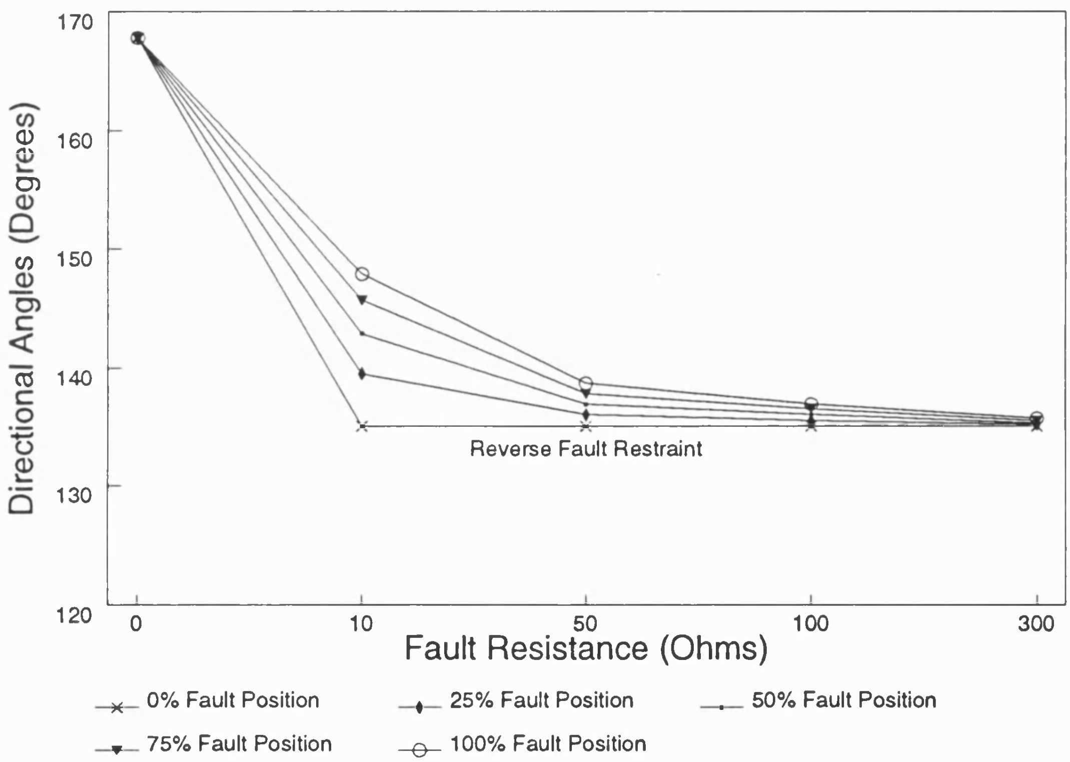
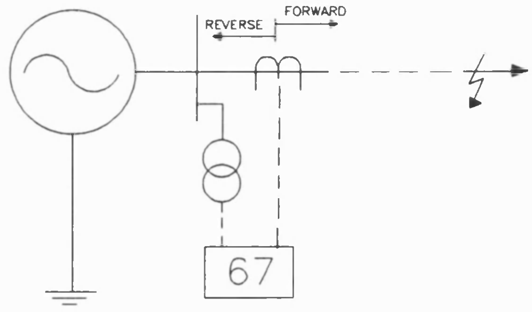



Figure 7.6.1.1.9 Variations of Directional Angle $\theta_C$ for Reverse 3-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Overhead Line System

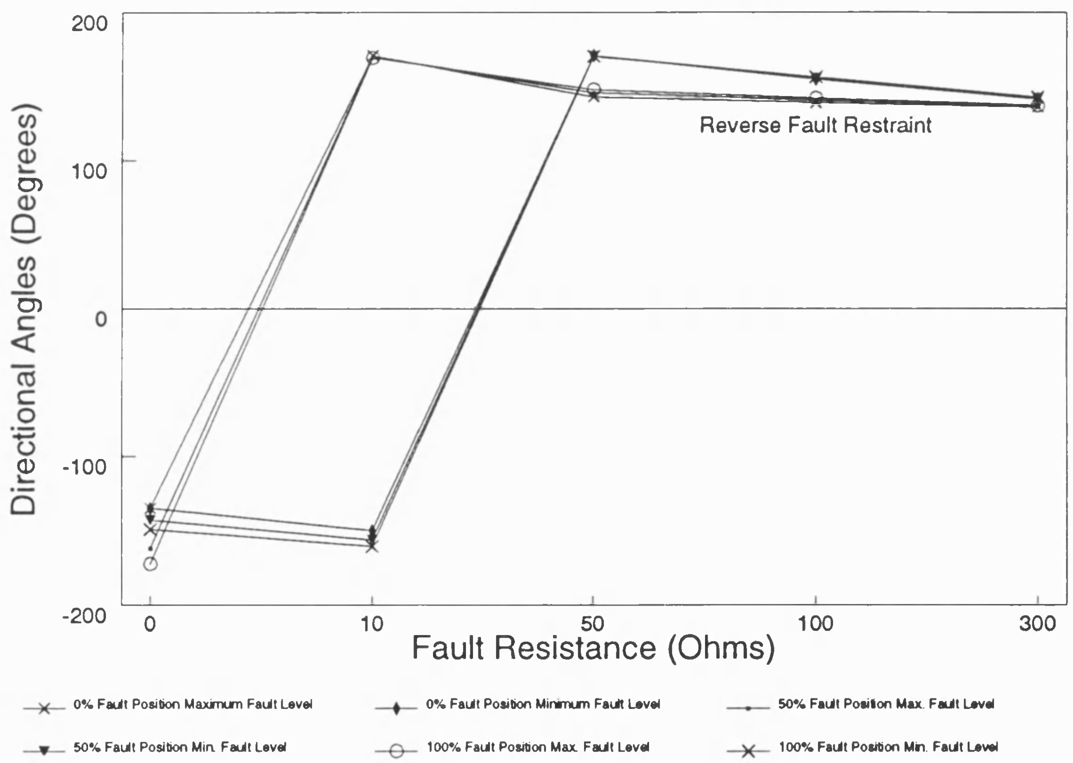
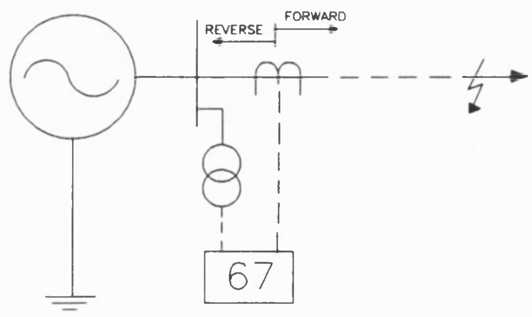



Figure 7.6.1.1.10 Variations of Directional Angle $\theta_C$ for Reverse Phase-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Overhead Line System

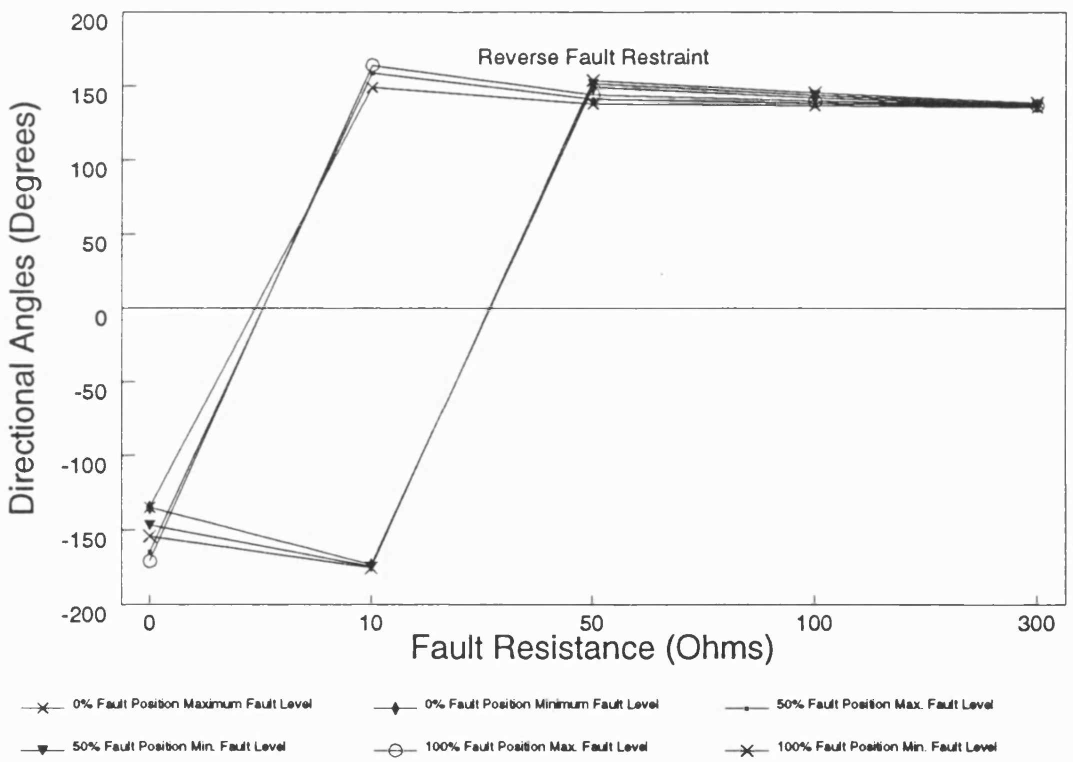
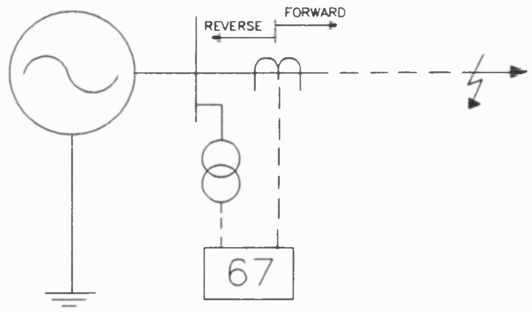



Figure 7.6.1.1.11 Variations of Directional Angle $\theta_C$ for Reverse Single-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Overhead Line System

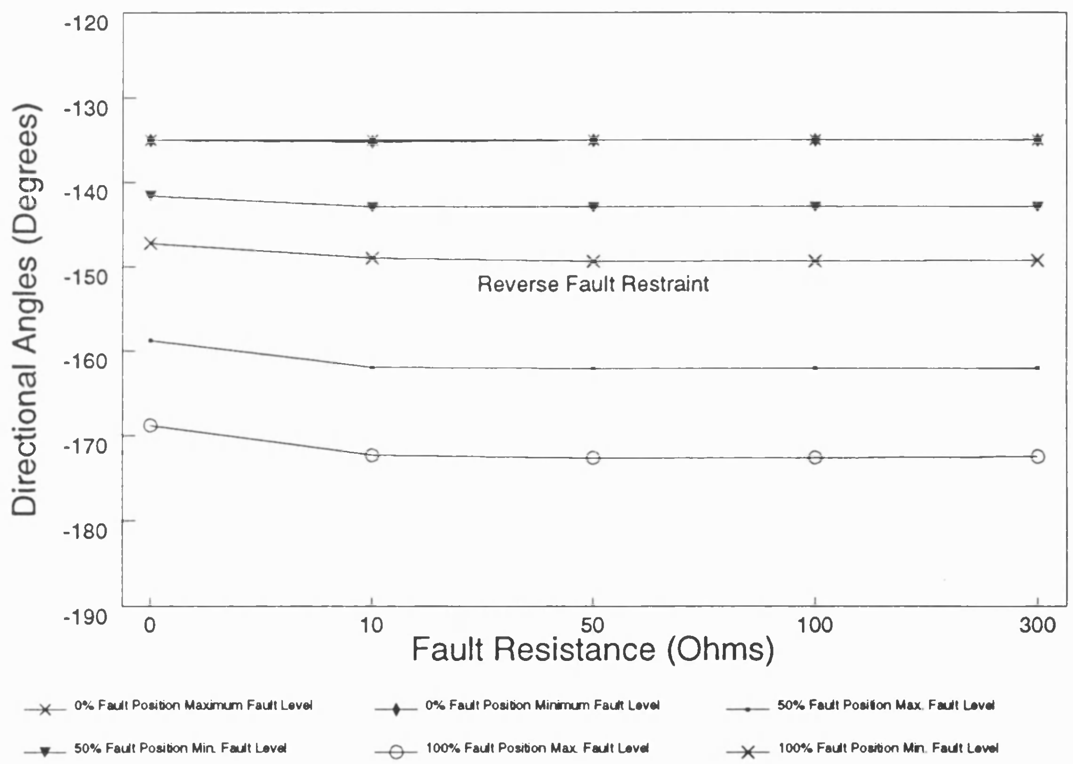
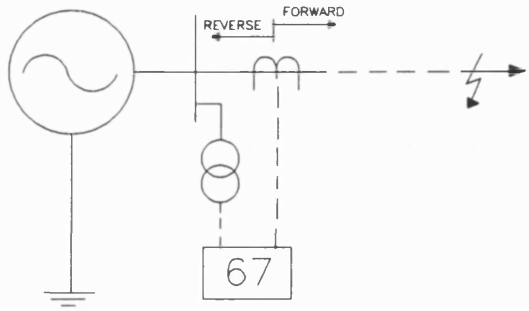



Figure 7.6.1.1.12 Variations of Directional Angle $\theta_C$ for Reverse Phase-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Underground Cable System

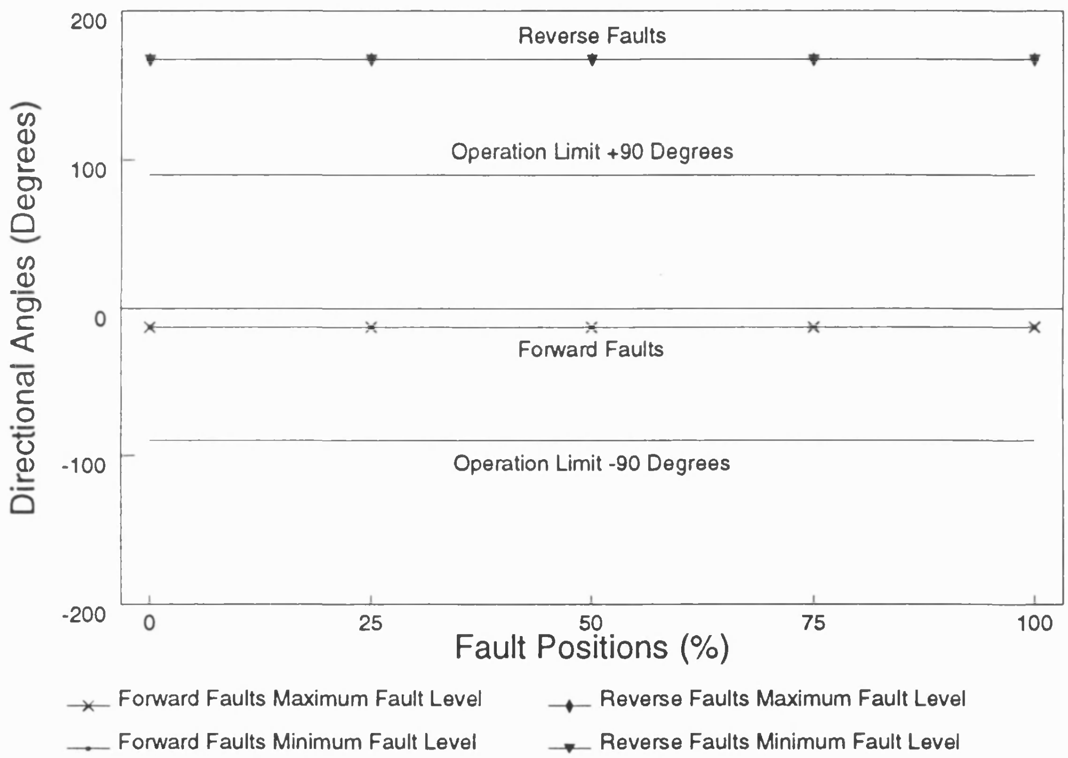
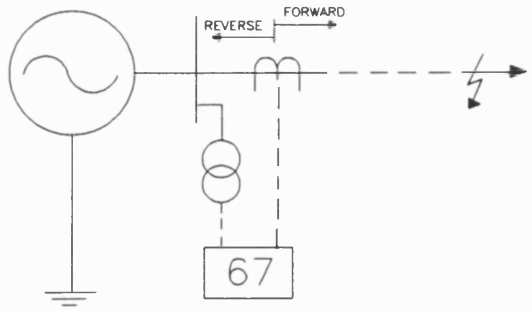



Figure 7.6.1.1.13 Variations of Directional Angle $\theta_C$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for 3-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11kV Underground Cable System

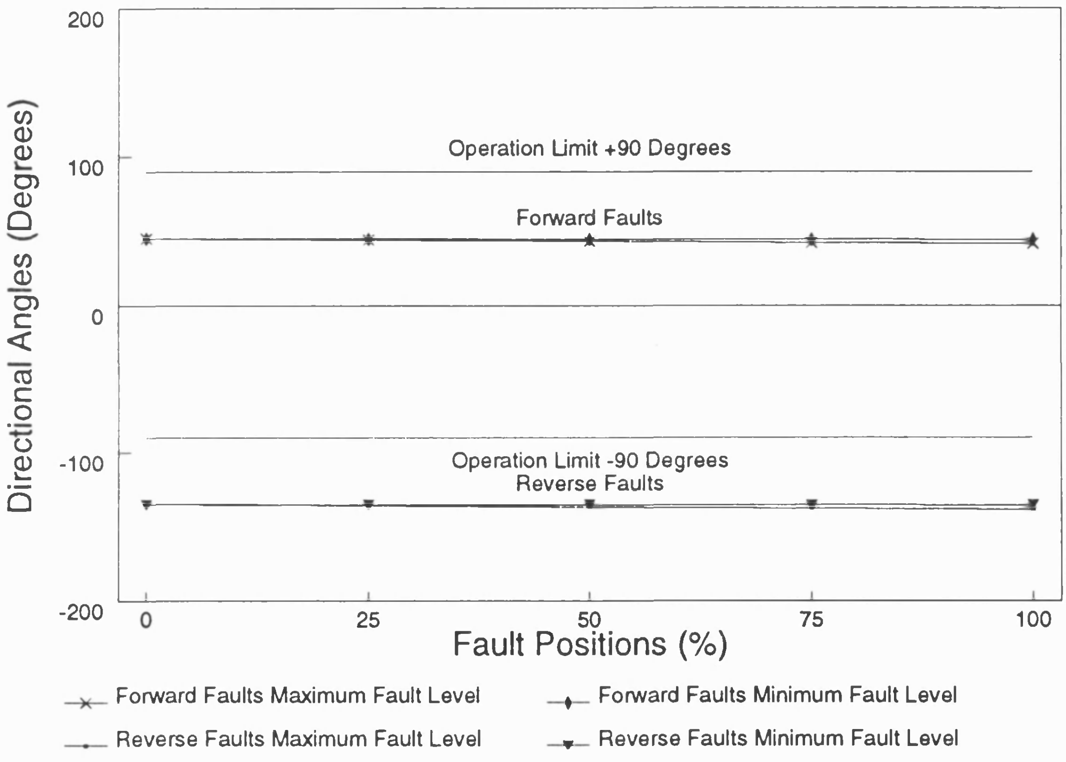
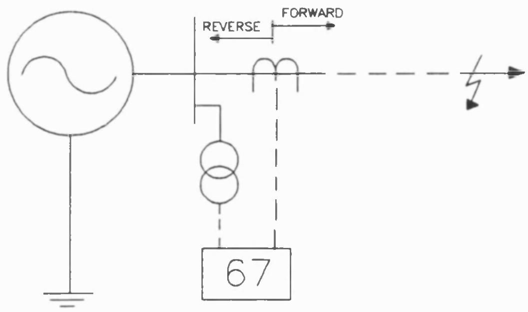



Figure 7.6.1.1.14 Variations of Directional Angle $\theta_C$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for Phase-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11kV Underground Cable System

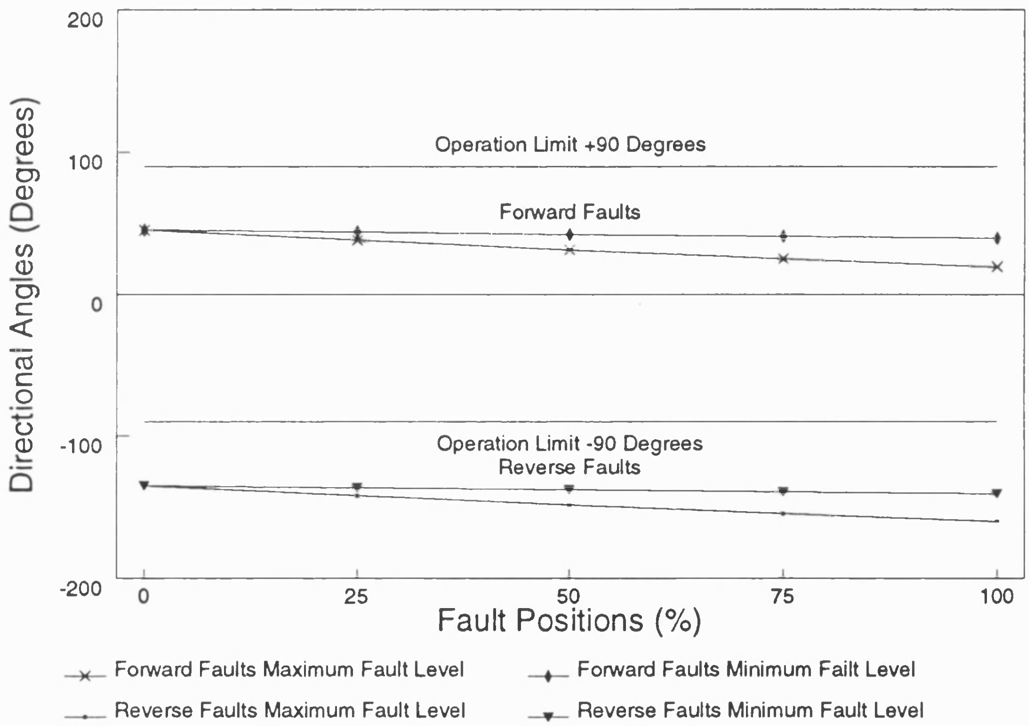
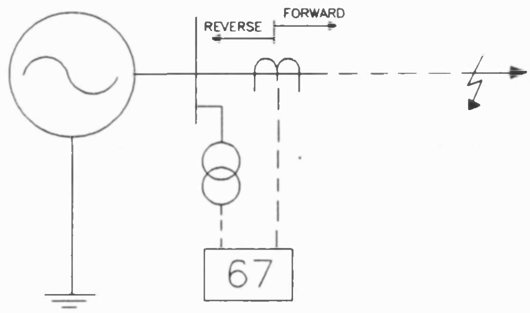



Figure 7.6.1.1.15 Variations of Directional Angle $\theta_C$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for Single-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11kV Underground Cable System

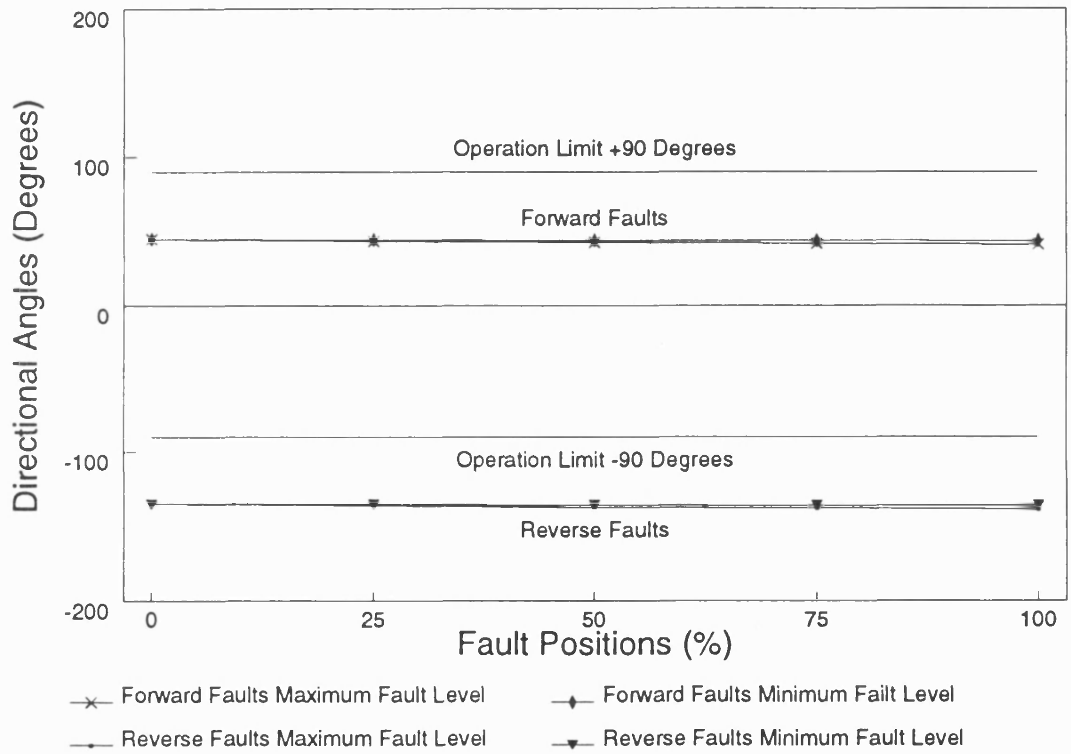
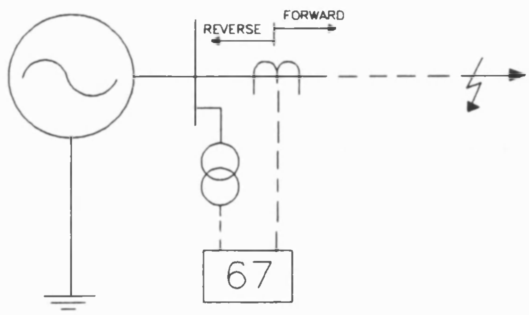



Figure 7.6.1.1.16 Variations of Directional Angle $\theta_C$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for Phase-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11kV Underground Cable System

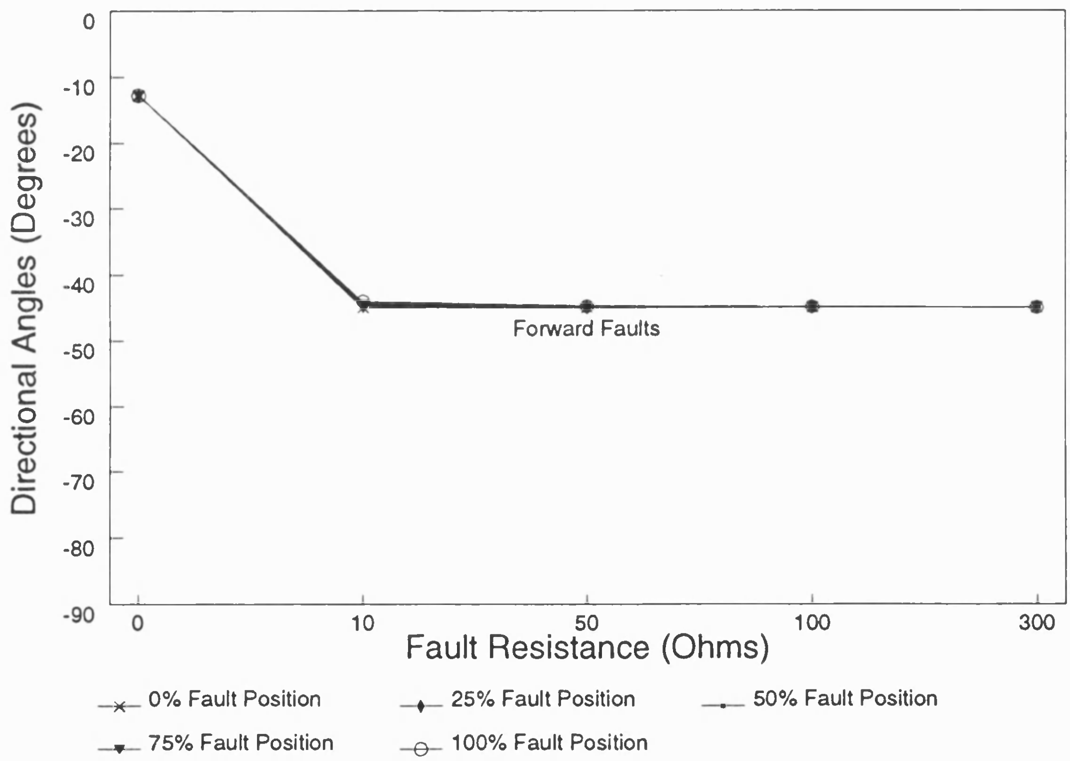
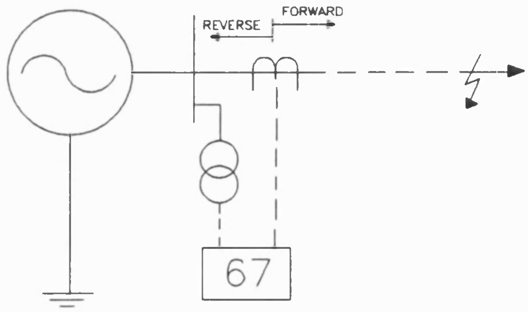



Figure 7.6.1.1.17 Variations of Directional Angle $\theta_C$ for Forward 3-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Underground Cable System

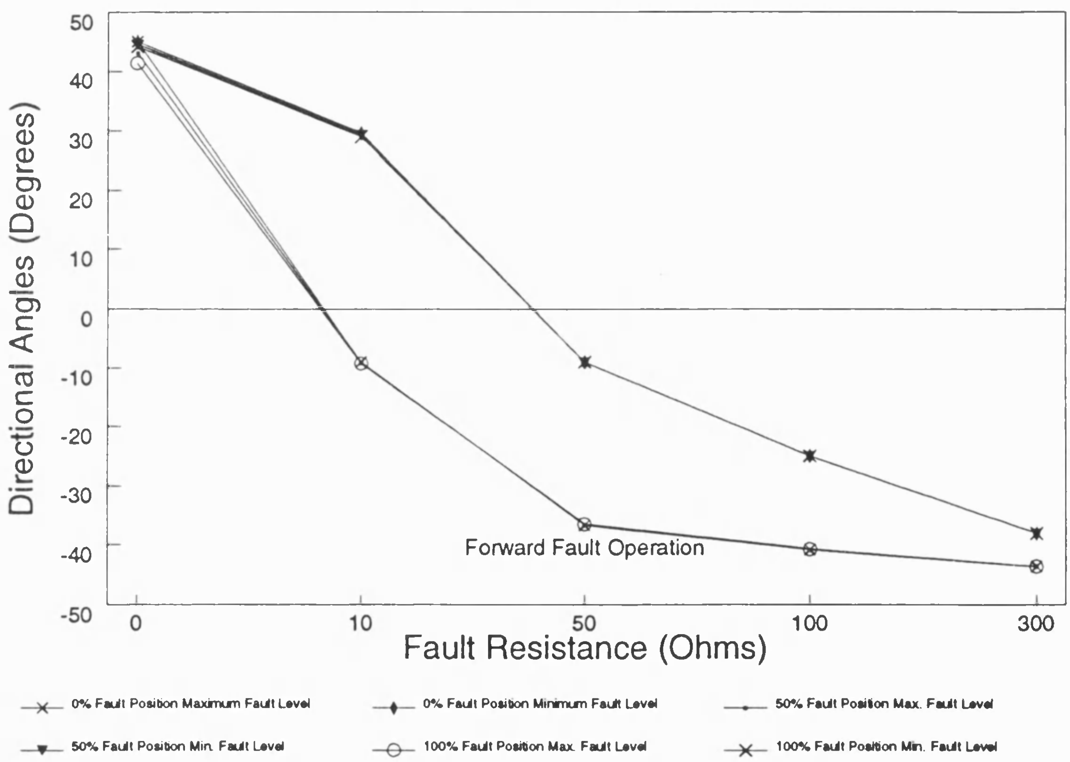
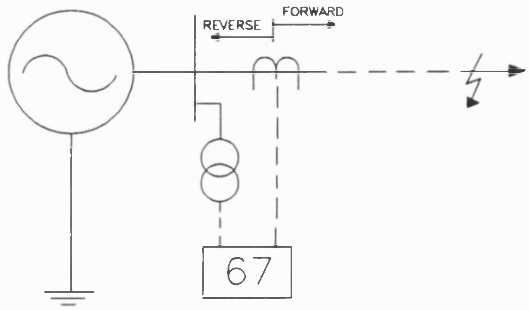



Figure 7.6.1.1.18 Variations of Directional Angle $\theta_C$ for Forward Phase-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Underground Cable System

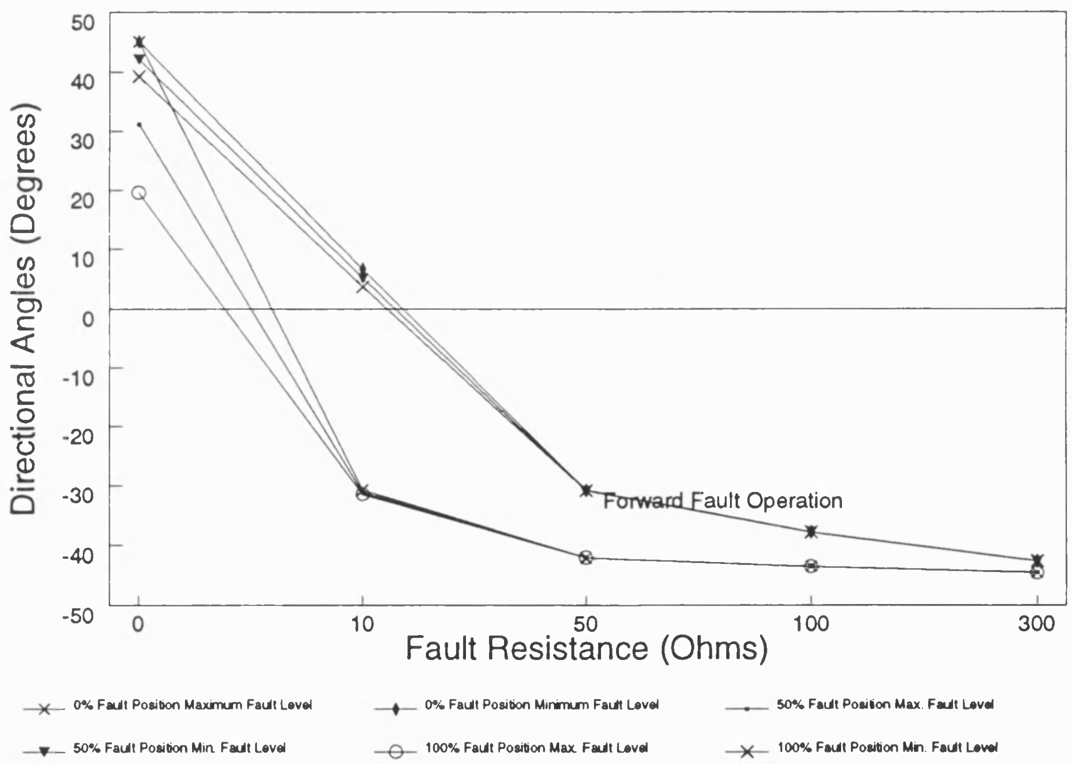
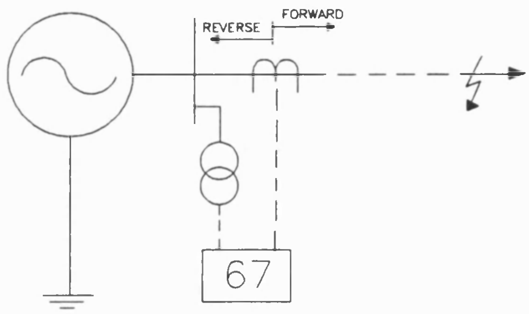



Figure 7.6.1.1.19 Variations of Directional Angle $\theta_C$ for Forward Single-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Underground Cable System

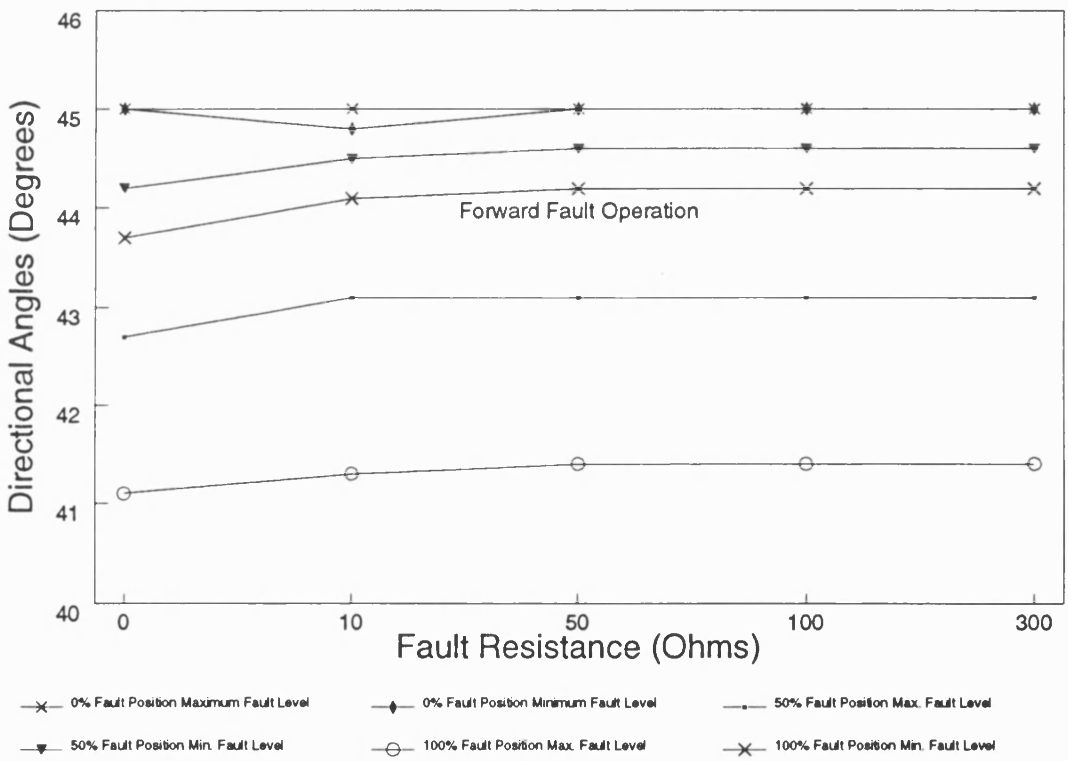
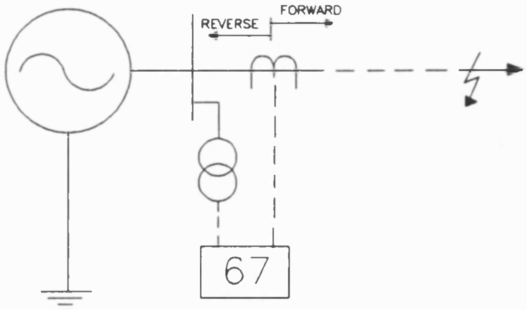



Figure 7.6.1.1.20 Variations of Directional Angle $\theta_C$ for Forward Phase-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Underground Cable System

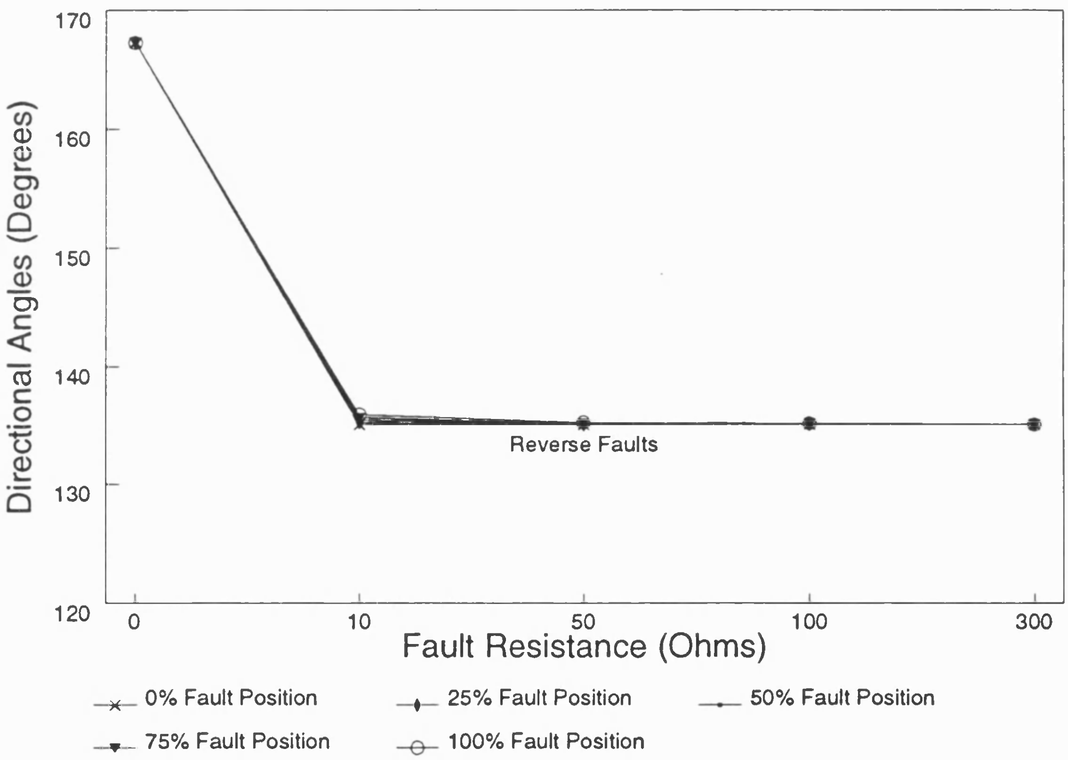
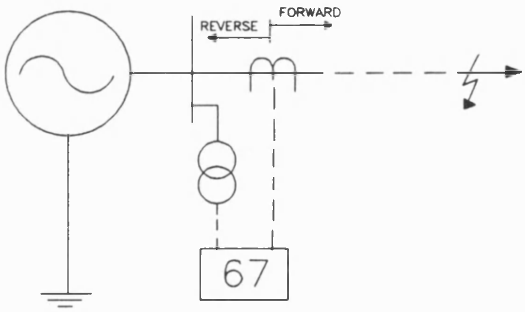



Figure 7.6.1.1.21 Variations of Directional Angle $\theta_C$ for Reverse 3-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Underground Cable System

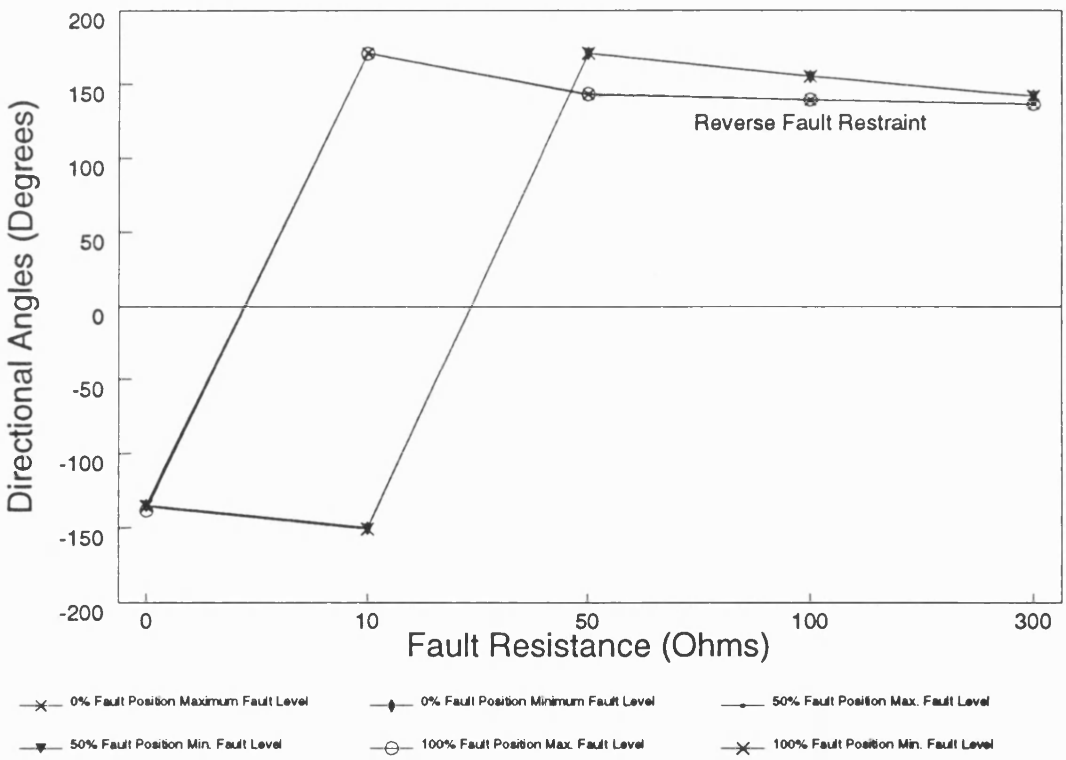
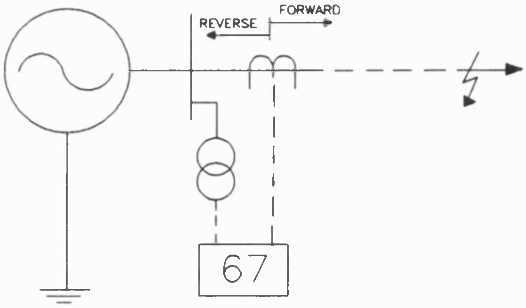



Figure 7.6.1.1.22 Variations of Directional Angle $\theta_C$ for Reverse Phase-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Underground Cable System

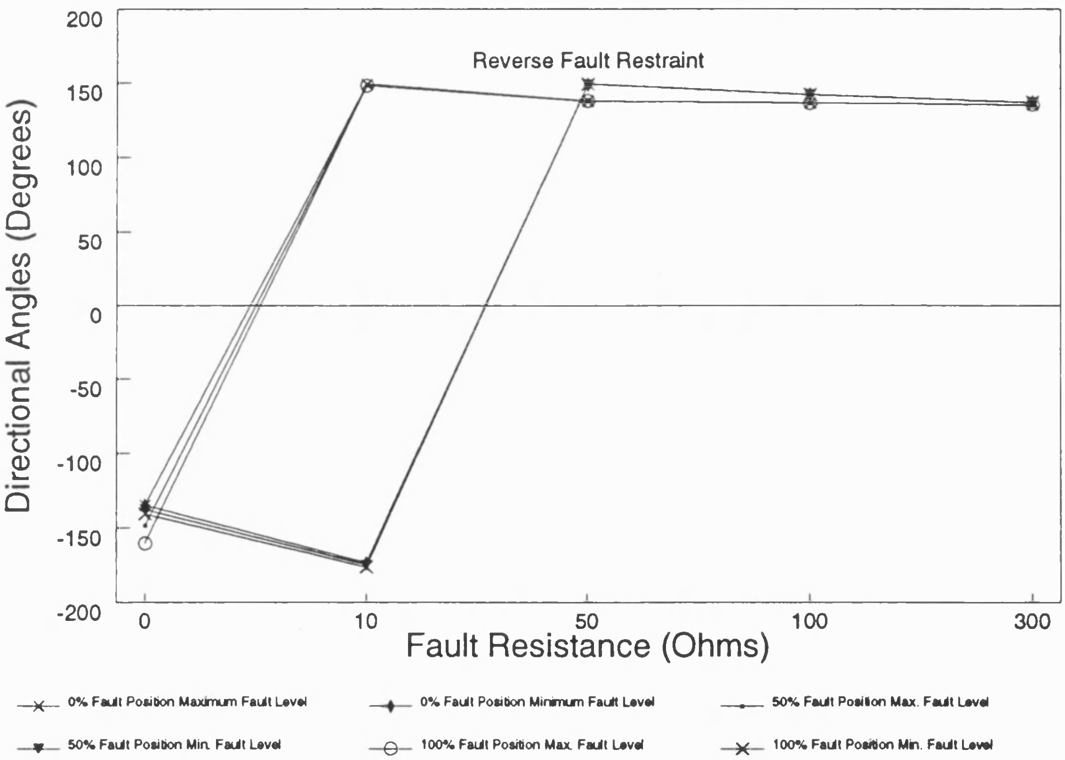
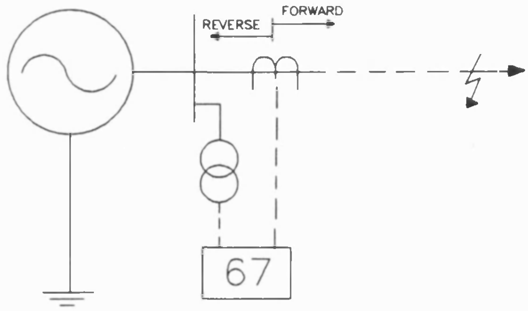



Figure 7.6.1.1.23 Variations of Directional Angle $\theta_C$ for Reverse Single-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




11kV Underground Cable System

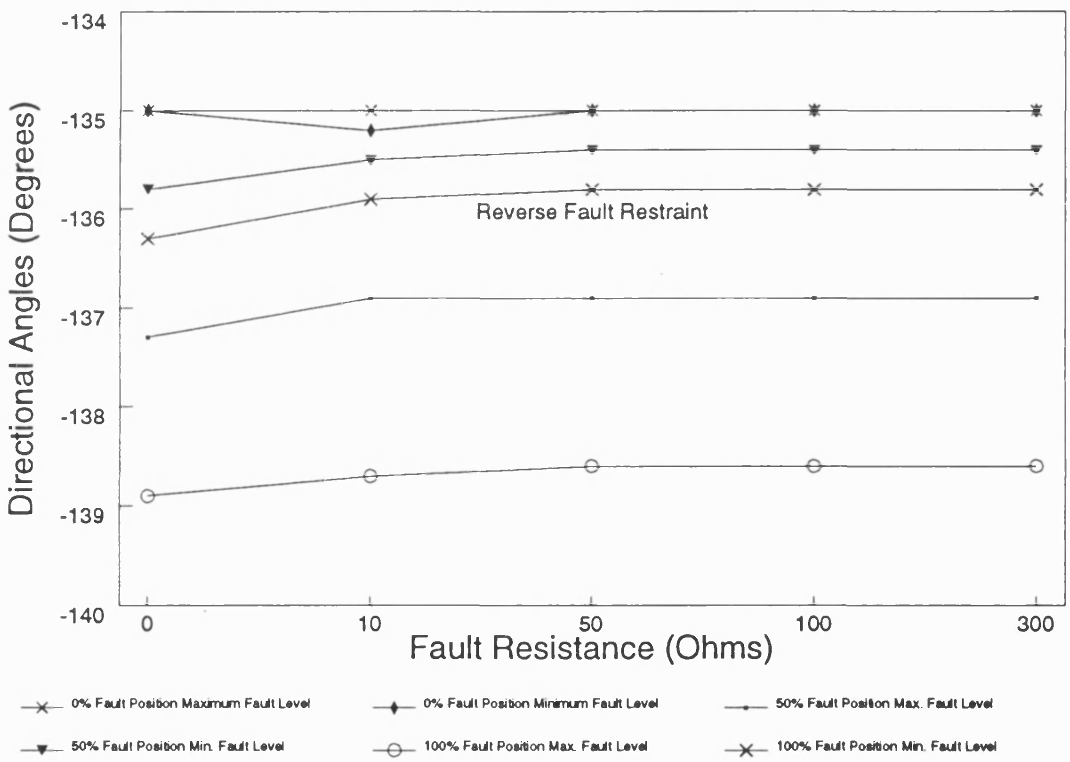



Figure 7.6.1.1.24 Variations of Directional Angle $\theta_C$ for Reverse Phase-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.

For the 11kV system shown the followings are observed in addition to the presentations given in the various figures:

- For 3-phase faults with zero fault resistance the different fault levels of the source have no effect on the resulting values of the directional angle $\theta_C$; the values of $\theta_C$ are not influenced by the source emf magnitudes and its associated angles and for different fault point positions.

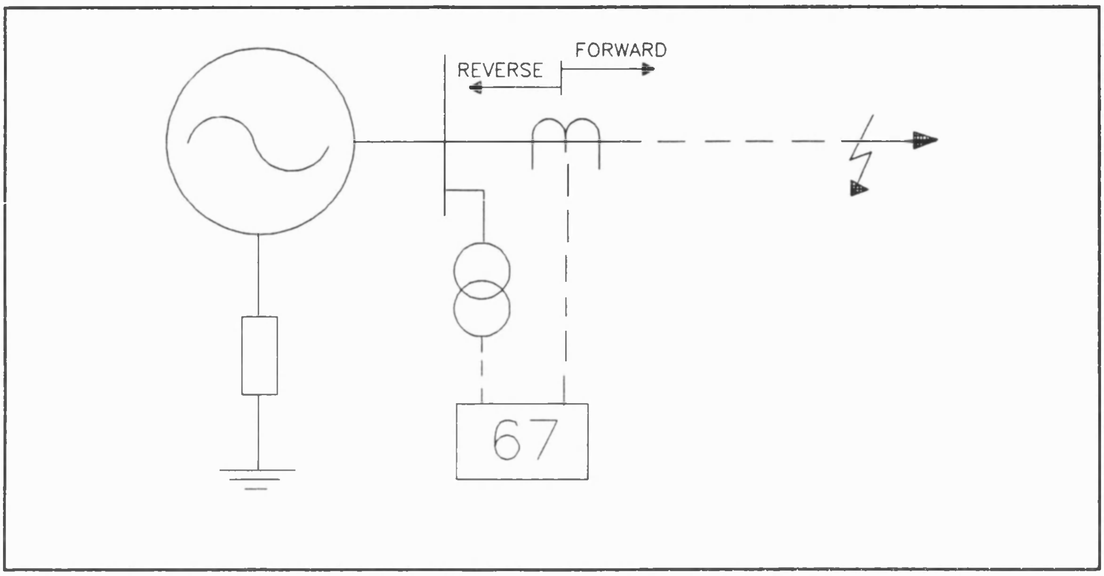
- For 3-phase faults the source fault levels have no additional effect on the variation of the directional angle $\theta_C$ with fault resistance at different fault point positions.

- For phase-phase and single-phase-earth reverse faults the directional angles $\theta_C$ appear to encroach onto the operation limits of $\pm 90^0$ with variation of the fault resistance. This is because of the values of $\theta_C$, being less than $-180^0$, are expressed as positive angles (e.g. $-200^0$ is expressed as $+160^0$) and the points are joined by the line graph.

- The values of the directional angle $\theta_C$ for forward and reverse faults are well within the defined limits for operation and for restraint respectively. It is also worth noting that for this type of distribution system the amount of fault resistance detectable ($>300\Omega$) is very high, well above practical values for some fault types.

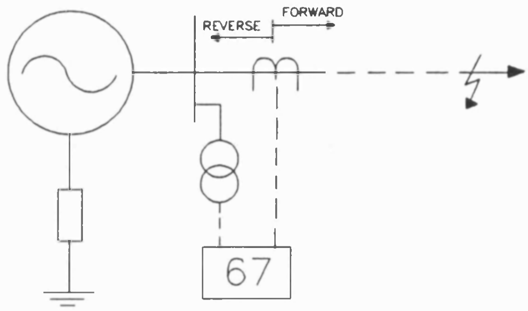
### 7.6.1.2 33kV Single Source System of either Overhead Line or Underground Cable Feeder

The system is shown below:




A directional relay 67 is arranged to protect a feeder of a resistance-earthed 33kV distribution system with a single source of supply. This is to check the effect, if any, of the system neutral earthing arrangement.

The directional angles $\theta_C$ for various fault types on the feeder under maximum and minimum fault levels and their variations with fault point positions and fault resistances are presented in Figure 7.6.1.2.1 to 7.6.1.2.24 with the directional relay arranged to "see" the faults as being either of forward or reverse direction. The results for faults on both overhead line and underground cable feeders are presented.




33kV Overhead Line System

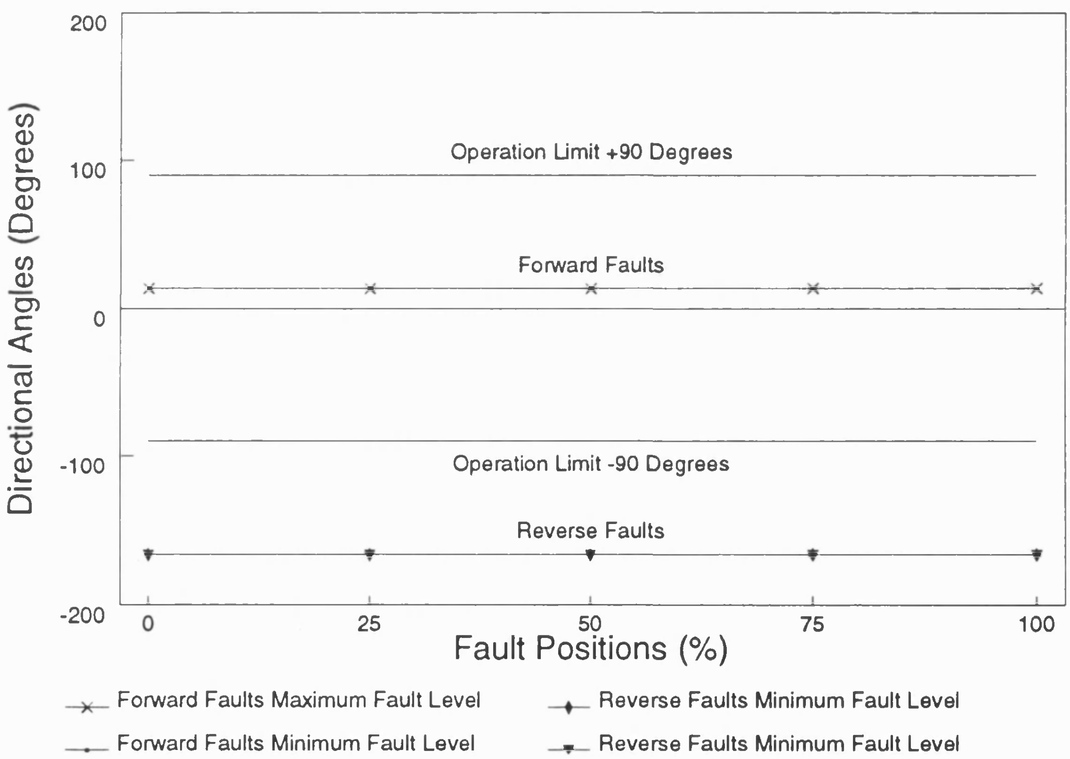
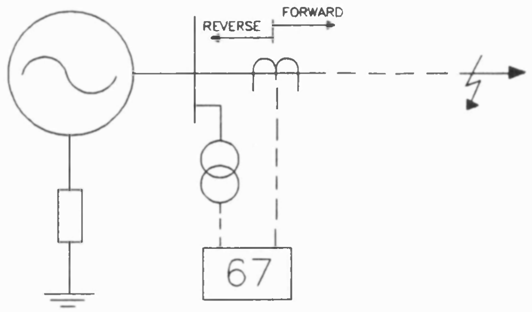



Figure 7.6.1.2.1 Variations of Directional Angle $\theta_C$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for 3-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33kV Overhead Line System

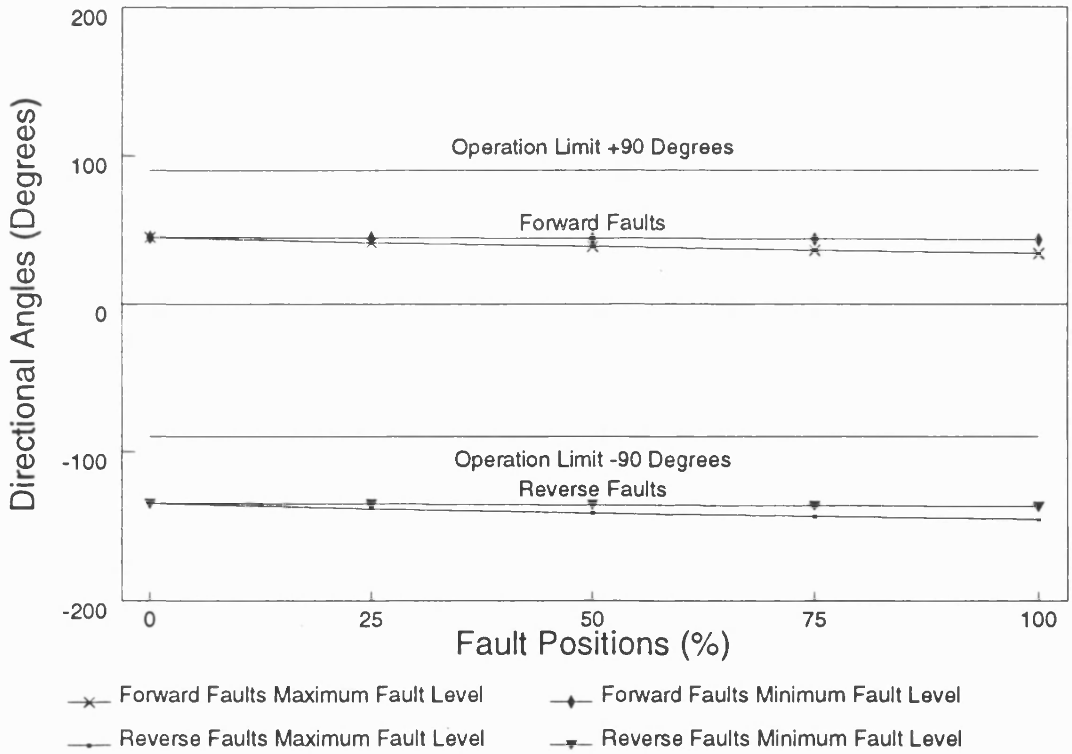
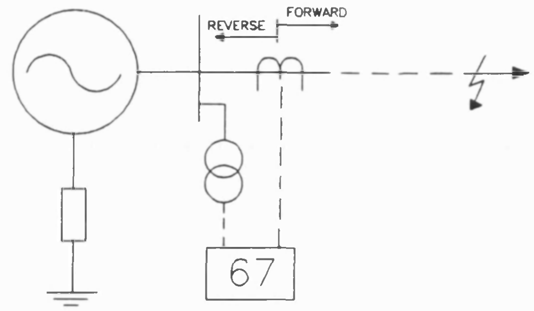



Figure 7.6.1.2.2 Variations of Directional Angle $\theta_c$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for Phase-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33kV Overhead Line System

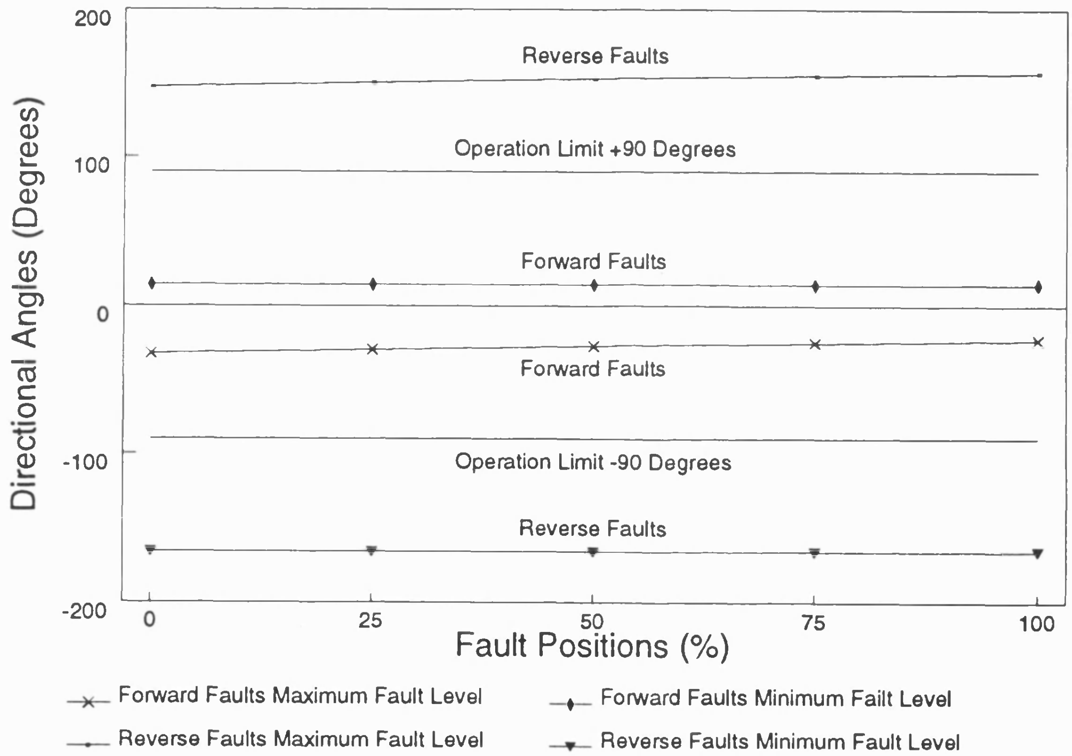
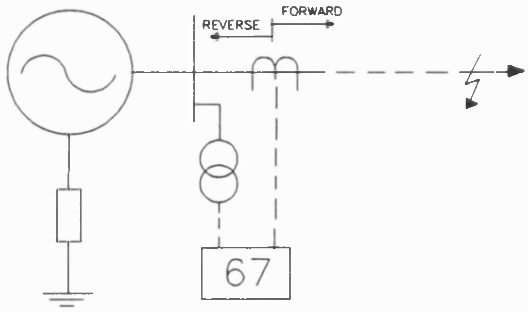



Figure 7.6.1.2.3 Variations of Directional Angle $\theta_c$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for Single-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33kV Overhead Line System

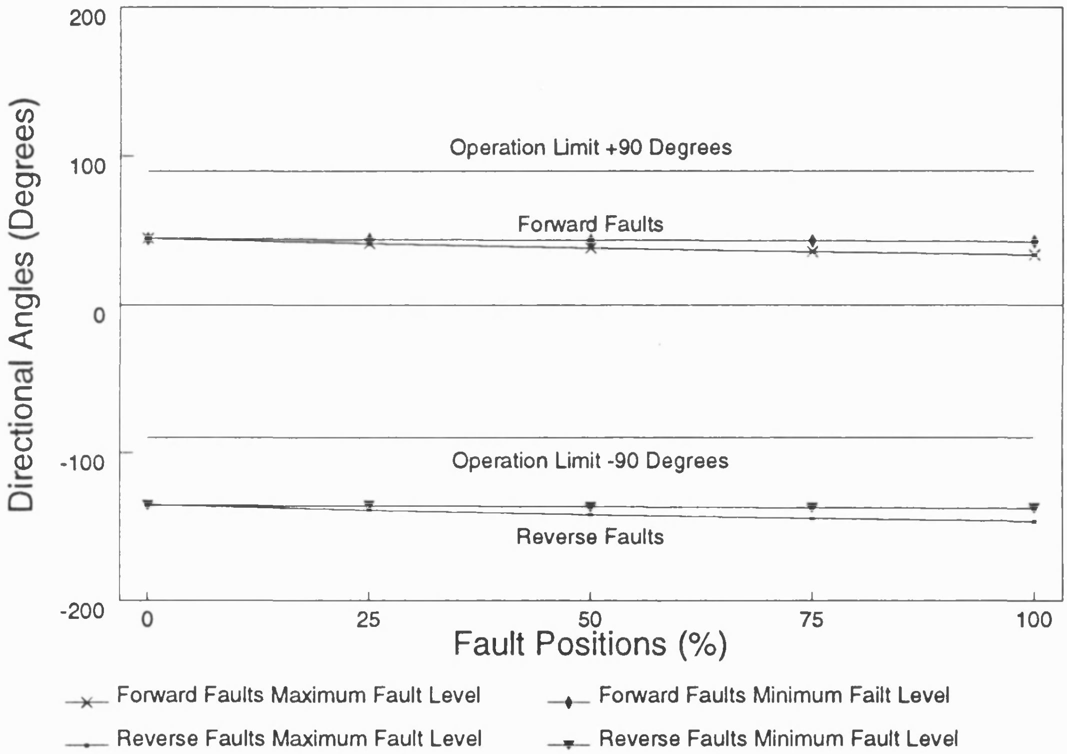
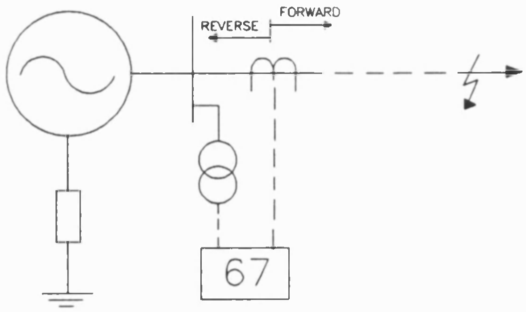



Figure 7.6.1.2.4 Variations of Directional Angle $\theta_C$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for Phase-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33kV Overhead Line System

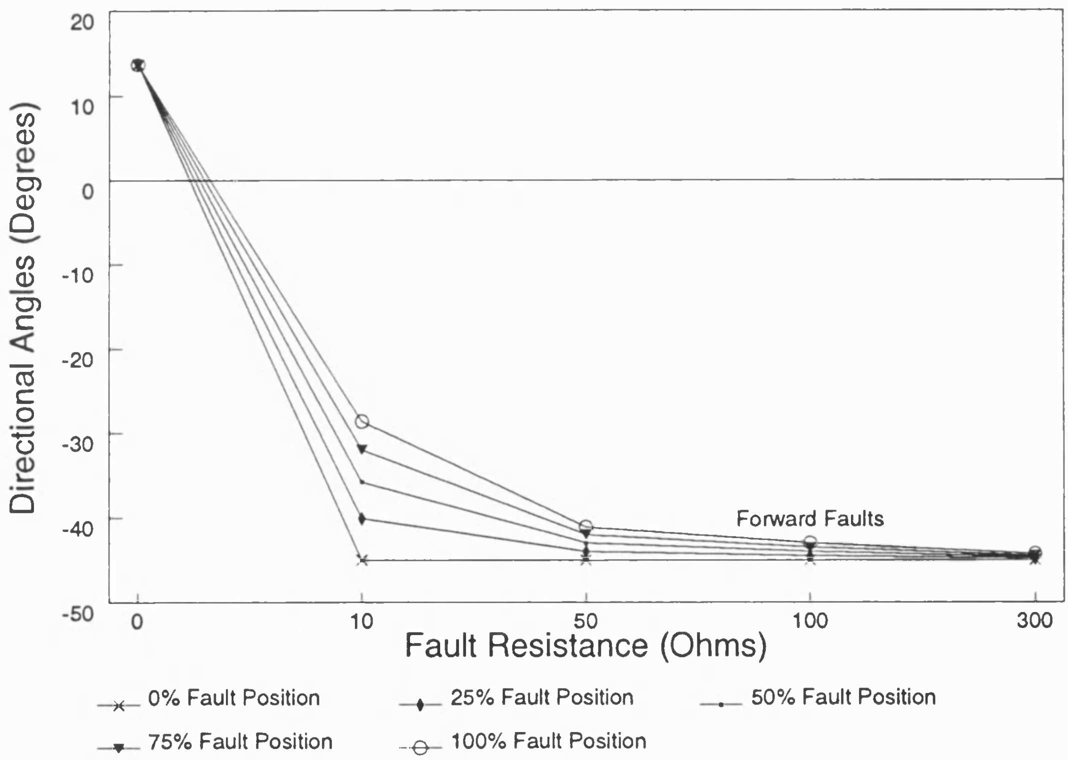
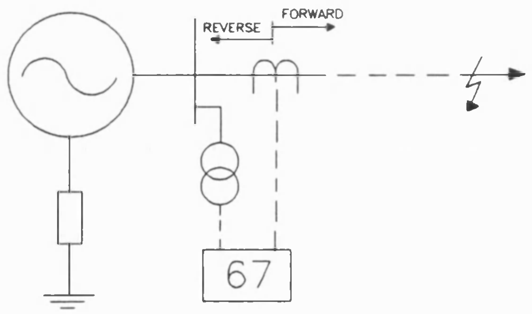



Figure 7.6.1.2.5 Variations of Directional Angle $\theta_C$ for Forward 3-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




33kV Overhead Line System

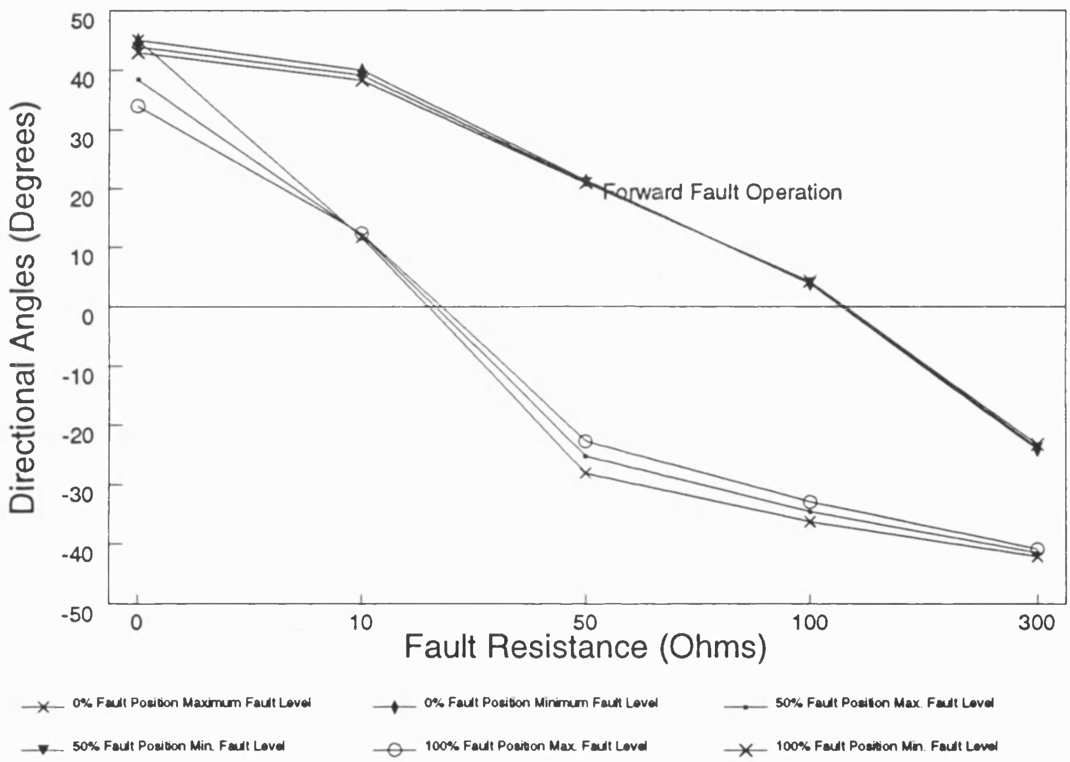
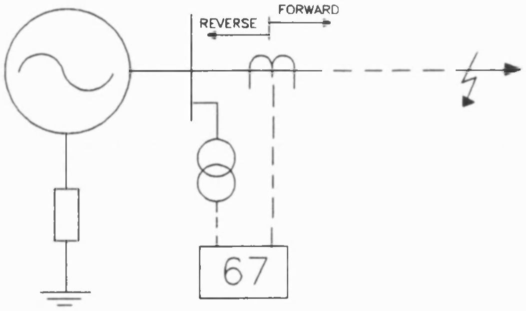



Figure 7.6.1.2.6 Variations of Directional Angle $\theta_C$ for Forward Phase-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Position s for Maximum and Minimum Fault Levels.




33kV Overhead Line System

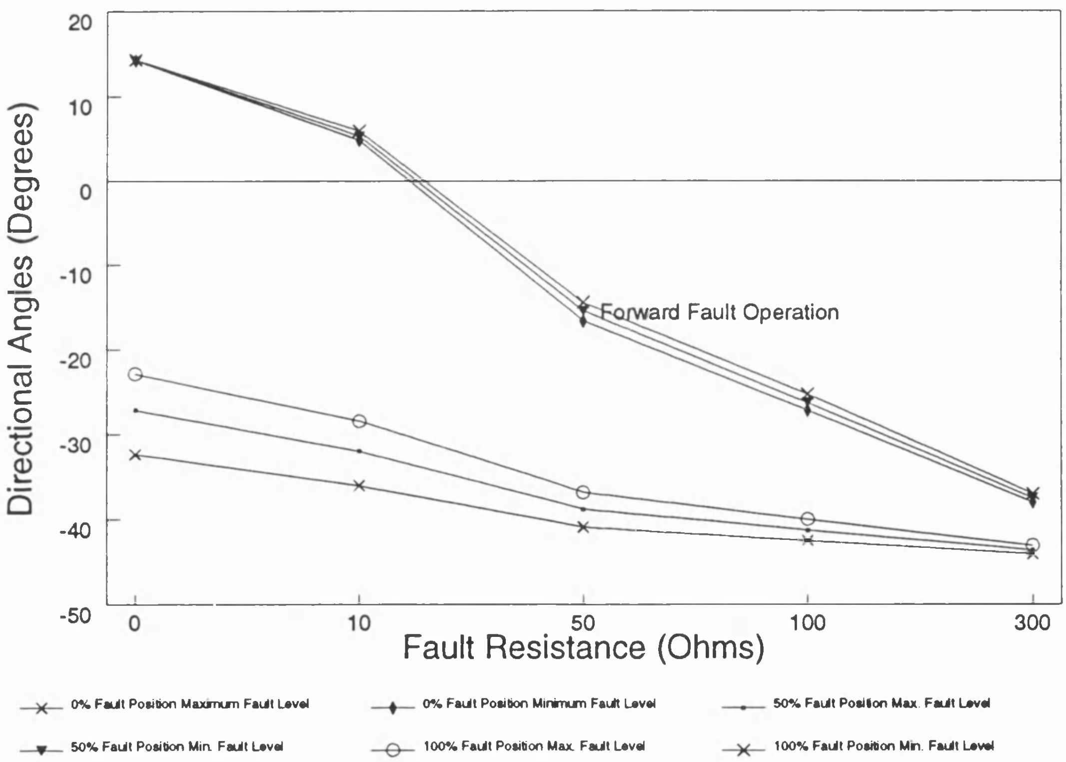
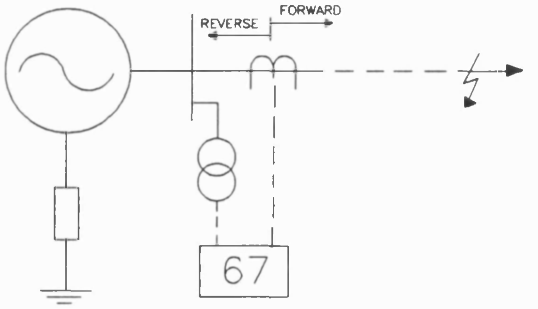



Figure 7.6.1.2.7 Variations of Directional Angle $\theta_C$ for Forward Single-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




33kV Overhead Line System

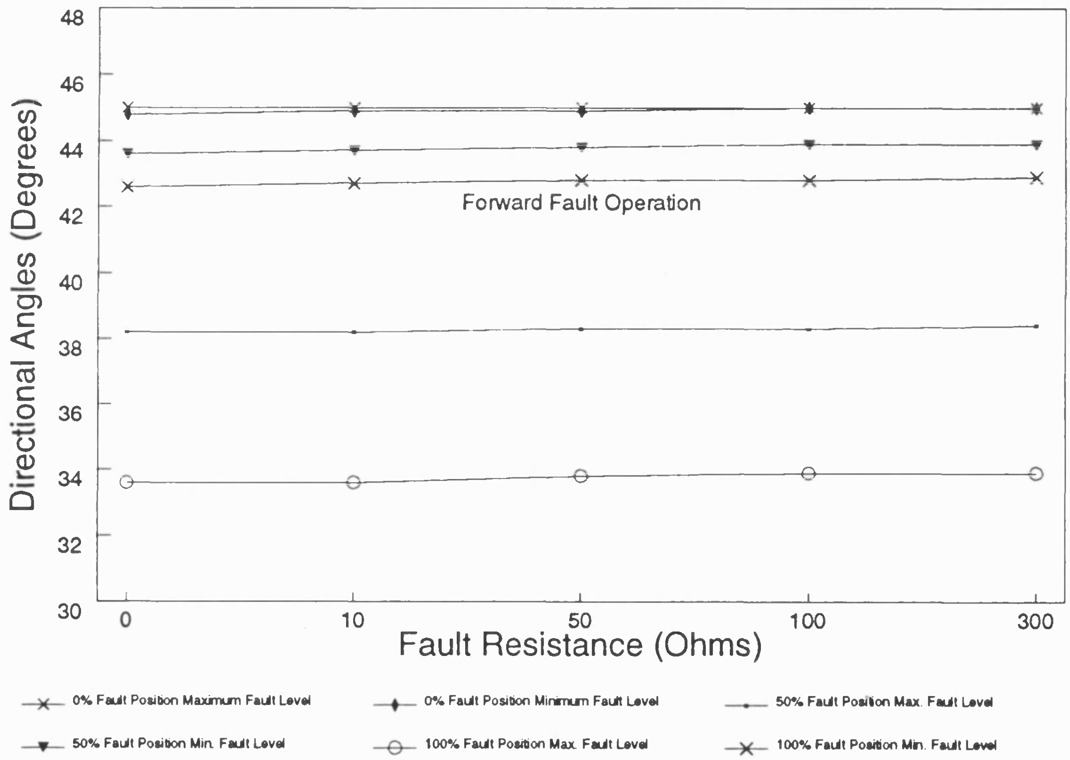
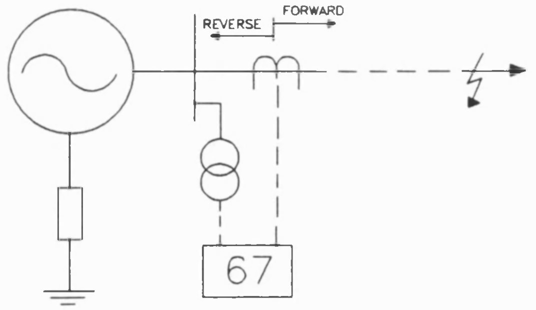



Figure 7.6.1.2.8 Variations of Directional Angle $\theta_C$ for Forward Phase-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




33kV Overhead Line System

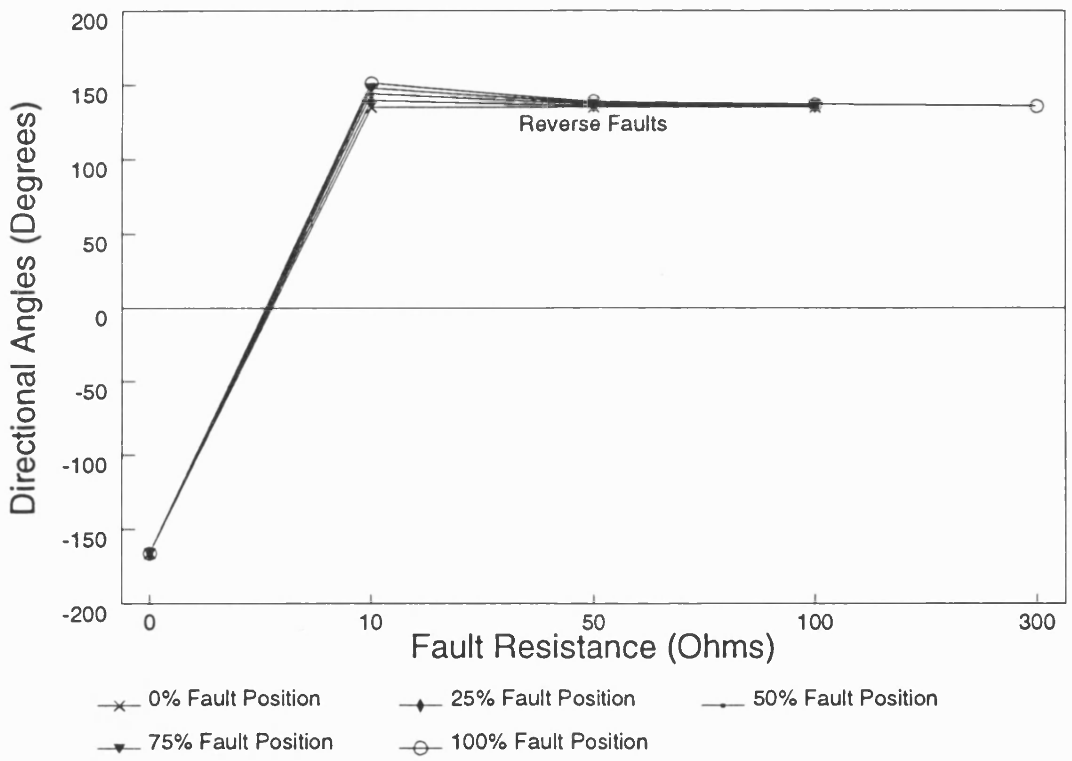
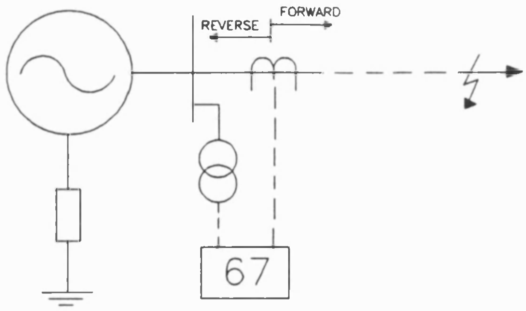



Figure 7.6.1.2.9 Variations of Directional Angle $\theta_C$ for Reverse 3-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




33kV Overhead Line System

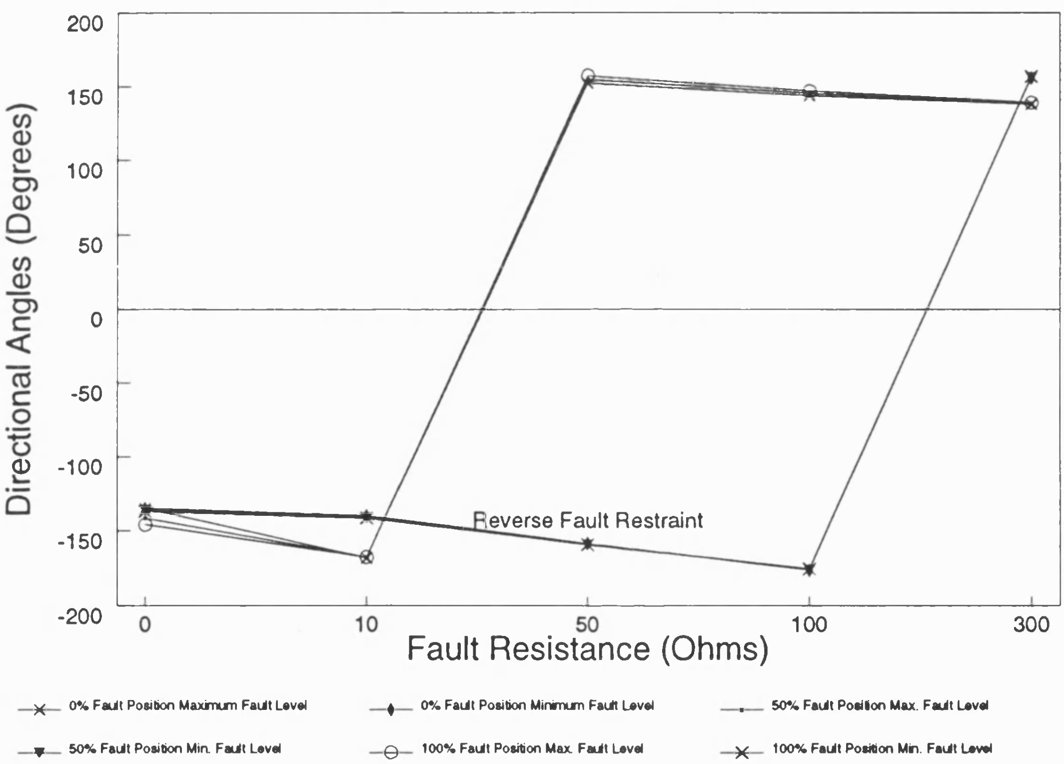
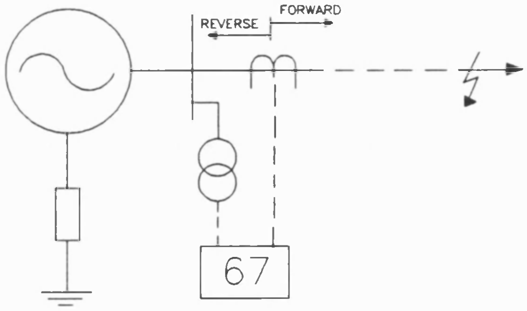



Figure 7.6.1.2.10 Variations of Directional Angle $\theta_C$ for Reverse Phase-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




33kV Overhead Line System

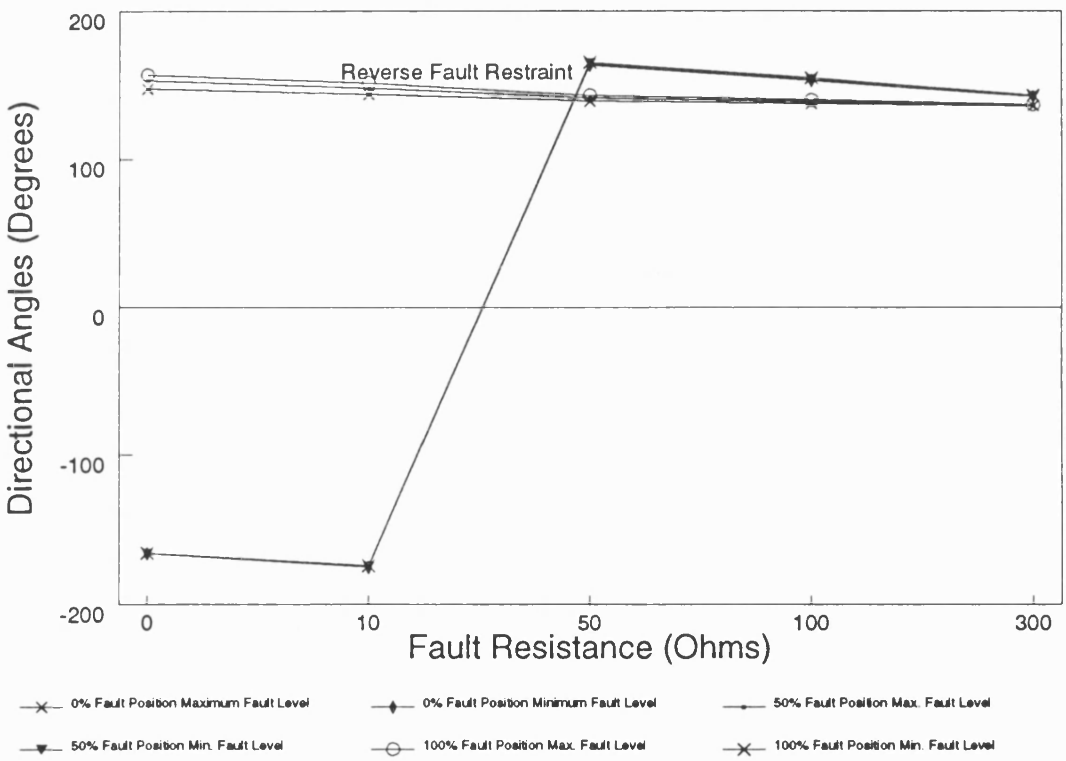
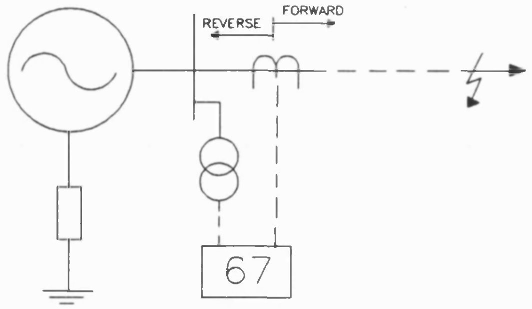



Figure 7.6.1.2.11 Variations of Directional Angle $\theta_C$ for Reverse Single-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




