Directional Detection for Overcurrent Protection without Voltage Sensors in Systems with Distributed Generation

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Approval Sheet

This thesis entitled "Directional Detection for Overcurrent Protection without Voltage Sensors in Systems with Distributed Generation" by Gopu Dinesh Kumar is approved for the degree of Master of Technology from IIT Hyderabad.

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Abstract

As the yearly electric energy demand grows, there is a significant increase in the penetration of distributed generation (DG). Since the conventional sources of energy such as coal, petroleum and natural gas etc. are fast disappearing, a study of distributed renewable generation systems becomes very important. Integration of a DG into an existing distribution system has many impacts on the system, with the power system protection being one of the major issues. Short circuit power of a distribution system changes when its state changes. It also changes when some of the generators in the distribution system are disconnected. This may result in elongation of fault clearing time and hence disconnection of equipment's in the distribution system or unnecessary operation of protective devices. This thesis mainly deals with the protection algorithms that are to be met in order to avoid false tripping problem because of bidirectional power flow.

In this work, to reduce the cost, a principle for the directional relay using only current measurements, which is based on fault current slope and pre-fault current slope, is proposed and tested with simulations in case of Inverter-Interfaced DGs. Also the other algorithm calculated from the sequence currents, the I_2/I_0, I_2/I_1 ratio is plotted which created two separate areas on the complex plane from which upstream or downstream faults could be easily determined. In this thesis, optimal boundaries for separating the two areas are studied. The algorithm shows good performances in most situations with these boundaries. Overall, the project work involves study, design; modelling and simulation to find fault direction of grid connected Solar Photovoltaic Energy Conversion System.

Nomenclature

I_1 : Positive Sequence of fundamental Current

I_2 : Negative Sequence of fundamental Current

I_o : Zero Sequence Current

PV : Photovoltaic

LG : Single-line to ground fault

LL : Phase to phase fault

LLG : Double-phase to ground fault

LLL : Three-phase fault

LLLG : Three-phase to ground fault

SPVECS : Solar photovoltaic energy conversion system

DOCR : Directional Over-Current Relay

OCR : Over-Current Relay

MPP : Maximum power point

PCC : Point of Common Coupling

AC : Alternating current

DC : Direct current

MPPT : Maximum power point tracking

VSC : Voltage Source Converter

DER : Distribution Energy Resource

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Chapter 1

Introduction

1.1 Traditional Concept of Power System

At present, most of the power generation is produced in bulk amount in large power plants, normally located far away from the consumers. Here power is sent to load points using a large passive distribution system which involves high voltage (HV), medium voltage (MV) and low voltage (LV) networks, which are designed in such a way that power is delivered to load points radially. Hence, power flow only is in unidirection mode: from higher voltage levels to the customers located along the radial feeders. There are three stages of power flow as shown below.

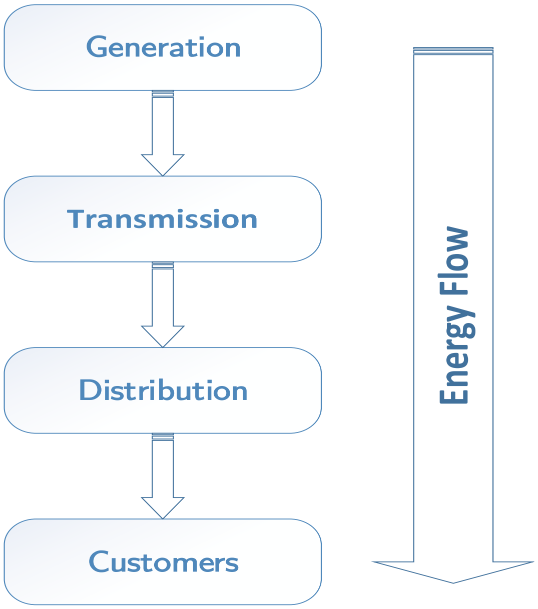

Fig: 1.1 Uni-directional power flow

In first stage, electricity is generated from large plants located in remote areas. Second stage includes various power systems equipment's like overhead transmission lines, underground cables, transformers. The final stage is nothing but a distribution, the link between consumers and utility system. This stage is substantially important as the final quality of power depends on its reliability. In traditional system, as the load demand increases generating capacity is enhanced at level 1.

1.2 Distributed Generation

Nowadays, with the technological development and environmental policies, there comes the new conditions in the power sector, which led the electric power to be generated in small sized plants. In addition, to reduce the environmental impact there is an increase in use of renewable sources, which leads to the development and presentation of new schemes in electrical energy. In this new phenomenon, the generation is not limited to level 1. Hence, the bulk-generated plants supply some part of the energy demand and another part is produced by distributed generation. This electricity is going to be produced closer to the customers.

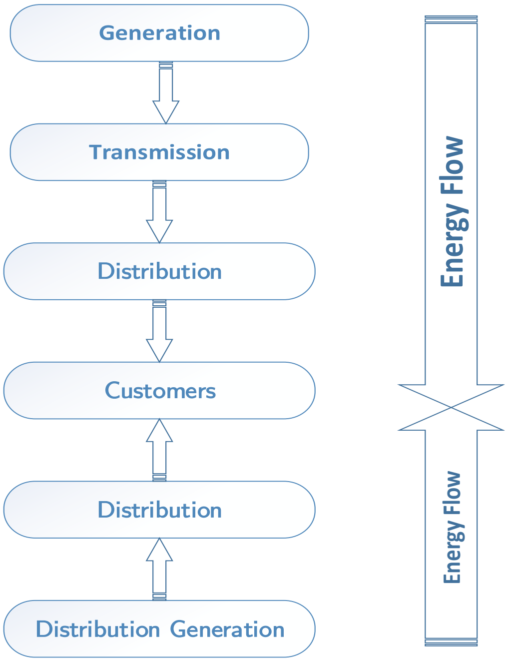

Fig 1.2 Bidirectional power flow

1.3 Motivation

The bidirectional power flow results in directionality concept in overcurrent relays for distribution system. Most of the efforts have been made to implement DOCR detection techniques for distribution systems. While some of the techniques depends on the neutral impedance and fault impedance values, it becomes difficult to detect the variation between forward and backward faults. In spite of these disadvantages, due to overlapping of forward and backward areas, there arises a need for the development of new algorithm for directionality in distribution system.

During this research, the ultimate focus was on proposing directionality algorithm for grid-connected solar photovoltaic energy conversion systems by using only current data. Elimination of voltage data during fault condition will reduce the cost of whole system protection and also improve the reliability issues because number of dependent devices are being reduced. Scope of the work is outlined in the next section.

1.4 Scope of work

Research on DOCR (Direction Over Current Relay) based algorithms for Inverter Interface Distributed Generation (IIDG) systems in comparison to the synchronous generator connected systems is less. However, due to increase in distributed generated renewable energy sources like Solar, wind, biomass etc. make the radial system bidirectional. Hence, there is a necessity to analyze these systems during fault conditions and trip finest relays to make least power interruption to the consumers. It is important to decrease the overall cost and at the same time improve reliability of these systems. Current dependent algorithms, which do not need voltage sensors, offers a viable alternative, which reduce the cost of potential transformers. With respect to these issues main objectives of this research are

- Analysis, design, control and simulation of grid-connected, three-phase, SPVEC systems with different kinds of faults.

- Analysis of the existing directional overcurrent relay algorithms and developing the reliable and low cost DOCR technique.
- Highlighting the advantages of using the proposed DOCR control techniques over the traditional directional detection techniques by eliminating the requirement of voltage transformers

Outline of chapters

This chapter gives an introduction and common features of solar energy systems, traditional and distributed power system and objectives of this project in precise and orientation of the thesis.

Chapter 2: This chapter covers the literature survey on overcurrent relays, review of fault types, methods of directional overcurrent relaying techniques.

Chapter 3: This Chapter deals with the modelling of Solar Photovoltaic systems, MPPT techniques, boost converter and DC link voltage controller.

Chapter 4: This Chapter deals, sequence component based algorithms for direction detection.

Chapter 5: This Chapter deals with the implementation of proposed algorithm for grid connected Solar Photovoltaic Energy conversion systems.

Chapter 6: This Chapter deals with the conclusions and suggestions for future work.

Chapter 2

Literature Review

A brief introduction, highlighting focus of the thesis was given in the previous chapter. This chapter consists of a brief literature survey, which covers various types of overcurrent relays, review of fault types, methods of directional overcurrent relaying techniques.

2.1 Review of Fault types:

There are four major types of faults:

- Single line to ground (LG): This is an unsymmetrical fault, where there is a sudden rise in phase current and fall in the faulted phase voltage
- Double line to ground (LLG): This is also an unsymmetrical fault shows the same tendency as LG fault involving two faulted phases
- Triple line to ground (LLLG): This is a symmetrical fault in which there will be collapse of all three phase voltages and sudden rise in all the three phase currents
- Line to Line fault (LL): Unsymmetrical fault where the trend is to see a depression in phase voltage and sharp rise in currents on all the three phase voltages and currents and does not include any zero sequence component.

2.2 Principles of Protection Scheme

Protection Philosophy:

At distribution level, directional relays are the most common type of relays. This work concentrates on using these directional relays to diminish the issues faced in the system when DG's are interconnected. The existing system becomes more complicated since there may be tripping due to the current fed from DG's when they are interconnected to the radial feeders. By giving a time delayed approach to the settings, primary and back up protection is selected.

2.3 Overcurrent Protection in Distribution System

Short Circuit normally results in high current levels in power system networks. The type of faults and requirement of protection devices are decided by these high currents. The general type of protection devices are molded-case circuit breakers, Miniature Circuit Breakers, thermo-magnetic switches, fuses and over-current relays. Over-current relay is the most common type of protection device used to detect high currents in power systems.

Over-current protection should not operate in overload conditions. They should operate only under fault conditions and therefore, they should not be installed merely as a way to protect systems against over loads. However, settings of the relay are selected considering both into account, over-current and over-load conditions.

An over-current protection relay will sense any change in the current signal, which it is receiving normally from a current transformer and carry out a definite operation if the incoming current is outside a preset range. Usually the operation of relay takes place by opening or closing the electrical contacts, such as the tripping of a circuit breaker.

2.3.1 Types of Over-current Relays

Depending on relay operating characteristics, over-current relays may be classified
Into three groups: definite current relay, definite time relay and inverse time relay

- Definite Current Relay

This type of relay operates instantaneously when current reaches the pickup value.

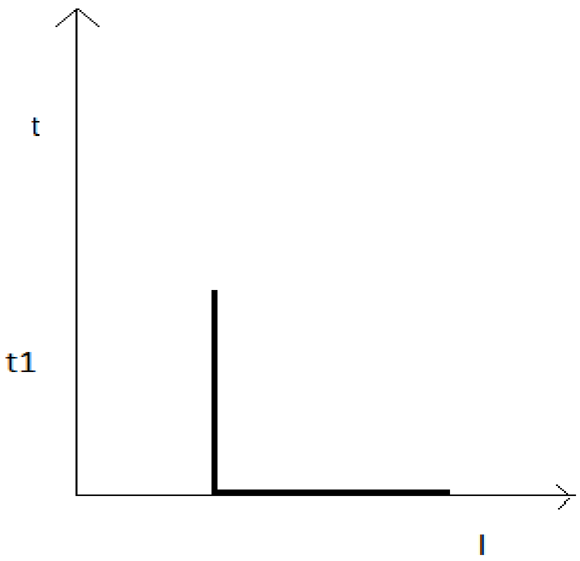

Figure 2.1: Definite Current Characteristic of Over-Current Relays

The relay that is at the far end substation has the least operating current preset value. These operating presets current values increases as we move towards the source side relays. Hence, the farthest relay operates first and disconnects the load, which is down to the location of the relay.

Here the protection setting is based on three-phase short circuit current, thereby when a fault current is lower than this maximum current setting, the relay may not assume as fault and left un-cleared until it reaches the preset current value. Hence, to clear the fault it will take some time during which the equipment may be damaged. If in case, the settings are based on lower value of fault current, it may result in unnecessary operation of breakers as the fault level increase. Because of these disadvantages, definite current relays are not employed as a sole over-current protection, but they can used as an instantaneous component in combination with other types of protection.

- Definite Time Relay

In definite time relay different levels of fault current has different operating times. The settings can be adjusted in such a way that the relay, which is at the farthest location from the source, is tripped in the least time, and the remaining are tripped in sequence of moving back in the direction of the source.

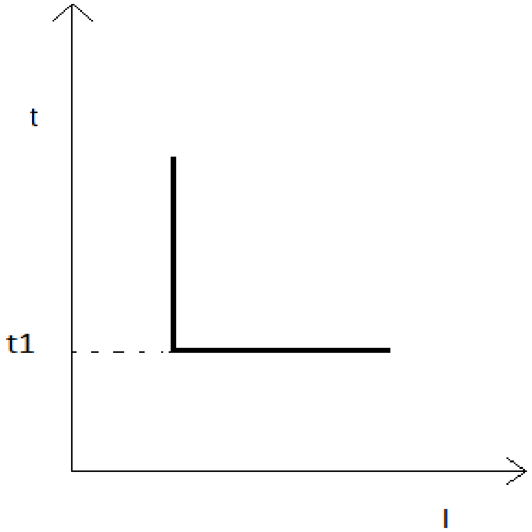

Figure 2.2: Definite Time Relay Characteristics

- Inverse Time Relays

The operating time of this type of relay is inversely proportional to the magnitude of the fault current. Hence, these have an advantage of fast tripping during severe fault conditions. Again, these type of relays are classified as inverse, very inverse or extremely inverse based on their characteristic curves. Their defining curve shape is shown in Fig.2.3

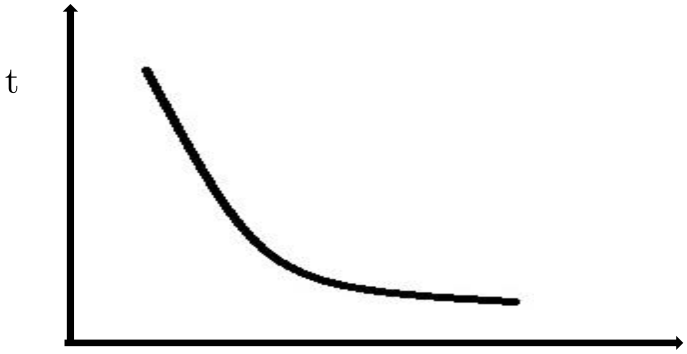

Figure 2.3: Inverse Time Relay Characteristics

2.4 Brief Review on Directional Overcurrent Relay

The directional overcurrent relays has a vital role in power system protection design. In high voltage network protection, directional detection forms the basis of many protection schemes such as directional comparison schemes of high voltage transmission systems. By comparing the direction of faults shown by the direction relay at the two end of the line, this type of operation occurs. Both directional relays will operate for the internal faults whereas only one direction relay will see the external faults. The comparison process is supported by the use of a signaling 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.

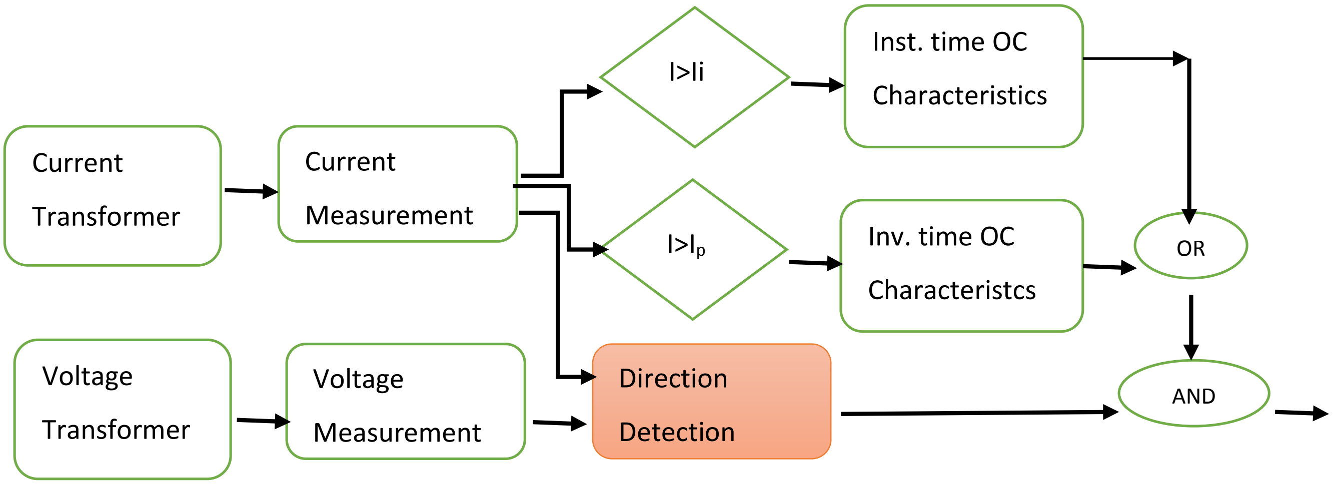

Figure 2.4: Block diagram of DOCR

2.4.1 Principle of Operation of Directional Detection

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

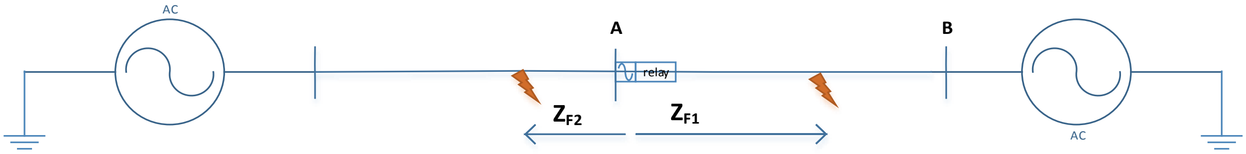

Figure 2.5: Principle of operation of directional Overcurrent Relay

Let a fault be at location F_1 with fault impedance ZF_1 from the fault point to the relay location. Let IF_1 be the fault current be seen by the relay.The measured voltage by the relay will be $V_{F1}=I_{F1}Z_{F1}$

The angular displacement θ_{F1} between V_{F1} and I_{F1} is the impedance angle of Z_{F1}

θ_{F1}=Angle of $\frac{VF1}{IF1}$ = θ_{FI} = angle of Z_{F1}

The range of variation of the angular displacement between the voltage and current signals for this forward fault condition is therefore limited to: θ_{FI} = angle of Z_{F1} = 0° to 90°.

The fault will be in the reverse direction as seen from the same relay, if fault occurs at F_2 the measured voltage with a fault current IF_2 is given as $V_{F2} = - I_{F2}Z_{F2}$.

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

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

angle of $\frac{VF2}{IF2}$ = θ_{F2} = 180° + angle of Z_{F2}

The range of variation of the angular displacement between the voltage and the current signals for this reverse fault condition is therefore given by: θ_{F2} = 180° to 270°

From equations θ_{F1} and θ_{F2} it can be concluded that:

(i) 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°.

(ii) 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 2.8.

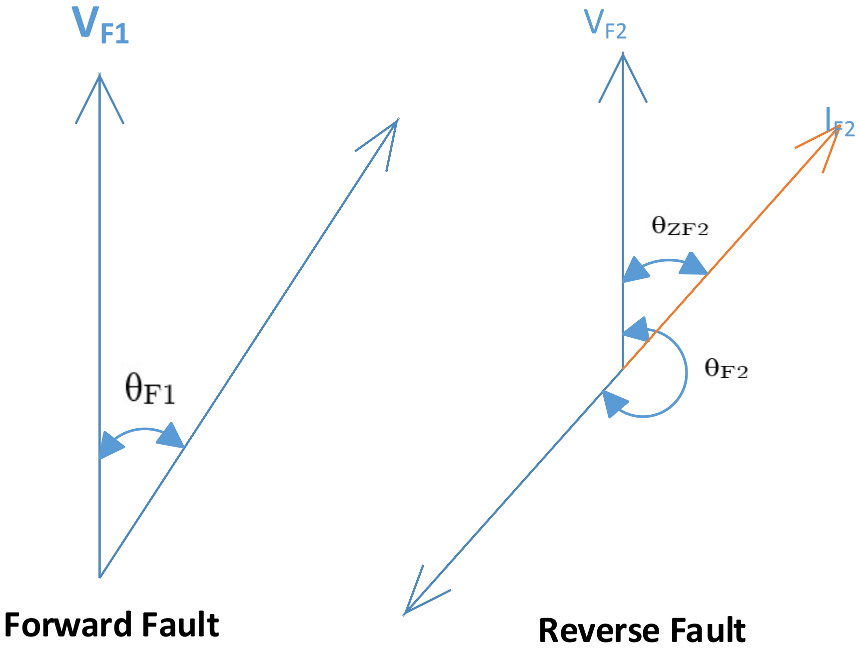

Figure 2.6: Angular displacement between voltage and current phasors for forward and reverse faults

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:

$$\text{Power} = VI\text{Cos}\,\theta \qquad (2.1)$$

Where V = voltage, I = current, θ = angle between V and I.

The sign of the power value depends on the value of the angle θ. For positive power flow, determined by the values of θ, it can be defined for $-90^\circ < \theta < +90^\circ$ as the forward or operating direction and for negative power flow as the reverse or restraint direction. 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 polarizing quantities and the angular range of measurement between them.

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

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Table 2.1: Different Connections of Directional Relays

Connections	Input Signals		
	A Phase Relays	B Phase Relays	C Phase Relays
30^0	I_A V_{AC}	I_B V_{BA}	I_C V_{CB}
60^0	I_{AB} V_{AC}	I_{BC} V_{BA}	I_{CA} V_{CB}
60^0	I_A $-V_C$	I_B $-V_A$	I_C $-V_B$
90^0	I_A V_{BC}	I_B V_{CA}	I_C V_{AB}

The objectives of selecting the correct operating current and polarizing 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.

2.4.2 Various Methods of Directional Detection

There are a number of directional elements being employed in practical applications for detection of direction of the fault. Some of these techniques are given below:

- Artificial Neural Network based techniques
- Product type directional relays
- Amplitude comparator based algorithm
- Curve-fitting algorithm
- Phase-angle-measurement directional relays
- Impedance type directional relays
- Phase-compensated type directional relays
- Transient-based directional protection using wavelet transforms

This author describes the design and development of an ANN based novel directional overcurrent relay. A multi-layer feedforward neural network (FFNN) trained with the error backpropagation algorithm has been developed to realize this relay. The ANN based algorithm is off line tested using different simulation equations for overcurrent and voltage under fault conditions to evaluate the performance of the proposed method in terms of accuracy and speed [1].

The first generation of directional relay was based on the effect of mixing voltage and a current signal that depend on the magnitudes of the signals and their angular displacement. The author proposed a design based on electromechanical techniques and employed mainly for the directional control of overcurrent and earth fault protection relays, which 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 whereas reverse faults will result in contact opening or restraint torque [2].

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, travelling-wave-phenomenon type directional relays came into literature. The operating speed of directional impedance relays is limited to about one cycle operating time though half cycle operating time is possible with present day commercially available directional impedance relays. 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. 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. Positive current is defined at the relay location as a current flowing from the bus bar to the line. 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. 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. From the principles outlined above, the author 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 [2].

In this work, author proposed a high-speed directional comparison relay based on an evaluation of the locally measured deviations of the voltage and the phase-shifted current from their pre-fault values. The operation of the relay depends on the power frequency components of the voltage and phase-shifted current deviation signals. The direction to a fault is determined by an amplitude comparator technique, which compares a discriminant value with a positive or negative threshold. Studies over a wide range of faults and source impedance angles show that the amplitude comparator technique performs better than an analogous phase comparator technique [3].

The author describes a curve-fitting algorithm that extracts information from the measurement sensors necessary to determine the direction to a fault. Generally current sensors are the current transformers (CTs) which are designed for measuring load current and saturate during a fault. They are unsuitable for a conventional directional relaying scheme, which requires protection CTs rated for operation at the highest level of fault current. Directional relay based on this algorithm detects the direction to the fault correctly, even when the CTs are deeply saturated [4].

An overcurrent protection of an islanded distribution system is still an issue due to the difference in fault current when the distribution system is connected to the grid and when it is islanded. Adaptive protection can be used to overcome the challenges of the overcurrent protection in distribution systems with distributed generation, using local information. The trip characteristics of the relays are updated by detecting operating states (grid connected or island) and the faulted section. This also proposes faulted section detection using time overcurrent characteristics of the protective relays [5].

A directional comparison technique for the protection of E.H.V. transmission lines uses analogue processing is performed using charge-coupled devices to extract the fault or superimposed components impressed on a power system following a disturbance. The author designed a new arrangement for use in conjunction with carrier blocking communication equipment and tripping times of typically 2 to 4 ms are shown to be feasible for most faults [6].

The phase-angle-measurement directional relays are proposed by the author 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. In this, the author proposes that 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. 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 [2].

Based on phase comparison between two of the three compensated phase voltages the author proposed an algorithm 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-polarized characteristic which provides better directional sensitivity with increased fault resistance coverage without load encroachment [2].

The basic principle of the directional relay is based on comparing high-frequency component energy of directional traveling waves of each bus outgoing line. The relay comparison scheme is designed with intrinsic mode function (IMF) from empirical mode decomposition. The IMF is used to extract transient features from fault-generated traveling-wave signals propagating along transmission lines during a post-fault period. The arithmetic differential of the IMF first layer can represent the time instant corresponding to the initial traveling-wave arriving at the directional relay. This scheme is capable of providing correct responses under various fault conditions [8].

2.4.3 Directional Relays for Earth fault 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 polarizing source and the zero phase sequence current as the operating signal. In some applications, the dual-polarized directional relay is also used which requires a suitable zero phase sequence current source as the additional polarizing signal to the relay

2.4.4 Directional Detection based on Phase Sequence Quantities

There are two types of poly-phase directional relay available based on the use of negative phase sequence quantities or positive phase sequence quantities

(i) Using Negative Phase Sequence Quantities

One of the major shortcomings of poly-phase 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. 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. 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 [9].

(ii) 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 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 earth fault 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 [10].

Chapter 3

Introduction to Photovoltaic Energy Conversion System Modeling

3.1 Brief review on solar power conversion

A solar photovoltaic system uses solar cells to convert solar energy into electricity. The photovoltaic (PV) cells, sidestepping thermodynamic cycles and mechanical generators, utilizes sunlight photons free electrons from silicon, generates voltage at the PV terminals. This phenomenon was first discovered in the 18th century and in 1950, the early photovoltaic cells were developed at Bell Labs, mainly for space applications. Solar cells have proved to be cost effective. Other than space applications, the photovoltaic cells are now being used in rural health clinics for refrigeration, streetlights and water pumps in agriculture sector and for small-scale power generation. Since the output power of the solar cell depends upon the irradiation level, and at a definite irradiation level, there is a nonlinear relationship I-V characteristic of a solar cell. Different methods have been developed to locate the maximum power point of the cell, i.e., the operating point at which maximum power can be obtained from the cells .The PV plants occupy large geographical area to produce same power compared to conventional energy sources of generation which is the main drawback of photovoltaic generation systems. On some dim days, the irradiation level is low to produce the expected energy, which is the second drawback that lowers the reliability of the system. These photovoltaic systems will be connected to the grid, which is the ocean of energy from which the power can be taken when generation is less or load is more than PV generation or power can be transferred to the grid depending on the irradiation level and local loads. In stand-alone mode of operation, the excess energy is stored in the battery or energy is drawn from the battery when generation is low.

A two-stage PV energy conversion system is employed to connect a PV array to an electrical power system. In the first stage, the DC/DC converter is controlled in such a way that photovoltaic system operates at the maximum power point, to transfer energy to the inverter and batteries. In the second stage in grid-connected mode, to transfer power to the grid at unity power factor, the inverter is controlled to produce an output current in phase with the grid voltage. The efficiency of the entire conversion system is compromised because of the large number of individual devices like inverters and choppers

3.2 MPPT algorithms for SPVECS

Tracking the maximum power point (MPP) of a photovoltaic (PV) array is usually an essential part of a PV system to extract the maximum power from the solar cells, MPPT control algorithms are used. The PV system operates at these maximum power points, at which we can extract maximum power output. The operating PV system becomes 40% more efficient than the systems operating without the maximum point algorithms. Some of the popular MPPT algorithms are –

- Incremental Conductance method
- Hill Climbing method (P&O Algorithm)
- Modified hill climbing method
- Constant Voltage Method
- Current sweep algorithm
- Load current or load voltage maximization

Incremental conductance: The slope of the PV array power curve will be zero at the maximum power point, on the left of the MPP, it will be positive and negative on the right. Maximum Power Point is obtained by comparing the instantaneous conductance (I/V) with the incremental conductance ($\Delta I/\Delta V$), where V is the PV array output voltage and I is the PV array output current. Based on the above comparison Inc. Cond. decides the operating voltage for converter controller [13].

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V} \quad \text{At MPP}$$

$$\frac{\Delta I}{\Delta V} > -\frac{I}{V} \text{ Left of MPP}$$

$$\frac{\Delta I}{\Delta V} < -\frac{I}{V} \text{ Right of MPP}$$

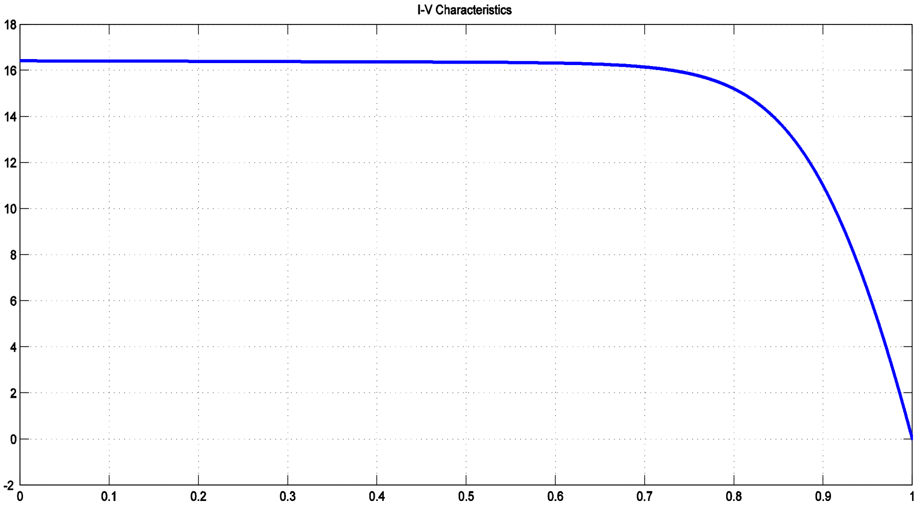

Figure 3.1: Characteristic curve of PV

Hill climbing method: The modified form of perturb and observe MPPT algorithm is Hill climbing method. DC/DC converters are used to control the PV array output voltage. Hill climbing involves a perturbation in the duty ratio of the power converter and P&O a perturbation in the operating voltage of the PV array. Perturbing the duty ratio of a power converter perturbs PV array current and consequently perturbs the PV array voltage.

As it can be seen in Figure 3.1, that the power when operating on the left of the MPP decrementing (incrementing) the voltage decreases (increases). Therefore, if there is a decrease in power, the subsequent perturbation should be kept in the opposite direction in order to reach the MPP and if there is an increase in power, the perturbation direction should be reversed [14].

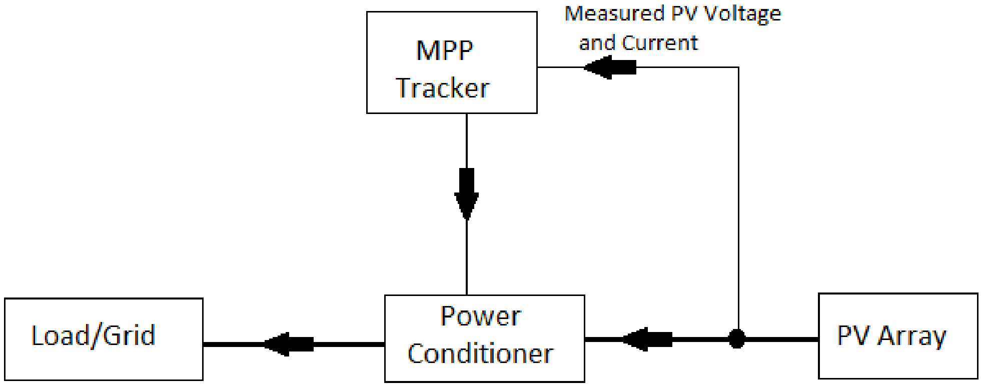

Figure 3.2: Block diagram of maximum power point tracking in PV

Table 3.1: Summary of Hill climbing and P & O algorithm

Perturbation	Change in Power	Next Perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

3.3 PV System Configuration

The system description, system modeling and implemented algorithms for finding the direction of fault is presented in this section

3.3.1 System description

In this research work, two Photovoltaic systems with peak power capacity of 100kw are interfaced with the power grid along with a shunt connected local load and local radial feeder network.