33kV Overhead Line System

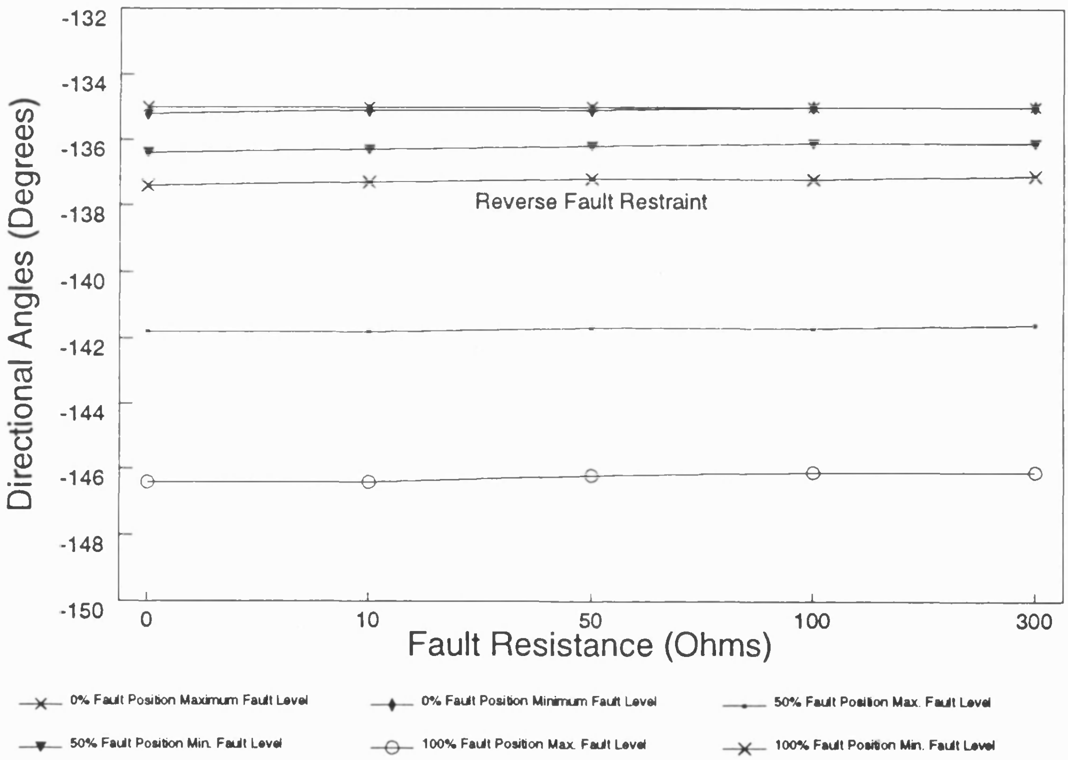
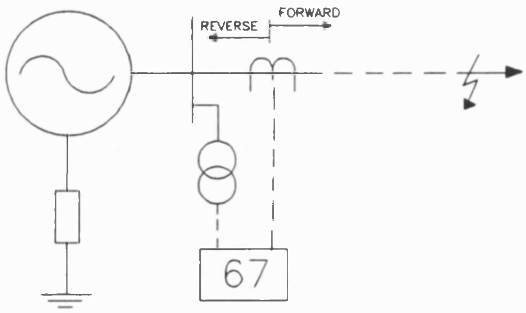



Figure 7.6.1.2.12 Variations of Directional Angle $\theta_C$ for Reverse Phase-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




33kV Underground Cable System

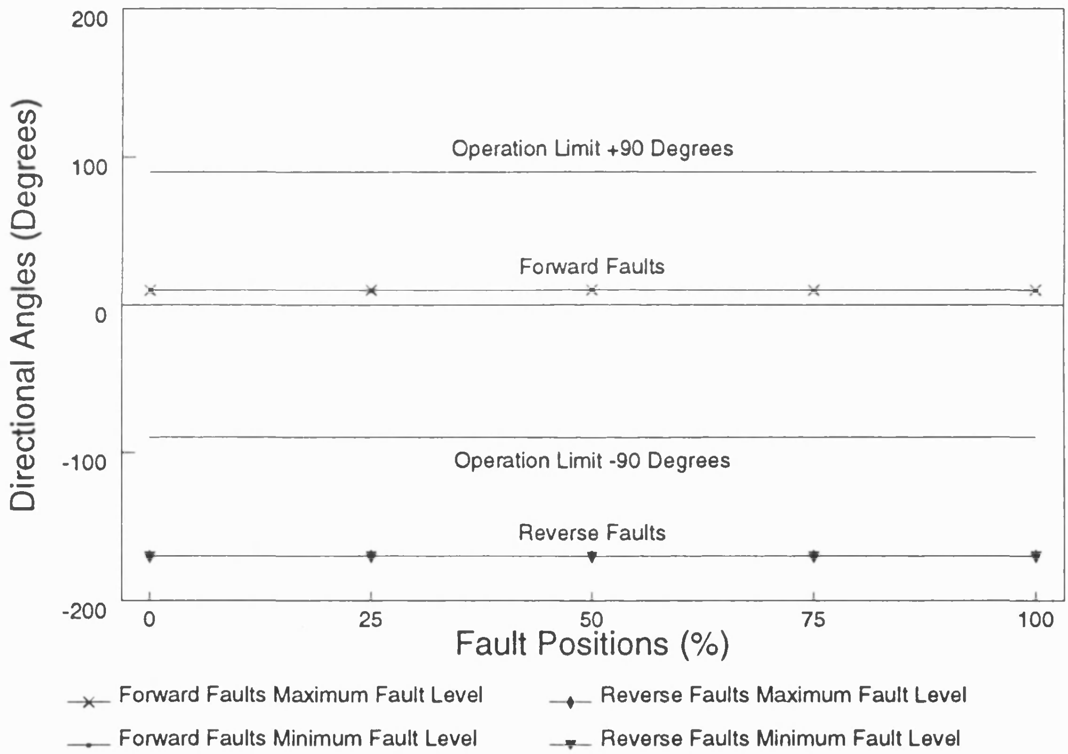
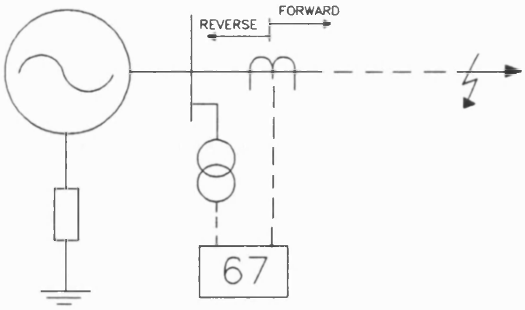



Figure 7.6.1.2.13 Variations of Directional Angle $\theta_C$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for 3-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33kV Underground Cable System

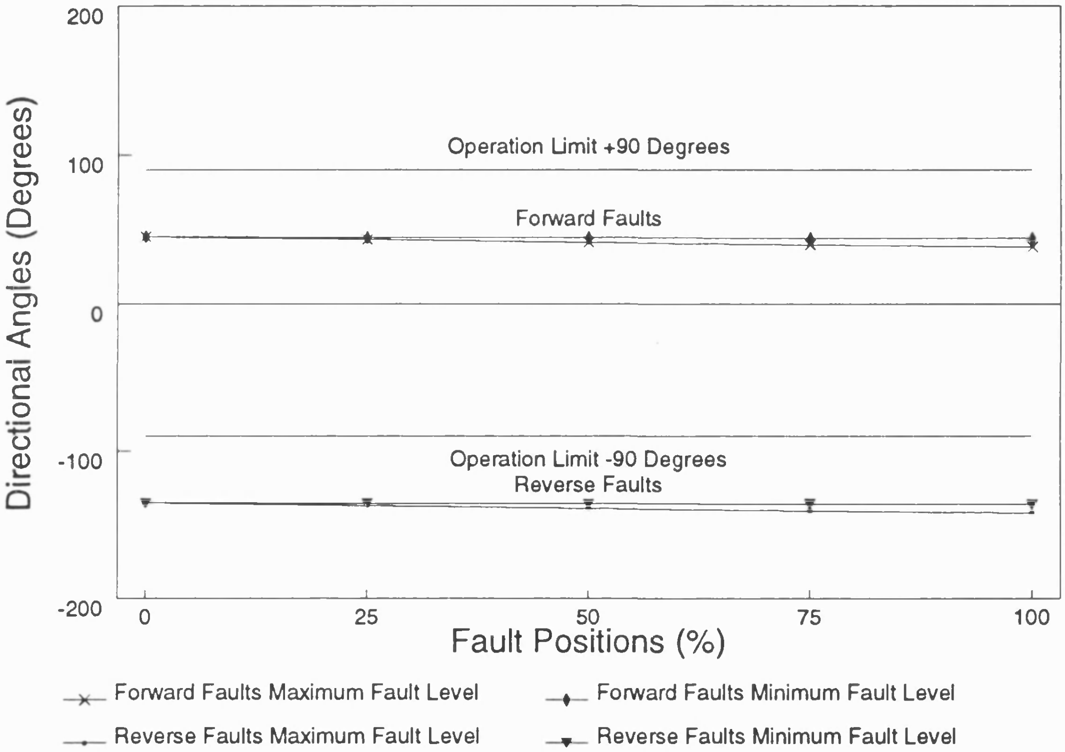
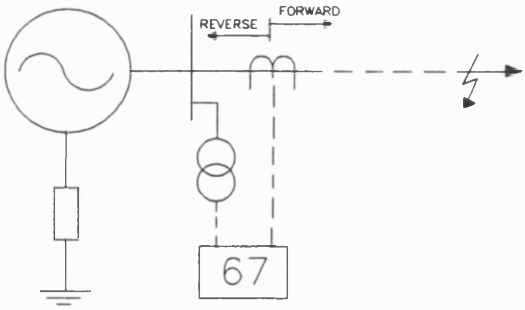



Figure 7.6.1.2.14 Variations of Directional Angle $\theta_C$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for Phase-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33kV Underground Cable System

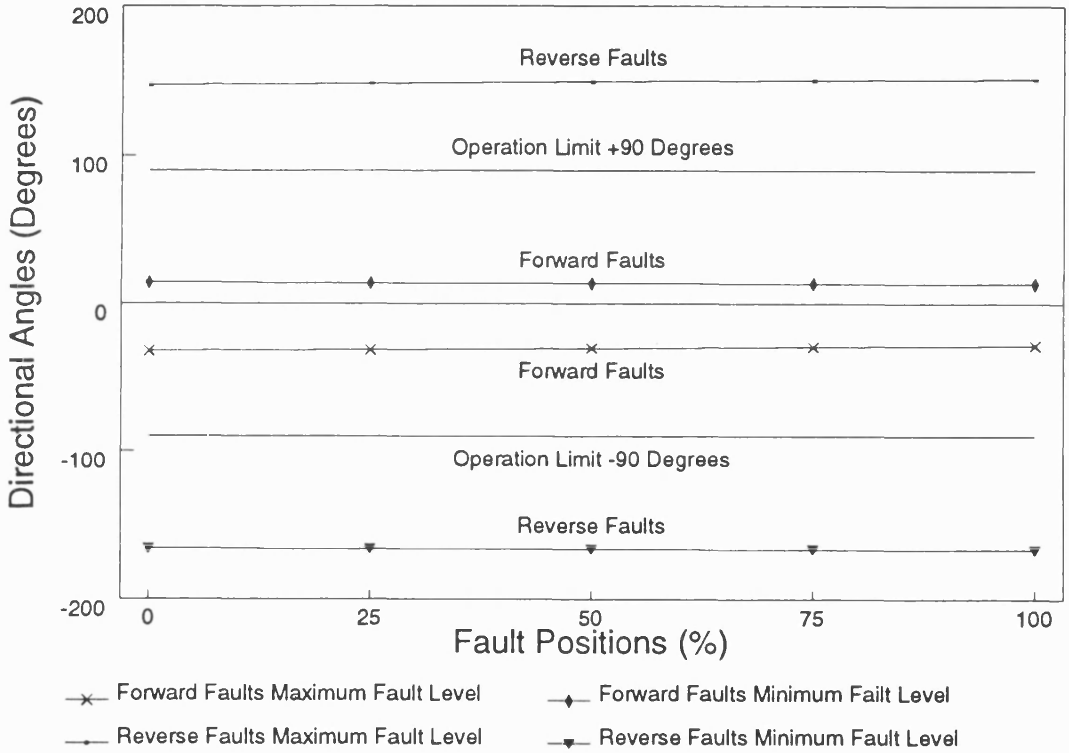
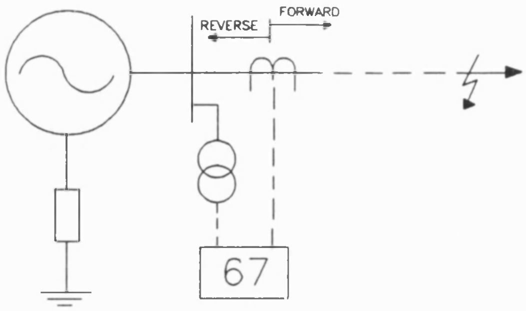



Figure 7.6.1.2.15 Variations of Directional Angle $\theta_C$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for Single-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33kV Underground Cable System

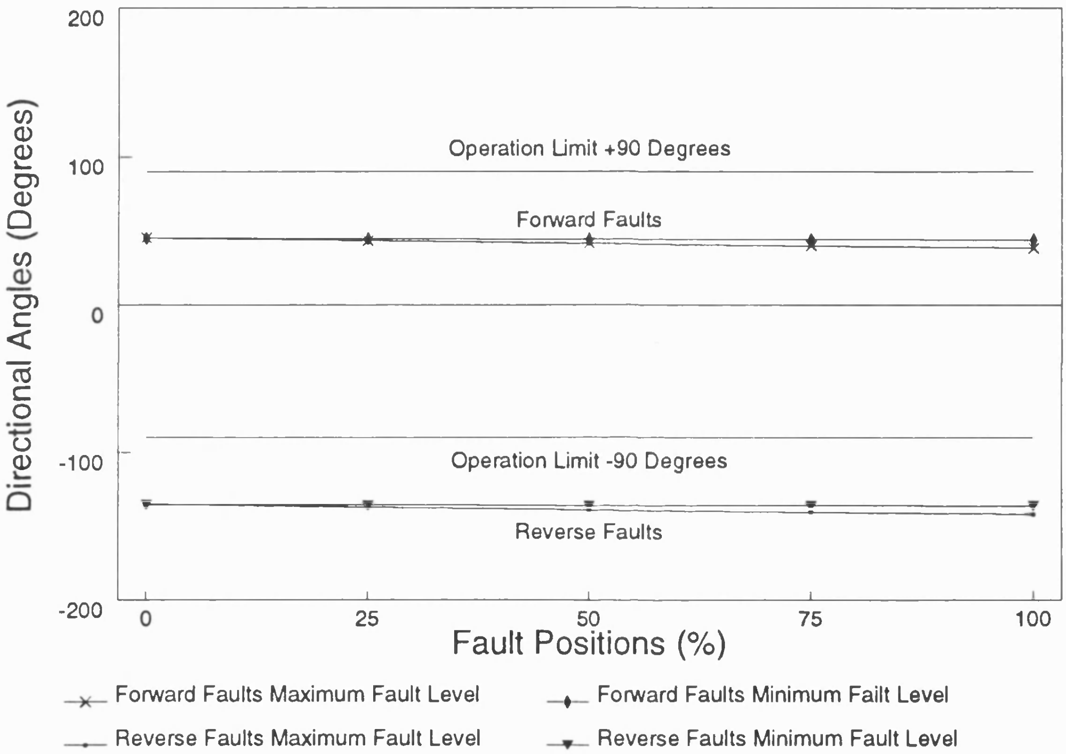
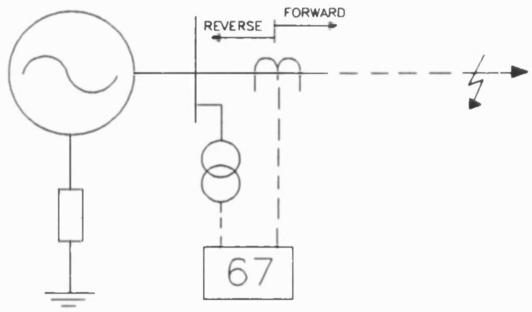



Figure 7.6.1.2.16 Variations of Directional Angle $\theta_C$ with Fault Positions for Maximum and Minimum Fault Levels and Zero Fault Resistance for Phase-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33kV Underground Cable System

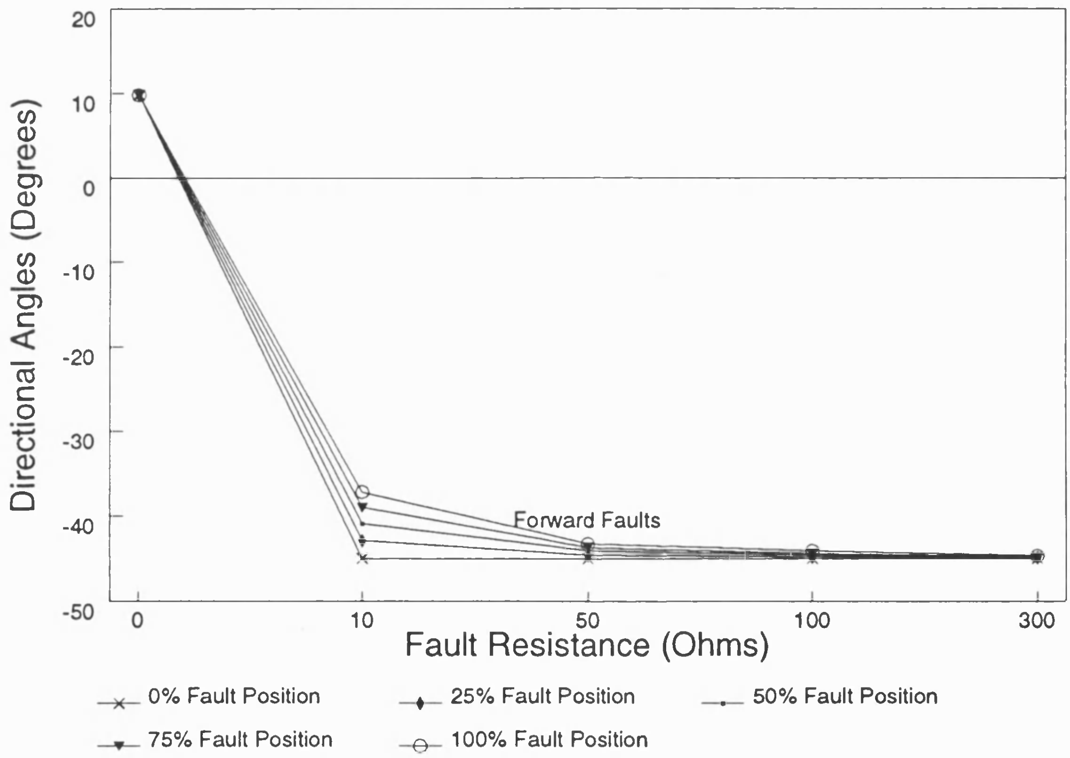
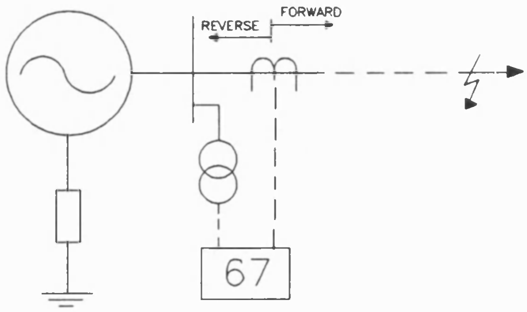



Figure 7.6.1.2.17 Variations of Directional Angle $\theta_C$ for Forward 3-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




33kV Underground Cable System

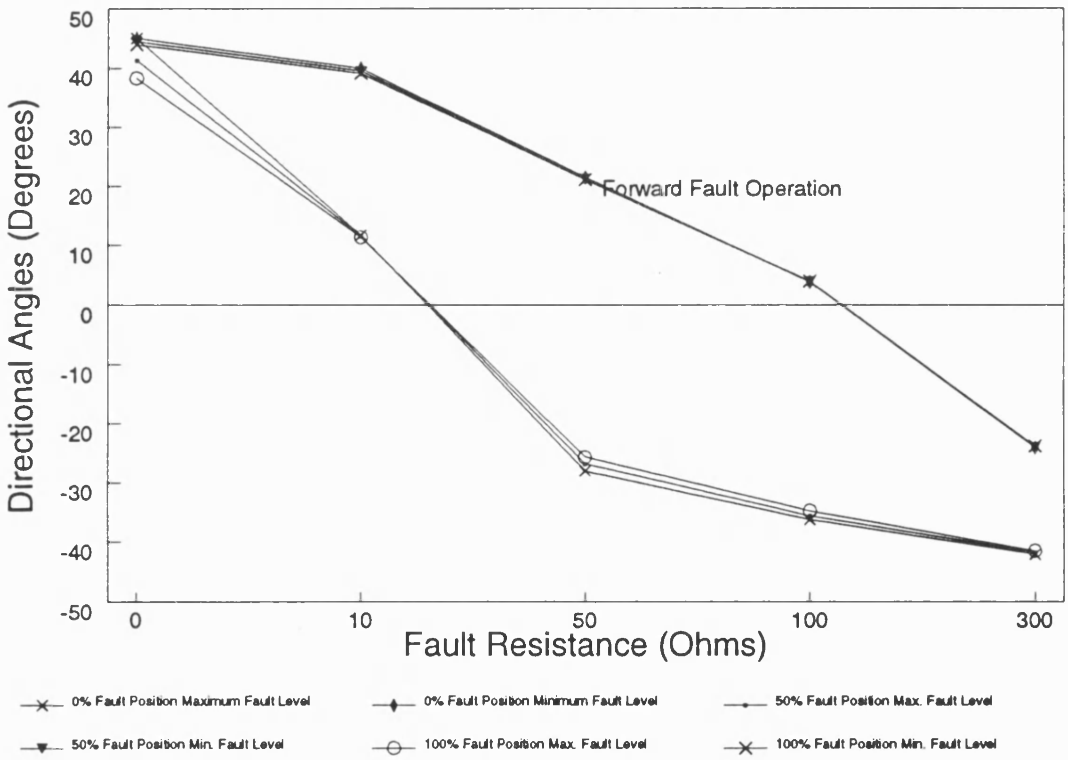
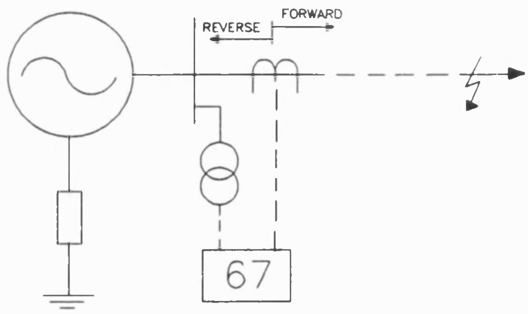



Figure 7.6.1.2.18 Variations of Directional Angle $\theta_C$ for Forward Phase-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




33kV Underground Cable System

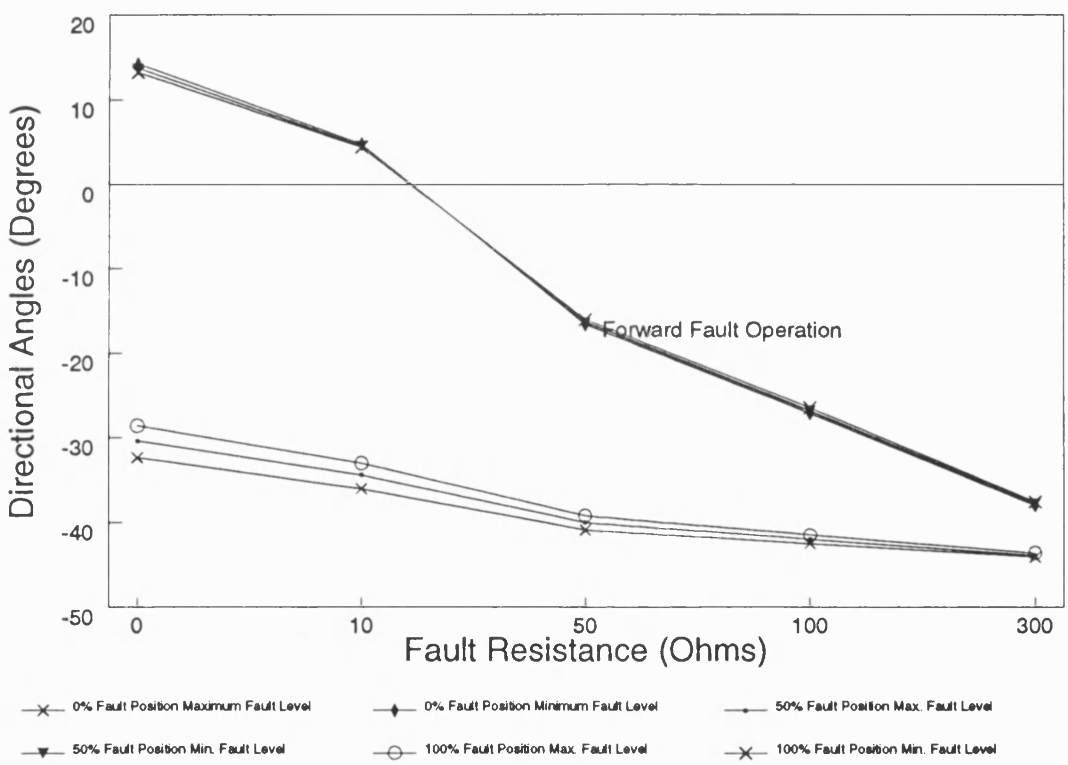
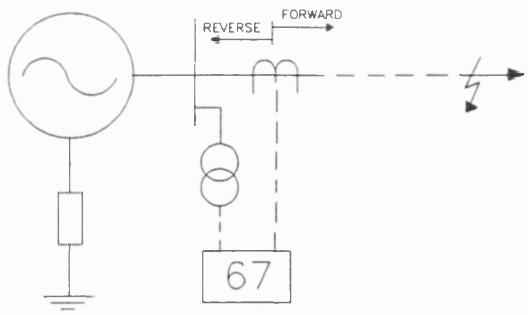



Figure 7.6.1.2.19 Variations of Directional Angle $\theta_C$ for Forward Single-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




33kV Underground Cable System

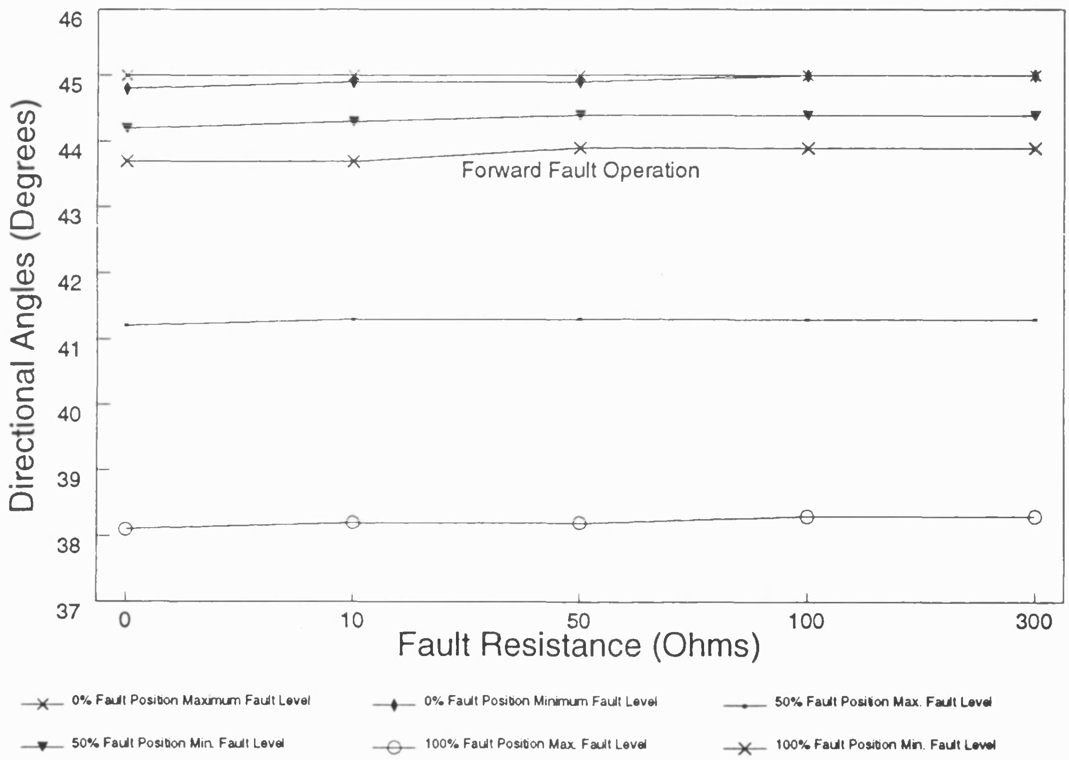
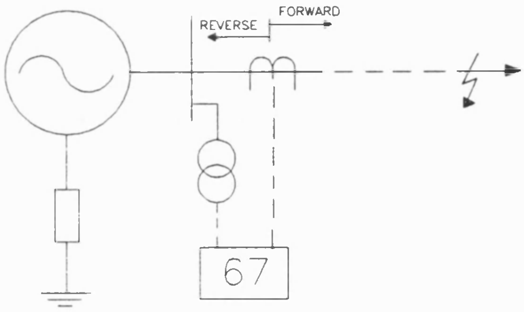



Figure 7.6.1.2.20 Variations of Directional Angle $\theta_C$ for Forward Phase-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




33kV Underground Cable System

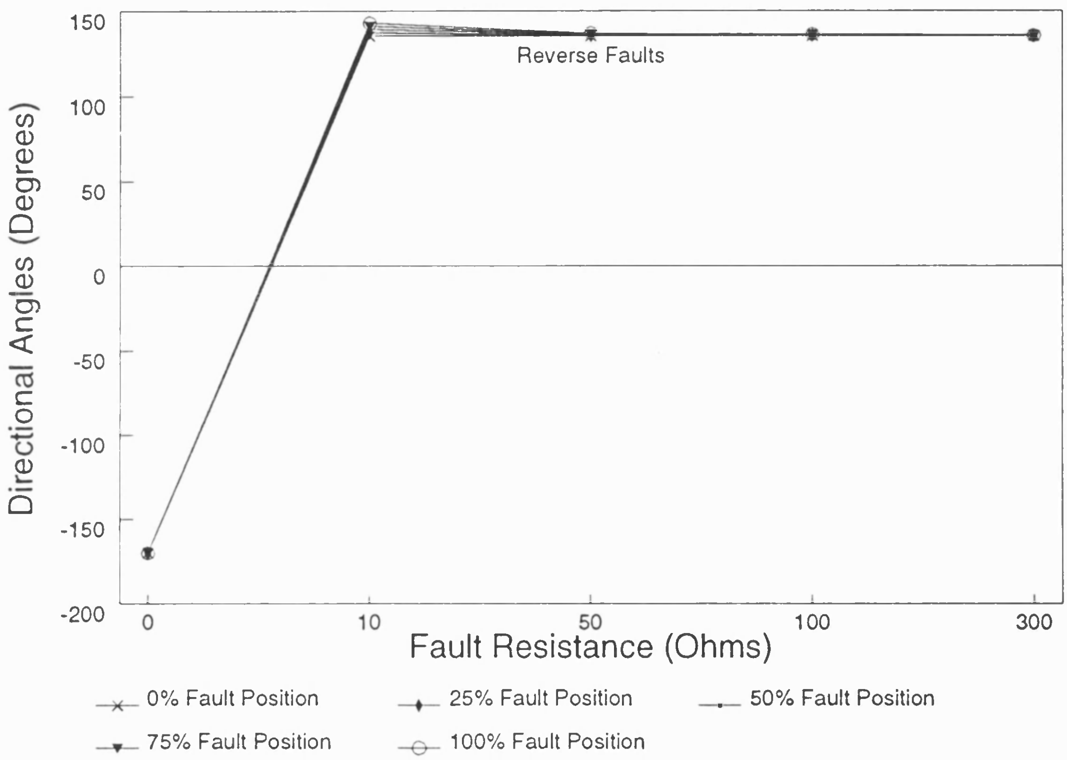
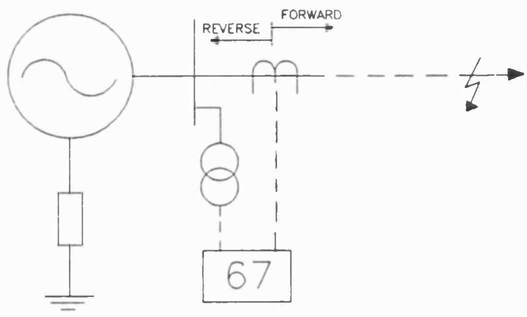



Figure 7.6.1.2.21 Variations of Directional Angle $\theta_C$ for Reverse 3-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




33kV Underground Cable System

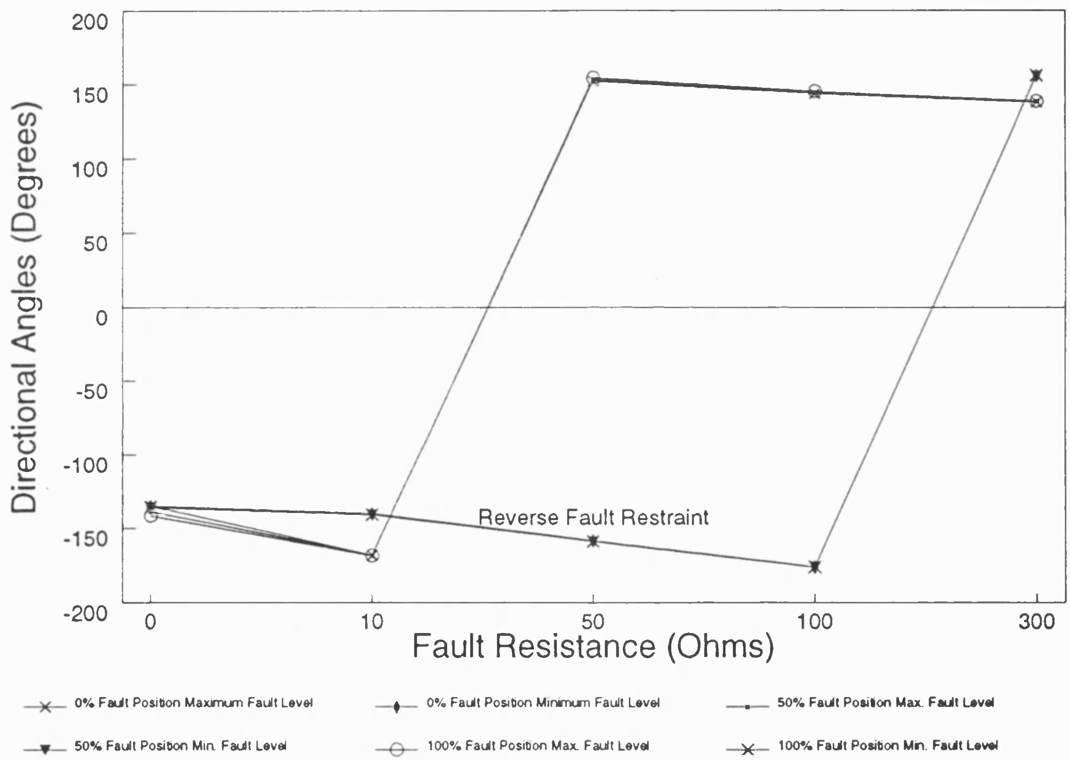
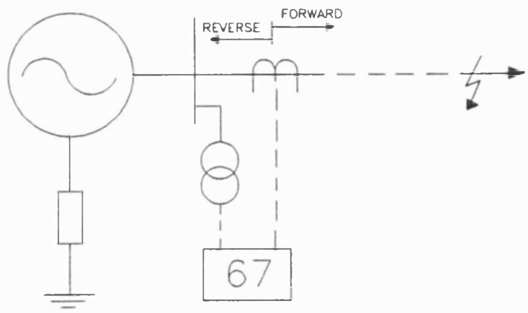



Figure 7.6.1.2.22 Variations of Directional Angle $\theta_C$ for Reverse Phase-phase Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




33kV Underground Cable System

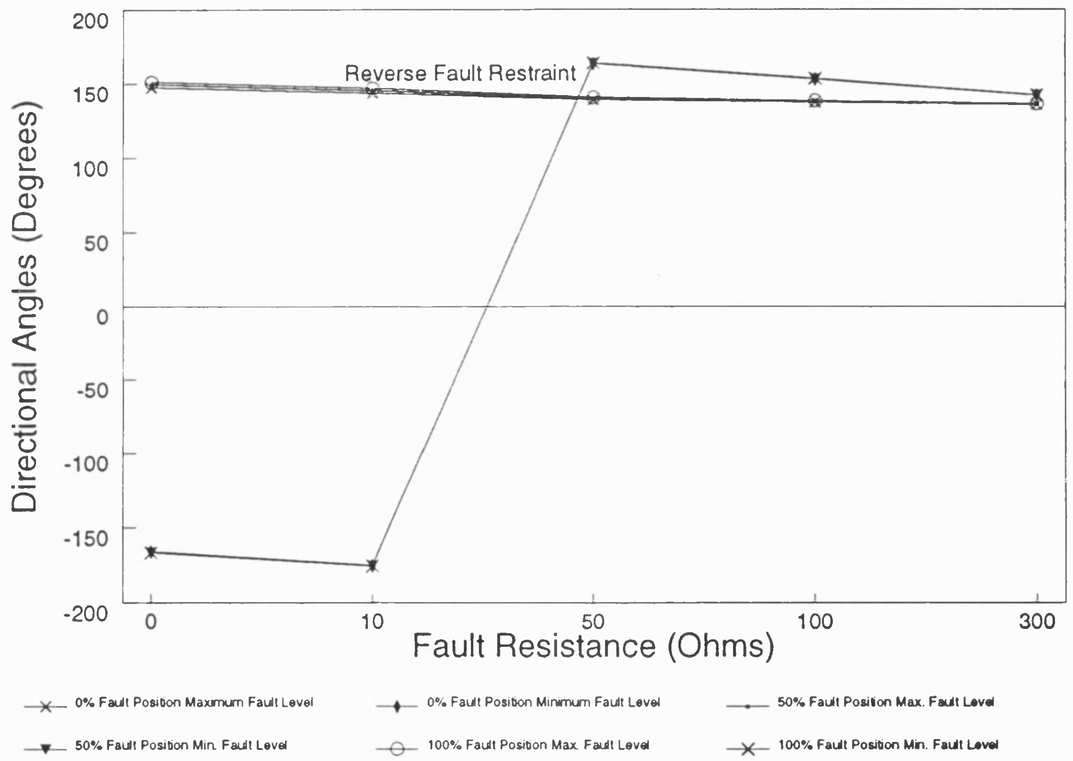
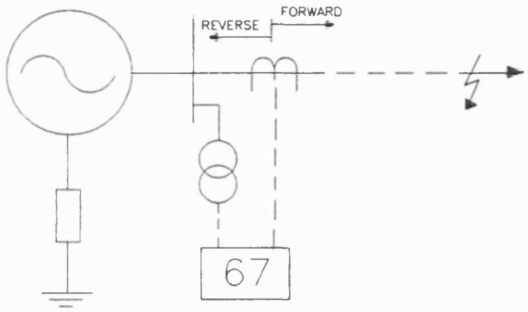



Figure 7.6.1.2.23 Variations of Directional Angle $\theta_C$ for Reverse Single-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.




33kV Underground Cable System

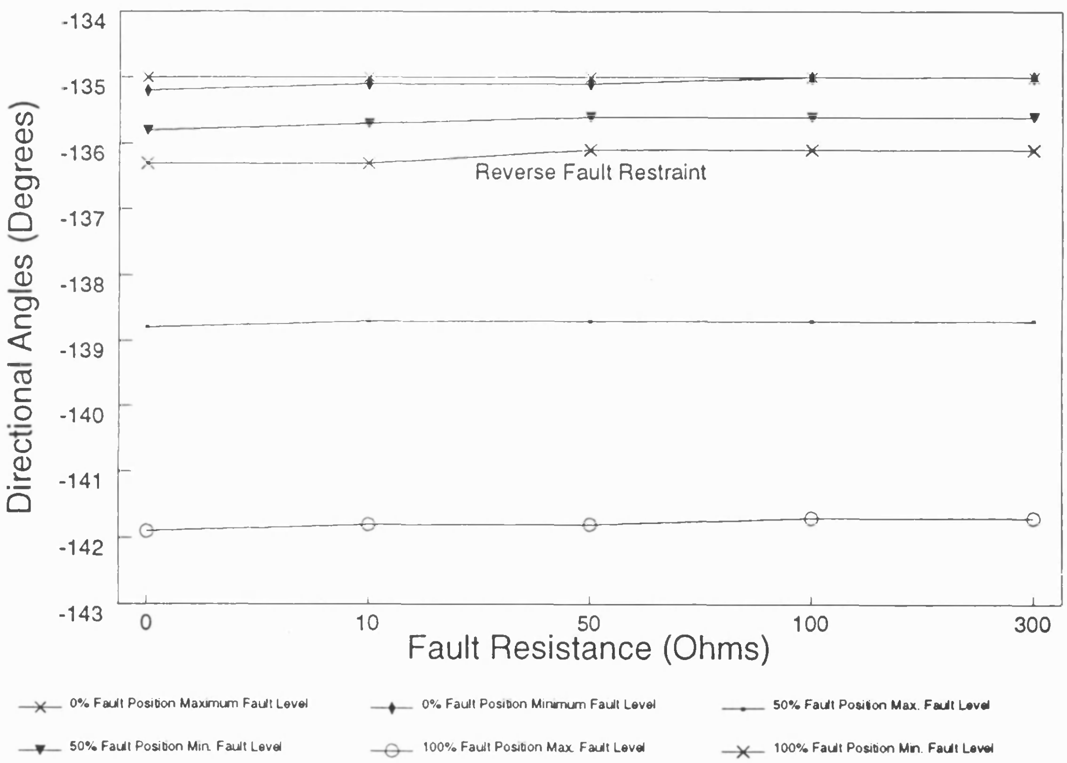


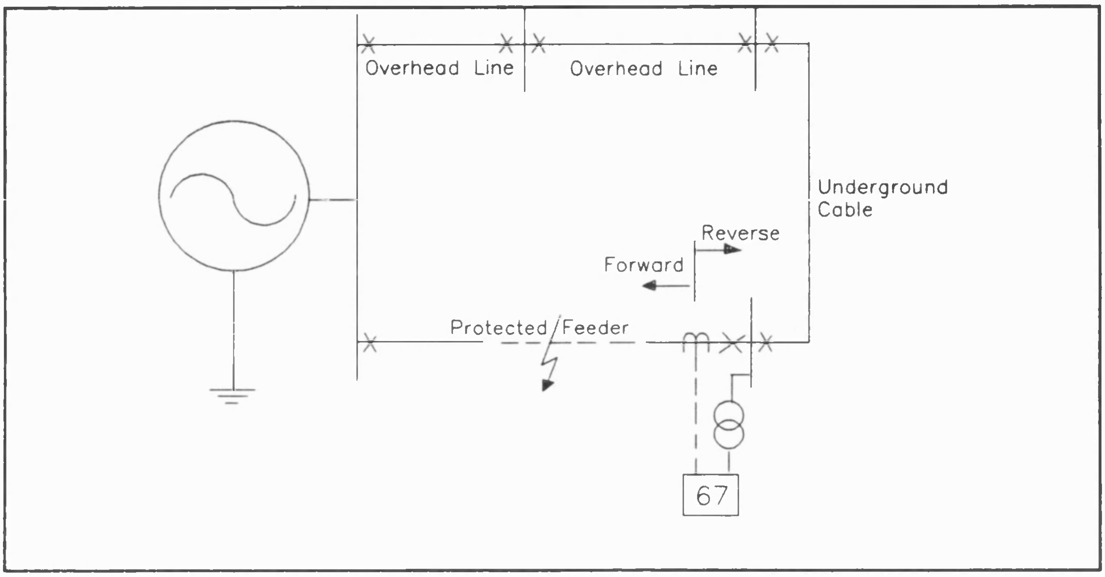

Figure 7.6.1.2.24 Variations of Directional Angle $\theta_C$ for Reverse Phase-phase-earth Faults seen by the Directional Relay with Fault Resistances at Different Fault Positions for Maximum and Minimum Fault Levels.

For the 33kV system shown the same observations as those for the 11kV system can be made. The apparent encroachment of the directional angle $\theta_C$ for reverse faults onto the operation limits of $\pm 90^0$ for this system also includes the results for the 3-phase reverse faults in addition to phase-phase and single-phase-earth reverse faults.

The values of the directional angle $\theta_C$ under the studied conditions fall within the defined limits for forward fault operation or for reverse fault restraint. The fault resistance coverage still maintains at the very high value of over 300Ω for all the types of faults.

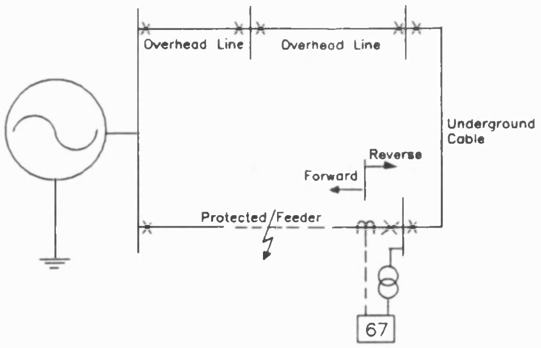
### 7.6.1.3 11kV Single Source Distribution Ring System of either Overhead Line or Underground Cable Feeder

The system is shown below:




This system is a very common configuration at distribution level. A directional relay 67 is arranged to protect a section of the ring as shown.

The directional angles $\theta_C$ for the various fault types under different fault conditions with variation in fault point positions along the protected feeder and fault resistances are presented in Figures 7.6.1.3.1 to 7.6.1.3.16. The directional relay is arranged to detect the faults as forward and then reverse faults. The results for the protected feeder being both overhead line and underground cable are presented.




11kV Distribution Ring System Protecting an Overhead Line Feeder

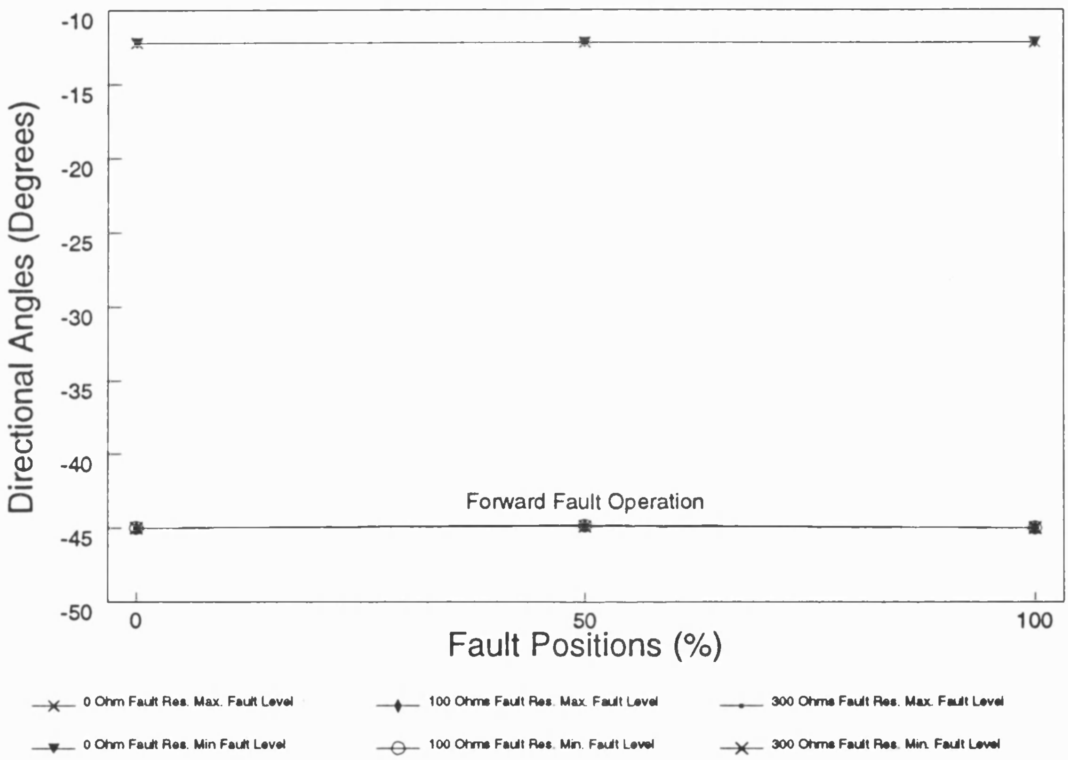
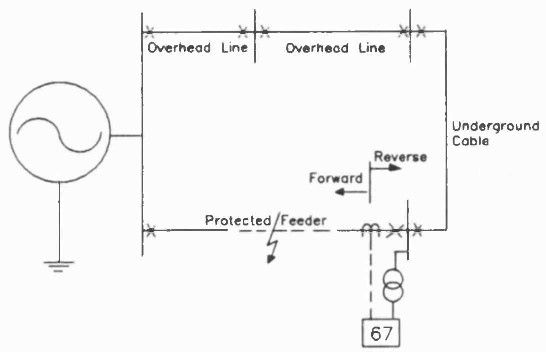



Figure 7.6.1.3.1 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for 3-phase Faults with the Directional Relay arranged to detect the Faults as Forward Faults.




11kV Distribution Ring System Protecting an Overhead Line Feeder

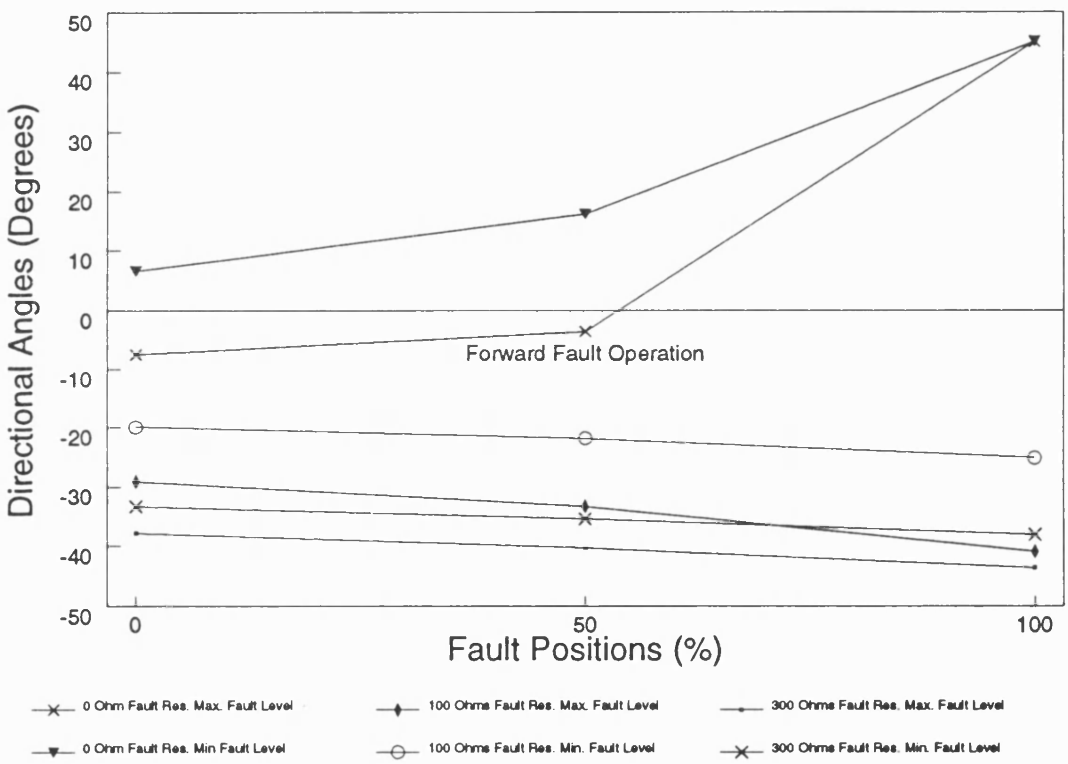
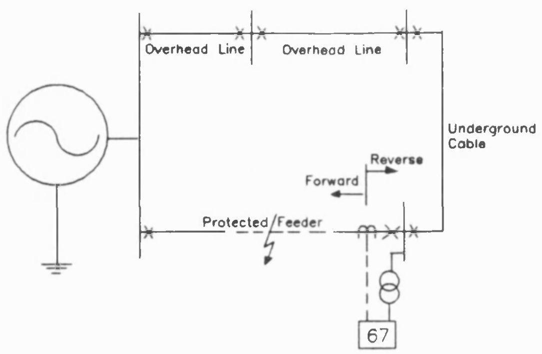



Figure 7.6.1.3.2 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for Phase-phase Faults with the Directional Relay arranged to detect the Faults as Forward Faults.




11kV Distribution Ring System Protecting an Overhead Line Feeder

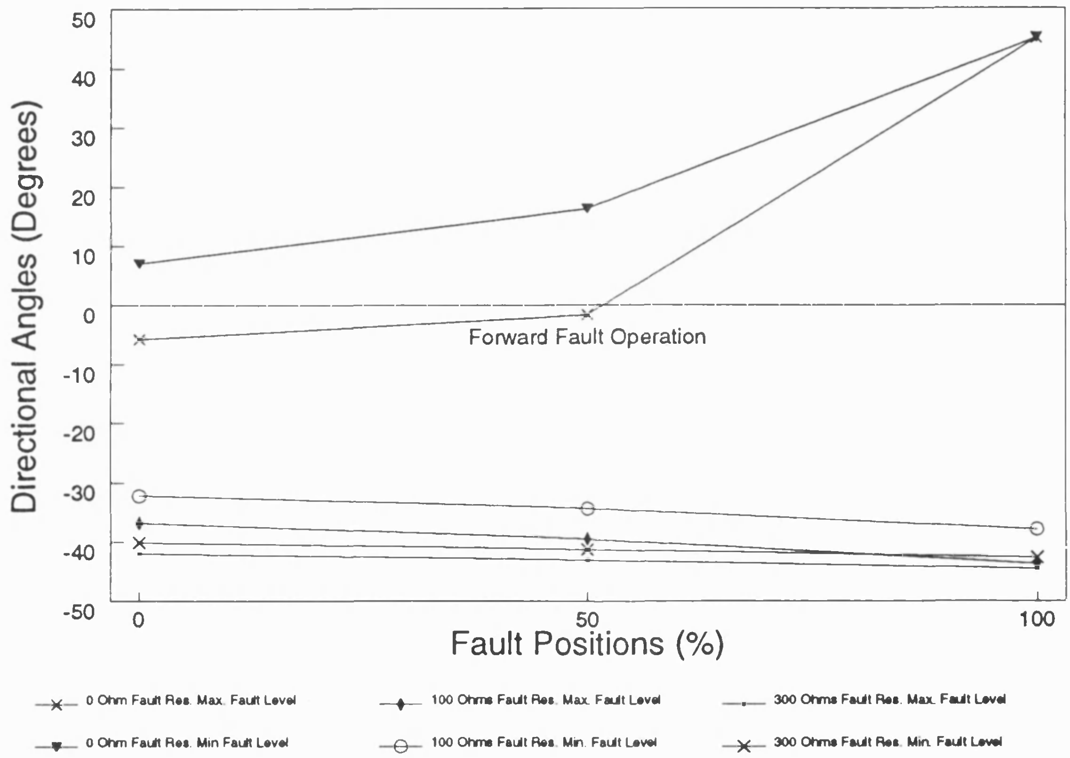
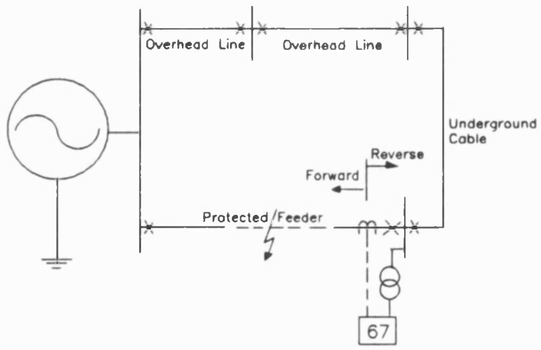



Figure 7.6.1.3.3 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for Single-phase-earth Faults with the Directional Relay arranged to detect the Faults as Forward Faults.




11kV Distribution Ring System Protecting an Overhead Line Feeder

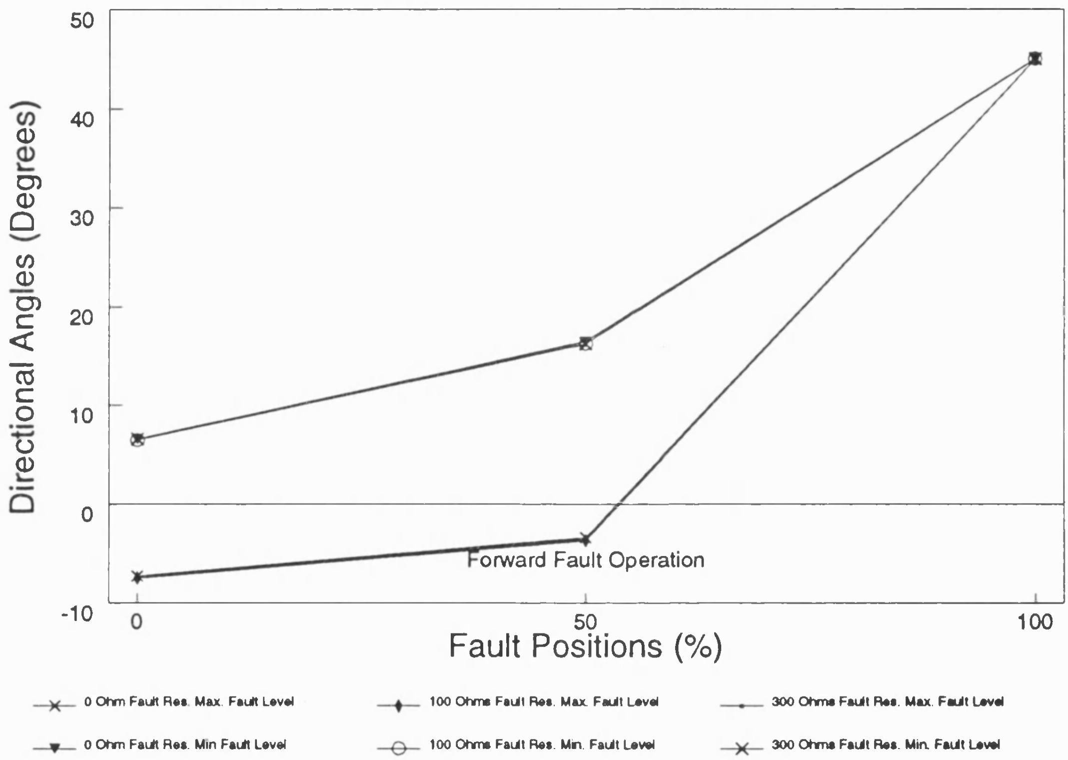
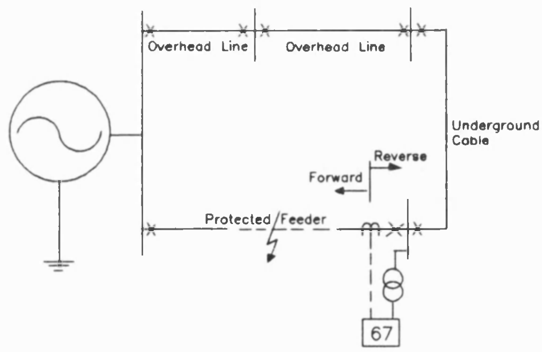



Figure 7.6.1.3.4 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for Phase-phase-earth Faults with the Directional Relay arranged to detect the Faults as Forward Faults.




11kV Distribution Ring System Protecting an Overhead Line Feeder

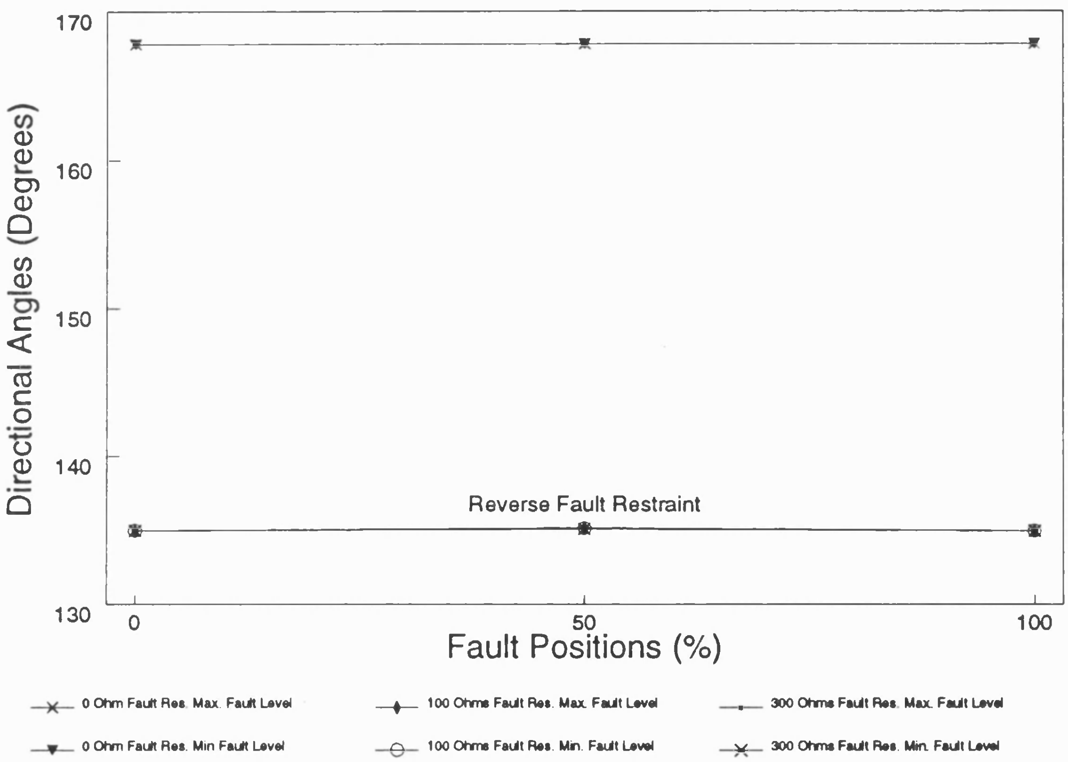
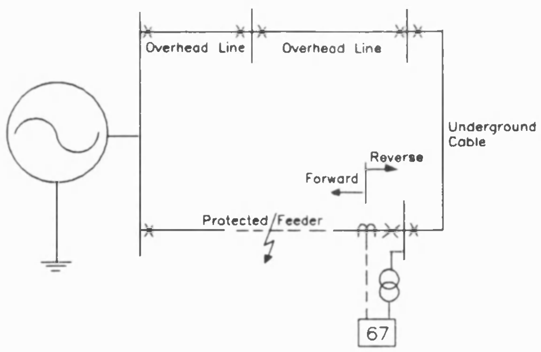



Figure 7.6.1.3.5 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for 3-phase Faults with the Directional Relay arranged to detect the Faults as Reverse Faults.




11kV Distribution Ring System Protecting an Overhead Line Feeder

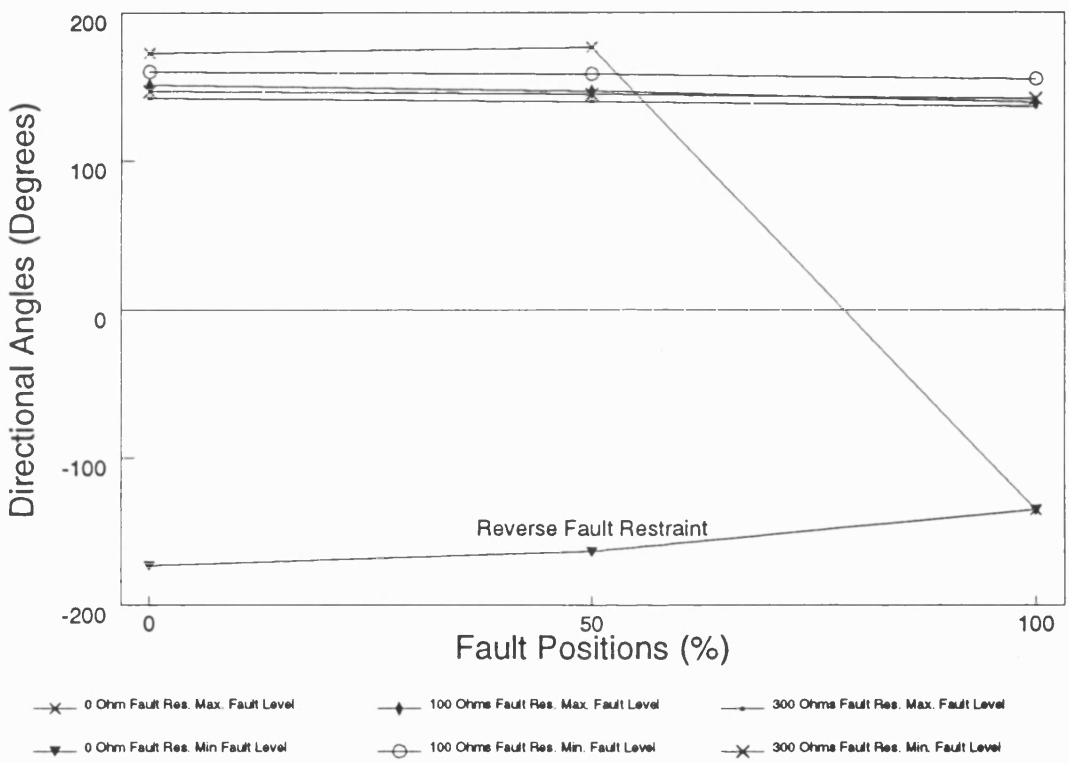
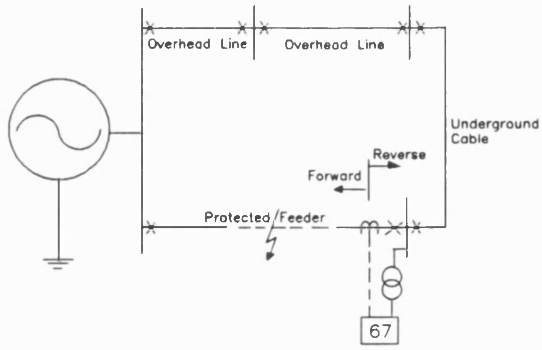



Figure 7.6.1.3.6 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for Phase-phase Faults with the Directional Relay arranged to detect the Faults as Reverse Faults.




11kV Distribution Ring System Protecting an Overhead Line Feeder

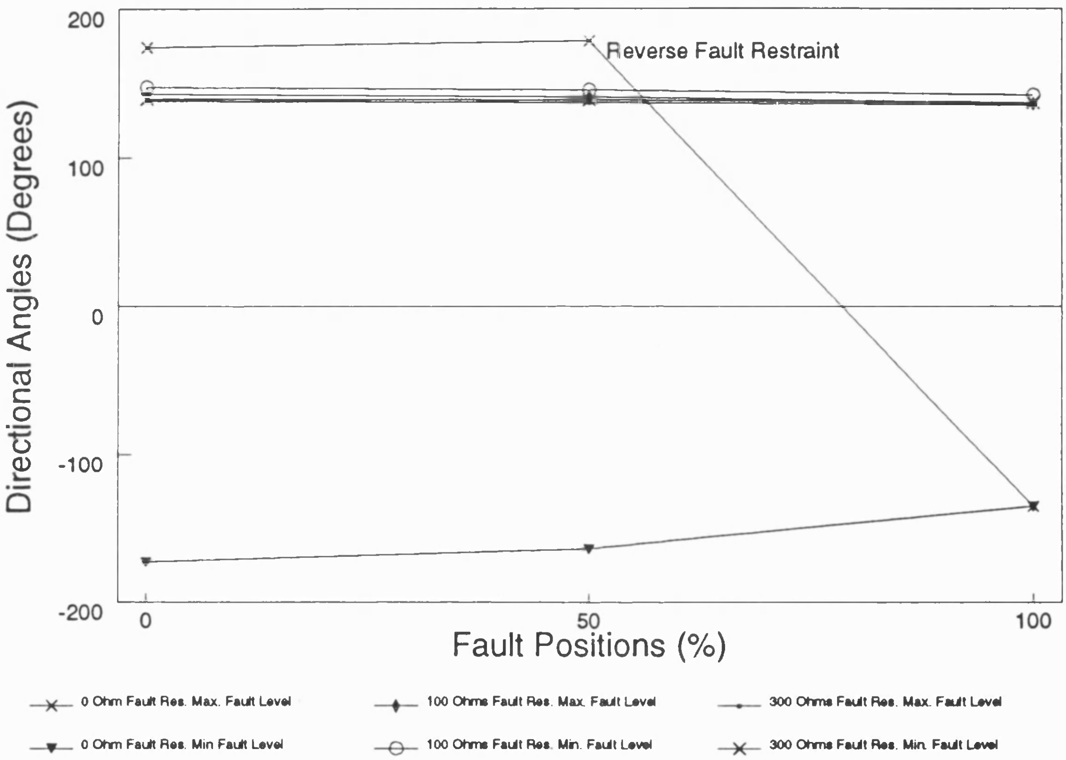
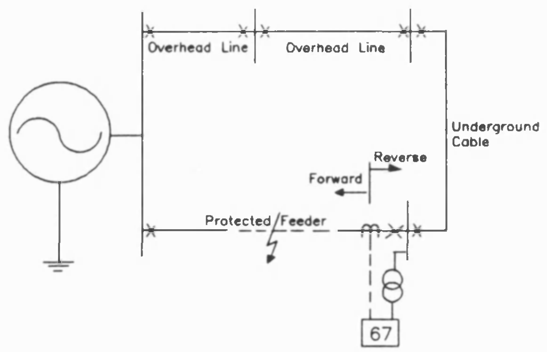



Figure 7.6.1.3.7 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for Single-phase-earth Faults with the Directional Relay arranged to detect the Faults as Reverse Faults.




11kV Distribution Ring System Protecting an Overhead Line Feeder

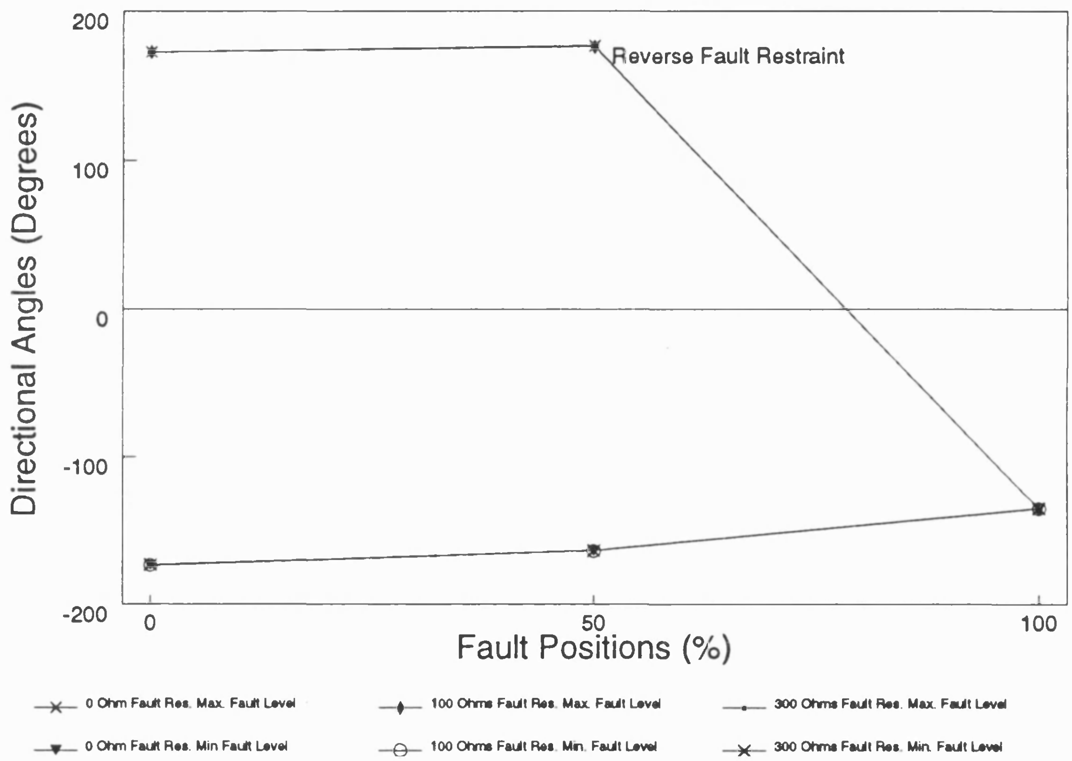
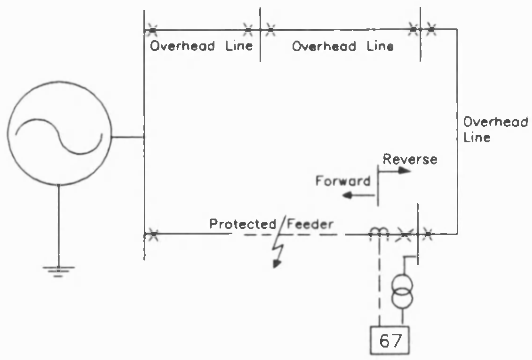



Figure 7.6.1.3.8 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for Phase-phase-earth Faults with the Directional Relay arranged to detect the Faults as Reverse Faults.




11kV Distribution Ring System Protecting an Underground Cable Feeder

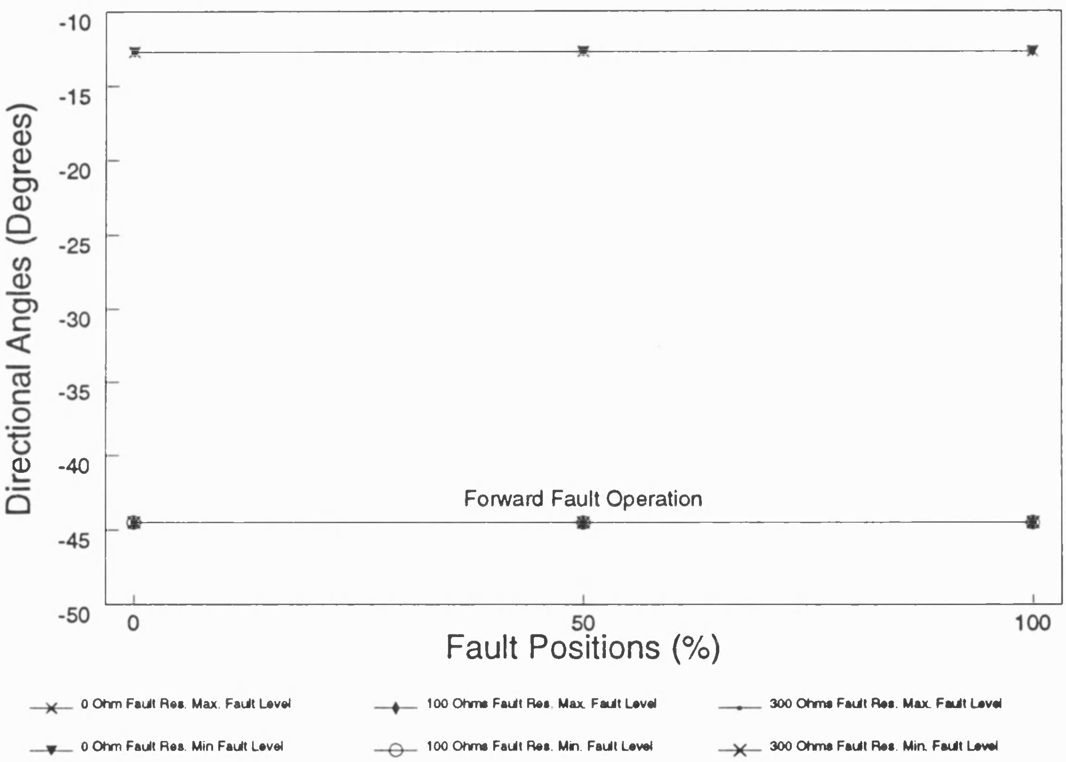
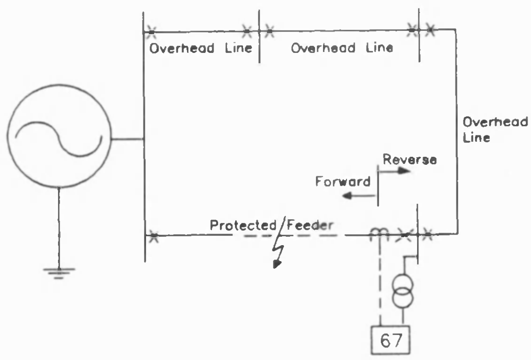



Figure 7.6.1.3.9 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for 3-phase Faults with the Directional Relay arranged to detect the Faults as Forward Faults.




11kV Distribution Ring System Protecting an Underground Cable Feeder

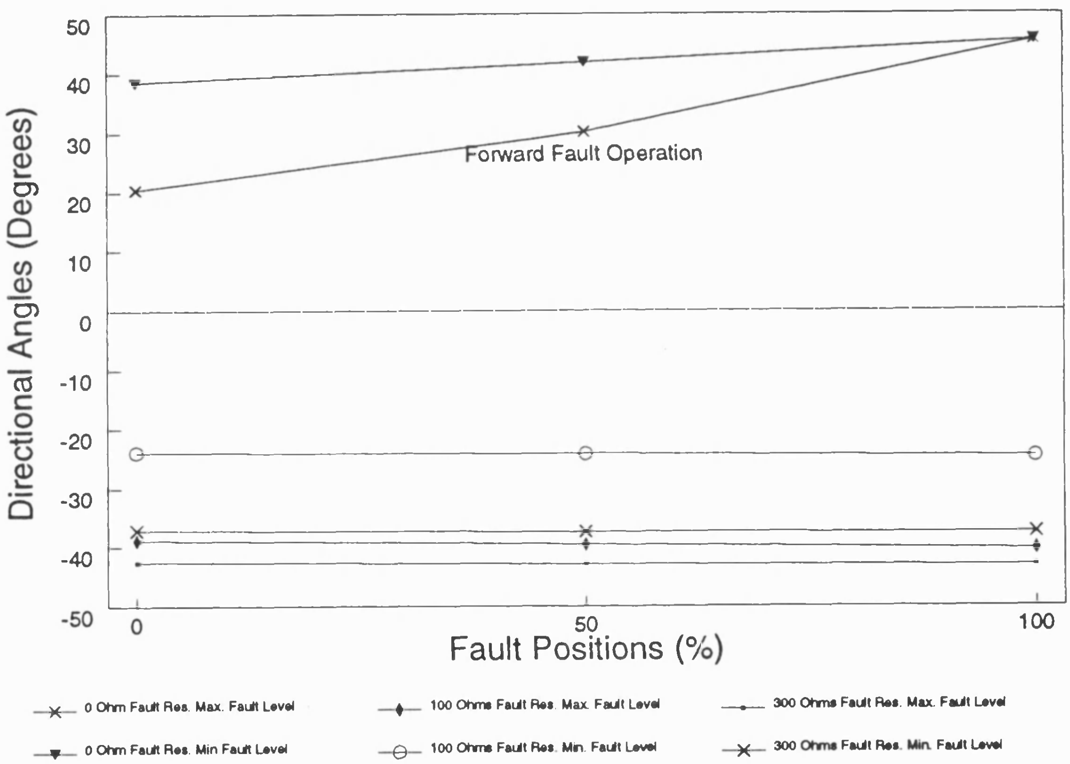
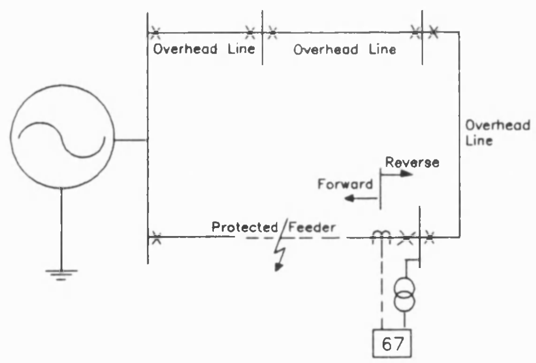



Figure 7.6.1.3.10 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for Phase-phase Faults with the Directional Relay arranged to detect the Faults as Forward Faults.




11kV Distribution Ring System Protecting an Underground Cable Feeder

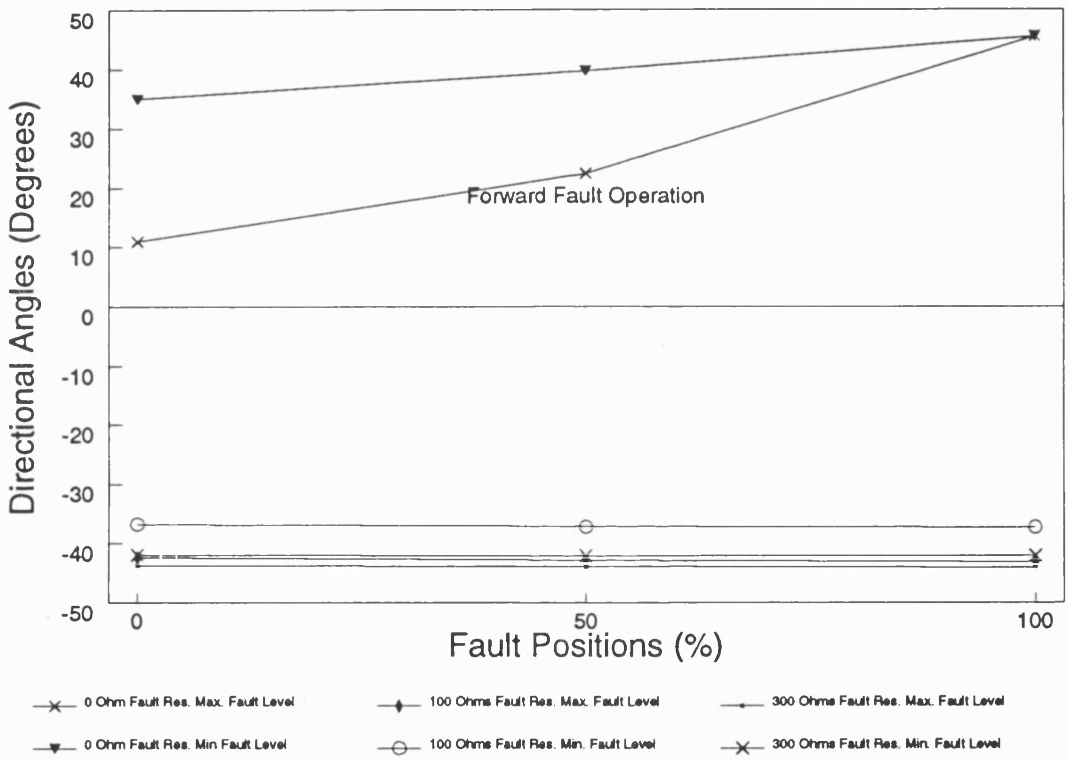
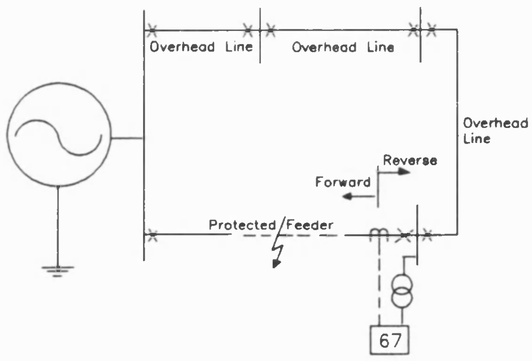



Figure 7.6.1.3.11 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for Single-phase-earth Faults with the Directional Relay arranged to detect the Faults as Forward Faults.




11kV Distribution Ring System Protecting an Underground Cable Feeder

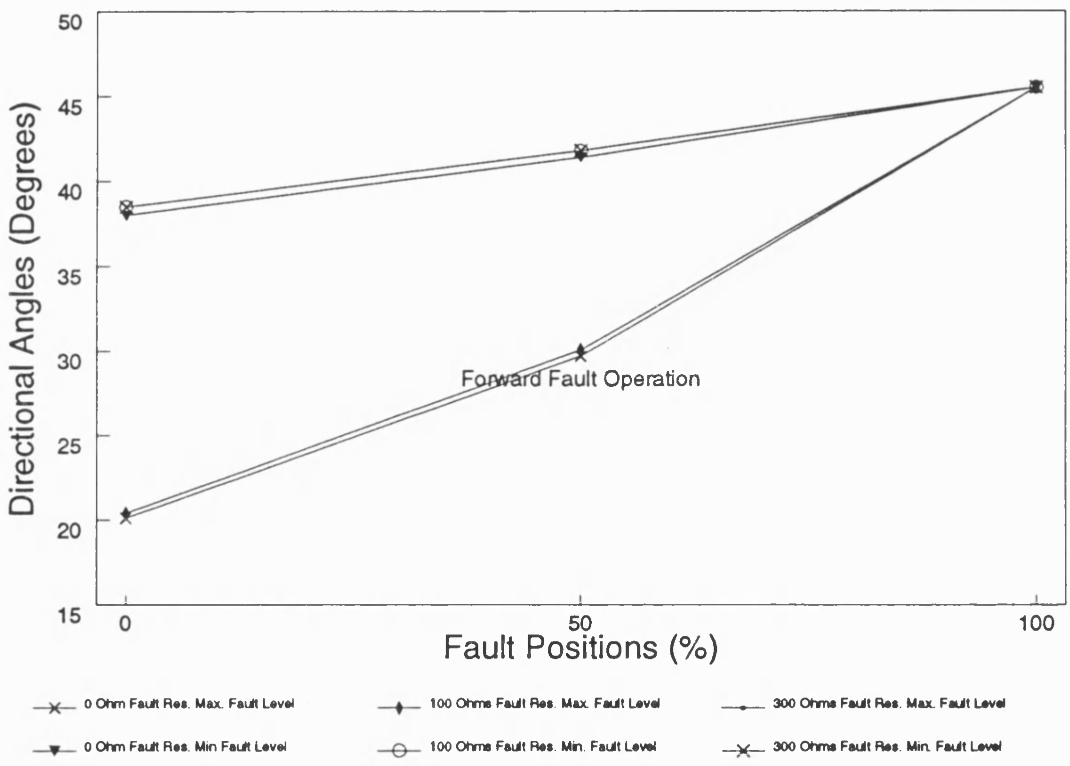
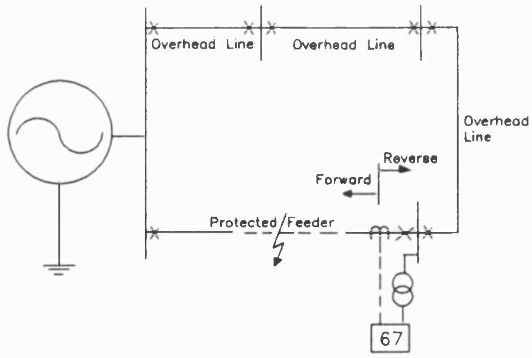



Figure 7.6.1.3.12 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for Phase-phase-earth Faults with the Directional Relay arranged to detect the Faults as Forward Faults.




11kV Distribution Ring System Protecting an Underground Cable Feeder

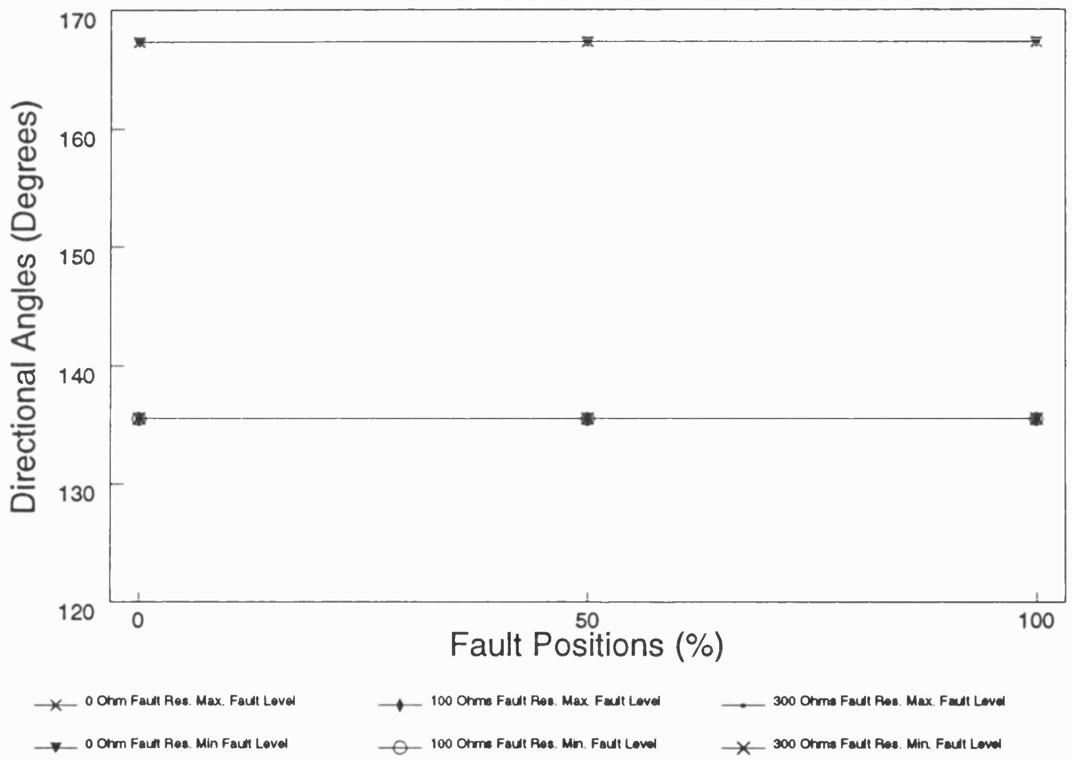
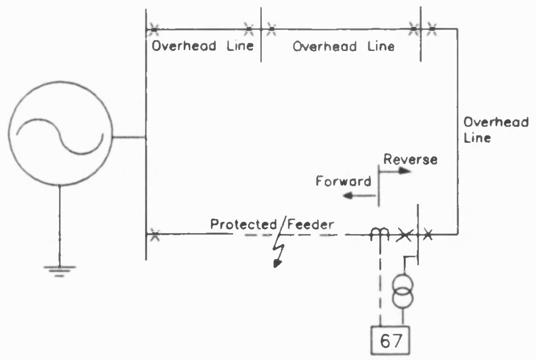



Figure 7.6.1.3.13 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for 3-phase Faults with the Directional Relay arranged to detect the Faults as Reverse Faults.




11kV Distribution Ring System Protecting an Underground Cable Feeder

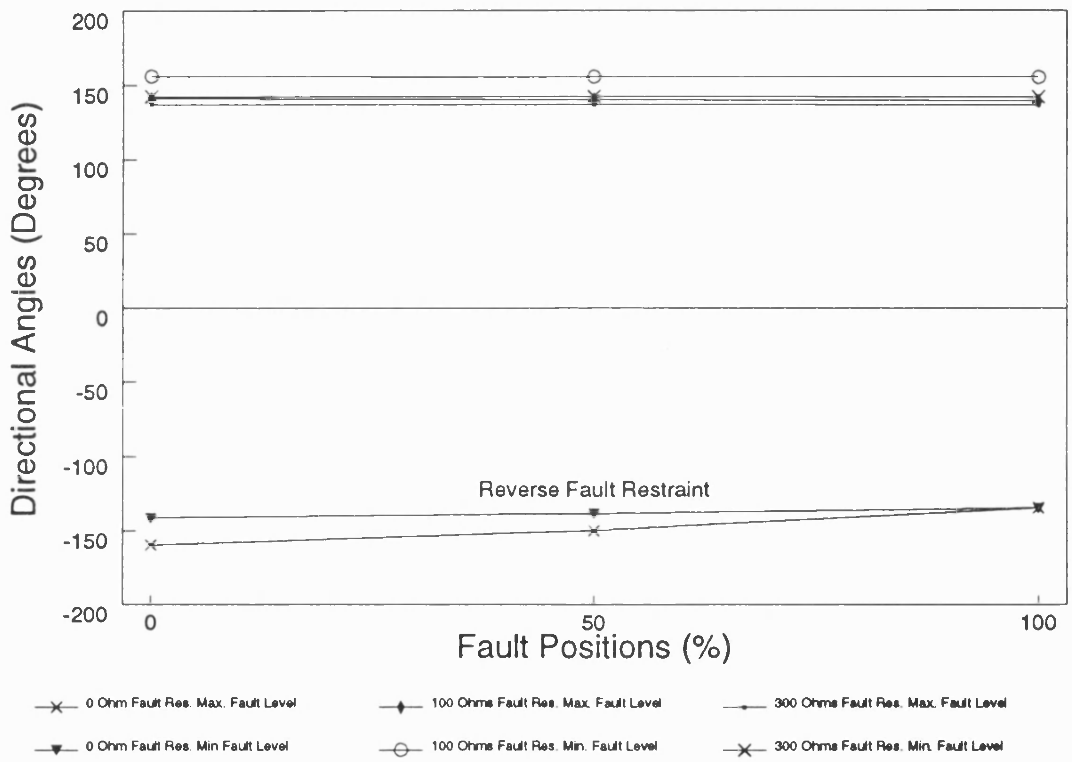
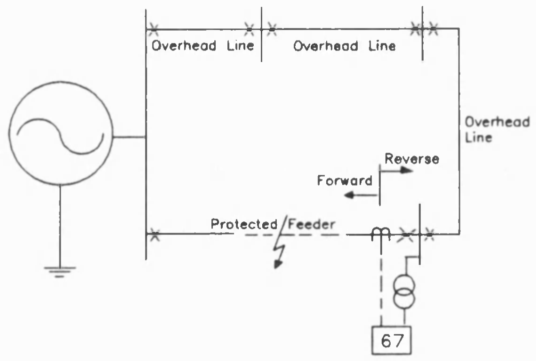



Figure 7.6.1.3.14 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for Phase-phase Faults with the Directional Relay arranged to detect the Faults as Reverse Faults.




11kV Distribution Ring System Protecting an Underground Cable Feeder

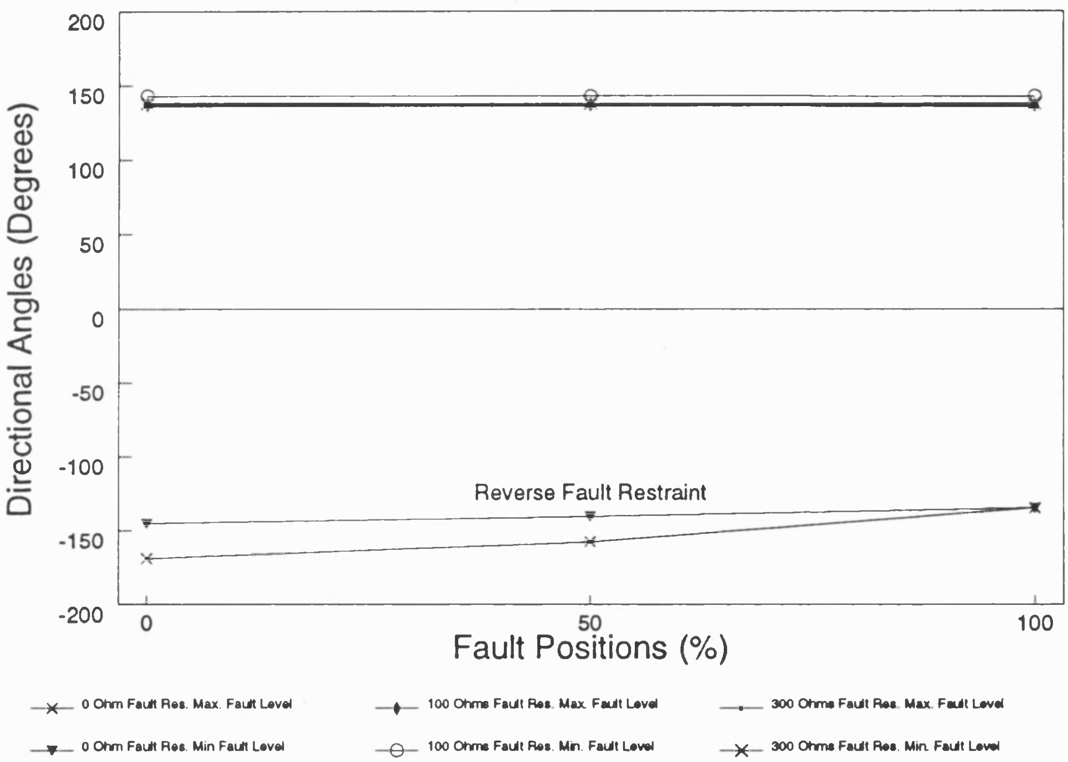
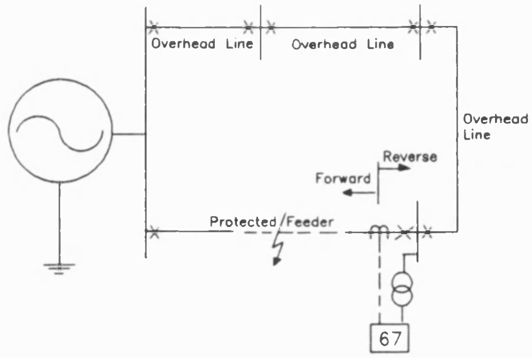



Figure 7.6.1.3.15 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for Single-phase-earth Faults with the Directional Relay arranged to detect the Faults as Reverse Faults.




11kV Distribution Ring System Protecting an Underground Cable Feeder

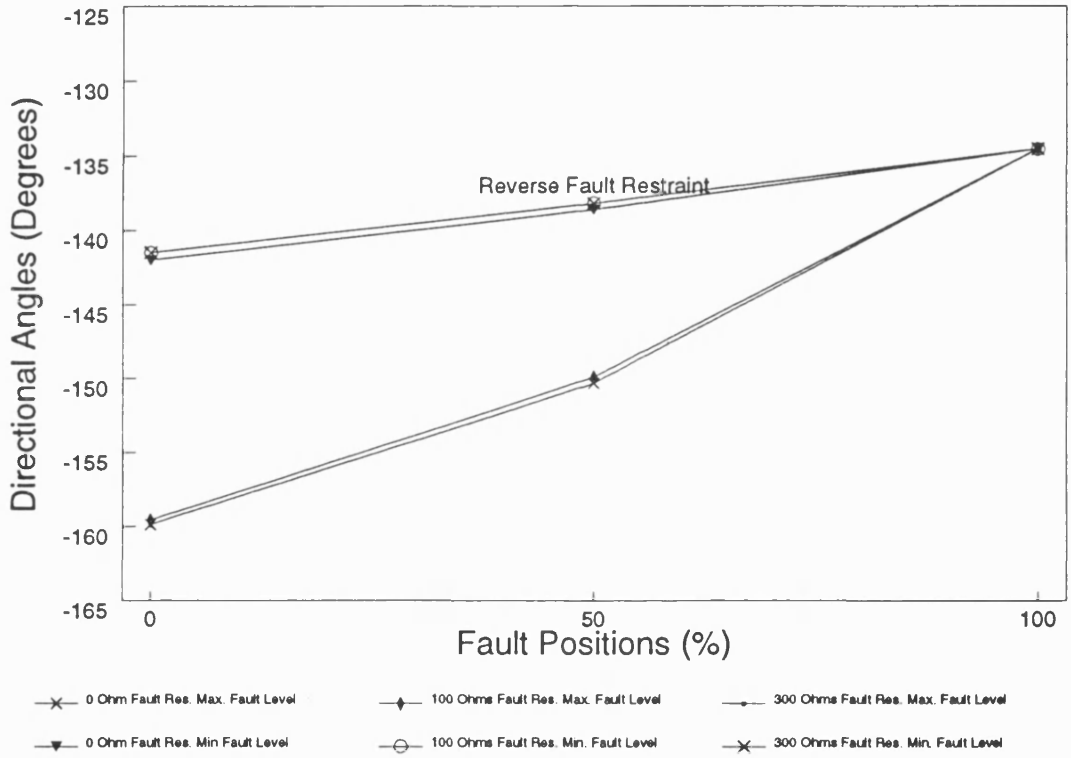



Figure 7.6.1.3.16 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances under Maximum and Minimum Fault Level Conditions for Phase-phase-earth Faults with the Directional Relay arranged to detect the Faults as Reverse Faults.

For the 11kV distribution ring system the following additional observations can be made:

- The values of the directional angle $\theta_C$ for forward and reverse faults fall within the defined limits by the new directional detection method for both forward fault operation and reverse fault restraint. The fault resistance detectable remains at the very high value of over 300Ω.

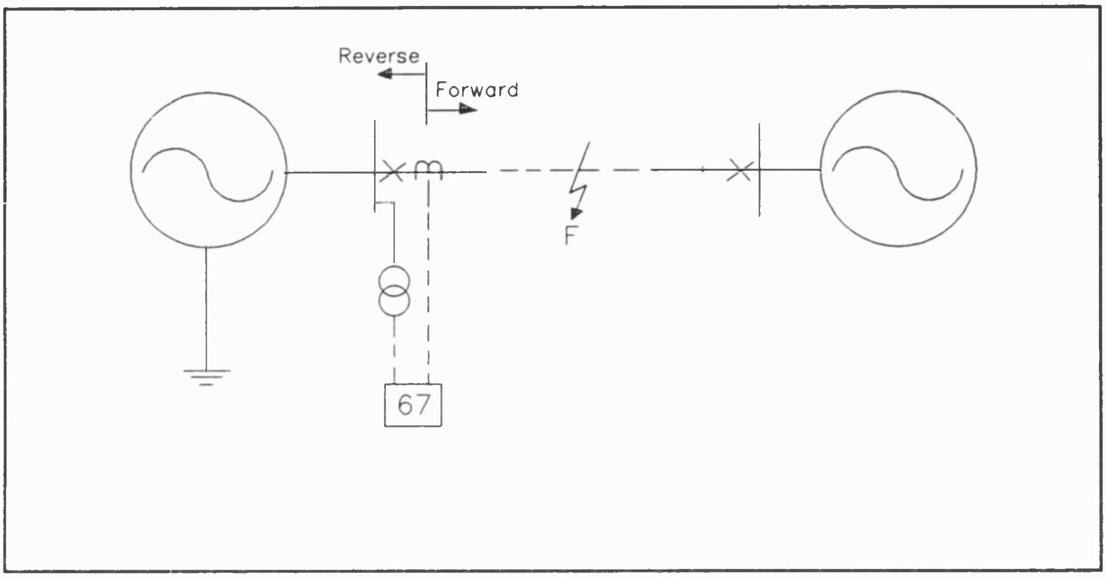
- For a given fault condition of fault position and fault resistance the magnitudes and the associated angles of the source have no effect on the values of the directional angle $\theta_C$.

- For 3-phase faults the fault levels and fault positions have very little effect on $\theta_C$.

- For phase-phase, single-phase-earth and phase-phase-earth reverse faults the apparent encroachment of the reverse directional angle $\theta_C$ onto the $\pm 90^0$ limits is because the angular values, being more than $+180^0$, are expressed as negative angles (e.g. $+200^0$ is expressed as $-160^0$) and the various points are joined by line graph.

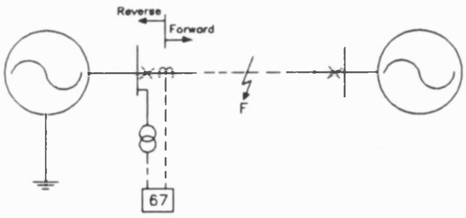
### 7.6.1.4 11KV Distribution System of either Overhead Line or Underground Cable Feeder with Sources at both Feeder Ends

The system is shown below:




This system provides tests for the capability of the new directional detection method to detect direction of faults with pre-fault load current flow. Though this system arrangement is not common at distribution levels the studies are to confirm the reliable detection of fault directions under all operating conditions.

The directional angles $\theta_C$ for the various fault types under different fault conditions with and without pre-fault load current flow are presented in Figures 7.6.1.4.1 to 7.6.1.4.16 with variations in fault positions and fault resistances.




11KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

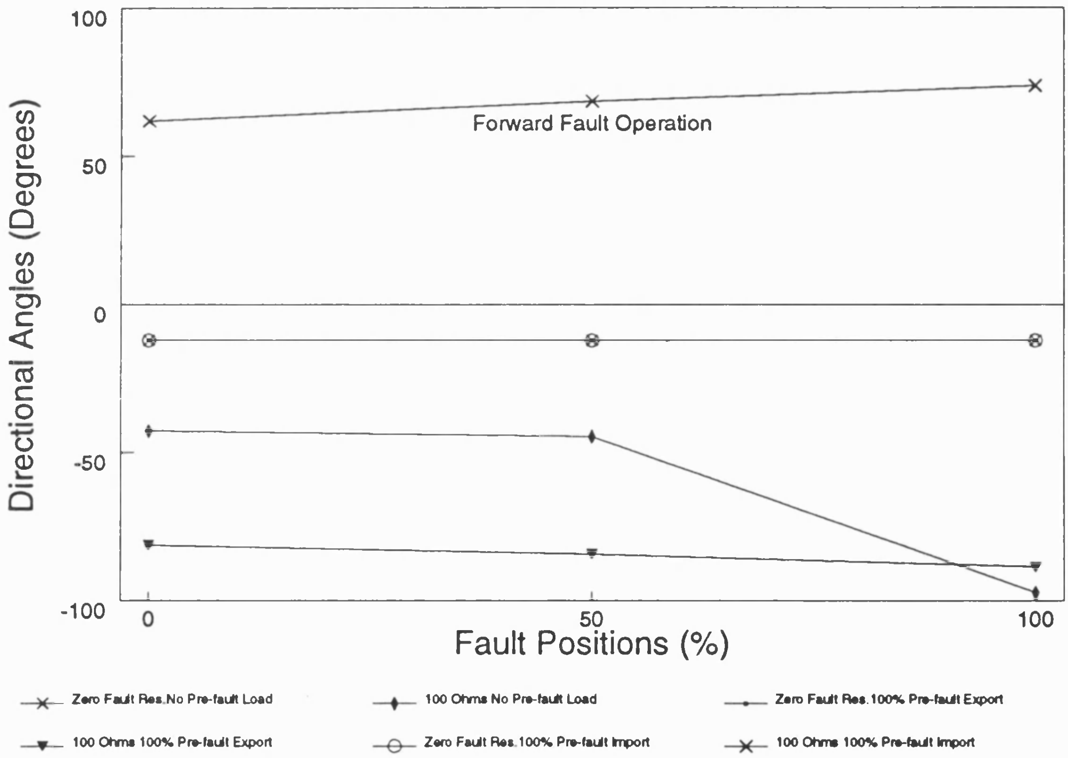
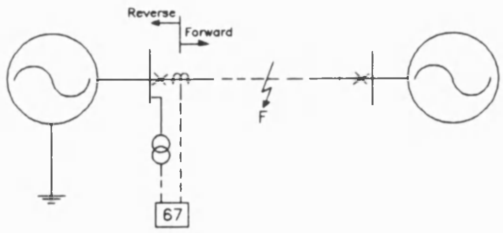



Figure 7.6.1.4.1 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




11KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

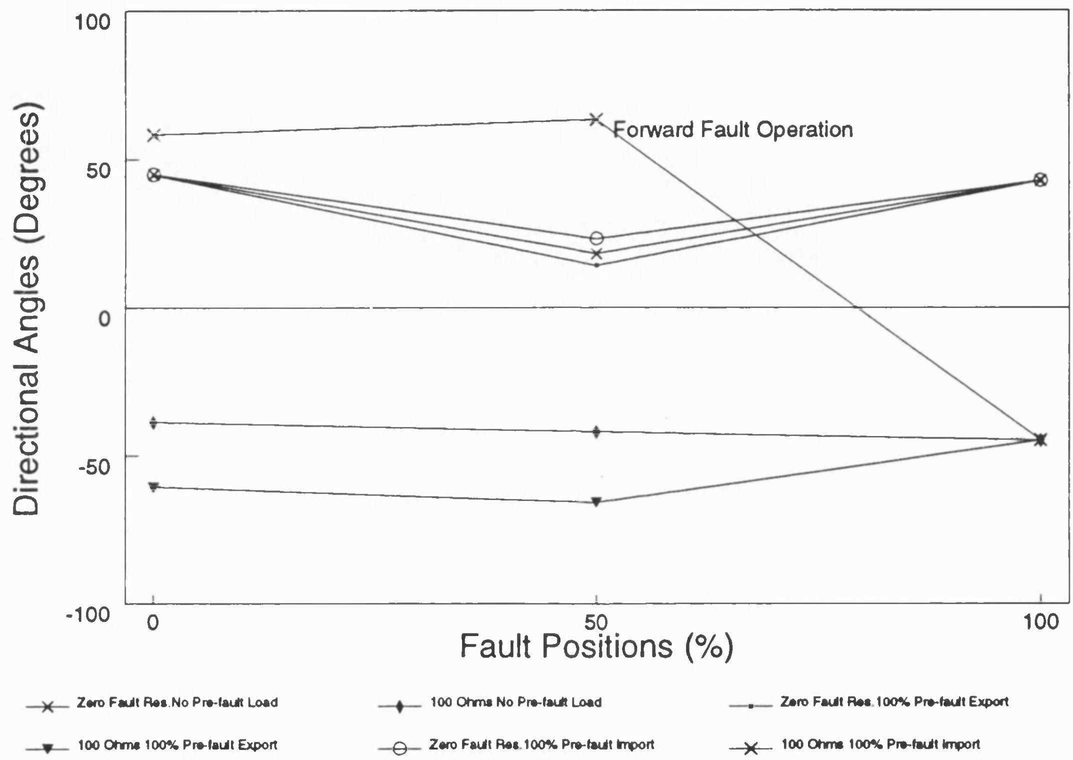
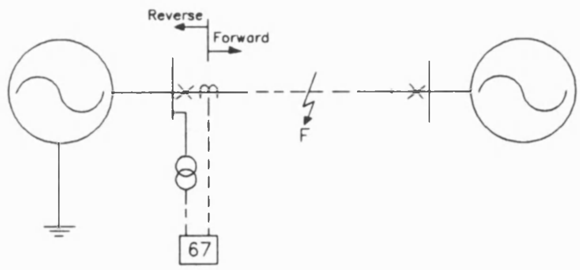



Figure 7.6.1.4.2 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




11KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

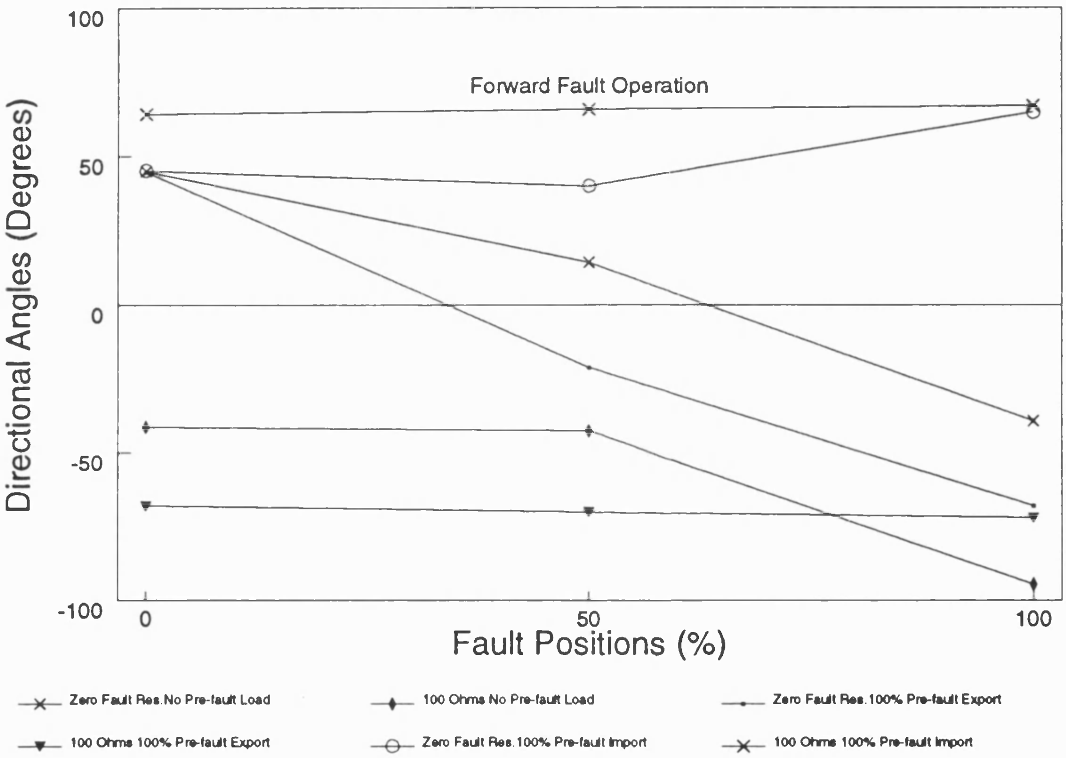
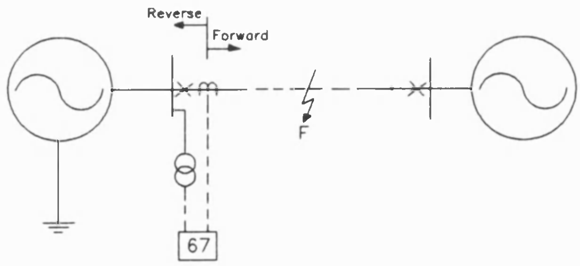



Figure 7.6.1.4.3 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




11KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

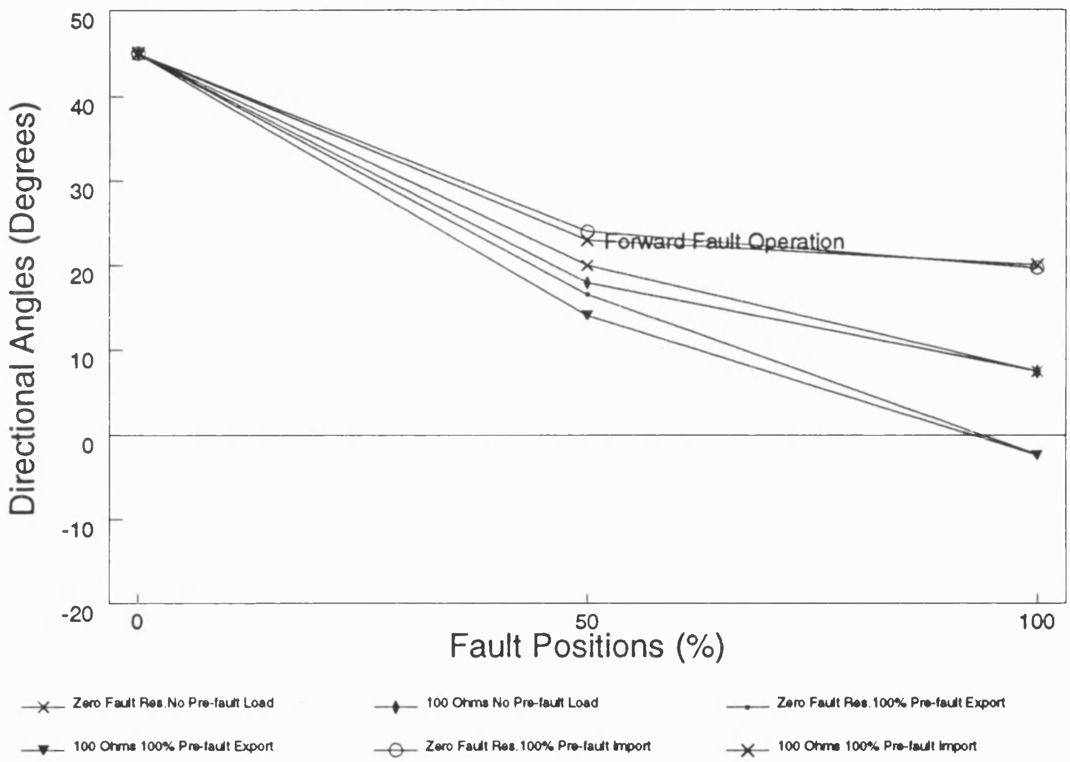
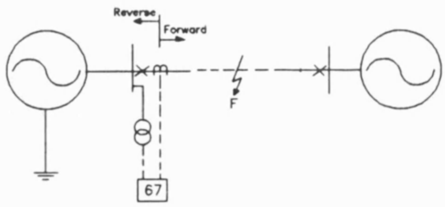



Figure 7.6.1.4.4 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




11KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

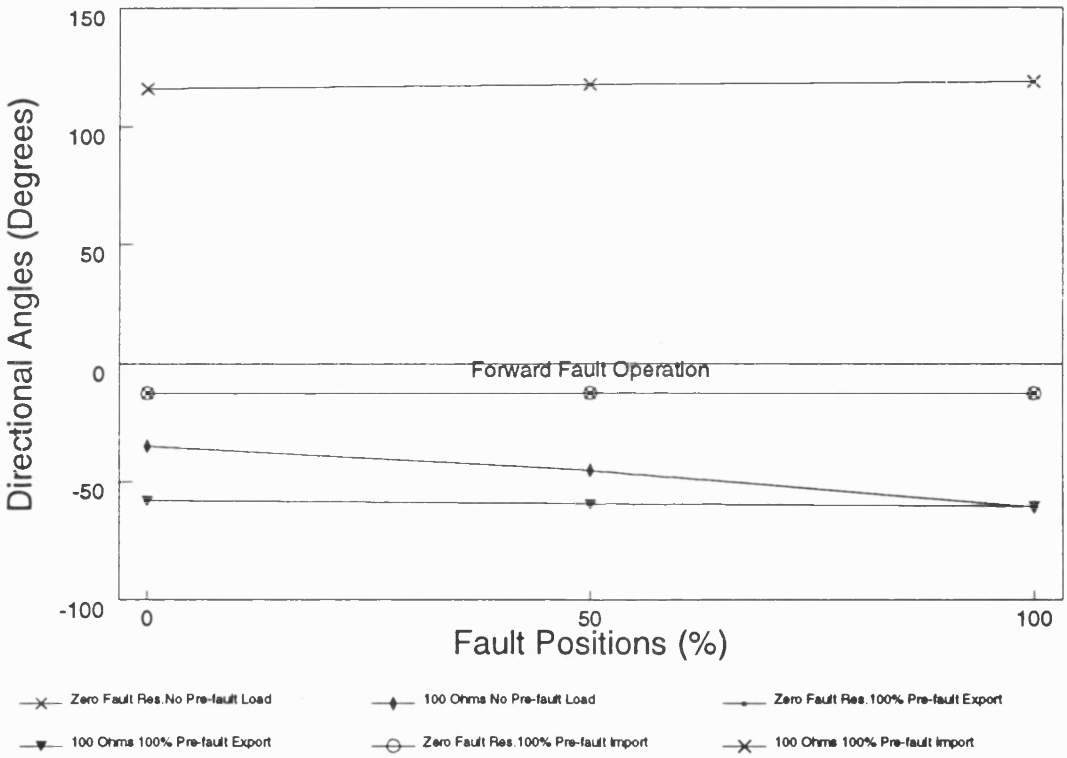
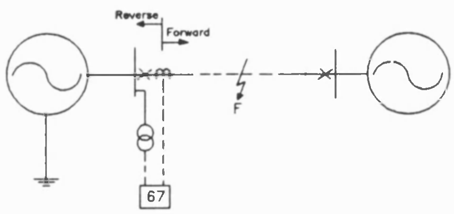



Figure 7.6.1.4.5 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




11KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

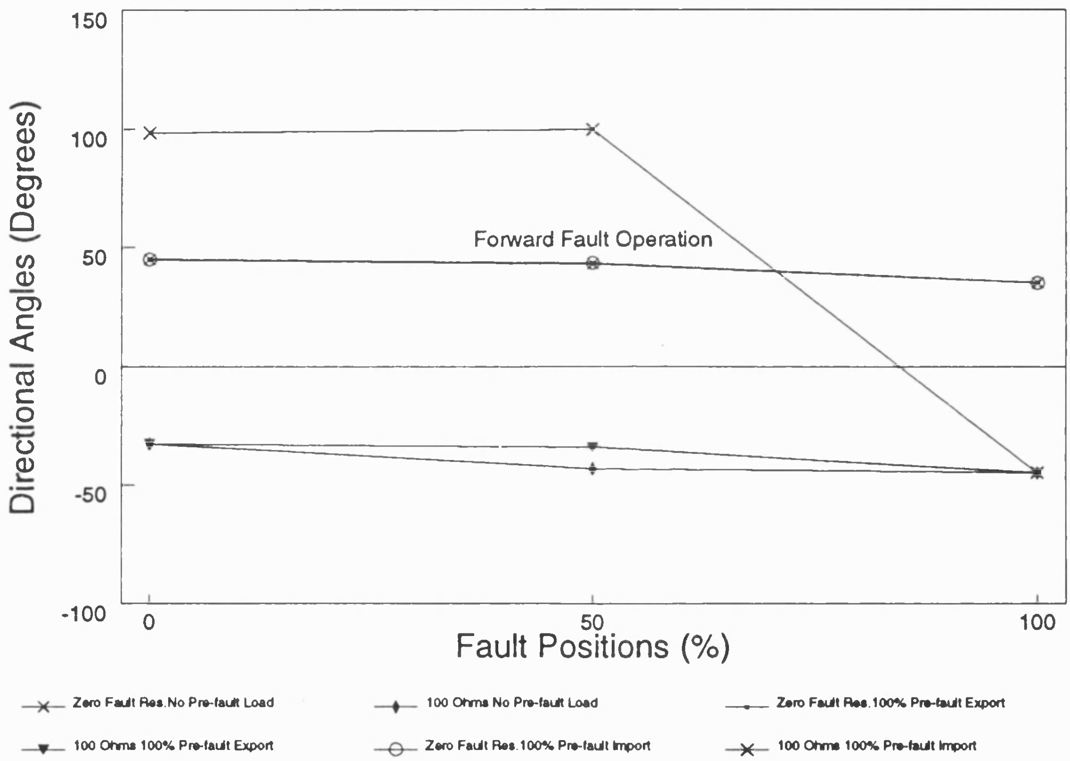
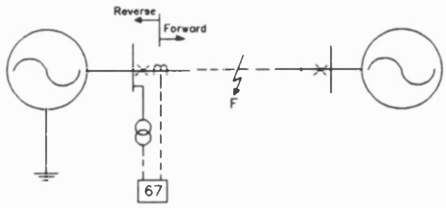



Figure 7.6.1.4.6 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




11KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

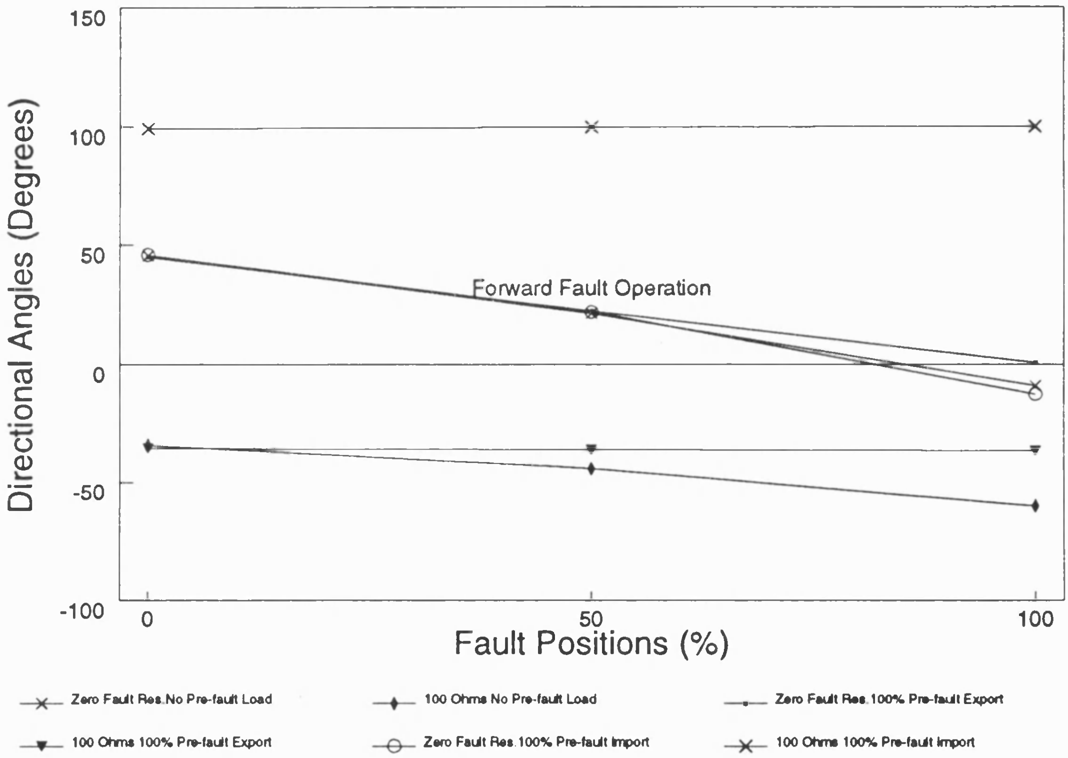
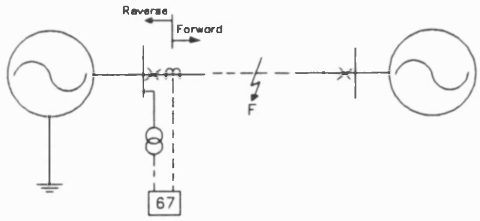



Figure 7.6.1.4.7 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




11KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

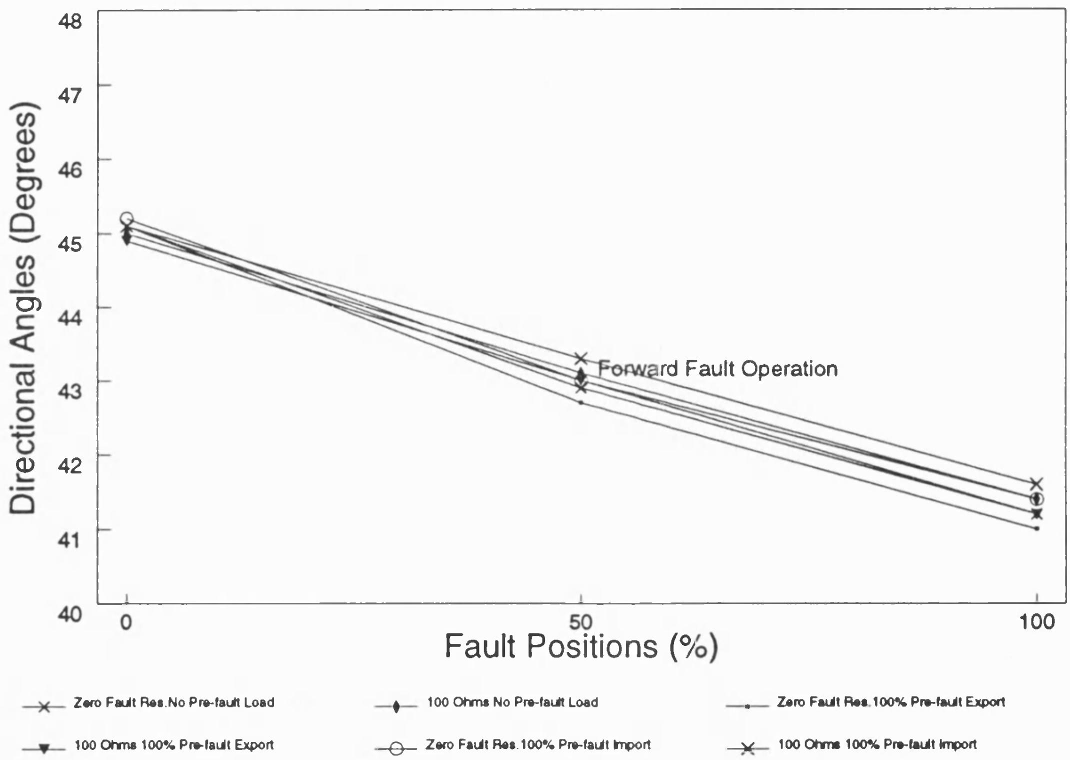
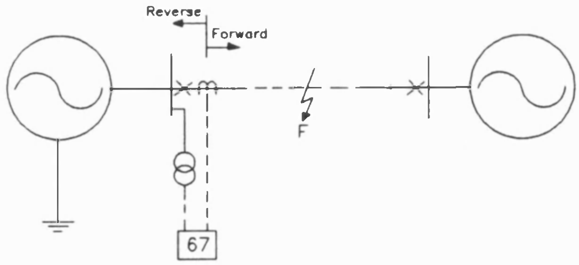



Figure 7.6.1.4.8 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




11KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

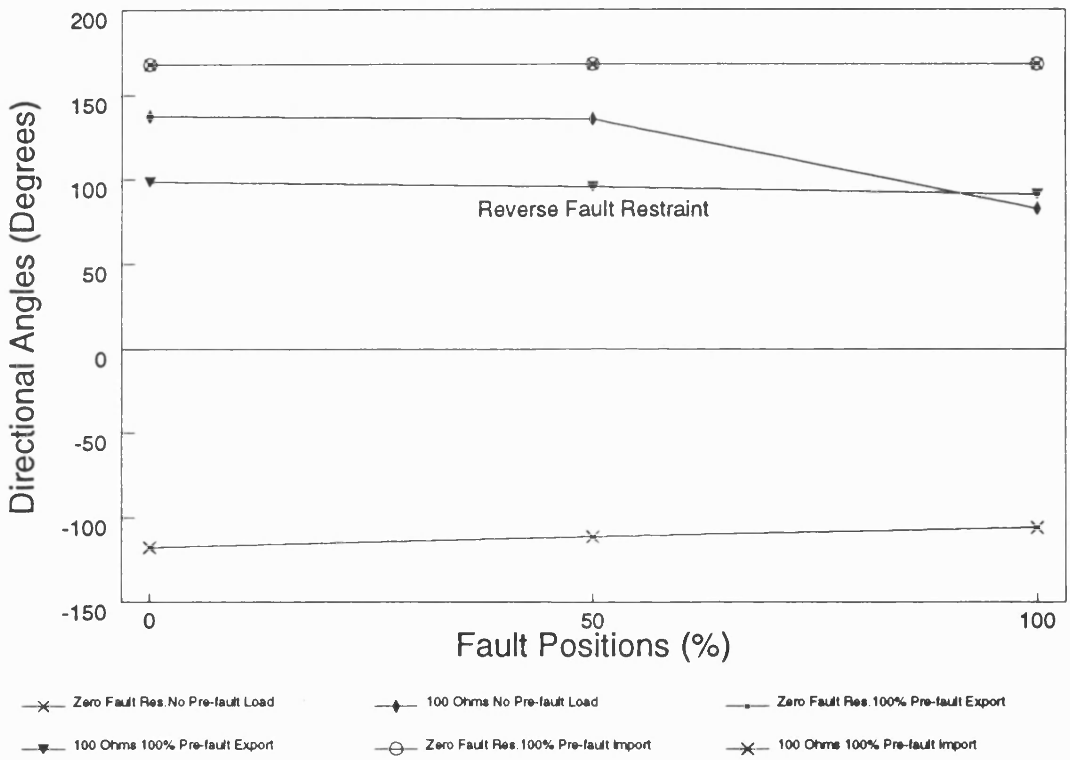
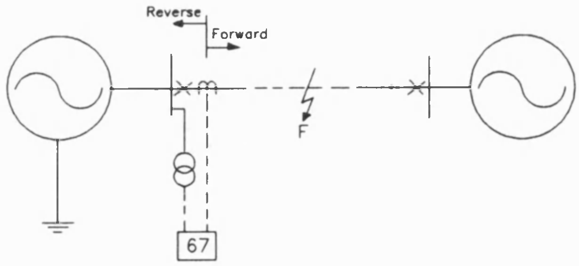



Figure 7.6.1.4.9 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.




11KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

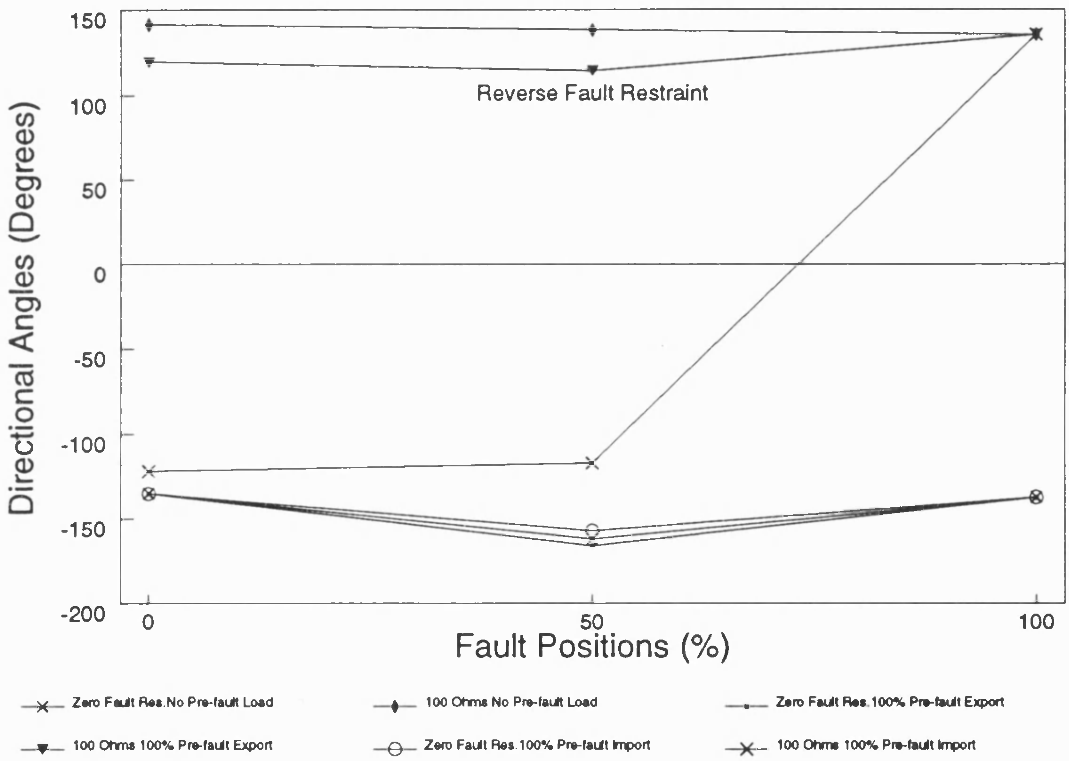
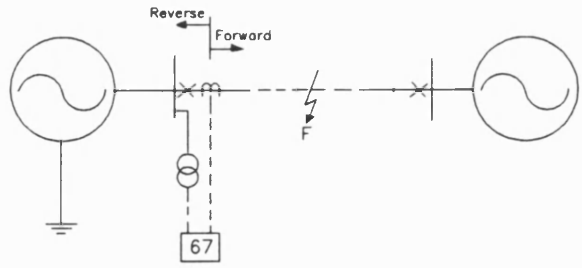



Figure 7.6.1.4.10 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.




11KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

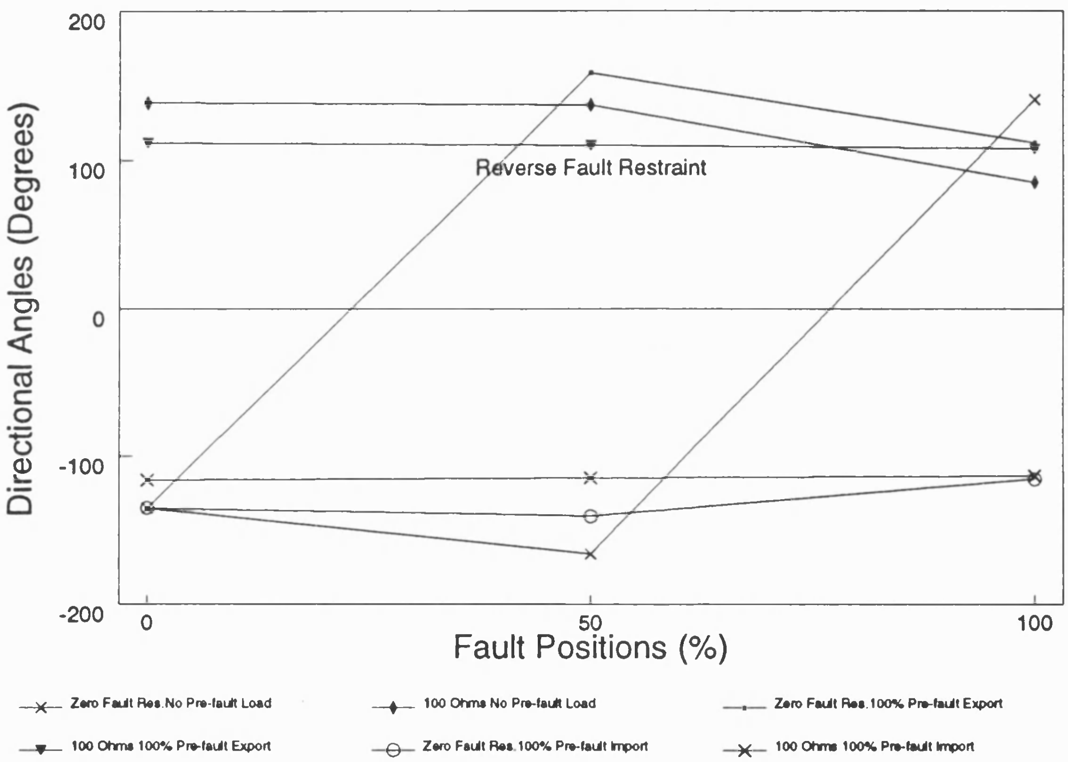
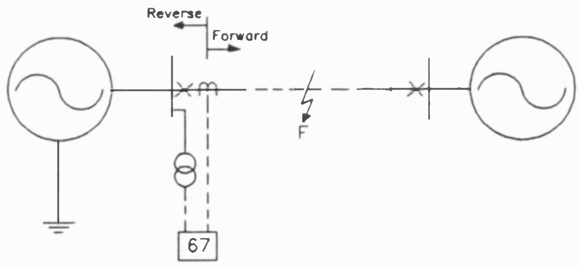



Figure 7.6.1.4.11 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.




11KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

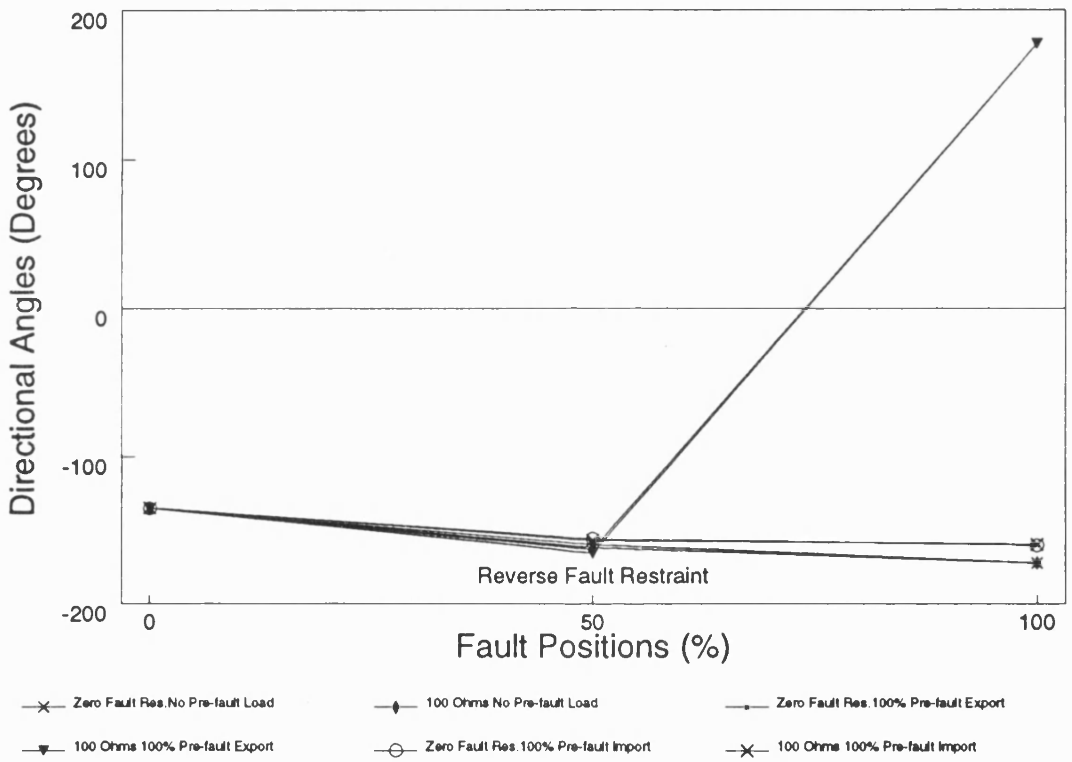
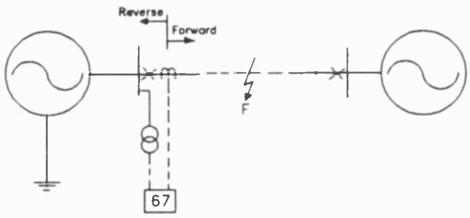



Figure 7.6.1.4.12 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.




11KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

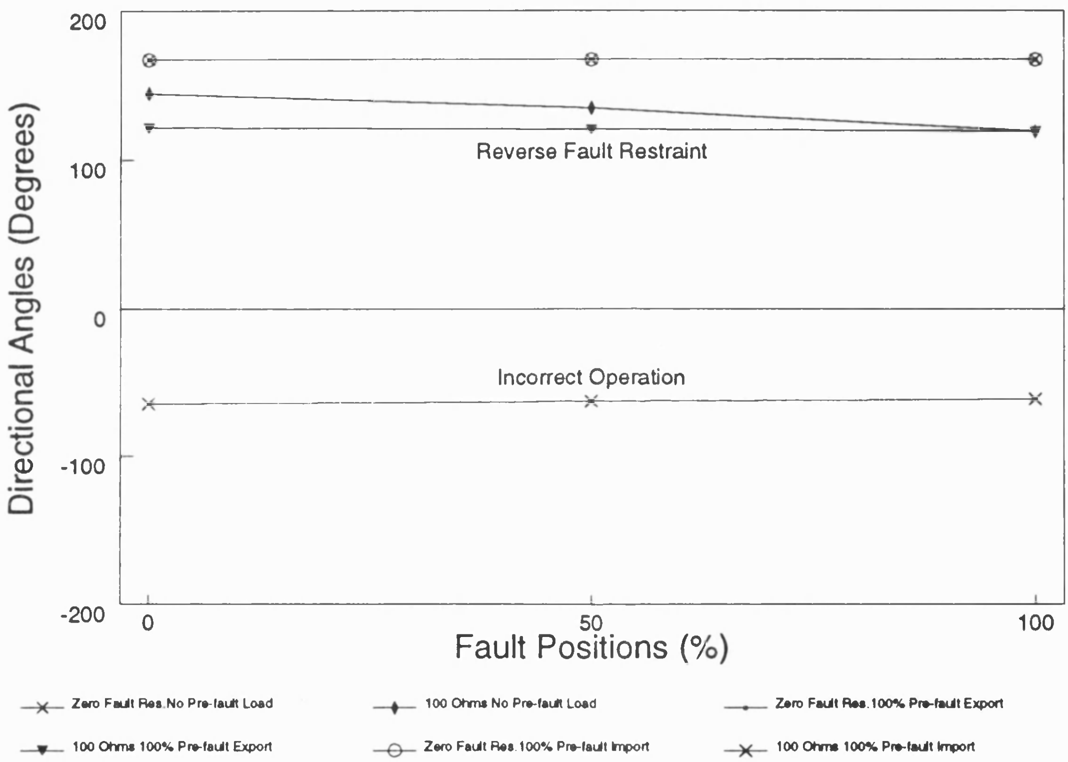
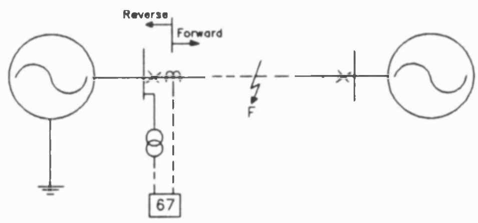



Figure 7.6.1.4.13 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.




11KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

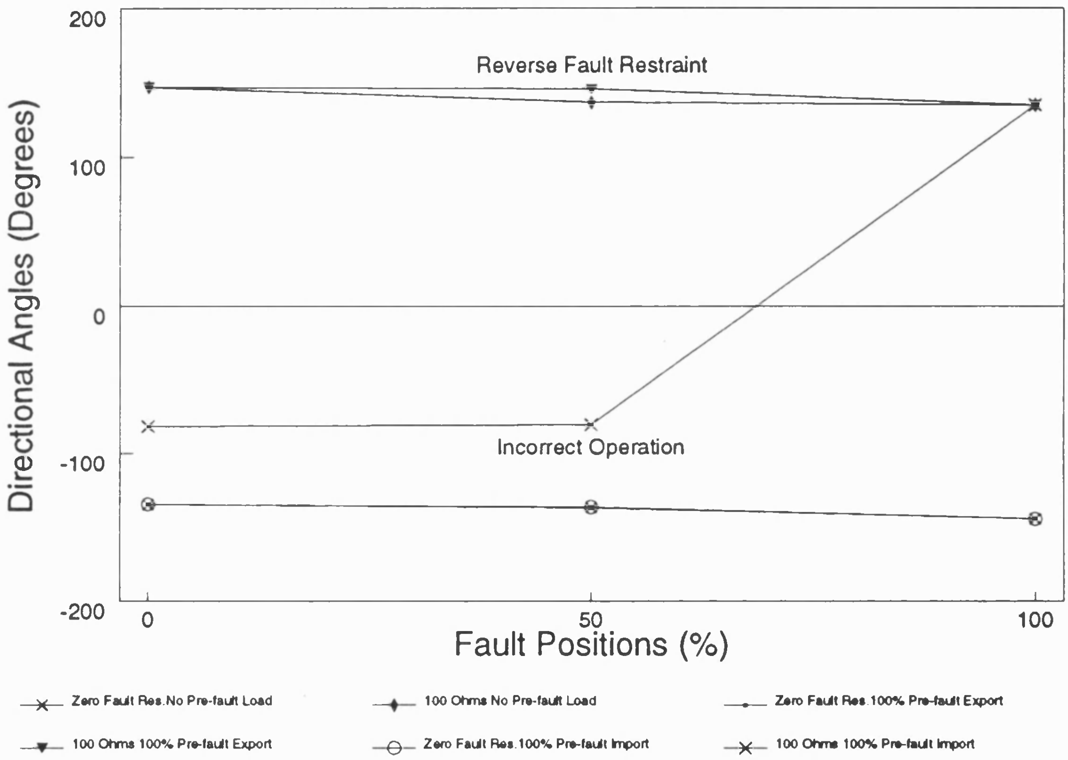
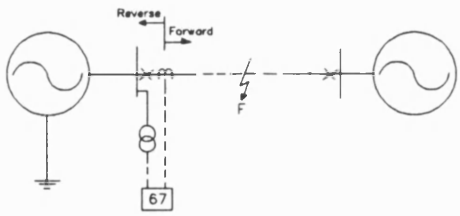



Figure 7.6.1.4.14 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.




11KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

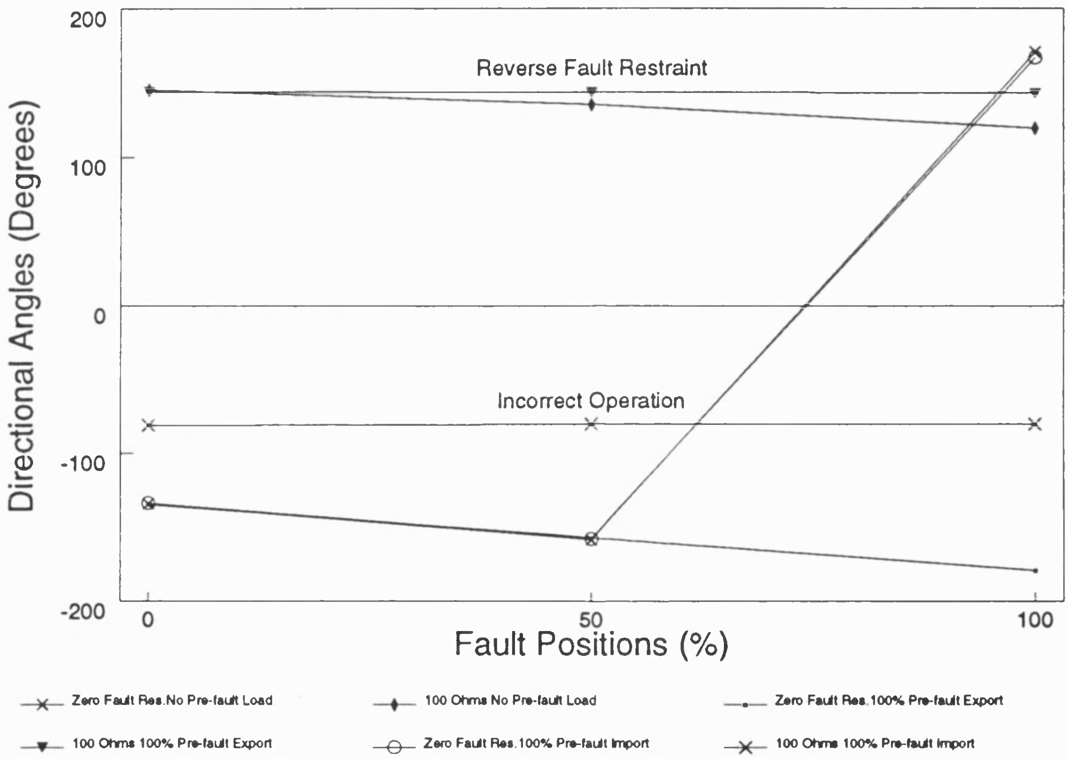
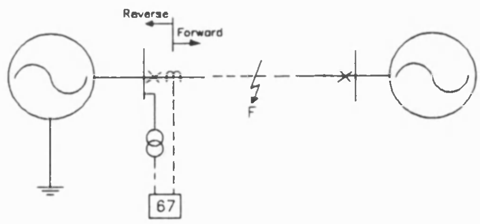



Figure 7.6.1.4.15 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.




11KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

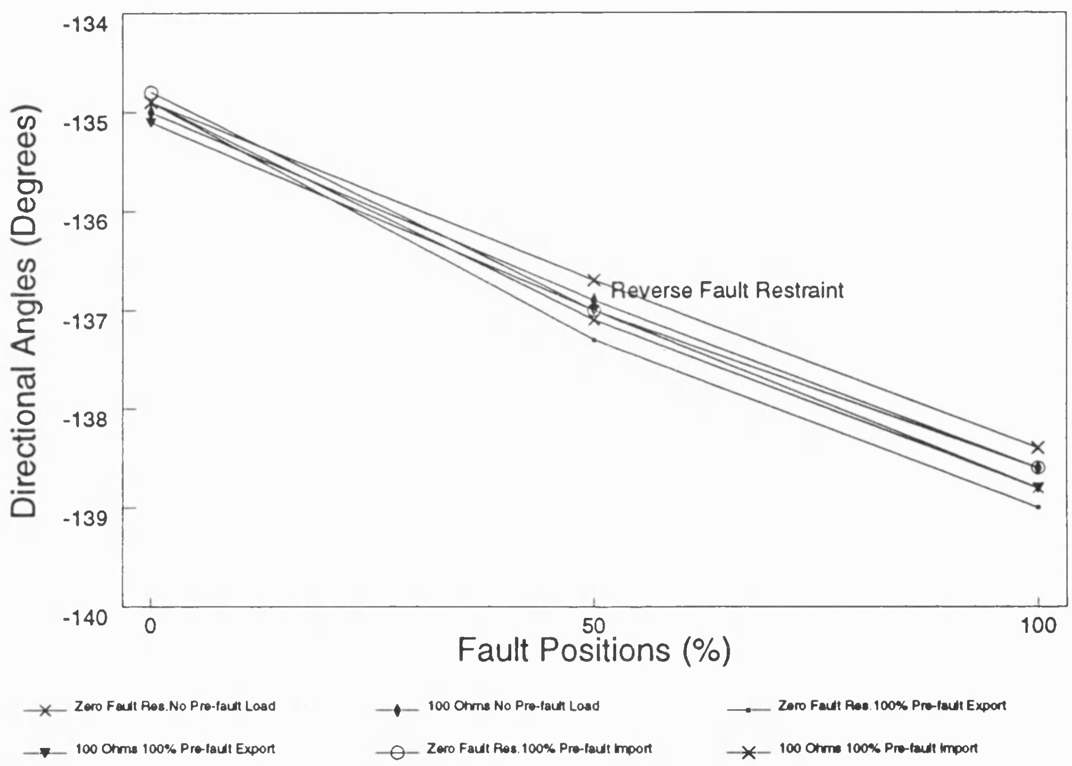



Figure 7.6.1.4.16 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.

For the 11kV distribution system with sources at the two ends of the protected feeder the following observations can be made:

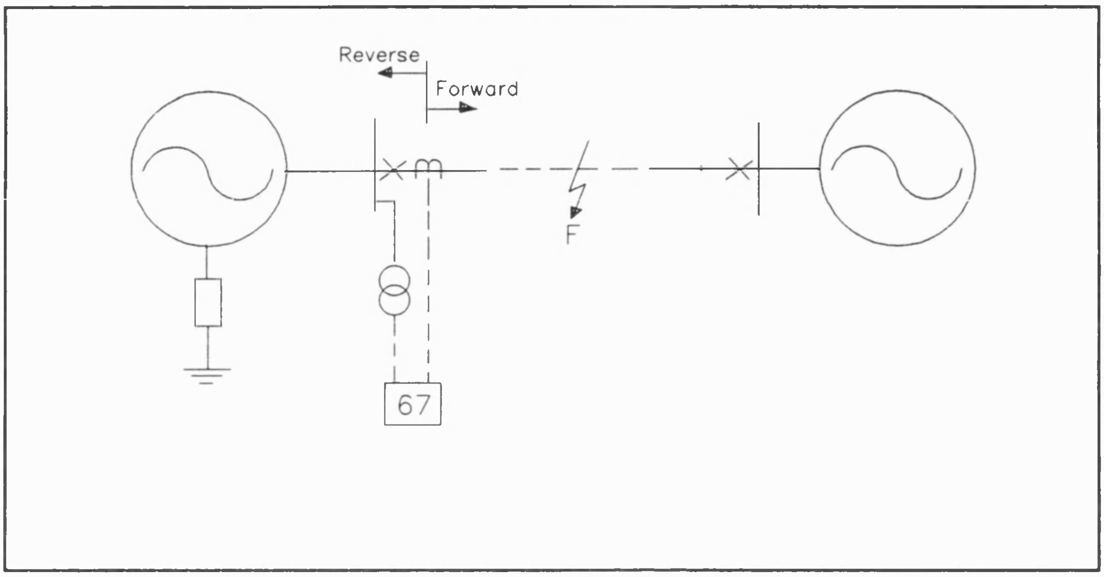
- For the overhead line feeder the directional angle $\theta_C$ exceeds the $\pm 90^0$ limits for 3-phase faults at the end of the feeder with 100Ω fault resistance and no pre-fault load current flow. The same applies to the case of single-phase-earth fault for the same conditions.

- For the underground cable feeder $\theta_C$ exceeds the $\pm 90^0$ limits for 3-phase faults with 100Ω fault resistance and 100% pre-fault importing load current flow. The same applies for single-phase-earth faults and for phase-phase faults up to 50% of the protected cable, both for the same conditions.

For multiple-source-fed systems the proposed combined function $F_C$ is not able to operate correctly for all types of faults with high fault resistance in the presence of full importing load current flow.

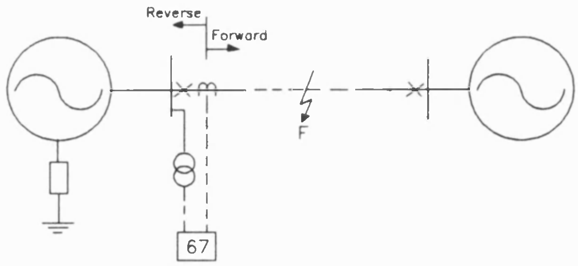
### 7.6.1.5 33KV Distribution System of either Overhead Line or Underground Cable Feeder with Sources at both Feeder Ends

The system is shown below:




This resistance-earthed system provides tests on the effect of primary system earthing arrangement on the proposed directional detection method and the effect of the subsequent limit on the earth fault current with pre-fault load current flow.

The variations of the directional angle $\theta_C$ under different pre-fault loading and fault conditions for different fault types are presented in Figures 7.6.1.5.1 to 7.6.1.5.16 with variations in fault positions and fault resistances.




33KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

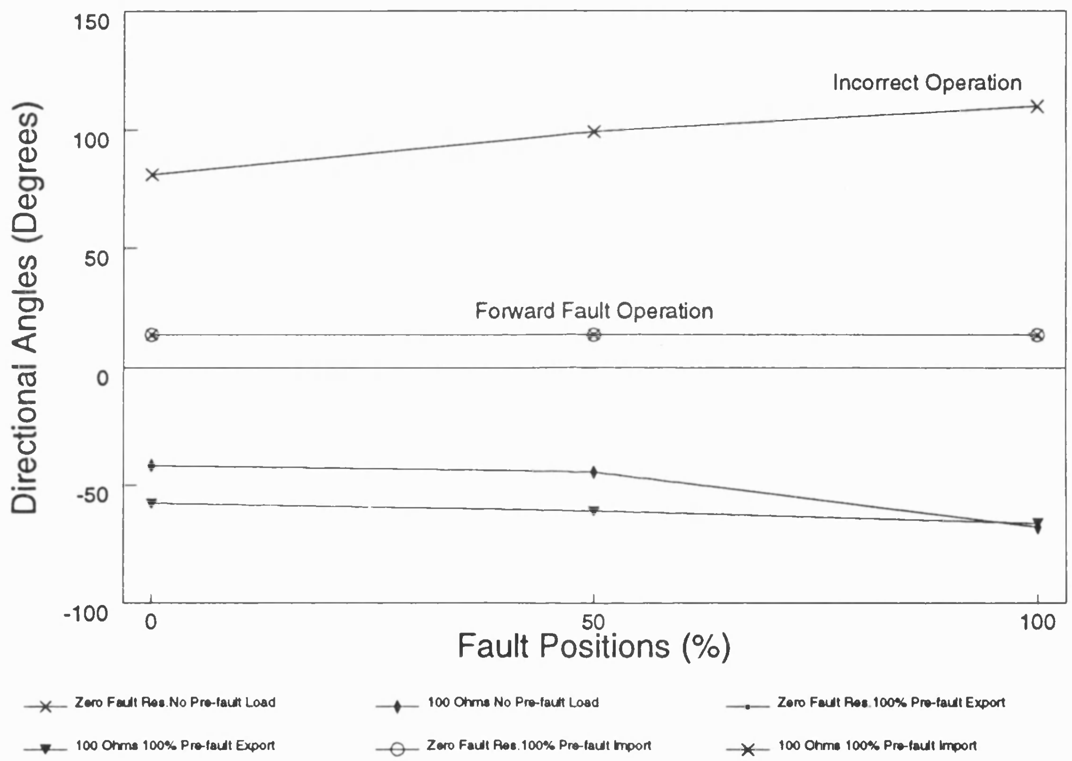
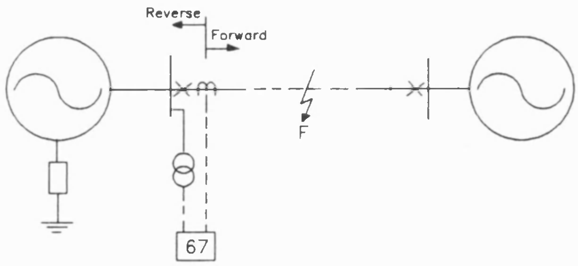



Figure 7.6.1.5.1 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




33KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

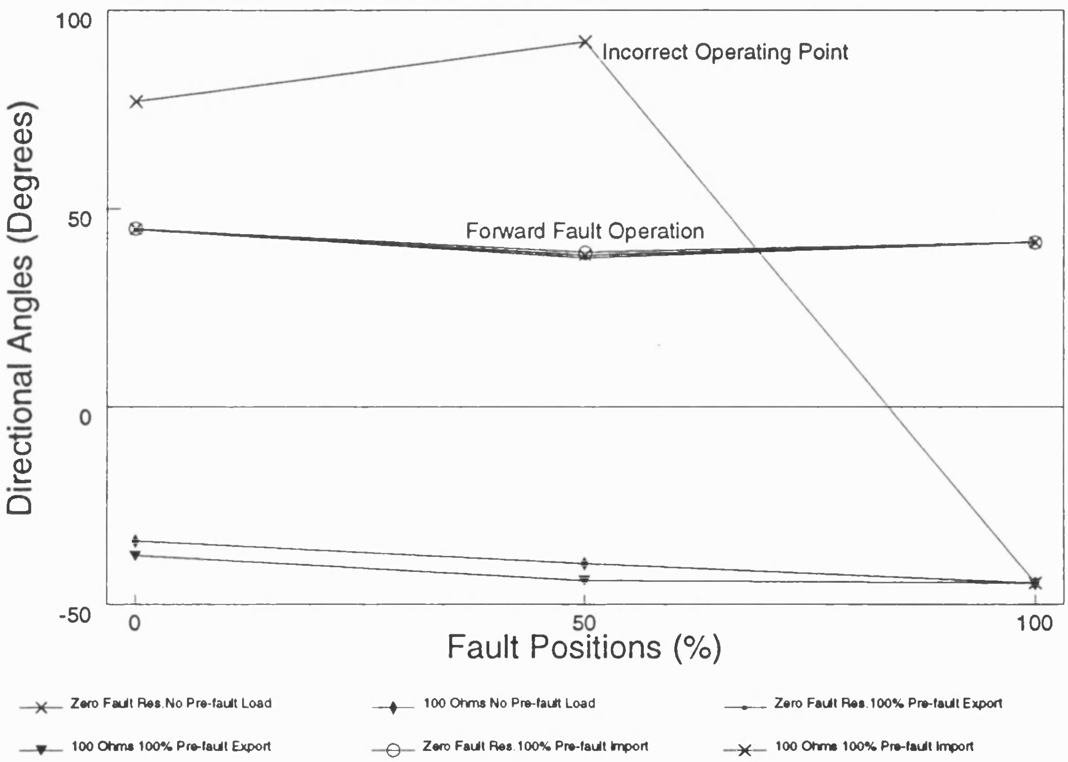
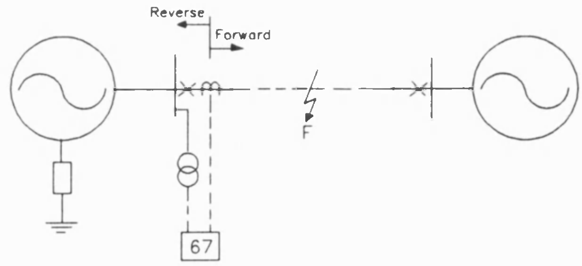



Figure 7.6.1.5.2 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




33KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

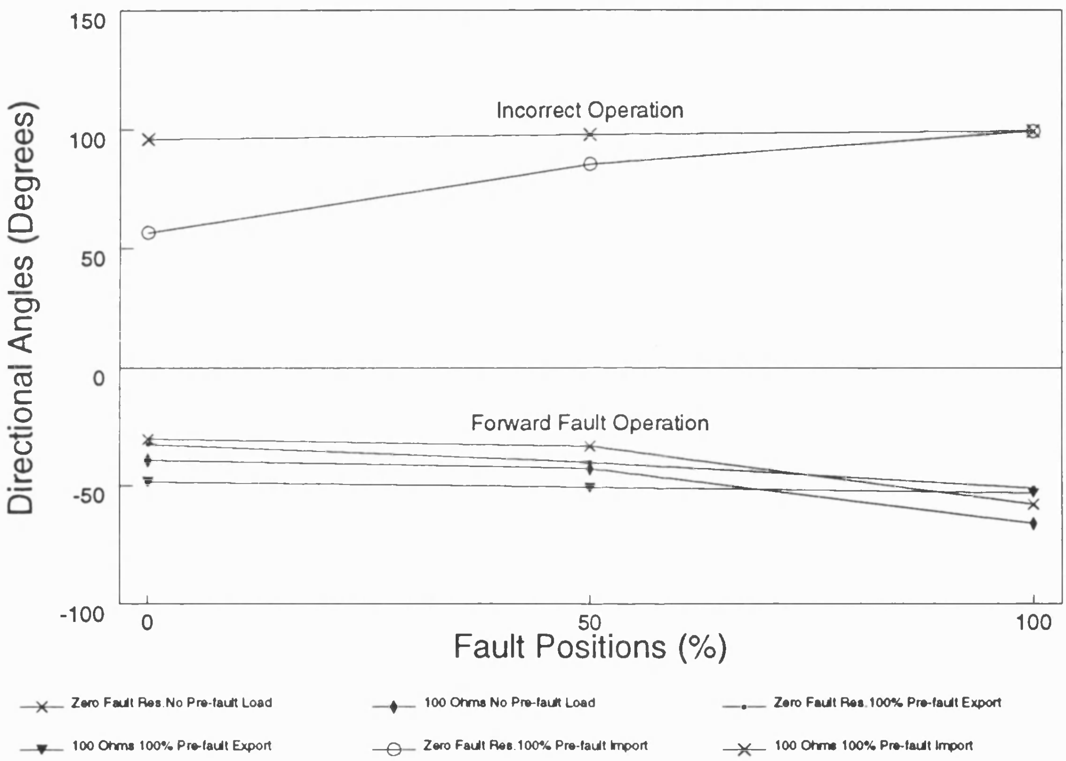
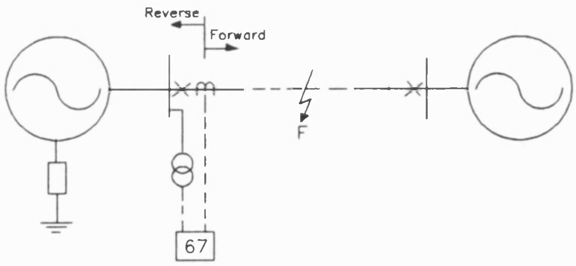



Figure 7.6.1.5.3 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




33KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

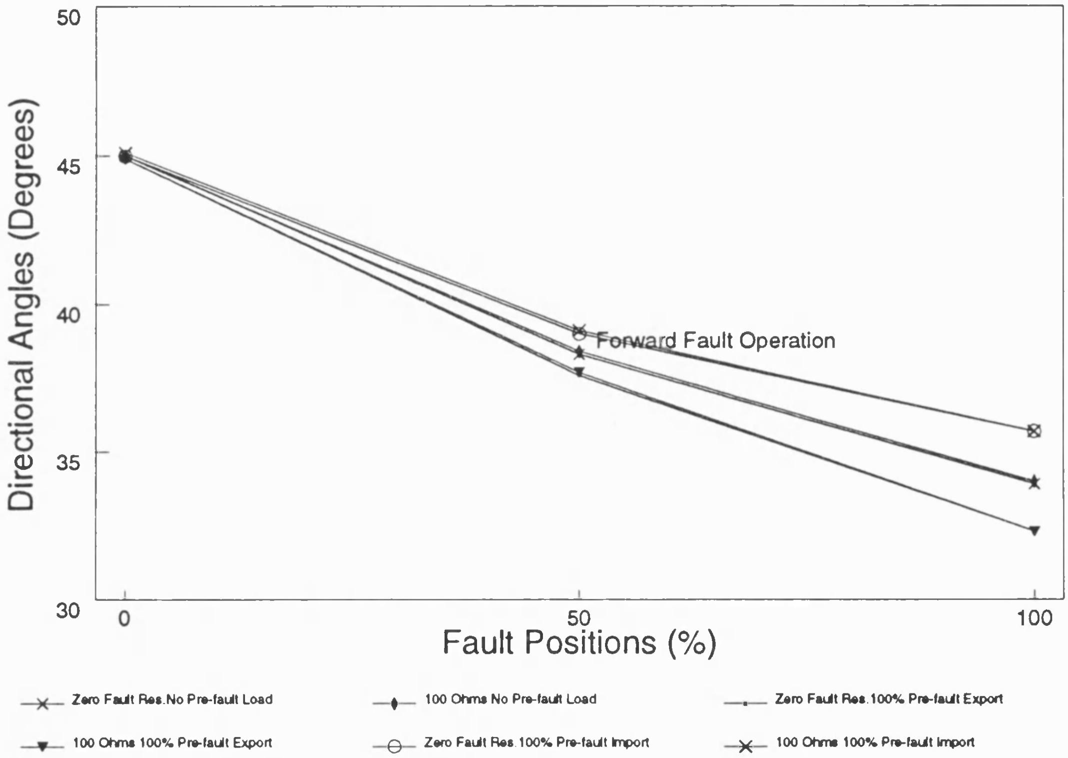
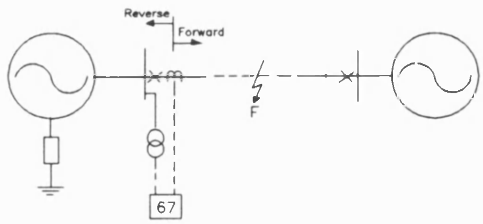



Figure 7.6.1.5.4 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




33KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

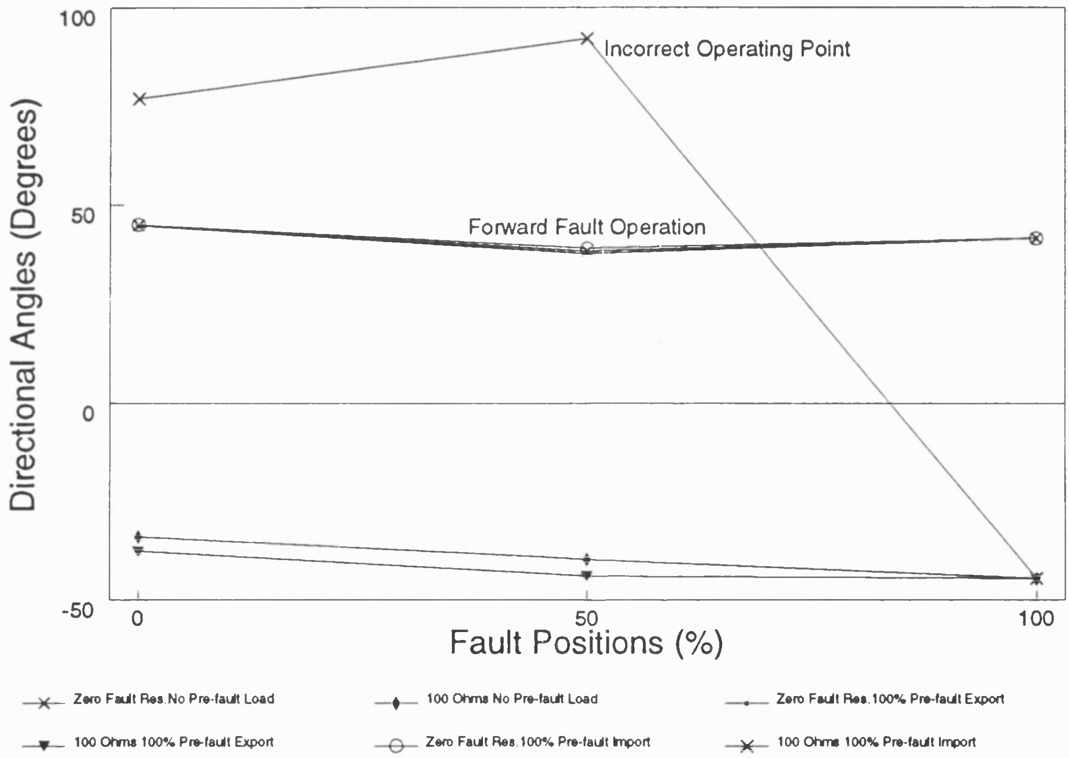
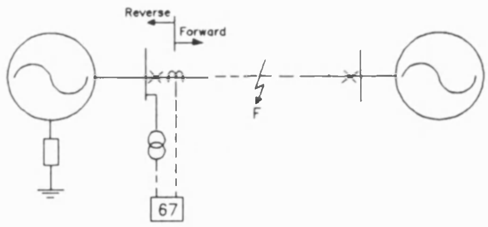



Figure 7.6.1.5.5 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




33KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

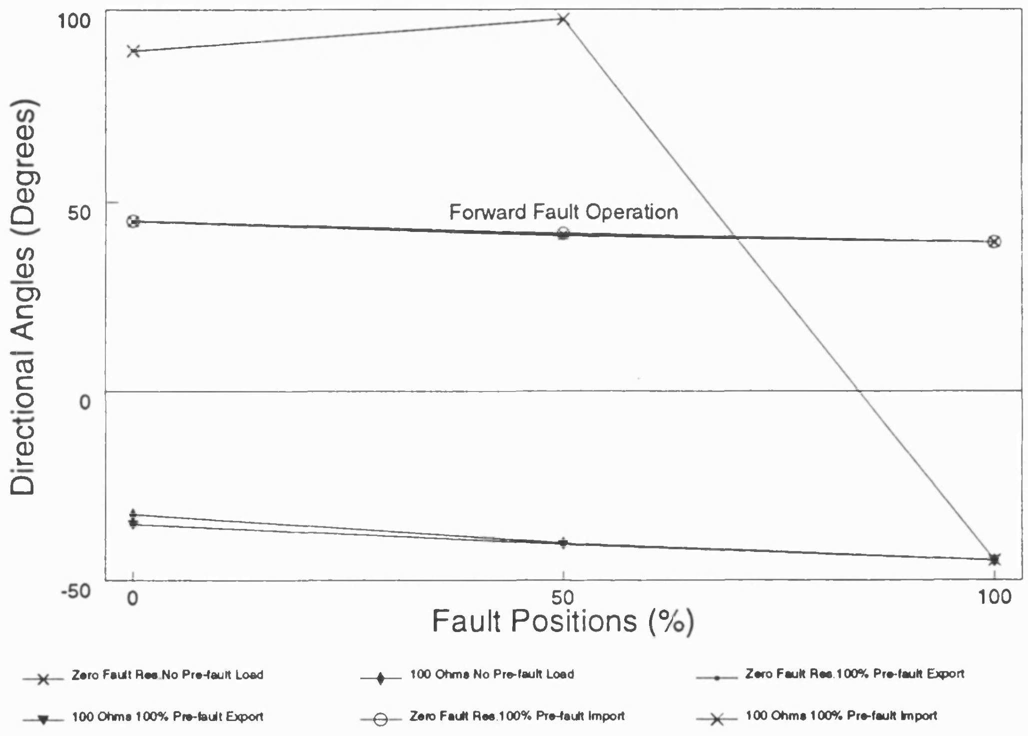
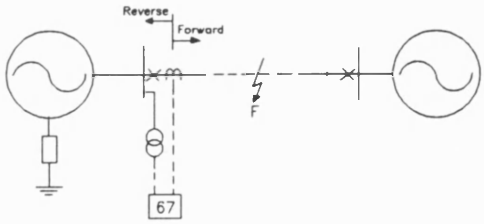



Figure 7.6.1.5.6 Variations of Directional Angle $\theta_c$ with Fault Positions and Fault Resistances for Phase-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




33KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

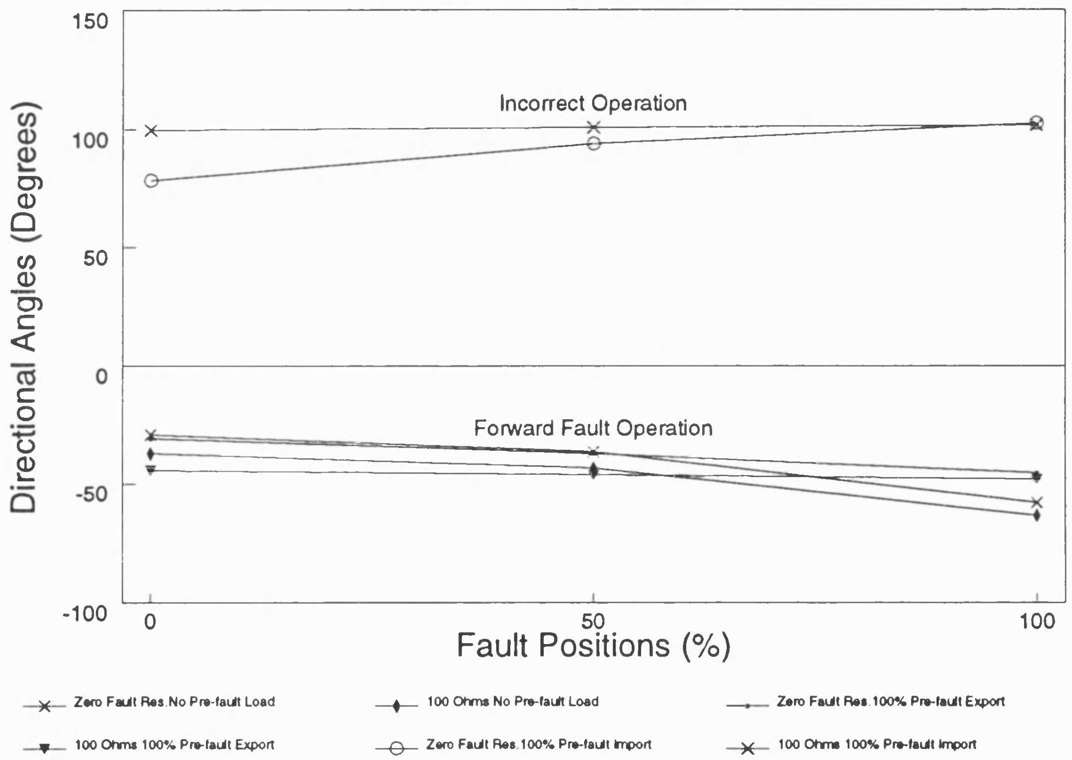
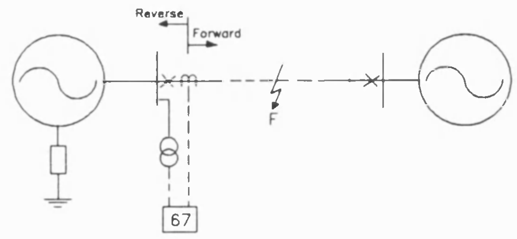



Figure 7.6.1.5.7 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




33KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

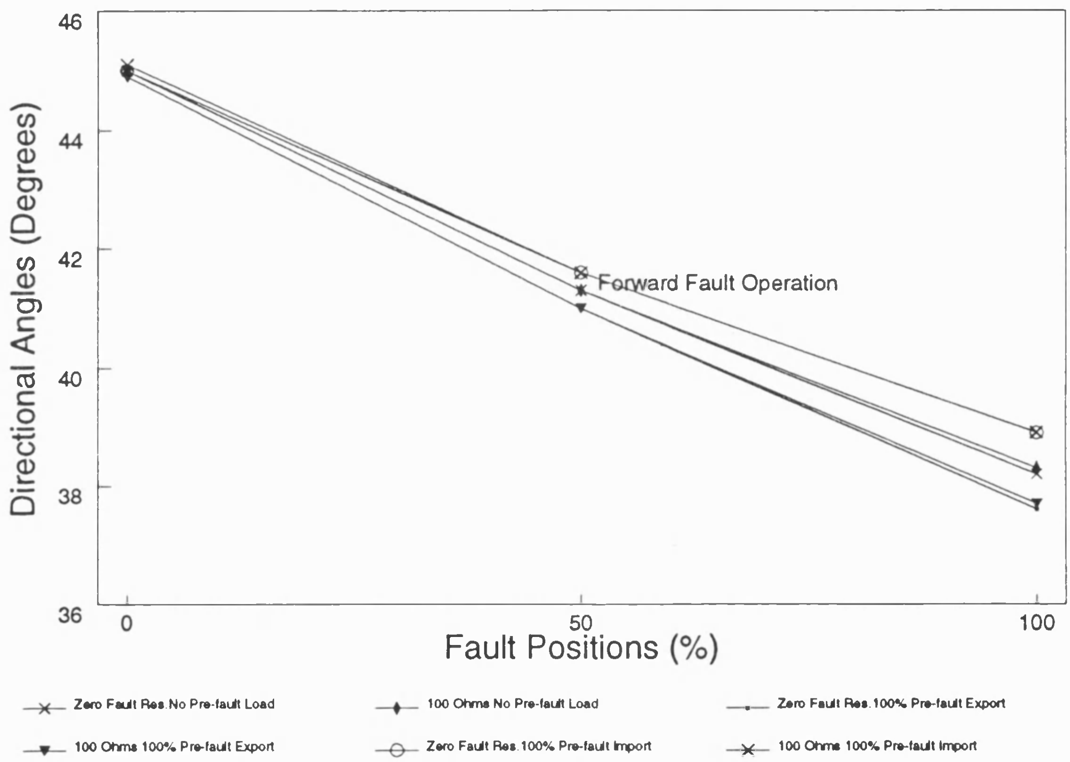
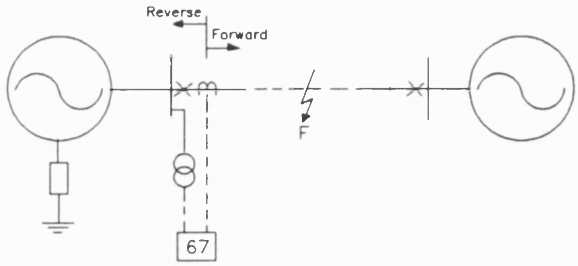



Figure 7.6.1.5.8 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Forward Faults.




33KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

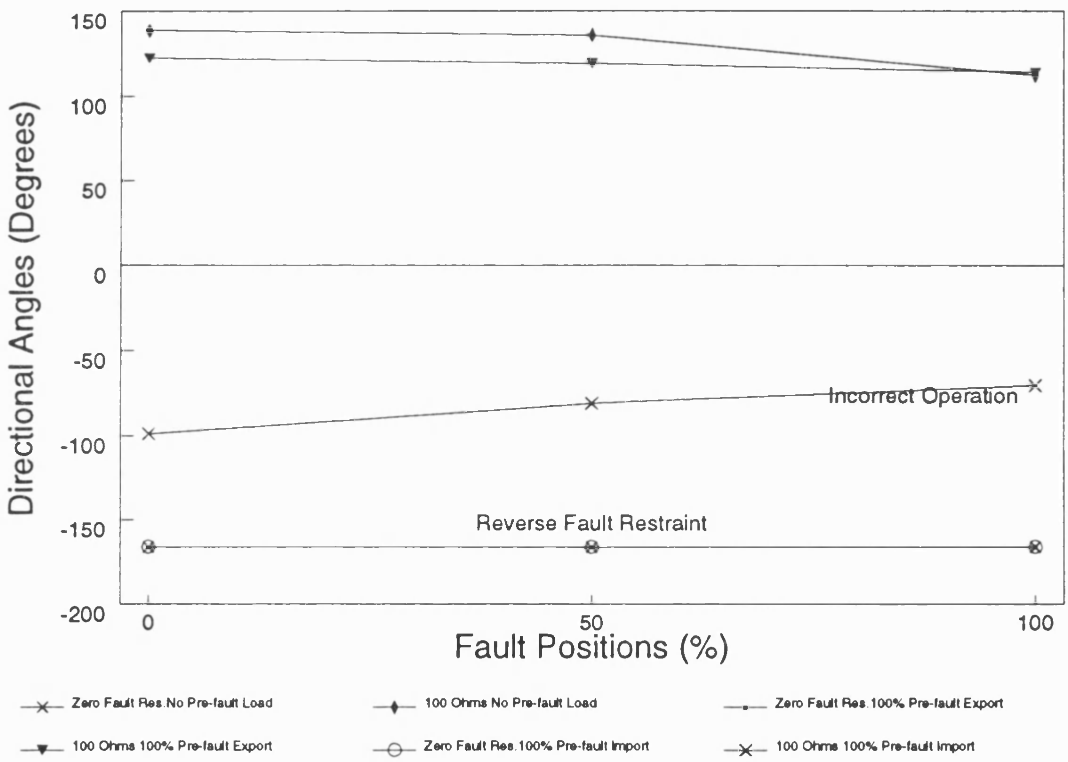
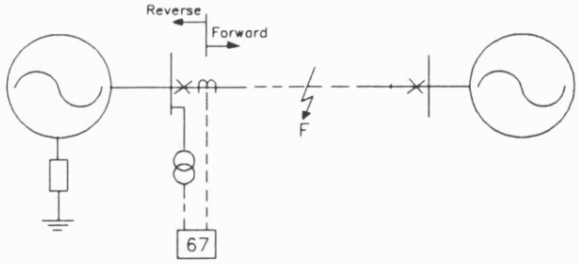



Figure 7.6.1.5.9 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.




33KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

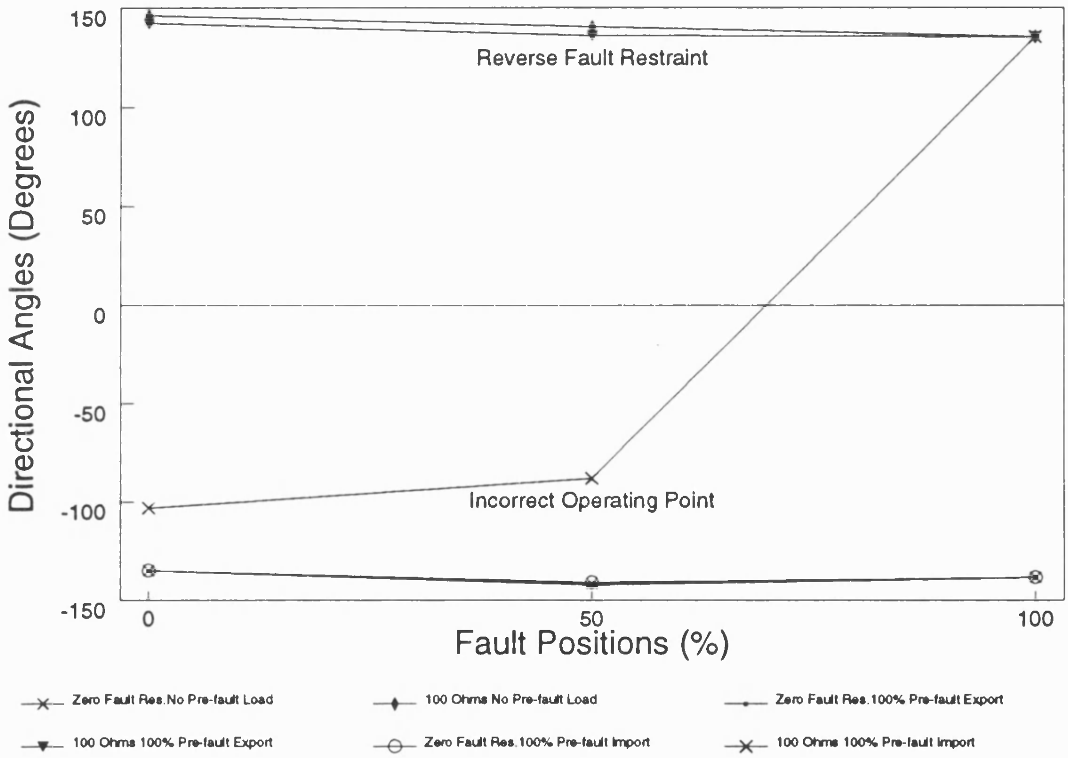
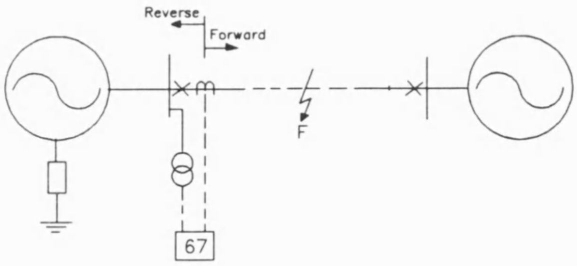



Figure 7.6.1.5.10 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.




33KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

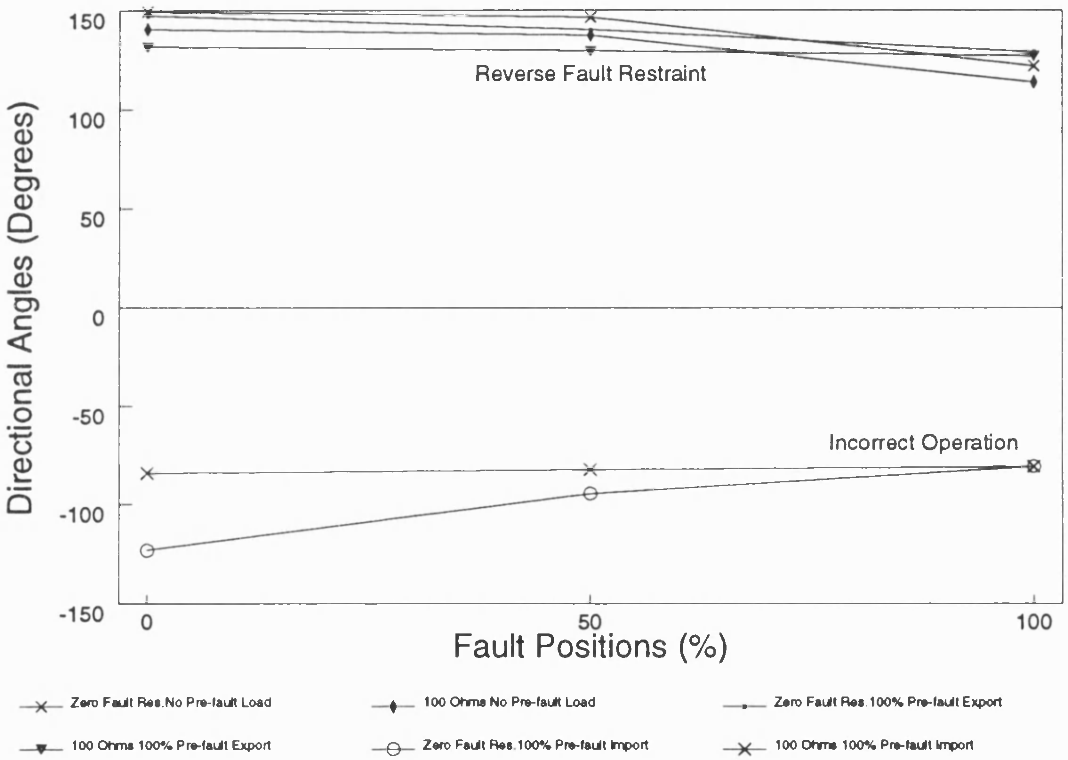
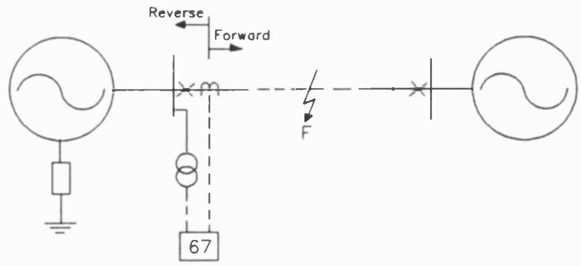



Figure 7.6.1.5.11 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.




33KV Distribution System with Two Line-end Sources on an Overhead Line Feeder

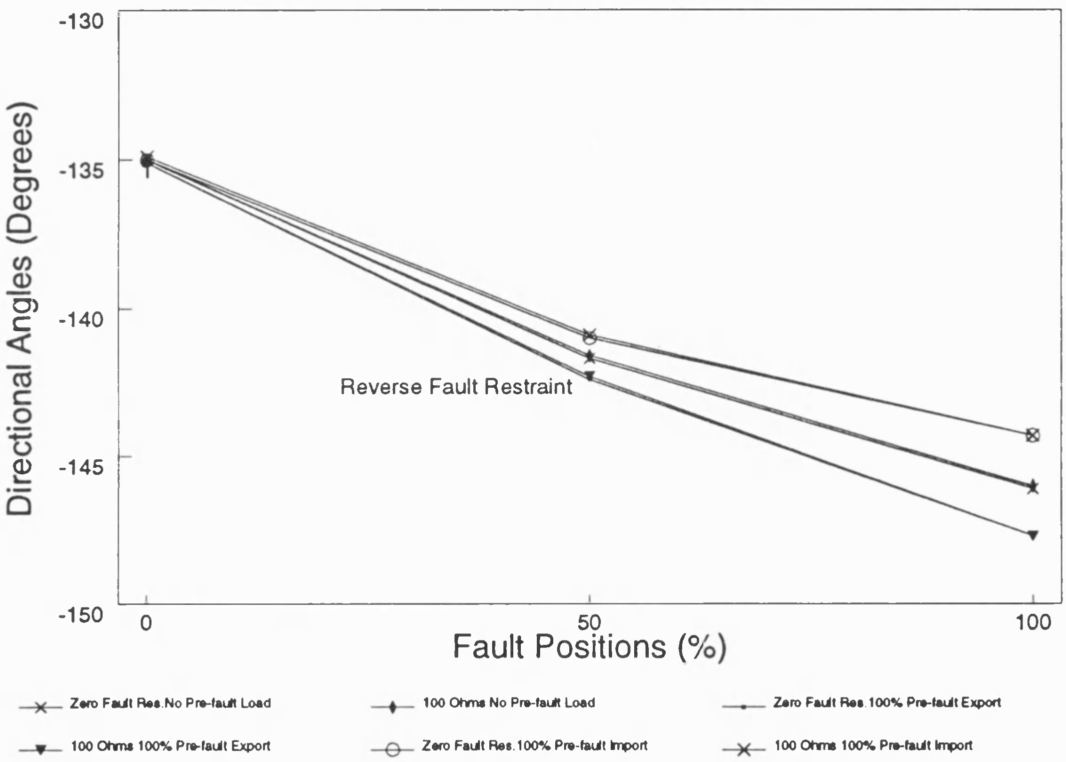
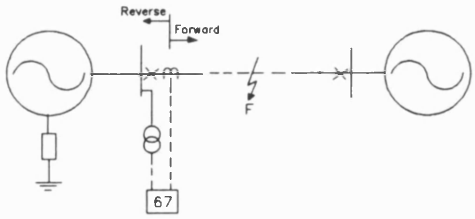



Figure 7.6.1.5.12 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.




33KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

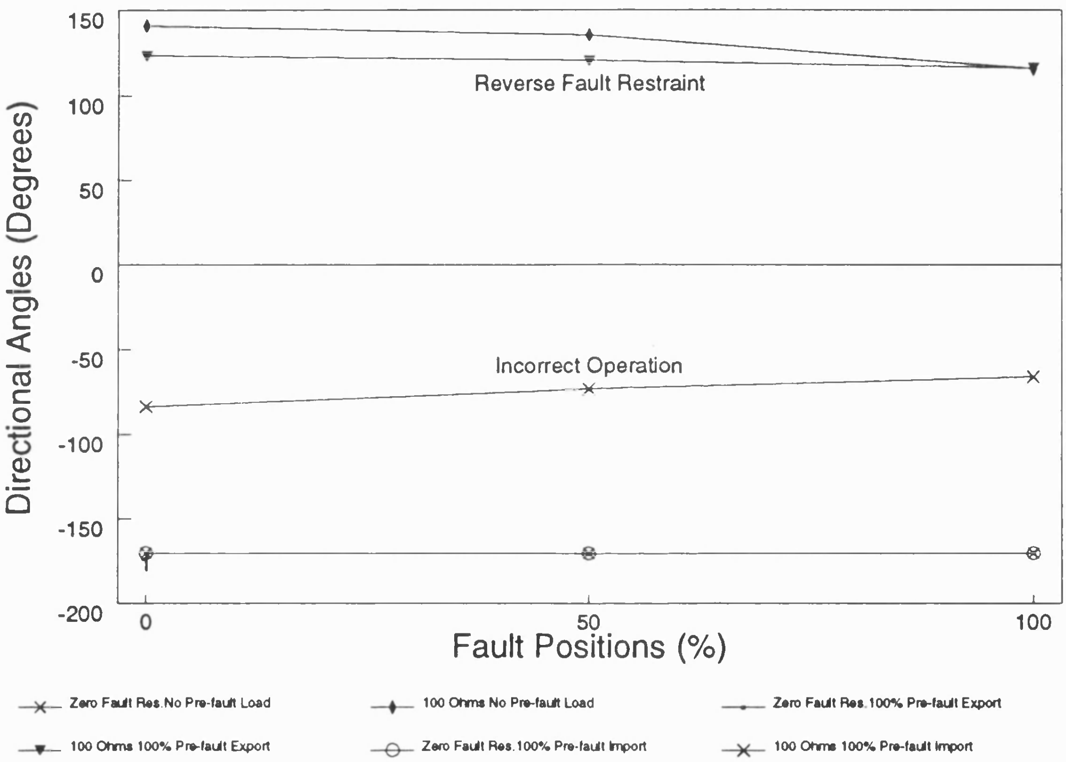
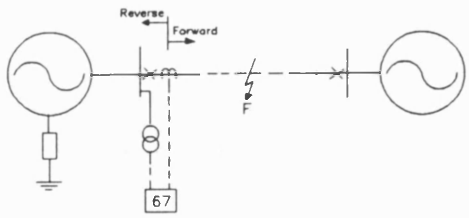



Figure 7.6.1.5.13 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.




33KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

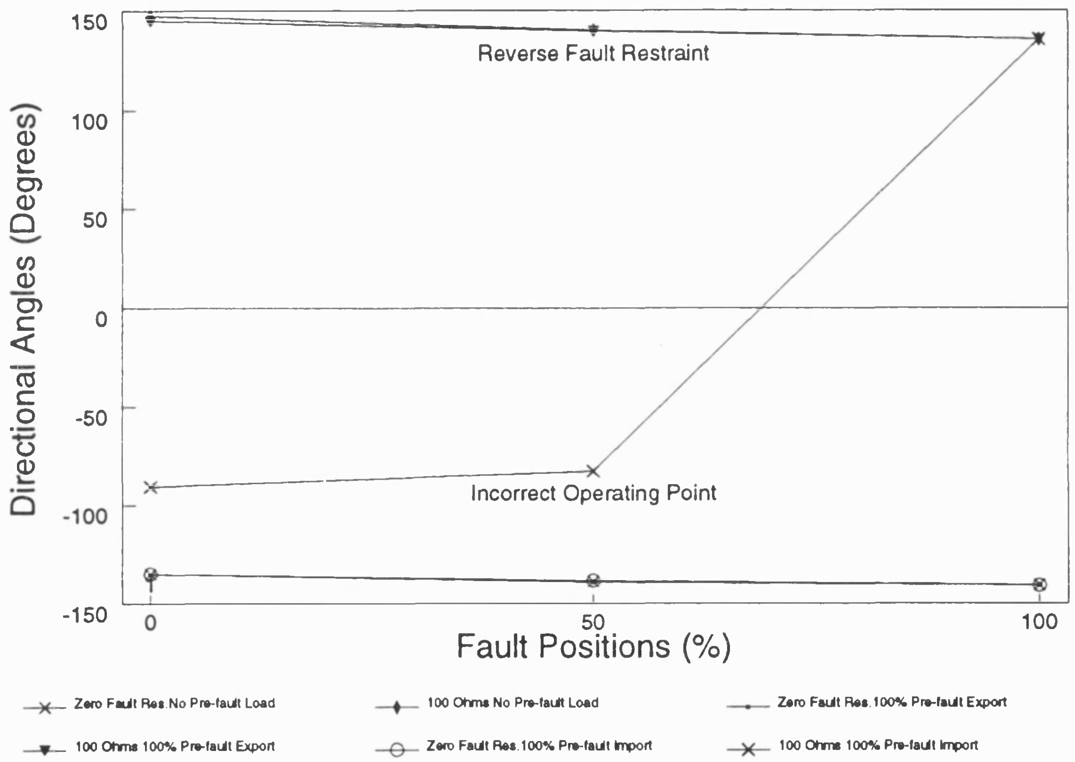
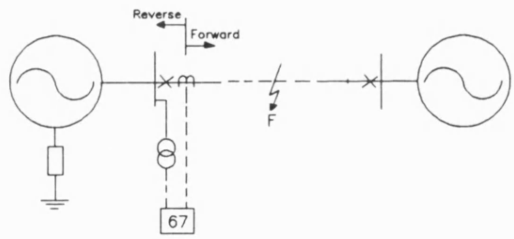



Figure 7.6.1.5.14 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.




33KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

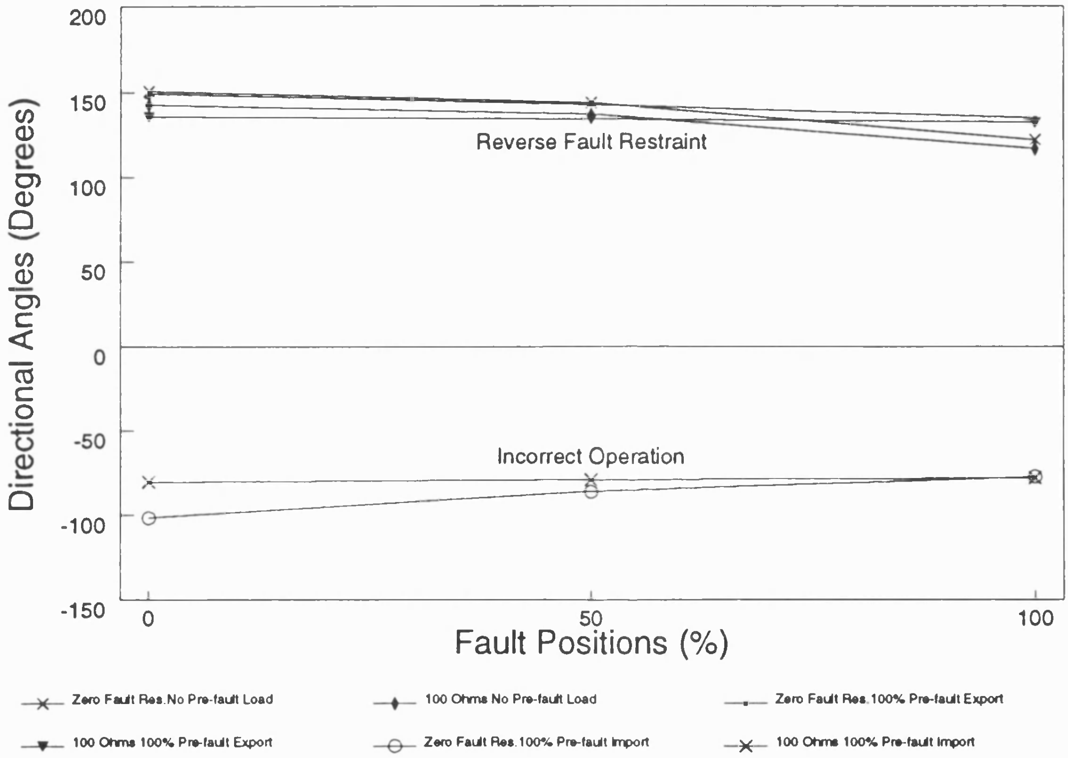
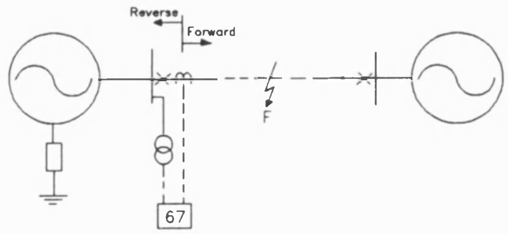



Figure 7.6.1.5.15 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.




33KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

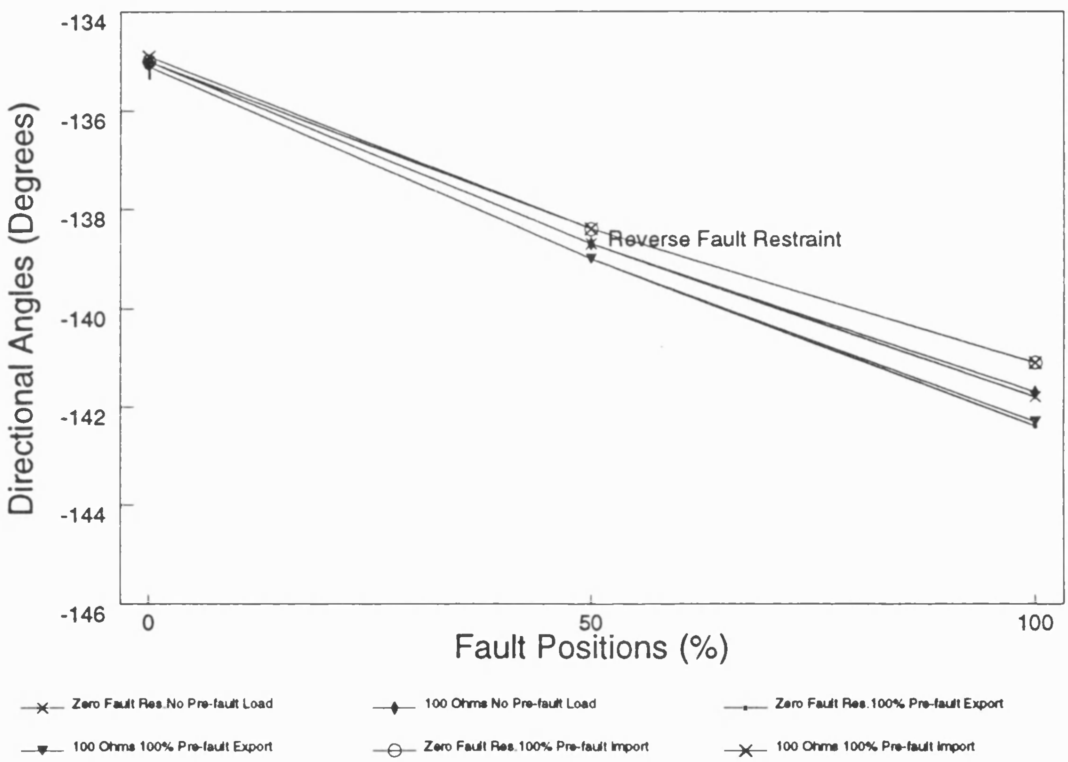



Figure 7.6.1.5.16 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults without and with 100% pre-fault exporting and importing load current flow with the Directional Relay arranged to detect the Faults as Reverse Faults.

For the 33kV distribution system with sources at the two ends of the protected feeder the following observations can be made:

- For the overhead line feeder the directional angle $\theta_C$ exceeds the $\pm 90^0$ limits for 3-phase faults along the remote half of the feeder with 100Ω fault resistance and 100% pre-fault importing load current flow. The same applies in the case of the single-phase-earth faults under the same pre-fault conditions and with 100Ω fault resistance.

- At mid-point of the overhead line feeder $\theta_C$ also slightly exceeds the $\pm 90^0$ limits for phase-phase faults with 100Ω fault resistance and 100% pre-fault importing load current flow.

- For the underground cable feeder the new basis of directional detection is not capable of coping with 100Ω fault resistance for single-phase-earth fault with 100% pre-fault importing load current flow. Under the same pre-fault conditions and with 100Ω fault resistance the directional angle $\theta_C$ also exceeds the $\pm 90^0$ limits for 3-phase and phase-phase faults at the mid-point of the cable.

### 7.6.2 **Transformer-feeder Systems**

When a power transformer is placed between the relay location and the fault point there is a phase shift between the voltage and current phasors on the fault side and those on the relay side of the transformer caused by the intrinsic phase shift, if any, produced by the power transformer between its low-voltage and high-voltage windings. This phase shift applies to the symmetrical components of voltages and currents with the same phase shift for both voltage and current of the same phase sequence.

#### 7.6.2.1 Effect of Phase Shift on the New Directional Detection Method

When a phase shift is produced between the voltage and current phasors from one winding to the other, traditional directional relays based on the product of a polarising voltage and an operating current and a function of the phase displacement between them are affected by this phase shift as explained in Chapter 4. This is because of the effect of phase shift to the voltage and current phasors is cumulative. To take this phase shift into account the selection of maximum torque angle value of directional overcurrent relays has to be different for plain- and for transformer-feeders. It is recommended [3.8, 3.9] that $30^0$ leading and $45^0$ leading maximum torque angles are used for application to plain- and transformer-feeders respectively.

For the new proposed method of detecting direction, the ratio between the voltage and current signals is examined to derive the phase angle displacement between them and to determine the fault direction as defined by the combined function given by equation 6.60 in Chapter 6:

$$F_C = 1\angle{-45°}\left(\frac{V_1}{I_1}\right) + 20\angle{+135°}\left(\frac{V_2}{I_2}\right)$$

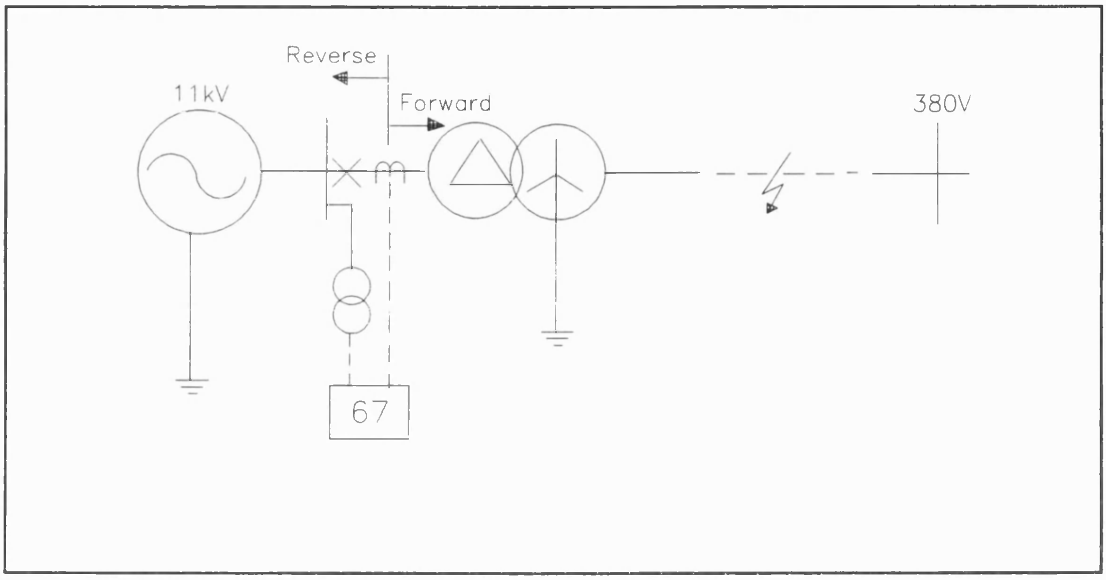
The phase shift introduced by power transformers is the same for the voltage and the current phasors of the same phase sequence. Consequently, when the ratio of the same phase sequence of voltage and current is taken the effect of the phase shift is cancelled. The power transformer is, therefore, "transparent" to the new directional detection method as far as any phase shift introduced by the power transformer is concerned.

### 7.6.2.2 Results of Studies on Transformer-feeder Systems

The followings are the results of studies on the transformer-feeder systems shown in Figure 7.2. The effects of fault levels, fault positions, pre-fault load levels and fault resistances on the new directional detection method are examined and the results presented. The form of presentation in terms of the directional angle is similar to the case for the plain-feeder system.

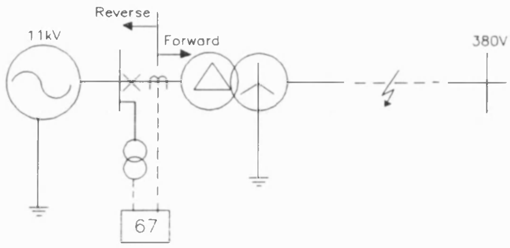
### 7.6.2.2.1 11KV Supply Transformer from Utility to Consumer Low-voltage System

The system is shown below:




This system is commonly used by utilities to provide power supply to consumers. A directional relay installed at the high voltage side of the power transformer serves to ensure that no fault infeed from the local low voltage generation where installed.

The effects of the phase shift between the high and low voltage sides of the transformer on the directional angle $\theta_c$ under various fault conditions and for different parameters of the low voltage cable feeder are presented in Figures 7.6.2.2.1.1 to 7.6.2.2.1.8.




11kV Consumer Supply Transformer System

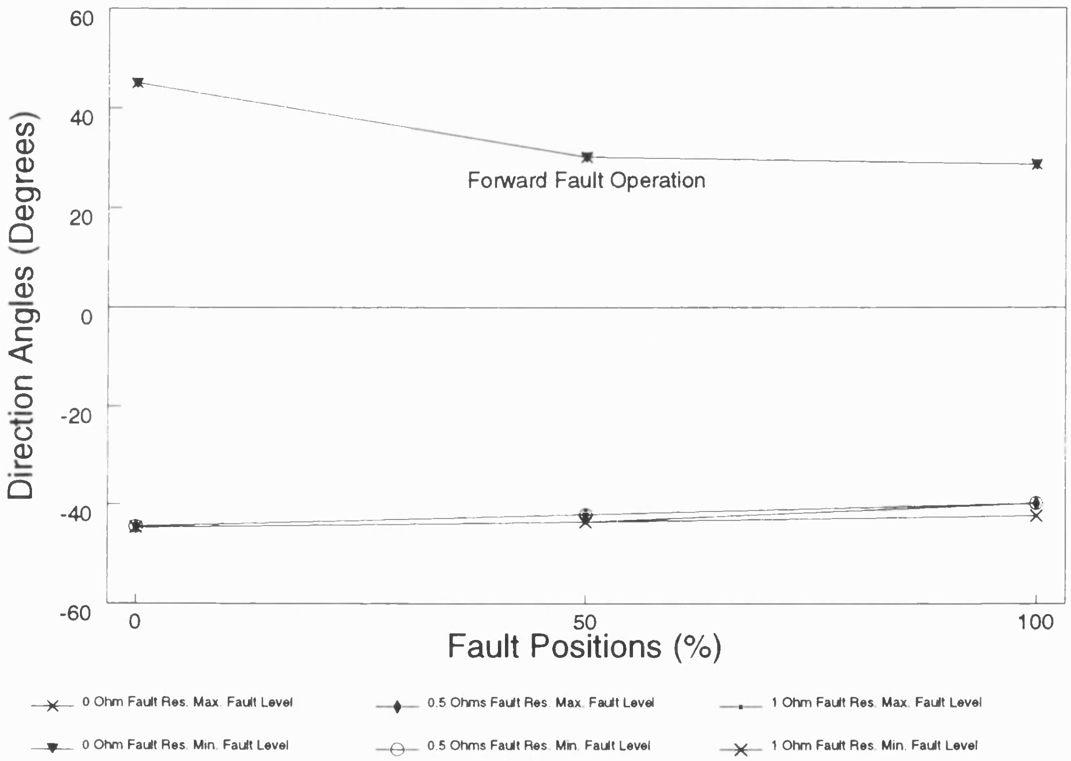
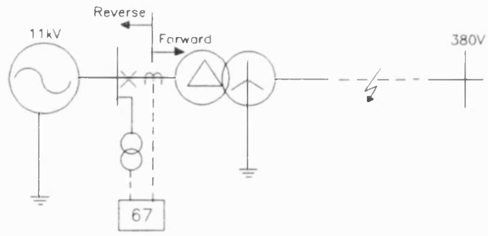



Figure 7.6.2.2.1.1 Variations of Directional Angle $\theta_c$ with Fault Positions for 3-phase Faults on the Low Voltage Cable Feeder and with Fault Resistances under Maximum and Minimum Fault Level Conditions with the Directional Relay arranged to detect the Faults as Forward Faults




11kV Consumer Supply Transformer System

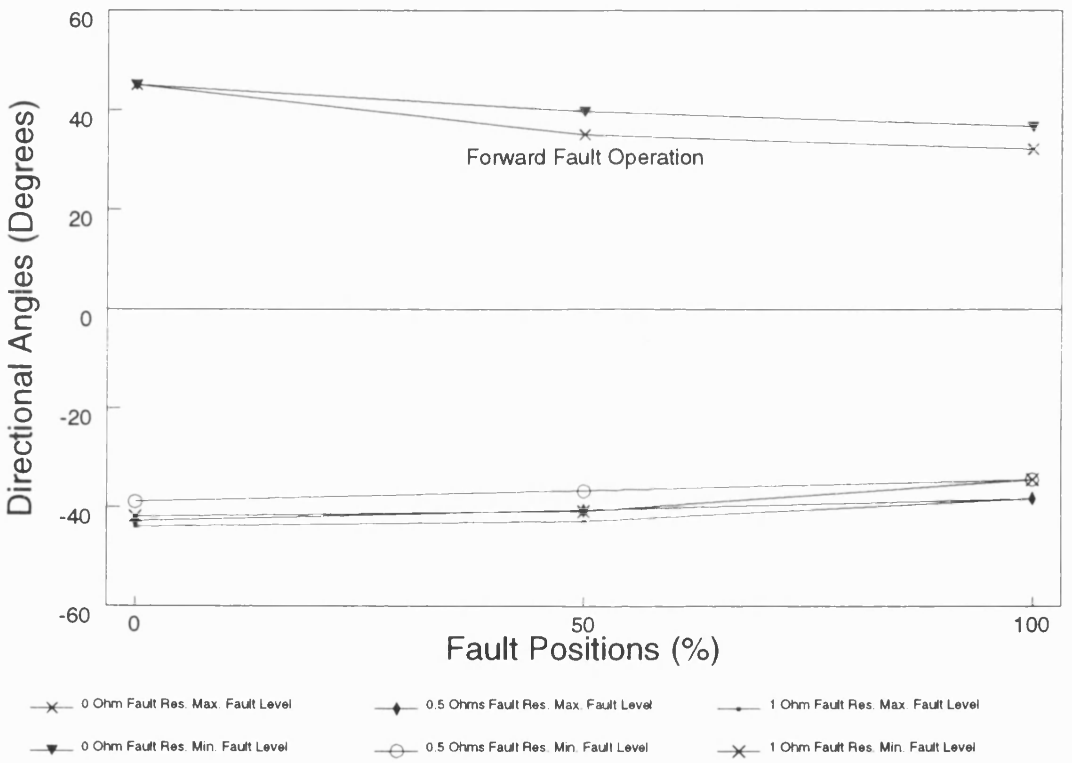
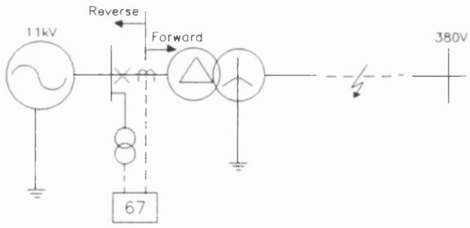



Figure 7.6.2.2.1.2 Variations of Directional Angle $\theta_c$ with Fault Positions for Phase-phase Faults on the Low Voltage Cable Feeder and with Fault Resistances under Maximum and Minimum Fault Level Conditions with the Directional Relay arranged to detect the Faults as Forward Faults




11kV Consumer Supply Transformer System

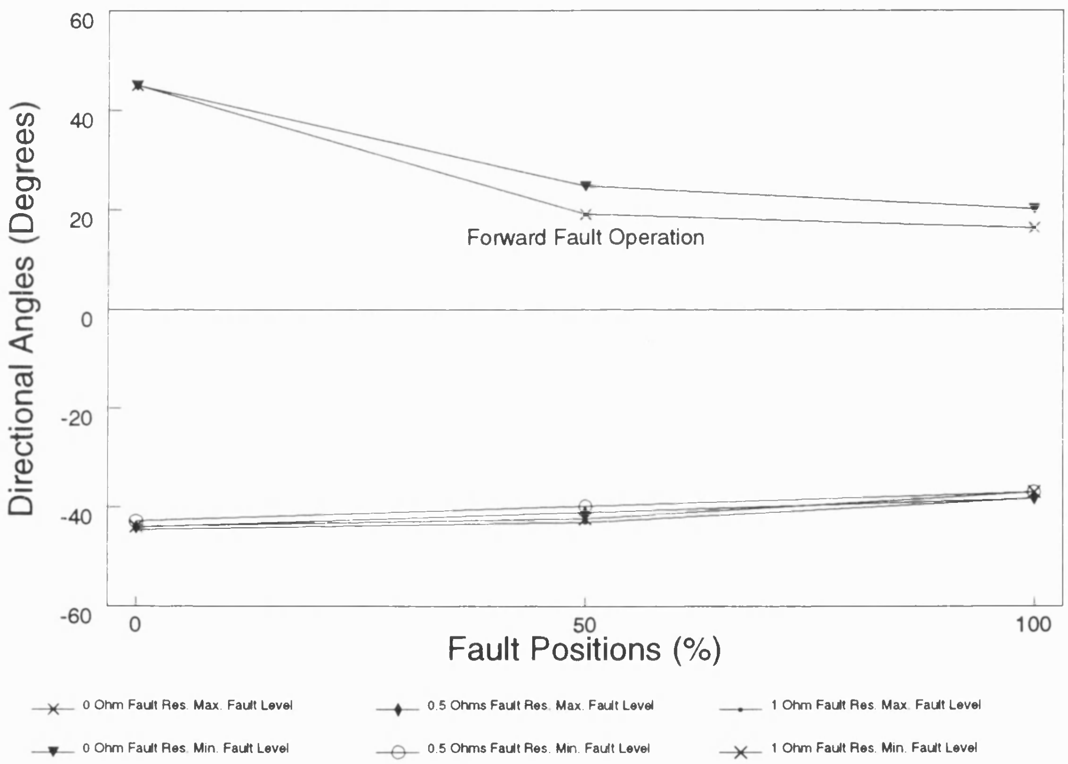
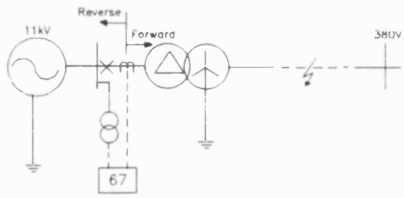



Figure 7.6.2.2.1.3 Variations of Directional Angle $\theta_c$ with Fault Positions for Single-phase-earth Faults on the Low Voltage Cable Feeder and with Fault Resistances under Maximum and Minimum Fault Level Conditions with the Directional Relay arranged to detect the Faults as Forward Faults




11kV Consumer Supply Transformer System

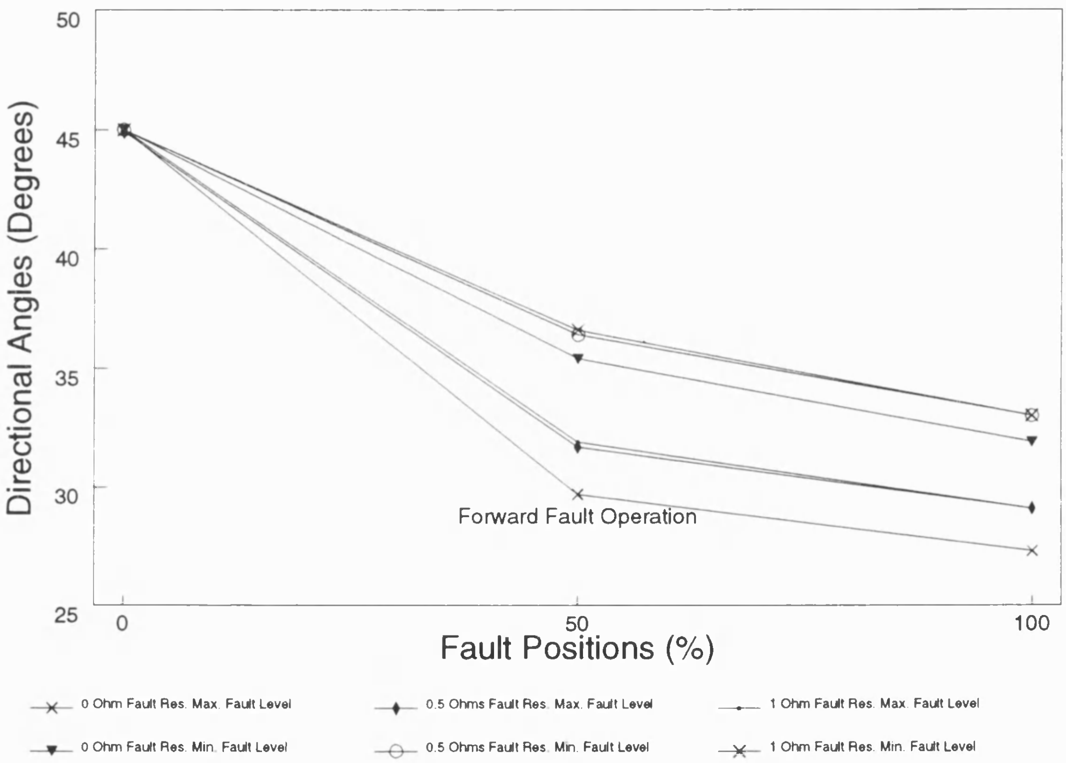
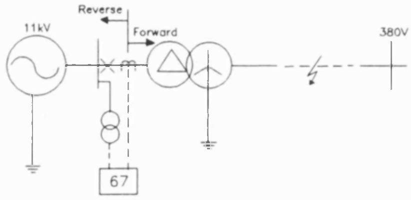



Figure 7.6.2.2.1.4 Variations of Directional Angle $\theta_C$ with Fault Positions for Phase-phase-earth Faults on the Low Voltage Cable Feeder and with Fault Resistances under Maximum and Minimum Fault Level Conditions with the Directional Relay arranged to detect the Faults as Forward Faults.




11kV Consumer Supply Transformer System

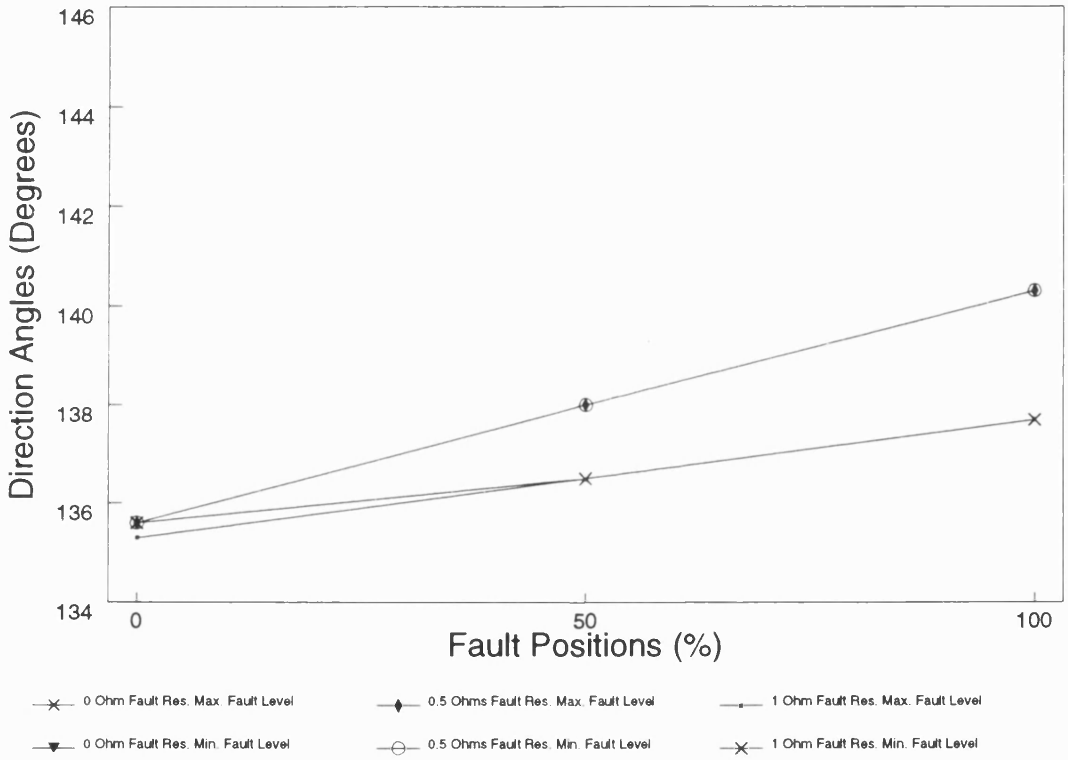
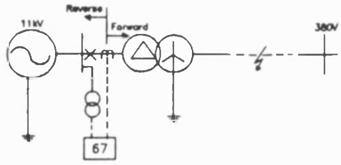



Figure 7.6.2.2.1.5(A)




11kV Consumer Supply Transformer System

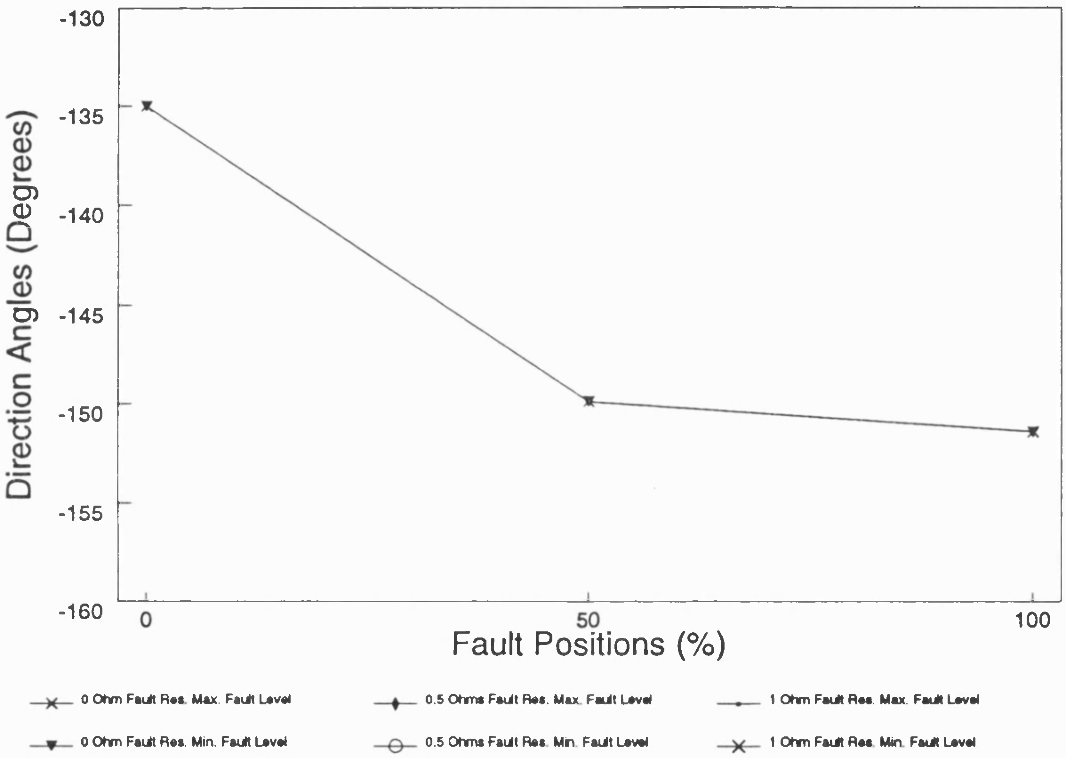
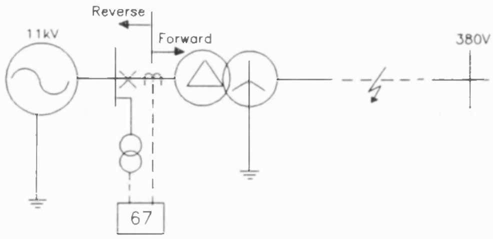



Figure 7.6.2.2.1.5(B)

Figure 7.6.2.2.1.5 Variations of Directional Angle $\theta_C$ with Fault Positions for 3-phase Faults on the Low Voltage Cable Feeder and with Fault Resistances under Maximum and Minimum Fault Level Conditions with the Directional Relay arranged to detect the Faults as Reverse Faults.




11kV Consumer Supply Transformer System

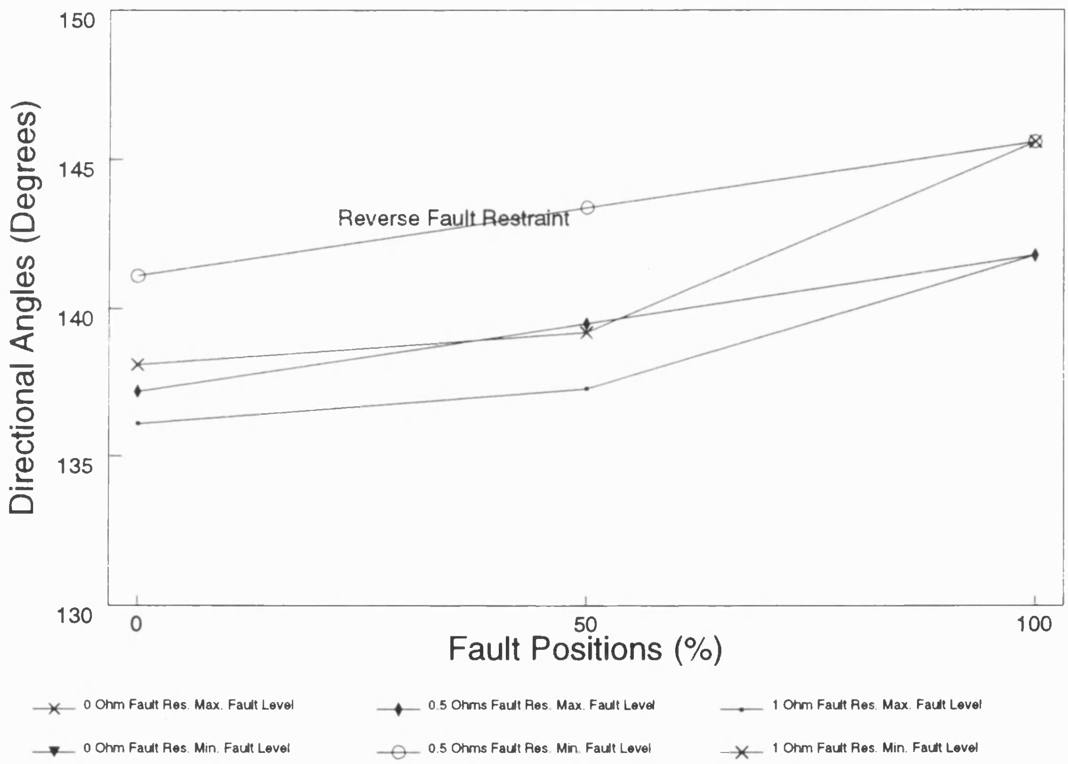
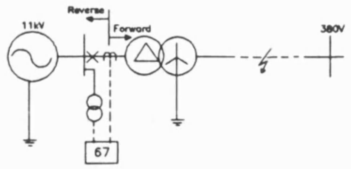



Figure 7.6.2.2.1.6(A)




11kV Consumer Supply Transformer System

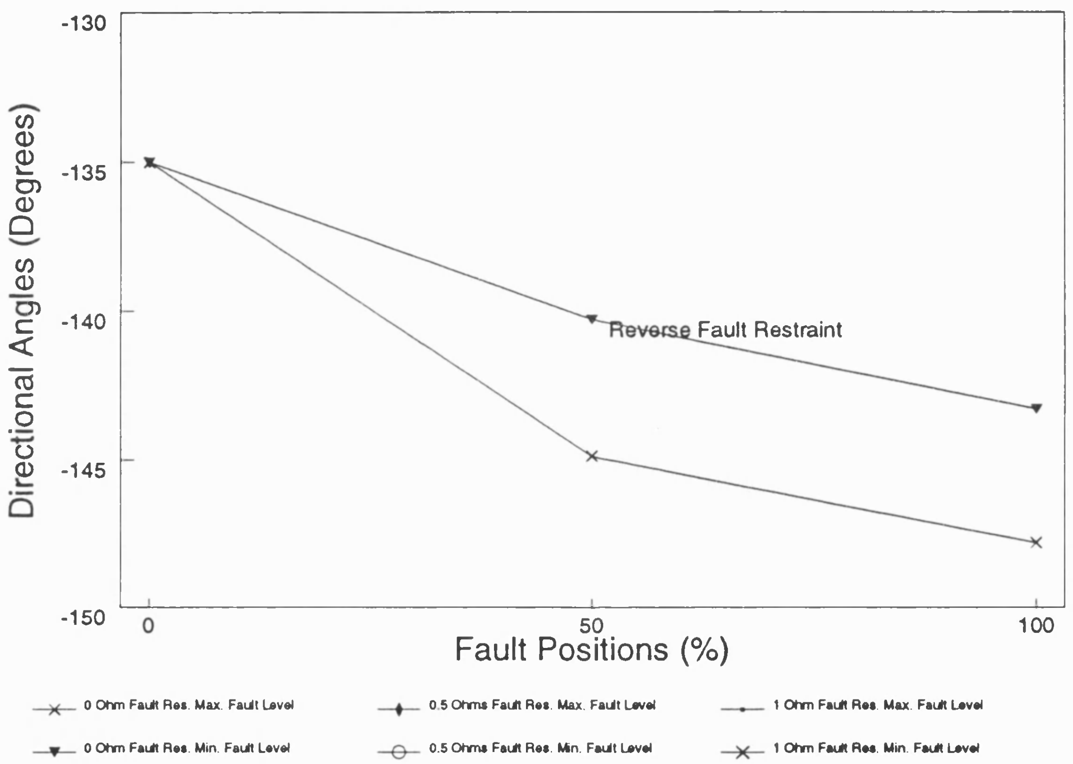
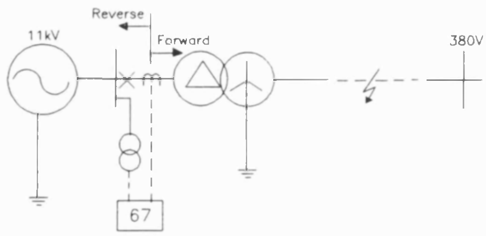



Figure 7.6.2.2.1.6(B)

Figure 7.6.2.2.1.6 Variations of Directional Angle $\theta_C$ with Fault Positions for Phase-phase Faults on the Low Voltage Cable Feeder and with Fault Resistances under Maximum and Minimum Fault Level Conditions with the Directional Relay arranged to detect the Faults as Reverse Faults.




11kV Consumer Supply Transformer System

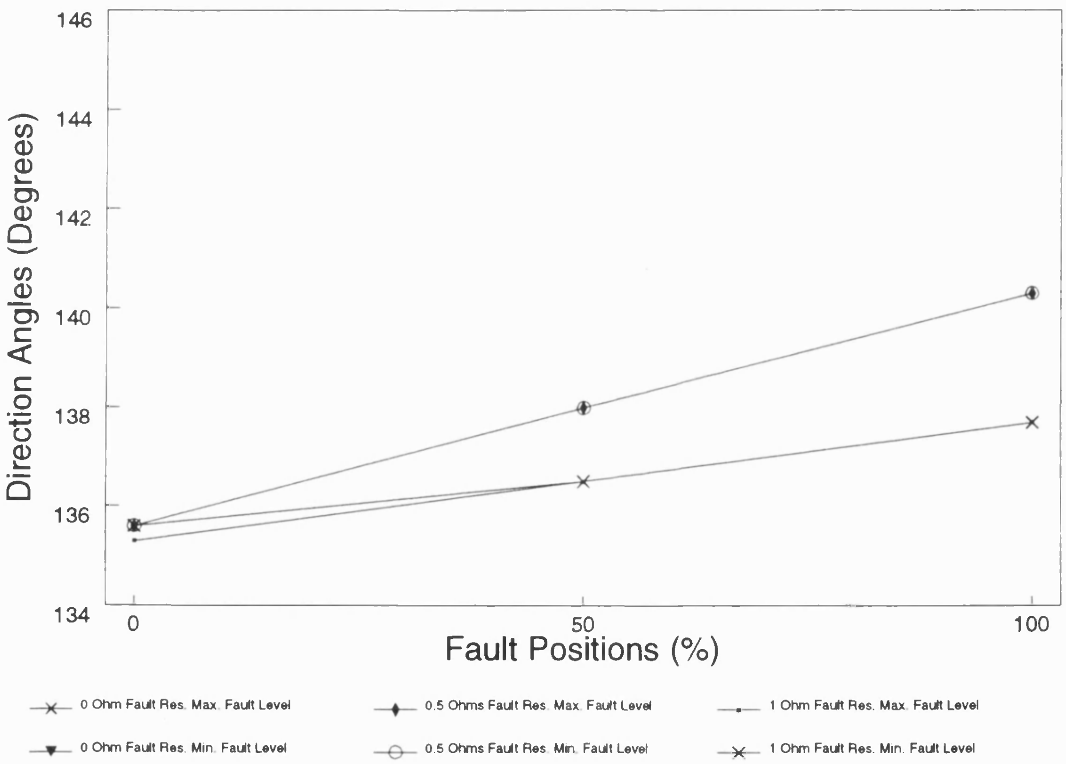
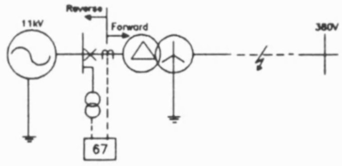



Figure 7.6.2.2.1.7(A)




11kV Consumer Supply Transformer System

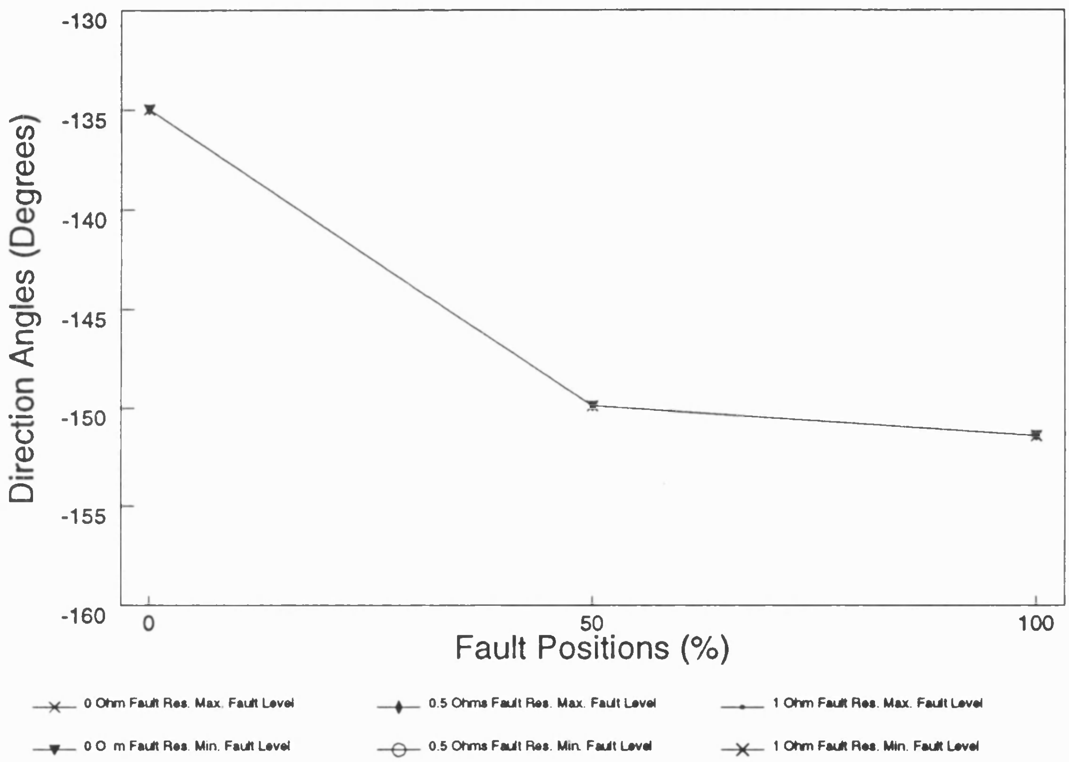
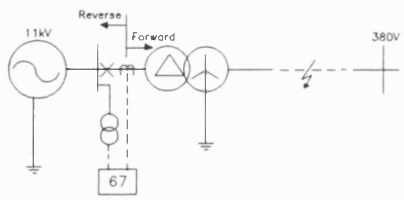



Figure 7.6.2.2.1.7(B)

Figure 7.6.2.2.1.7 Variations of Directional Angle $\theta_C$ with Fault Positions for Single-phase-earth Faults on the Low Voltage Cable Feeder and with Fault Resistances under Maximum and Minimum Fault Level Conditions with the Directional Relay arranged to detect the Faults as Reverse Faults.




11kV Consumer Supply Transformer System

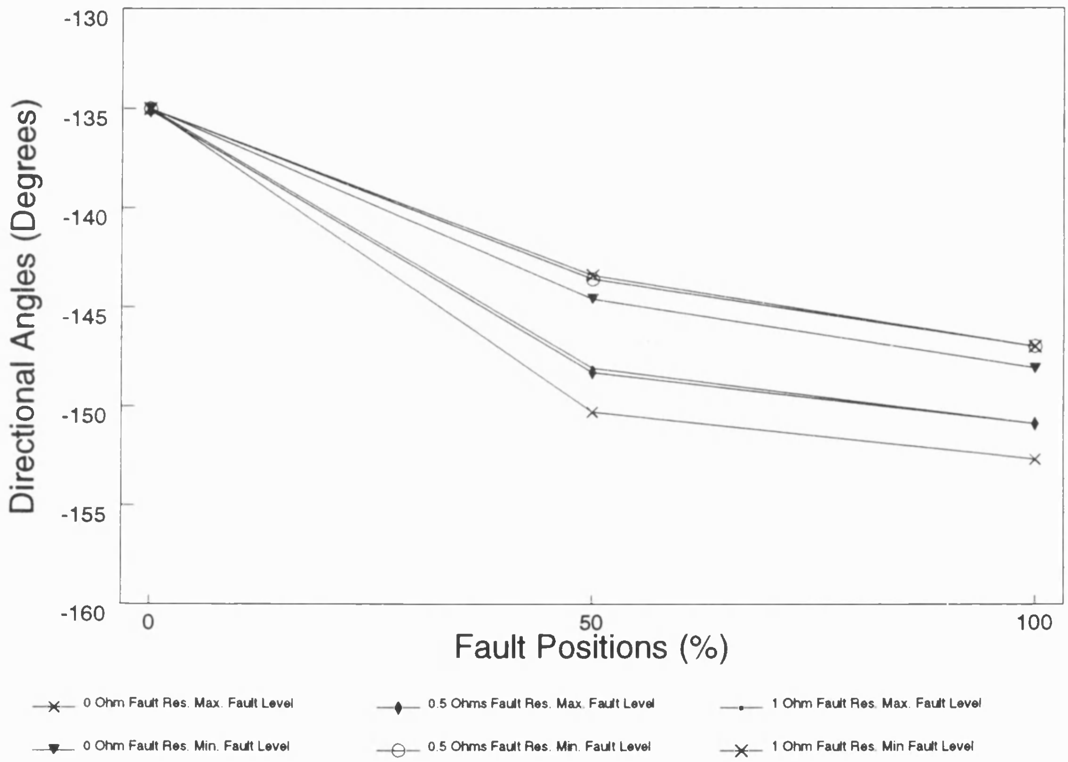



Figure 7.6.2.2.1.8 Variations of Directional Angle $\theta_C$ with Fault Positions for Phase-phase-earth Faults on the Low Voltage Cable Feeder and with Fault Resistances under Maximum and Minimum Fault Level Conditions with the Directional Relay arranged to detect the Faults as Reverse Faults.

For the 11kV consumer supply transformer system the followings are additional observations on the performance of the directional relay based on the new directional detection method at the high voltage side of the transformer:

- The phase shift caused by the transformer has no effect on the new directional detection method.

- The values of the directional angle $\theta_c$ are within the defined limits for forward fault operation and reverse fault restraint for all the fault types with fault resistances.

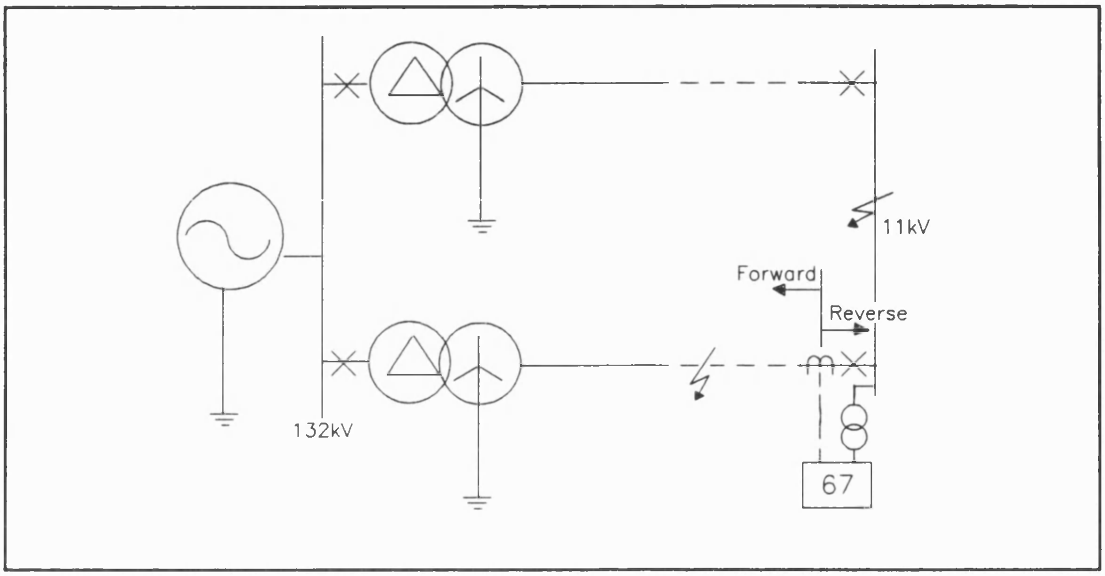
- For a given fault condition of fault position and fault resistance the magnitudes and the associated angles of the source emf have no effect on $\theta_C$.

- For 3-phase faults the fault levels have negligible effect on the values of the directional angle $\theta_C$ under the various conditions studied.

- The directional relay is capable of detecting the earth faults on the low voltage system even with the delta winding of the power transformer blocking the flow of zero phase sequence current.

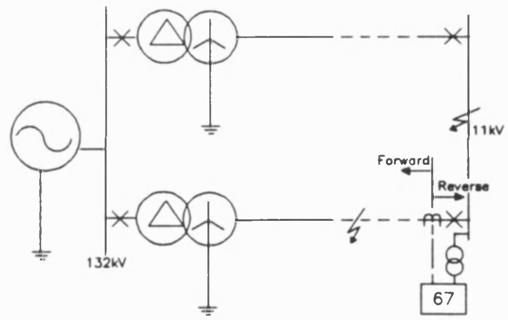
### 7.6.2.2.2 11KV Single Source Transformer Parallel Circuits of either Overhead Line or Underground Cable Feeder

The system is shown below:




A directional relay 67 is arranged to protect an 11kV feeder as shown.

The directional angles $\theta_C$ for various fault types on the feeder under maximum and minimum fault levels and their variations with fault point positions and fault resistances are presented in Figures 7.6.2.2.2.1 to 7.6.2.2.2.8 with the directional relay arranged to "see" the faults as being either in the forward or reverse direction. The results for faults on both overhead line and underground cable feeders are presented.




11KV Single Source Parallel Transformer Overhead Line Feeder System

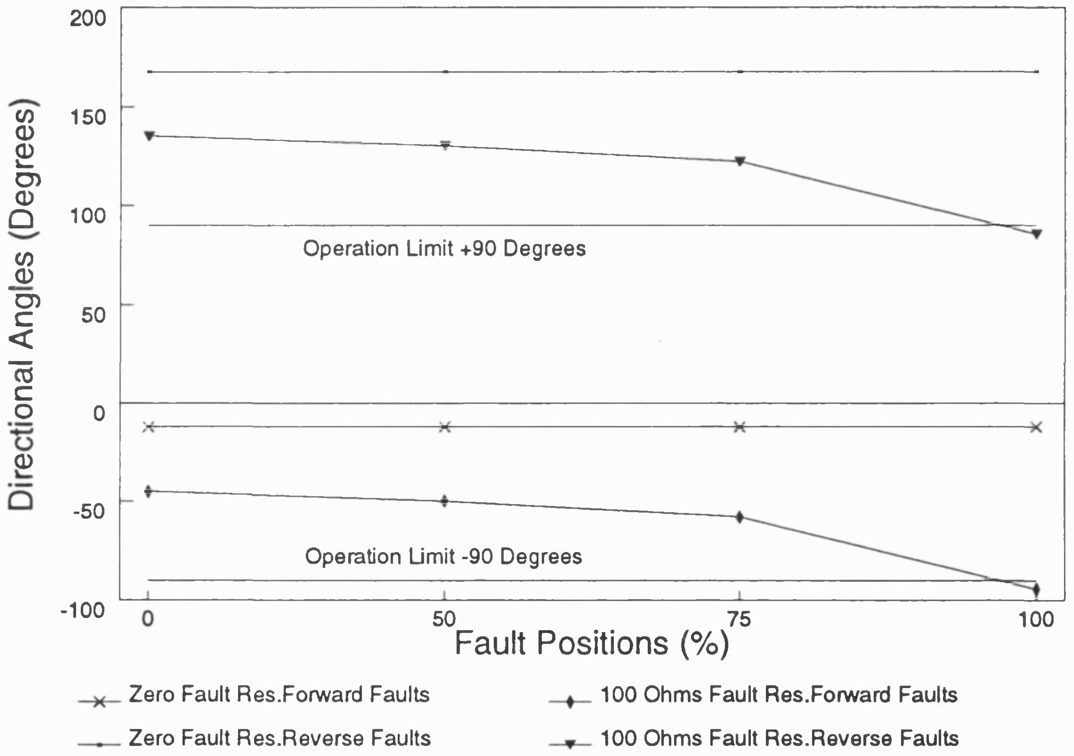
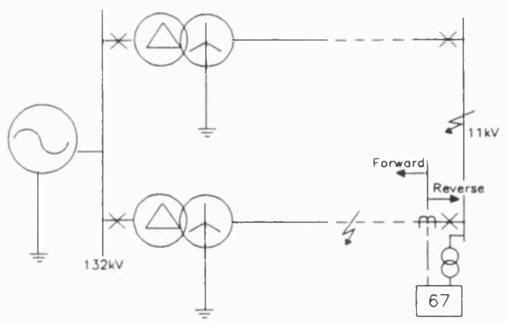



Figure 7.6.2.2.2.1 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11KV Single Source Parallel Transformer Overhead Line Feeder System

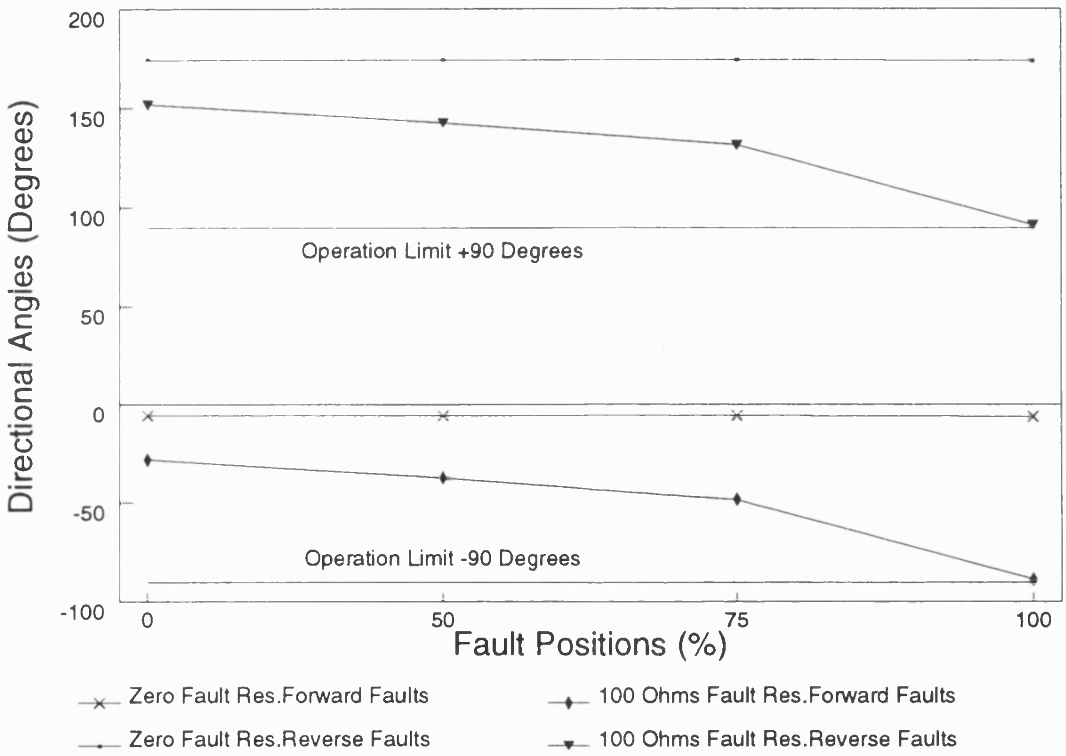
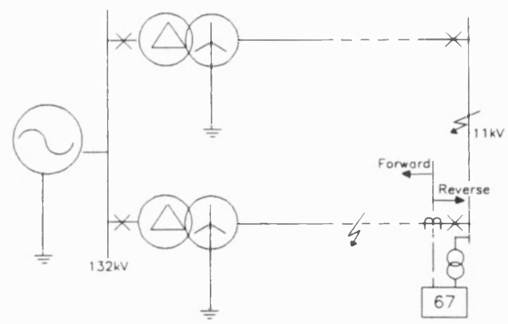



Figure 7.6.2.2.2.2 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11KV Single Source Parallel Transformer Overhead Line Feeder System

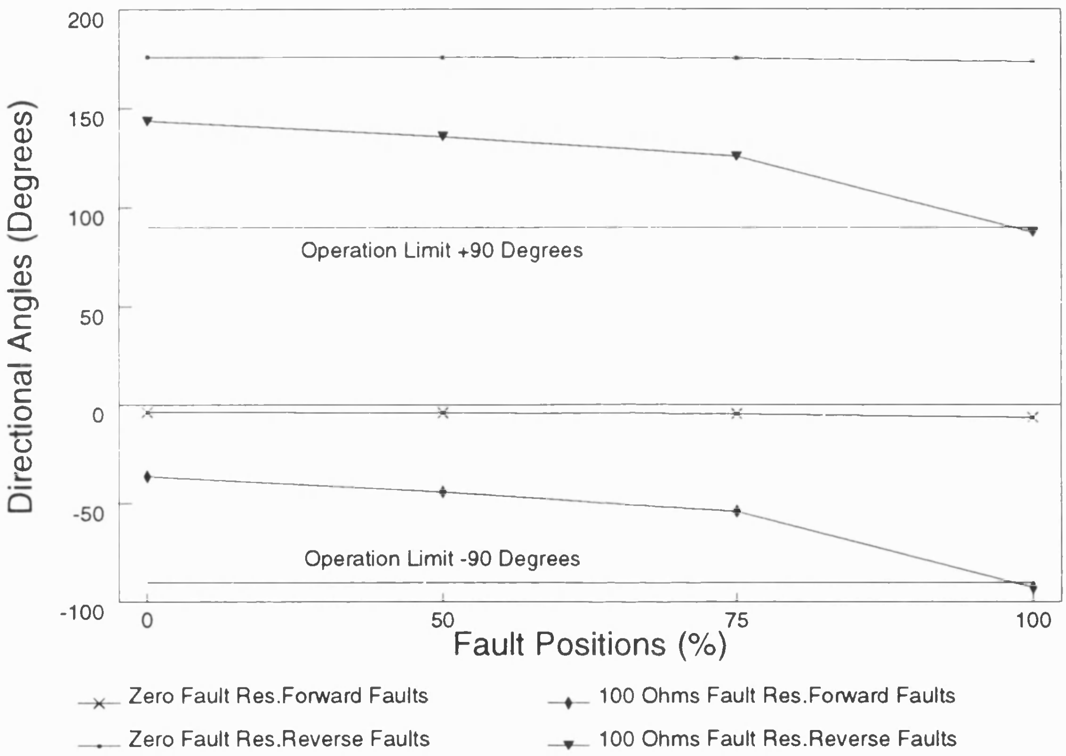
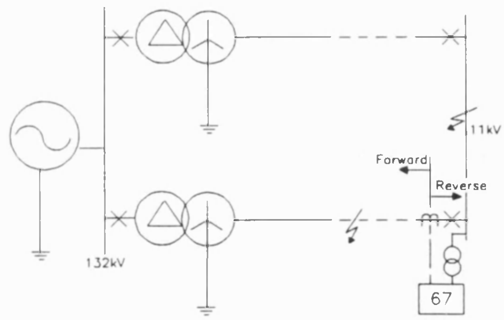



Figure 7.6.2.2.2.3 Variations of Directional Angle $\theta C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11KV Single Source Parallel Transformer Overhead Line Feeder System

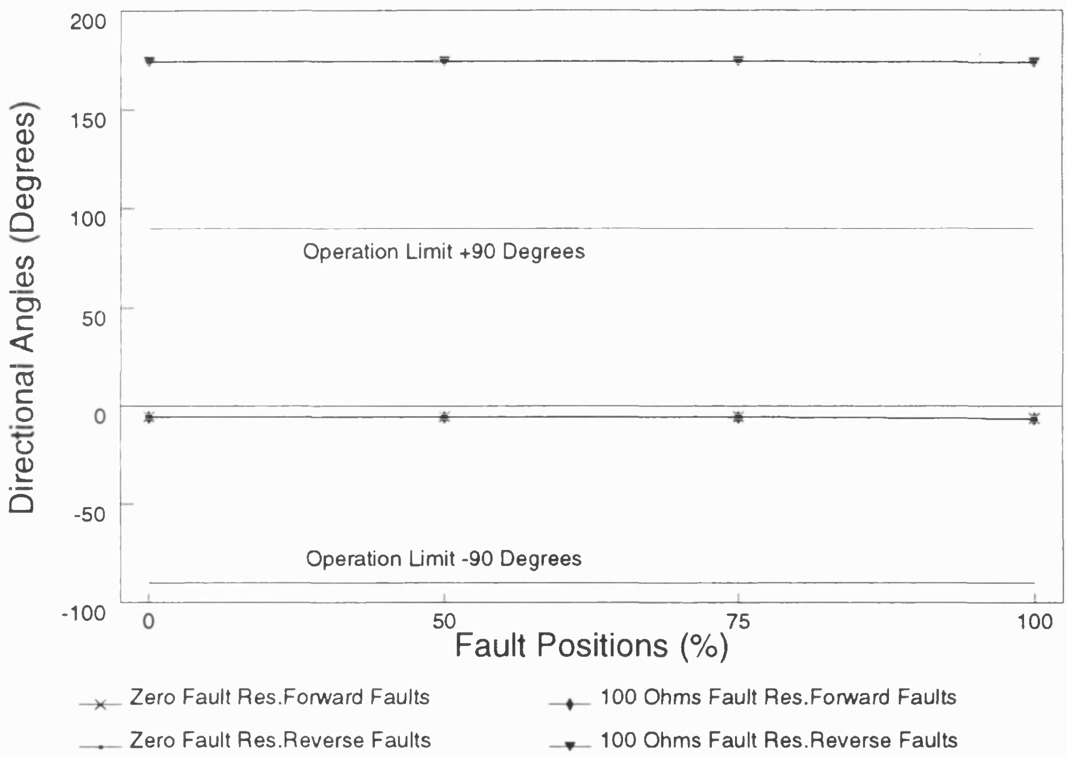
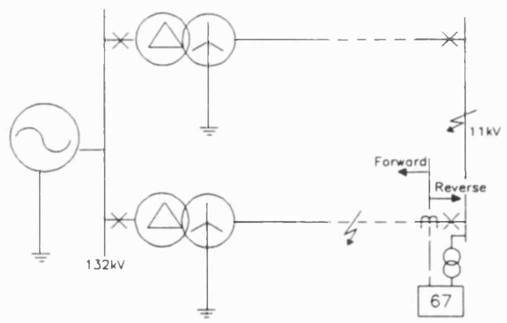



Figure 7.6.2.2.2.4 Variation of Directional Angle $\theta C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11KV Single Source Parallel Transformer Underground Cable Feeder System

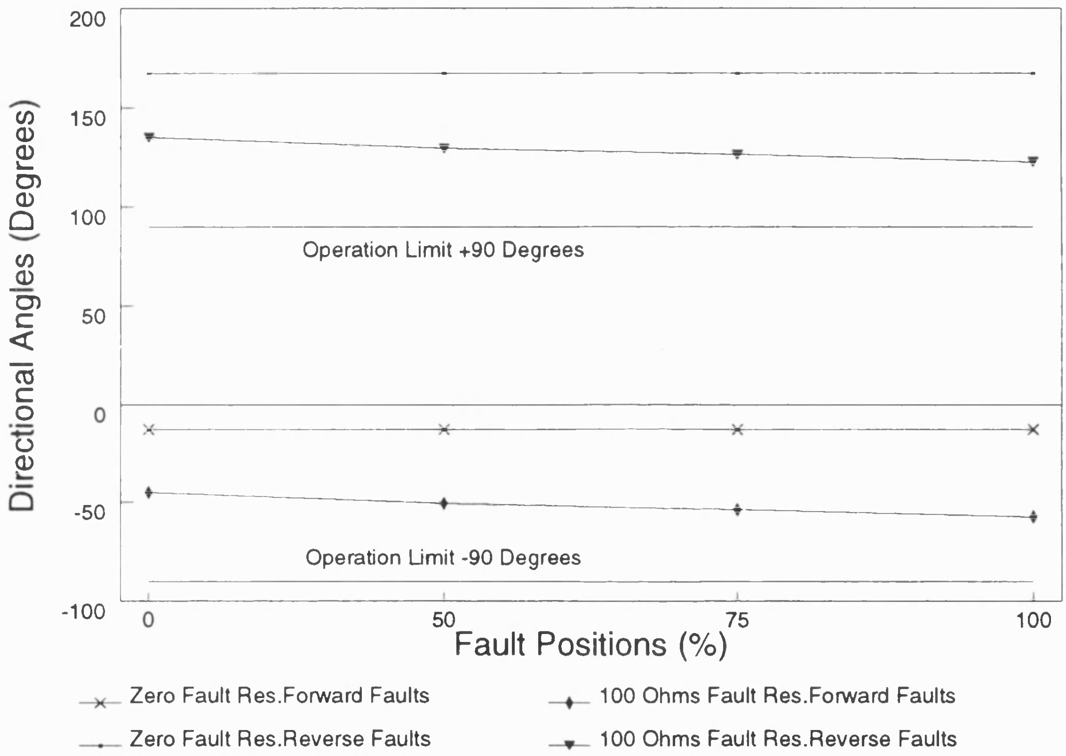
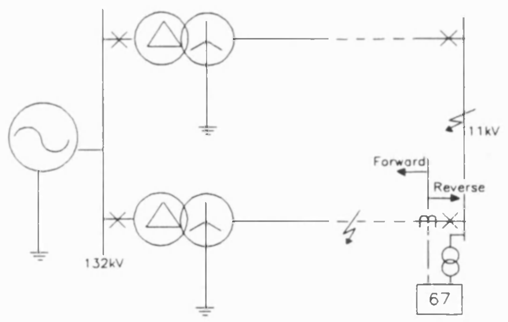



Figure 7.6.2.2.2.5 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11KV Single Source Parallel Transformer Underground Cable Feeder System

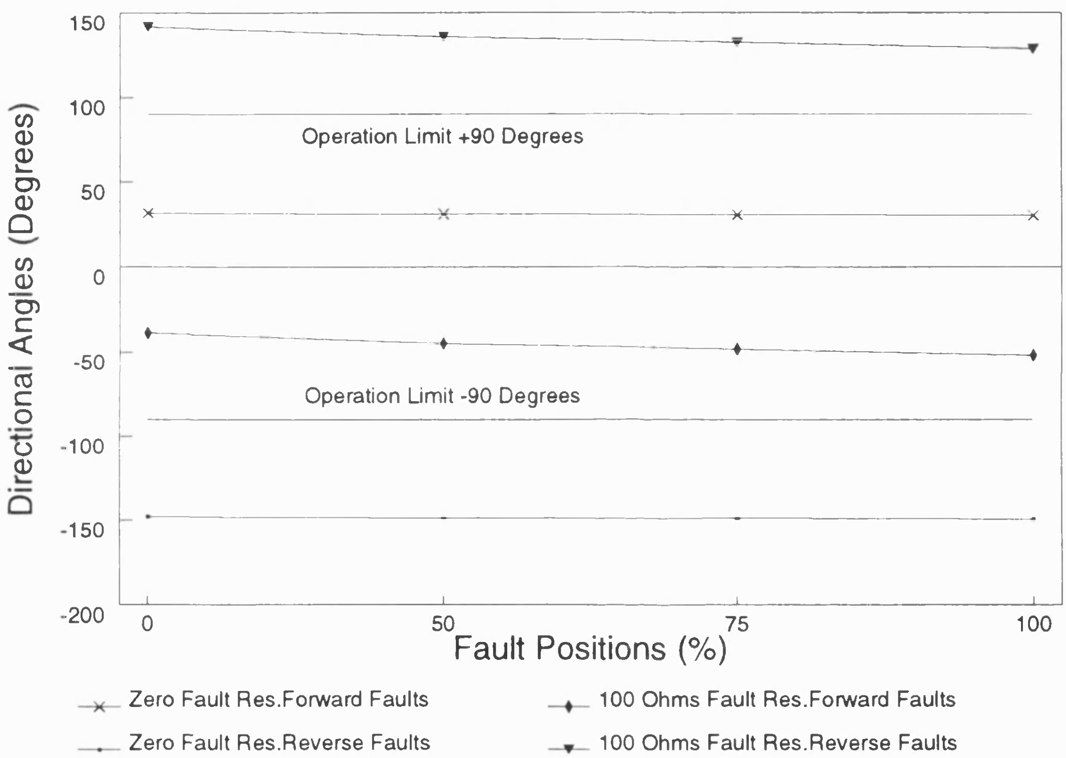
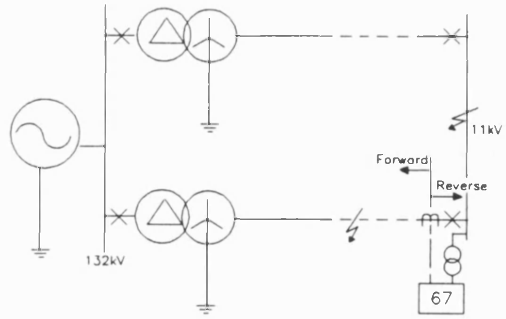



Figure 7.6.2.2.2.6 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11KV Single Source Parallel Transformer Underground Cable Feeder System

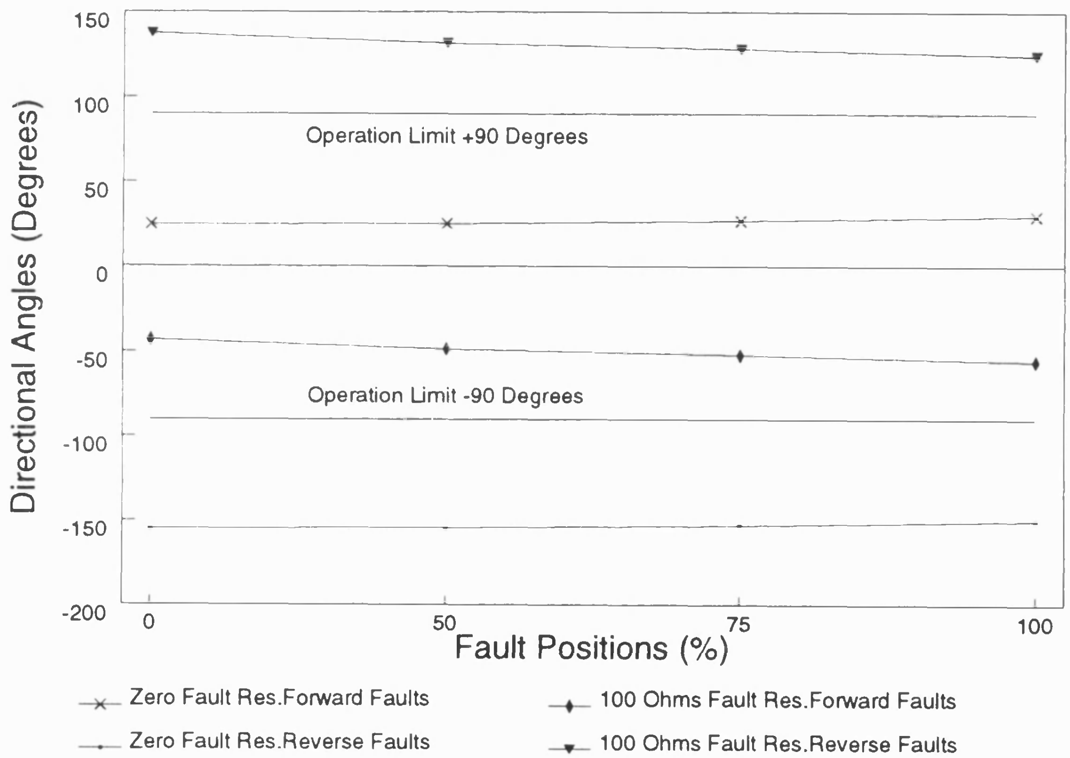
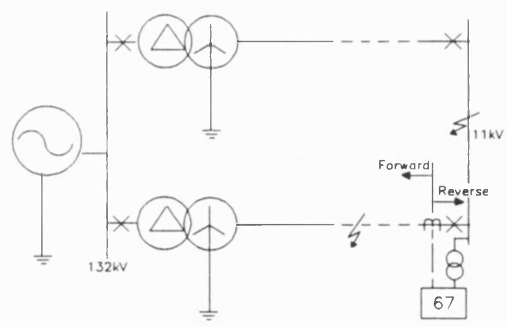



Figure 7.6.2.2.2.7 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




11KV Single Source Parallel Transformer Underground Cable Feeder System

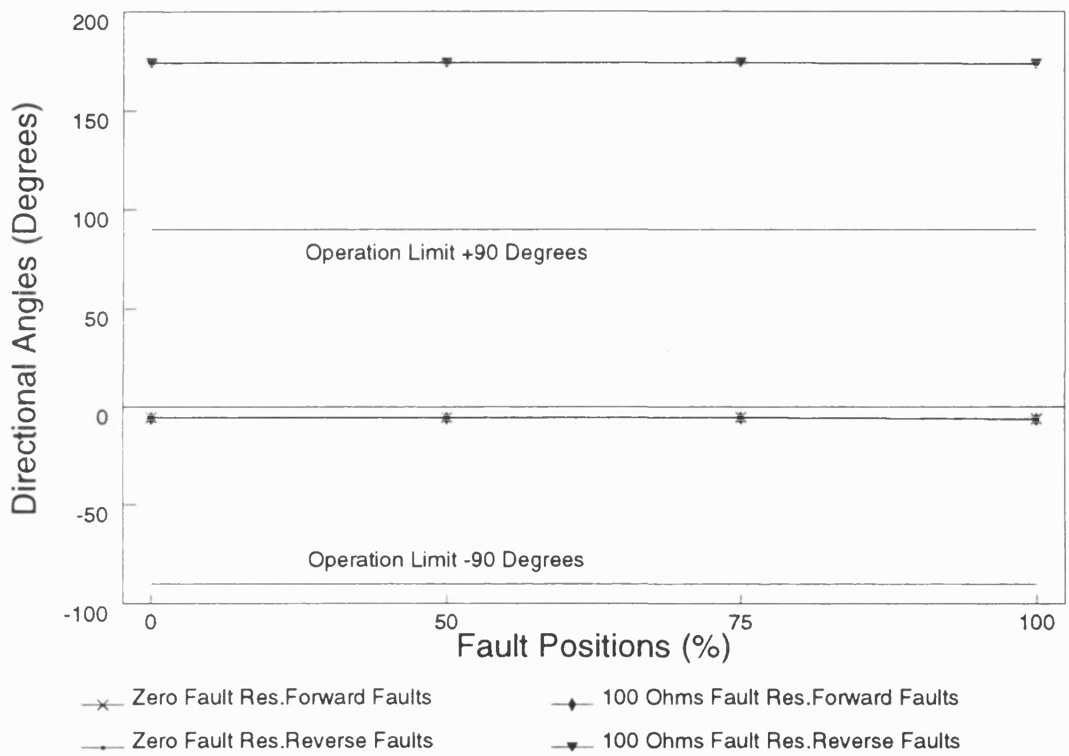



Figure 7.6.2.2.2.8 Variations of Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.