Table 3.2: SPVEC System Parameters

C (Output capacitance)	12000 µF
L (Inductance of boost converter)	5 mH
F_{SW} (Switching frequency of buck converter)	5 kHz
V_{LL} (Line to line inverter voltage)	260 V

Table 3.3: The PV panel parameters

N_S (Number of PV cells in series)	480
N_P (Number of PV cells in parallel)	66
Q (Charge of an electron)	$1.6\text{x}10^{-19}$C
K (Boltzmann constant)	$1.3805\text{x}10^{-23}$Nm/K
A (ideality factor)	1.3
K (PV cell's temperature coefficient)	0.0017A/^{O}C
I_{SCR} (PV cell short circuit current)	8.66 A
Series Resistance Rs	0.037998 Ω
Shunt Resistance Rp	993.51 Ω

3.3.2 System modeling

A. Photovoltaic Panel modeling

Single-diode model [12] equivalent circuit of a practical photovoltaic device including the series and parallel resistances is used to model photovoltaic cell. It is modelled as a current source given in the below equation

$$I = I_{pv} - I_o \left[e^{\frac{V+IR_s}{V_t a}} - 1 \right] - \frac{V+IR_s}{R_p} \tag{3.1}$$

$$I_o = \frac{K_i(T-T_n)+I_{scn}}{\left(e^{\frac{V_{ocn}+K_v(T-T_n)}{V_t a}}-1\right)} \tag{3.2}$$

Where I_{pv} and I_0 are the photovoltaic and saturation currents of the array and $V_t = Ns*k*T/q$ is the thermal voltage of the array with N_s cells connected in series. The cells if connected in series provide larger output voltages and Cells connected in parallel gives higher current. If the array is composed of N_p parallel connections of cells the photovoltaic and saturation currents may be expressed as: $I_{pv}=I_{pv,cell}*N_p$, $I_0=I_{0,cell}N_{p.}$k is the Boltzmann constant, T is the cell reference temperature, a is the ideality factor. The photo-generated current's (I_{ph}) dependence on the irradiation (G) and cell temperature (T) is modelled as follows

$$I_{pv} = [I_{pvn} + K_i(T - T_n)]\frac{G}{G_n} \tag{3.3}$$

Where I_{pvn} is the short circuit current of the PV cell, K_i is the short circuit current temperature coefficient, T_n is the cell reference temperature.

B. Boost converter modeling

A nonlinear state space model of boost converter is used here

This non linear state space model is given as,

$$\dot{\mathbf{x}} = f(\mathbf{x}) + g(\mathbf{x})u \tag{3.4}$$

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & o \\ 0 & \frac{1}{C} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}.$$

Where, $\mathbf{x} = \begin{bmatrix} V_{pv} & I_0 \end{bmatrix}^T$

C. DC Link voltage controller

The DC-link voltage should be maintained at a reference voltage level for satisfactory operation of the inverter, which is given below

$$V_{dc}^{*} = \frac{2\sqrt{2}V_{ll}}{\sqrt{3}m} \qquad (3.5)$$

Where, m is the modulation index and V_{ll} is the line voltage of the grid. According to the system parameters considered, the DC-link voltage should be retained at 500V. PI-controller is used in order to maintain this reference voltage level. Reference DC voltage (V_{DC}^{*}) is compared with actual DC-link voltage (V_{DC}) and the error signal is given input to PI controller. Current reference (I_d^{*}) for the VSI is generated from the output of the PI controller.

A PV system to the distribution network as shown in Figure 3.3. The first stage consists of DC-DC boost converter. A three-leg two-level voltage source inverter (VSI) is used for transferring the power from PV panels to the point of common coupling (PCC). Three inductors are used to interface the inverter with the grid. A shunt RC-filter is used as a ripple filter to remove high frequency ripple, which are caused due to high frequency switching of the inverter, from the PCC voltage.

There are total of four feeders of which feeder A is connected from grid to PCC. Relay A is placed at PCC along feeder A which becomes primary relay for feeder A. Other two relays are placed in feeders B and D. There are two PV plants of 100 kW each connected to feeders B and D respectively. The feeder C is connected to load directly without any generation connected to it. Relay C is placed in feeder C.

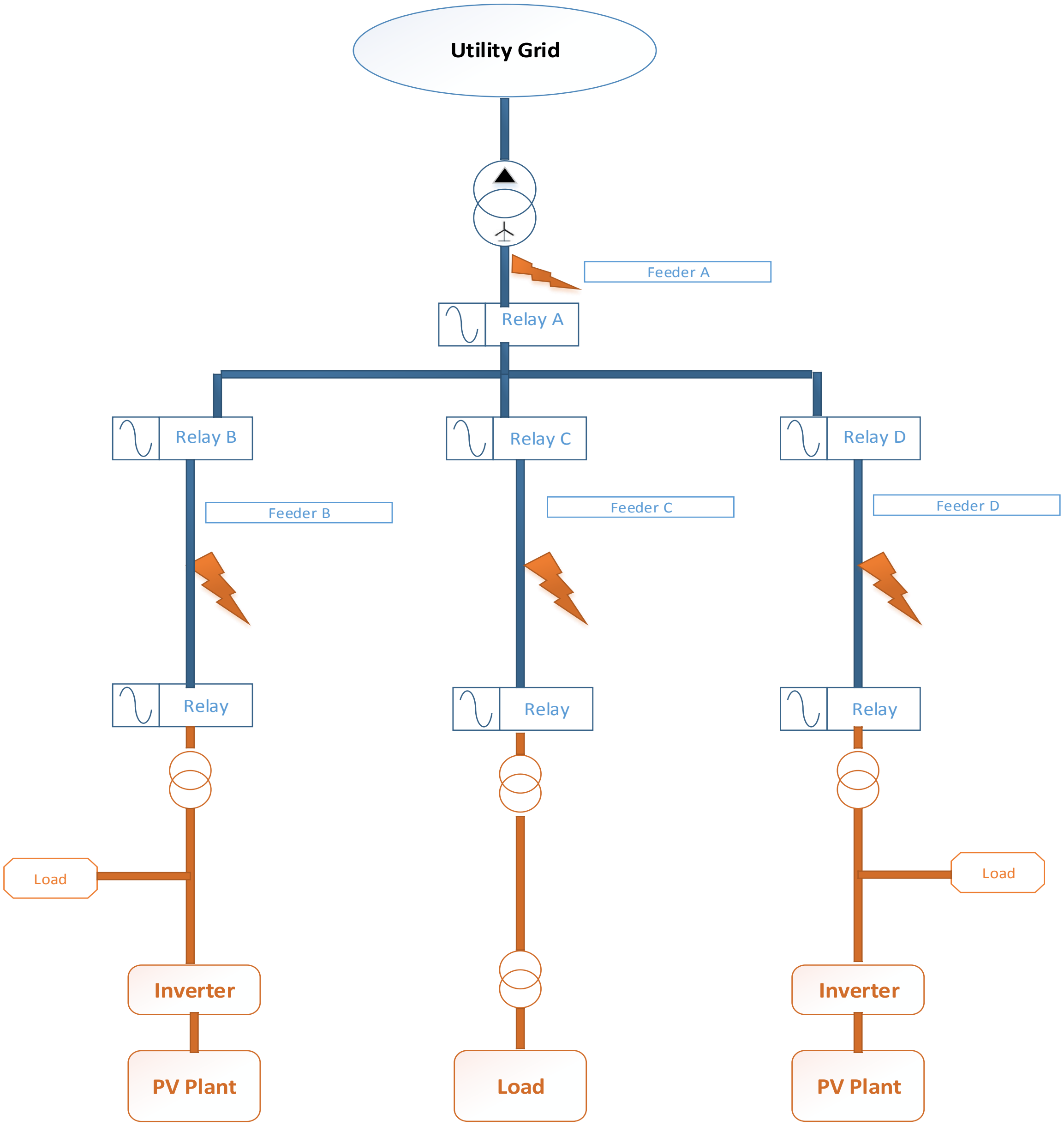

Figure 3.3: Distribution system Configuration

Chapter 4

Sequence Current Based Directional Over-Current Relay

Various algorithms for directional detection of fault were discussed in chapter-2. This chapter deals with the sequence currents combinations for distribution system with SPV energy conversion system. In this chapter, we will discuss about extraction of positive, negative and zero sequence currents and their ratios to determine boundaries for estimating directionality.

4.1 Use of Sequence Components to detect fault direction

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 [15]. One criticism against the use of poly phase directional relays is the loss of phase selection capability to identify the faulted phase. Other means have to be designed where faulted phase 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 the identification of faulted phase. It is imagined that the new approach of poly phase 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.

4.1.1 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 except 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. 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. 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.

4.1.2 Algorithm based on combined sequence components for direction detection in Line-Line Faults:

- Algorithm based on symmetrical components method are used to detect the fault Direction
- Here positive and negative sequence are considered for fault analysis

- $\frac{I2}{I1}$ ratio is taken for detection of directionality In Line to Line faults
- Plots of Real value vs imaginary value of $\frac{I2}{I1}$ has been used to detect if fault is in forward or reverse direction

Extraction of Sequence Components

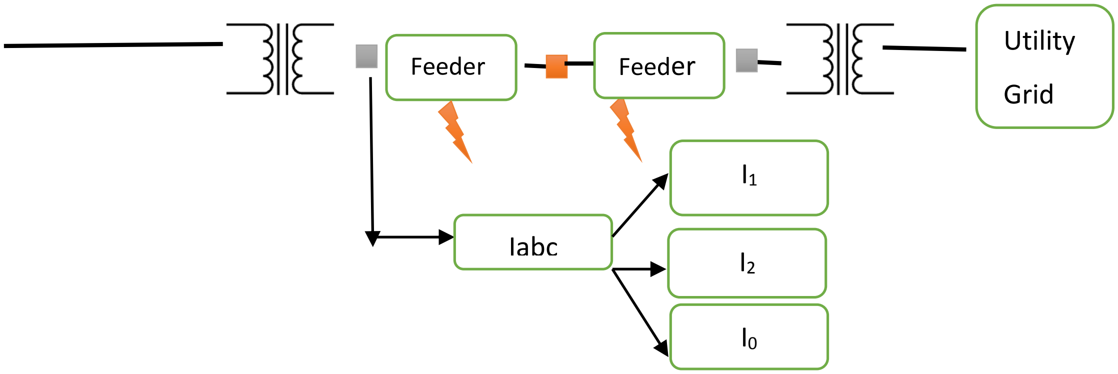

Figure 4.1: Extraction of Sequence Components

The sequence component currents are extracted from abc current phases as shown below

$$\begin{bmatrix} I_1 \\ I_2 \\ I_0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$a = 1\angle 120^\circ = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$$

$$a^2 = 1\angle 240^\circ = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$$

$$a^3 = 1\angle 360^\circ = 1\angle 0^\circ = 1$$

Response of Relay B for forward and reverse faults:

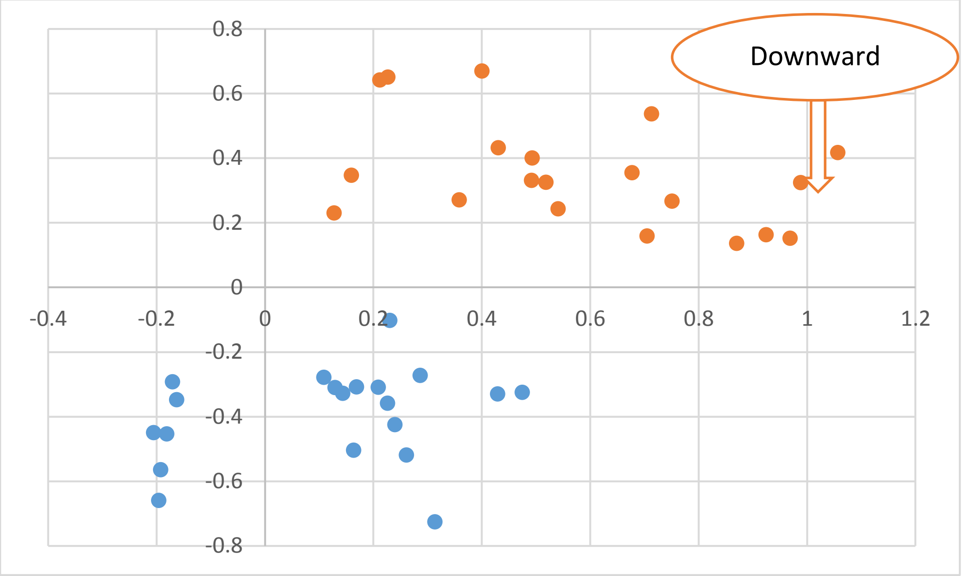

Figure 4.2 I_2/I_1 Plot for R_f=0, 50% distance

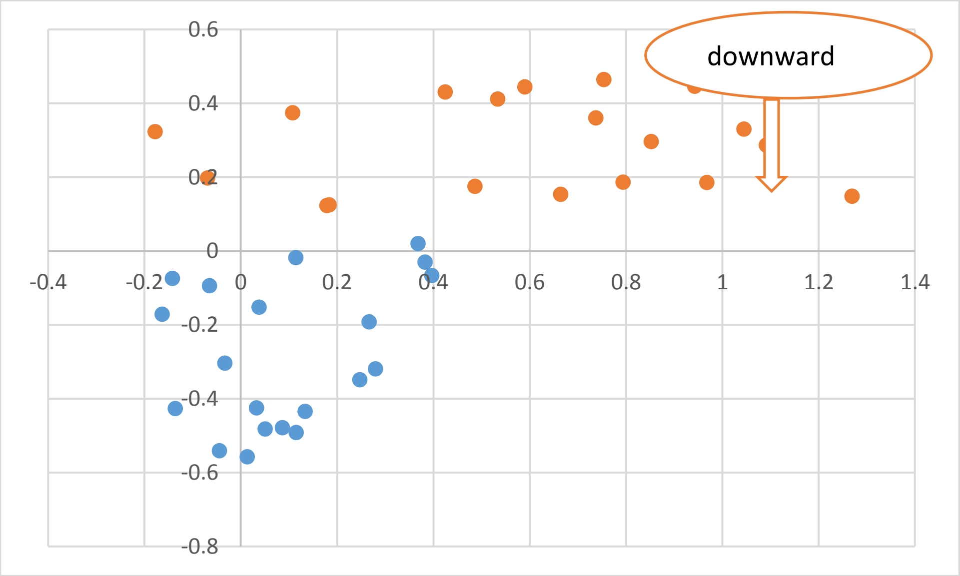

Figure 4.3 I_2/I_1 Plot for R_f=10, 50% distance

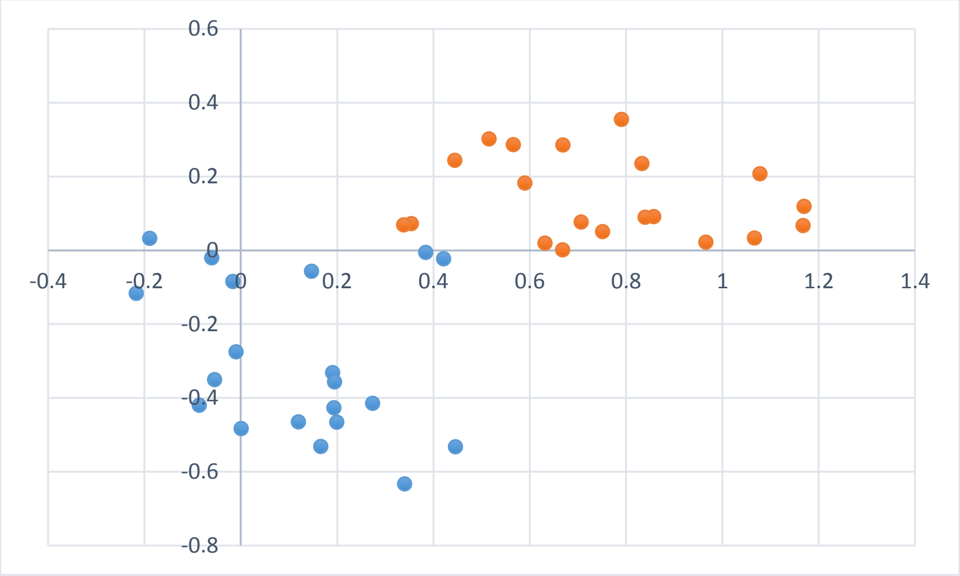

Figure 4.4 I_2/I_1 Plot for R_f=0, 25% distance

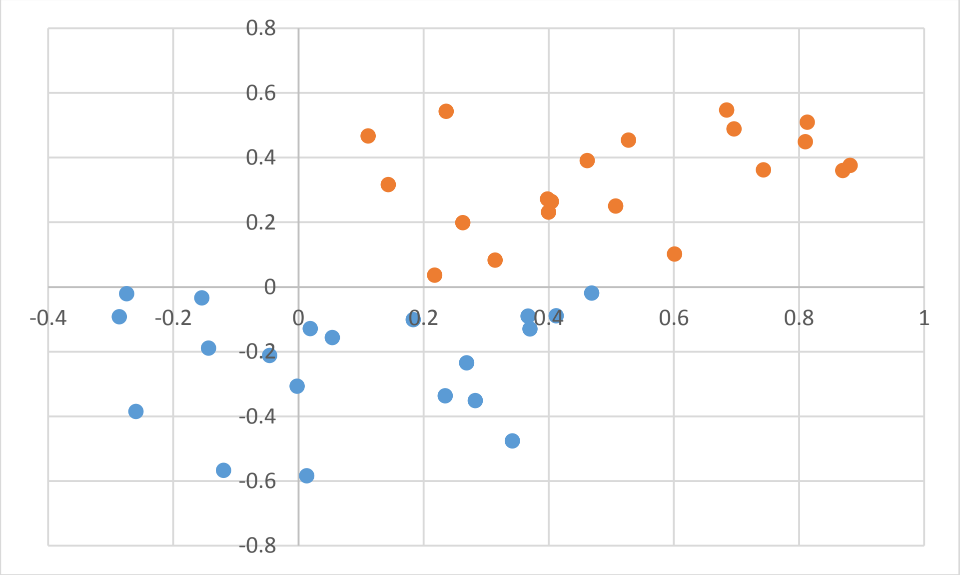

Figure 4.5 I_2/I_1 Plot for R_f=10, 25% distance

From figures 4.1 to 4.4, the response of relay B for different fault resistances and different distances can be seen. In this, for downward fault the plotting of I_2/I_1 gives the plots mostly in the first quadrant whereas for upward faults it is below the x-axis.