For this 11kV arrangement of parallel transformer feeders where directional relays are normally installed as shown the performance of the new directional detection method is satisfactory except the following:

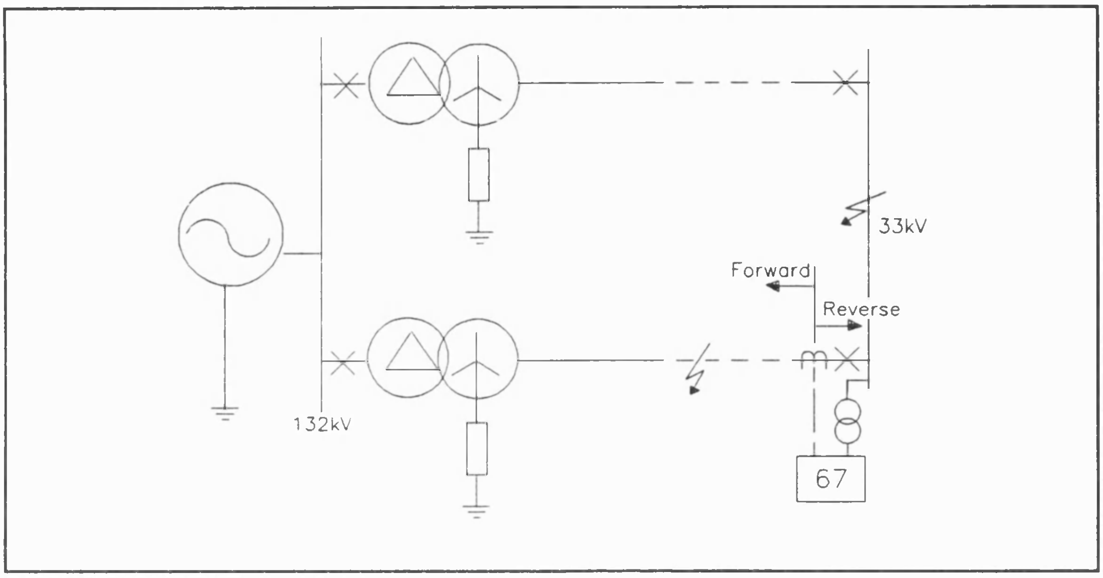
- For 3-phase, phase-phase and single-phase-earth faults at 100% of the overhead line feeder, i.e., at the 11kV terminals of the transformer, the new method is not able to determine correctly the fault direction when 100Ω fault resistance is present.

- For underground cable feeder the new method is able to determine correctly the direction of all fault types in the presence of high fault resistances.

- The magnitude and the associated angle of the source emf have no effect on the resulting values of the directional angle $\theta_C$.

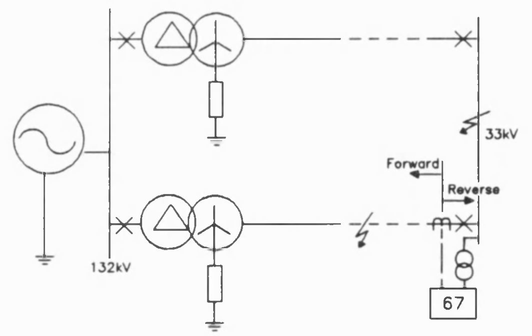
### 7.6.2.2.3 33KV Single Source Transformer Parallel Circuits of either Overhead Line or Underground Cable Feeder

The system is shown below:




The same arrangement as that of the 11kV system in Section 7.6.2.2.2 is used. The directional relay 67 is installed at the end of the 33kV feeder.

The variations in the directional angle $\theta_C$ with fault positions and fault resistances under similar conditions are examined and the results are presented in Figures 7.6.2.2.3.1 to 7.6.2.2.3.8 for faults on both overhead line and underground cable feeders.




33KV Single Source Parallel Transformer Overhead Line Feeder System

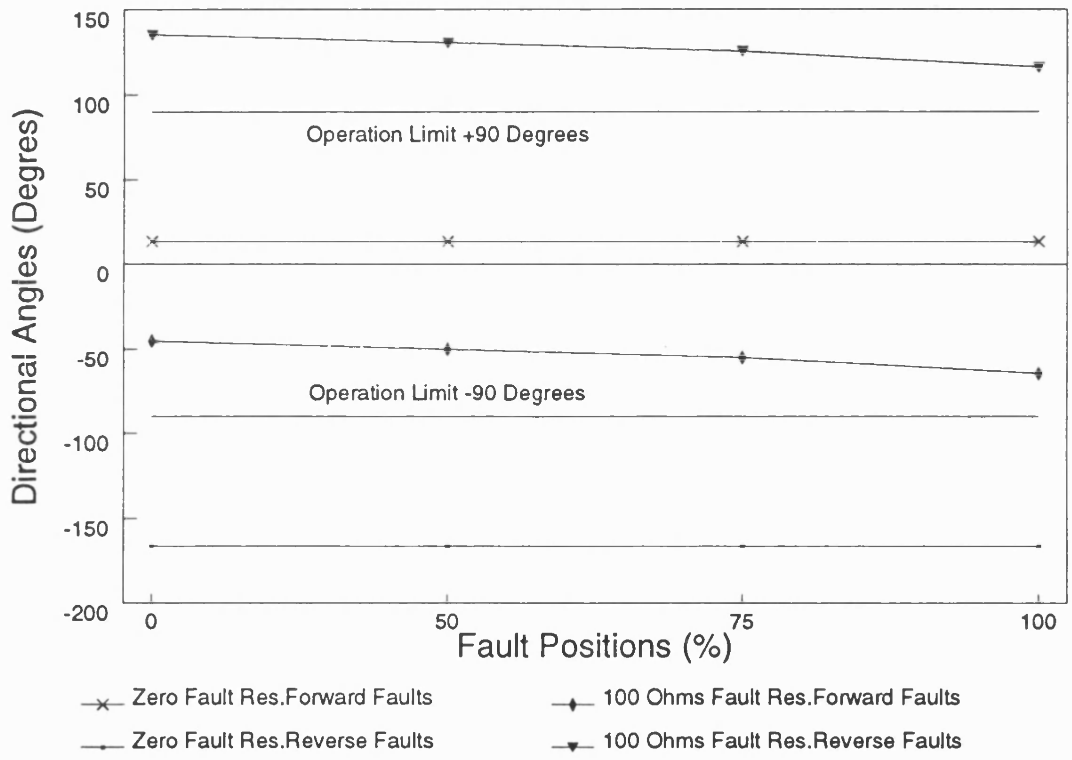
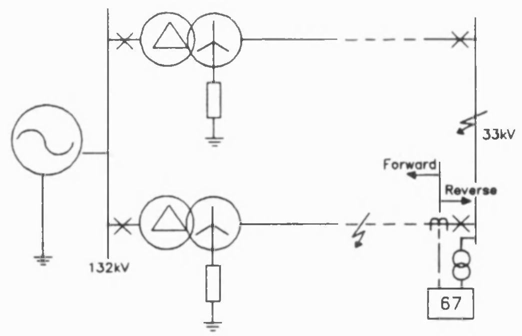



Figure 7.6.2.2.3.1 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33KV Single Source Parallel Transformer Overhead Line Feeder System

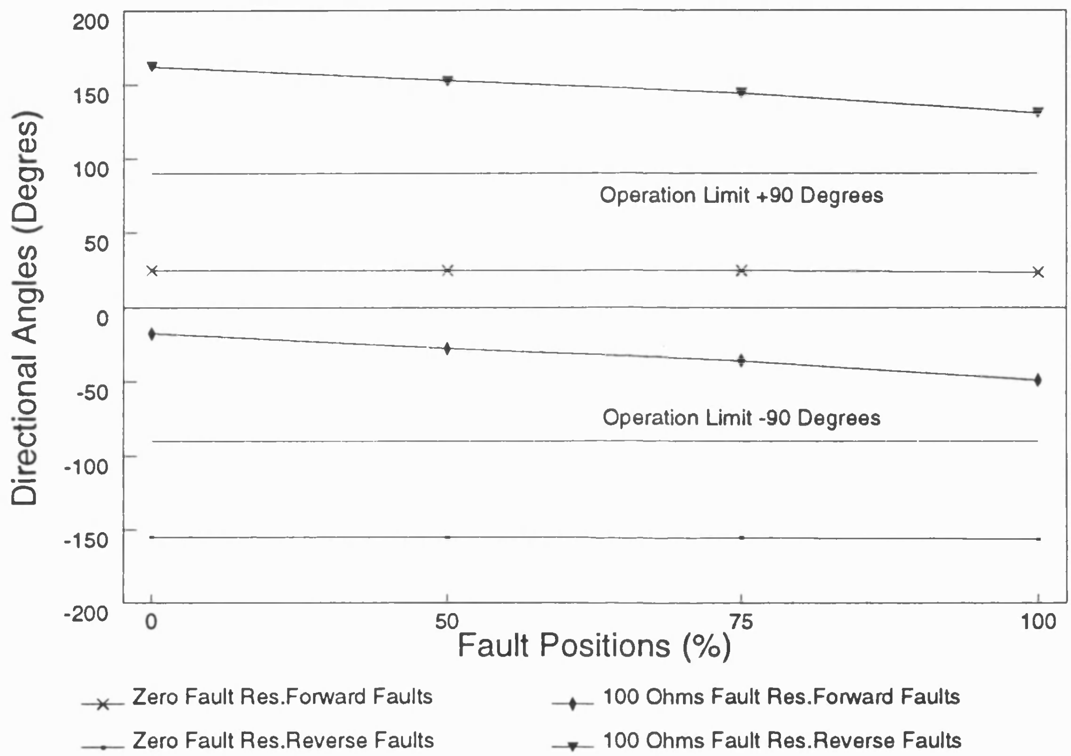
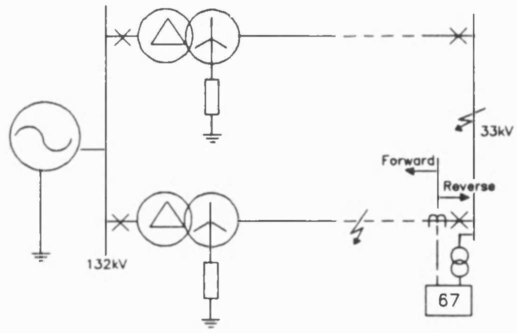



Figure 7.6.2.2.3.2 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33KV Single Source Parallel Transformer Overhead Line Feeder System

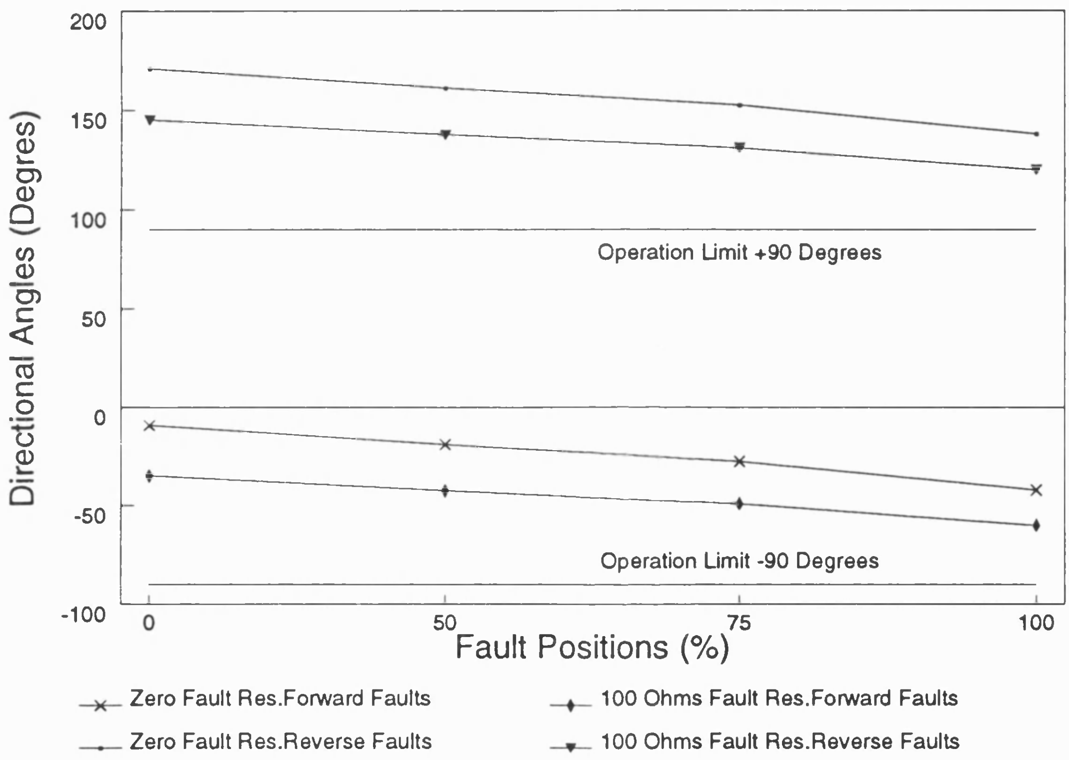
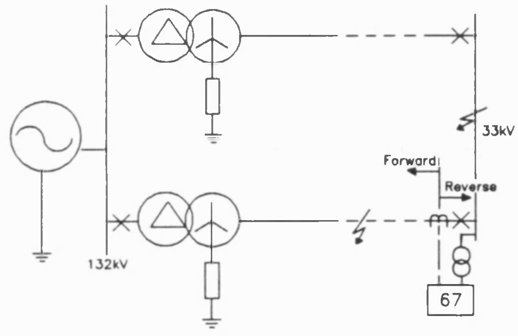



Figure 7.6.2.2.3.3 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33KV Single Source Parallel Transformer Overhead Line Feeder System

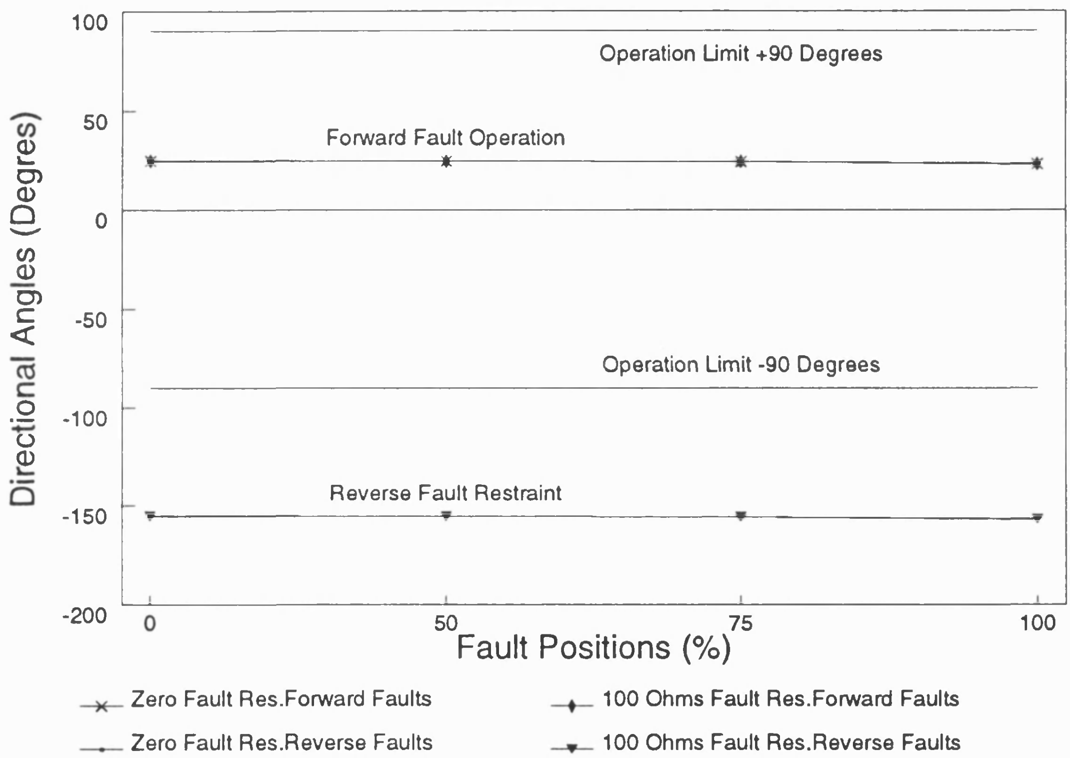
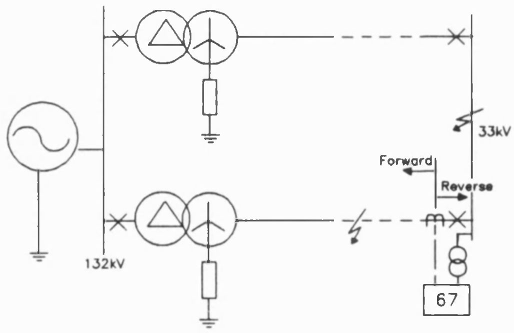



Figure 7.6.2.2.3.4 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33KV Single Source Parallel Transformer Underground Cable Feeder System

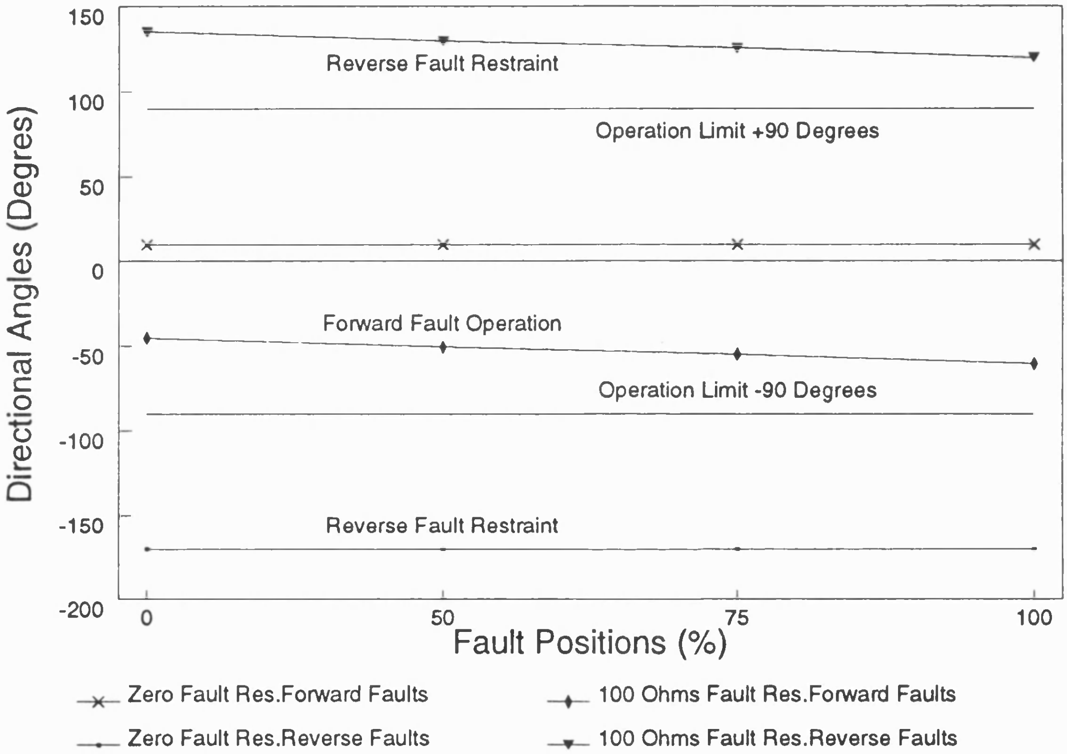
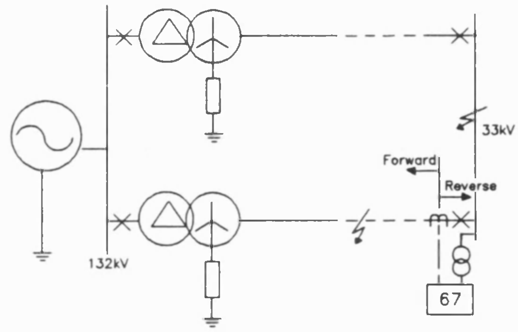



Figure 7.6.2.2.3.5 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33KV Single Source Parallel Transformer Underground Cable Feeder System

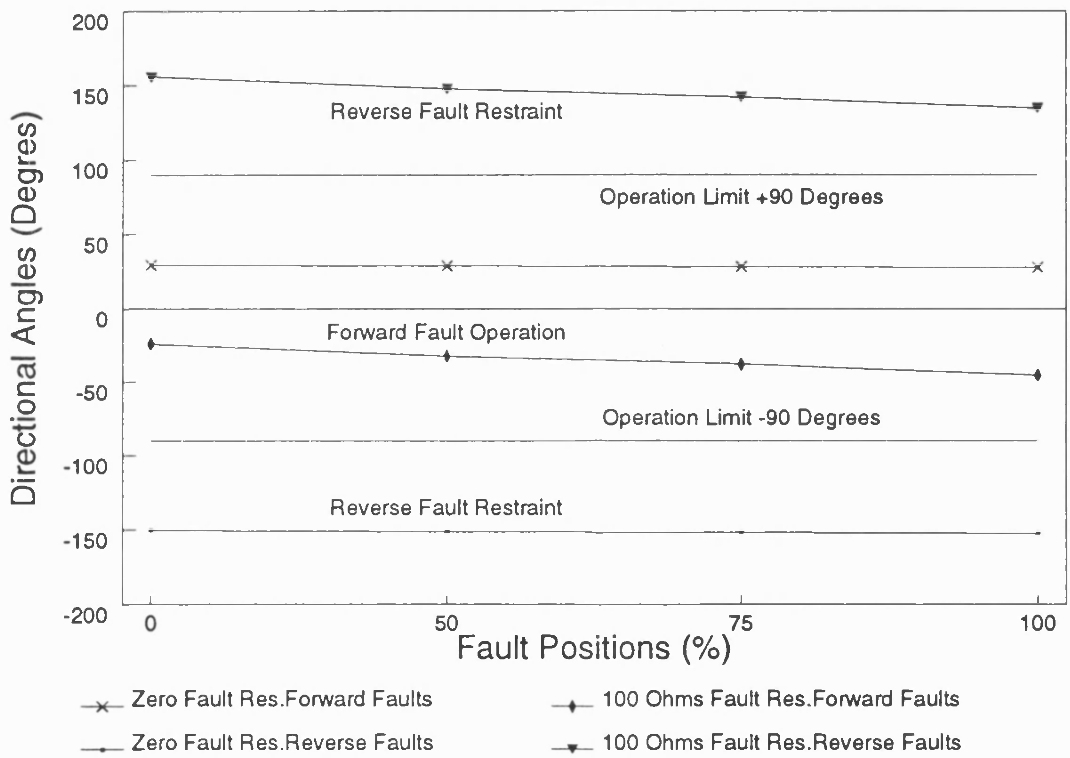
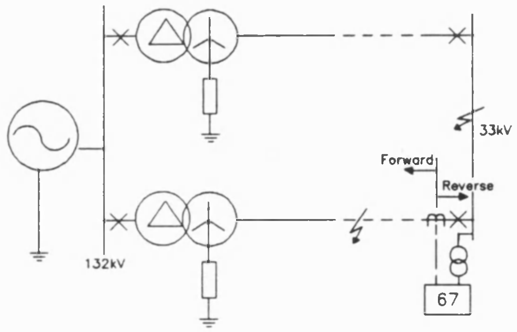



Figure 7.6.2.2.3.6 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33KV Single Source Parallel Transformer Underground Cable Feeder System

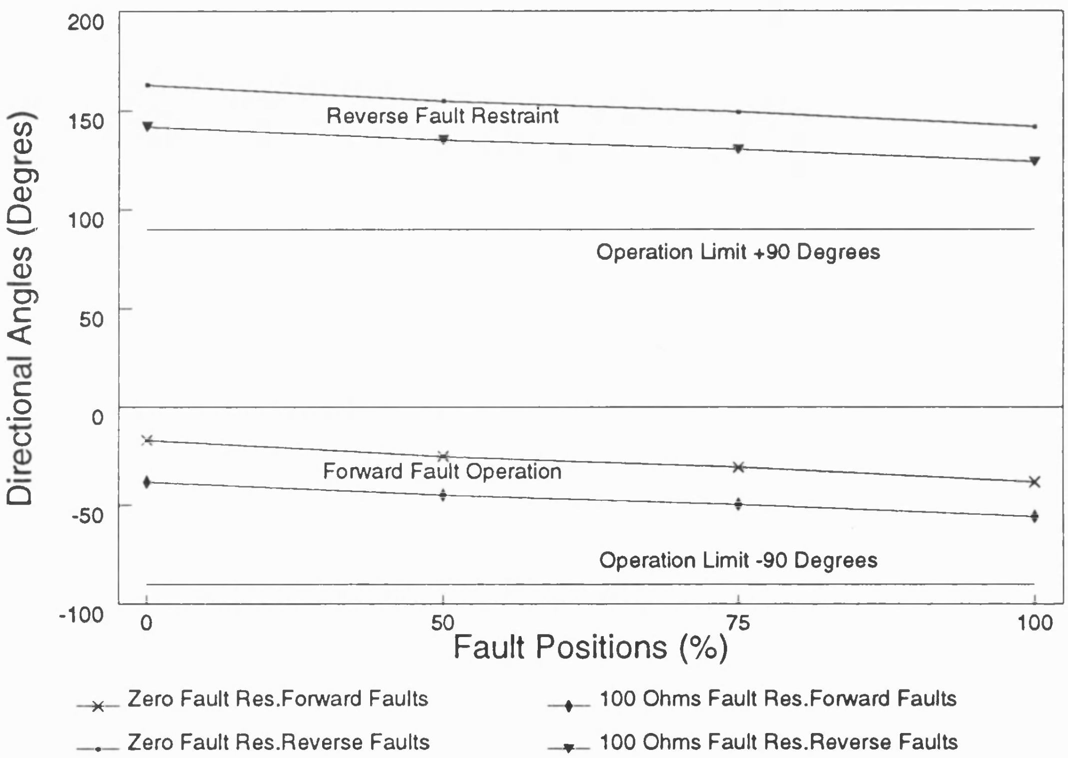
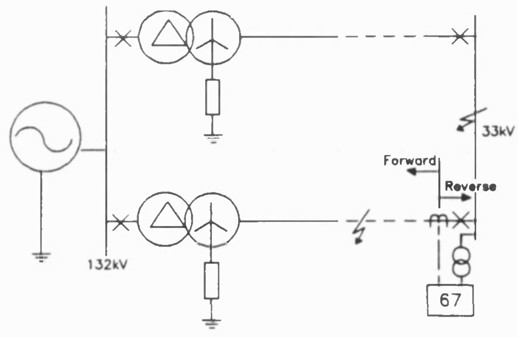



Figure 7.6.2.2.3.7 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.




33KV Single Source Parallel Transformer Underground Cable Feeder System

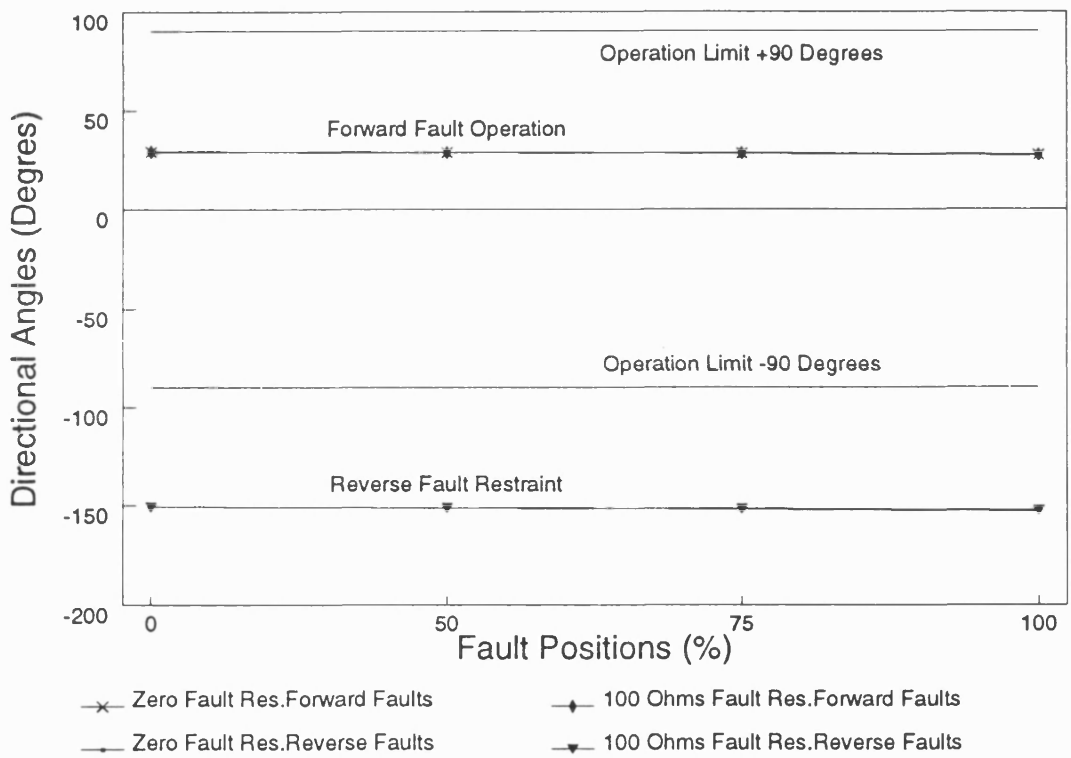



Figure 7.6.2.2.3.8 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Forward and then Reverse Faults.

For this 33kV parallel transformer feeder arrangement the following observations can be made on the performance of the new directional detection method.

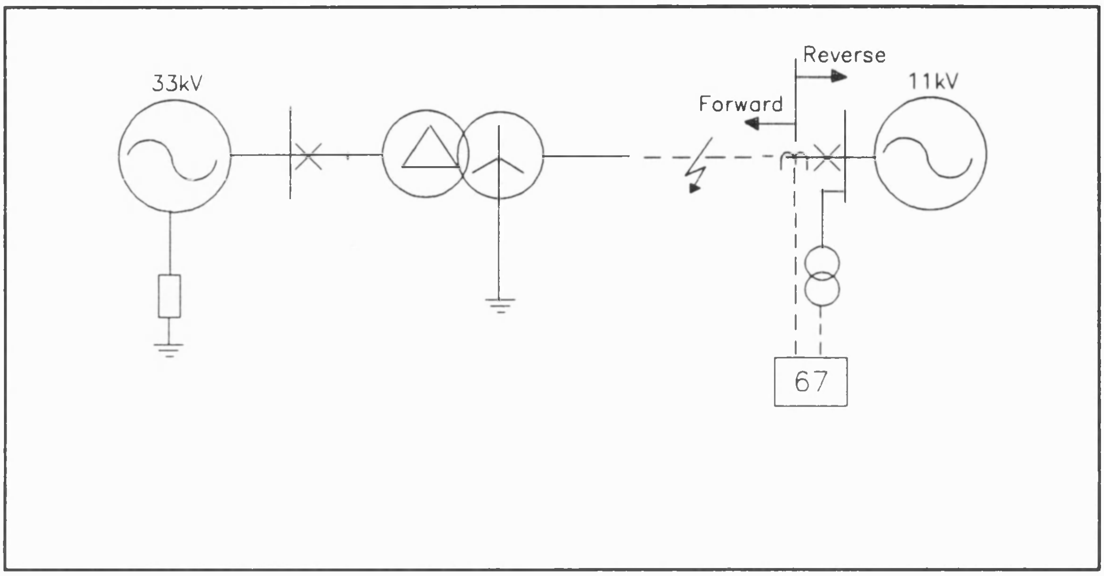
- The new method is able to operate for a resistance-earthed system.

- The directional angle $\theta_C$ for all types of faults along the feeder are well within the $\pm 90^0$ limits with fault resistances up to 100Ω for both overhead line and underground cable feeders.

- The magnitude and the associated angle of the source emf have no effect on the resulting values of $\theta_{C.}$

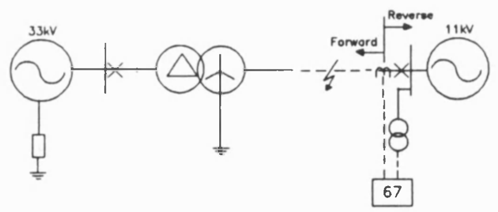
### 7.6.2.2.4 11KV Distribution System with 33KV Transformer Source to either Overhead Line or Underground Cable Feeder

The system is shown below:




In this system the 11kV distribution feeder is also supplied from a 33kV source via a transformer.

The variations of the directional angle $\theta_C$ for various fault types on the feeder with fault positions and fault resistances are examined and presented in Figures 7.6.2.2.4.1 to 7.6.2.2.4.16 for both overhead line and underground cable feeders. The directional relay 67 is arranged to "see" the faults as being either in the forward or reverse direction and without and with 100% pre-fault load current flow importing from the 33kV source.




11KV Distribution Overhead Line Feeder with a 33kV Transformer Source at One End

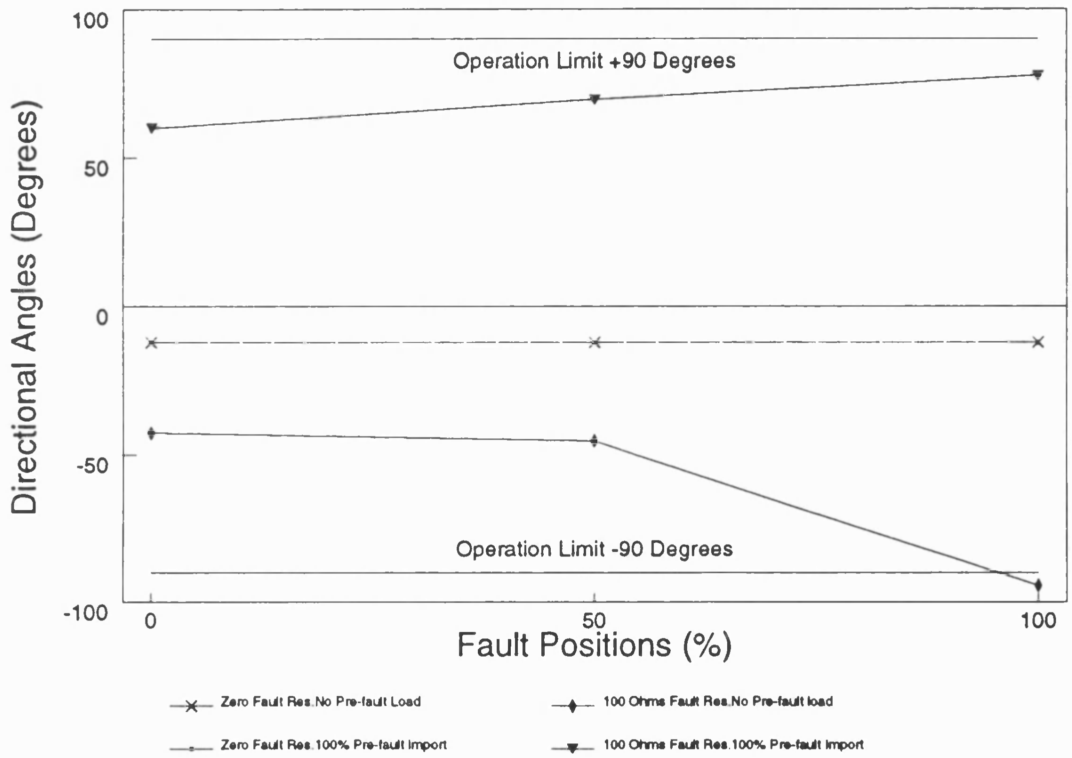
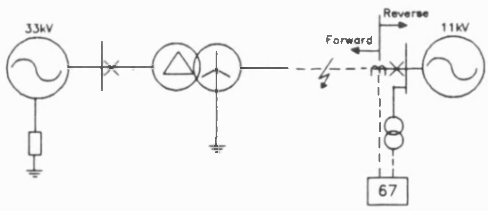



Figure 7.6.2.2.4.1 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Overhead Line Feeder with a 33kV Transformer Source at One End

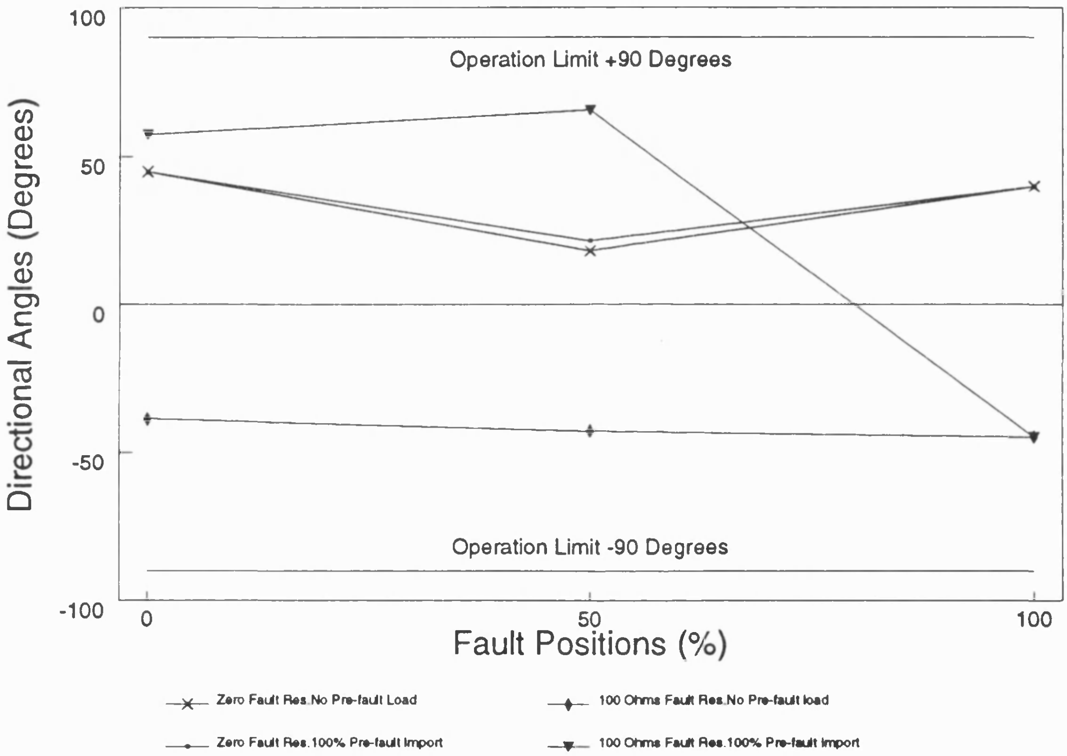
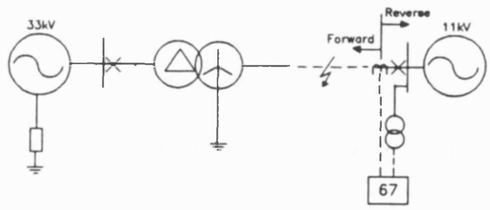



Figure 7.6.2.2.4.2 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Overhead Line Feeder with a 33kV Transformer Source at One End

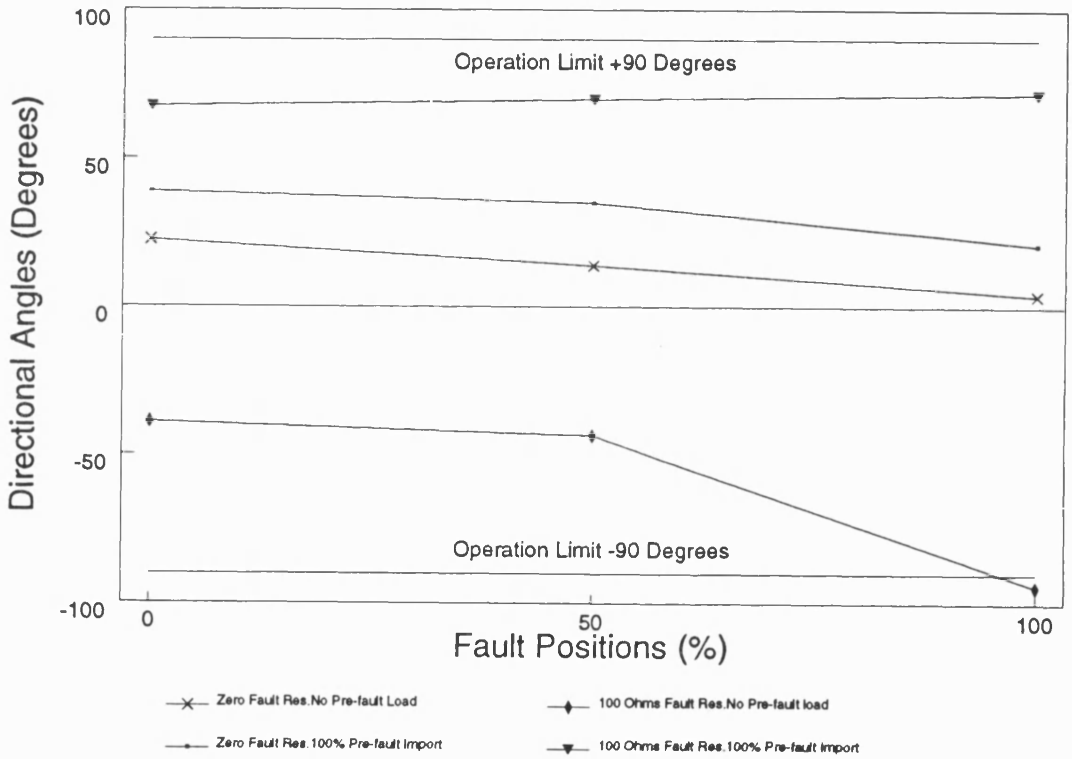
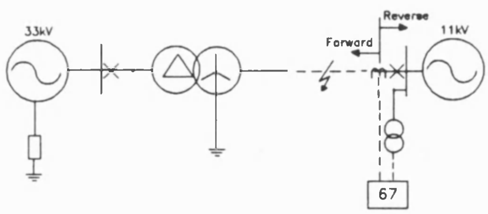



Figure 7.6.2.2.4.3 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Overhead Line Feeder with a 33kV Transformer Source at One End

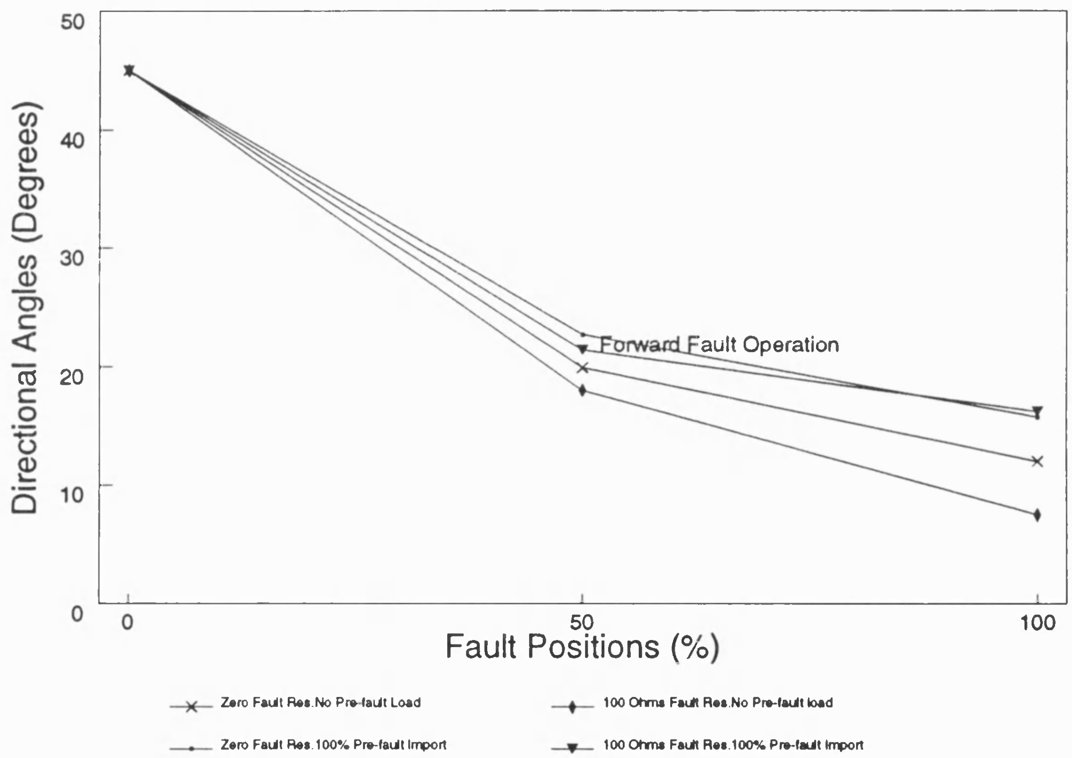
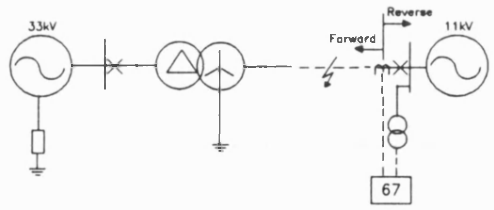



Figure 7.6.2.2.4.4 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Underground Cable Feeder with a 33kV Transformer Source at One End

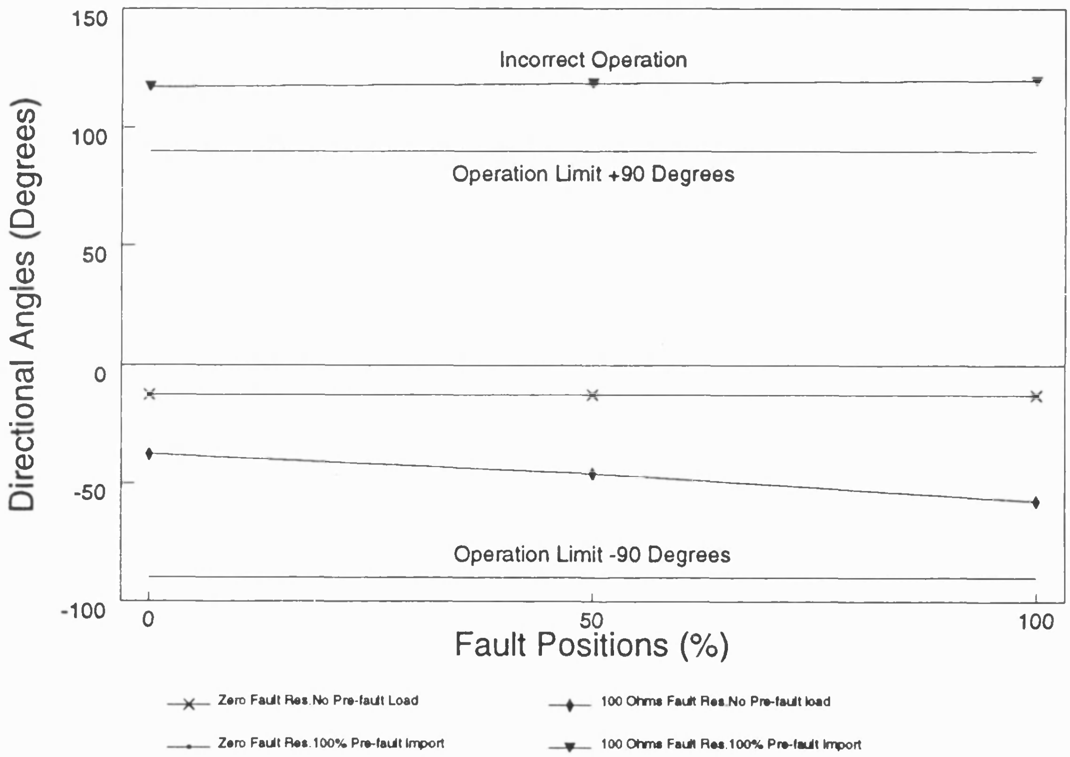
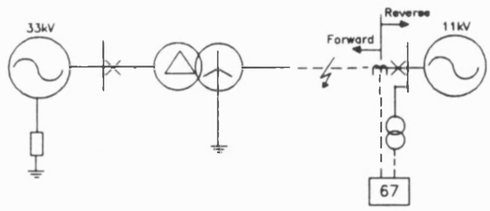



Figure 7.6.2.2.4.5 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Underground Cable Feeder with a 33kV Transformer Source at One End

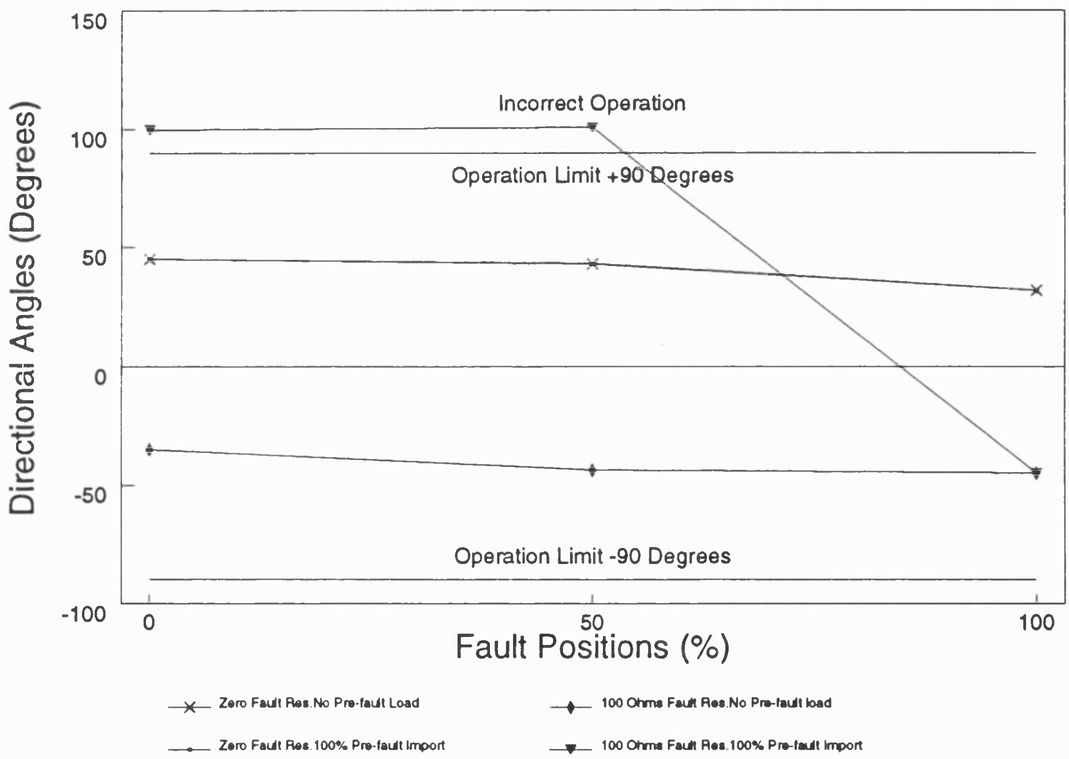
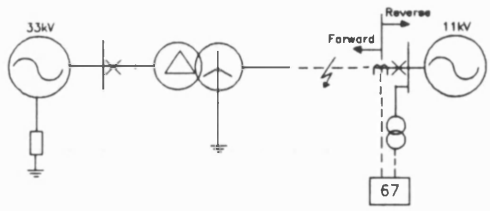



Figure 7.6.2.2.4.6 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Underground Cable Feeder with a 33kV Transformer Source at One End

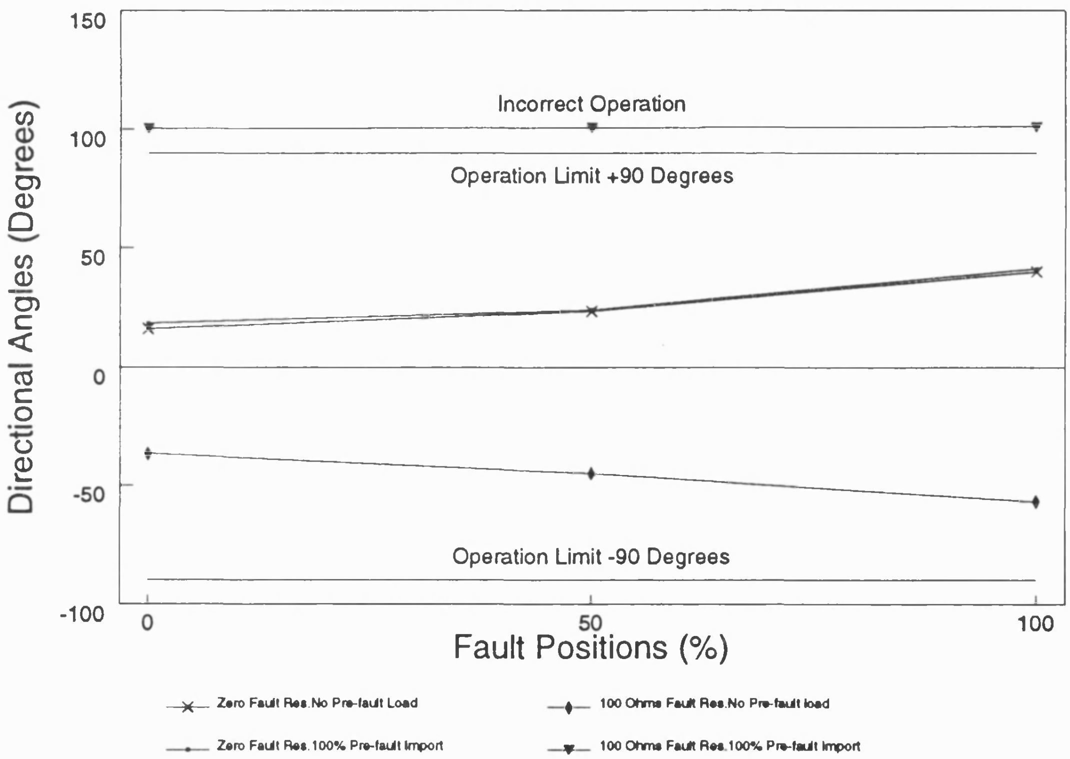
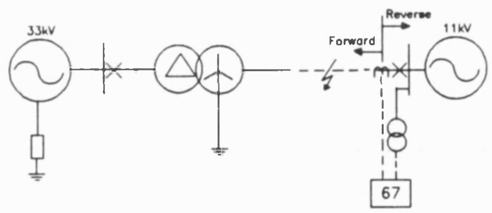



Figure 7.6.2.2.4.7 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Underground Cable Feeder with a 33kV Transformer Source at One End

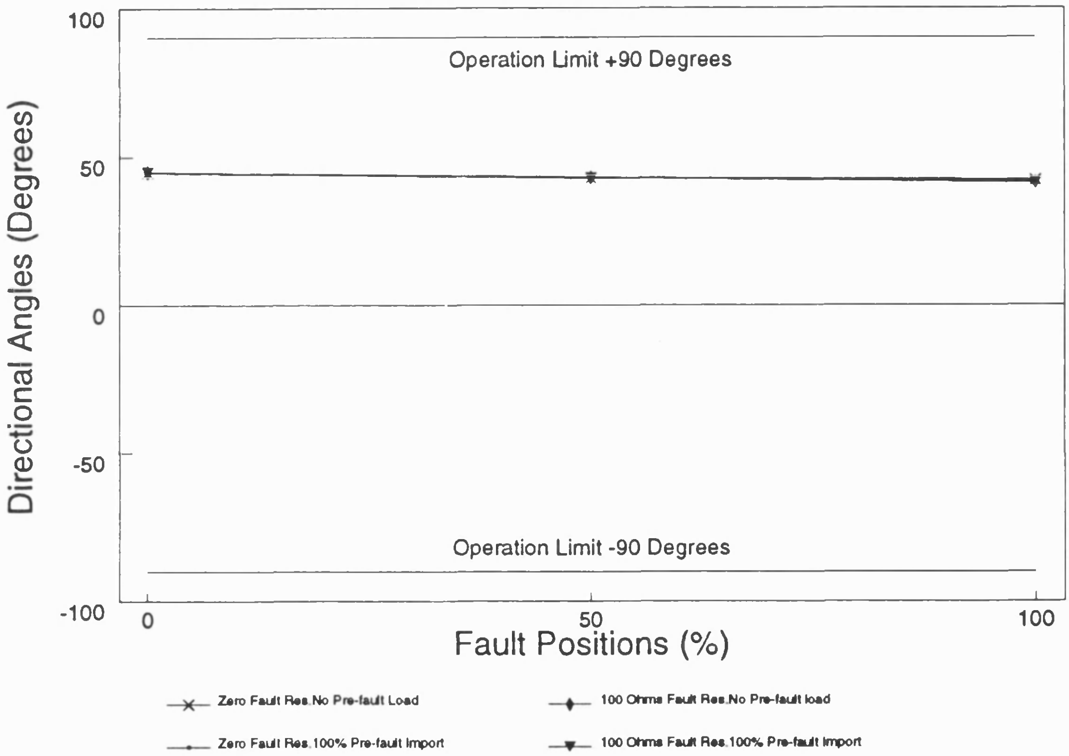
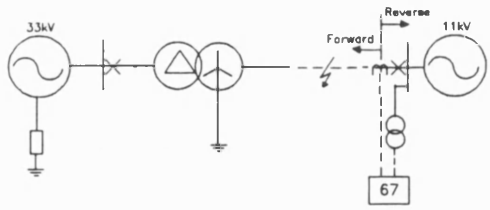



Figure 7.6.2.2.4.8 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Overhead Line Feeder with a 33kV Transformer Source at One End

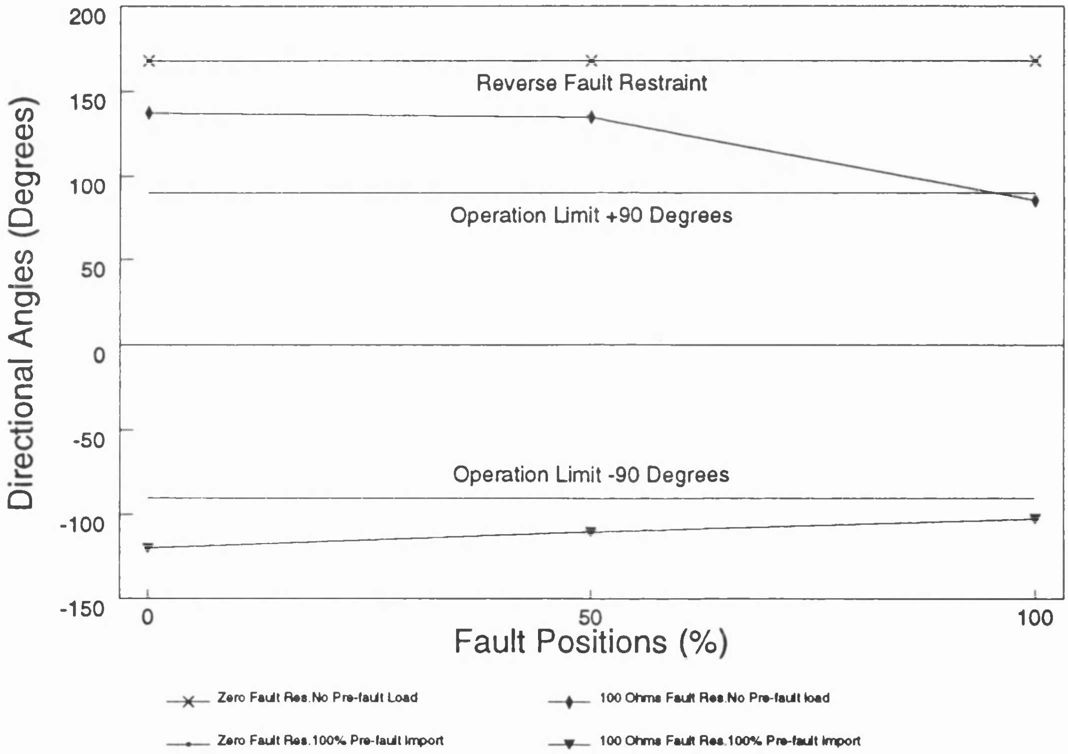
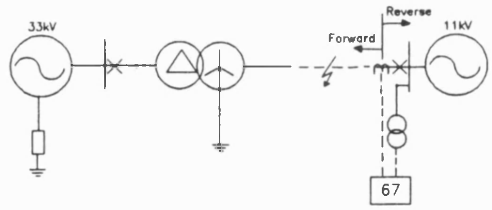



Figure 7.6.2.2.4.9 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Overhead Line Feeder with a 33kV Transformer Source at One End

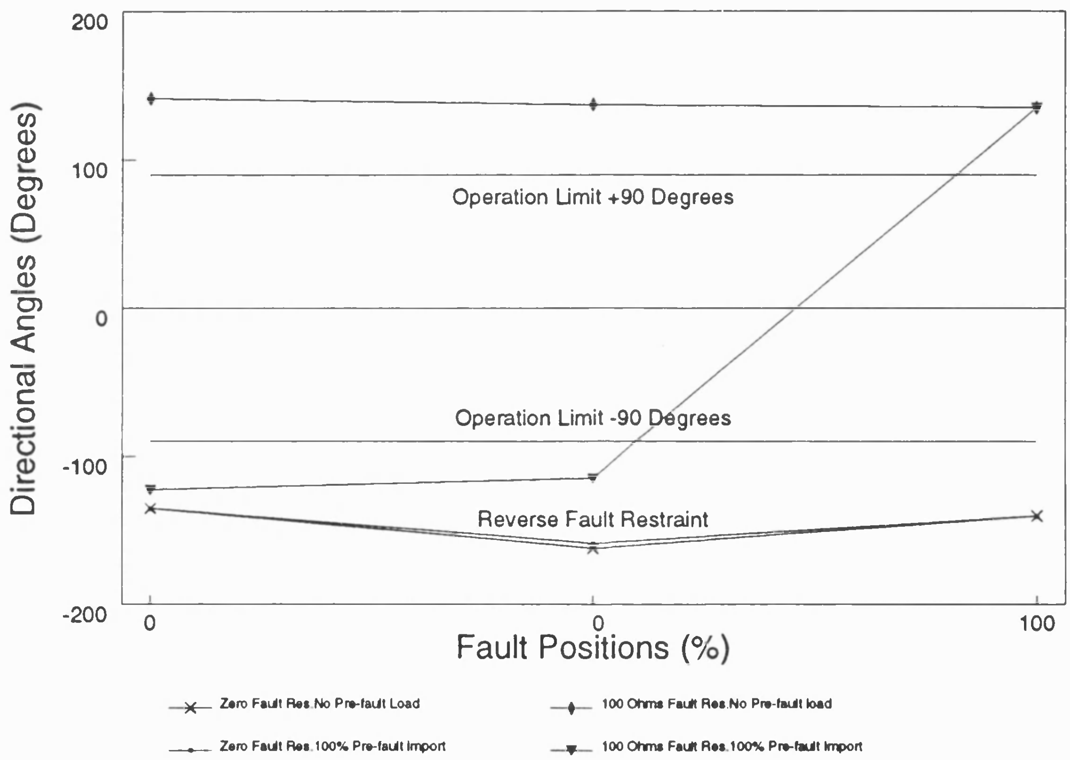
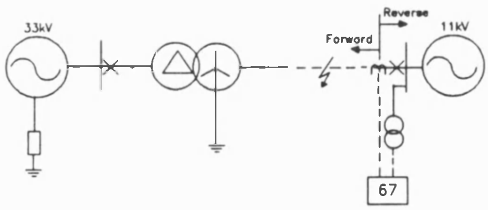



Figure 7.6.2.2.4.10 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Overhead Line Feeder with a 33kV Transformer Source at One End

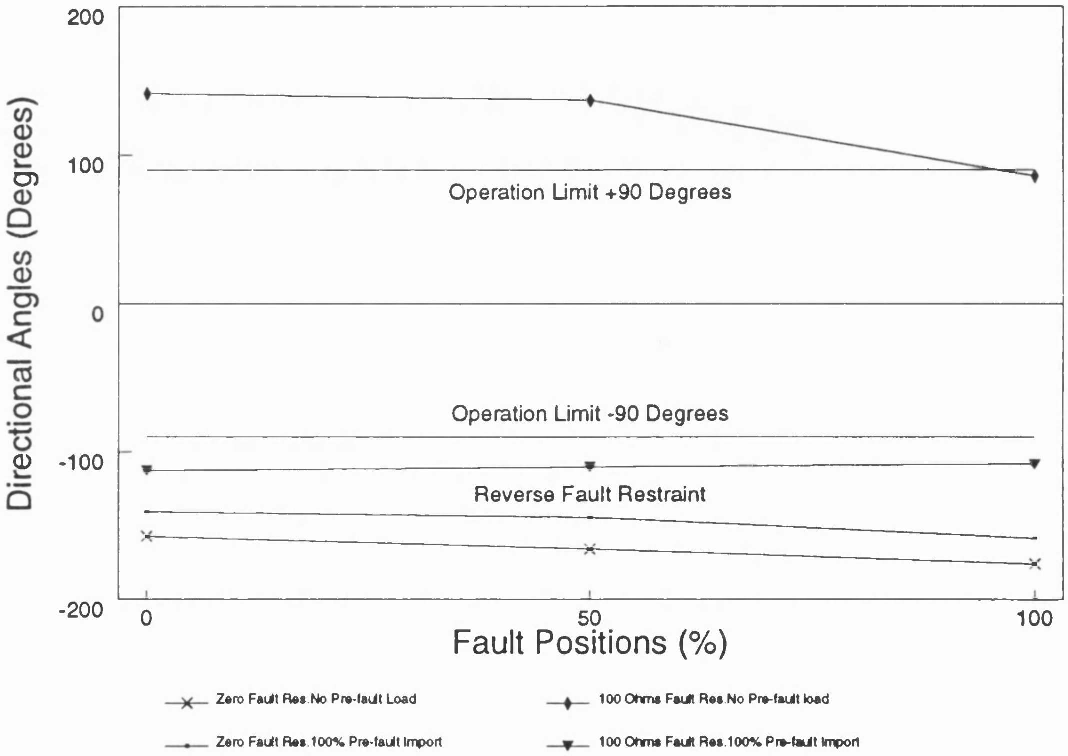
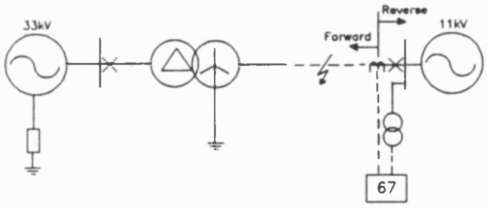



Figure 7.6.2.2.4.11 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Overhead Line Feeder with a 33kV Transformer Source at One End

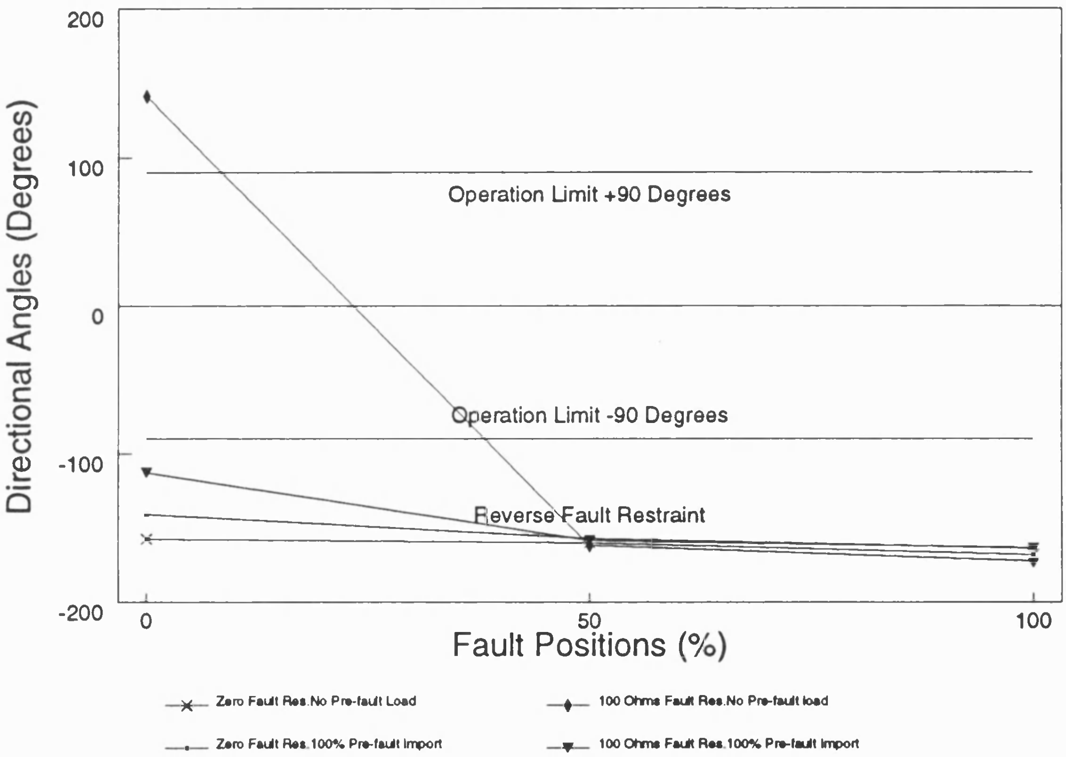
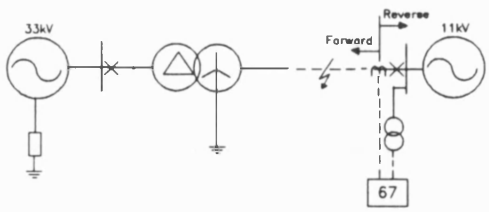



Figure 7.6.2.2.4.12 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Underground Cable Feeder with a 33kV Transformer Source at One End

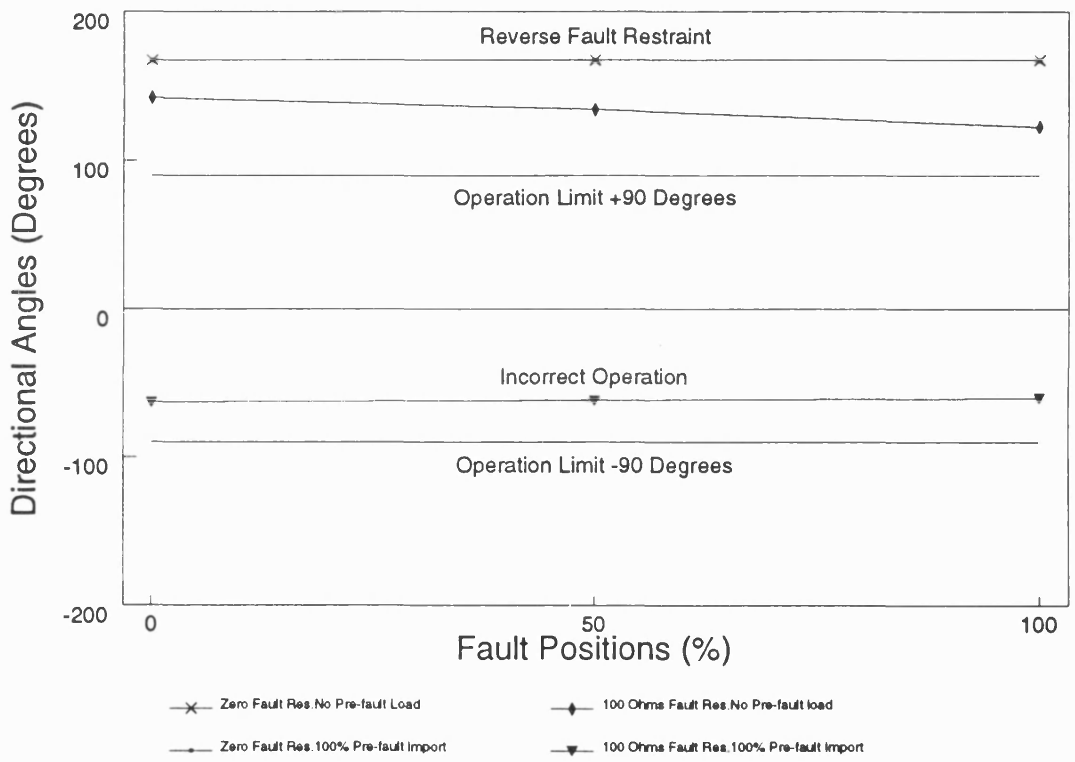
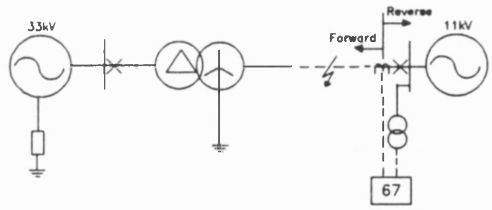



Figure 7.6.2.2.4.13 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Underground Cable Feeder with a 33kV Transformer Source at One End

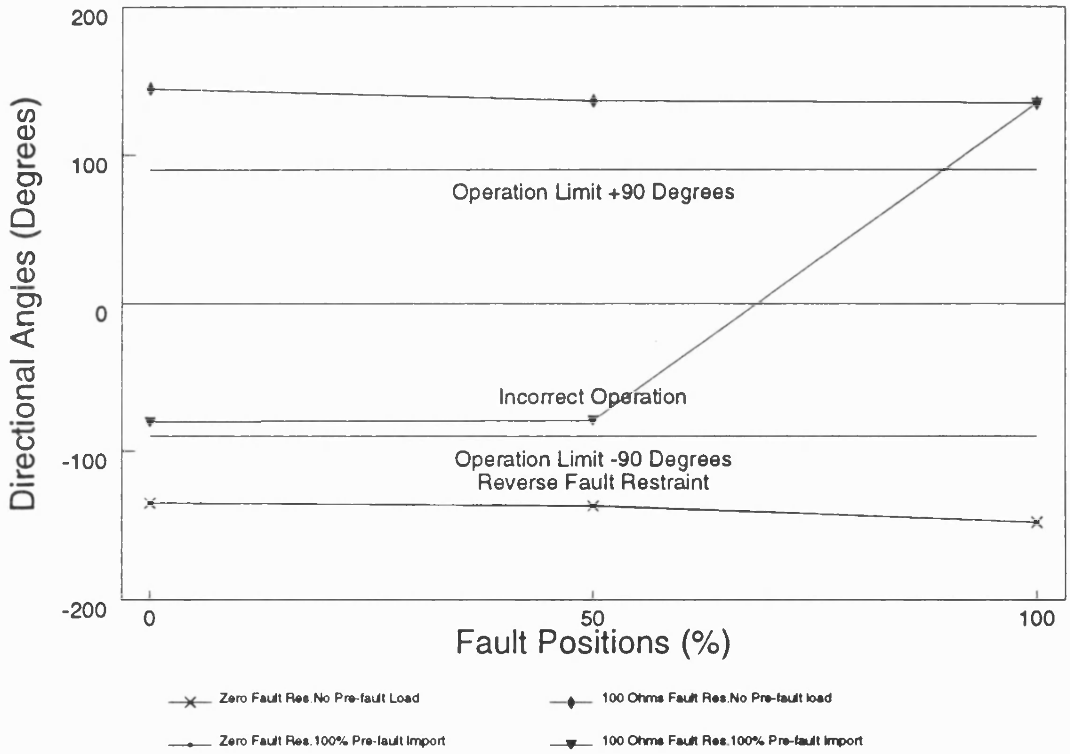
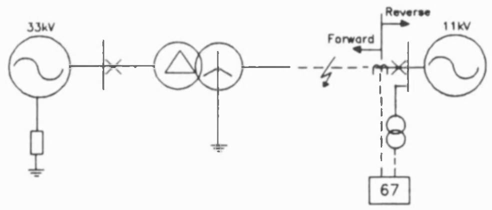



Figure 7.6.2.2.4.14 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Underground Cable Feeder with a 33kV Transformer Source at One End

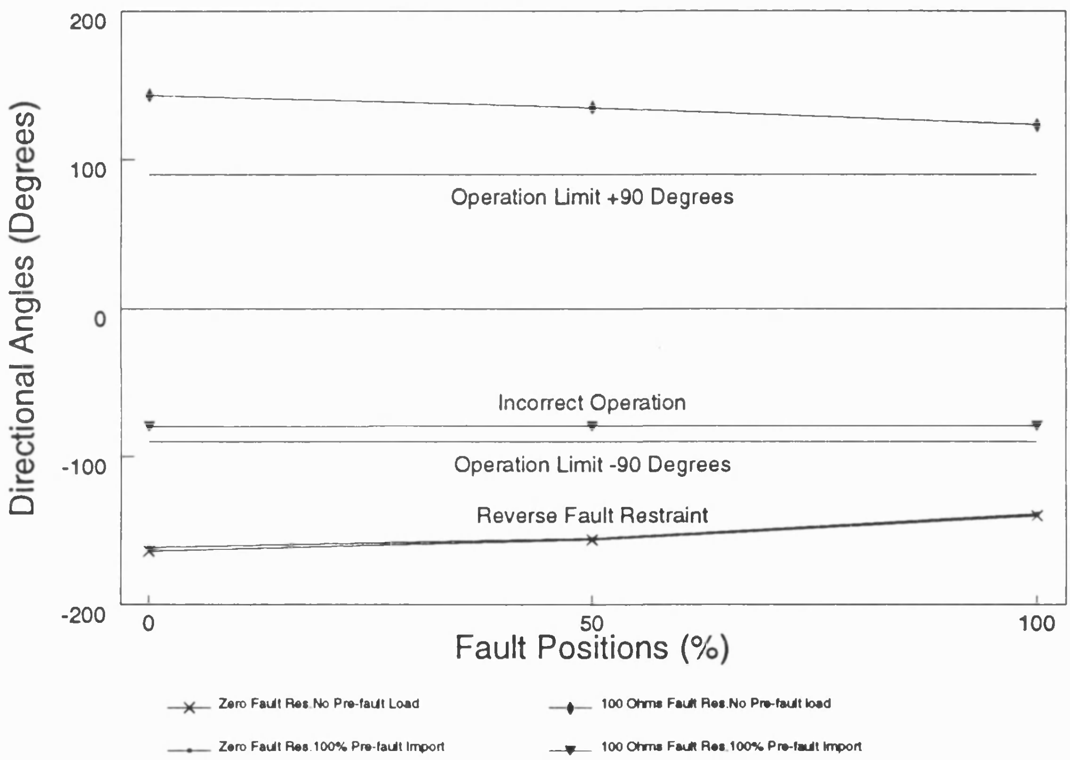
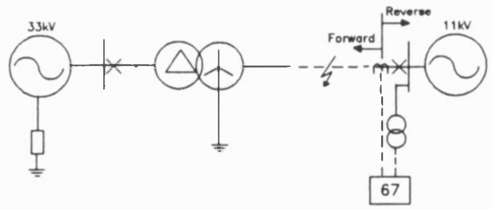



Figure 7.6.2.2.4.15 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.




11KV Distribution Underground Cable Feeder with a 33kV Transformer Source at One End

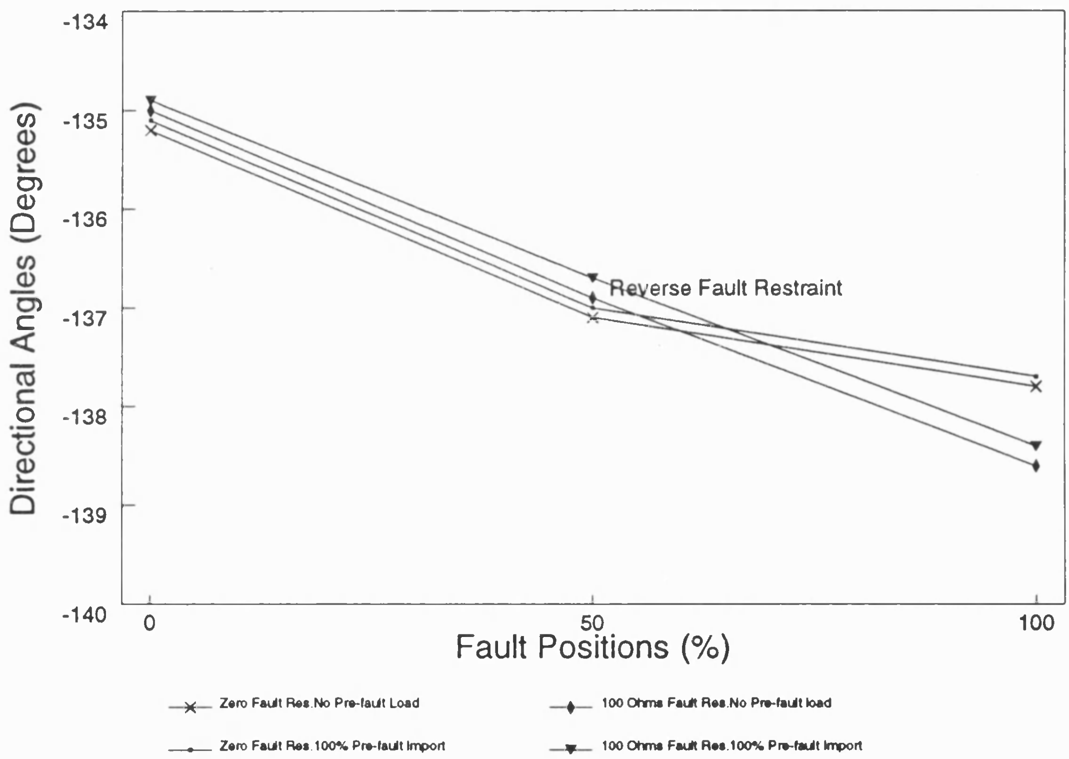



Figure 7.6.2.2.4.16 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 33kV Source.

For this 11kV feeder which is also fed from a 33kV source the following observations can be made on the performance of the new directional detection method.

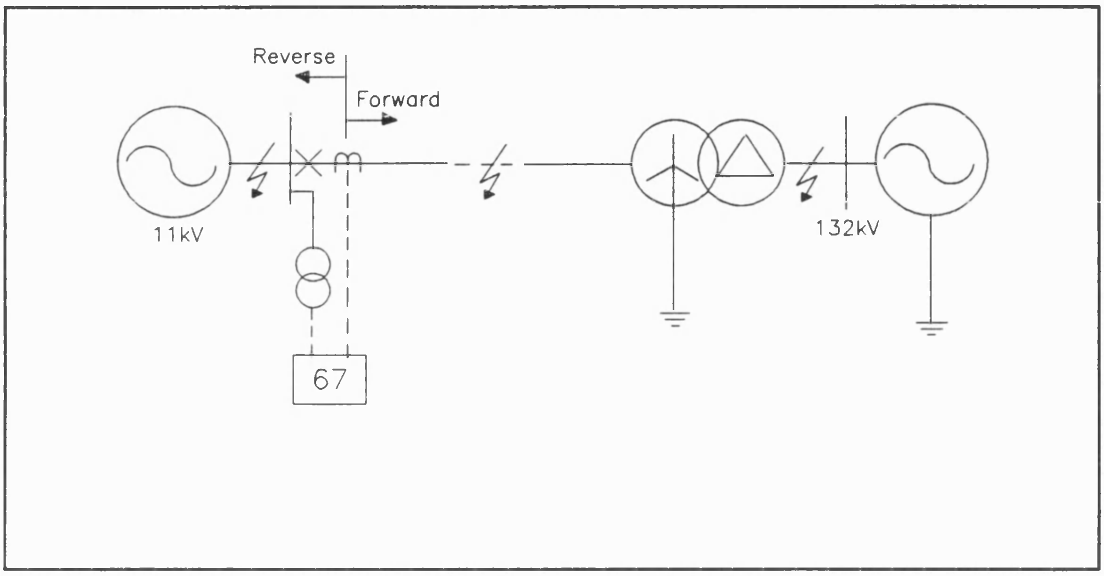
- The new method is not able to determine the correct fault direction for 3-phase and single-phase-earth faults on the overhead line feeder near the transformer terminals with fault resistance of 100Ω.

- The method also fails for high resistance faults on the underground cable feeder for 3-phase, phase-phase and single-phase-earth faults with 100Ω fault resistance and 100% pre-fault load importing from the 33kV source.

The results show that the proposed function $F_C$ as defined in Chapter 6 is not able to determine correctly the direction of all types of faults on both overhead line and underground cable feeders with high fault resistance and in the presence of full load current flow in opposite direction to the fault current.

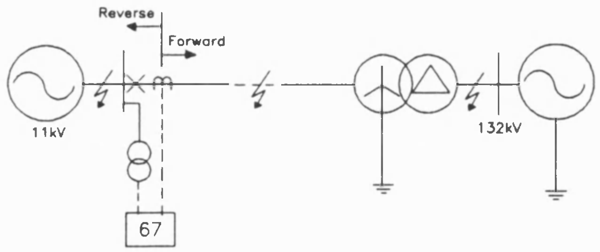
**7.6.2.2.5 11KV Distribution System with 132KV Transformer Source to either Overhead Line or Underground Cable Feeder**

The system is shown below:




This configuration is not common for distribution systems, but it provides an opportunity to examine the performance of the proposed directional detection method in the presence of pre-fault load current flow importing from the 132kV system.

The variations of the directional angle $\theta_C$ for various fault types on the feeder with fault positions and fault resistances are presented in Figures 7.6.2.2.5.1 to 7.6.2.2.5.16 for both overhead line and underground cable feeders. The directional relay 67 is arranged to "see" the faults as being either in the forward or reverse direction and without and with 100% pre-fault load current flow importing from the 132kV source.