Response of Relay D for forward and reverse faults

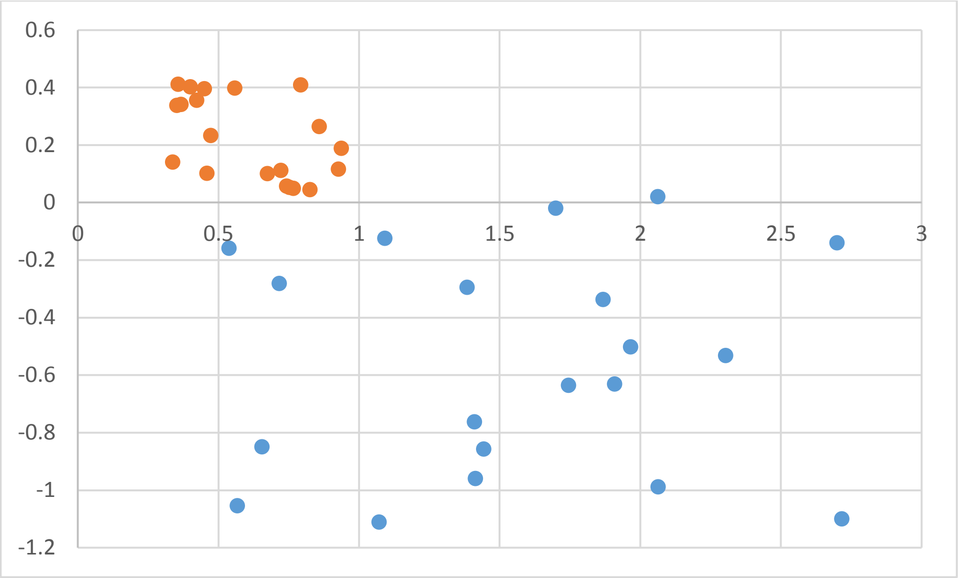

Figure 4.6 I_2/I_1 Plot for R_f=0, 50% distance

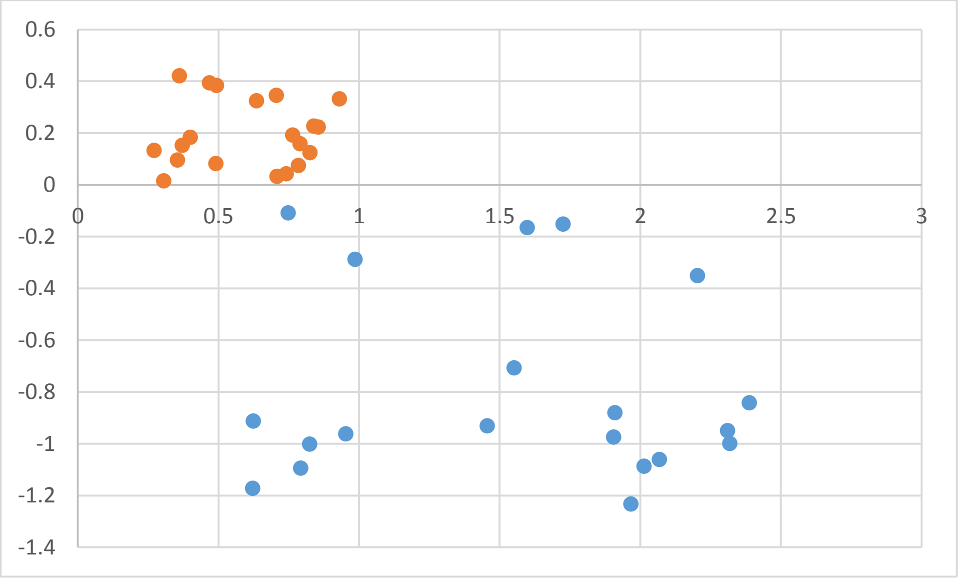

Figure 4.7 I_2/I_1 Plot for R_f=10, 50% distance

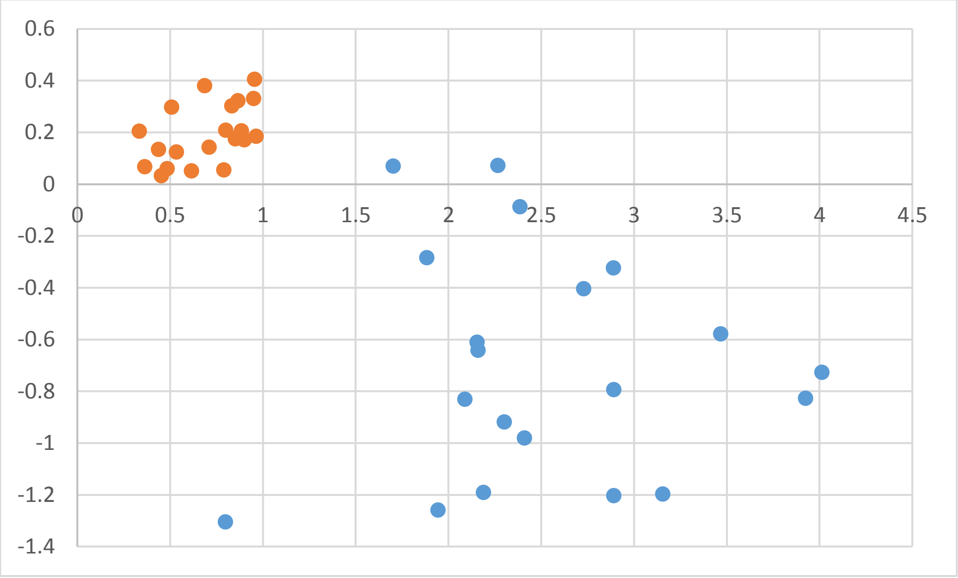

Figure 4.8 I_2/I_1 Plot for R_f=0, 25% distance

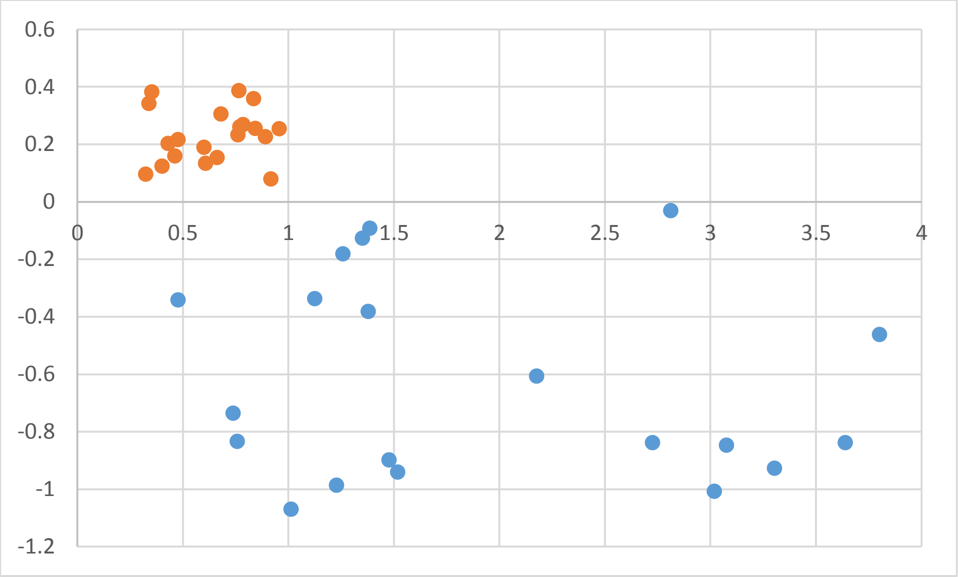

Figure 4.9 I_2/I_1 Plot for R_f=10, 25% distance

The response of relay D can be seen from figures 4.5 to 4.8 for different distances and different fault resistances. Here for downward fault, the plotting of I_2/I_1 for first 20 ms gives the points accumulated in first quadrant whereas for upward fault, the points are spreaded below the x-axis.

Response of Relay A for forward and reverse faults at feeder B:

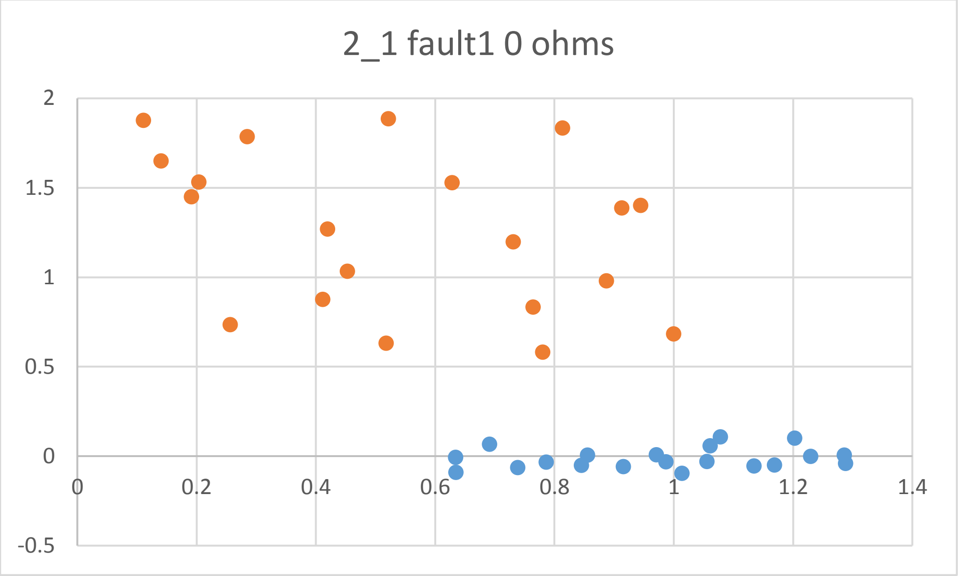

Figure 4.10 I_2/I_1 Plot for R_f=0, 50% distance

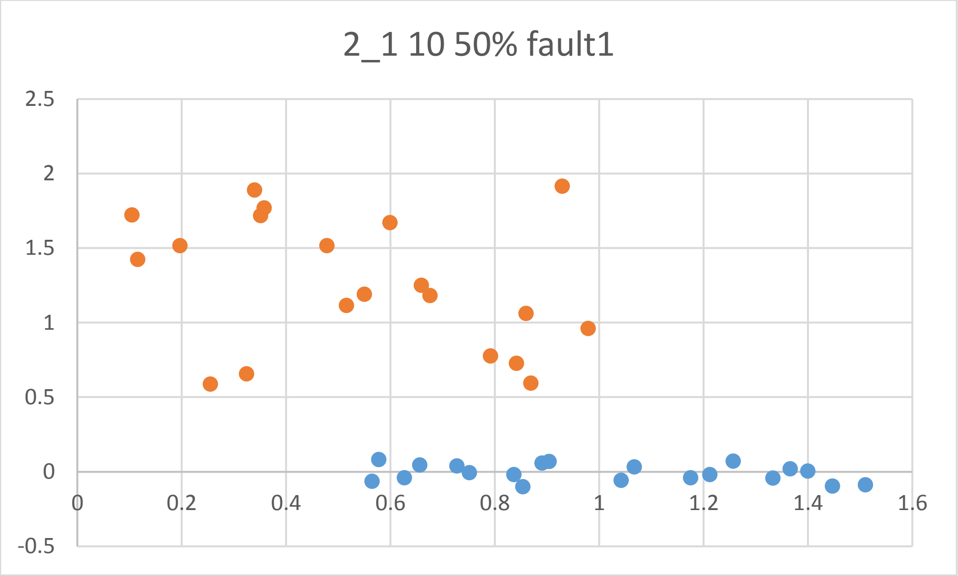

Figure 4.11 I_2/I_1 Plot for R_f=10, 50% distance

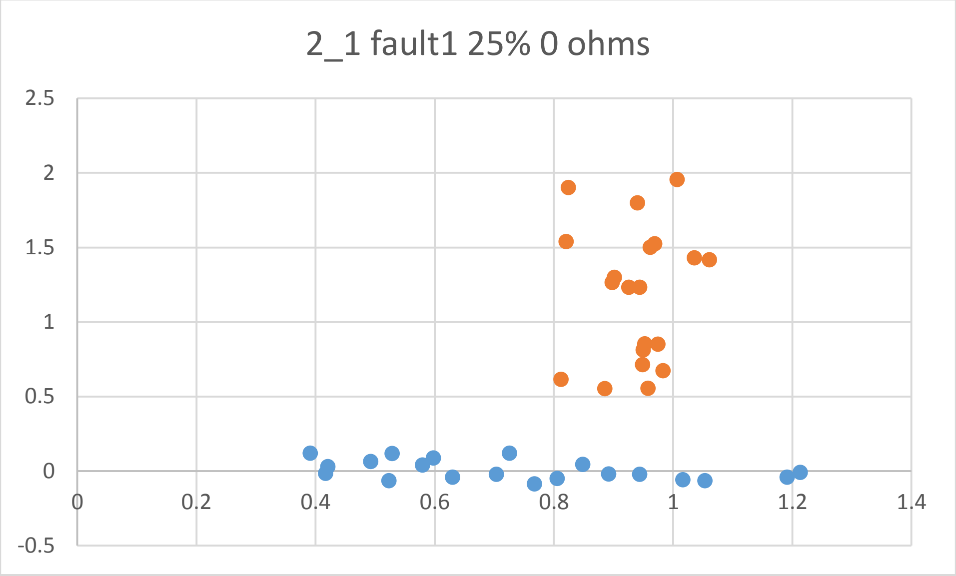

Figure 4.12 I_2/I_1 Plot for R_f=0, 25% distance

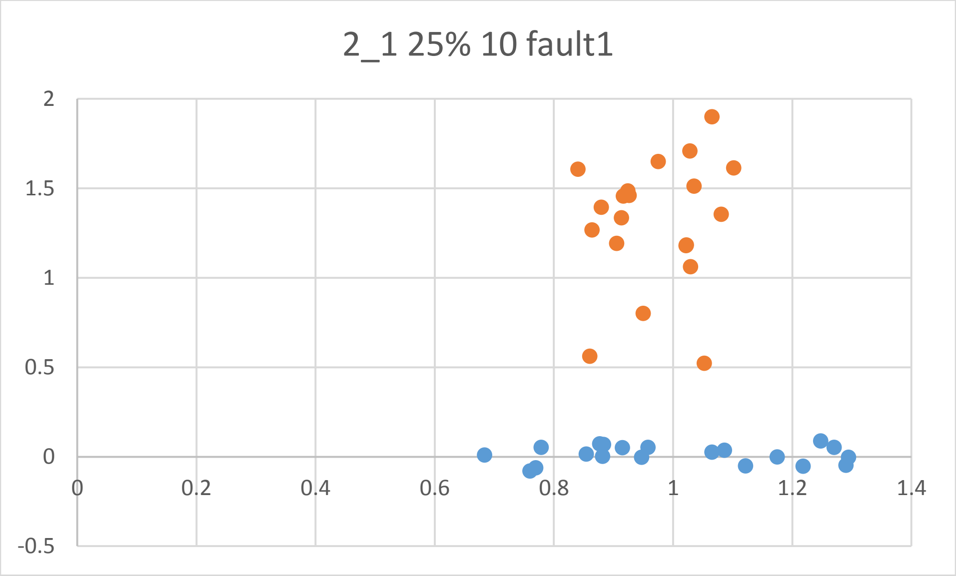

Figure 4.13 I_2/I_1 Plot for R_f=10, 25% distance

The response of relay A for reverse fault occurring at feeder B can be seen from figures 4.9 to 4.12 for different distances and different fault resistances. Here for downward fault, the plotting of I_2/I_1 for first 20 ms gives the points accumulated in first quadrant but slightly away from the previous case, whereas for upward fault, the points are spreaded along the x-axis.

Response of Relay A for forward and reverse faults at feeder D:

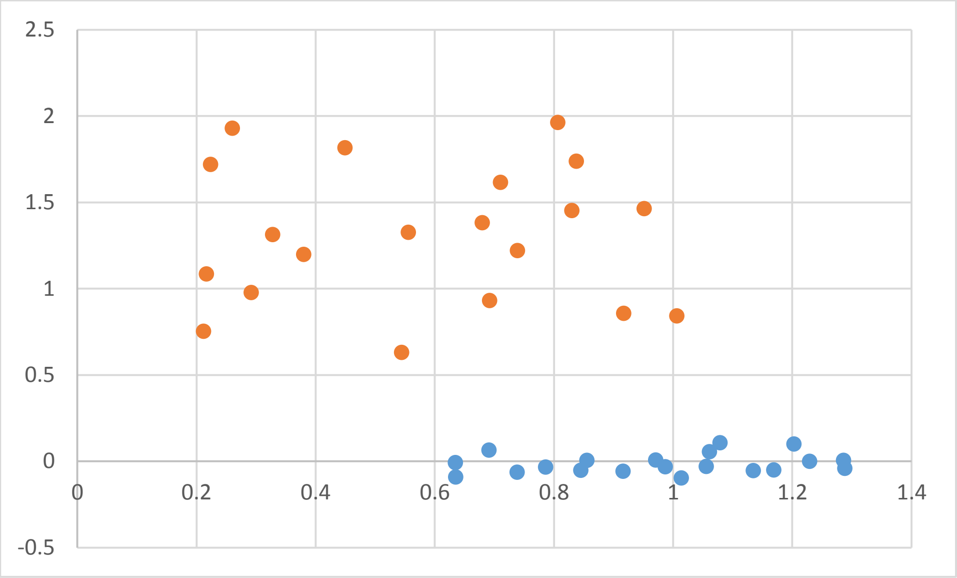

Figure 4.14 I_2/I_1 Plot for R_f=0, 50% distance

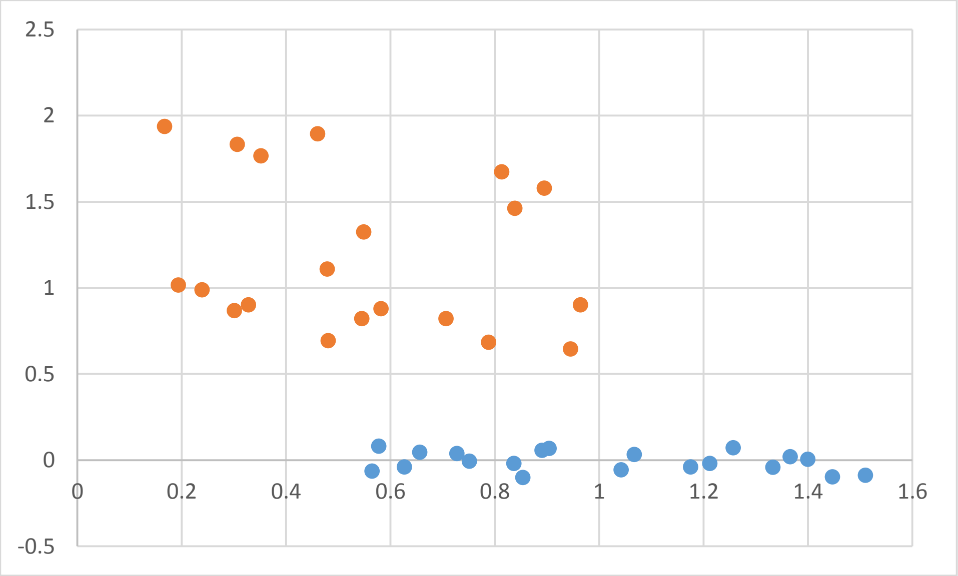

Figure 4.15 I_2/I_1 Plot for R_f=0, 50% distance

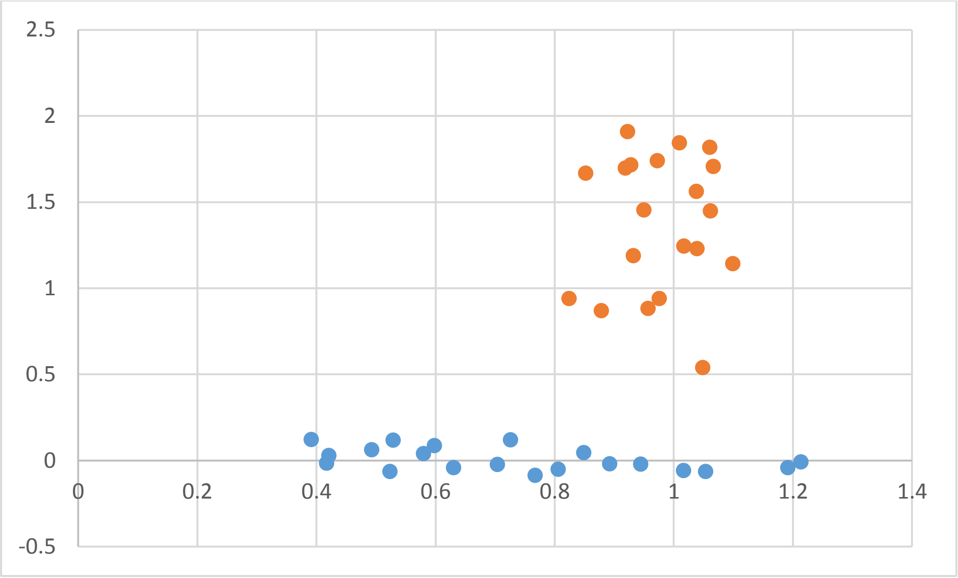

Figure 4.16 I_2/I_1 Plot for $R_f=0$, 25% distance

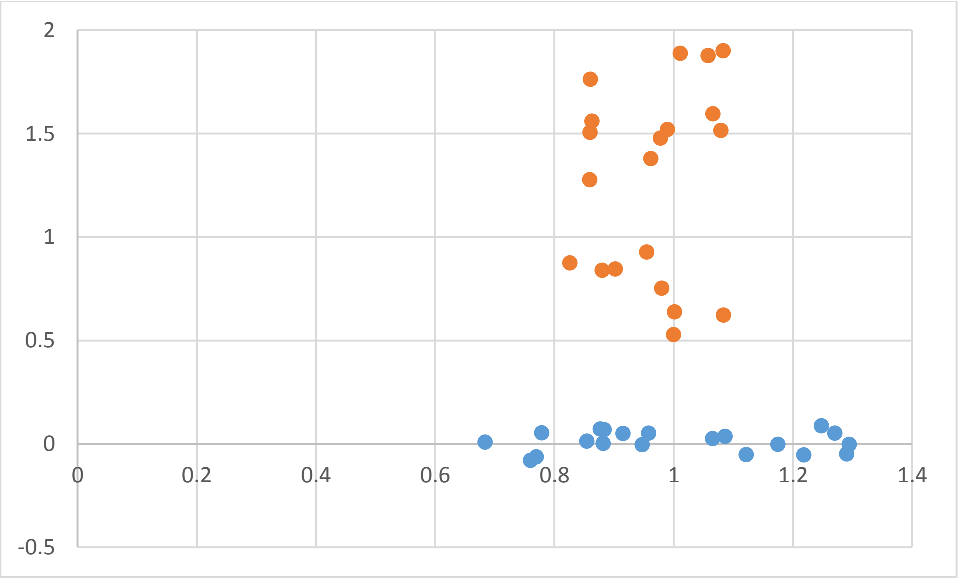

Figure 4.17 I_2/I_1 Plot for $R_f = 10$, 25% distance

The response of relay A for reverse fault occurring at feeder D, can be seen from figures 4.13 to 4.16 for different distances and also different fault resistances. Here for downward fault, the plotting of I_2/I_1 for first 20 ms gives the points accumulated in first quadrant but slightly away from the previous case, whereas for upward fault, the points are spread along the x-axis.

4.1.3 Algorithm based on combined sequence components for direction detection for ground faults [15]:

- Algorithm based on symmetrical components method are used to detect the fault Direction
- Positive sequence current is not taken for analysis
- The main drawback comes from the positive current that depends on the power flows on the feeders. These power flows depend both on loads power and power injected by the DG
- Hence negative and zero sequence are considered for fault analysis

  $\frac{I2}{I0}$ ratio is taken for detection of directionality

Plots of Real value vs imaginary value of $\frac{I2}{I0}$ has been used to detect if fault is in forward or reverse direction.

Results of above algorithm:

Line to Ground Fault:

Fault Resistance of 0 ohms:

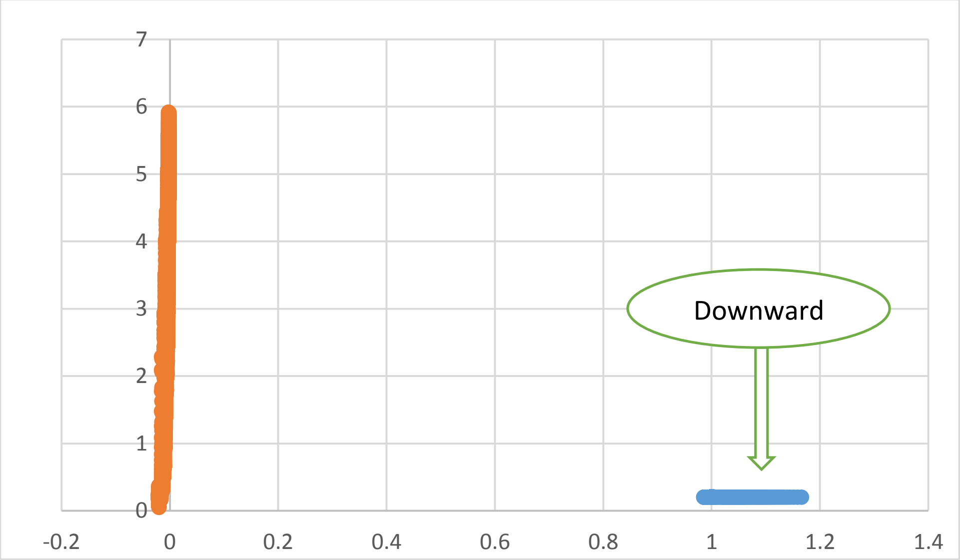

Figure 4.18 I_2/I_0 Plot for R_f=0

(i) Fault Resistance of 10 ohms

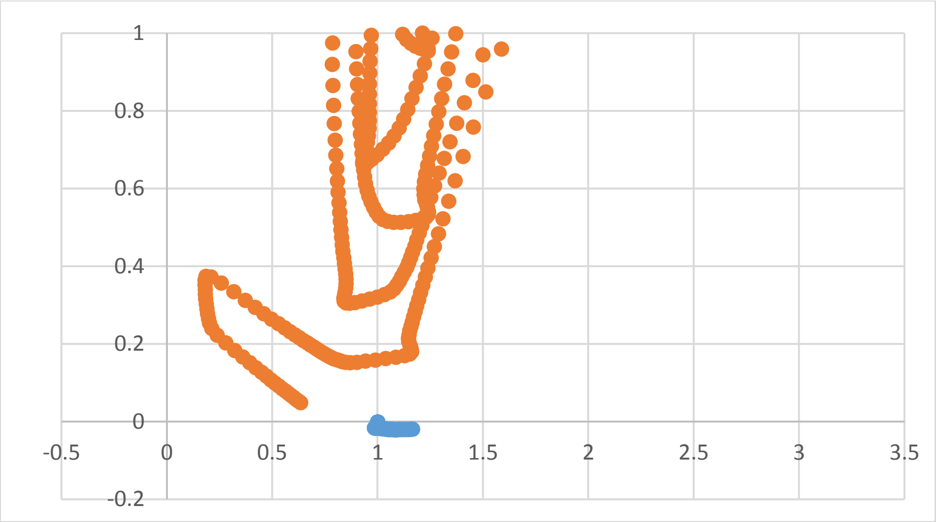

Figure 4.19 I_2/I_0 Plot for R_f=10

(ii) Fault Resistance of 50 ohms

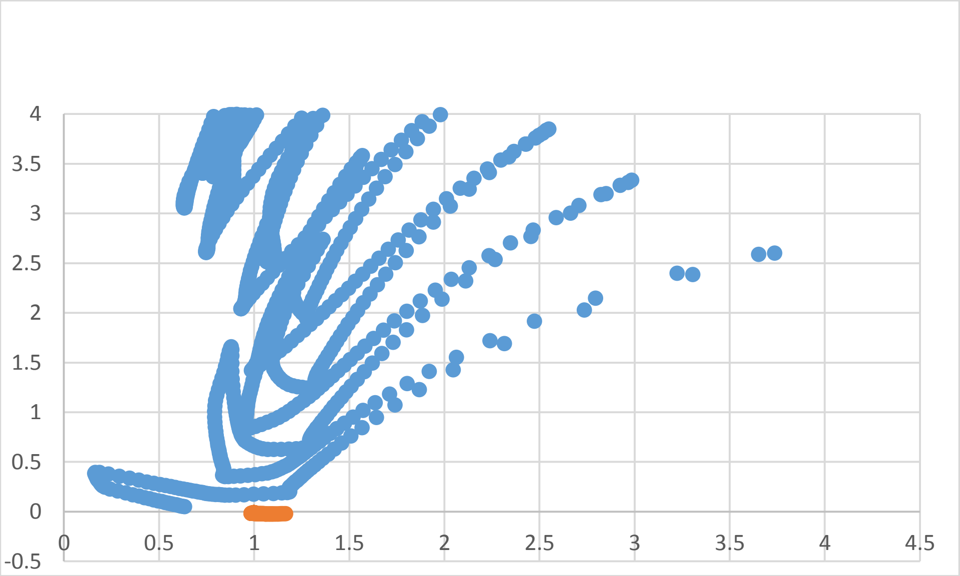

Figure 4.20 I_2/I_0 Plot for $R_f = 50$

From figures 4.18 to 4.20, the plot I_2/I_0 gives the points on x-axis for downward faults, whereas for upward faults the points are spreaded over the first quadrant in which there is no overlap between the both directions of faults. Hence detection of direction of fault can be done.

Conclusion:

- The simulated algorithm suppress voltage sensors in the directional relays for medium voltage networks with distributed generation. These algorithms only use the symmetrical components of the currents.
- This algorithm calculates the ratio of the negative and zero sequences of the currents at the fundamental frequency I_2/I_0. As the algorithms use the zero sequence, only phase-to-earth faults can be detected.
- The method was presented with only one distributed generator connected to one feeder. However, it can be adapted for several distributed generators connected to various feeders.

In the complex plan, areas can be defined to locate a fault upstream or downstream the detector. The borderlines between the "up" and "down" areas seen in the figures. As no voltage sensors are required reduces the cost of directionality block.

- The Ground fault direction detection has been done using negative & zero sequence post fault currents only.

The following are the problems associated with the sequence current based approach

(i) For the algorithm based on I_2/I_1, since the positive sequence current exists both before fault and during fault, the ratio depends upon the load current. If the load current varies the ratio varies during fault, hence this variation in load current leads to overlap of upward and downward regions. This leads to improper direction detection.

(ii) For the algorithm based on I_2/I_0, since the zero sequence current passes through neutral and fault path, it depends on the neutral impedance and also fault impedance. If these impedance values are high, it will reduce the zero sequence currents to a low values which finally affects the I_2/I_0 values. Hence, there is a chance to overlap of upward and downward regions.

Chapter 5

Proposed New Algorithm for Directional Detection

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. It also provides a review of performance of various existing directional relays. It specifies that there is a need to explore an alternative method for fault direction detection for use with overcurrent and earth fault protection applied to distribution systems.

To make the direction estimation of the fault to be more reliable, independent of the phase voltages and low detection cost, a novel algorithm based on pre-fault current slope and post fault current slope is proposed. In this chapter, we will discuss the implementation of proposed algorithm for two solar photovoltaic energy conversion systems connected to grid that are located at different places in distribution generation along with some local loads.

5.1 Proposed Algorithm

In this algorithm, the pre-fault current and post-fault current are the inputs required for the directional block. No phase voltages are involved in the algorithm. Assuming 5 ms time delay for the fault detection after the occurrence of fault, the samples after 5 ms of fault occurrence and samples of pre-fault cycle current with 20 ms delay from the instant of occurrence of fault are taken for analysis. Now the rate of change of these samples both pre-fault and post-fault currents are taken which are nothing but slopes of both the cycles at respected time instances. It is observed that the slope of pre-fault current before 20 ms of fault instant and slope of post-fault currents after 5 ms are same for downward faults and opposite for upward faults. Hence, product of these slopes is used for direction detection. When the product of slopes is positive, the fault location is in downward position and fault is upward direction if the product is negative.