11KV Distribution System with a 132kV Source on an Overhead Line Feeder

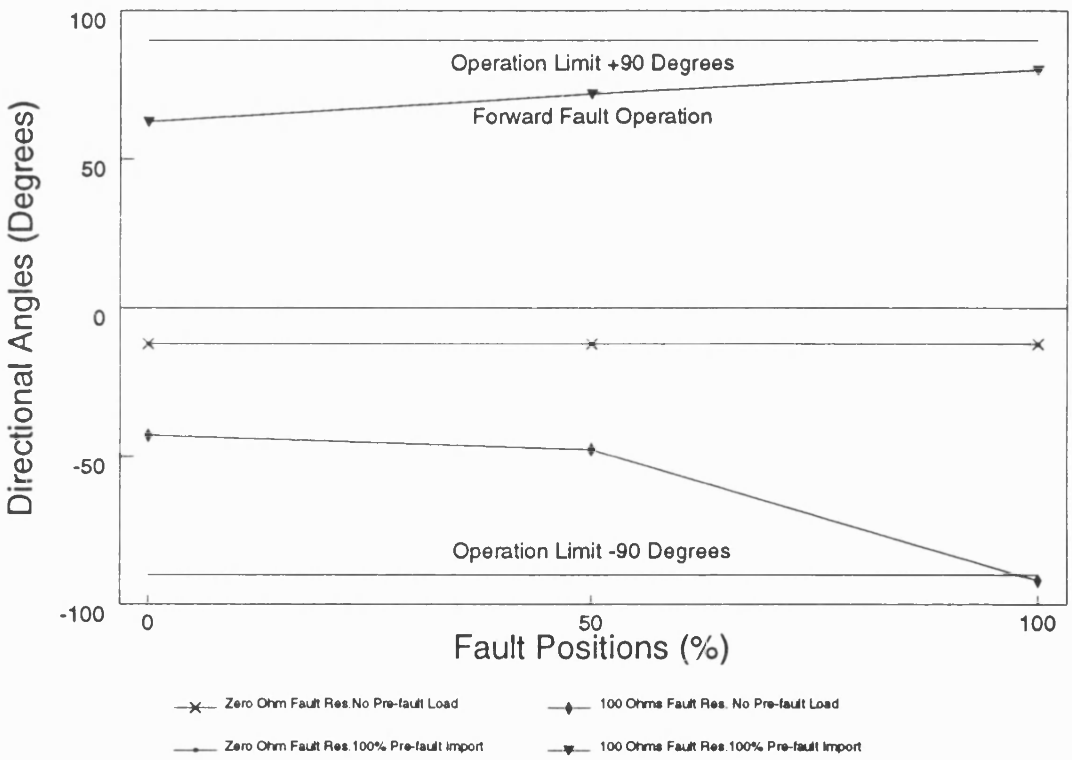
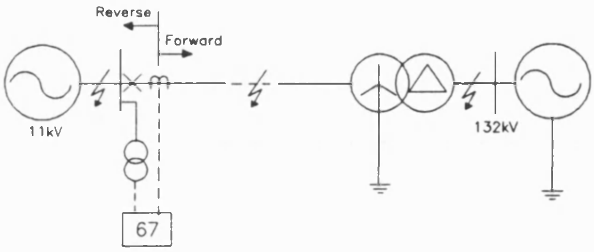



Figure 7.6.2.2.5.1 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Overhead Line Feeder

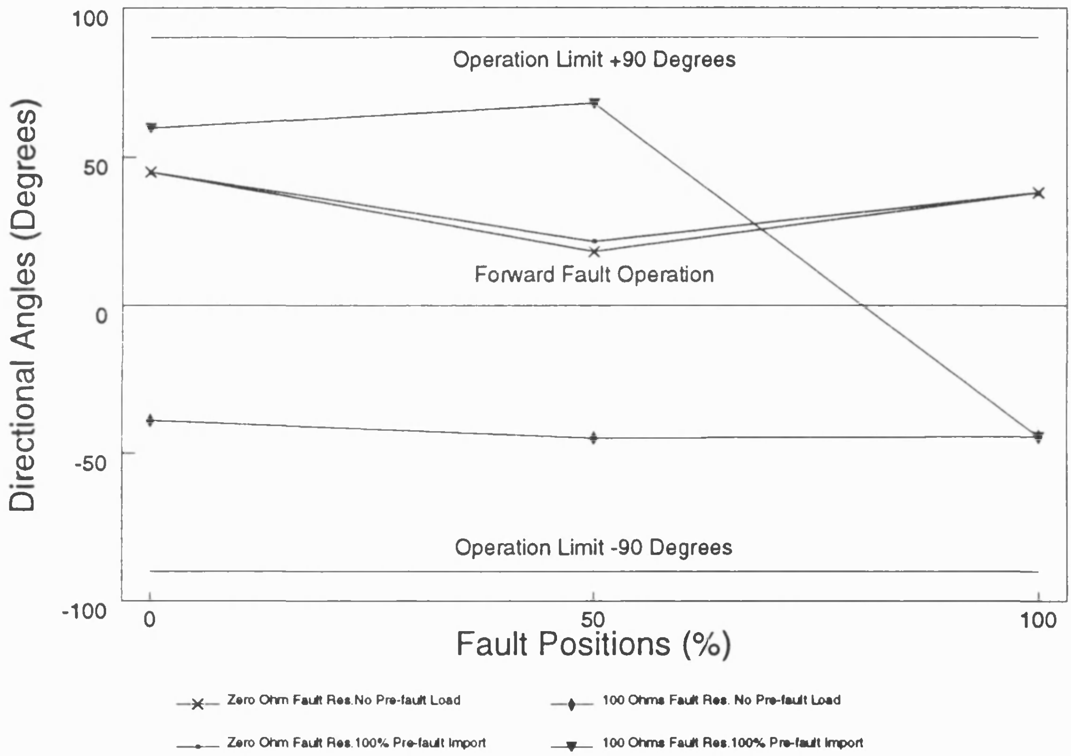
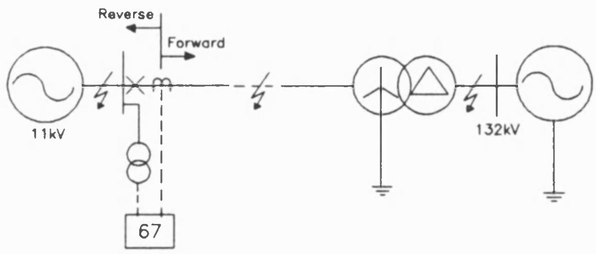



Figure 7.6.2.2.5.2 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Overhead Line Feeder

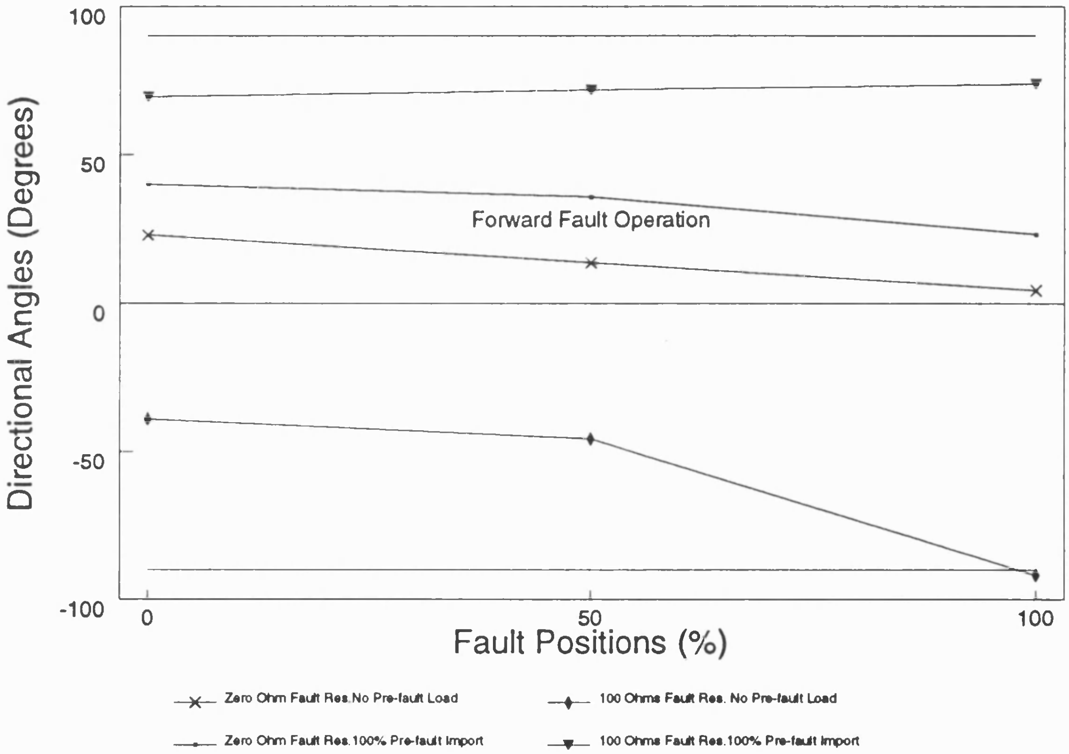
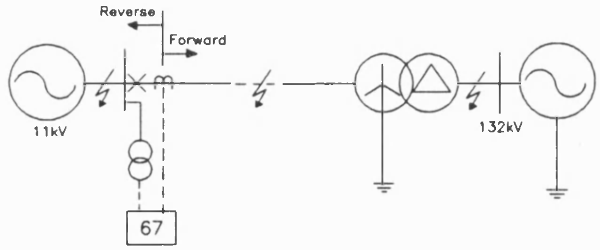



Figure 7.6.2.2.5.3 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Overhead Line Feeder

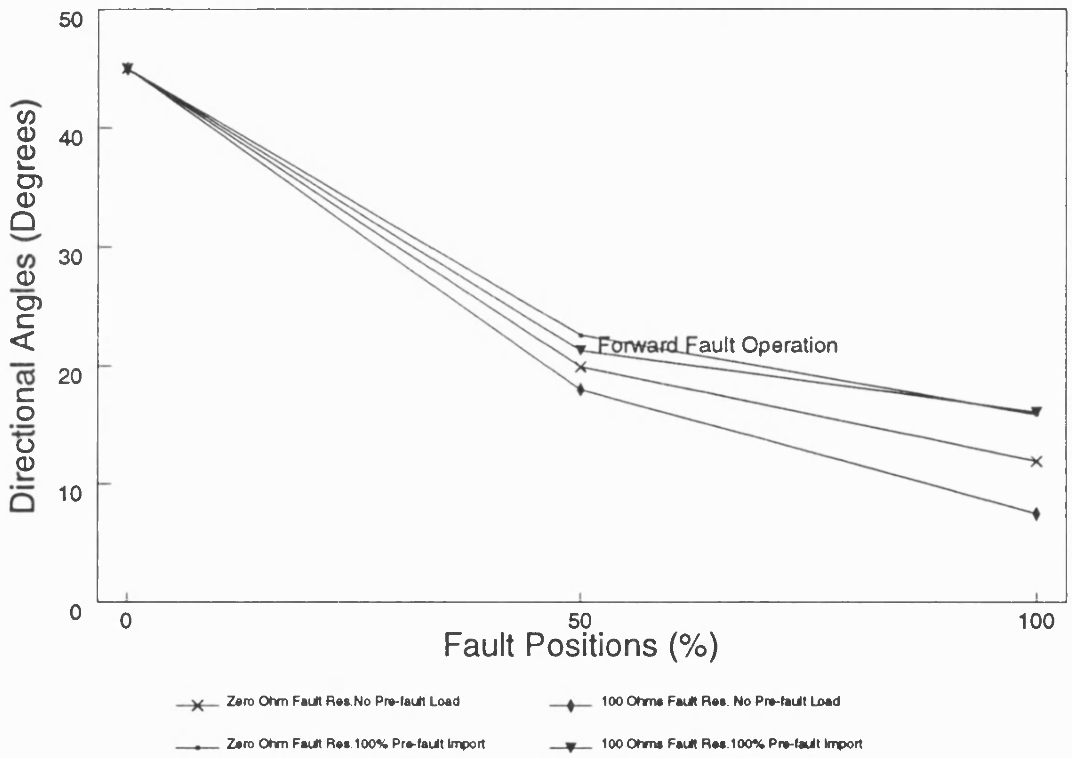
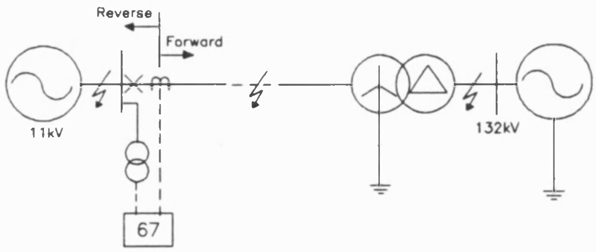



Figure 7.6.2.2.5.4 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Underground Cable Feeder

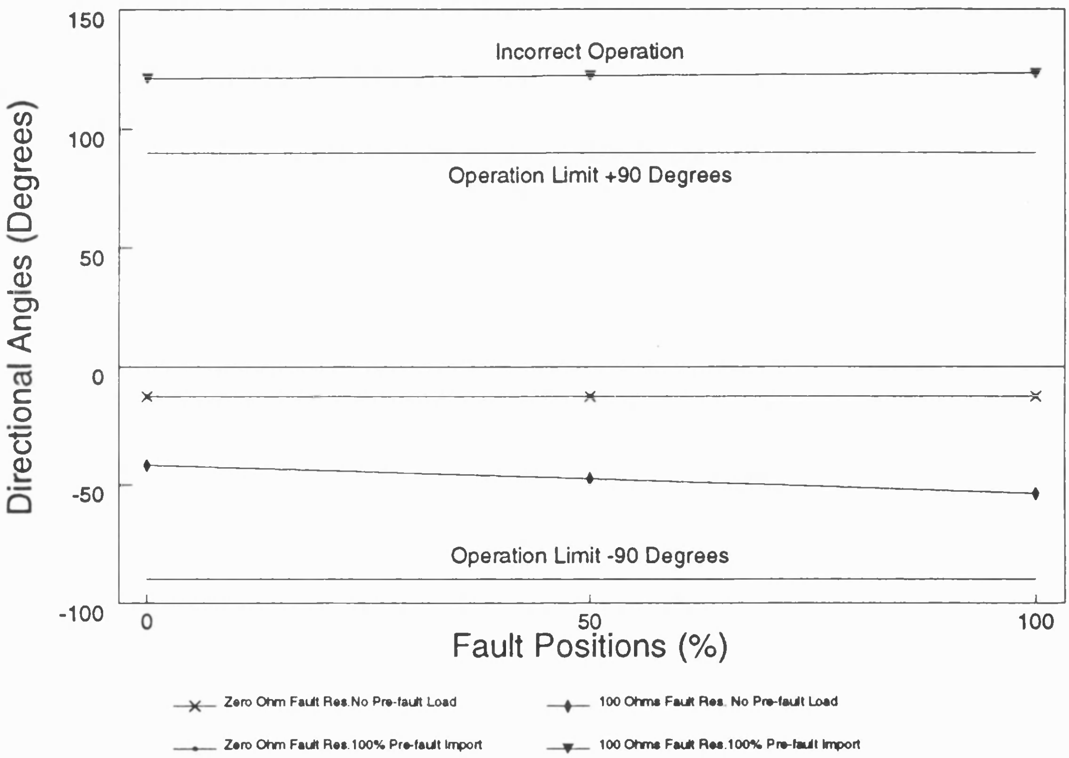
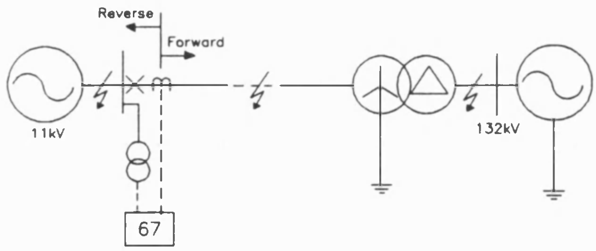



Figure 7.6.2.2.5.5 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Underground Cable Feeder

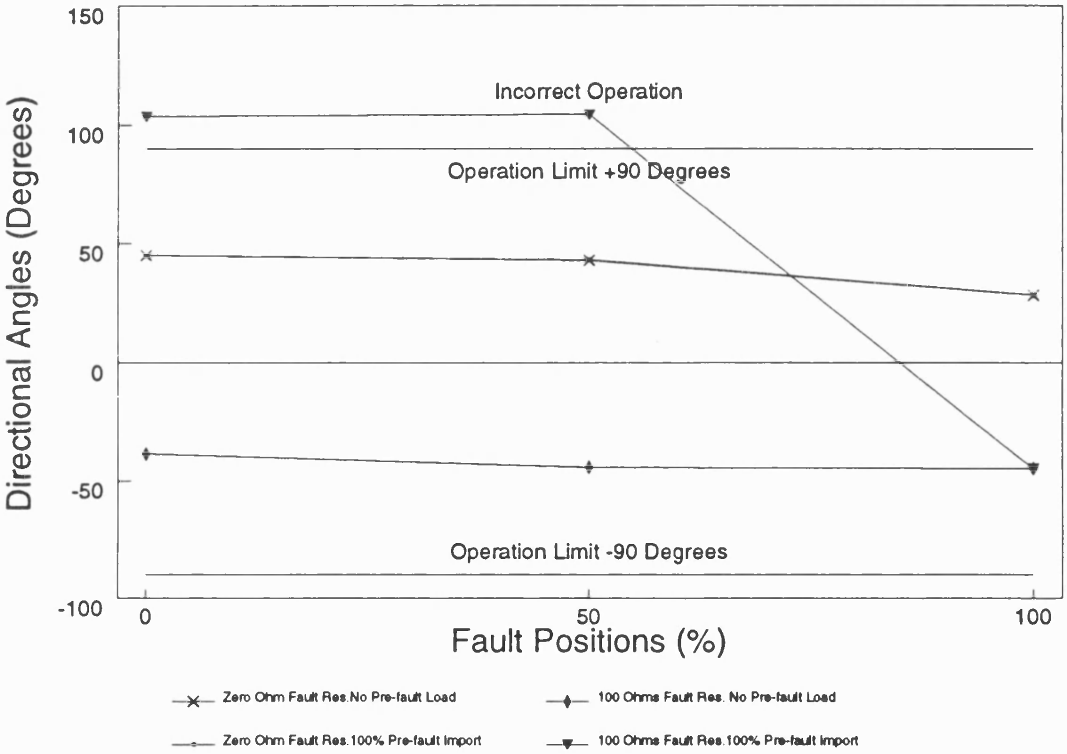
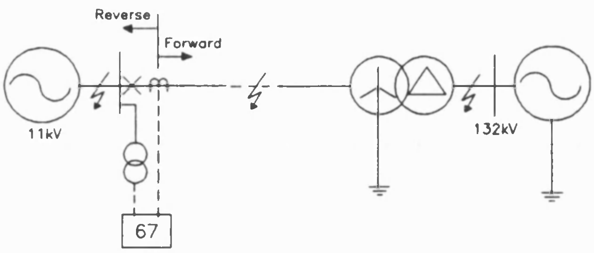



Figure 7.6.2.2.5.6 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Underground Cable Feeder

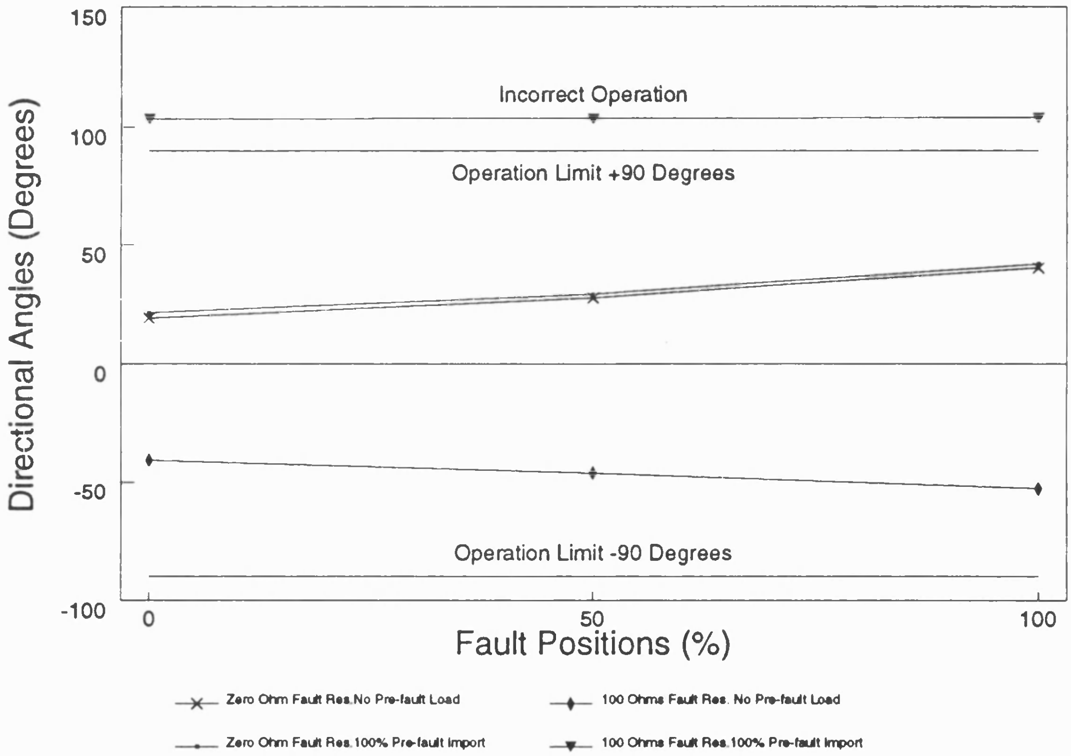
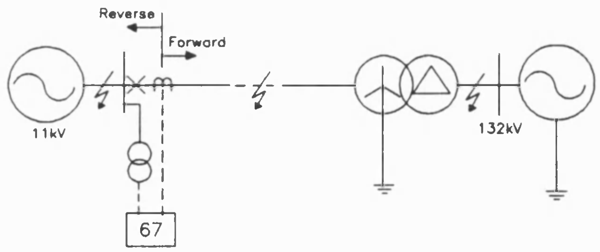



Figure 7.6.2.2.5.7 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Underground Cable Feeder

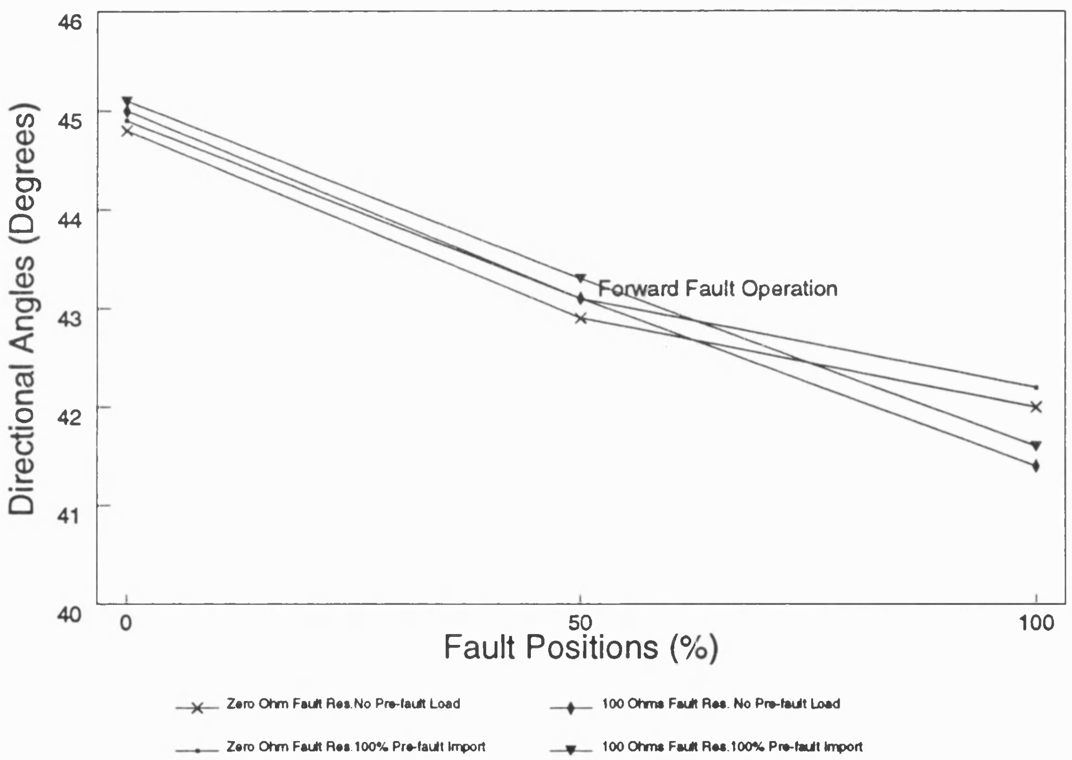
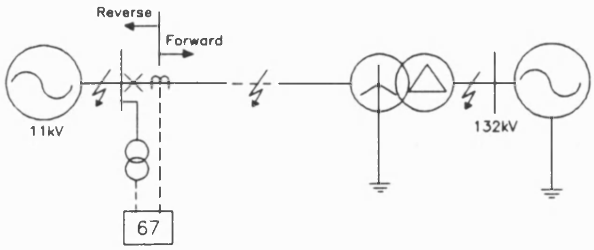



Figure 7.6.2.2.5.8 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Overhead Line Feeder

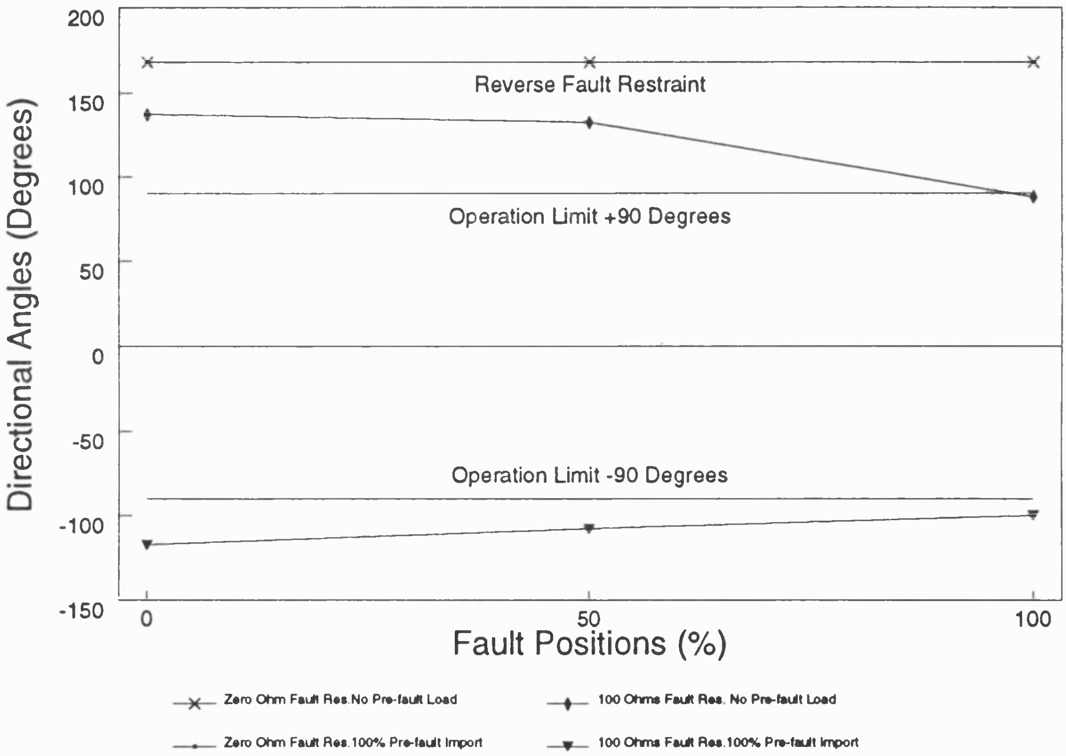
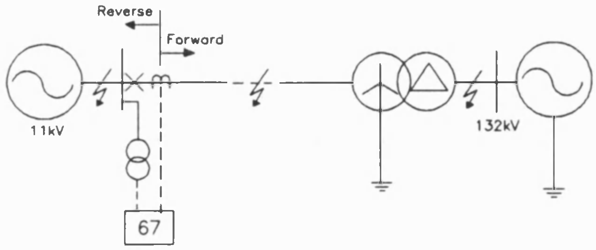



Figure 7.6.2.2.5.9 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Overhead Line Feeder

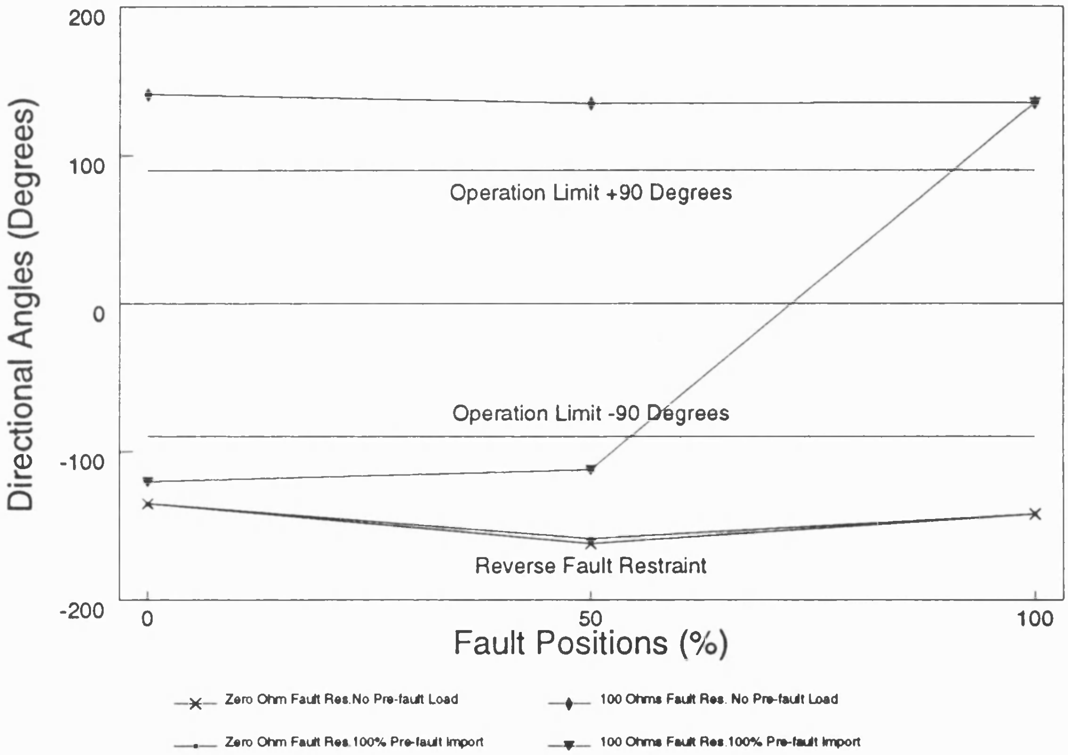
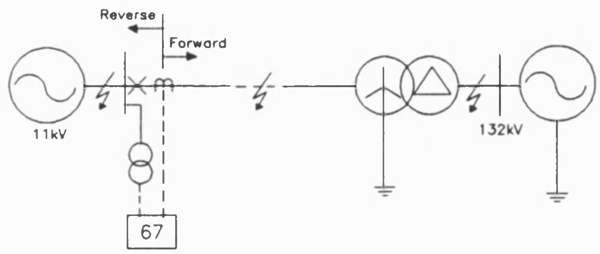



Figure 7.6.2.2.5.10 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Overhead Line Feeder

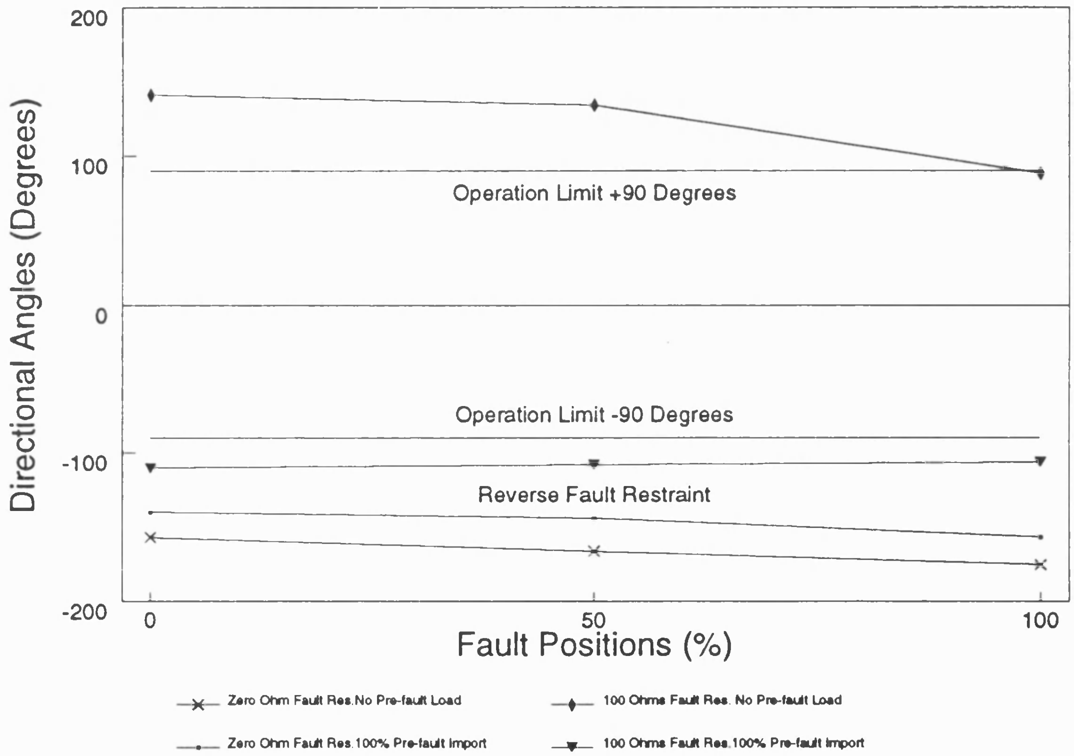
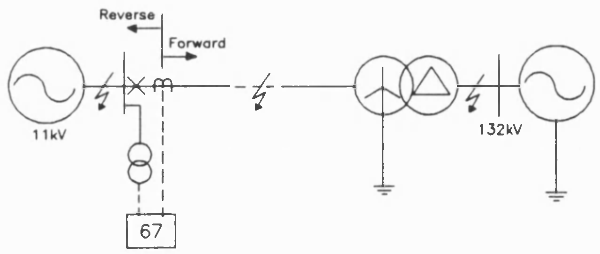



Figure 7.6.2.2.5.11 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Overhead Line Feeder

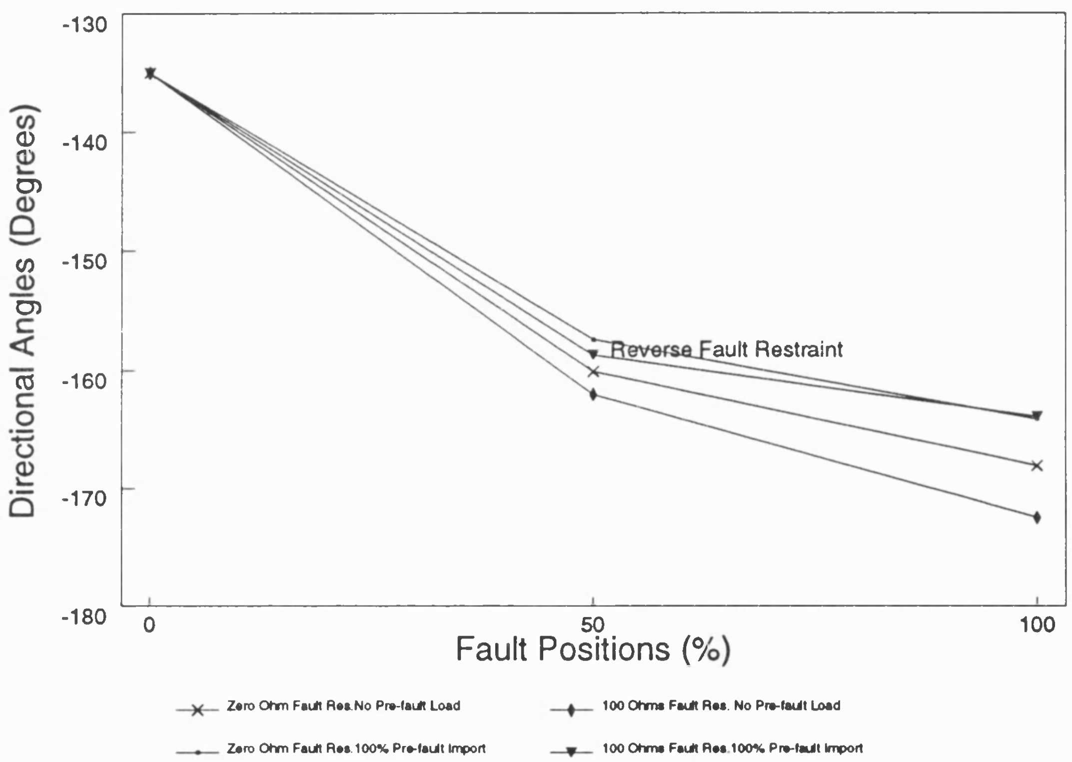
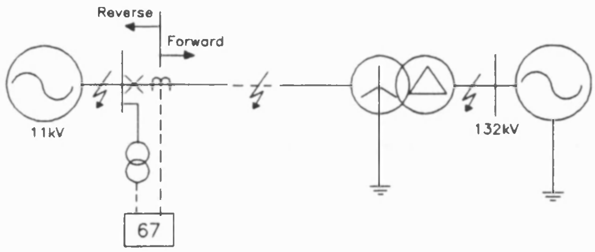



Figure 7.6.2.2.5.12 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Underground Cable Feeder

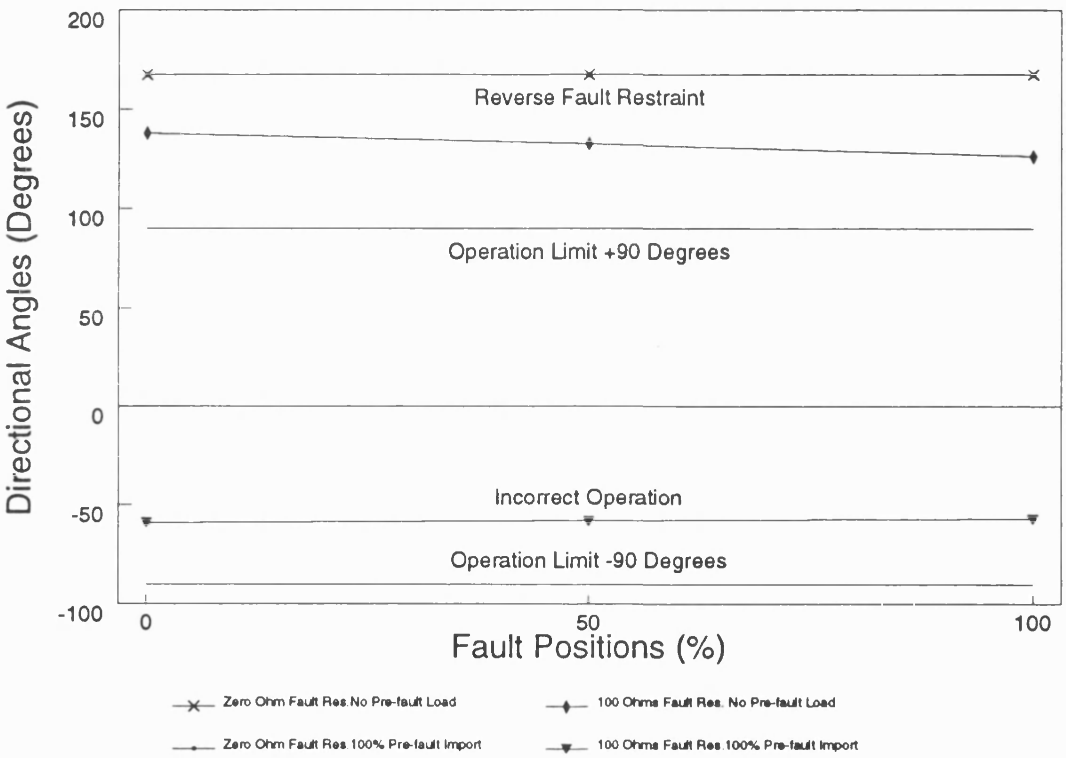
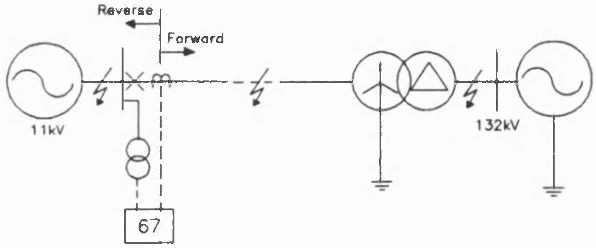



Figure 7.6.2.2.5.13 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Underground Cable Feeder

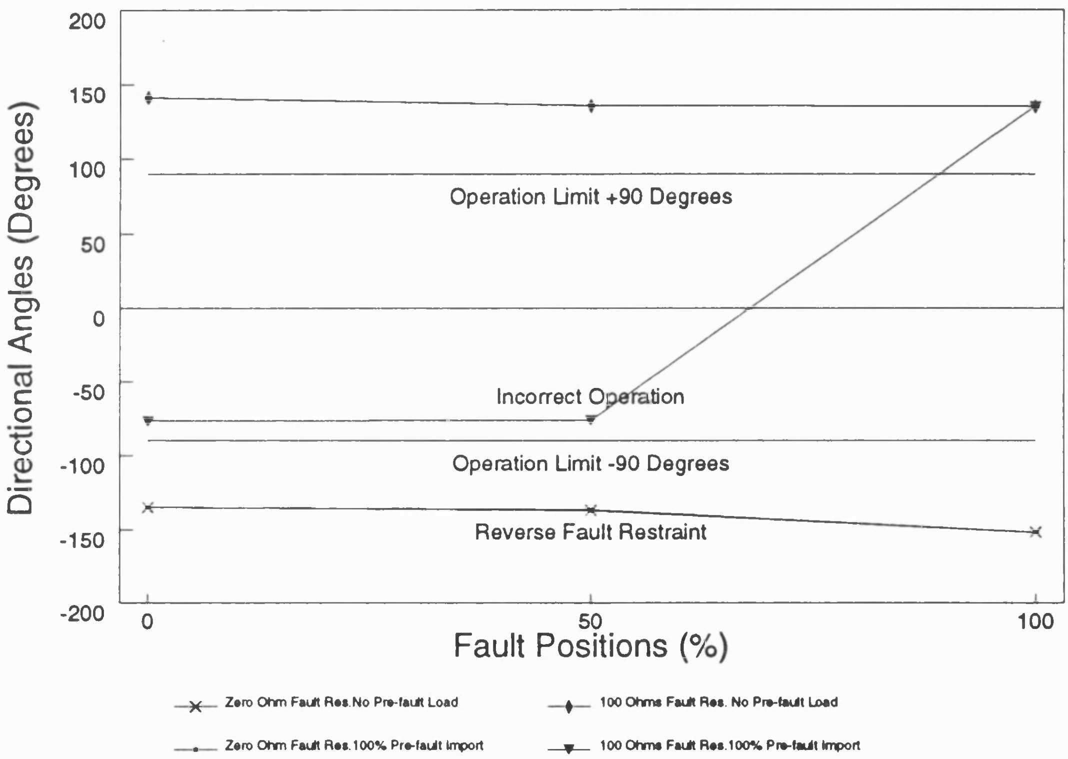
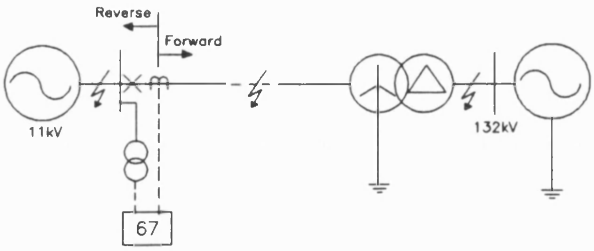



Figure 7.6.2.2.5.14 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Underground Cable Feeder

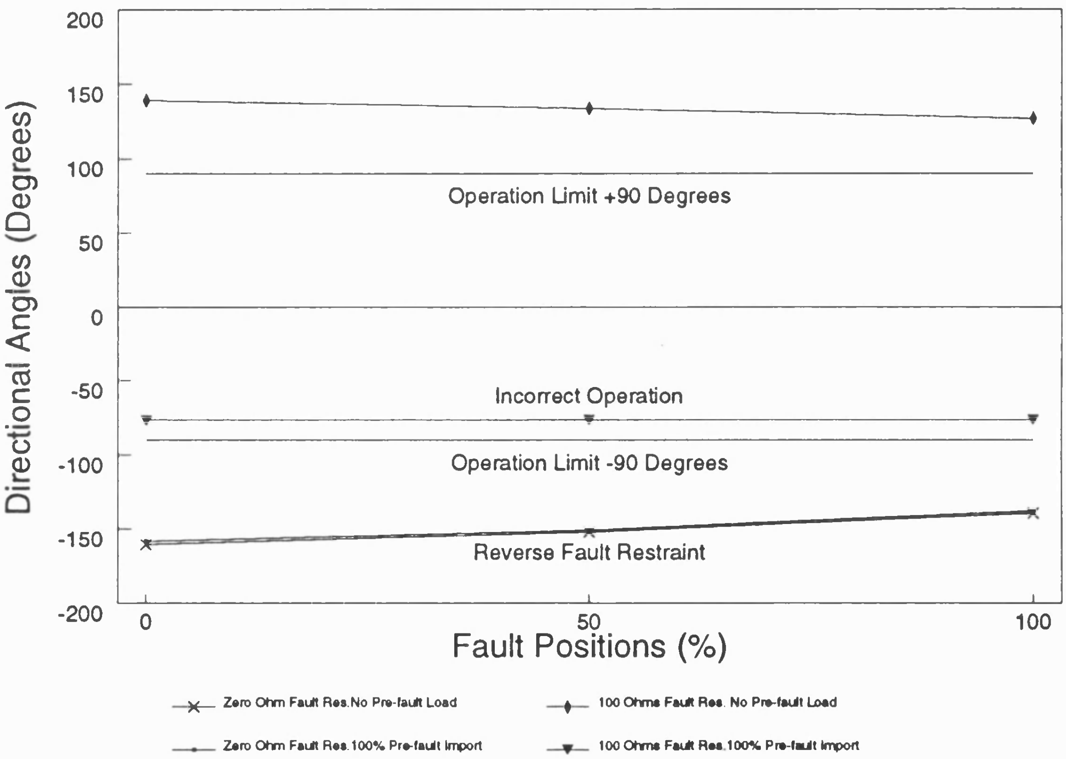
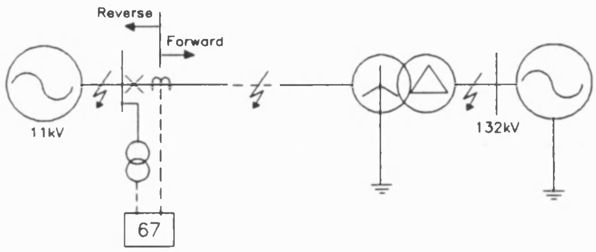



Figure 7.6.2.2.5.15 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




11KV Distribution System with a 132kV Source on an Underground Cable Feeder

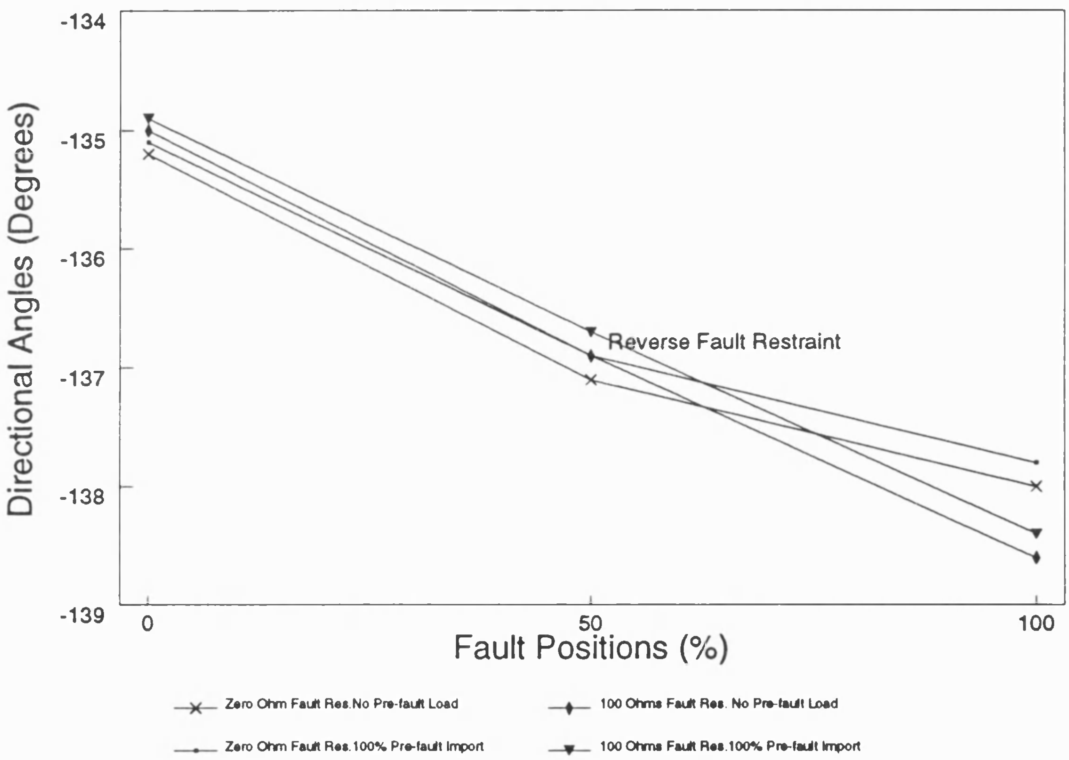



Figure 7.6.2.2.5.16 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.

For this system the following observations can be made on the performance of the new directional detection method.

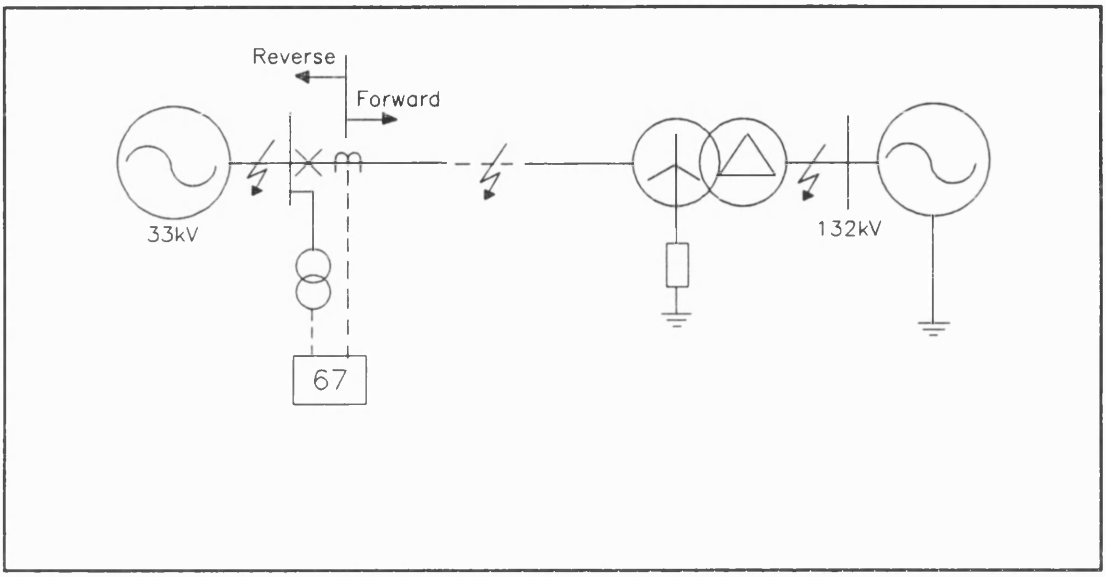
- For 3-phase and single-phase-earth faults on the overhead line feeder the new method is not able to determine the correct direction when 100Ω fault resistance is present in the fault near the transformer terminals.

- In the case of the underground cable feeder the new method is also not able to determine the correct direction of 3-phase, phase-phase and single-phase-earth faults with 100Ω fault resistance when there is full pre-fault load current flow in opposite direction to the fault current.

The proposed function $F_C$ as defined in Chapter 6, from which direction information is derived, is affected by pre-fault load current flow and high fault resistance. The resulting angle, $\theta_C$ are outside the $\pm 90_0$ limits for forward faults under such pre-fault and fault conditions.

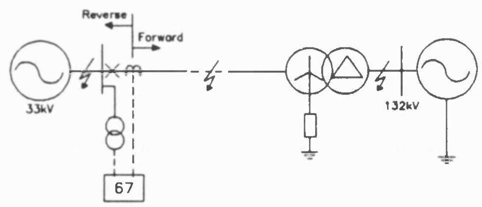
### 7.6.2.2.6 33KV Distribution System with 132KV Transformer Source to either Overhead Line or Underground Cable Feeder

The system is shown below:




This arrangement is similar to Section 7.6.2.2.5 for 11kV system with the 33kV feeder also being fed from the 132kV source.

The variations of the directional angle $\theta_C$ for different fault types under the same fault and pre-fault conditions are presented in Figures 7.6.2.2.6.1 to 7.6.2.2.6.16 for both overhead line and underground cable feeders. The directional relay 67 is arranged to "see" the faults as being either in the forward or reverse direction.




33kV Distribution System with a 132kV Source on an Overhead Line Feeder

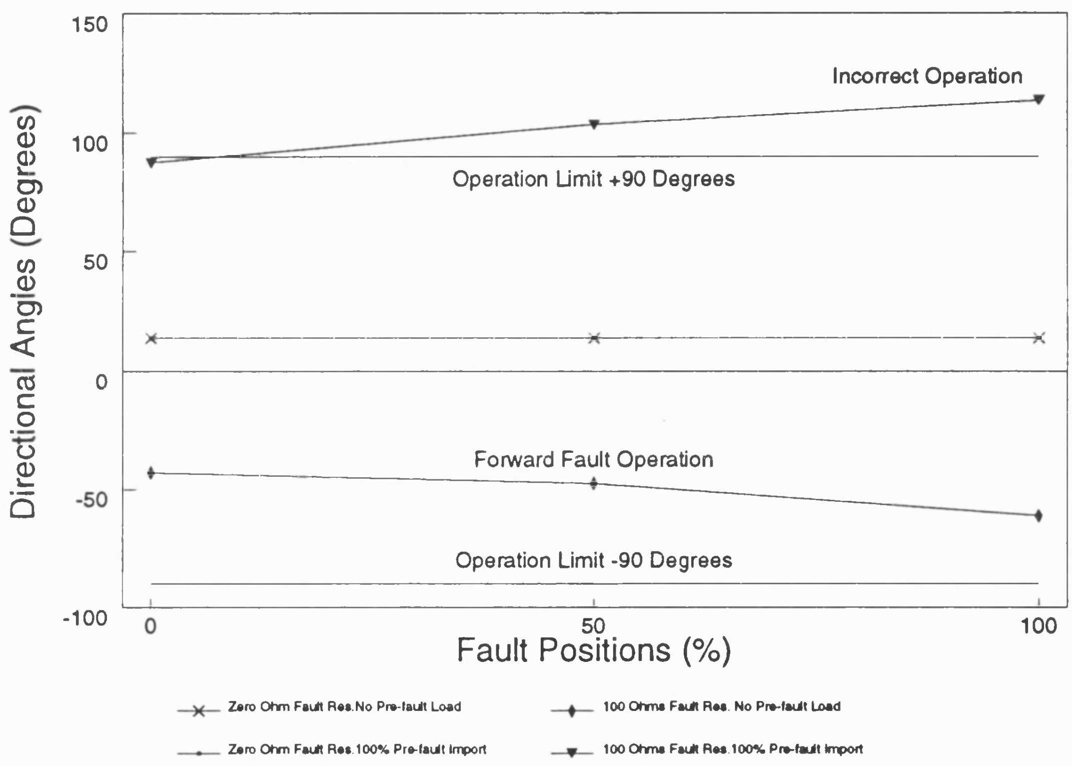
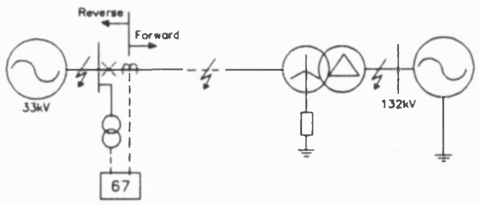



Figure 7.6.2.2.6.1 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Overhead Line Feeder

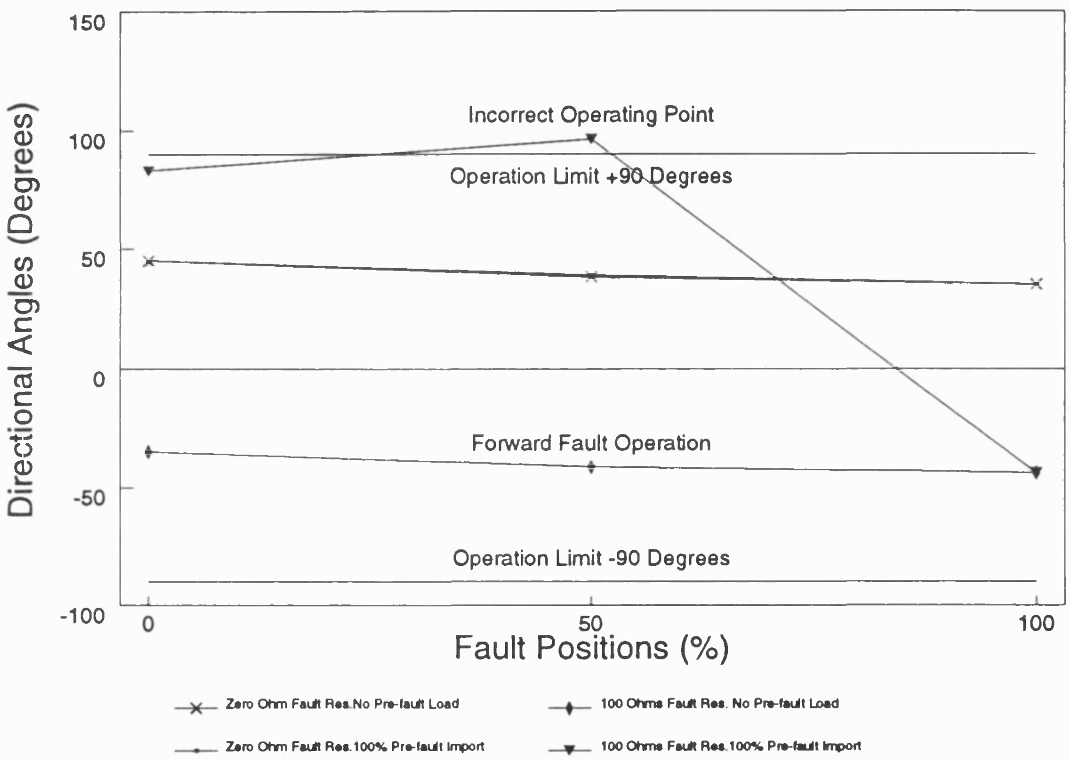
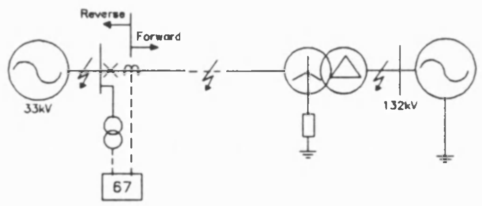



Figure 7.6.2.2.6.2 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Overhead Line Feeder

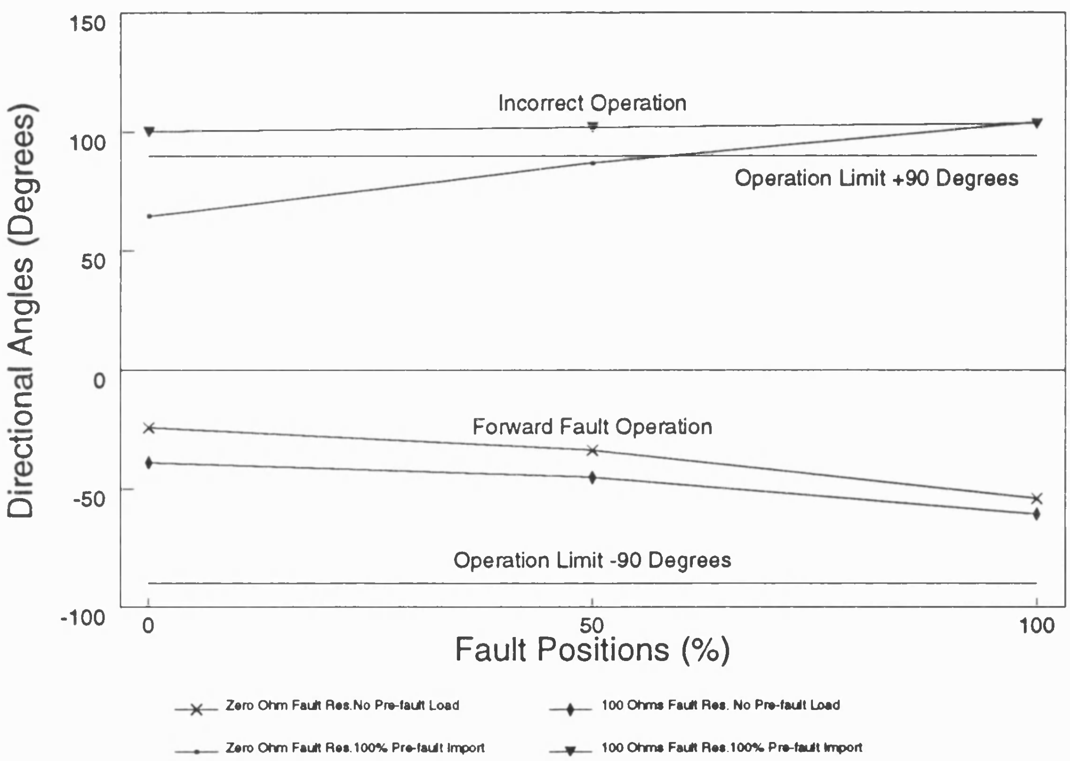
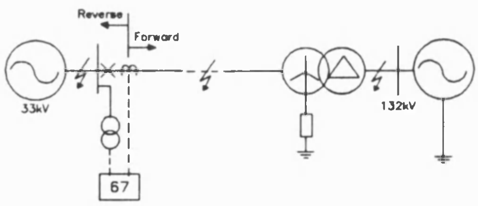



Figure 7.6.2.2.6.3 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Overhead Line Feeder

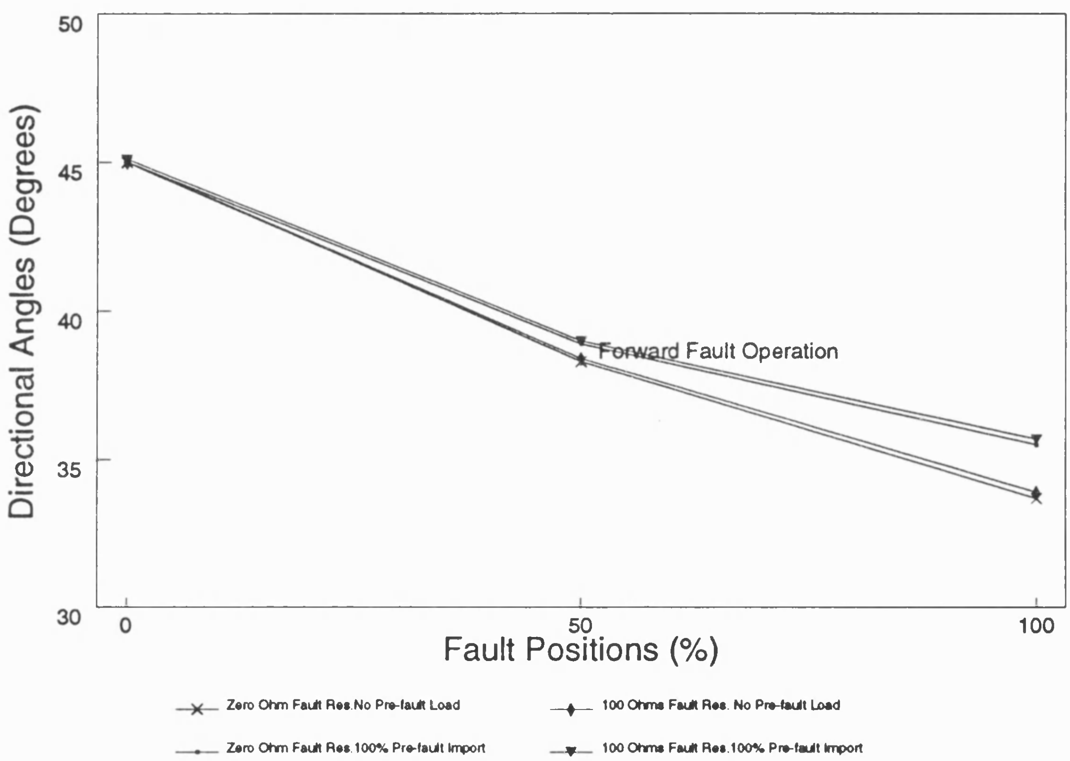
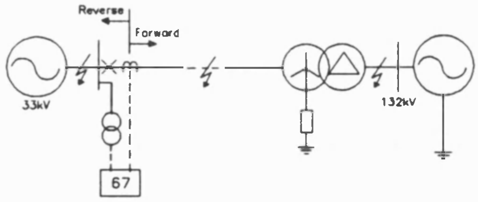



Figure 7.6.2.2.6.4 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Underground Cable Line Feeder

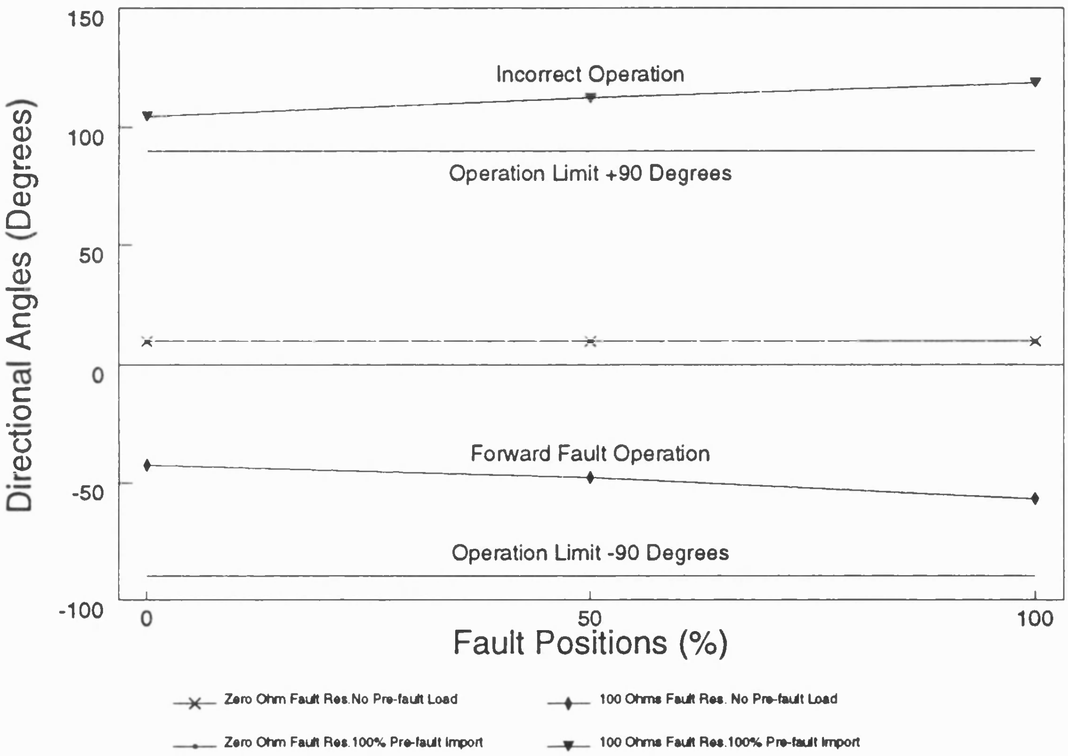
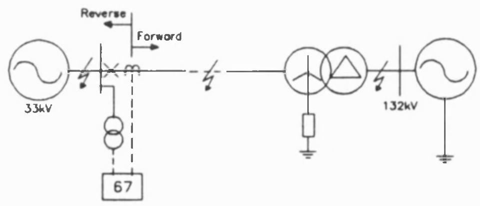



Figure 7.6.2.2.6.5 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Underground Cable Line Feeder

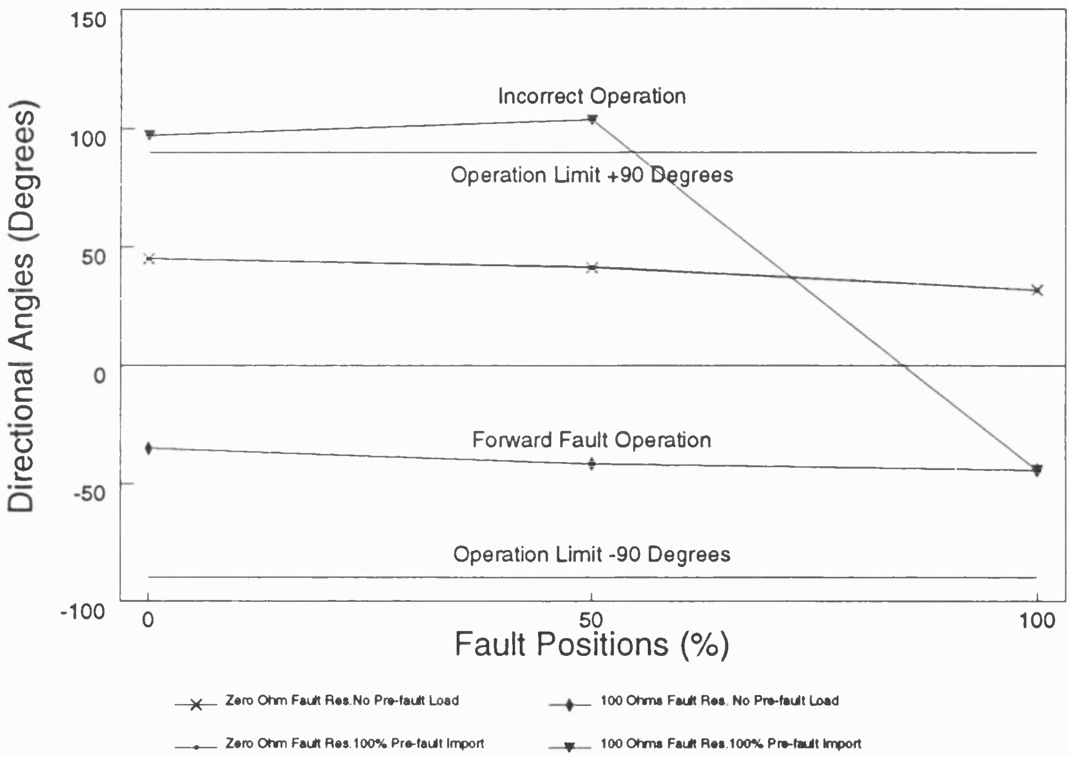
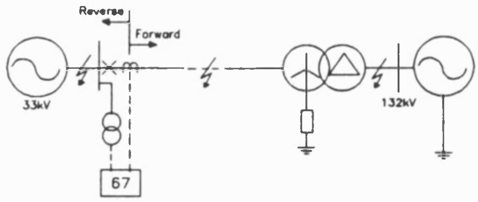



Figure 7.6.2.2.6.6 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Underground Cable Line Feeder

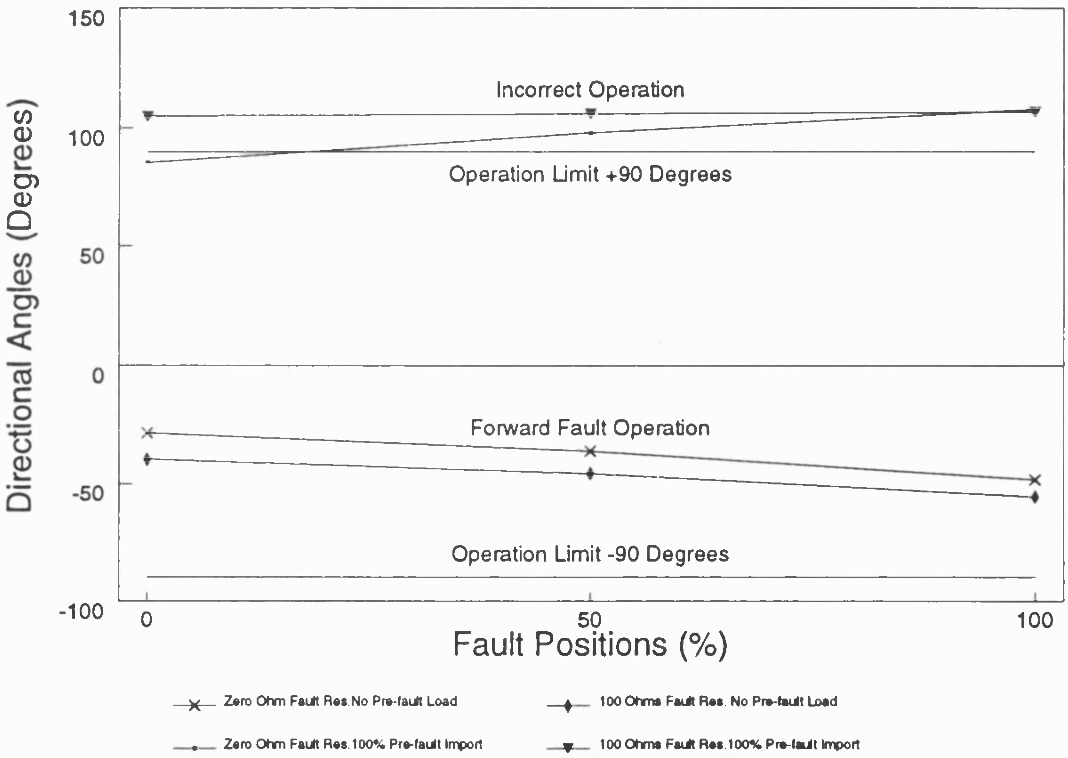
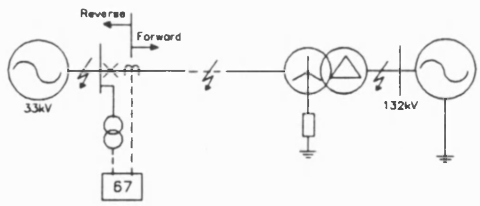



Figure 7.6.2.2.6.7 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Underground Cable Line Feeder

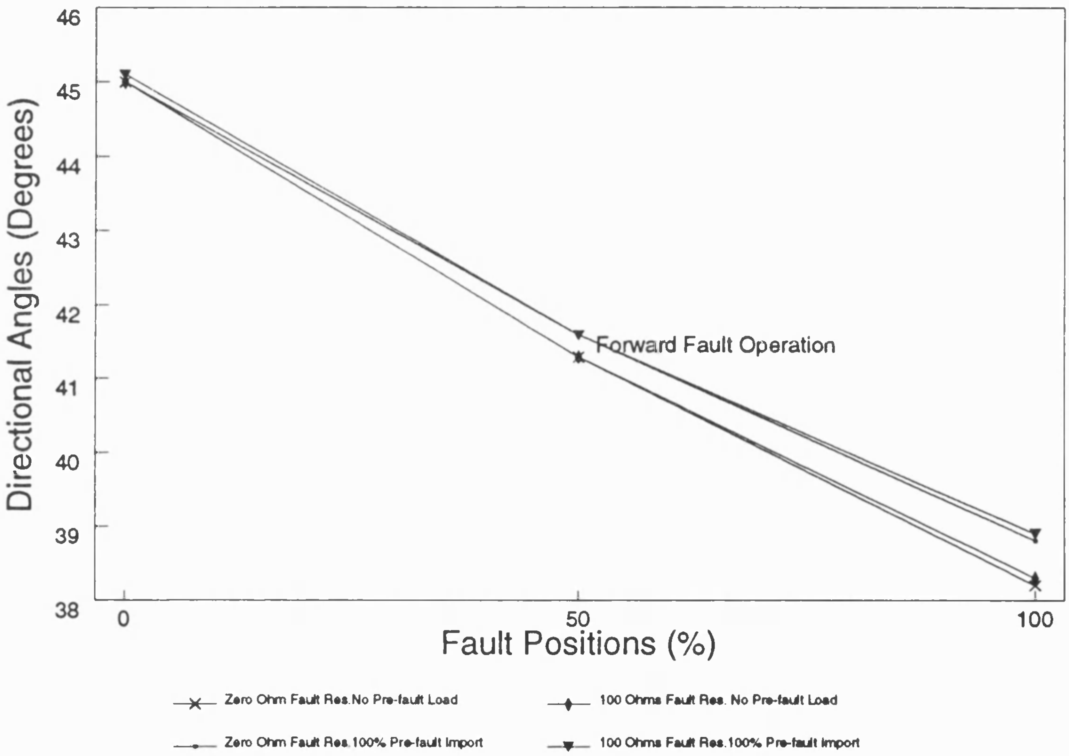
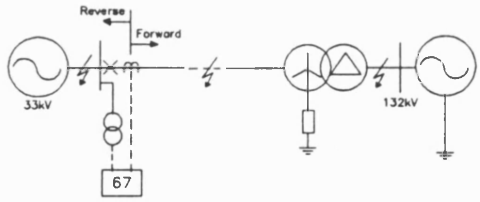



Figure 7.6.2.2.6.8 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Forward Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Overhead Line Feeder

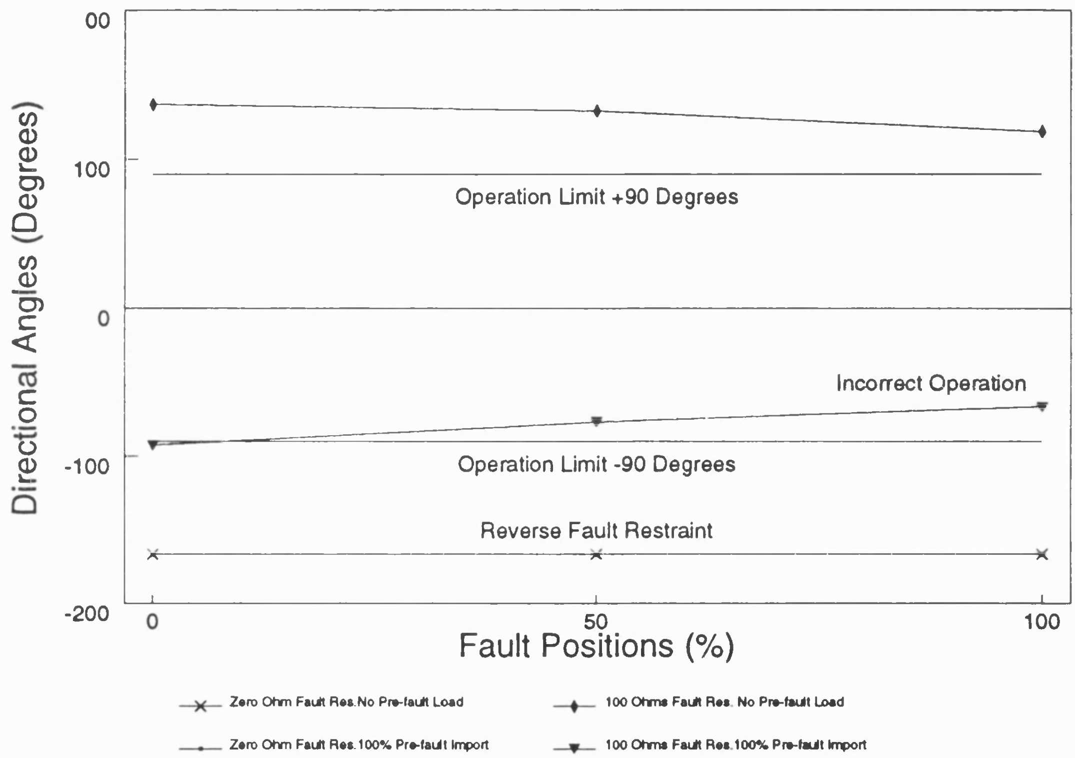
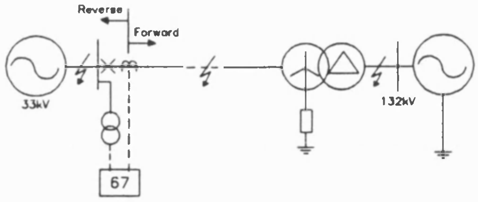



Figure 7.6.2.2.6.9 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Overhead Line Feeder

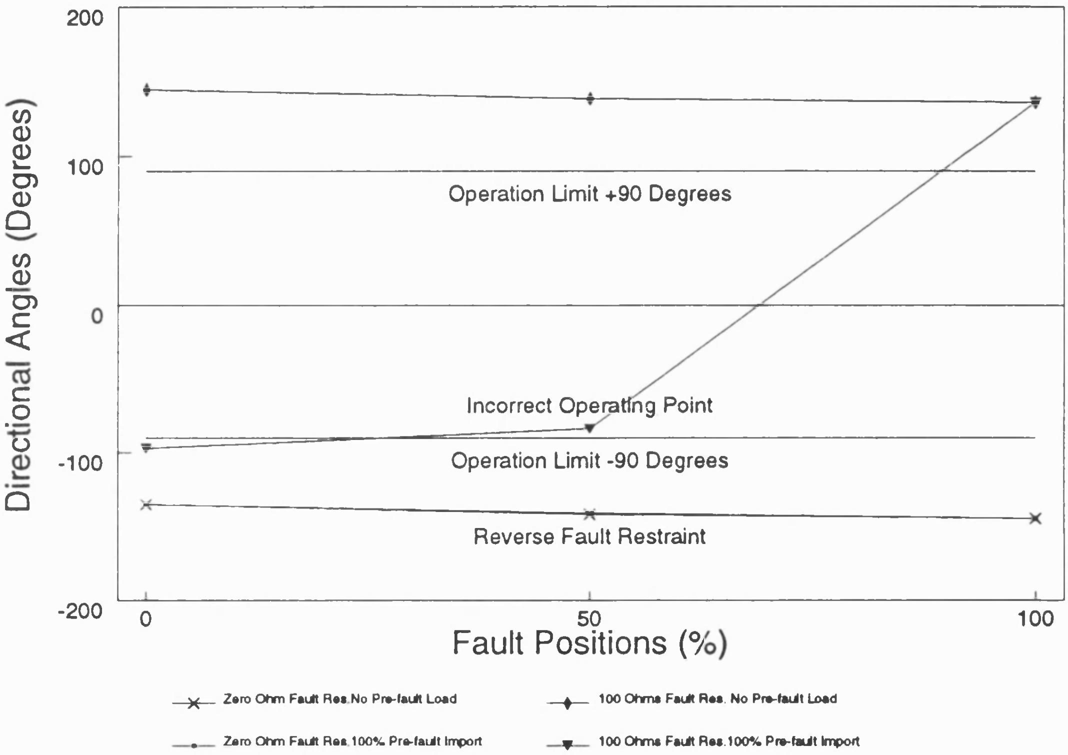
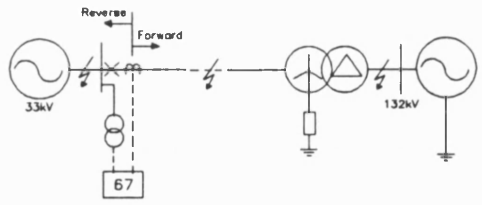



Figure 7.6.2.2.6.10 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Overhead Line Feeder

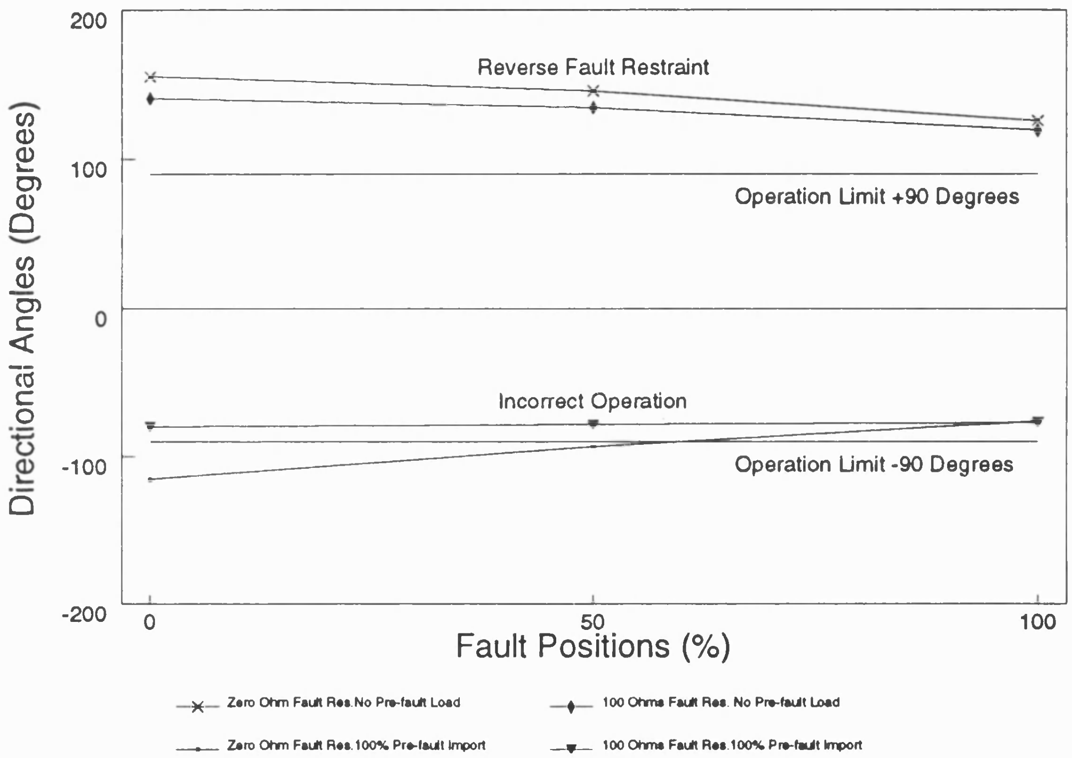
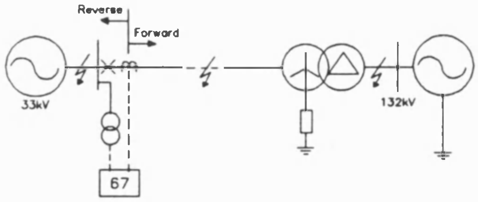



Figure 7.6.2.2.6.11 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Overhead Line Feeder

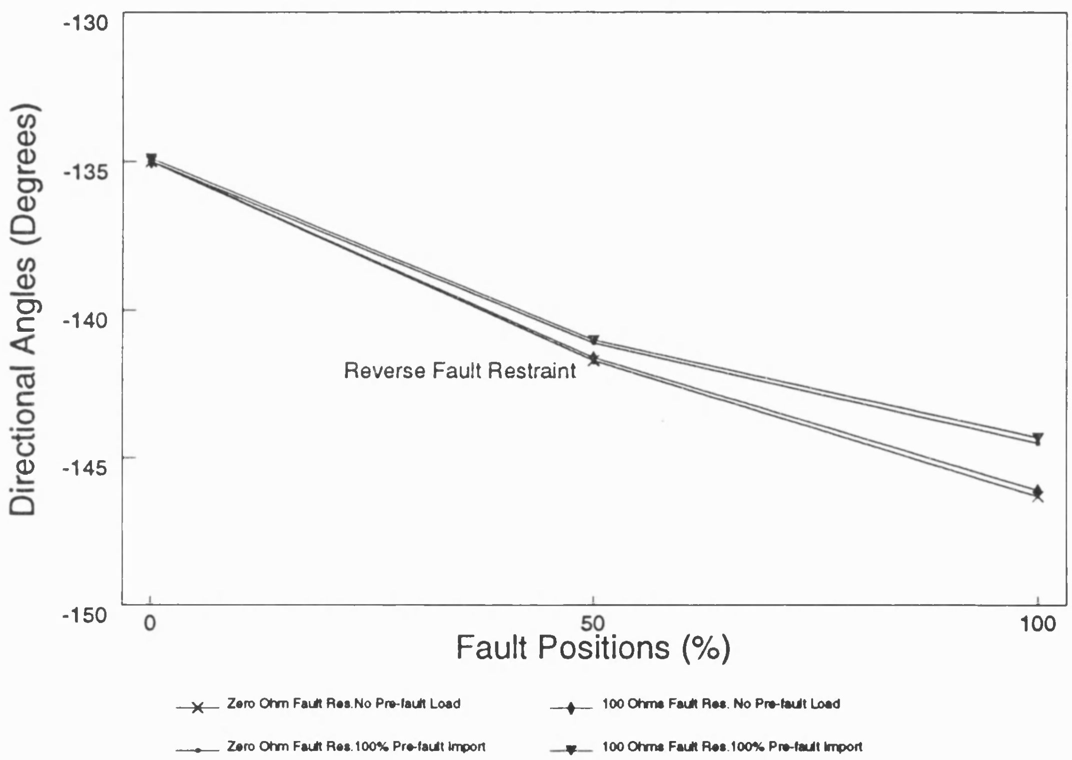
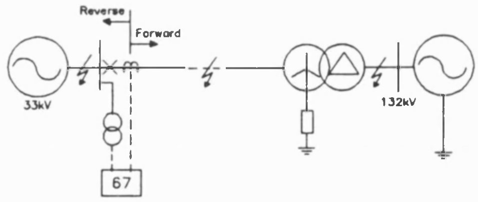



Figure 7.6.2.2.6.12 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Underground Cable Feeder

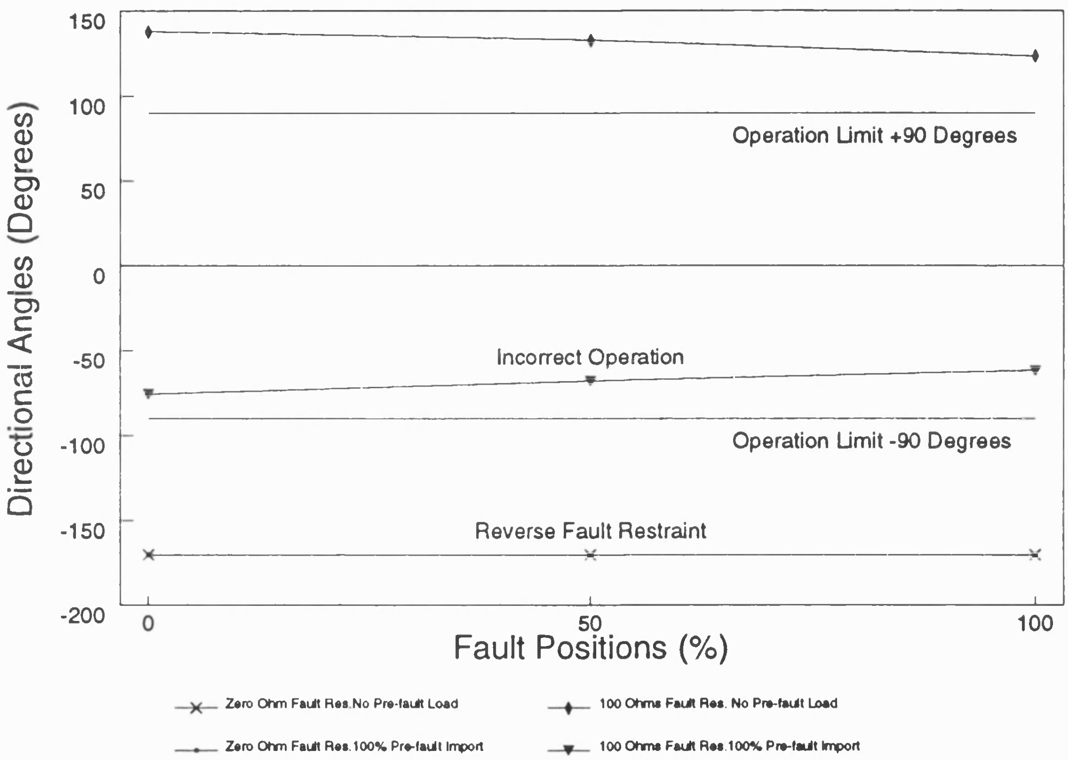
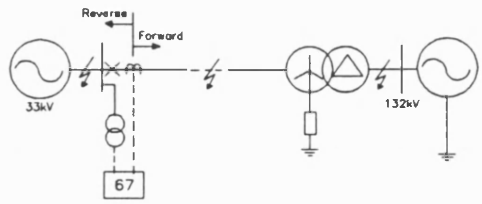



Figure 7.6.2.2.6.13 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for 3-phase Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Underground Cable Feeder

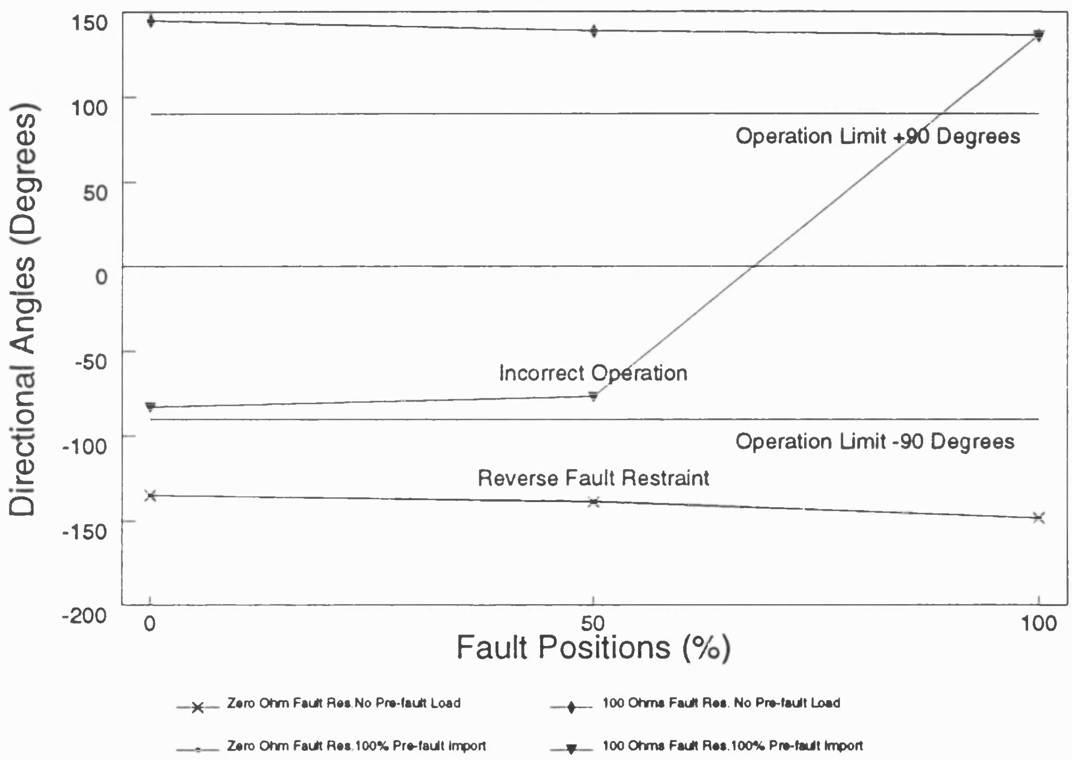
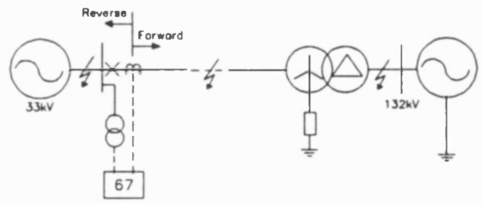



Figure 7.6.2.2.6.14 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Underground Cable Feeder

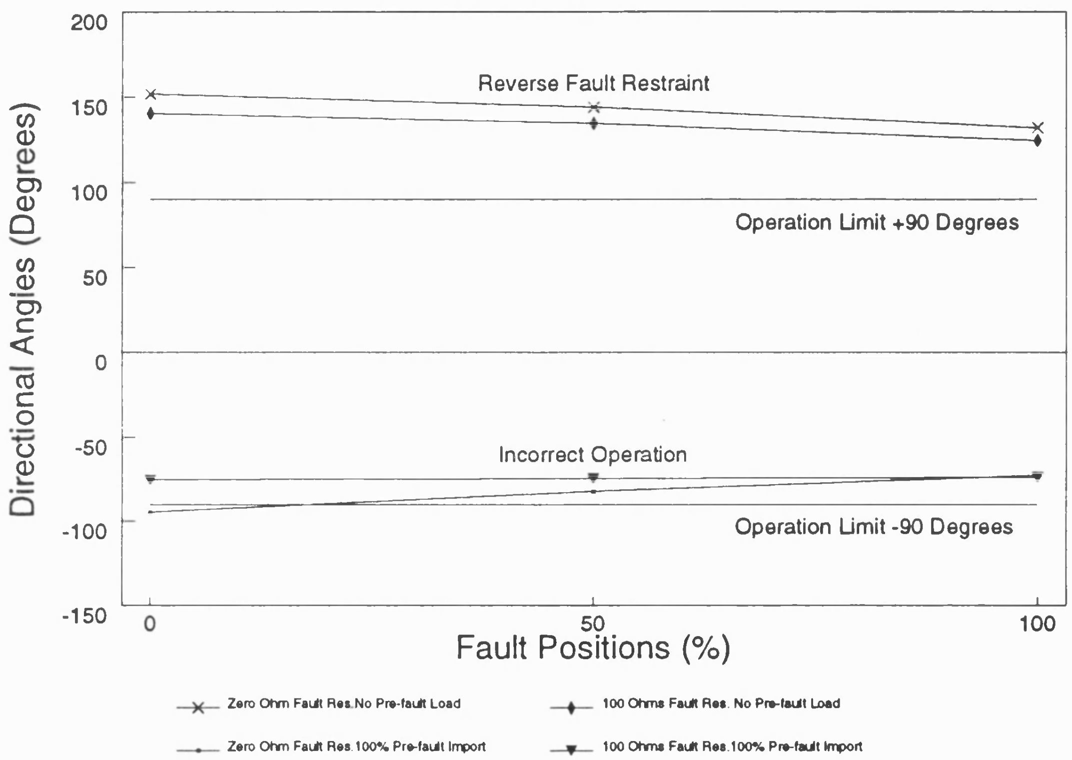
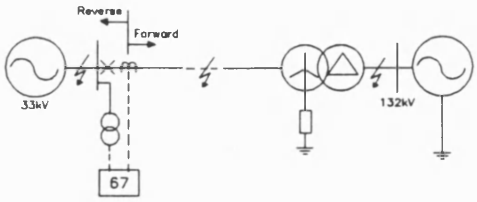



Figure 7.6.2.2.6.15 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Single-phase-earth Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.