5.2 Flow Chart of Proposed Algorithm

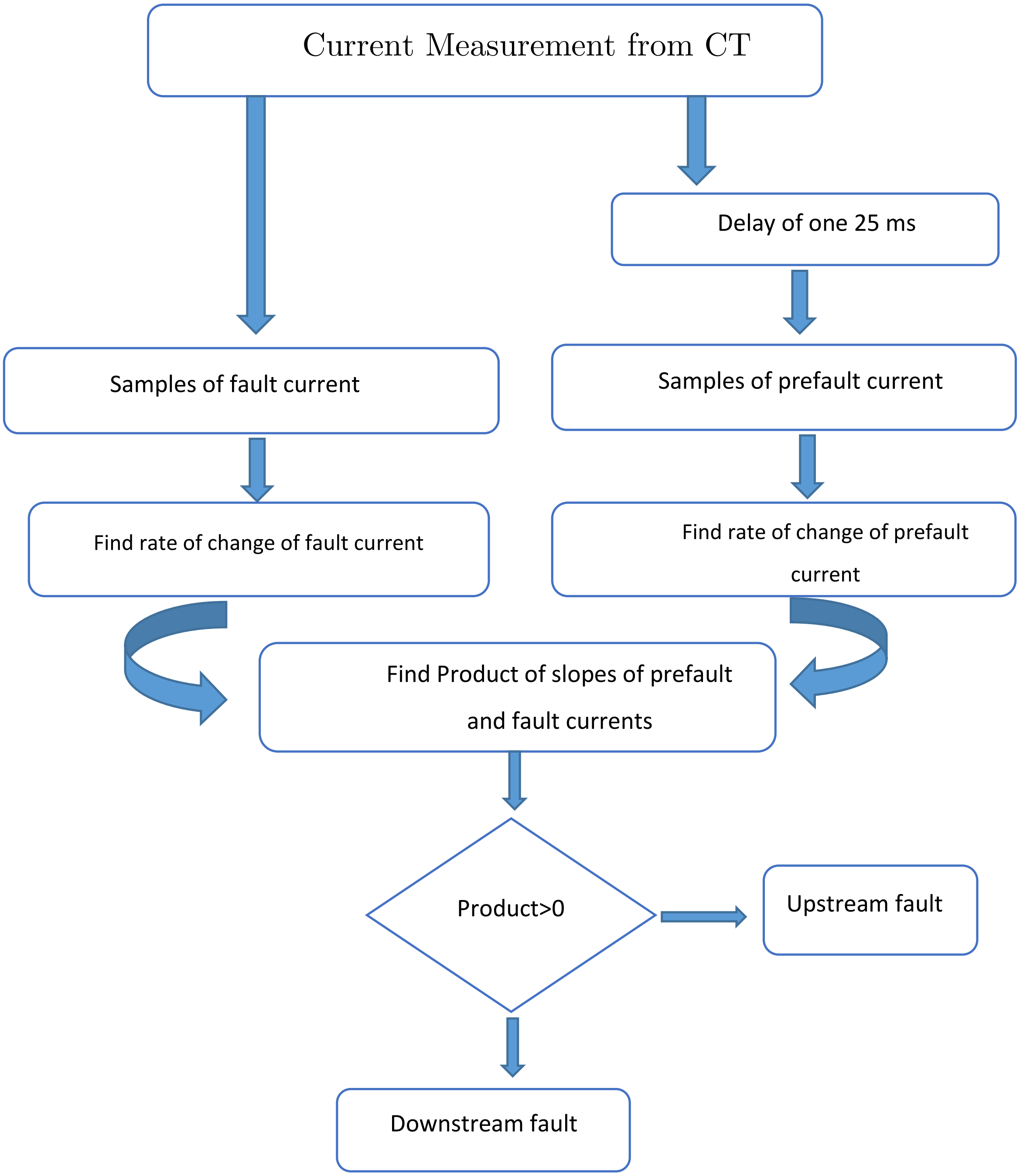

Figure 5.1: Direction Algorithm for upstream power flow

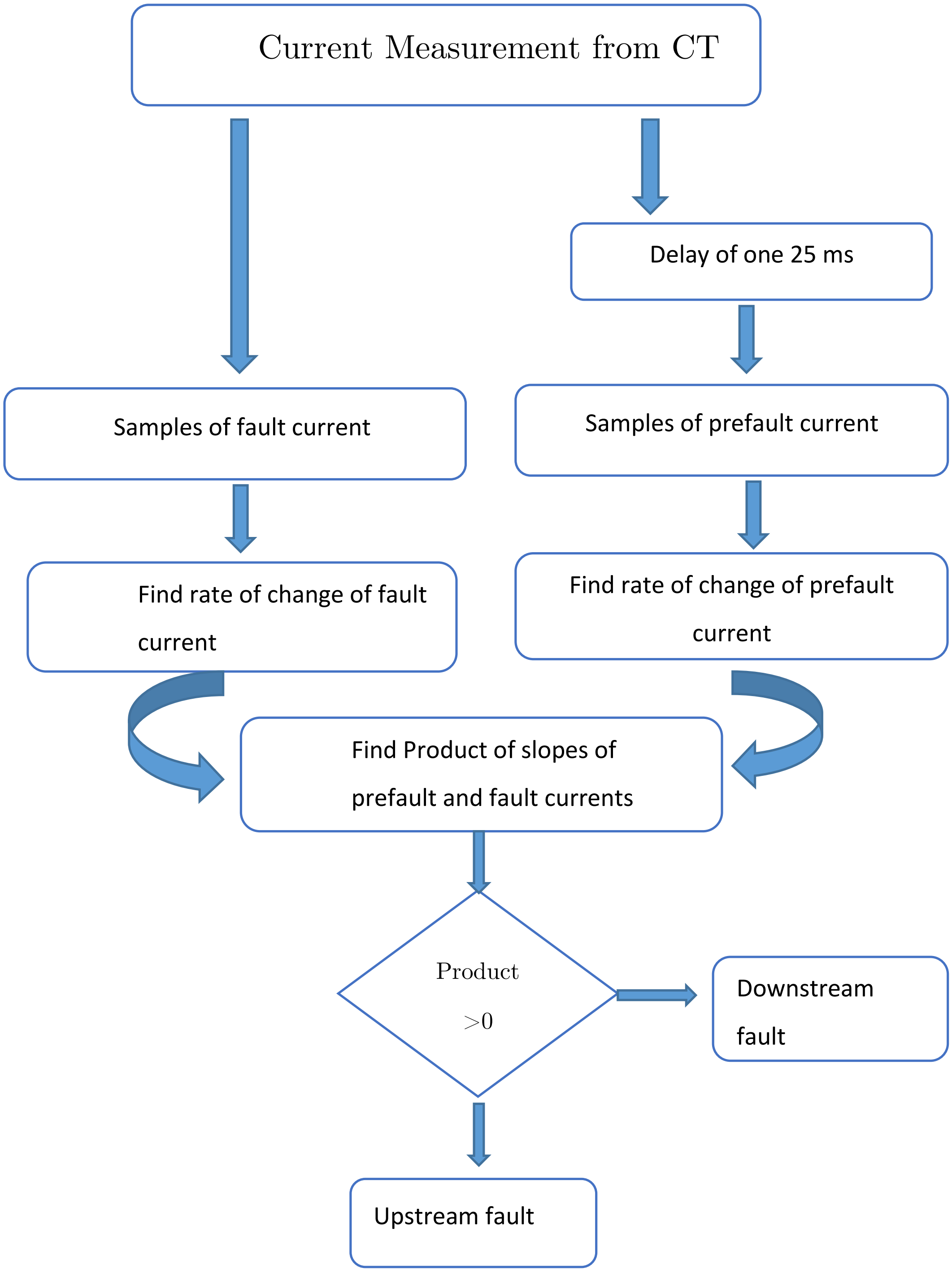

Figure 5.2: Direction Algorithm for downstream power flow

From Fig. 5.1, the current measurements from the current transformer is taken and stored for atleast for two consecutive cycles. Whenever the fault detector gives an output signal as existence of fault, there the calculation of the rate of change of instantaneous fault cycle and also rate of change stored prefault current cycle are multiplied. The fault detection time is taken as 5 ms. This slopes product value if it becomes positive, then it is upward fault else it becomes downward fault.

From Fig. 5.2, since the prefault power flow direction changes when compared to Fig. 5.1, only the last condition changes i.e., if the slopes product is positive then fault is downward else it is upward fault.

5.3 Observations from fault current waveforms

For prefault power flow in downward direction:

(i) Fault occurrence waveform when both slope and value is positive

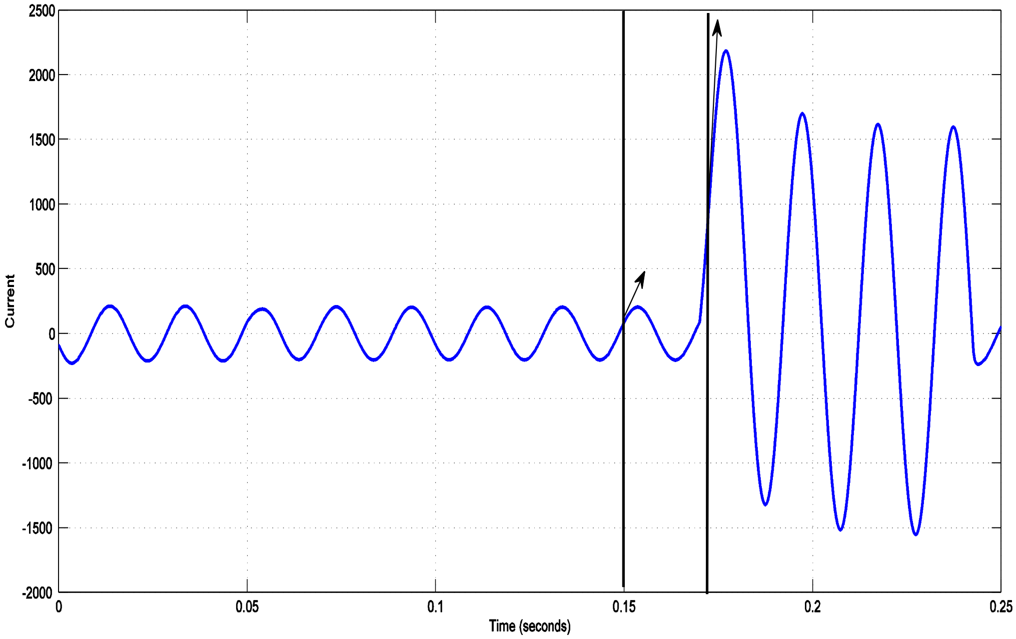

Figure 5.3: Fault in first quarter cycle

(ii) Fault occurrence waveform when slope is negative and value is positive

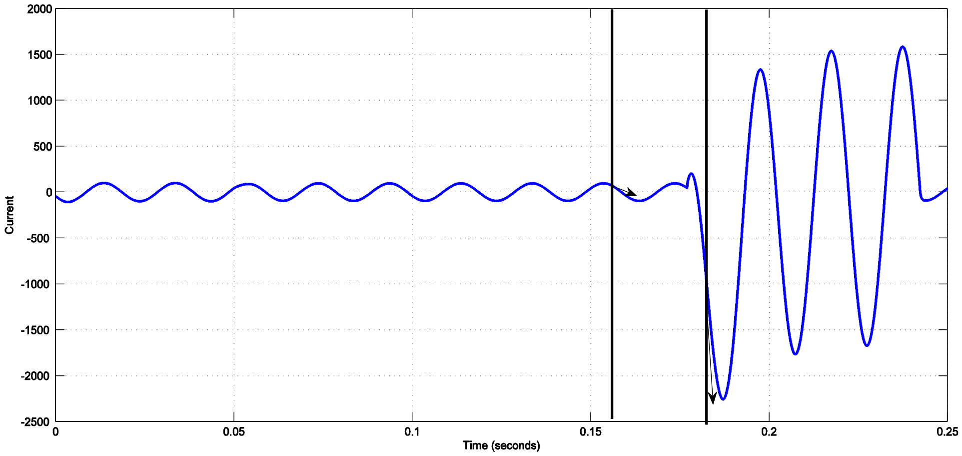

Figure 5.4: Fault in second quarter cycle

(iii) Fault occurrence waveform when slope is positive and value is negative

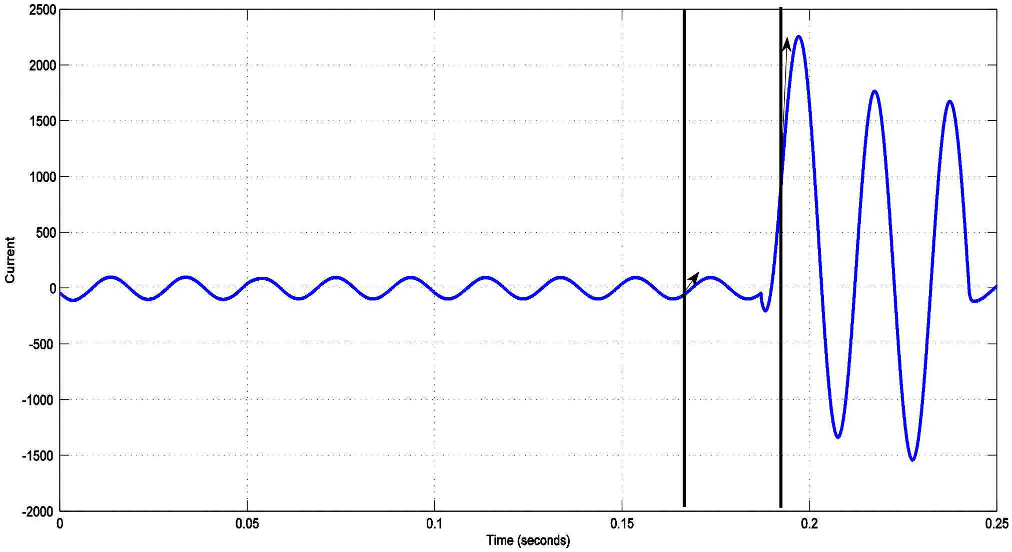

Figure 5.5: Fault in fourth quarter cycle

(iv) Fault occurrence waveform when both slope and value is negative

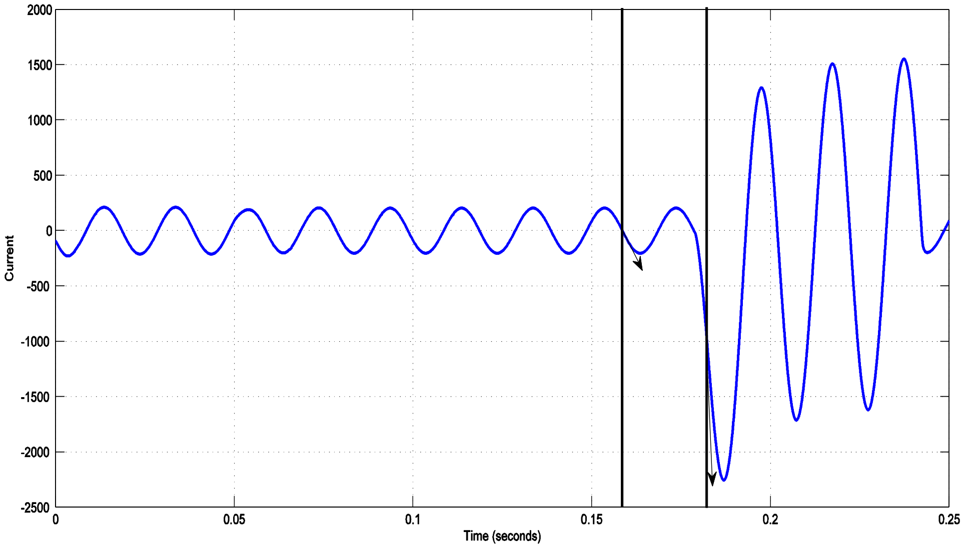

Figure 5.6: Fault in third quarter cycle

It can be seen that

(i) From the figure 5.3 in case (i), when the fault occurs at the instant when the slope is positive and the value of prefault current is also positive, i.e., in first quarter cycle, the fault current slope continue to be positive for more than 5 ms.

(ii) From the figure 5.4 in case (ii), when the slope is negative and value is positive, i.e. in second quarter cycle the slope becomes negative within 5 ms of occurrence of fault.

(iii) From the figure 5.5 in case (iii), when the slope is positive and value is negative, i.e., in third quarter cycle, the slope becomes negative for less than 4 ms and then becomes positive after 5ms of occurrence of fault.

(iv) From the figure 5.6 in case (iv), when both the slope is negative and value is negative, i.e., in fourth quarter cycle, the slope becomes negative even after 5ms of occurrence of fault.