33kV Distribution System with a 132kV Source on an Underground Cable Feeder

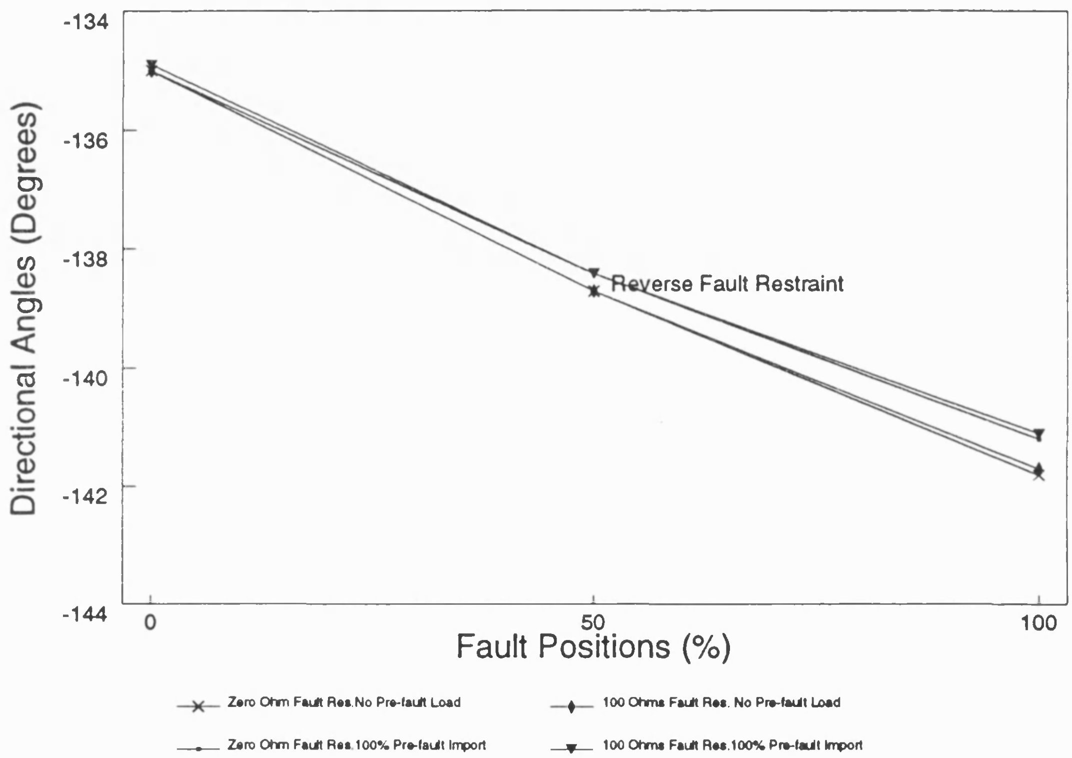



Figure 7.6.2.2.6.16 Variations of the Directional Angle $\theta_C$ with Fault Positions and Fault Resistances for Phase-phase-earth Faults with the Directional Relay arranged to detect as Reverse Faults without and with 100% Pre-fault Load Current Flow importing from the 132kV Source.

Similar to the 11kV system in Section 7.6.2.2.5 the new directional detection method is not able to determine correctly the direction of all high resistance faults with pre-fault load current flow in opposite direction to fault currents. The following observations can be made:

- The new method fails to perform correctly for 3-phase, phase-phase and single-phase-earth faults with 100Ω fault resistance and full pre-fault load importing from the 132kV source.

- The new method is able to determine correctly the direction of all phase-phase-earth faults with high fault resistance and full pre-fault load current flow which is in opposite direction to the fault current.

### 7.6.3 Discussion on the Performance of the New Directional Detection Method

The results of the analyses of the different systems and the responses of the proposed directional detection method to different fault types under various pre-fault and fault conditions presented in Sections 7.6.1 and 7.6.2 indicate the followings.

- For single source radial systems the proposed approach is fully capable of correct detection of fault directions under all the envisaged operating and fault conditions and for the common distribution system configurations. A feature of the new method is the correct direction detection capability of high resistance faults with fault resistances much higher than practical values.

- For multiple-source systems the capability of correct direction detection for high resistance faults is reduced. In a few cases the proposed directional detection method fails for high resistance faults with pre-fault load current flow in a direction opposite to the fault current direction. Correct fault direction detection can only be ensured for reduced fault resistances which are still near to practical values.

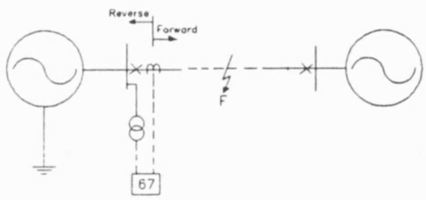
In the initial proposal for the combined function $F_C$ there are two considerations for the two constants associated with the two terms making up the function. These are the magnitudes and angles of the constants $K_{C1}$ and $K_{C2}$.

The consideration for the associated angles is to enable a definition of angular limits for forward fault operation or reverse fault restraint. There is no possibility of putting higher weighting factor to a given term based on the angular value alone.

Different weighting factors on magnitudes are proposed to the two constants with the negative phase sequence term having a 20:1 higher differential to provide good sensitivity for earth fault detection in the presence of heavy pre-fault load transfer. There is no consideration for the influence of this higher magnitude of $K_{C2}$ on the resulting directional angle $\theta_C$.

The following illustrations show the effect of increasing the magnitude of $K_{C2}$ giving more dependence on the reliable detection of direction of unbalanced faults. For 3-phase faults there is only the angle associated with $K_{C1}$ that can be varied to ensure the $\pm 90^0$ operation limits match with the fault profile.

Figures 7.6.3.1 to 7.6.3.4 show the improvement in the effectiveness of the combined function to detect correctly high resistance unbalanced faults. Initially the results show a failure in the directional detection process for $|K_{C1}|=1$ and $|K_{C2}|=20$ for same pre-fault and fault conditions. The higher the magnitude of $K_{C2}$ the better the performance. The limit would be influenced only by the transient performance of the digital filters extracting the negative phase sequence component. Errors at the output of the filters which are amplified could cause incorrect decision in the direction detection process. The optimal value would be derived at the implementation stage of the proposed method into a practical product. Alternatively, if $|K_{C1}|=0$ there is no possibility of incorrect fault direction detection and is independent of $|K_{C2}|$.




11kV Distribution System with Two Line-end Sources on an Underground Cable Feeder

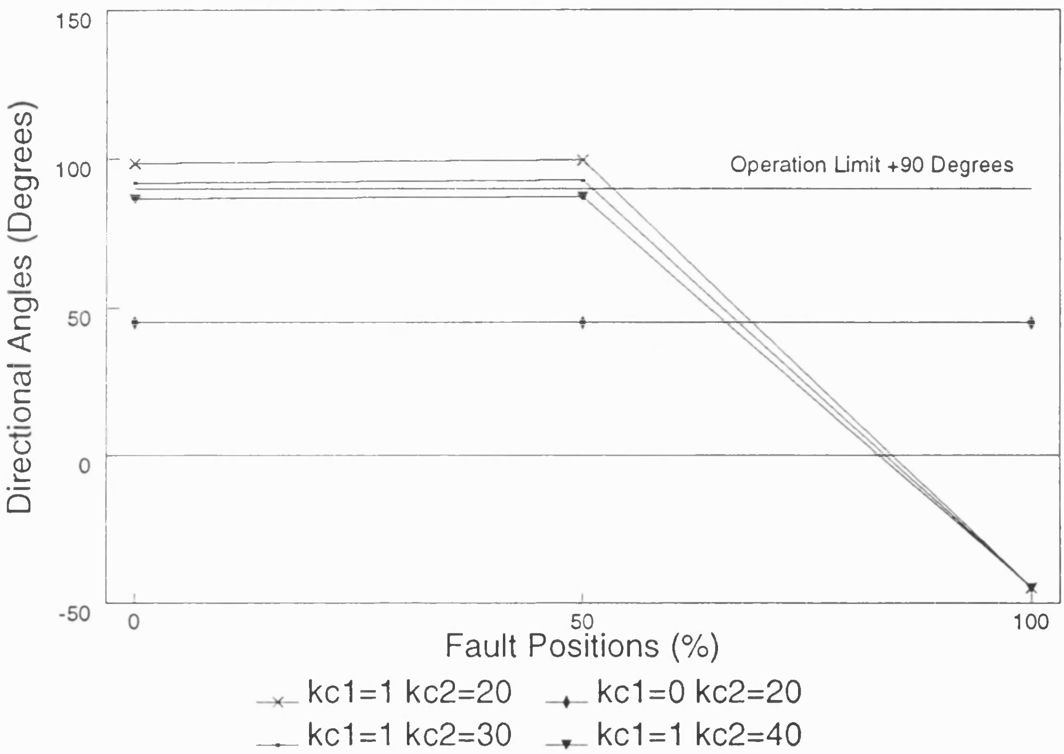
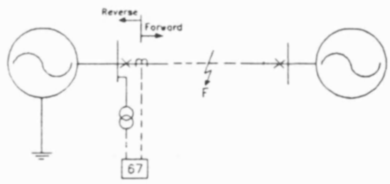



Figure 7.6.3.1 Variations of Directional Angle $\theta_C$ with the Magnitudes of $K_{C1}$ and $K_{C21}$ Constants in the Combined Function $F_C$ to detect a Phase-phase Forward Fault with 100Ω Fault Resistance and 100% Pre-fault Load Current Flow importing from Remote-end Source.




11KV Distribution System with Two Line-end Sources on an Underground Cable Feeder

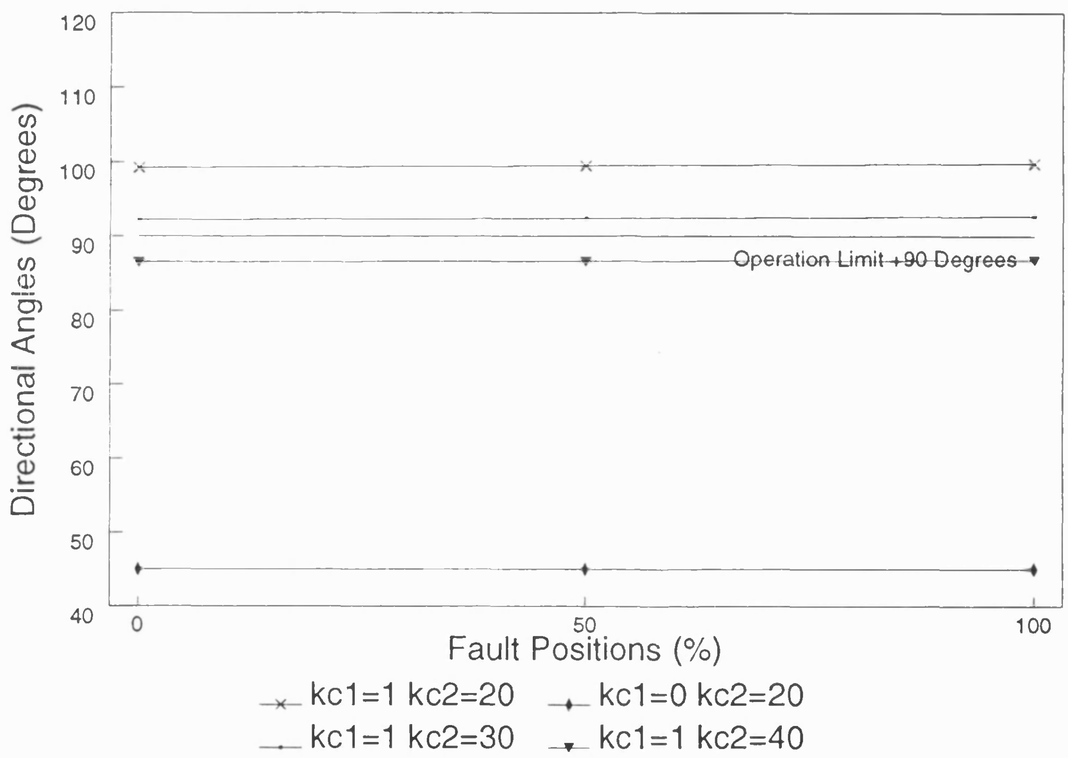
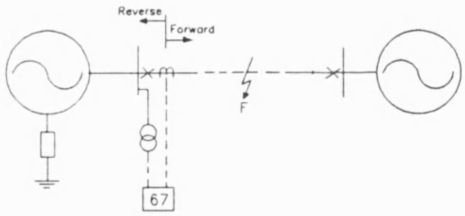



Figure 7.6.3.2 Variations of Directional Angle $\theta_C$ with the Magnitudes of $K_{C1}$ and $K_{C21}$ Constants in the Combined Function $F_C$ to detect a Single-phase-earth Forward Fault with 100Ω Fault Resistance and 100% Pre-fault Load Current Flow importing from Remote-end Source.




33kV Distribution System with Two Line-end Sources on an Overhead Line Feeder

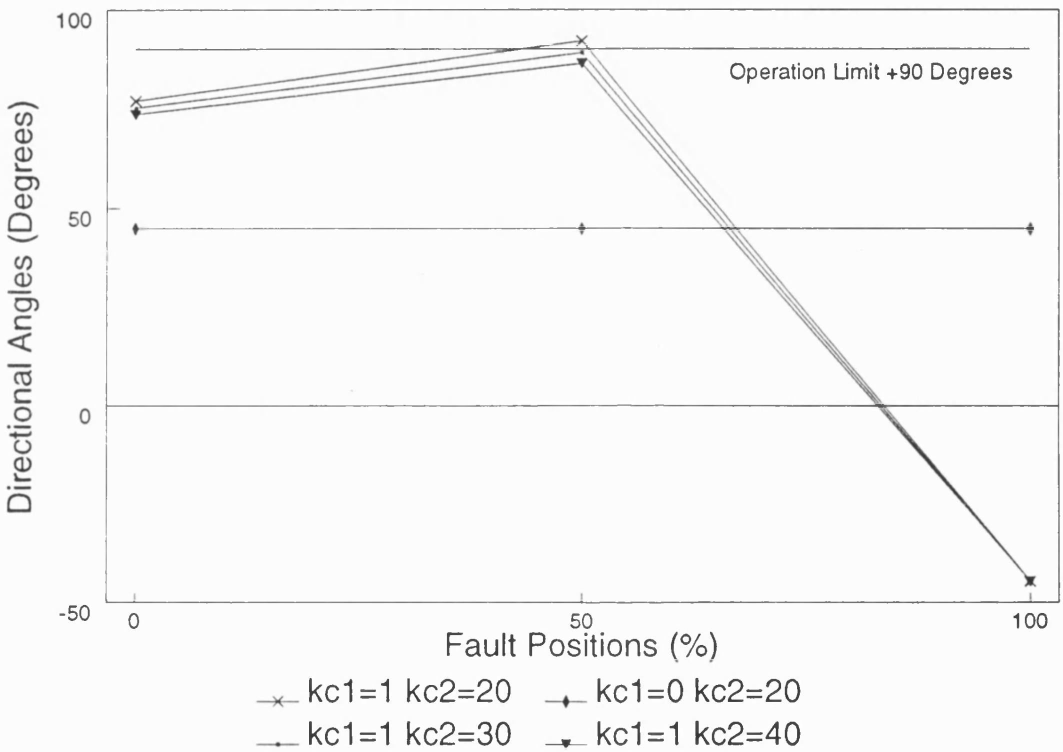
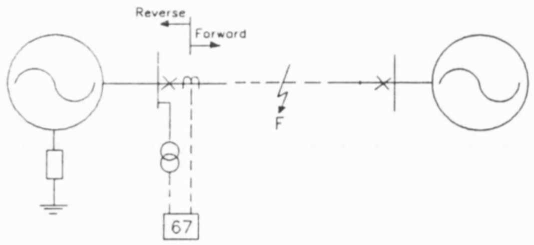



Figure 7.6.3.3 Variations of Directional Angle $\theta_C$ with the Magnitudes of $K_{C1}$ and $K_{C21}$ Constants in the Combined Function $F_C$ to detect a Phase-phase Forward Fault with 100Ω Fault Resistance and 100% Pre-fault Load Current Flow importing from Remote-end Source.




33kV Distribution System with Two Line-end Sources on an Overhead Line Feeder

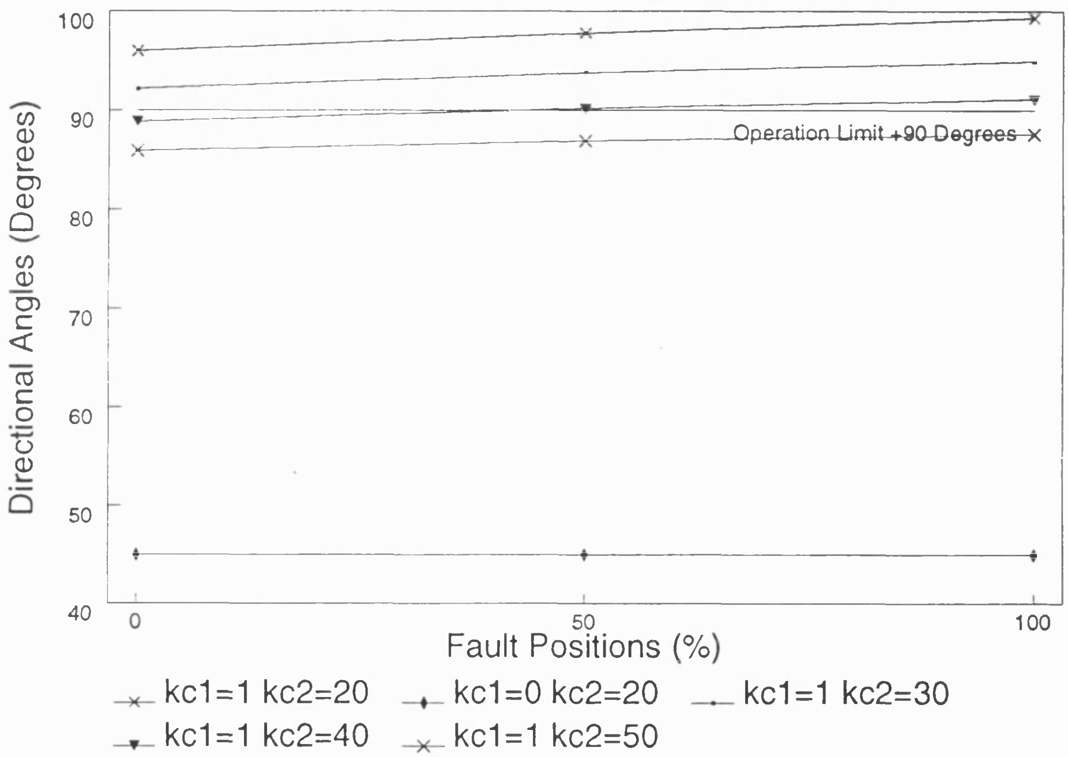
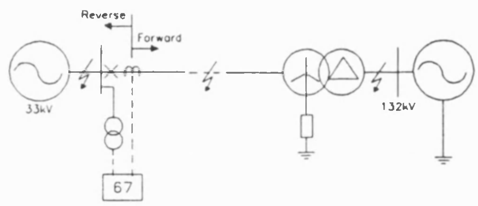



Figure 7.6.3.4 Variations of Directional Angle $\theta_C$ with the Magnitudes of $K_{C1}$ and $K_{C21}$ Constants in the Combined Function $F_C$ to detect a Single-phase-earth Forward Fault with 100Ω Fault Resistance and 100% Pre-fault Load Current Flow importing from Remote-end Source.

It can, therefore, be concluded that the new directional detection method should not have any problem to determine correctly the direction of all types of unbalanced faults with high fault resistances and full pre-fault load current flow.

For balanced 3-phase faults, either in the forward or reverse direction, the wide variation of the angle between the positive phase sequence voltage and current reduces the discriminative performance of the new directional detection method. The results indicate that for multiple-source systems the capability for correct direction detection of high resistance 3-phase faults is reduced. However, the occurrence of 3-phase high resistance faults or even 3-phase faults is not common with any fault resistance that may be present consists of mainly arc resistance which is generally low. It is also recognized that majority of distribution system feeders only have single end source. This source may be connected by automatic switching to one of the feeder ends to re-configure the system to maintain the power supply instead of the feeders being fed by two sources simultaneously. Figure 7.6.3.5 below shows the limits of the fault resistance coverage at different fault positions for 3-phase faults on the overhead line feeder shown. Initially, Figure 7.6.2.2.6.1 for the same arrangement in Section 7.6.2.2.6 shows that for 100Ω fault resistance the directional detection method is not able to determine the correct direction when there is pre-fault load current flow in opposite direction to the fault current. However, the method performs correctly for fault resistances up to the values shown in this Figure 7.6.3.5 under the same fault and pre-fault conditions. Though the fault resistance values are much reduced for faults at some fault positions they are near to practical values.




33kV Distribution System with a 132kV Source on an Overhead Line Feeder

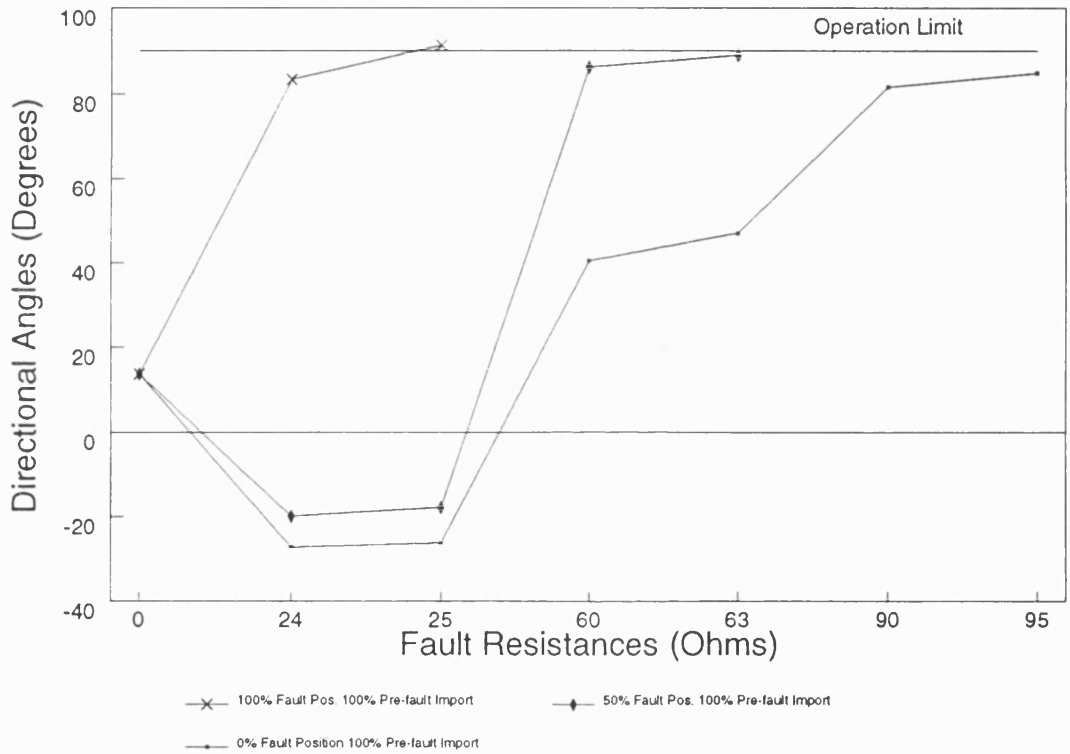



Figure 7.6.3.5 Limits of Fault Resistance Coverage for a 3-phase Forward Fault at Different Fault Positions with the Directional Angle $\theta_C$ still within $\pm 90^0$.

Overall performance of the proposed new method of detecting direction indicates the validity of the new approach to directional detection on a polyphase basis. In the implementation stage of the proposed method there are facilities that can be employed to improve the performance further. One such facility is to rely on the negative phase sequence quantities alone for unbalanced faults with control to inhibit maloperation on unfaulted and unbalanced operating conditions. These are discussed in Chapter 10 as recommendations for further work.

The magnitude of the combined function $F_C$ has not been examined as it does not affect the decision on the fault direction, forward or reverse, which is based on the values of the directional angle $\theta_C$ to be within or outside $\pm 90^0$ respectively. The important requirement is that both the voltage and current signals are above the threshold of operation of the final design of the hardware. This can be determined at the implementation stage.

## 7.7 Discussion on the Envisaged Transient Performance of the New Directional Detection Method

This project concentrates on finding a new method of directional detection. The investigation has been successful in deriving a new basis in the form of a combined function in terms of the symmetrical components of voltages and currents at a given relay location to determine the direction of fault points. This work has been based on the steady-state analyses of the power systems examining the symmetrical components of voltages and currents generated at the relay location for various types of faults on the systems. The results of the steady-state analyses prove the validity of the proposed function from which the direction information of a fault point is derived. Forward faults are defined by the resulting phase angle associated with the proposed function to be within the set limits, outside of which results in the classification of reverse faults.

It is assumed that the constituent parameters of the proposed function are available, i.e., the phase sequence components of voltages and currents have already been extracted from the input signals fed from the instrument transformers. Power system transients generated on the inception of faults do not affect the basis of the decision on fault direction. However, the transients generated affect the extraction of the phase sequence components to be free from dc component and harmonics in the data acquisition and signal processing routines when the complete working process of a directional relay using the new method is to be considered. The direct effect on the directional detection routine is that the transients will influence the settling of the output response and hence the overall operating time from fault inception to the determination of fault direction.

In order to implement the new directional detection method to develop into a directional relay the data acquisition and signal processing sub-systems form an important part of the whole process. Hence, the transients that appear on the occurrence of power system faults have significant effects on the overall performance of the finished product. It is important, therefore, that the effects of transient conditions are reviewed to demonstrate their influences in the design of the finished product to ensure satisfactory performance to meet the needs of the actual systems. The fundamental basis of the detection of fault directions remains unchanged.

The transient performance of the finished product depends on the methods used in acquiring the required data and their conditioning which are in turn governed by the operating speed required. These are discussed in the following sections.

### 7.7.1 Power System Transients

There are a number of transient conditions that protection relays operating in an electrically hostile environment have to deal with, though the importance and effects of each is dependent on the design and application of the relay under consideration. These conditions include:

(i) A decaying exponential or dc-offset transient in the current signal.

(ii) A dc offset in the voltage signal results from the dc component of current in systems where the source impedance angle is different from the line impedance angle.

(iii) High-frequency transients generated as a consequence of line shunt capacitance having different charges prior and during a fault and generated during the transition. The effect depends on the magnitudes and frequency spectrum of the transients.

(iv) Transients due to capacitor voltage transformers where they are employed. These transients, resulted from a sudden change in the primary applied voltage and impressed on the resistance, inductance and capacitance associated with the voltage transformers, depend on the circuit parameters of the transformers, its burden and magnitude change of the applied voltage [1.43].

(v) Transients and errors generated by current transformers due to the core saturation.

(vi) Transients due to series capacitors which are used in series-compensated long extra high voltage lines.

Transients associated with capacitor voltage transformers and series capacitors used in series-compensated lines do not appear on distribution systems. These devices are generally employed on extra high voltage systems only.

The effect of the exponential component depends on the primary system time constant, the larger the time constant the longer the duration of the dc component in the signal and hence the greater the effect on the relay performance. The effect is in turn dependent on the targeted operating speed of the relay under consideration. In accordance with International Electrotechnical Commission (IEC) standard IEC 56 [3.17] on high-voltage alternating-current circuit-breakers a figure of 45ms has been taken as the typical primary system time constant for the design consideration of circuit breakers to handle asymmetrical current waveform. The document also stipulates the decrement of the dc component in the fault current varies with the duration of the fault. This is shown in Figure 7.3:

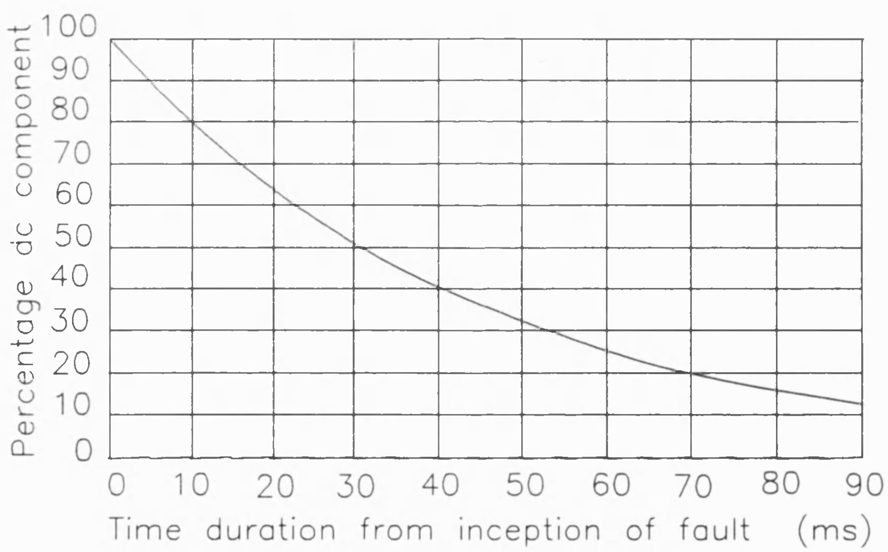



Figure 7.3 Decrement of the DC Component in Fault Current with Fault Duration.

It shows that after 2 cycles the dc component is reduced to ½ of its initial value at fault inception.

It was reported [3.16] that in 1981 IEC Secretariat document 213 brought up a proposal from a working group to the Sub-committee 17 to increase the primary system time constant to 60ms due to the development and expansion of power systems worldwide. For systems with voltages of 100kV and above, the decrement of the dc component follows curve 2, which is at a lower rate, shown in Figure 7.4:

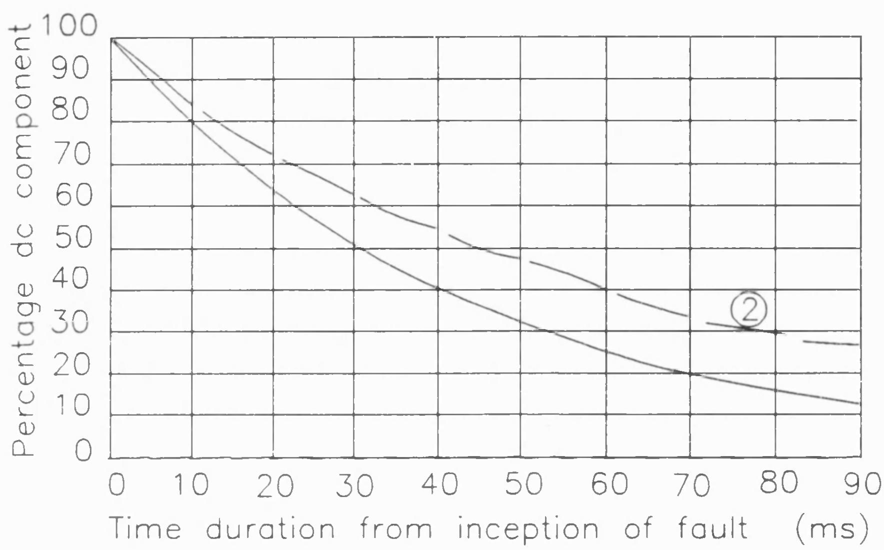



Figure 7.4 Decrement of the DC Component in Fault Current at a Lower Rate with Fault Duration with Increased Primary System Time Constant.

For distribution systems the time constant is very short due to heavy damping and the distant locations of generators. Consequently the effect of dc component in the current signal is minimal or negligible. This dc component can be effectively eliminated by analogue or digital filtering by well established techniques.

The travelling-wave effect in the current signal is also negligible for generally very short feeders having only very low shunt capacitance associated with distribution systems. The high-frequency travelling-wave effect is heavily damped.

It is generally accepted that transients generated by current transformer saturation affect the performance of a protection relay. Hence, every protection relay that requires current signal always specifies adequate output from the feeding current transformers to operate the particular relay within the latter's capability. The effect of current transformer saturation depends on relay design.

### 7.7.2 Speed of Operation

It is necessary to consider the requirements of the power systems before the speed required from the relay under consideration can be realistically specified, apart from the natural desire to have the shortest fault clearance times to limit fault damages to equipment. The usual criterion is based on the system transient stability requirement. This is generally applicable to transmission systems. For distribution systems there has not been the need for high speed relaying based on system stability criterion.

Traditionally, distribution systems use current-operated relays as the main protection and these relays do not provide fast fault clearance times. Typically, using inverse definite minimum time lag overcurrent relays the minimum time multiplier setting (TMS) is 0.1 [2.7, 2.8, 2.9]. This gives a range of relay operating times of 0.3 to 3.0 seconds at a fault level of 10 times the relay current setting for the standard inverse time characteristic commonly employed. For directional overcurrent or earthfault relays the need to have time delay in the overall operation provides ample time to derive direction information and to carry out current measurement.

For directional overcurrent or earthfault protection schemes using separate directional and current detection elements there is a need to have shortest possible time for the directional detection element to minimize any timing errors of the overall operation of the scheme. However, for digital design with integral directional detection and current measurement routines, it can be arranged to have more time for directional and less time delay in the current measurement process to obtain an overall required operating time of the scheme. Currently available digital directional overcurrent or earthfault relay [2.18] implemented on moderately powerful microprocessor has an operating time of 1½ to 2 cycles. An operating speed of two cycles for the direction detection process is, therefore, acceptable.

### 7.7.3 Signal Acquisition and Conditioning

A directional relay receives the analogue voltage and current signals from the instrument transformers. These signals usually consist of unwanted noise in addition to the fundamental components which are the required signals for the relay's decision making routine. The acquired signals from the instrument transformers, therefore, require conditioning to extract the fundamental components. This process generally consists of two parts for a digital relay, the analogue signal pre-processing and the digital signal processing after the analogue signal has been sampled and converted to digital form in order to obtain an estimate of the required original analogue signal parameters.

#### 7.7.3.1 Analogue Signal Pre-processing

Analogue filtering of the signals is very often implemented, though this may be dependent on the data requirements of the particular relay design. The purpose is to allow the transfer of certain frequencies in the input signal and to attenuate other unwanted frequencies. Generally, analogue inputs are low-pass filtered before they are sampled to limit the effects of noise and unwanted signal component in frequency ranges above the folding frequency, i.e., ½ the sampling frequency, to eliminate aliasing.

For the current input circuit, interposing input transactors or transphasors [2.36, 2.37, 2.38] can be used before any analogue filters are employed. These are proven effective means of removing dc offset component in the current signal before the latter is further subjected to the low-pass filtering. Alternatively, suitable digital filters can be used to remove the dc component.

#### 7.7.3.2 Analogue Signal Sampling and Analogue-to-digital Signal Conversion

Before digital filters are used the concerned signal has to be sampled and converted to a digital equivalent. The sampling rate affects the signal tracking capability and multiplexing schemes, if employed. A balance has to be struck between the operating speed and computation burden on the microprocessors in choosing the most suitable sampling rate.

In order to obtain an estimate of the fundamental-frequency information from a group of samples the sampling rate chosen should be faster than any significant changes in the analogue signal to retain all the useful information. It is recognized [3.14, 3.15] that sampling rate of less that 4 samples per cycle will degrade the fundamental quantity whose changes are examined in the relaying routine. At the other extreme, sampling rate above 16 times per cycle does not significantly shorten the response time of relays that are dependent on the fundamental-frequency component due to the limited information content of a group of samples with short sampling intervals.

It can be established (Chapter 10, Section 10.3.2) that the time-domain representation of symmetrical components at time instant t is given by:

$$\begin{bmatrix} f_0(t) \\ f_1(t) \\ f_2(t) \end{bmatrix} = \frac{1}{3} \begin{bmatrix} f_A(t) & f_B(t) & f_C(t) \\ f_A(t) & f_B(t-2T/3) & f_C(t-T/3) \\ f_A(t) & f_B(t-T/3) & f_C(t-2T/3) \end{bmatrix} \qquad .......7.1$$

where T is the time period of fixed frequency $\omega$.

Equation 7.1 shows that samples at instants t, $(t - \frac{T}{3})$ *and* $(t - \frac{2T}{3})$ are required to compute the symmetrical components. The sampling frequency should, therefore, be a multiple of 150Hz or multiple of 3 samples per cycle for 50Hz systems. With the dc, 100Hz and 150Hz components that may appear on 50Hz systems during faults and have to be suppressed, the sampling frequency should, therefore, be at least 300Hz or 6 samples per cycle.

From the sampled analogue signals the digital equivalents are derived. There are many techniques developed to convert analogue electrical quantities to equivalent digital representations. The converter should offer sufficient precision, speed and accuracy for the application. The particular methods by which the digital representations are generated and the rate at which the conversion process proceeds influence the nature of the data acquisition system. The criteria for considering the choice of a particular analogue-to-digital conversion process are, therefore, the resolution desired and the sampling rate used in the data acquisition system.

The resolution for a given digital representation is a function of the number of available bits and the form of the bit code. Analogue-to-digital converter with 8 to 12 bits of precision have been applied [2.10, 2.11, 2.18, 2.20] with the 8-bit converters used for some overcurrent relay designs and 12-bit converters used for transmission system protection relays.

The conversion rate adopted for a given application depends on the allowable signal tracking error which in turn depends on the sampling rate and should be faster than the multiplexing rate.

Sampling rate of 6 samples per cycle or 300Hz together with an 8-bit analogue-to-digital converter have been used to successfully design digital filters employing the early generation of 8-bit microprocessor to extract the symmetrical components of current [1.35, 1.38]. It was reported that the filters' response settled after 7 samples [1.38] or 9 samples [1.35] for a single-phase-to-earth fault.

#### 7.7.3.3 Digital Signal Processing

Digital signal processing of filtered, sampled and scaled analogue signals and which have been converted to digital equivalents involves the application of suitably selected/designed algorithms to obtain estimates of parameters of interest for protection. There are well established algorithms [3.14, 3.15] proposed or applied in either experimental or commercially available digital relaying schemes.

These algorithms may be classified into two groups, one models on the signal waveform and the other models on the primary system.

It is envisaged that, for the purpose of considering the application to this investigation, algorithms based on the model of the signal waveform will be used. The parameter of interest for relaying application is contained in the description of the model. The range of available algorithms in this category includes the more well known:

- Fourier Algorithms
- Walsh-function Algorithms
- Curve-fitting Algorithms

Equation 7.1 enables the extraction of symmetrical components which will contain dc and harmonic symmetrical components if the latter are present in the phase quantities. The extracted samples of $f_n(t)$, $n=0,1,2$ are then subjected to suitably designed digital filters to obtain the fundamental components of the various phase sequence quantities. This is illustrated in Figure 7.5.

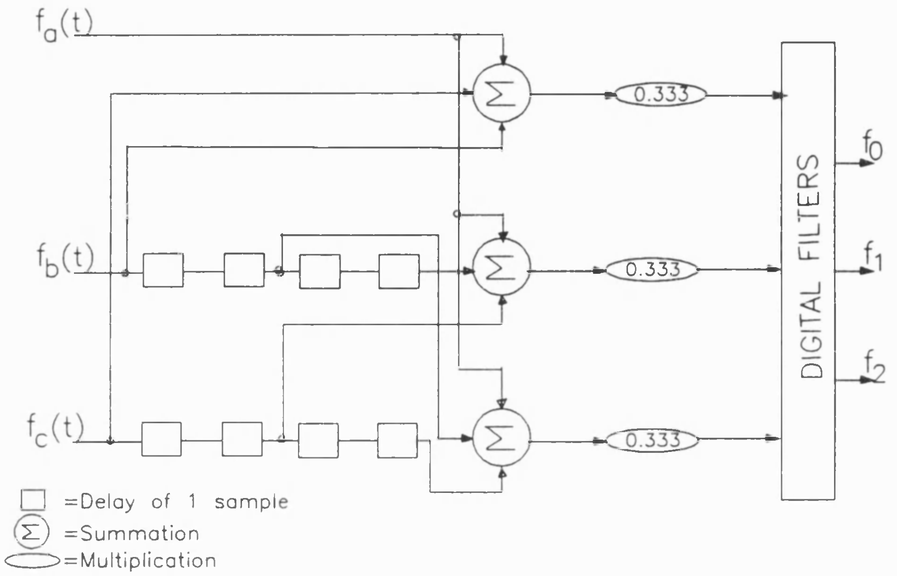



Figure 7.5 Extraction of Symmetrical Components from Phase Signals before Digital Processing.

The symmetrical components are obtained using equation 7.1 with a sampling rate of 6 samples per cycle.

For this investigation the phase information of the symmetrical components is required at the output of the digital filters. The samples of the symmetrical components are, therefore, processed by suitable algorithms to estimate their magnitude and phase information. The Fourier algorithms appear to have been adopted by most of the commercially available digital protection relaying schemes to date [1.41, 2.10, 2.18, 2.20, 2.40, 2.41] to obtain the magnitude and phase angle information of the primary system signals.

There are also other signal processing algorithms that can provide the required level of performance [3.14, 3.15]. The tradeoff between the speed of response and accuracy of the result is an inherent consideration in the selection process. Theoretical advantages and disadvantages between competing algorithms can be masked in clever implementations or highlighted in less efficient implementations. The various issues related to the ultimate objective of extracting the symmetrical components accurately and speedily have to be addressed and investigated to select the most suitable algorithm.

**7.8 Conclusion**

From the foregoing discussions on the nature and sources of power system transients and the various processes involved in obtaining the digital signals representing the fundamental-frequency information it can be concluded that the signal acquisition and conditioning sub-systems including the analogue portion play an important role in the overall performance of a digital relay. These sub-systems are subjected to the influence of power system transients. There are various technical factors to be considered. Only when these sub-systems perform satisfactorily will the correct response of the main protection algorithm, in this case the detection of fault direction, be ensured.

However, the proposed method of detecting direction is not directly influenced by the power transients generated in terms of the basis of deciding the correct direction of faults, but may be influenced by the performance of various processes in extracting the required parameters for the direction decision routine and may affect the settling of the output response because of its dependence on the output from the preceding processes which take a finite time to settle. This will in turn determine the operating speed. With the advent of powerful microprocessors that have floating point capability it is reckoned that the target operating time of about 2 cycles will not present any difficulty in achieving it.

The steady-state investigation of the proposed new approach of directional detection should be satisfactory in proving the validity of the proposed method and the correct criterion adopted to determine fault direction. The transients, however, influence the speed and accuracy of estimating the fundamental-frequency information to enable the directional detection process to make the correct decision.

There are published work [1.35, 1.36, 1.37, 1.38, 1.46, 1.48] in the extraction of symmetrical components by digital techniques and also their applications in commercially available equipment [1.46, 2.40, 2.41]. They illustrate that the techniques, taking transient performance into account, are maturing both in terms of operating speed and accuracy.

As part of further work it is recommended that the transient performance is examined in conjunction with the implementation of the new principle into an operational hardware to obtain optimal response of the overall directional detection process from acquiring signals from the instrument transformers to issuing output to indicate the direction of faults. One objective is to improve the operating speed to enable consideration to apply the new device to transmission systems. These are discussed in Chapter 10.

# CHAPTER EIGHT

# APPLICATION OF THE PROPOSED NEW POLYPHASE DIRECTIONAL DETECTION METHOD

## 8.1 Introduction

Chapters 6 and 7 demonstrate that it is possible to develop a new method of detecting the direction of a fault point on a polyphase basis with reference to a relay location based on a study of the symmetrical components of the voltages and currents generated at the relay location.

The proof of the validity of the proposed new method does not result in a new directional relay. A finished product involves the successful design of the hardware implementing the new method of directional detection that includes all the necessary input data acquisition, the directional detection algorithm and output facilities. The relay must also be able to operate in the hostile electrical environment of power supply systems.

On the basis that the new directional detection method is successfully implemented into a new directional relay this Chapter makes some proposals to apply the new directional relay. These proposals are aimed at improving performance of existing directional relays and also at creating new applications to overcome shortcomings in existing schemes or to widen the traditional use of directional relays to include application to the protection of plant items.

## 8.2 Application to the Directionalisation of Current-operated Relays

The main objective of this project is to investigate a new method of detecting direction on polyphase basis to be used in the traditional directional overcurrent and earthfault protection schemes of distribution systems. Chapter 4 illustrates the problems of the present standard single-phase 90°-connected directional relays widely used in this area and also the deficiency of the currently available polyphase directional relays. A new polyphase directional relay based on the new directional detection method offers improved performance. The application of the new directional relay in this area is very simple, merely to replace existing directional elements but with improved performance, as illustrated below:

### 8.2.1 Application to the Directionalisation of Existing Current-operated Relays

The output of the new polyphase directional relay in the form of a contact can be used to enable the conventional current-operated relays having an input to accept such enable signal. This is illustrated in Figure 8.1 for a currently available solid-state overcurrent and earthfault protection relay [2.6].

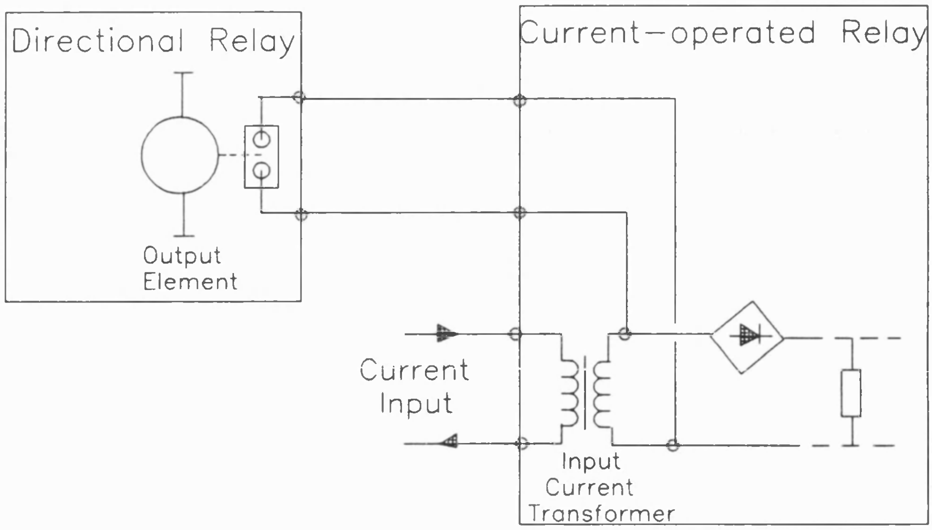



Figure 8.1 The use of a Separate Directional Relay to directionalise a Current–operated Relay.

The directional relay output contact short-circuits the secondary winding of the current-operated relay input current transformer when the current flow is in the restraint direction. When a fault occurs in the forward direction the directional relay output contact opens to enable the current measuring element to determine the output depending on whether the current flowing exceeds the pre-set operating level.

It is assumed that the design of the current-operated relays allows access by the separate directional relays in order to effect control of the current detection process. This is not always possible for currently available relays. For electromechanical type overcurrent and earthfault protection relays the directional control is more difficult to achieve by a separate directional relay. The directionalised overcurrent and earthfault protection relays based on the electromechanical design always incorporate the directional element as part of the overall design. It is generally not possible to access the current detection elements to effect directional control. Figure 8.2 illustrates the use of a separate directional relay to control an induction disc overcurrent or earthfault protection relay [2.3, 2.8].

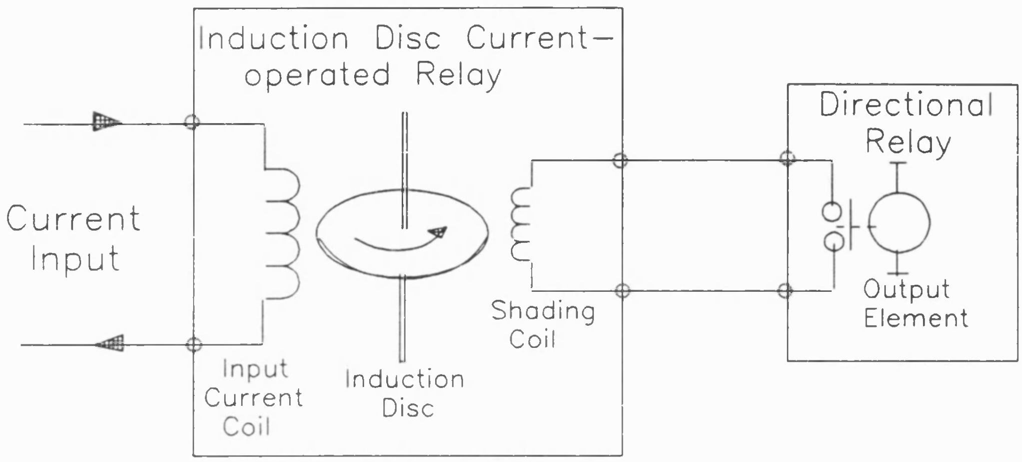



Figure 8.2 Directional Control of an Induction Disc Current-operated Relay by a Separate Directional Relay.

In this arrangement [2.7, 2.8] the solid shading ring normally used in an induction disc current-operated relay is replaced by a shading coil whose two end terminals are shorted by the output contact of the directional relay when it operates for forward faults providing a closed circuit and enabling the operation of the induction disc relay if the current flowing exceeds its setting.

The new directional relay can be used to control a current-operated relay for phase faults or for earth faults only. In the latter application the current detector is only fed with zero phase sequence current from the current transformer neutral connection. This is shown in Figure 8.3.

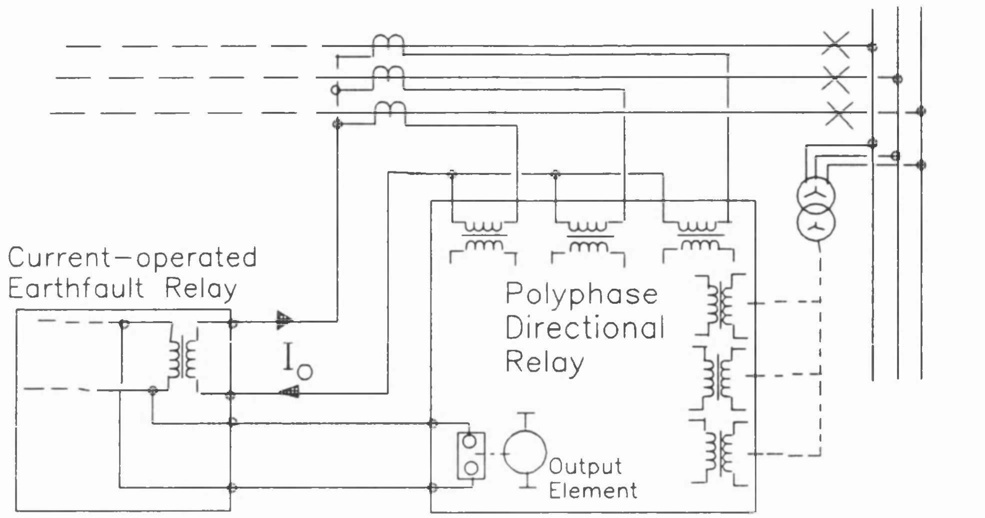



Figure 8.3 The Directional Control of a Current-operated Earthfault Relay by a Polyphase Directional Relay.

The non-usage of zero-phase sequence components of voltage and current in the derivation of direction information eliminates the effect of mutual zero phase sequence coupling causing wrong detection of direction when parallel circuits are considered as explained in Chapter 4.

### 8.2.2 Application to the Directionalisation of the Latest and Future Generation of Current-operated Relays

The design of the latest and also future generation of current-operated relays will be based on digital techniques [1.25]. It is envisaged that the new directional method will also be implemented into digital relays providing integrally a directional control to the current measurement process. With the advent of increasingly powerful microprocessors a single processor is able to handle both the directional detection and the current measurement routines within acceptable operating times.

The integral facilities enable a better directional control and coordination between the two processes. The directional detection output arranged to enable the current measurement eliminates the traditional "contact race" problem [3.3]. As a complete unit of directional overcurrent or earthfault relay it can be structured to remain stable on the presence of only one signal, either voltage or current. The polarising voltage signal, similar to the current measurement process, has to exceed a pre-set level before an output is permitted [2.18]. Figure 8.4 shows the control by the direction detection process on the current measurement process in the latest range of digital directional overcurrent or earthfault relays commercially available [2.18]. The directional detection is based on the traditional single-phase $90^0$ connection arrangement.

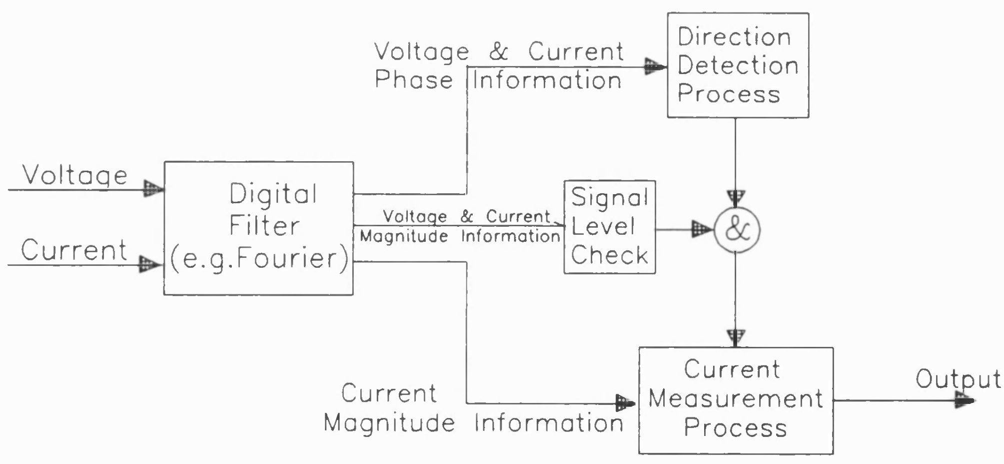



Figure 8.4 The Integral Directional Control on a Digital Directional Overcurrent Relay with Signal Level Check.

## 8.3 Application to the Protection of Plant Items

The proposed new relay, though is designed primarily as a directional detector, can be used to provide main protection for plant items. This necessitates the addition of current level measurements to provide conventional current level setting facilities to meet different application sensitivity requirements. Separate level detectors may be incorporated to measure the individual symmetrical components of voltages and currents.

### 8.3.1 Application to the Protection of AC Motors

One of the main protection functions associated with ac motor protection is the detection of thermal overloading. Depending on the sizes of motors different methods are used [3.8], mostly based on current measurements. The relay design uses the current signal I to generate a "$I^2t$=constant" current/operating-time characteristic where t is the operating time with energizing current I.

Due to the different phase sequence impedances of a given motor and the corresponding different heating characteristics due to the flow of phase sequence currents it has been the practice in the relay design for overload protection of motors to use an equivalent current in form of $I_1^2 + nI_2^2$ [3.8]. By giving different values to n ($n > 1.0$) the increase in the heating effect of the negative phase sequence current in actual motor is simulated in the relay thermal replica. This provides a relay operating characteristic closely matched to the motor capability allowing maximum utilization of the motor.

The availability of phase sequence currents in the proposed polyphase directional relay can easily be combined to form an equivalent current to generate a thermal overload protection characteristic.

The negative phase sequence current alone with a level detector provides unbalanced voltage supply protection of the motor including single phasing condition.

The presence of negative phase sequence voltage will also serve as a useful indicator of the degree of unbalance of the supply system. As any significant degree of supply system unbalance will affect the performance of an ac motor. The motor has to be derated in order to keep the temperature rise in the motor to be within the design limits. It is estimated that a 10% negative phase sequence voltage may cause upto 40% reduction in the motor output to avoid overheating [3.8]. The detection of negative phase sequence voltage can provide an alarm to the equipment operator with option to trip the supply on persistent unbalance.

Simultaneously, the polyphase directional element arranged to "look" into the motor can provide discriminative tripping in case of internal faults. This function is normally provided by a unit form of protection such as high impedance or biased differential scheme and is generally applied to large size machines because of cost. To avoid maloperation because of the high sensitivity of the direction detection process the operation should be qualified by both the positive and negative phase sequence current level detections to cover all types of faults. The directional control eliminates the effect of fault contribution from the protected motor to external faults.

This new approach of protecting ac motors generates a very cost effective scheme that is not available to date. It provides functions previously given by several separate thermal overload protection relay, unbalanced supply and single phasing protection relay and main differential protection relay requiring two sets of current transformers.

The new scheme provides not only the traditional protection functions but adds extra facilities that are near-impossible to have in equipment presently available.

### 8.3.2 Application to the Protection of AC Generators

The proposed new directional relay can also provide improved protection to small-to-medium size a.c. generators. It enhances existing schemes in sensitivity, selectivity and security.

#### 8.3.2.1 Discriminative Protection Scheme

Biased differential and high impedance differential protection schemes, either for both phase and earth fault or for earth fault coverage only , have been the standard schemes for the protection of a.c. generators providing discriminative tripping of only the faulted machine. In some applications directional earthfault relay has been used [2.27] to protect ac generators against earth faults on the stator winding when fault current is severely limited by the high impedance earthing of the generator stator winding neutral. The traditional biased differential and restricted earthfault protection schemes are not sensitive enough to detect such low-current earth faults. Directional relays, with much lower operating current and without current-level detection, are employed to provide discriminative protection of generators against earth faults. The scheme is shown in Figure 8.5.

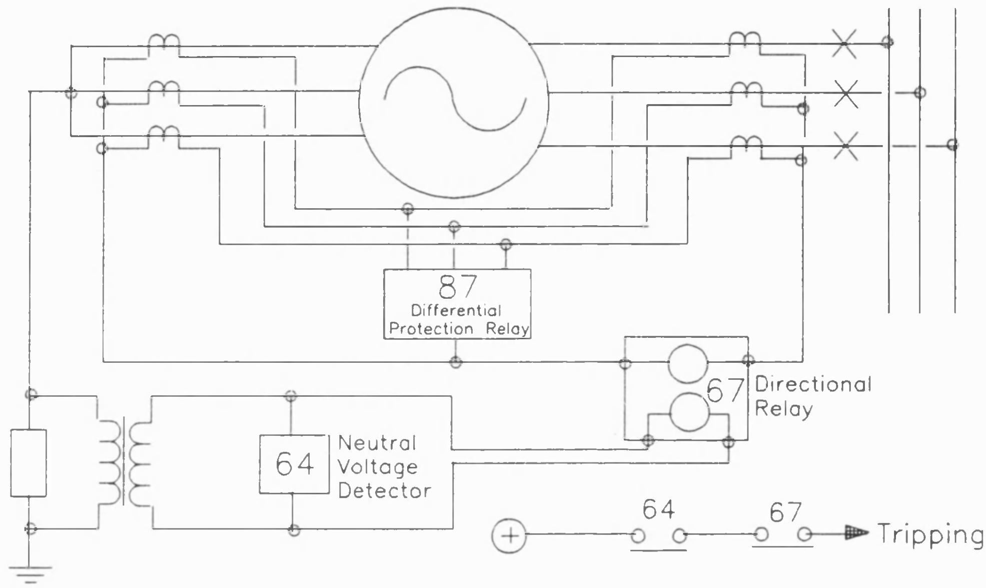



Figure 8.5 The use of a Directional Relay to provide Discriminative Protection Scheme for Earth Faults on a Generator.

To prevent spurious operation of the scheme due to electrical noise because of the high sensitivity of the directional relays the tripping is checked by a neutral voltage detector connected in the earthing path of the generator stator winding. The detection of zero phase sequence voltage plus the flow of zero phase sequence current into the machine indicating the presence of internal earth faults will trip the generator circuit breaker to isolate the machine from the system.

The proposed new relay can perform the same function but without the need for the separate neutral voltage displacement relay. The direction detection can be qualified by the presence of negative phase sequence voltage indicating the presence of an earth fault before issuing a trip signal to the circuit breaker.

In addition, the new relay can also provide protection against phase-phase and 3-phase faults on the stator winding since the same direction detection is effective. However, the qualifying signal can be changed to include both phase sequence voltages and currents. Both the positive and negative phase sequence components can be used to provide maximum sensitivity without compromising on security.

### 8.3.2.2 Voltage-dependent Overcurrent Protection Scheme

In protection schemes that make use of both voltage and current signals the loss of the voltage signal very often creates possible maloperation of the schemes. These include impedance-measurement-based protection and voltage controlled/restrained overcurrent protection schemes. This problem may also exist in directional elements depending on the design and the principle of operation. The solution is to provide voltage supply supervision facility such that any detection of the voltage supply failure due to tripping of the voltage supply miniature circuit breaker or blowing of the voltage supply fuse(s) an alarm or an alarm with blocking of the main protection function is effected.

The voltage supply supervision function is implemented by detecting the presence of negative or zero phase sequence voltage without any corresponding phase sequence currents [1.12, 1.24]. The presence of both phase sequence voltage and current signals indicates primary-system-fault-generated condition and is ignored by the supervision facility.

Voltage supply supervision function is normally incorporated in high voltage system protection schemes where the additional cost is justified but not in the case of directional overcurrent or earthfault protection. The new scheme can address this issue without any significant increase in the cost.

For the new proposed directional relay incorporating current level measurement and forming a directional overcurrent and earthfault protection scheme, the negative phase sequence components of voltage and current can be employed to detect voltage supply failure. Maloperation is prevented by the presence of negative phase sequence voltage and not the current component.

In addition, improvement can also be incorporated in the new proposed directional overcurrent and earthfault relay to provide voltage-dependent overcurrent protection applied to ac generator protection. The traditional voltage-dependent overcurrent protection relay senses the primary system voltage level and increases its sensitivity with reduction to the voltage level. This adaptive sensitivity is to match the fault current decrement characteristic of ac generators. The sensitivity adjustment can either be a step change when the voltage falls below a pre-set level (termed voltage-controlled overcurrent protection relay) or be a gradual change in line with the voltage depression profile (termed voltage-restrained overcurrent protection relay). The two types of characteristics are shown in Figure 8.6.

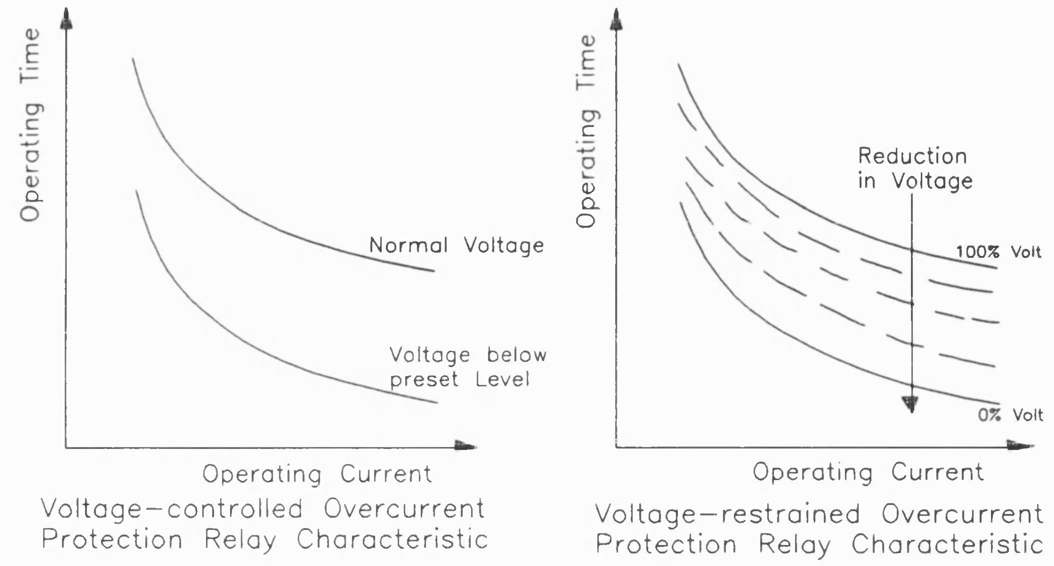



Figure 8.6 Voltage-dependent Overcurrent Protection Relay Characteristics.

Depending on the location of the current transformers as shown in Figure 8.7 the zone of protection of the voltage-dependent overcurrent protection relay is different.

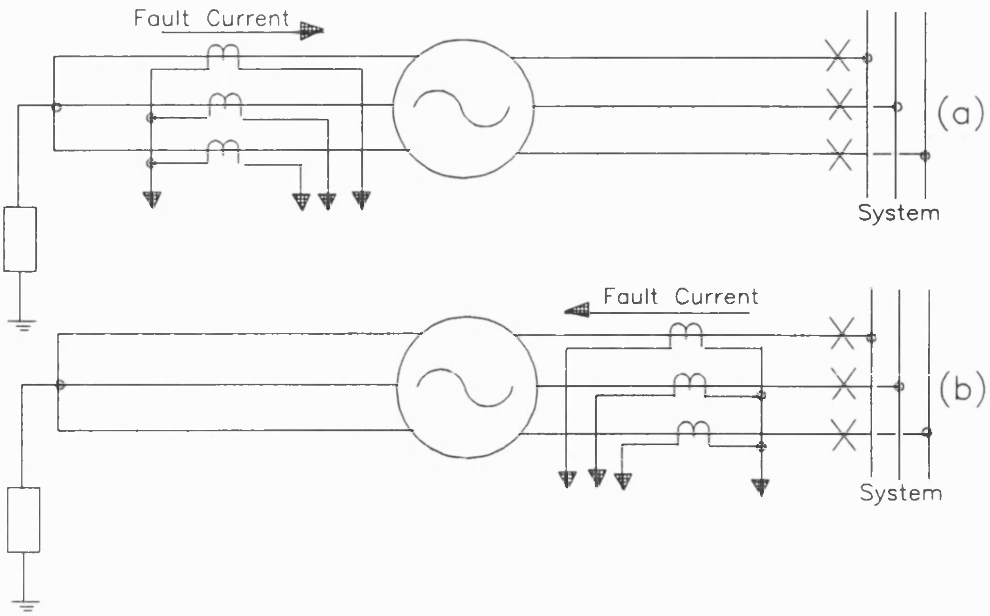


Figure 8.7 The Location of Current Transformers and the Zone of Protection.

In Figure 8.7a where the current transformers are located at the neutral end of the generator stator winding the zone of protection, relying on fault current produced by the generator, includes both the generator and the system. In Figure 8.7b where the current transformers are installed at the outgoing terminal end of the generator the zone of protection, relying on fault current produced by the generator, covers the system only. For internal faults on the generator in the latter case the relay operation depends on the fault current fed from the system. This is not subjected to the generator fault current decrement characteristic.

The new directional overcurrent and earthfault protection relay incorporating the proposed method of directional detection provides improvements in the above discussed scheme. The arrangement is shown in Figure 8.8.

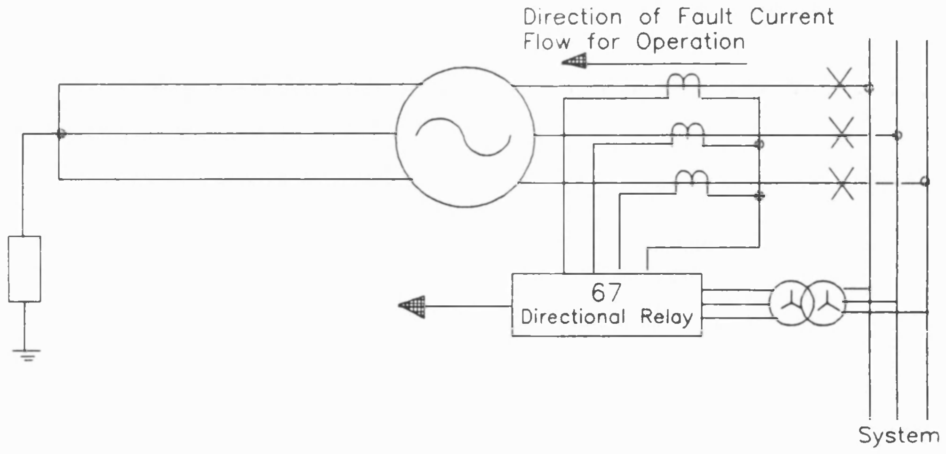



Figure 8.8 Discriminative Voltage−dependent Overcurrent Protection Scheme for a Generator.

The directional relay is arranged to operate for faults on the generator only. This arrangement provides both discriminative protection as detailed in Section 8.3.2.1 and voltage-dependent characteristic. The current measurement provides self-ranging setting by increasing its sensitivity with reduction in the positive phase sequence component of voltage or with increase in the negative phase sequence component. There is no requirement for co-ordination with protection schemes installed on the system to which the generator is connected.

The same unit with the availability of the negative phase sequence component of current can also provide the standard unbalanced loading protection ($I_2{}^2t=K$) for the generator without any additional units. This feature is independent of the directional control.

# CHAPTER NINE

## CONCLUSIONS

From a study of the principle of operation of electromechanical directional relays, in particular the single-element polyphase design, it is established that a new method of detecting fault direction is possible by examining the symmetrical components of voltages and currents generated at the relay location. It is decided that only the positive and negative phase sequence components are employed to cover all types of fault with the negative phase sequence component having a higher weighting factor to provide high sensitivity for earthfault detection especially in the presence of load current flow. The exclusion of the zero phase sequence component eliminates problems associated with zero phase sequence mutual coupling between parallel lines and multiple-earthed systems having several zero phase sequence current sources.

A combined function comprising a positive and a negative phase sequence terms of voltage and current at the relaying point is derived from which a study is made on the variations of the angle associated with the function for different system configurations and operating conditions. Forward faults generate a range of angles that are within the defined limits for operation whilst reverse faults produce angles whose values are outside the limits.

The computer studies results indicate the validity of the proposed method of fault direction detection based on a polyphase approach using symmetrical components of voltages and currents in a combined function.

The new approach to directional detection overcomes the following problems experienced by existing directional elements used in the overcurrent and earthfault protection schemes applied on distribution systems:

- No restriction imposed by primary system configurations and primary system fault current levels experienced by existing polyphase directional relays other than the normal sensitivity provided by standard overcurrent and earthfault protection.

- No maloperation due to circulating zero phase sequence current caused by mutual coupling of parallel circuits experienced by directional earthfault relays using zero phase sequence quantities as input signals.

- No effect caused by the phase shift introduced by a power transformer when the latter is placed between the fault point and the relay location.

The new method also provides the following advantages:

- The use of a single unit instead of three or four units of single-phase design providing a saving in equipment cost.

- A polyphase unit that can incorporate phase selection capability.

- The dependable performance of directional detection based on negative phase sequent quantity is preserved with the main shortcoming of this method in failure to detect balanced three phase fault overcome.

- The problems of maloperation of directional relay based on negative phase sequence quantity due to unbalance operation of the primary systems can be overcome by incorporating new features as part of recommended further work to be detailed in Chapter 10.

The new method of directional detection also generates potential to provide improved or additional applications that are not possible in present day products:

- New and improved method in the protection of a.c. motors

- New and improved methods in the protection of a.c. generators

The development of a new idea, does not necessarily mean the coming into existence of a new relay. It is the intention of this investigation that it should provide the basis for a new approach to directional detection which, hitherto, has been developed from the electromechanical theory without any additional work being carried out to improve it. The new proposal described should form the framework for longer term development and improvement in the detection of direction of faults on distribution systems. There is a need to further refine the combined function $F_C$ in terms of the magnitudes of the two constants $K_{C1}$ and $K_{C2}$ associated with the positive and negative phase sequence terms respectively of the function. This is more for applications to sub-transmission and transmission systems which is not within the scope of this project. The objective is to ensure correct direction detection for high resistance faults in the presence of pre-fault load current flow as discussed in Section 7.6.3.

The next step is to implement the idea into an operational product that can be put into service in the power system environment for which it is designed to provide fault detection. It is envisaged that this will be implemented by digital techniques. The process will, therefore, involve further work to develop the idea to include extraction of the symmetrical components and the associated digital signal processing and the operating algorithm. These are discussed in Chapter 10.

Whatever method of realisation is eventually used, it is the underlying decision principle which largely determine the performance attainable. It is, however, sufficient for the purpose of this project to conclude that a new method of directional detection has been proposed and proved workable and can be implemented. A simple operating algorithm can be developed as outlined in further work in Chapter 10. With added facilities and logic control this new method of directional detection can be implemented and developed into a directional current-operated relay that has improved performance. It will widen the traditional application of directional relays on distribution systems and create new applications in the protection of machines such as generators and motors.

CHAPTER TEN

# RECOMMENDATIONS FOR FURTHER WORK

## 10.1 Introduction

The main objective of this project is fulfilled. A new method of detecting the direction of a fault point on a polyphase basis using symmetrical components of voltages and currents generated at the relaying point has been proposed and the validity of this new approach proven. There is a need to refine the proposed approach to improve its capability to detect correct direction for high resistance faults with pre-fault load current flow, though this may not be common for distribution systems.

In addition, this new principle of direction detection also creates a potential for the development of new protection application schemes for plant items that are not available in the present commercial market. It also enhances the performance of traditional directional overcurrent and earthfault protection schemes.

The next stage should, therefore, be the practical realization of the proposed idea. With the recent use of digital techniques and technology in all new relay developments [2.28] it is envisaged that this process will also employ such techniques. This will involve the development of an efficient algorithm to execute the new directional detection method and the design of hardware together with the accompanying operating system and data acquisition sub-systems to realize into a practical product. Much more design and development efforts are necessary in these areas. Until this process is completed a new digital polyphase directional relay cannot exist even when the operating principle has been proven.

This Chapter recommends further work towards refining the basic approach and towards the realization of this new method of detecting direction into an actual product.

## 10.2 Further Investigation into the Values of the Constants $K_{C1}$ and $K_{C2}$ of the Combined Function $F_C$

In Chapter 7 the studies results indicate that the proposed combined function $F_C$ derived in Chapter 6 needs further investigation in terms of the suggested values for the two constants $K_{C1}$ and $K_{C2}$ in the function. The originally suggested values for $K_{C1}$ and $K_{C2}$ provide a magnitude differential of 1:20 with higher weighting factor to $K_{C2}$ to give better sensitivity for high resistance earth fault detection in the presence of heavy load current flow. The results indicate that the proposed differential of 1:20 is not sufficient to cover high fault resistance with significant pre-fault load current flow.

Section 7.6.3 in Chapter 7 shows the magnitude of $K_{C2}$ also influences the resulting directional angle $\theta_C$ of the function $F_C$ with the higher value leading to more dependence on the reliable directional detection capability of the negative phase sequence components of voltage and current. Increased magnitude for $K_{C2}$ enables correct direction detection of faults with higher fault resistances.

It is recommended that the magnitude differential between $K_{C1}$ and $K_{C2}$ is further examined to improve the fault resistance coverage of the proposed approach to directional detection taking into consideration the response of the digital filters extracting the negative phase sequence components of voltage and current.

### 10.3 Realization into a Practical Product

This process requires additional work in data acquisition, signal processing, decision-making routine based on the new found method and consideration for any other features needed to enable the finished product to operate successfully when it is put into service in the electrically hostile environment of substations.

Figure 10.1 shows the block diagram of one possible configuration of a directional relay incorporating the new method of detecting direction and showing the areas that require further work to complete the development of such a new directional relay.

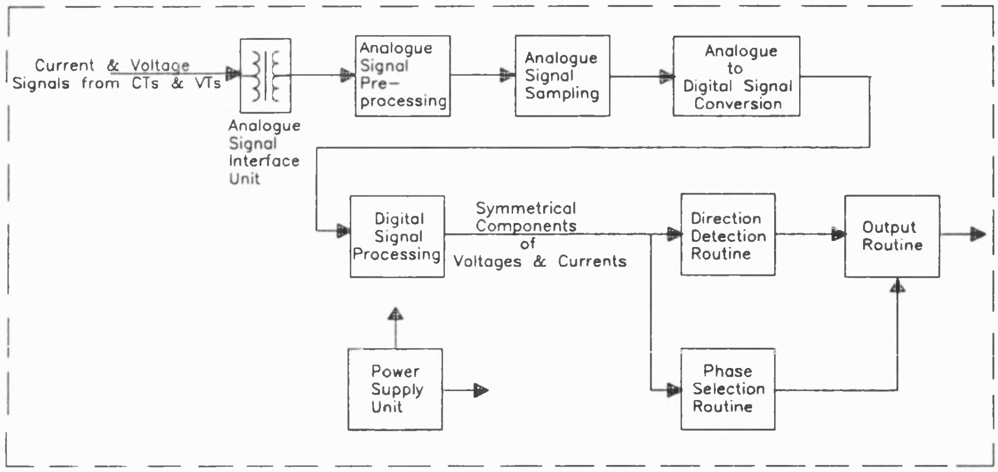



Figure 10.1 Block Diagram of a Possible Configuration of a Digital Directional Relay based on the New Method of Detecting Direction.

### 10.3.1 Proposed Algorithm for the New Directional Detection Method

With the new principle of detecting direction established, an algorithm is required next to enable its implementation in a digital relay. This is the decision-making routine. The new method of detecting fault direction is based on the combined function defined in Chapter 6 and is given by:

$$
\begin{aligned}
F_C &= K_1 \frac{V_1}{I_1} + K_2 \frac{V_2}{I_2} \\
&= \frac{V_1}{I_1} \angle -45° + 20 \frac{V_2}{I_2} \angle +135° \\
&= |F_C| \angle \theta_C
\end{aligned}
$$

For forward faults:

$$-90° \leq \theta_C \leq +90°$$

For reverse faults:

$$-90° \geq \theta_C \geq +90°$$

With a phase angle range of $\pm$ $90^0$ to make a decision a simple amplitude comparator can be implemented to determine these two boundaries.

Figure 10.2 shows an amplitude comparison of two signals $S_1$ and $S_2$ resulting in a limiting range of angular displacement of -90° to +90° between the two signals for operation or restraint.

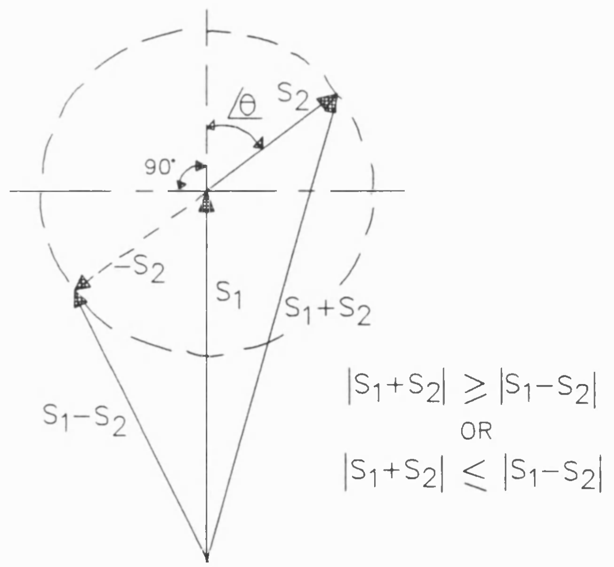



Figure 10.2 Amplitude Comparison of Two Signals to establish ±90° Angular Displacement limits between Them.

For the angular range of $\theta$ to be within -90° to +90°:

$$|S_1 + S_2| \geq |S_1 - S_2|$$

For the angular range of $\theta$ to be outside -90° to +90°:

$$|S_1 + S_2| \leq |S_1 - S_2|$$

Digitally, the implementation of this amplitude comparison to determine the phase angle between the two signals to be within or outside the range of -90° to +90° and hence operation for forward faults, or restraint for reverse faults can easily be achieved by comparing the amplitude of two corresponding samples of the two signals.

This amplitude comparison can be implemented between the respective phase sequence components of voltage and current. The $\angle -45^0$ and $\angle +135^0$ phase shifts applied to the positive and negative phase sequence voltages $V_1$ and $V_2$ respectively of the combined function can be easily implemented. These phase shifts on sampled $V_1$ and $V_2$ voltages can be effected by selecting the appropriate samples. Chapter 7 Section 7.7 determined that the sampling rate should be a multiple of 3 samples per cycle. If 24 samples per cycle rate is selected each sampling interval represents $15^0$ phase shift. Thus:

$-45^0$ corresponds to $-\dfrac{T}{8}$ delay in time.

$135^0$ equivalent to $-225^0$ corresponds to $-\dfrac{5T}{8}$ delay in time.

where T is the time of one period.

Samples of $V_1$ and $V_2$ at these time intervals of $-\dfrac{T}{8}$ and $-\dfrac{5T}{8}$ can, therefore, be used in the amplitude comparison.

With the combined function consisting of two terms associated with the positive and negative phase sequence components the comparison may be implemented for the two terms separately. Logic control may also be incorporated to have a decision based on the combined results of the two comparison processes or based on comparison of only one term for a certain types of faults. An example is in the case of unbalanced faults, only the dependable performance of the negative phase sequence term may be employed as suggested in Chapter 7, Section 7.6.3.

A counter at the output of the comparison can be used to determine the number of counts corresponding to the number of samples in meeting the operating criterion. Each comparison indicating an operation condition increases the counter either at a fixed rate or at a varying rate. The varying rate concept [1.16] which is dependent on the magnitude of the angular displacement between the two signals means that high speed of operation can be achieved when the angular displacement is small leading to shortest operating time when the two signals are coincidental providing a definition of maximum torque angle or relay characteristic angle. A measure of the angular displacement is indicated by the relative magnitudes of $(S_1 - S_2)$ and $(S_1 + S_2)$. The number of counts has to be determined before issuing an operating signal to the output element. This is based on the requirement of speed and security of the operation.

### 10.3.2 Data Acquisition and Signal Processing

The next stage is to ensure that the directional decision-making routine has the correct input signals to make the right judgement on the direction of faults. The new method of detecting direction relies on an examination of the phase sequence components of voltages and currents at the relaying point. This necessitates the extraction of these phase sequence components from the phase quantities of voltages and currents. The decision to use digital techniques to realize the idea into an actual product enables the application of digital filters to compute the phase sequence components from the sampled and digitised phase quantities. This will overcome the disadvantages of traditionally employed analogue filters whose performance is affected by dc and harmonics in the signal and the aging and drift in the filter parameters.

Before the analogue signals are sampled there may be a need to pre-condition the analogue signals with analogue signal filters to remove unwanted noise. The sampling rate has to be determined from a knowledge of the highest frequency of the signal component to be processed and the computing power of the microprocessor employed. Knowing the frequency spectrum of the signal the sampling frequency must be at least equal to twice the highest frequency that is to be detected by the sampling process. The sampling frequency chosen should allow sufficient time between the samples for the microprocessor to compute the required fundamental frequency component.

Traditionally, symmetrical components are obtained as the result of a transformation of the three phase quantities represented as complex phasors at a fixed frequency. Digital filters operate in real time from the sampled data of the phase quantities. This requires that the transformation process be represented by a real time relationship between the symmetrical components and the phase quantities. This is illustrated as below:

If a signal in the time domain is represented by:

$$f(t)=F(\omega)Cos[\omega t+\phi(\omega)]$$
$$\textit{for a fixed frequency } \omega \qquad \text{...........10.1}$$

Its corresponding phasor representation is given by:

$$f(\omega)=F(\omega)e^{j\phi(\omega)} \qquad \text{..........10.2}$$

It follows that:

$$f(t) = \mathbb{R}\ [F(\omega)e^{j\phi(\omega)}\ e^{j\omega t}] \qquad \text{...........10.3}$$

The symmetrical components $F_0$, $F_1$ and $F_2$ are obtained from the phase quantities $F_A$, $F_B$ and $F_C$ by:

$$\begin{bmatrix} F_0 \\ F_1 \\ F_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} F_A \\ F_B \\ F_C \end{bmatrix} \qquad \text{..........10.4}$$

$$a \;= e^{j120°} = e^{-j240°} = e^{-j2T/3}$$

$$a^2 = e^{j240°} = e^{-j120°} = e^{-jT/3}$$

where T = time of one period at fixed frequency $\omega$

From equations 10.3 and 10.4 it follows that:

$$\begin{bmatrix} f_0(t) \\ f_1(t) \\ f_2(t) \end{bmatrix} = \frac{1}{3}\mathbb{R} \left\{ e^{j\omega t} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} F_A \\ F_B \\ F_C \end{bmatrix} \right\} \qquad \text{........10.5}$$

and

$$\begin{bmatrix} f_0(t) \\ f_1(t) \\ f_2(t) \end{bmatrix} = \frac{1}{3} \begin{bmatrix} f_A(t) & f_B(t) & f_C(t) \\ f_A(t) & f_B(t\text{-}2T/3) & f_C(t\text{-}T/3) \\ f_A(t) & f_B(t\text{-}T/3) & f_C(t\text{-}2T/3) \end{bmatrix} \qquad \text{.......10.6}$$

Equation 10.6 provides a means of computing the symmetrical components in real time by examining the past samples together with the present ones. Any dc component and harmonics present in the phase quantities also occur in the symmetrical components. This necessitates the use of filtering to remove unwanted signals. Degens [1.35] and Ahson *et al* [1.38] proposed digital filters to extract the symmetrical components with dc component and harmonics suppressed.

Alternatively, the fundamental frequency components of the 3-phase quantities can first be extracted from which the symmetrical component transformation is applied to obtain the phase sequence components. Fakruddin *et al* [1.39] used Haar transformation to extract the fundamental frequency signals in terms of the cosine and sine components as illustrated below:

The three phase quantities $F_A$, $F_B$ and $F_C$ can be expressed as :

$$F_A = F_{Ac} + jF_{As}$$
$$F_B = F_{Bc} + jF_{Bs}$$
$$F_C = F_{Cc} + jF_{Cs} \qquad \text{............10.7}$$

The subscripts c and s denote the cosine and sine terms respectively.

Using the symmetrical component transformation as shown in equation 10.4 and the expression for the phase quantities as in equation 10.7 the phase sequence components, again in terms of cosine and sine components, can be obtained as follows:

$$F_{0c} = \tfrac{1}{3}\,(F_{Ac} + F_{Bc} + F_{Cc})$$

$$F_{0s} = \tfrac{1}{3}\,(F_{As} + F_{Bs} + F_{Cs})$$

$$F_{1c} = \tfrac{1}{3}\,[F_{Ac} - 0.5\,(F_{Bc} + F_{Cc}) + 0.866\,(F_{Cs} - F_{Bs})\,]$$

$$F_{1s} = \tfrac{1}{3}\,[F_{As} - 0.5\,(F_{Bs}+F_{Cs}) + 0.866\,(F_{Bc} - F_{Cc})\,]$$

$$F_{2c} = \tfrac{1}{3}\,[F_{Ac} - 0.5\,(F_{Bc}+F_{Cc}) + 0.866\,(F_{Bs}-F_{Cs})\,]$$

$$F_{2s} = \tfrac{1}{3}\,[F_{As} - 0.5\,(F_{Bs}+F_{Cs}) - 0.866\,(F_{Bc}-F_{Cc})\,] \qquad \ldots\ldots\ldots\ldots 10.8$$

Similarly, Dash *et al* [1.40] calculated the negative phase sequence component from the fundamental frequency phase quantities obtained by Fourier technique.

There are commercially available digital relays [2.40, 2.41] that use Fourier algorithm to obtain the fundamental frequency phasor from which negative phase sequence component of current is extracted to implement protection function.

The work [1.35, 1.38, 1.39, 1.40, 1.46, 2.40, 2.41] concentrated only on obtaining the magnitude of the symmetrical components, the phase angle information was not made use of in the applications considered. For the present investigation the angles associated with the required symmetrical components are the critical parameter to determine fault direction.

When both magnitude and phase angle information is required suitable means has to be developed to derive the information from the samples of signals. One method using the Fourier algorithm may be investigated further.

A Fourier algorithm extracts the fundamental frequency phasor from samples of a periodic signal taken at equal intervals over a full period of the signal. In simpler terms, it is a harmonic analysis to find the fundamental sinusoidal terms. The general expression for the sine and cosine components of the signal S at a sample point K are given by:

$$S_{sine} = \frac{1}{N}\left\{2\sum_{n=1}^{N-1} S_{K-N+n}\, Sin(\frac{2\pi n}{N})\right\} \qquad \text{..........10.9}$$

$$S_{cosine} = \frac{1}{N}\left\{S_{K-N} + S_K + 2\sum_{n=1}^{N-1} S_{K-N+n}\, Cos(\frac{2\pi n}{N})\right\} \qquad \text{.......10.10}$$

Taken over a full period the Fourier calculation rejects harmonics of the fundamental frequency. The results are the real and imaginary components of a phasor representing the sampled signal from which the magnitude and phase angle can be determined:

$$Magnitude = \sqrt{(S_{sine})^2 + (S_{cosine})^2} \qquad \text{...........10.11}$$

$$Phase\ angle = \tan^{-1}\left\{\frac{S_{cosine}}{S_{sine}}\right\} \qquad \text{...........10.12}$$

Equation 10.11 is generally not employed to obtain the magnitude in microprocessor-based relays because of the time-constrained computation burden imposed on the microprocessor. Instead, the exact computation is usually replaced by piece-wise linear approximation. Although the approximations typically introduce errors in the results, they reduce processing time with ease of implementation [1.44]. This approximation method implemented in a commercial protection relay [2.10] produces an overall accuracy of -0.5% to +0.25%.

For the phase angle calculations equation 10.12 will not produce the correct angle for all values of $S_{sine}$ and $S_{cosine}$.

For example, $\dfrac{-S_{sine}}{-S_{cosine}}$ will appear the same as $\dfrac{S_{sine}}{S_{cosine}}$ .

However, if the signs of $S_{sine}$ and $S_{cosine}$ are noted the correct phase angle can be derived using the angular position information of the two components as shown in Figure 10.3.

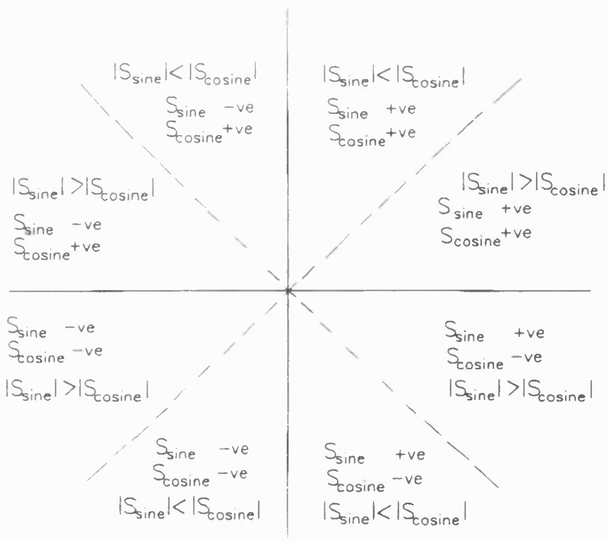



Figure 10.3 Angular Positions of the Sine and Cosine Components obtained from a Fourier Algorithm.

The actual phase angle is determined from the followings:

$$If\ S_{sine} > S_{cosine}\ \measuredangle = \tan^{-1}\left(\frac{S_{cosine}}{S_{sine}}\right) \qquad \ldots\ldots\ldots\ldots 10.13$$

$$If\ S_{sine} < S_{cosine}\ \measuredangle = 90^\circ - \tan^{-1}\left(\frac{S_{sine}}{S_{cosine}}\right) \qquad \ldots\ldots\ldots\ldots 10.14$$

This results in $\tan^{-1}$ values between 0 and 1 corresponding to an angular range of $0^0$ to $45^0$. It is also not possible to have division by zero. From the signs of $S_{sine}$ and $S_{cosine}$ and the values of $\measuredangle$ obtained from equations 10.13 and 10.14 the actual phase angle associated with the phasor can be determined:

If $S_{sine} = 0$ and $S_{cosine} = 0$, actual phase angle = $0^0$

If $S_{sine} > 0$ and $S_{cosine} > 0$, actual phase angle = $\measuredangle$

If $S_{sine} > 0$ and $S_{cosine} < 0$, actual phase angle = $0^0 - \measuredangle$

If $S_{sine} < 0$ and $S_{cosine} > 0$, actual phase angle = $180^0 - \measuredangle$

If $S_{sine} < 0$ and $S_{cosine} < 0$, actual phase angle = $\measuredangle - 180^0$

The calculation is recursive in which the complete summation of terms is not recalculated for each sample, but rather the oldest term of the summation is replaced by the newest term to give an updated summation.

One consideration needs to be made is the length of the summation or the window width [3.15]. Theoretically, a full-cycle window Fourier transform will produce the correct fundamental components but the process is slower. A half-cycle window may be considered to shorten the processing time but it depends on the sinusoidal symmetry of the signal waveform. With asymmetry associated with some transients it may take longer then half a cycle to arrive at the correct results. The use of half-cycle window assuming symmetry is less effective to attenuate the off-fundamental frequencies. This may cause difficulties for sub-harmonics which are often introduced in the voltage signal supplied through capacitive voltage transformers due to the transient response characteristics of the latter.

There are also other ways of extracting the symmetrical components of voltages and currents. Lobos [1.42] proposed the use of Kalman filter theory to develop non-recursive methods to estimate the symmetrical components from the input voltage and current signals.

From the foregoing discussions it can be seen that there are established means of extracting symmetrical components of voltages and currents from sampled phase voltages and currents. Work has to be carried out to find an optimal way of sampling the analogue voltage and current signals from the instrument transformers with suitable sampling frequency and analogue signal pre-processing filtering taking into account of microprocessor power.

### 10.4 Investigation into Transient Performance

As discussed in Section 7.7 of Chapter 7 it is unlikely that power system transients will affect significantly the performance of the new method of detecting direction.

Transients generated affect the data acquisition processes and the estimation of the parameters required for the directional relaying function. The criterion to determine fault directions, however, is not influenced by the power system transients.

The effects of transients on a given relay design depend on the targeted operating speed which in turn determines the design criteria for the data acquisition and signal processing sub-systems of the relay. Existing relays [2.1, 2.18, 2.24] for distribution system protection have been successfully designed using fairly low sampling rate and moderate powerful microprocessors. Sampling rates of 8 or 12 samples per cycle are used and the operating speed is typically 1½ cycles. However, with the availability of increasing power of microprocessors it is possible to improve the operating speed. The higher the operating speed the more effect will be imposed by the transient conditions on the filtering process.

There are now digital signal processors available and employed [1.47] to perform floating point operations in extremely short time. These can be used to effectively handle the transient effects.

It is, therefore, recommended that the transient performance be investigated with a view to achieve higher operating speed. One possibility is to employ digital signal processors as co-processors or front-end computer to extract the required symmetrical components. A central processor may then be used to perform the less demanding comparison function to determine the fault direction. This arrangement with improved operating speed needs to weigh against the cost factor. However, this improvement will enable the application of the new device to transmission systems.

This necessitates an examination of the data acquisition and signal filtering processes to extract the phase sequence components of voltages and currents that are free of dc and harmonic content as discussed in the foregoing Section 10.2.

## 10. 5 Additional Features

The following additional features have to be considered to enable the finished product to operate successfully under different operating conditions and to enable the new applications detailed in Chapter 8.

### 10.5.1 Level Detection

Though the directional detection process does not require an accurate measurement of the input signal levels for its operation it is recommended that level detection feature is incorporated to provide adjustment facilities. The magnitudes of the symmetrical components of voltages and currents can be determined after extraction by the digital signal processing and compared with adjustable references (settings) to provide facilities for the required applications discussed in Chapter 8.

### 10.5.2 Unbalanced Operating Condition

One of the main problems [3.7, 3.11] of a directional relay using negative phase sequence components of voltage and current is the possibility of maloperation when there is an unbalanced condition. An unbalanced condition may arise due to failure of the secondary equipment such as voltage and current transformers or failure of the primary system such as, typically, an open circuit due to broken conductor.

This unbalanced condition, whether it is apparent due to failure of secondary system or it is actual primary system problem, requires further investigation to ensure successful design and application of the new directional relay. Chapter 8 Section 8.3.2.2 outlined a proposal to detect secondary equipment failure that presents an apparent unbalanced condition of the primary system leading to possible maloperation.

For primary system failure due to a broken conductor causing an open circuit in one phase it is recommended that special logics be incorporated. One proposal is to have the individual phase current continuously monitored and memorized. When one phase is open circuited, logics can be arranged such that the disappearance of current in one phase preceded by current flow and with current flowing in others the directional detection process is inhibited. There may be consideration for the flow of charging current to determine broken conductor at remote end of a feeder.

### 10.5.3 Operation under Normal Loading Conditions

Under normal operating conditions the flow of load current in the forward direction produces a positive response from the directional detection process because of the use of the positive phase sequence components of voltage and current. It has been the design of some electromechanical [2.12, 2.25, 2.30] relays to use voltage restraint feature to prevent the directional element from giving an output on the flow of forward load current. The directional element has an additional voltage coil that produces a restraining torque acting against the operating torque produced by the normal polarising voltage and operating current in the direction detection process. With normal voltage level applied to the restraint winding the directional element is prevented from operation on forward load current flow.

This non-operation feature on forward load current flow improves the transient stability of a directional relay when the system condition changes, for example, from a forward load to a reverse fault condition. The incorporation of this feature in the proposed new relay should be investigated.

The availability of the phase sequence components of voltage provides a means of differentiating a normal healthy system condition from faulted system conditions. The presence of the positive phase sequence voltage alone and within limits of normal voltage range indicates a healthy condition. This can be further enhanced by the absence of negative phase sequence voltage or the presence of negative phase sequence voltage without corresponding component of current (This indicates failure of the voltage transformer supply). This healthy-system-condition signal can be used to prevent the directional relay from operation on forward load current flow.

An alternative method is to make use of impulse starters similar to those used in transmission line protection [2.2]. Impulse starters respond to a positive increment in the energizing signals instead of the absolute values. They, therefore, do not operate under normal loading conditions. Separate impulse starters are required for the two phase sequence components of currents to cover all types of faults. These impulse starters can be used to enable the directional detection process.

### 10.5.4 Phase Selection Capability

Appendix 11.7 shows how faulted phase(s) can be identified from an examination of the phasor relationships between the symmetrical components of voltages and/or currents. Though this method has limitations, mainly when it is applied to transmission systems, its performance is satisfactory for distribution systems where hitherto, it is not generally required to have phase selection facility in the protection schemes used.

With the availability of symmetrical components, implementation of phase selection facility can be investigated as a parallel routine to the direction detection routine after the extraction of symmetrical components from the phase voltages and currents.

When successfully implemented, the finished product of a polyphase directional relay with phase selection capability will be able to meet the needs of power system protection for such a relay with improved performance and enhanced features.

# CHAPTER ELEVEN

## APPENDICES

### Appendix 11.1 Nomenclature

a = Operator $1 \angle 120°$

$a^2$ = Operator $1 \angle 240°$

E = Source emf 'behind' the relay location

V = Voltage signal applied to a directional relay

$V_1$, $V_2$, $V_0$ = Positive, Negative, Zero phase sequence components of voltage

$V_A$, $V_B$, $V_C$ = Phase-neutral voltages of phases A, B and C respectively

$V_{AB}$, $V_{BC}$, $V_{CA}$ = Line-to-line voltages between the phases denoted by the subscript letters

i = Instantaneous value of current

I = RMS current signal applied to a directional relay

$\bar{I}$ = Conjugate of I

$I_A$, $I_B$, $I_C$ = Phases A, B and C currents respectively

$I_1$, $I_2$, $I_0$ = Positive, Negative, Zero phase sequence components of current

Subscripts 1, 2, 0 = Represent the positive, negative and zero phase sequence components respectively.

$\mathbb{R}$ = Real part of a complex variable

Z = System impedance

Subscripts L, S = Represent the line and source impedance respectively

RMS = Root-mean-square

$R_F$ = Fault resistance

$\Theta$ = Maximum torque angle or relay characteristic angle

or = Angle associated with an impedance

$\lambda$ = Phase shift introduced to the polarising voltage

$\alpha$ = Impedance angle associated with the voltage circuit of a directional relay.

S = Signal

T = Time for one period of signal

$\omega$ = Angular frequency

$\phi$ = Angular displacement between voltage and current of the same phase or phase sequence

$\beta$ = Voltage circuit impedance angle

$\angle$ = The phase angle of a phasor

$\Phi$ = Flux generated

$\hat{\Phi}$ = Peak value of $\Phi$

F = A given function

f(t) = Time-dependent function

f($\omega$) = Frequency-dependent function

$\longrightarrow$ = Tending to a given value

$\|$ = Parallel-connection of impedances

$\approx$ = Approximately equal to

67 = Device number representing a directional relay

## Appendix 11.2 Analysis of the Production of Driving Torque in Product-Type Directional Relays [1.6, 3.3]

Consider a moving element, which can rotate freely about its axis, that may be a disc or other form of rotor of non-magnetic current conducting material. Assume the moving element is prevented from rotating and is subjected to two alternating fluxes $\Phi_1$ and $\Phi_2$:

$$\Phi_1 = \hat{\Phi}_1 \sin(\omega t+\alpha_1)$$

$$\Phi_2 = \hat{\Phi}_2 \sin(\omega t+\alpha_2)$$

Each flux induces a voltage v around itself in the moving element given by:

$$v \propto \frac{d\Phi}{dt}$$

The resulting eddy current produced will be given by:

$$i = \frac{v}{Z}$$

$$and\ Z = |Z| \angle \lambda$$

where Z is the impedance presented by the moving element to the induced eddy current.

The induced currents due to the fluxes are, therefore, given by:

$$i_{\Phi 1} \propto \frac{1}{|Z|}\hat{\Phi}_1 Cos(\omega t+\alpha_1-\lambda) \qquad ...11.2.1$$

*and*

$$i_{\Phi 2} \propto \frac{1}{|Z|}\hat{\Phi}_2 Cos(\omega t+\alpha_2-\lambda) \qquad ...11.2.2$$

Assuming, with negligible error, that the paths in which the eddy currents flow have negligible self-inductance the eddy currents will be in phase with the induced voltages. The eddy currents, from equations 11.2.1 and 11.2.2, are:

$$i_{\Phi 1} \propto \frac{1}{|Z|}\hat{\Phi}_1 Cos(\omega t+\alpha_1) \qquad ..... 11.2.3$$

$$I_{\Phi 2} \propto \frac{1}{|Z|}\hat{\Phi}_2 Cos(\omega t+\alpha_2) \qquad .....11.2.4$$

The current produced by one flux reacts with the other flux, and vice versa, to produce forces that act on the moving element.

The fluxes and eddy current paths are diagrammatically shown in Figure 11.2.1:

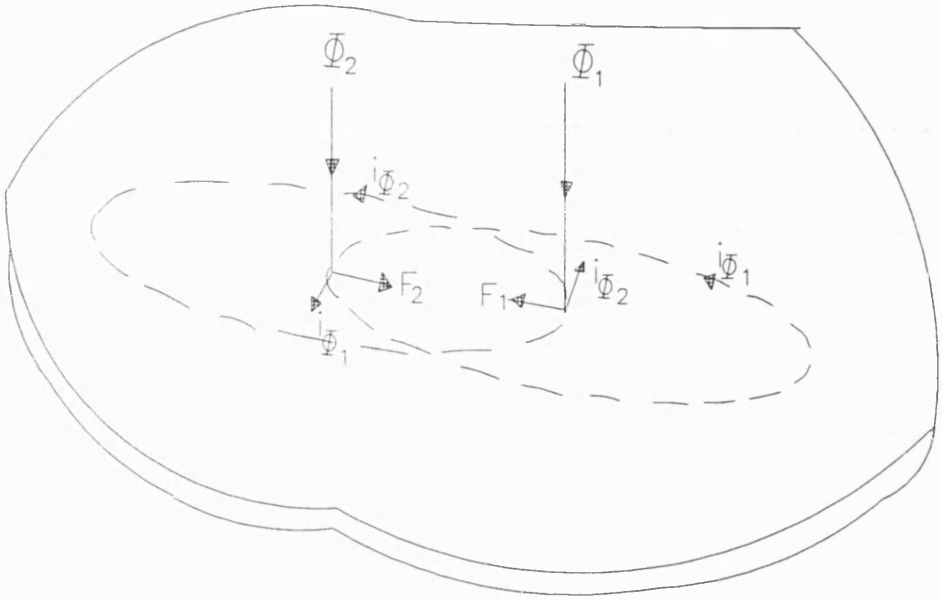



Figure 11.2.1 Production of Driving Torque due to Interaction of Two Alternating Fluxes.

It shows that two forces $F_1$ and $F_2$ in opposition are produced acting on the moving element to rotate. The resulting torque to drive the moving element is, therefore, given by:

$$Torque \propto \Phi_2\, i_{\Phi 1} - \Phi_1\, i_{\Phi 2}$$

$$\propto \hat{\Phi}_1 \hat{\Phi}_2 [\sin(\omega t + \alpha_2) Cos(\omega t + \alpha_1) - Cos(\omega t + \alpha_2) Sin(\omega t + \alpha_1)]$$

$$\propto \hat{\Phi}_1 \hat{\Phi}_2 Sin(\alpha_2 - \alpha_1) \qquad ....11.2.5$$

This expression shows that the net torque is the same at every instant. This is very significant in that the movement of the rotating element is positive and free from vibration.

Figure 11.2.2 shows the variation of the torque for the two components with changes in time.

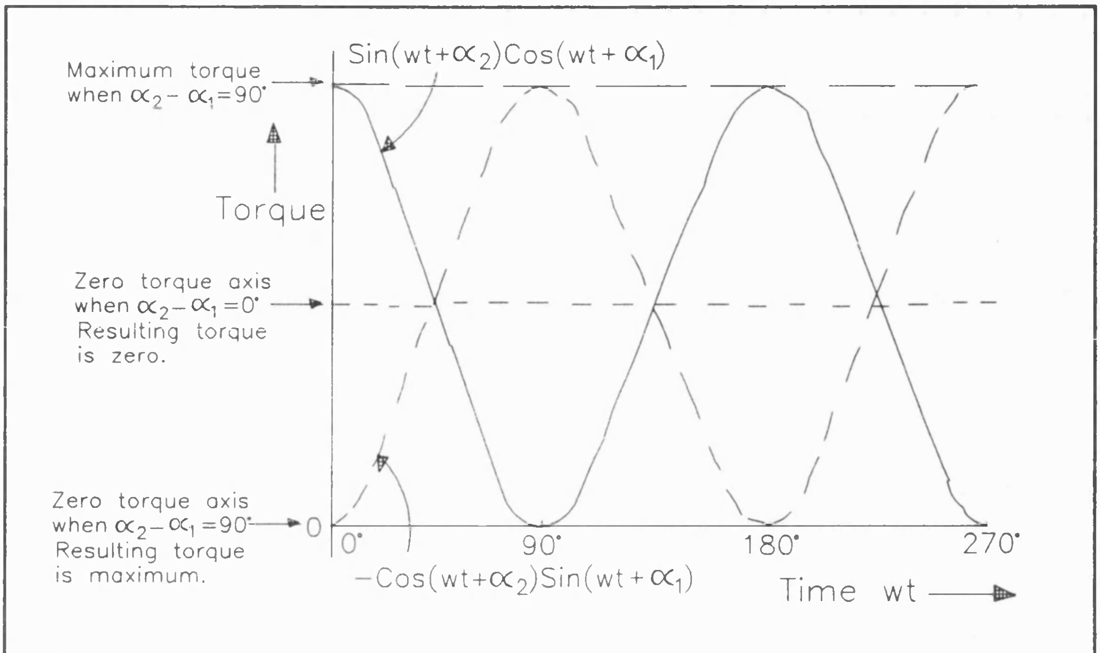



Figure 11.2.2 Production of a Constant Torque due to the Product of Two Time-varying Components.

It shows, however, that the net torque is always constant depending only on the displacement ($\alpha_2$ - $\alpha_1$) between the two fluxes.

When the angular displacement ($\alpha_2$ - $\alpha_1$) changes in sign the net torque also changes in sign. This provides a positive discrimination for direction detection.

For "symmetrical" structure such as induction cup used as the moving element it can be assumed that the flux is in phase with the actuating current. This means that the displacement angle ($\alpha_2$ - $\alpha_1$) between the two fluxes can also be defined as the phase angle between two actuating currents $I_1$ and $I_2$. The net torque produced, from equation 11.2.5, can be expressed as:

$$Torque = K \times I_1 \times I_2 \times \sin(\alpha_2 - \alpha_1) \qquad .......11.2.6$$

The magnitude of the flux generated is proportional to the actuating currents. This torque thus produced is maximum when ($\alpha_2$ - $\alpha_1$) is 90°. The angular displacement, under this condition, defines the maximum torque angle position.

It is, however, not necessary that maximum torque is to be produced at $\alpha_2 - \alpha_1 = 90°$. It may be desirable that maximum torque occurs at other value of angle to match with the primary system conditions for which the ultimate relay is designed to protect. This is achieved by phase shifting one of the actuating current, say $I_1$, so that the flux producing current is displaced from the original position of the actuating current phasor. This can be achieved by connecting a shunt resistor across the coil for input current $I_1$. The phasor diagram is shown in Figure 11.2.3.

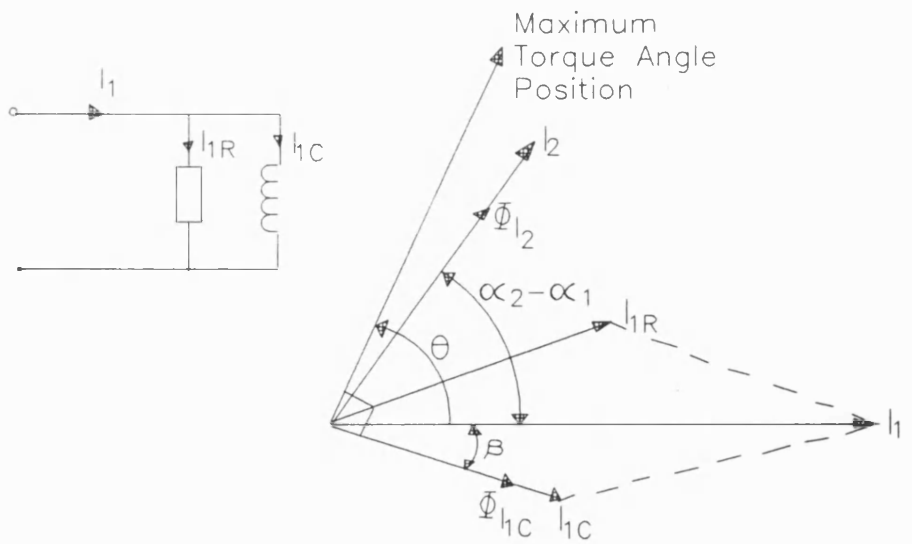



Figure 11.2.3 Effect of Displacing one of the Actuating Fluxes to obtain different Maximum Torque Angle Position.

Maximum torque will still occur when the displacement between the flux producing currents is 90° but in terms of the displacement between the actuating currents maximum torque will occur at some other angle than 90°.

Figure 11.2.3 shows that the torque produced based on equation 11.2.6 is:

$$
\begin{aligned}
Torque &= KI_1I_2Sin[\beta+(\alpha_2-\alpha_1)] \\
&= KI_1I_2Sin\{90°-[\theta-(\alpha_2-\alpha_1)]\} \\
&= KI_1I_2Cos[\theta-(\alpha_2-\alpha_1)] \qquad \text{........11.2.7}
\end{aligned}
$$

If one of the actuating source is a voltage signal and the current due to this voltage source is displaced from the voltage phasor by an angle $\beta$ as shown in Figure 11.2.4 and assume the phase displacement between the actuating voltage and current signals is $\phi$ the torque produced can be expressed as a function of this displacement.

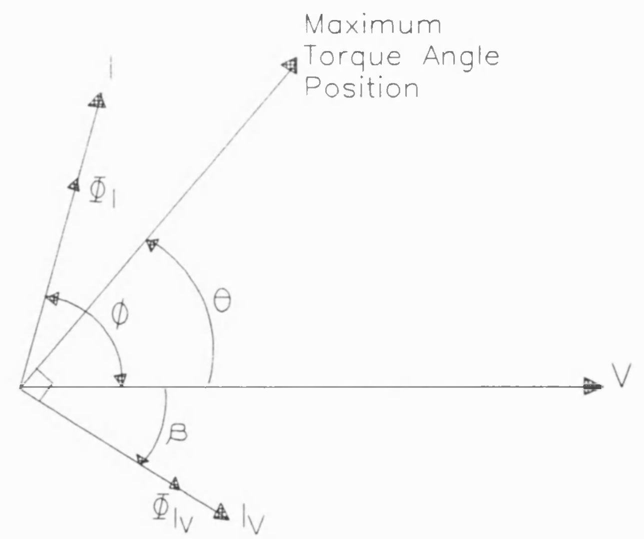



Figure 11.2.4 Production of Torque due to Interaction of a Voltage and a Current Signals.

From Figure 11.2.4 and equation 11.2.5:

$$Torque = K \times |\Phi_{IV}| \times |\Phi_I| \times \sin(\phi+\beta)$$

$$= K \times |\Phi_{IV}| \times |\Phi_I| \times \sin[90° + (\phi-\theta)] \qquad .......11.2.8$$

The torque produced in terms of the actuating quantities, their angular displacement $\phi$ and the maximum torque angle, is:

$$Torque = K \times |V| \times |I| \, Cos\ (\phi - \theta) \qquad .....11.2.9$$

The same principle applies for the actuating quantities to be both voltages.

It should be noted that torque is produced in the presence of out-of-phase fluxes. One flux alone will not produce a net torque. If only one actuating source is used such as induction disc overcurrent relay [2.8] some means has to be provided, such as the use of shaded pole structure in the core of the electromagnet so that out-of-phase components of fluxes are produced.

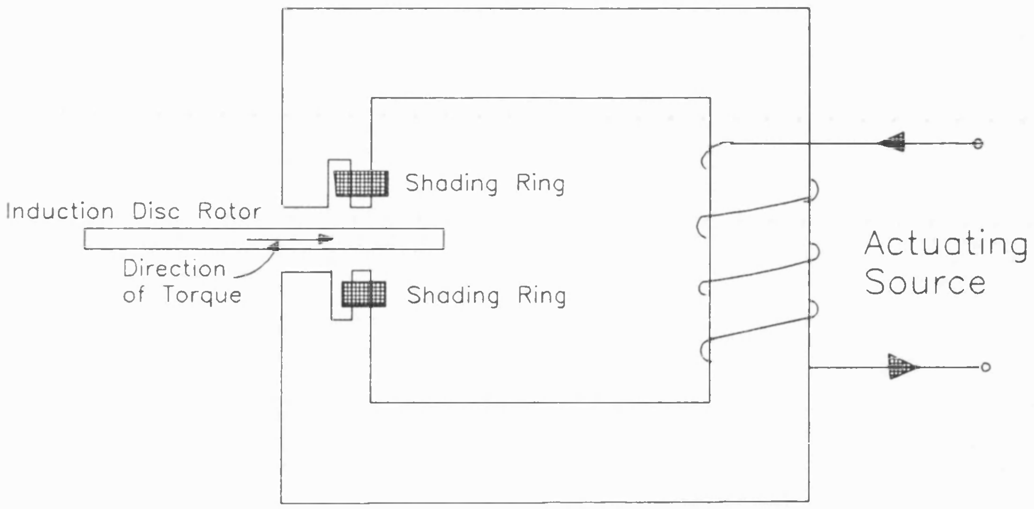



Figure 11.2.5 Use of Shading Ring generating Out-of-phase Fluxes to produce Driving Torque from Single Actuating Source.

This will produce a nett torque to drive the induction disc to close the output contact.

On the same basis, if because of the non-symmetrical structure of the moving element, a single energizing quantity of current or voltage will also produce two out-of-phase fluxes generating spurious torque to drive the moving element. For a relay with two actuating quantities of voltage and current the torque produced to drive the moving element will, therefore, consist of a number of components:

- Torque due to current signal acting alone.
- Torque due to voltage signal acting alone.
- Torque due to voltage and current signals acting together.

Thus:

$$Torque = K_I\, I^2 + K_v\, V^2 + K\, V\, I\, Cos(\phi - \theta) \qquad \ldots\ldots 11.2.10$$

For directional relay application it is important that the relay should not give an output in the presence of only one signal, either current or voltage. The torque components due to the current and voltage signal alone must be eliminated. In practical design [2.7] mechanical adjustments have to be made to eliminate these two torque components because it is not possible to achieve electrically and that a perfectly symmetrical moving element cannot be produced.

## Appendix 11.3 Analysis of a Single Phase Electromechanical Directional Relay [2.7, 3.11]

Figure 11.3.1 shows the basic construction of a single-phase electromechanical induction cup directional relay.

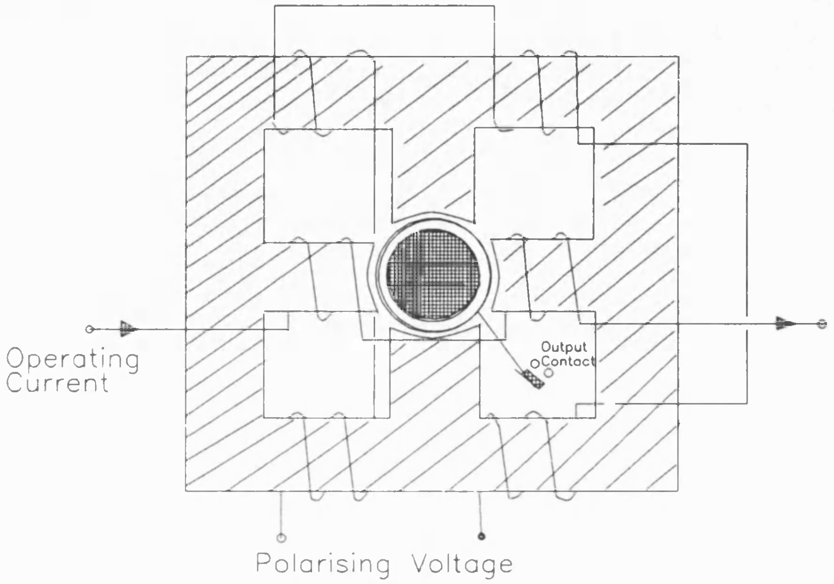



Figure 11.3.1 Construction of a Single-phase Induction Cup Directional Relay.

The two series-connected current coils wound on the central horizontal limb of the core produce a horizontal flux $\Phi_I$ whilst the four voltage wound coils on the outer horizontal limbs produce a vertical flux $\Phi_V$. The positions of these two fluxes are shown in Figure 11.3.2.

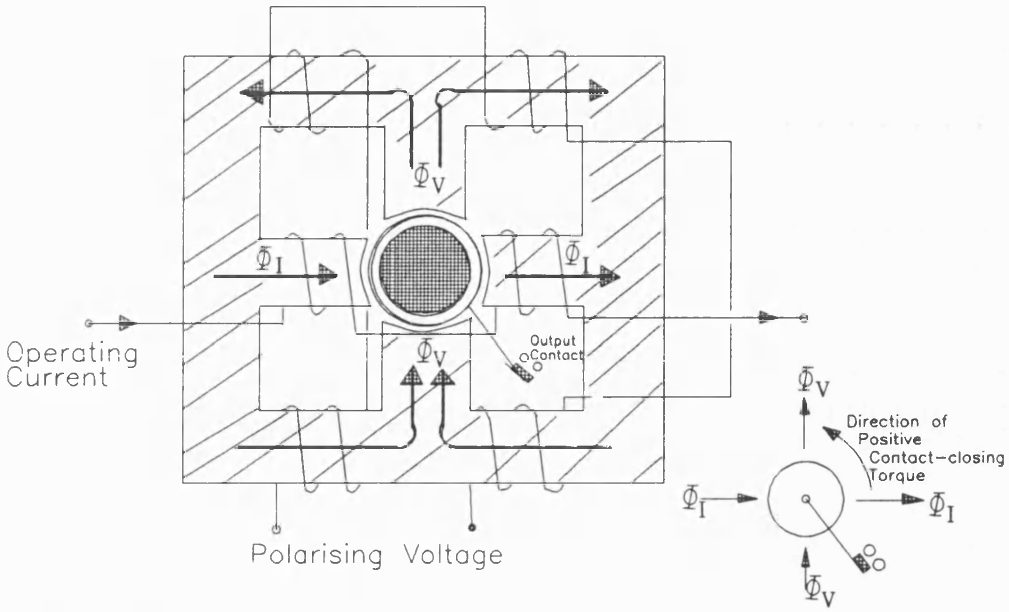



Figure 11.3.2 Generation of Two Fluxes by the Current and the Voltage Input Signals.

They are displaced by 90° in space. A torque is produced by these two fluxes acting on the moving element as shown. The phasor diagram is shown in Figure 11.3.3.

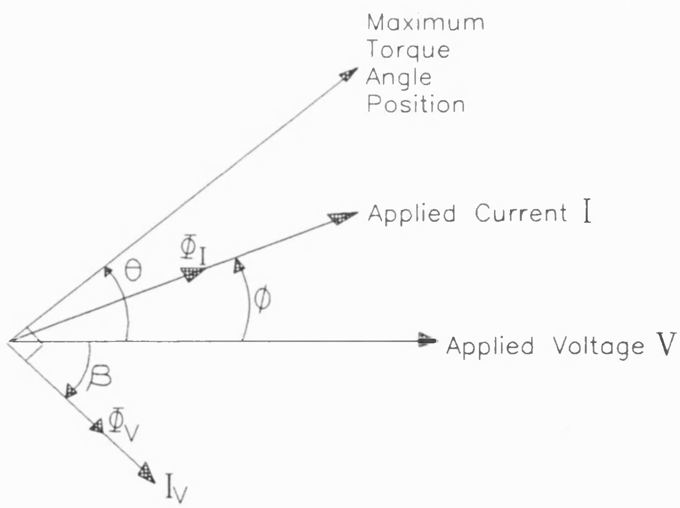



Figure 11.3.3 Phasor Diagram showing the Input Voltage and Current and their associated Fluxes.

The current $I_V$ flowing in the voltage coil lags the applied voltage V by the voltage coil impedance angle $\beta$. The two fluxes produced by the voltage-coil and current-coil currents are in phase with their respective currents. The torque produced by the interaction of the two fluxes can be derived from an examination of the phasor diagram.

The torque produced acting on the moving element given by equation 11.2.5 is:

$$Torque = \Phi_V \times \Phi_I \times Sin(\phi+\beta)$$

This can be expressed in terms of the maximum torque angle $\theta$ and the phase angle $\phi$ between the input voltage and the input current similar to equation 11.2.8:

$$\begin{aligned} Torque &= \Phi_V \times \Phi_I \times Sin[90°-(\theta-\phi)] \\ &= \Phi_V \times \Phi_I \times Cos(\theta-\phi) \end{aligned}$$

The magnitude of the flux produced is proportional the current flowing and hence the voltage applied.

The torque generated is thus given by:

$$Torque = K \times V \times I \times Cos(\theta - \phi)$$

where K is a constant.

The direction of movement is from the leading flux due to the current signal to the lagging flux due to the voltage signal as shown in Figure 11.3.2.

**Appendix 11.4 Analysis of a Polyphase Single-element Electromechanical Directional Relay [1.1, 1.2, 1.3]**

Figure 11.4.1 shows the construction of an eight-pole single-element induction cup polyphase directional relay with all the input signals defined.

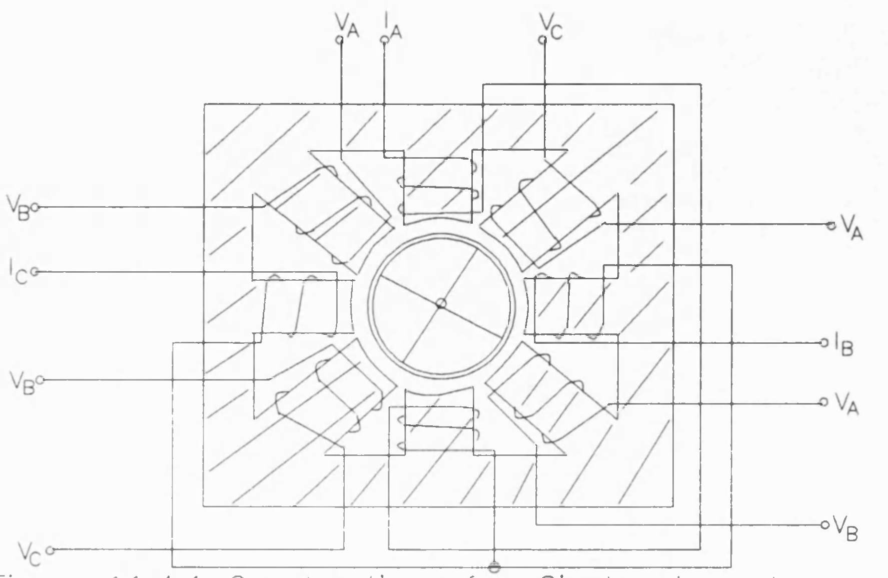



Figure 11.4.1 Construction of a Single-element Eight-pole Electromechanical Induction-cup Polyphase Directional Relay.

The torque produced acting on the induction cup moving element is due to the interaction of all fluxes generated by all the input voltage and current signals to the relay. This torque can be expressed as a function of the input power to the relay. This is given by :

$$Torque \propto \mathbb{R}\left\{\sum_{n=1}^{n} V_n \bar{I}_n\right\}$$

where n is the number of adjacent pairs of voltage and current coils.

The physical construction of the relay is arranged so that only the interaction of fluxes generated by the adjacent coils produces significant torque components to make up the total resulting torque acting on the induction cup moving element.

Alternatively, the input power and hence the torque produced can be expressed in terms of phase sequence components:

$$Torque \propto \mathbb{R}\ [K_1 V_1 \bar{I}_1 + K_2 V_2 \bar{I}_2 + K_0 V_0 \bar{I}_0]$$

For different directional relay connections using different input voltage and current signals intrinsic phase shifts are introduced. For example a 90°-connected directional relay has an inherent 90° phase shift between its input voltage and current signals.

The torque expression is thus modified to take into account of the inherent phase shifts. Thus:

$$Torque \propto \mathbb{R}\ [K_1 V_1 \bar{I}_1 \angle \pm \lambda_1 + K_2 V_2 \bar{I}_2 \angle \pm \lambda_2 + K_0 V_0 \bar{I}_0 \angle \pm \lambda_0]$$

where $\lambda_1$, $\lambda_2$ and $\lambda_0$ are the phase shift angles associated with the positive, negative and zero phase sequence quantities derived from the relay connection. The values change with connection types.

Maximum sensitivity corresponding to maximum power input depends on the angular displacement between the input voltage and current of the respective phase sequence components. This does not, however, necessarily occur for majority of forward faults the relay is required to detect. Therefore, maximum torque angles $\theta$s are intentionally introduced to ensure that the forward fault profile corresponds as closely as possible the maximum sensitivity area of the relay.

The final torque expression is thus given by:

$$Torque \propto \mathbb{R}\ [K_1 V_1 \bar{I}_1 \angle(\pm\lambda_1 \pm\theta_1) + K_2 V_2 \bar{I}_2 \angle(\pm\lambda_2 \pm\theta_2) + K_0 V_0 \bar{I}_0 \angle(\pm\lambda_0 \pm\theta_0)]$$

The polarities of $\theta$s for the different phase sequence components are necessarily different to ensure that the resulting torque is always positive for forward faults. This is because of the different directions for the different phase sequence powers, positive phase sequence power flowing into a fault point whilst the negative and zero phase sequence powers flowing away from it.

It is also not necessary that all the phase sequence components are present depending on the connection used. For example, the 90° connection does not produce the zero phase sequence component of torque.

Consider the design of a single-element polyphase directional relay by McConnell [1.1]. The construction is shown in Figure 11.4.2 with the input signals to the various coils as indicated.

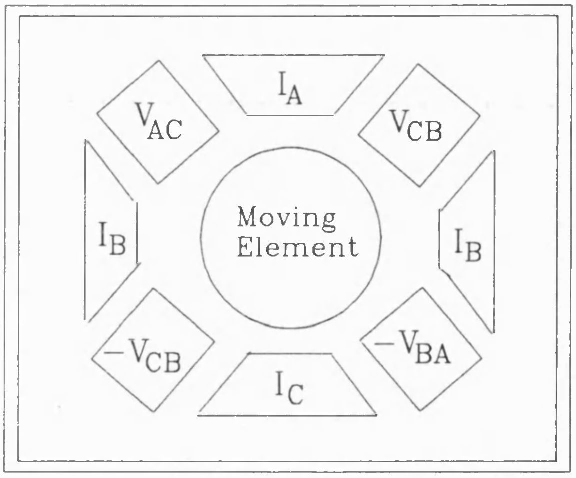



Figure 11.4.2 A Single-moving-element Polyphase Electromechanical Directional Relay with Input Signals for 60°-connection.

Each coil produces rotor currents which react with the flux produced by each other coil to generate torque. The torque produced by adjacent pairs of coils is much higher than that produced by alternative pairs with the latter balanced out substantially to zero by the physical layout and connections of the coils. Finer balancing is provided by mechanical adjustment of the position of the moving element.

Assuming the reaction between each current coil and the counter-clockwise voltage coil as positive, whilst the reaction with the clockwise voltage coil as negative, the total volt-ampere input to the relay is given by:

$$VA_{input} = V_{AC} I_A - V_{CB} I_A - V_{CB} I_B - V_{AC} I_B - V_{BA} I_C + V_{CB} I_C + V_{CB} I_B + V_{BA} I_B$$

$$= V_{AC} I_A - V_{CB} I_A - V_{AC} I_B + V_{BA} I_B - V_{BA} I_C + V_{CB} I_C \qquad .........11.4.1$$

The torque produced by this volt-ampere input is given by:

$$Torque \propto \mathbb{R}\ \{VA_{input}\}$$

From equation 11.4.1 the torque produced may be expressed as the input active power given by:

$$Torque \propto \mathbb{R}\ \{V_{AC}\ \bar{I}_A - V_{CB}\ \bar{I}_A - V_{AC}\ \bar{I}_B + V_{BA}\ \bar{I}_B - V_{BA}\ \bar{I}_C + V_{CB}\ \bar{I}_C\}$$

......11.4.2

This input power can be expressed in terms of the symmetrical components of voltages and currents. The various terms in equation 11.4.2 expressed in phase sequence quantities are given by:

$$\begin{aligned} V_{AC}\ \bar{I}_A &= (V_A - V_C)\ \bar{I}_A \\ &= [V_0 + I_1 + V_2) - (V_0 + aV_1 + a^2\ V_2)]\ (\bar{I}_0 + \bar{I}_1 + \bar{I}_2) \end{aligned}$$

Similarly, all other terms in the expression 11.4.2 may be expressed by using the symmetrical components. The result is given by:

$$Torque \propto \mathbb{R}\ \{-9a\ V_1\ \bar{I}_1 - 9a^2\ V_2\ \bar{I}_2\}$$

$$-9\ a^2\ V_2\ \bar{I}_2 = 1\angle 180° \times 9 \times 1\angle 240° \times V_2 \times \bar{I}_2 = 9V_2\ \bar{I}_2\ \angle{+60°}$$

$$-9\ a\ V_1\ \bar{I}_1 = 1\angle 180° \times 9 \times 1\angle 120° \times V_1 \times \bar{I}_1 = 9V_1\ \bar{I}_1\ \angle{-60°}$$

If $\phi_1$ = the angle by which $I_1$ lags $V_1$

and $\phi_2$ = the angle by which $I_2$ lags $V_2$,

The torque is given by:

$$Torque = 9 \times K \times [\,|V_1| \times |I_1| \times Cos(\phi_1 - 60°) + |V_2| \times |I_2| \times Cos(\phi_2 + 60°)]$$

...1.4.3

where K is a constant

The phase displacement between the voltage and current phasors to produce maximum torque may be changed to suit a particular application by introducing a maximum torque angle Θ in equation 11.4.3. The final expression for the torque produced is thus given by:

$$Torque = 9K[\,|V_1| \times |I_1| \times Cos(\phi_1 - 60° + \theta) + |V_2| \times |I_2| \times Cos(\phi_2 + 60° + \theta)] \quad ..11.4.4$$

**Appendix 11.5 Analysis of a Single-phase Product-type Electromechanical Directional Relay in Terms of Symmetrical Components of Voltage and Current [1.2].**

Consider the case of a directional relay having 90° connection and 45° leading maximum torque angle. The phasor diagram of the input signals is shown in Figure 11.5.1 for the A-phase relay. The operating characteristic is also shown with the given input signals.

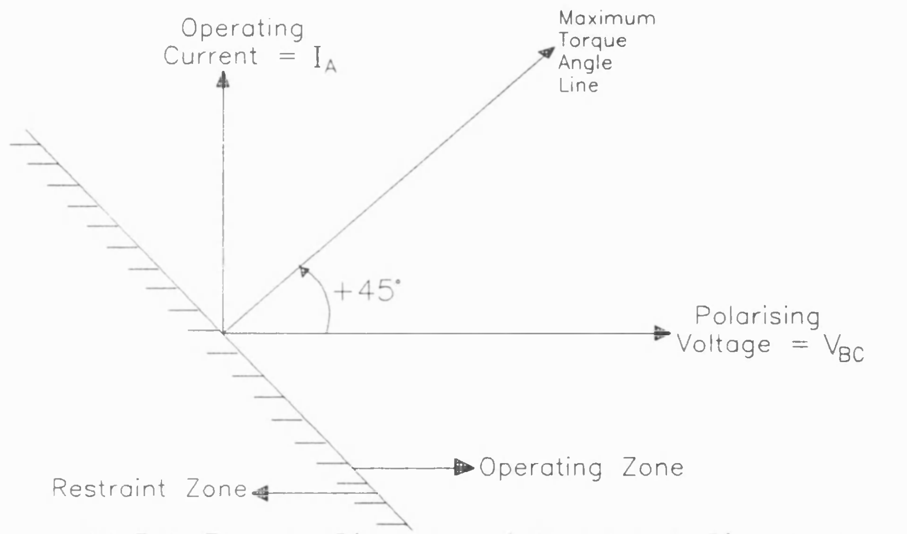



Figure 11.5.1 Phasor Diagram of the Input Signals to a 90°-connected +45° Maximum Torque Angle Single-phase Electromechanical Directional Relay for A-phase and its Operating Characteristic.

The torque produced by the interaction of flux due to the polarising voltage $V_{BC}$ and that due to the operating current $I_A$ acting on the moving element is proportional to the input power to the relay.

Thus:

$$Torque \propto \mathbb{R}\,(V_{BC}\,\bar{I}_A)$$

$$V_{BC} = V_B - V_C$$

$$= (a^2V_1 + aV_2 + V_0) - (aV_1 + a^2V_2 + V_0)$$

$$= (a^2 - a)V_1 + (a - a^2)V_2$$

$$\bar{I}_A = \bar{I}_1 + \bar{I}_2 + \bar{I}_0$$

It is only possible to obtain a volt-ampere product of the same phase sequence. The operating torque produced is, therefore, given by:

$$Torque \propto \mathbb{R}\,[(a^2 - a)V_1\bar{I}_1 + (a - a^2)V_2\,\bar{I}_2]$$

$$\propto \mathbb{R}\,\sqrt{3}[V_1\bar{I}_1\,\angle(-90°) + V_2\bar{I}_2\,\angle(+90°)]$$

This shows that:

- it is possible to analyse the resulting torque produced into phase sequence components.
- for $90^0$-connected directional relays there is no torque component produced due to the zero phase sequence components of voltage and current.
- there is an intrinsic phase shift between the input polarising voltage and operating current signals dependent on their selection. A 90° phase shift results in this 90°- connected directional relay.

In order to ensure that maximum torque is produced corresponding to majority of forward faults a maximum torque angle $\theta$ is introduced. Thus the torque is given by:

$$Torque \propto \mathbb{R}\ \sqrt{3}[V_1\bar{I}_1\ \angle(-90°\pm\theta_1) + V_2\bar{I}_2\ \angle(+90°\pm\theta_2)]$$

The signs of $\theta$s for the different phase sequence components are selected differently due to the difference in power flow directions on occurrence of a fault, positive phase sequence component flowing towards the fault point whilst negative and also zero phase sequence components flowing away from the fault point.

## Appendix 11.6 Analysis of a Rectifier-bridge Type Directional Relay [3.11].

Figure 11.6.1 shows the basic construction of a rectifier-bridge type directional relay.

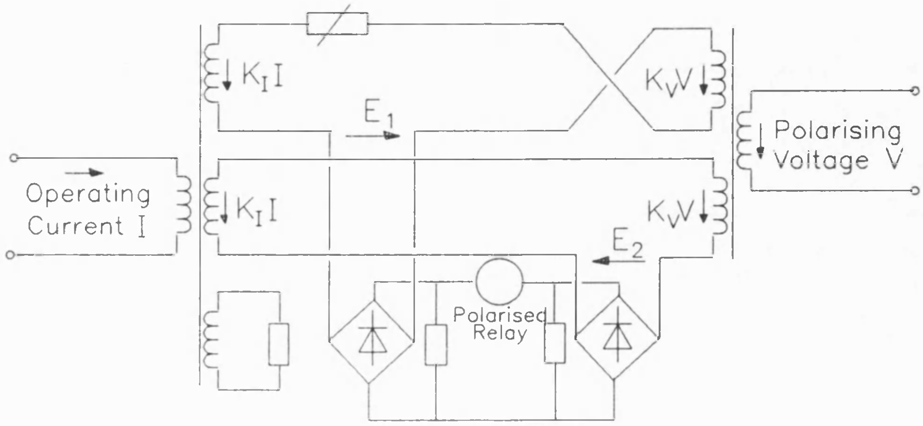



Figure 11.6.1 Construction of a Rectifier–Bridge Type Directional Relay with a Polarised Element.

The principle of operation of this type of directional relay is based on an amplitude comparison of two input signals to determine their angular displacement range and hence the direction of fault points.

As shown in Figure 11.6.1 two identical voltage signals $K_I$ I are produced at the secondary windings of the current input interface unit which are proportional to the input current. The third winding on the interposing transformer supplying a resistor provides adjustment for the angular displacement $\phi_I$ between the output voltage and the input current signals with the voltage $K_I$ I leading the current I.

Similarly, two voltage signals $K_V V$ are produced at the secondary windings of the voltage input interface unit which are proportional to the input voltage V. There is no phase displacement between the input voltage V and the output voltage $K_V V$.

With the two interface units for input current and voltage interconnected as shown two composite signals are derived:

$$E_1 = K_V V + K_I I$$

$$E_2 = K_V V - K_I I$$

These two signals are rectified by the two rectifier bridges before being applied to a polarity detector in the form of a polarised relay for an amplitude comparison of the two signals.

The potential difference across the polarity detector changes with variation of the two signals $E_1$ and $E_2$. The criterion for operation of the polarity detector is when the potential difference $\upsilon$ satisfies the following:

$$\begin{aligned} \nu &= |E_1| - |E_2| \geq 0 \\ &= |K_V V + K_I I| - |K_V V - K_I I| \geq 0 \end{aligned}$$

This operating criterion is illustrated in Figure 11.6.2.

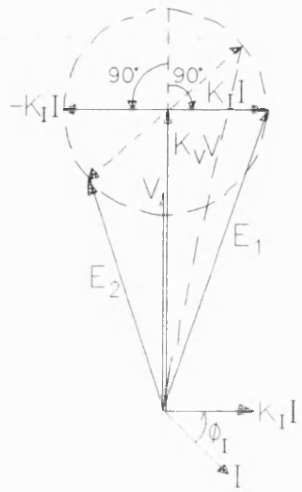



Figure 11.6.2 Principle of Operation of a Rectifier-bridge Type Directional Relay based on Amplitude Comparison of a Polarising Voltage and an Operating Current Signals.

As shown, the amplitude comparison process generates an angular operating range of $\pm 90^o$ between the two signals $K_V V$ or V and $K_I I$.

This angular range can be adopted as the directional range of a directional relay by selection of the appropriate input voltage V and current I signals and also phase shift $\varnothing_I$ adjustment to the current signal. This is illustrated in Figure 11.6.3a.

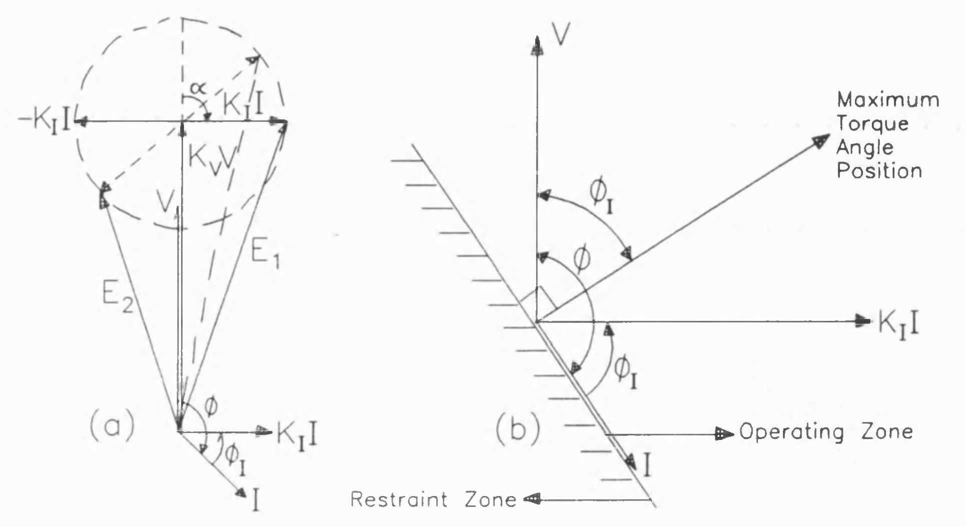



Figure 11.6.3 Design of a Rectifier–bridge Type Directional Relay based on Amplitude Comparison of a Polarising Voltage and an Operating Current Signals.

For operation, the range of the angle $\alpha$ between $K_V V$ or V and $K_I I$ is given by:

$$-90^0 \leq \alpha \leq +90^0$$

This indicates that the phase displacement $\varnothing$ between V and I must be:

$$-(90^0 + \varnothing_I) \leq \varnothing \leq +(90^0 - \varnothing_I)$$

When $\alpha = \pm 90^0$ , $\nu = |E_1| - |E_2| = 0$. This defines the boundaries of operation.

When $\alpha = 0^0$ , $\nu$ is maximum. This defines the maximum torque angle or relay characteristic angle position. This corresponds to a phase displacement $\varnothing_I$ between the voltage V and current I.

The operating zone of the directional relay is thus defined as shown in Figure 11.6.3b.

It can, therefore, be seen that by phase shifting the current signal with the angle $\phi_I$ producing an output signal $K_I I$ and with appropriate selection of voltage V and current I inputs a particular directional relay can be designed with a given operating zone.

For example, consider a directional earthfault relay with zero phase sequence voltage $V_0$ and current $I_0$ as input signals and an adjustment of $\phi_I = 45°$. This produces a directional earthfault relay with -45° maximum torque angle. The operating characteristic is shown in Figure 11.6.4.

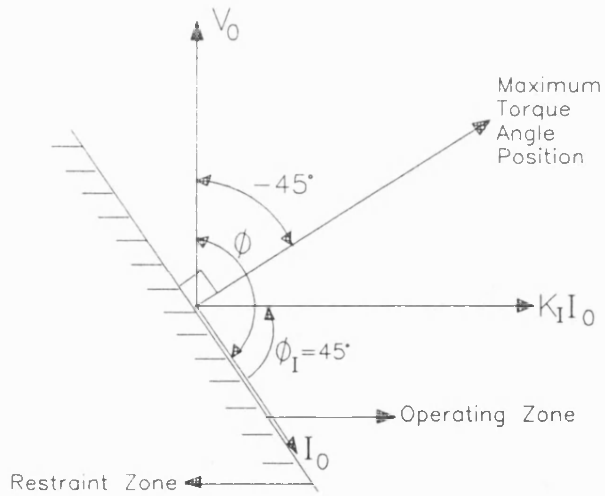



Figure 11.6.4 A Directional Earthfault Relay with −45° Maximum Torque Angle based on the Rectifier−bridge Type Design and Amplitude Comparison Principle.

## Appendix 11.7 Phase Selection Capability of the Proposed Polyphase Directional Detection Method [1.10, 1.11]

Phase selection capability in addition to fault detection is always desirable in power system protection. For transmission systems where single-phase tripping and auto-reclose facilities are employed phase selection is a necessary part of the associated protection and control schemes. For distribution systems phase selection facility is required in protection schemes such as switched distance relaying in which identification of the faulted phase(s) is needed to enable the measuring element to be switched to the faulted phase(s) for measurement. The identification of faulted phase(s) also helps to improve system operation efficiency in that useful information is provided to assist in post-fault analysis of both the primary and the secondary systems.

Phase selection within a composite scheme provides cost-effectiveness compared with the present practice of using individual hardware elements to implement the function. Typically, the use of separate three overcurrent and an earth fault elements in distribution system protection illustrates the current practice. This arrangement may also be considered a very simple form of phase selector which can only operate satisfactorily if the fault current always exceeds the settings of the elements involved in a particular fault.

### 11.7.1 Phase Selection Requirements

A phase selection relay should meet a number of requirements as illustrated below. Under fault conditions its operation must be independent of the followings:

- the system configuration and operation.
- the fault location and fault resistance.
- the prefault load condition and sound phase currents under fault conditions.
- the operation of the phase selector, the protective system and the circuit breaker located at the far end of the same circuit if installed.

In addition a phase selector should:

- continuously select correctly when the fault evolves
- have a fast speed of operation
- be insensitive to system instability
- not reduce the sensitivity or increase the operating time of the associated protection

Under post-fault conditions on systems where auto-reclose facilities are employed i.e. when the fault has been cleared and the auto-reclosing sequence is in progress a phase selector should:

- be insensitive to the position of the poles of the breaker both at the near and far end of the same circuit.
- measure correctly evolving faults occurring when the pole(s) of the faulted phase(s) are open.

- remain inoperative on circuit breaker closing with the fault cleared.

### 11.7.2 Existing Phase Selection Methods

Phase selectors can be classified into following types:

- Selectors using current signals only as the deciding parameter.
- Selectors using voltage signals only.
- Selectors using voltage and current signals together.

These selectors are designed to operate either on the absolute magnitude or the change in magnitude of the input signal(s). Alternatively, the phase sequence components of the input signal(s) is also used to determine the faulted phase(s). The following sections give an outline of some of the available methods of phase selection.

#### 11.7.2.1 Phase Selection using Current Signal as the Input

The simplest method is to employ overcurrent detectors with preset levels and with one unit in each phase using line current as the input parameter. This method of phase selection can be used satisfactorily except for the following limitations:

- For multiple-earthed systems large sound phase currents on occurrence of an earth fault can exceed overcurrent level detector setting and cause maloperation.
- With large fault resistances the setting on the faulted phase may not be

exceeded causing malfunction by not being able to operate.

To ensure the satisfactory performance of phase selector employing overcurrent detectors the following logics have been implemented [2.34] in commercially available phase selector:

Phase A is selected if $I_A > 4I_N$ and $I_B < 2I_N$ and $I_C < 2I_N$ and $Ir > (0.2\ I_N + 0.24I_P)$

where $I_N$ = rated current of the phase selector 1A or 5A

$Ir$ = residual current

$Ip$ = highest current of the three phases

The selection of phases B and C follows the same logics and can be derived by cyclic permutation.

Phases AB is selected if $[I_A > 2\ I_N$ and $I_B > 4I_N]$ or $[I_A > 4I_N$ and $I_B > 2I_N]$. Similarly, phases BC and CA are selected using the same logics.

Another method of current-signal-based selection used is to examine phase sequence components. This has been employed in practical relaying equipment [2.34].

**11.7.2.2 Phase Selection using Voltage Signal as the Input:**

One phase selector that employs only voltage signal is the undervoltage detectors in which selection is made when the phase to neutral voltage falls to a preset level e.g.

70% of nominal. This has been used [2.35] for resistance-earthed systems and for selection of earth faults only. For solidly-earthed systems with multiple sources the selection fails to occur for medium to higher resistance earth faults.

Another phase selector using voltage signal alone is based on a comparison between the phase to neutral voltage raised by a factor of $\sqrt{3}$ and the quadrature phase to phase voltage. Selection is made when the phase to neutral voltage falls below quadrature voltage.

#### 11.7.2.3 Phase Selection Using Voltage and Current Signals as the Inputs

An example of this type of phase selector is the impedance or distance relays which have been used extensively as phase selector for distance protection schemes [2.26, 2.36, 2.37, 2.38] and phase comparison scheme [2.39]. The major limitations are the inability to cover high-resistance earth faults and the loss of discrimination on close-up fault operations [3.8].

### 11.7.3 Phase Selection using Symmetrical Components

Phase selection using the symmetrical components of voltage and current has been employed by protection relay manufacturers [2.4, 2.34]. The principle of operation is based on the measurement of the phase difference between symmetrical components of either currents or voltages or of currents and voltages.

The use of symmetrical components in the proposed directional detection method, therefore, also provides a convenient method of identifying the faulted phase(s). This overcomes the drawback of not having phase selection capability within a polyphase directional relay especially in the use of composite signals to decide on the fault direction.

An example of phase selection using symmetrical components is the phase sequence current selector. Figure 11.7.1 shows the relationships between the various symmetrical components of currents for different phase-to-earth faults.

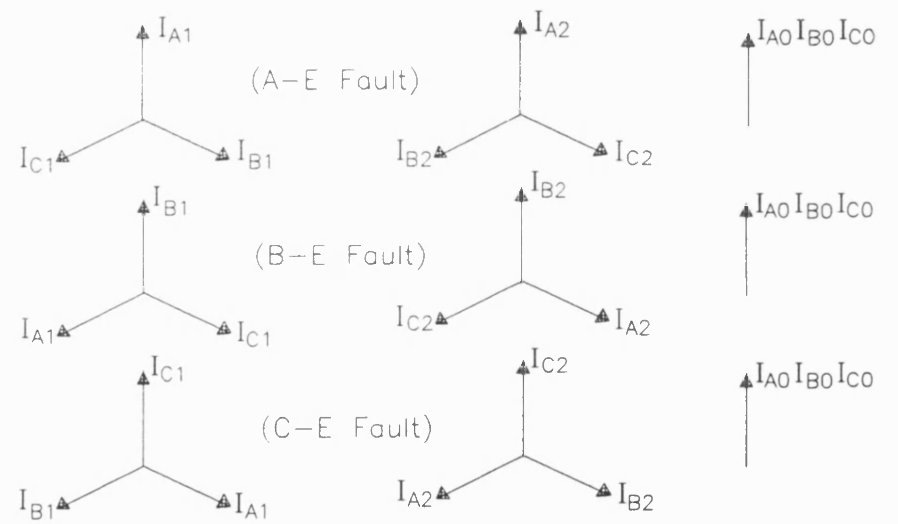



Figure 11.7.1 Phase Relationships between the Three Symmetrical Components of Currents for different Phase−to−earth Faults.

By examining the phase relationship between the various phase sequence currents it is possible to deduce the faulted phase. For a A-phase-earth fault the symmetrical components networks are connected in series to represent the fault such that the positive, negative and zero phase sequence currents for "A" phase are all in phase. For other phase-to-earth faults the faulted phase negative phase sequence current in the fault is in phase with the zero phase sequence current. This relationship provides a possibility of identifying the faulted phase.

However, a BC-phase-earth fault causes zero phase sequence current to be in phase with the negative sequence current of the "A" phase as well, assuming equal phase angles for the zero and negative phase sequence networks. This is shown in Figure 11.7.2

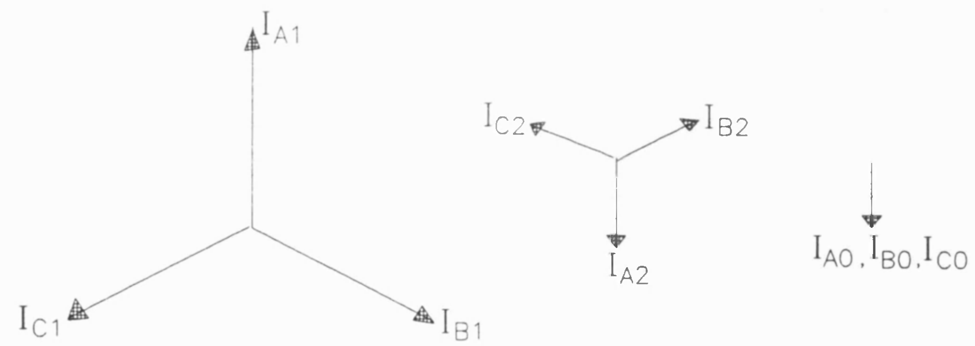



Figure 11.7.2 Phase Relationships between the Three Symmetrical Components of Currents for B-C-earth Fault.

This obviously creates confusion with a genuine A-phase-earth fault producing the same phase relationship between zero phase sequence and negative phase sequence currents.

To overcome this problem [2.4] logic can be added to examine the phase relationship between zero phase sequence and negative phase sequence currents for each phase and the cross polarising voltage. The conceptual logic is illustrated in Figure 11.7.3.

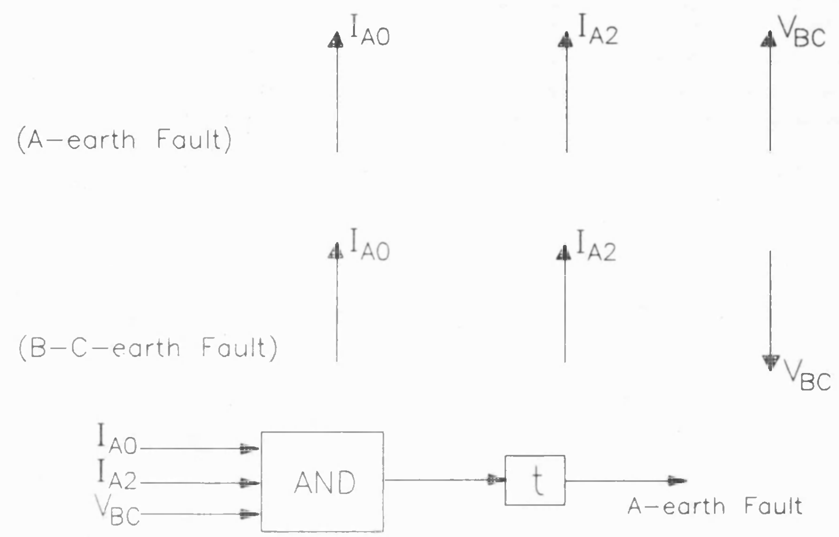



Figure 11.7.3 Conceptual Logic to Identify A–phase–to–earth Fault.

Similar comparisons for the other two phases would allow B or C phase to be identified for B-phase-earth or C-phase-earth faults respectively.

Alternatively, the phase sequence voltages can be considered to derive the faulted phase information. Figure 11.7.4 shows the phase relationship between the various phase sequence components of voltages for the different types of faults using the "A" phase as the reference.

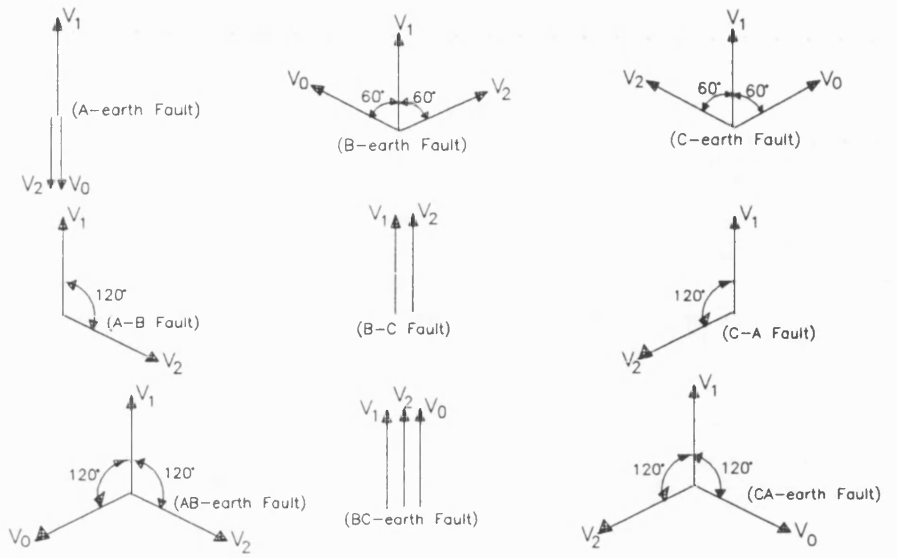



Figure 11.7.4 Phase Relationships between the Three Symmetrical Components of Voltages for different Types of Faults.

From an examination of the phasor relationships on a similar basis as in the case of using phase sequence currents, the angle between $V_0$ and $V_2$ will identify the fault to be either A-phase-earth fault or BC-phase-earth fault. This can be further distinguished by the phase angle between $V_2$ and $V_1$. For phase faults only, indicated by non-operation of a separate zero-phase-sequence current detector, the fault is identified by the phase angle between $V_2$ and $V_1$. It can, therefore, be seen that for faults related to "A" phase the logics of the other two phases would not produce an output. The logic detection is illustrated in Figure 11.7.5.

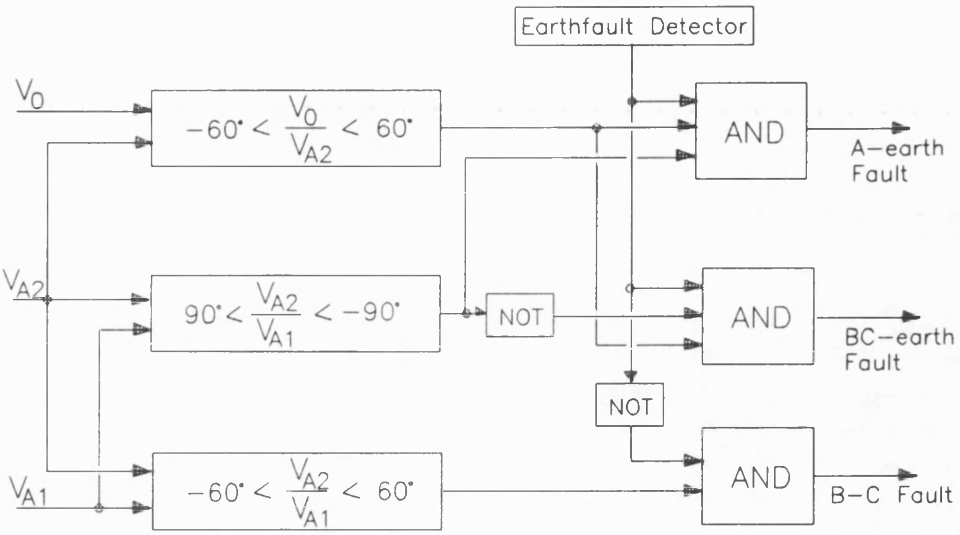



Figure 11.7.5 Phase Selection Logics based on the Phase Relationships between the Three Symmetrical Components of Voltages.

The foregoing illustrations show that the identification of faulted phase(s) is possible from a knowledge of the symmetrical components. The new method of detecting direction using symmetrical components of voltages and currents can, therefore, implement this phase selection facility with only the addition of extracting the zero phase sequence components of voltage or current. It is known that this method of phase selection has limitations [1.10, 1.11] which are mainly confined to transmission systems protection where high resistance earth faults with load transfer are of concern and single-phase tripping and auto-reclosing are used. For distribution systems, single-phase tripping and auto-reclosing are not employed and high resistance earth faults with significant load transfer simultaneously are not generally common.

**Appendix 11.8 The Use of Pre-fault Voltage in Fault Analyses for Balanced Three-phase Faults [1.9].**

For an energised power supply system supplying loads at various points on the system the occurrence of a fault at a point on the system will result in the flow of fault currents through various branches of the power network. The branch currents consist of two components, the pre-fault load current and a current resulting from the occurrence of the fault.

One method of calculating the current distribution in a system when there is a balanced three-phase fault at a particular point is to consider all the generator emf's at the moment of fault.

Consider a system fed from two sources of generation $E_A$ and $E_B$ as shown in Figure 11.8.1:

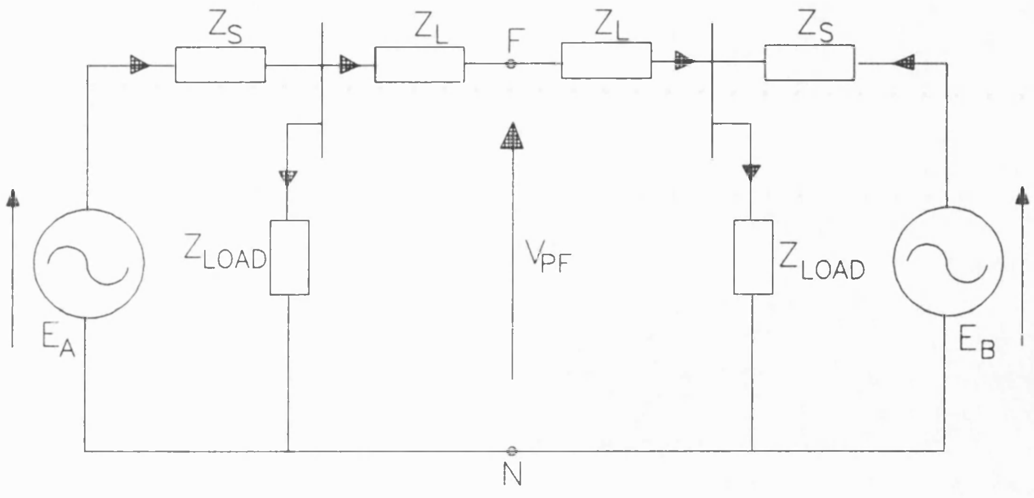



Figure 11.8.1 Generation of Pre–fault Voltage for Balanced Three–phase Fault Calculations.

The currents in the various branches are the pre-fault currents.

Consider a point F where a balanced three-phase fault is to occur. The pre-fault current flow generates a pre-fault voltage $V_{PF}$ between this point F and the neutral.

A short circuit at the fault point F will lead to fault currents flowing through various branches as shown in Figure 11.8.2.

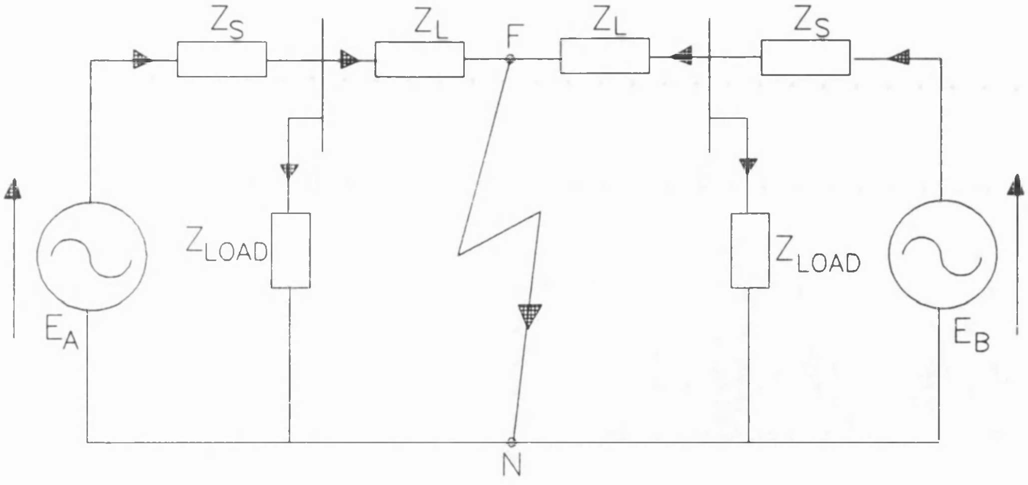



Figure 11.8.2 System Representation of a Balanced Three-phase Fault at a Point F.

These branch currents together with the current through the fault point can be determined from all the known impedances and also all the source emf's, both magnitudes and relative phase angles.

With a simple system this method of calculation is easily achieved. However, with multiple-end fed systems it is generally difficult to establish the magnitudes and angles of all generator emf's at the moment of fault and even when these are available, the calculation of distribution of fault current is complicated.

An alternative method is to run a load flow study of the system and establish the pre-fault voltage at the fault point. This use of pre-fault voltage can simplify the calculation of complicated system.

Consider the system shown in Figure 11.8.1 again with a fault at point F. This circuit can be Thevenised across the fault point F to determine the current in this fault path. This Thevenised circuit is shown in Figure 11.8.3.

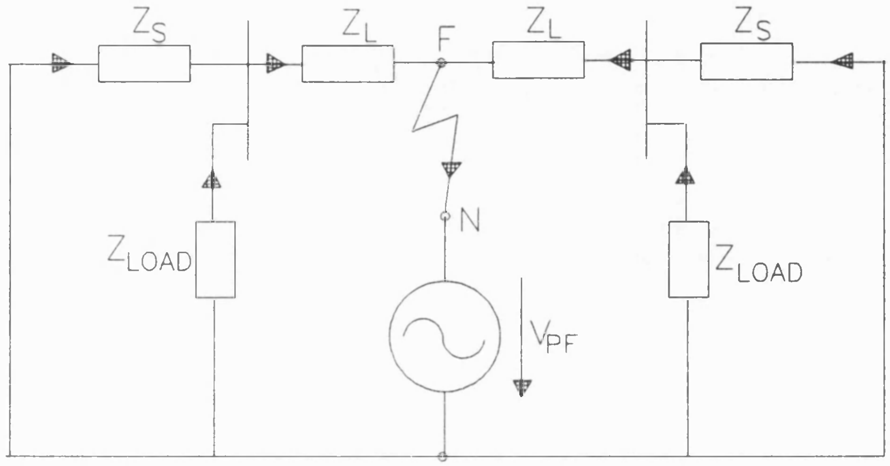



Figure 11.8.3 Thevenised Circuit Looking at the Fault Point F on the System shown in Figure 11.8.2.

The equivalent source emf in this Thevenised circuit is the pre-fault voltage $V_{PF}$ at the fault point. The fault current can be easily determined by working through this equivalent circuit.

Apart from the current through the fault path the values of currents in each branch of the Thevenised circuit are not the same as the currents obtained from the calculations based on the system shown in Figure 11.8.2 i.e. the actual currents in the branches.

Consider the circuit shown in Figure 11.8.1 again but with a fictitious emf $V_{PF}$ inserted across the fault point F without affecting the load current. This is shown in Figure 11.8.4.

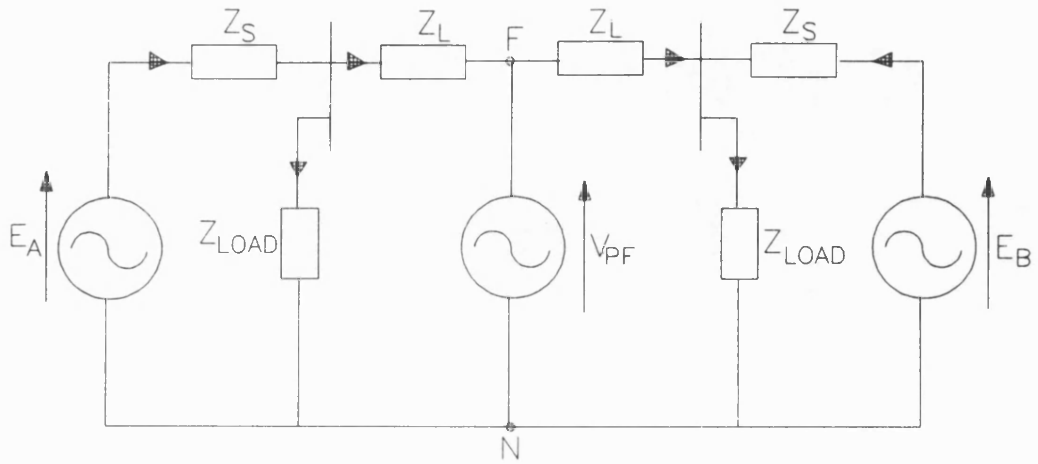



Figure 11.8.4 Pre-fault Voltage at the Fault Point and Current Distribution in Various Branches.

This circuit can be analysed by superposition theory in two parts as shown in Figure 11.8.5:

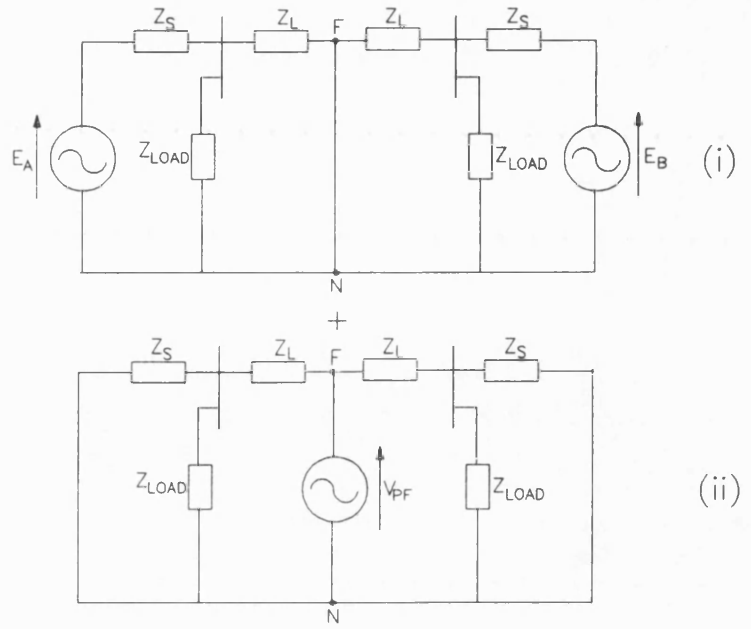



Figure 11.8.5 Analysis of the System shown in Figure 11.8.4 by Superposition.

From an examination of Figure 11.8.5 it can be stated that in terms of currents:

Part (i) is equivalent to the circuit shown in Figure 11.8.2 which is the faulted system.

Part (ii) is equivalent to the circuit shown in Figure 11.8.3 which is the Thevenised equivalent looking at the fault point, but with the source emf shown in reverse polarity.

It can therefore be established that in any branch of the network:

The load current $I_L$ = Fault current $I_F$ - Thevenised current $I_T$

The fault current $I_F$ is thus given by:

$$I_F = I_L + I_T$$

where $I_L$ is determined from a pre-fault load study whilst $I_T$ is determined from the Thevenised circuit using pre-fault voltage at the fault point.

For the majority of applications pre-fault load currents are small compared with current obtained from the Thevenised circuit and can be neglected.

i.e. $\quad I_F \approx I_T$

In this case the value of $V_{PF}$ used in the Thevenised circuit is the no-load open-circuit voltage at the fault point.

# CHAPTER TWELVE

## REFERENCES

### 1. Articles


1.1 McConnell, A.J., "A Single-Element Polyphase Directional Relay", AIEE Transactions, Vol. 56, pp 77-80, January 1937.

1.2 Kimbark, E.W., "Discussions on A Single-Element Polyphase Directional Relay by McConnell, A.J.", AIEE Transactions, pp 1025-1028, August 1937.

1.3 Baldwin, C.J. and Gafford, B.N., "An Analysis of Polyphase Directional Relay Torques", AIEE Transactions, pp. 752-759, August 1953.

1.4 Sonnemann, W.K., "A Study of Directional Element Connections for Phase Relays", AIEE Transactions, Vol. 69, pp 1438-1450, August 1950.

1.5 Roland Nylen, "The Dead Zone of Directional Relays For Overcurrent Protective Schemes", ASEA Journal, Vol. 45, No. 3, pp. 91-92, 1972.

1.6 Rusinowski, S.H., "Induction Disc and Induction Cup Theory", Analysis and Protection of Power System Course Notes, GEC ALSTHOM Protection & Control.

1.7 Urdaneta, A.J., Nadira, R., Pierez Jimenez, L.G., "Optimal Coordination of Directional Overcurrent Relays in Interconnected Power Systems", IEEE Transactions, Power Delivery, Vol. 3, No. 2, pp. 903-911, 1988.

1.8 He Jia-Li, Zhang Yuan-Hui, Yang Nian-Ci, "New Type Power Line Carrier Relaying System With Directional Comparison For EHV Transmission Lines", IEEE Transactions, PAS Vol. 103, No. 2, pp. 429-436, 1984.

1.9 GEC ALSTHOM Protection & Control Limited, "Basic Fault Calculations and Analysis of Balanced Faults", The Analysis and Protection of Power System Course Notes.

1.10 Gray, H., "Phase Selectors-General Study", GEC Measurements internal report S/PE3000.

1.11 Mouton, L. and Souillard, M., "High Speed Static Relays for Distance Measurements", Paper 31-08, CIGRE, June 1968.

1.12 Weller, G.C., Newbould, A. and Millar, R.B., "New Principles for Distance Protective Relays", IEE Conference Publication No. 185, pp.182-186, June 1980.

1.13 Lai, A.L., "Development of an Expert System for Power System Protection Coordination", IEE Conference Publication No. 302, pp. 310-314, April 1989.

1.14 Horowitz, S.H., Phadke, A.G. and Thorp, J.S., "Adaptive transmission system relaying", IEEE PES Summer Meeting, San Francisco, California, July 12 - 17, 1987.

1.15 Rockefeller, G.D., Wagner, C.L., Linders, J.R., Hicks, K.L. and Rizy, D.T., "Adaptive transmission relaying concepts for improved performance", IEEE PES Summer Meeting, San Francisco, California, July 12-17, 1987.

1.16 Moore, P.J., "Adaptive Digital Distance Protection", Ph.D. Thesis, City University, UK, April 1989.

1.17 Shah, K.R., Detjen, E.R. and Phadke, A.G., "Feasability of adaptive distribution protection using Computer Overcurrent Relaying Concept", IEEE Rural Electric Power Conference, San Antonio, Texas, May 3-5, 1987.

1.18 Zhang, Z. and Chen, D., "An adaptive approach in digital distance protection", IEEE PES 1988 Winter Meeting, New York, New York.

1.19 Elmore, W.A., "Recent Uses of Symmetrical Components in Relays", Georgia Institute of Technology Protective Relaying Conference, May 1985.

1.20 Crossley, P.A., Elson, S.F., Rose, S.J., Williams, A., "The Design of a Directional Comparison Protection for EHV Transmission Lines", IEE Conference Publication No. 302, pp. 151-155, April 1989.

1.21 Central Electricity Generating Board, "Low Forward Power Interlock Relay", Specification CEGB-P4, March 1977.

1.22 Ge, Y.Z., Wang, A.D., Tao, H.L., "Phase-Comparison Pilot Relays using Fault Superimposed Components", IEE Conference Publication No. 348, pp. 833-838, November 1991.

1.23 Wang, A.D., Ge, Y.Z., Lai, L.L., Johns, A.T., "Application of a New Technique to HV Transmission Line Distance Relaying", IEE Conference Publication No. 348, pp. 449-454, November 1991.

1.24 Chin, N.F., "A New Distance Relaying Scheme for the Protection of Medium and High Voltage Transmission and Distribution Lines", BEAMA Technical Seminar for NEB, pp. 51-68, June 1985.

1.25 Chin, N.F., Cheetham, W.J., Weller, G.C., "Progress in Digital Protection", BEAMA Technical Seminar for TNB, pp. 26-34, October 1991.

1.26 Adamson, C., Talkhan, E.A., "Selection of Relaying Quantities for Differential Feeder Protection", IEE Proc, Paper No. 3137M pp. 37-47, February 1960.

1.27 Hoard, B.V., "An Improved Polyphase Directional Relay", AIEE Transactions, Vol.60, pp. 246-250, May 1941.

1.28 Teo, C.Y., Chan, T.W., "Overall Assessment of Distribution Backup Protection using Microcomputer", IEE Conference Publication No. 302, pp. 107-112, April 1989

1.29 Chamia, M., Liberman, S., "Ultra High Speed Relay for EHV/UHV Transmission Lines - Development, Design and Application", Paper F78215-6 IEEE PES, November 1977.

1.30 Lidgate, D., Askarian Abyaneh, H., "Computer Assessment of IDMT Relay Performance for Phase and Earth Faults on Interconnected Power Systems", IEE Proc., Vol. 135, Pt.C, No. 2 pp 157-165, March 1988.

1.31 Jampala, A.K., Venkata, S.S., Damborg, M.J., "Adaptive Transmission Protection: Concepts and Computational Issues", IEEE Transactions on Power Delivery, Vol. 4, No. 1, pp 177-185, January 1989.

1.32 Girgis, A.A., Hart, D.G., "Implementation of Kalman and Adaptive Kalman Filtering Algorithms for Digital Distance Protection on a Vector Signal Processor", IEEE Transaction on Power Delivery, Vol. 4, No. 1, pp. 141-154, January 1989.

1.33 Blackburn, J.L., "Ground Relay Polarization", AIEE Trans. Part III, Vol. 71, pp. 1088-1093, December 1952.

1.34 Elmore, W.A., Blackburn, J.L., "Negative-Sequence Directional Ground Relaying", AIEE Trans., pp. 913-921, February 1963.

1.35 Degens, A.J., "Microprocessor-implemented digital filters for the calculation of symmetrical components", IEE Proc., Vol 129, Pt C, No. 3, pp. 111-117, May 1982.

1.36 Phadke, A.G., Ibrahim, M., and Hlibka, T., "Fundamental basis for distance relaying with symmetrical components", IEEE Trans., PAS-96, pp. 635-646, 1977.

1.37 Phadke, A.G., Hlibka, T., Ibrahim, M., and Adamiak, M.G., "A microcomputer based symmetrical component distance relay", IEEE 1979 Power Industry Computer Applications Conference, 79CH1301-3-PWR, pp. 47-55.

1.38 Ahson, S.I., Henry, J., and Rundhay, D.S., "Microprocessor-based negative-sequence relay", Electrical Power & Energy Systems, Vol 8, No. 4, pp. 205-210, October 1986.

1.39 Fakruddin, D.B., Parthasarathy, K., Jenkins, L., and Ramanjaneyulu, K.S., "Microprocessor-based algorithm for symmetrical-components calculation", IEEE Proc., Vol 71, No. 12, pp. 1463-1464, December 1983.

1.40 Dash, P.K., Malik, O.P., Hope, G.S., "Fast Generator Protection Against Internal Asymmetrical Faults", IEEE Trans. Vol. PAS-96, No. 5, pp 1498-1503, September/October 1977.

1.41 Bunch, J.B., Das, D.P., Patel, S.C., Cunningham, G.W., "Distribution Feeder Microprocessor Protection, Control and Monitoring", paper presented at Georgia Tech Protective Relaying Conference, Atlanta, GA, 29 April - 1 May 1992.

1.42 Lobos, T., "Non-recursive Methods for On-line Estimation of Voltages or Currents and Symmetrical Components Using Kalman Filter Theory", Electric Power Systems Research, 9 (1985), pp 243-252.

1.43 Hughes, M.A., "Distance Relay Performance as affected by Capacitor Voltage Transformers", IEE Proc., Vol. 121, No. 12, pp 1557-1566, December 1974.

1.44 Adams, W.T., Brady, J., "Magnitude Approximations for Microprocessor Implementation", IEEE MICRO, October 1983, pp 27-31.

1.45 Eichhorn, K.F., Lobos, T., "On-line Determination of Symmetrical Components by Sampling", 8th Power System Computation Conference, Helsinki, 1984, pp 1155-1162.

1.46 Yip, H.T., "An Integrated Approach to Generator Protection", International Conference on Power System Technology, Beijing, China, October 1994.

1.47 Ziegler, G., "Experiences and Proceedings in Co-ordinated Control and Protection of Substations", International Conference on New Developments in Power System Protection & Local Control, Beijing, China May 1994.

1.48 Kalaiaiasi, P., Pauldoss, B., Malathy, N., "True Digital Motor Protection and Management Relay MotPRO", Relay Development Report MDR/20/KP, GEC ALSTHOM India.

**2. Manufacturers' Publications:**

2.1 RMX 913 Directional Relay, ABB Relays publication CH-ES62-56.20 March 1988.

2.2 P10 Phase Comparison Carrier Protection, GEC ALSTHOM Protection & Control publications R5247 and R5258.

2.3 PCD Polyphase Directional Relay, GEC ALSTHOM Protection & Control publication R5127.

2.4 LDAR Protection Relay Systems Installation, Operation & Maintenance Instructions I.L. 40-380.4, Westinghouse Electric Corporation.

2.5 RL91 Definite-time Directional Overcurrent Relay, ABB Relays publication CH-ES65-50.10.

2.6 METI Directional Relay, GEC ALSTHOM Protection & Control Limited publication R6003, .

2.7 CDD Directional Inverse Time Overcurrent/Earthfault Relays, GEC ALSTHOM Protection & Control Limited publication R5089, .

2.8 CDG Inverse Time Overcurrent/Earthfault Relays, GEC ALSTHOM Protection & Control publication R5090, .

2.9 TJM Inverse Definite Minimum Time Lag Relays, Reyrolle Protection Ltd publication leaflet TJM10/11/12/13.

2.10 LFCB Digital Current Differential Protection Relay, GEC ALSTHOM Protection & Control Limited publication R4054.

2.11 MCGG Overcurrent and Earthfault Protection Relay, GEC ALSTHOM Protection & Control Limited publication R6054.

2.12 H-3, HV-3, HV-4 High Speed Directional Relays, Westinghouse Electric Corporation publication DB 41-225.

2.13 CR, CRC, CRP, CRD, CRQ Directional Overcurrent Relays, Westinghouse Electric Corporation publication DB 41-130A.

2.14 LFDC Digital Directional Comparison Protection Relay, GEC ALSTHOM Protection & Control Limited publication R4078.

2.15 LCB-II Current Differential Line Protection Relay System, Westinghouse Electric Corporation publication I.L.40-219.

2.16 CTD Static Directional Relay, GEC Measurements publication RS5131.

2.17 CDD Directional Overcurrent Relay Operating Instructions, GEC Measurements publication R3402.

2.18 MIDOS K Range User Manual, GEC ALSTHOM Protection & Control Limited publication.

2.19 REL 100/RELZ 100 Line Protection, ABB Relays publication 1MDB06004-EN

2.20 DLP Digital Line Protection System, GE Relay publication MOD-10DLP.

2.21 SPAJ Combined Phase and Neutral Overcurrent Protection Relays, ABB Relays publication SPAJ 4 GB 90-01.

2.22 LR91 Directional-wave Relay, ABB Relay publication 1MDB06011-EN.

2.23 RALZA Combined Directional-wave and Phase and Ground Distance backup Relay for Transmission lines, ABB Relay publication B03-7016.

2.24 7SP20 Directional Relay, Protection Relays Catalog R-1989, Siemens publication E86010-K4500-A101-A3-7600

2.25 IRC, IRP, IRD, IRQ, IRV Directional Overcurrent Relays, Westinghouse Electric Corporation publication DB 41-130B

2.26 LFZP Optimho Distance Relay Manual, GEC ALSTHOM Protection & Control Limited publication R5911.

2.27 Industrial Generator Protection Application Guide, GEC Measurements publication R4016B.

2.28 Microcomputers on the March, Siemens publication E50001-U321-A10-X-7600

2.29 Circuit Data, China Light & Power Co., Ltd., Hong Kong, January 1993.

2.30 IBC, IBCV, IBCG Phase and Ground-directional Overcurrent Relays, GE Protection & Control Products Catalog, publication GEZ-7278A.

2.31 PR331 Digital Directional Relay, AEG Relay Catalogue ART-NR.1411.

2.32 TCC Directional Overcurrent Relay, GE Protection & Control Product Catalogue GEZ-7278A.

2.33 7SJ512 Digital Overcurrent-time Protection Relay, Siemens relay publication R2-21-1993.

2.34 DLDS3000 Self-contained Fault Locator, GEC ALSTHOM T&D publication ND 1.6886-G.

2.35 SSMM3T Switched Distance Relay Scheme, GEC Measurements publication R5742.

2.36 YTG31 Distance Protection Relay, GEC Measurements publication R5764.

2.37 SHNB Micromho Static Distance Protection Relays, GEC Measurements publication R5406.

2.38 SHPM Quadramho Static Distance Protection Relay, GEC ALSTHOM T&D Protection & Control Limited publication R5580.

2.39 YTG33 Phase Selector Scheme, GEC Measurements publication R5294.

2.40 MCHNM Digital Motor Protection and Management Relay, GEC ALSTHOM India publication PRM.05:105.

2.41 LGPG111 Digital Integrated Generator Protection Relay, GEC ALSTHOM T&D Protection & Control Limited publication R4106A.

3. **Books:**


3.1 Warrington, A.R. van C., "Protective Relays - their Theory and Practice", Chapman & Hall

3.2 Jones, D., "Analysis and Protection of Electrical Power Systems", Pitman Publishing

3.3 Mason, C. Russell, "The Art and Science of Protective Relaying", John Wiley & Sons, Inc.

3.4 Blackburn, J. Lewis, "Protective Relaying-Principles and Applications", Marcel Dekker, Inc., New York, 1987.

3.5 Wagner, C.F., Evans, R.D., "Symmetrical Components", McGraw-Hill, New York, 1933.

3.6 Anderson, Paul M., "Analysis of Faulted Power Systems", the Iowa State University Press, Ames, Iowa, 1973.

3.7 Ma Chang Kuai, "High Voltage Electric Network Protection Principles (Chinese)", Shandong Technology University, Hydro Power and Electric Publishing Bureau, China, 1987.

3.8 GEC Measurements, "Protective Relays Application Guide", GEC UK, 1975.

3.9 Westinghouse Electric Corp., "Applied Protective Relaying", Westinghouse Electric Corp., Newark, N.J., 1979.

3.10 Horowitz, Stanley H., "Protective Relaying for Power System", IEEE Press, 1980.

3.11 Ma Chang Kuai, "Protective Relay Fundamentals (Chinese)", Shandong Technology University, Hydro Power & Electric Publishing Bureau, China, 1986.

3.12 GEC ALSTHOM Protection & Control Limited, "Power System Steady-State And Fault Analysis User Manual 9105.0912", August 1985.

3.13 Lotus Development Corporation, "Lotus 1-2-3 Release 3.1 Reference Manual".

3.14 IEEE Tutorial Course, "Computer Relaying", Course Text 79EH0148-7-PWR.

3.15 IEEE Tutorial Course, "Microprocessor Relays and Protection Systems", Course Text 88EH0269-1-PWR.

3.16 Cao Rong Jiang, "High Voltage Alternating-current Circuit Breaker Operation (Chinese)", Hydro Power & Electric Publishing Bureau, China, 1985.

3.17 IEC56, "High-voltage Alternative-current Circuit-breakers", 4th edition, 1987.

3.18 ABB Power T&D Company Inc., "Protective Relaying Theory and Applications", Marcel Dekker, Inc., New York, 1994.