For Prefault Power flow in upward direction:

(i) Fault occurrence waveform when both slope and value is positive

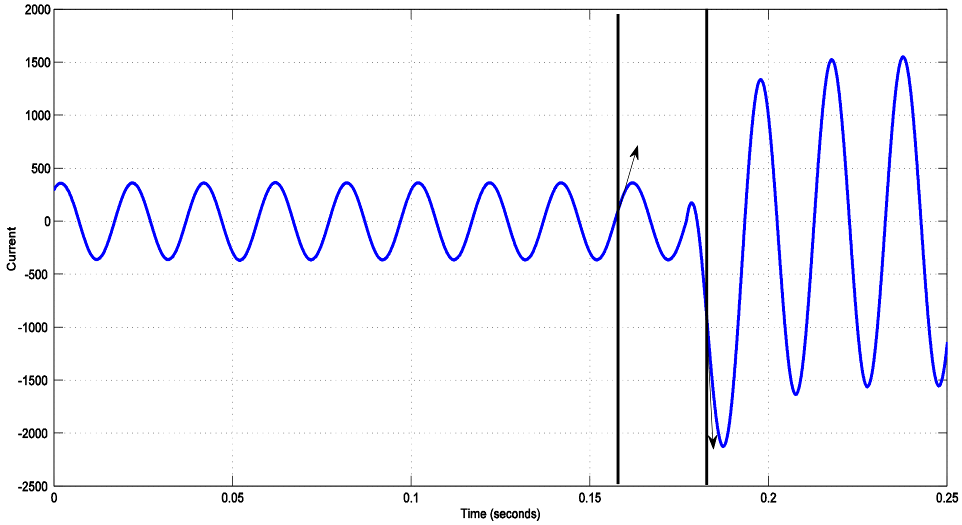

Figure 5.7: Fault in first quarter cycle

(ii) Fault occurrence waveform when slope is negative and value is positive

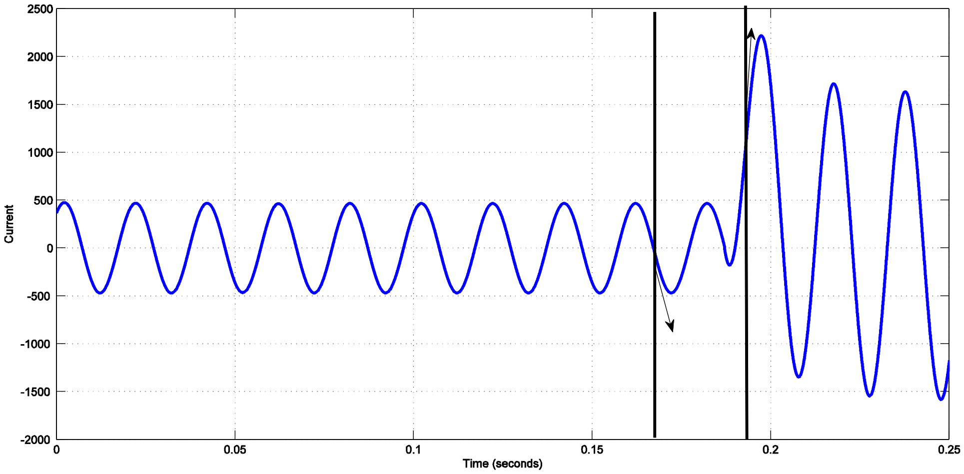

Figure 5.8: Fault in second quarter cycle

(iii) Fault occurrence waveform when slope is positive and value is negative

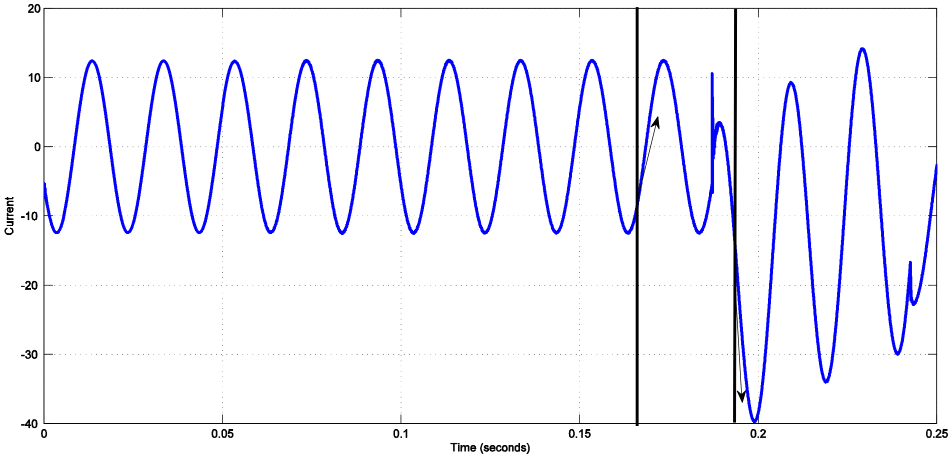

Figure 5.9: Fault in fourth quarter cycle

(iv) Fault occurrence waveform when both slope and value is negative

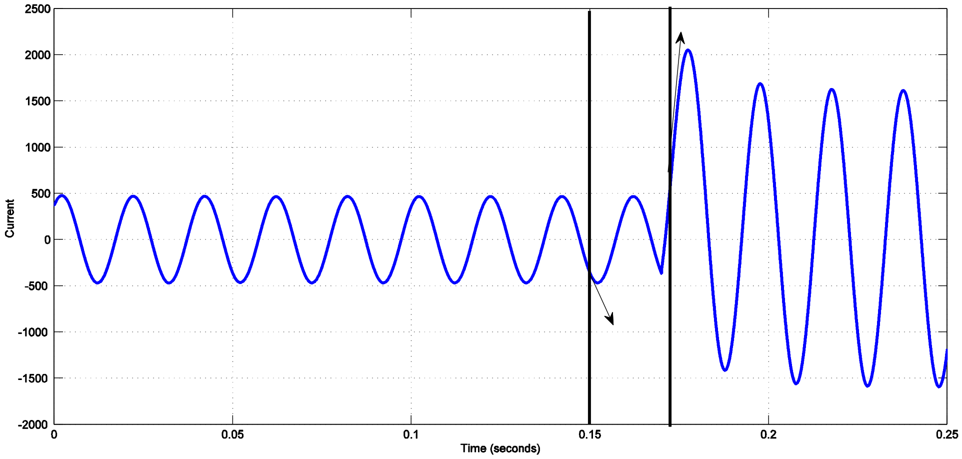

Figure 5.10: Fault in third quarter cycle

(i) From the figure 5.7 , when the fault occurs at the instant when the slope is positive and the value of prefault current is also positive, i.e., in first quarter cycle, the fault current slope becomes negative within 5 ms.

(ii) From the figure 5.8, when the slope is negative and value is positive, i.e. in second quarter cycle the slope becomes negative for less than 2 ms and becomes positive after 2 ms of occurrence of fault.

(iii) From the figure 5.9, when the slope is positive and value is negative, i.e., in third quarter cycle, the slope becomes positive for less than 4 ms and then becomes negative after 4ms of occurrence of fault.

(iv) From the figure 5.10, when both the slope is negative and value is negative, i.e., in fourth quarter cycle, the slope becomes positive for more than 5ms of occurrence of fault.

It can be seen that, when we compare the above waveforms with the waveforms with prefault power flow in downward direction, we can conclude that slopes are just opposite. Hence, by comparing prefault power direction at the relay location, with the above mention algorithm we can conclude fault direction.

Fault at Feeder B during first quarter cycle:

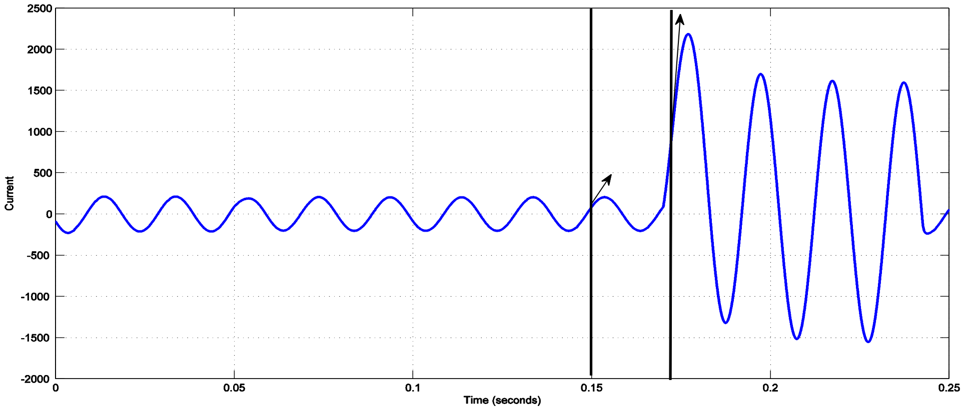

Fig 5.11: Relay A response

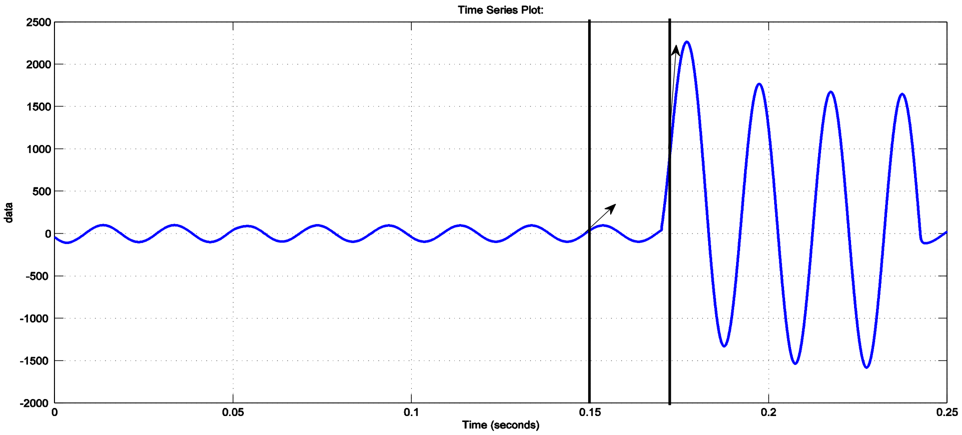

Fig 5.12: Relay B response

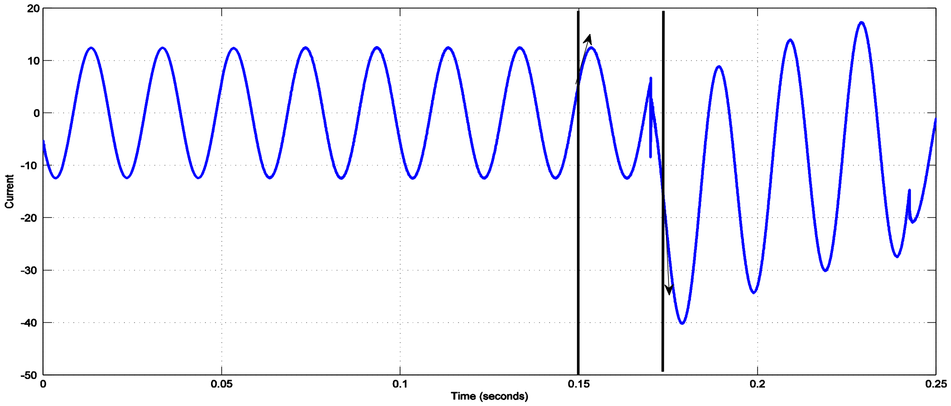

Fig 5.13: Relay D response

Fault at Feeder B during second quarter cycle:

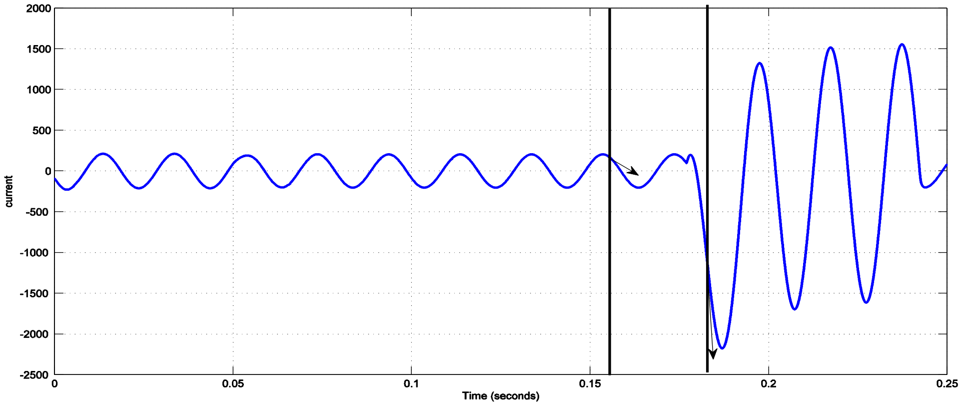

Fig 5.14: Relay A response

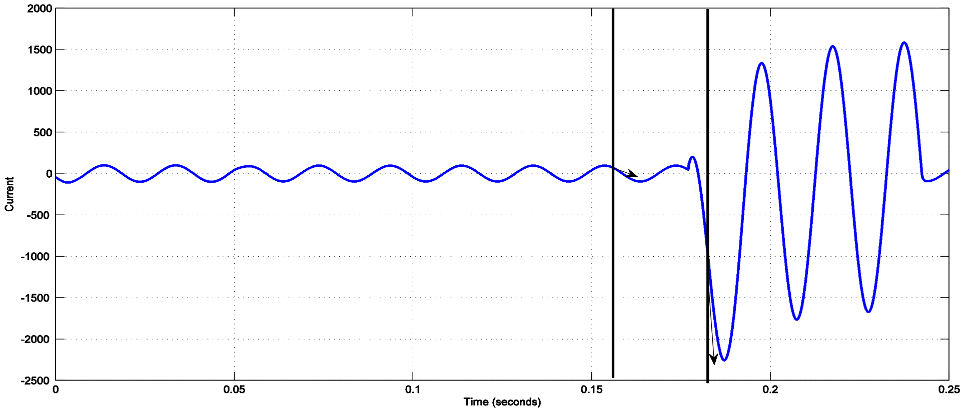

Fig 5.15: Relay B response

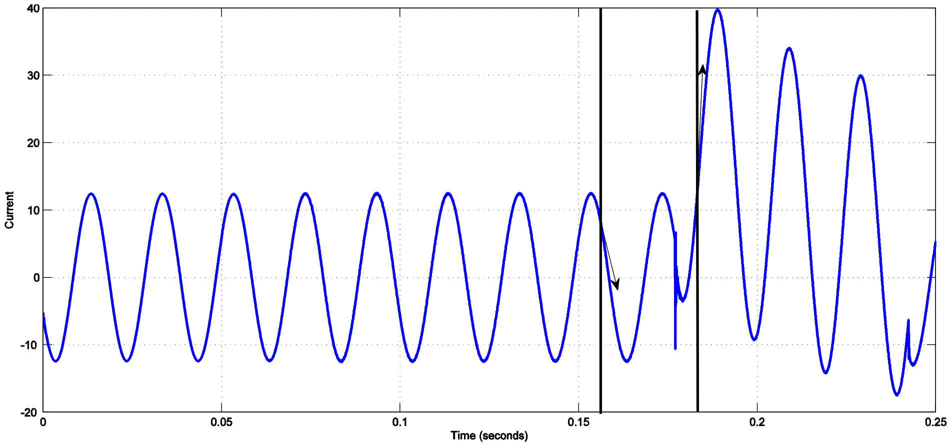

Fig 5.16: Relay D response

Fault at Feeder B during third quarter cycle:

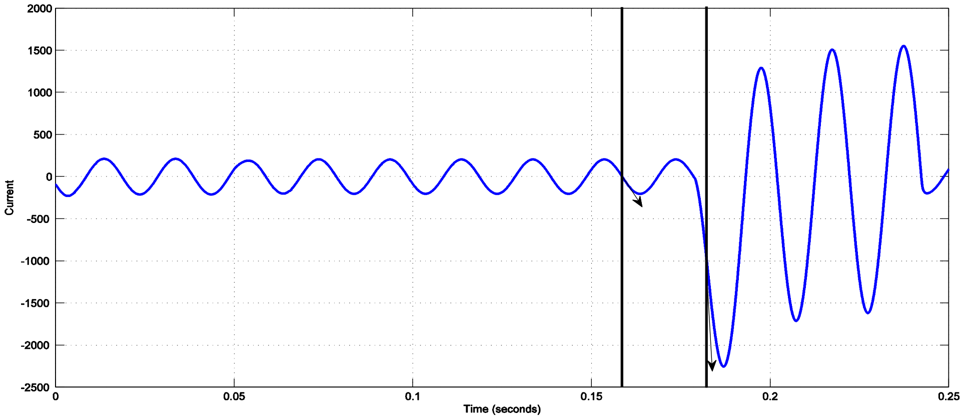

Fig 5.17: Relay A response

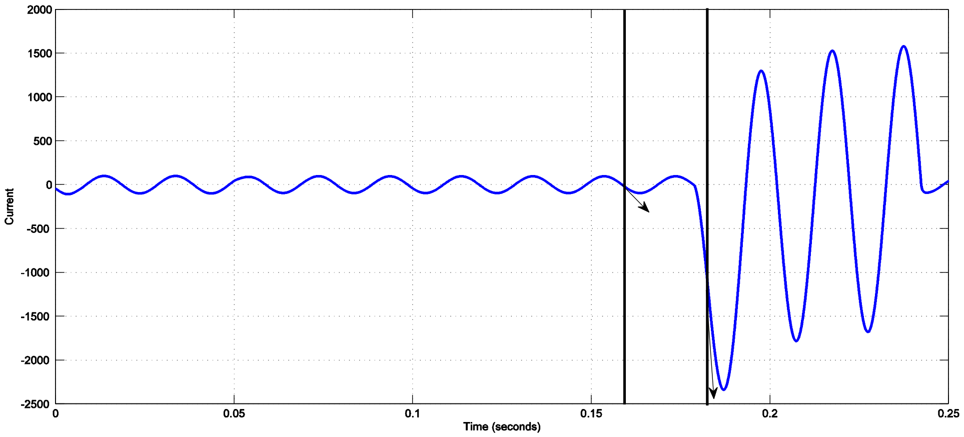

Fig 5.18: Relay B response

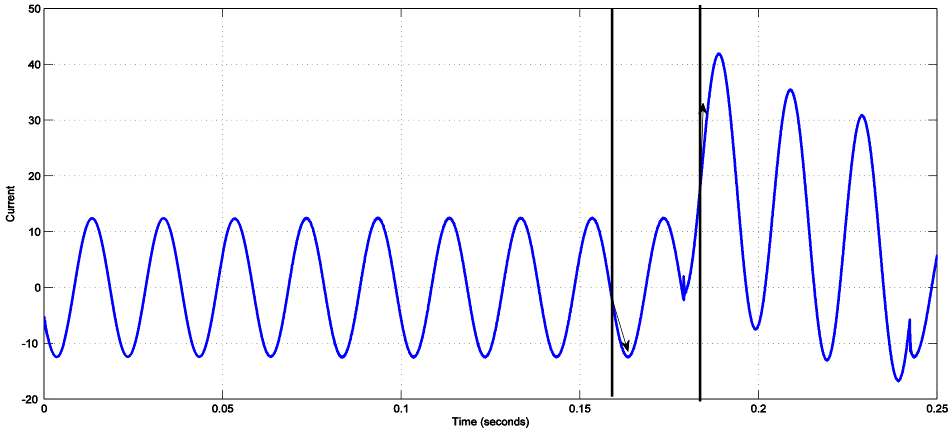

Fig 5.19: Relay D response

Fault at Feeder B during fourth quarter cycle:

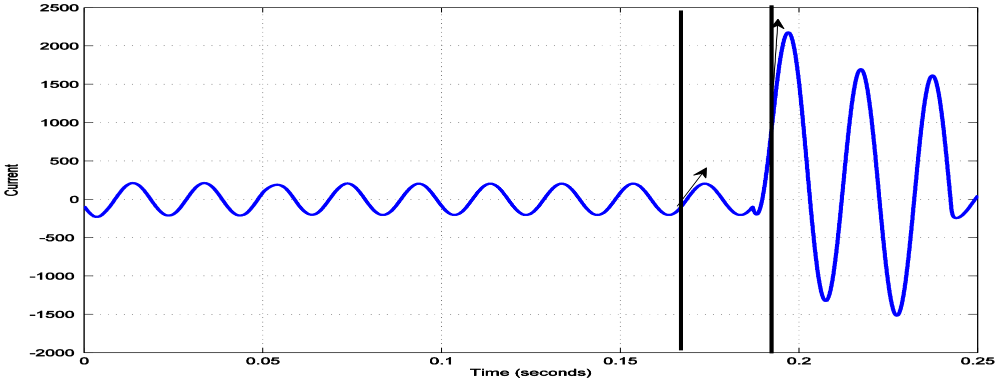

Fig 5.20: Relay A response

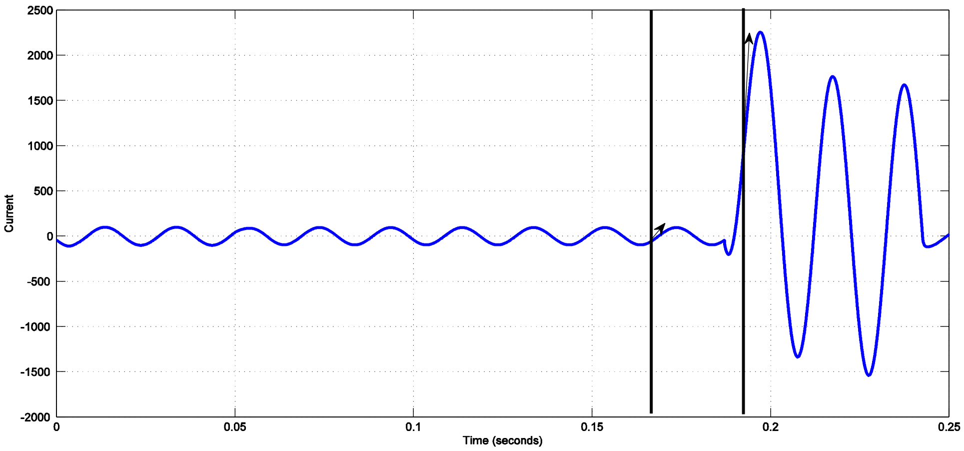

Fig 5.21: Relay B response

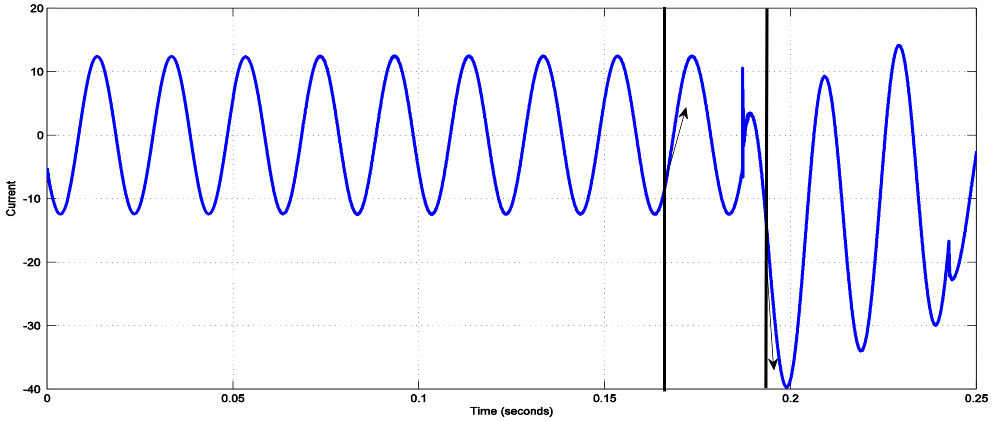

Fig 5.22: Relay D response

For Reverse Power Flow:

Fault at Feeder B during fourth quarter cycle:

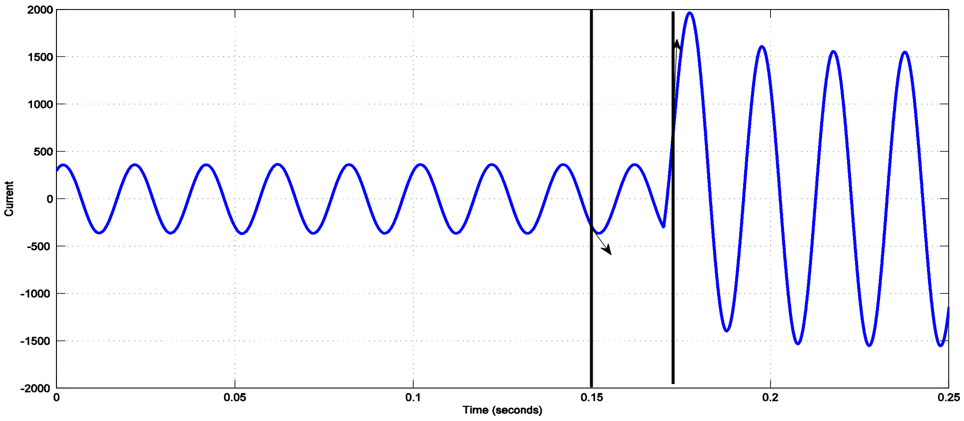

Fig 5.23: Relay A response

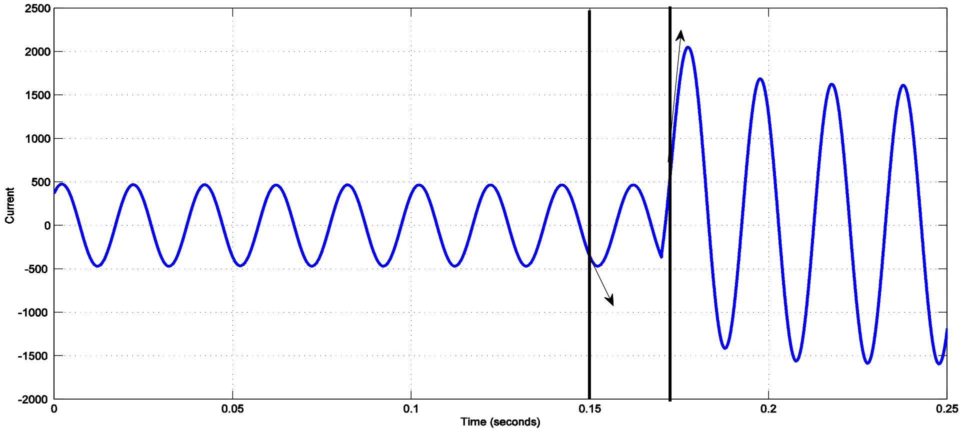

Fig 5.24: Relay B response

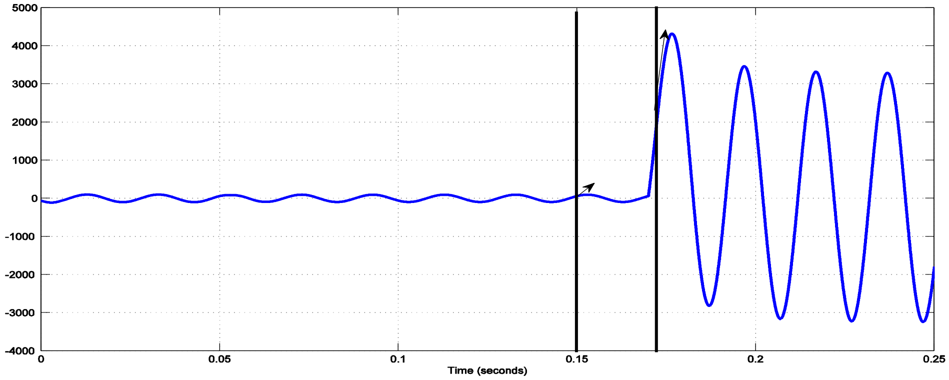

Fig 5.25: Relay D response

Fault at Feeder B during first quarter cycle:

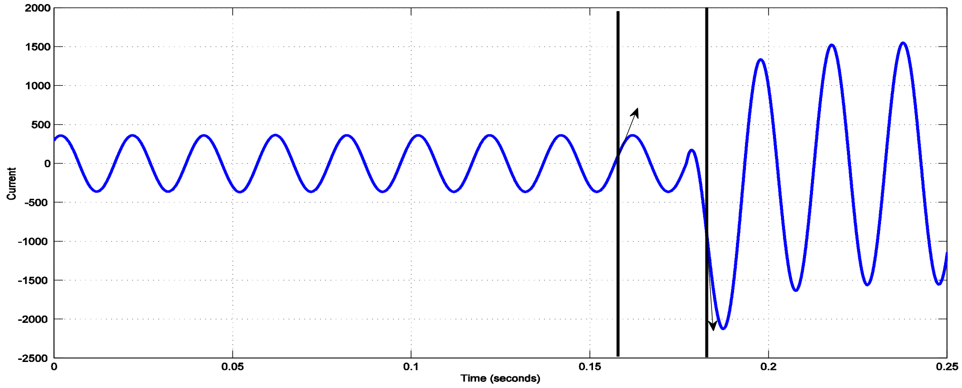

Fig 5.26: Relay A response

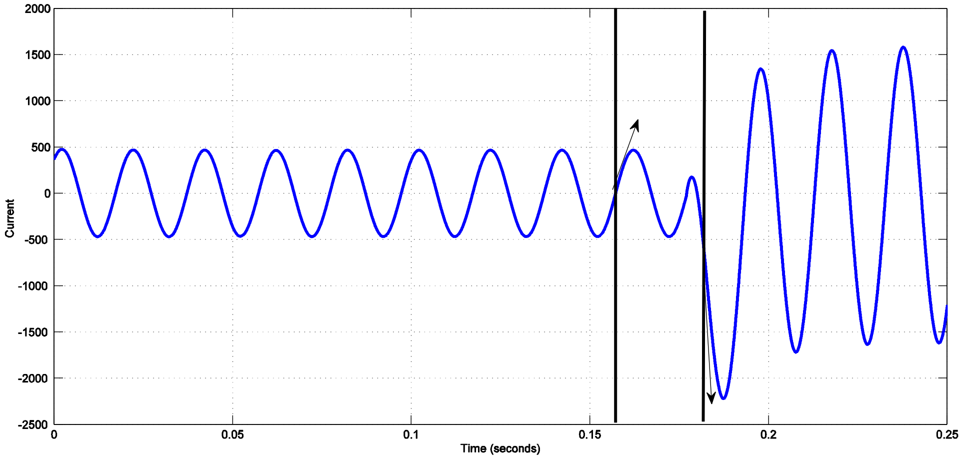

Fig 5.27: Relay B response

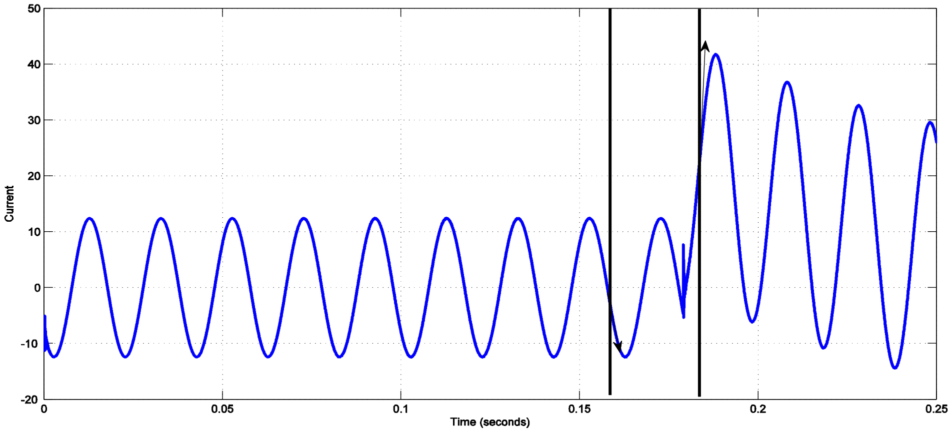

Fig 5.28: Relay D response

Fault at feeder B during first quarter cycle:

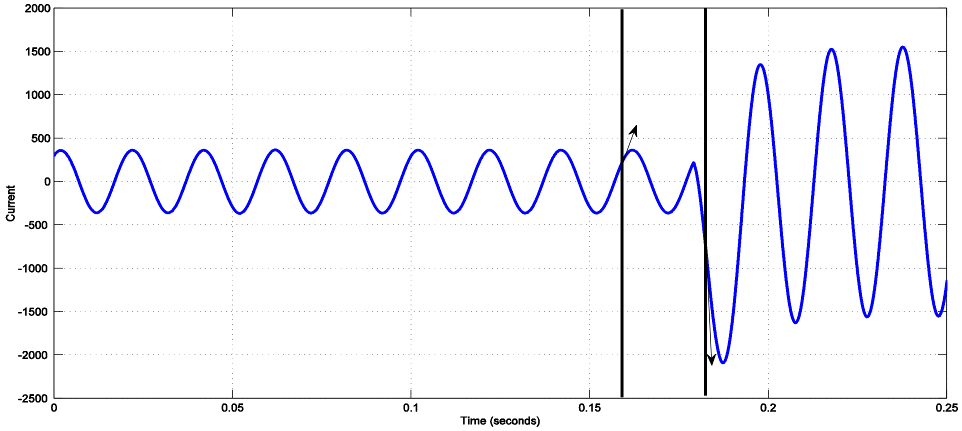

Fig 5.29: Relay A response

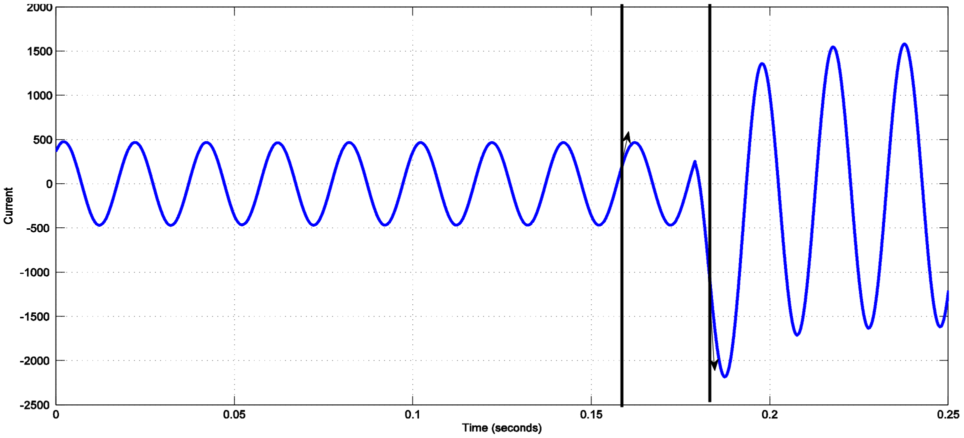

Fig 5.30: Relay B response

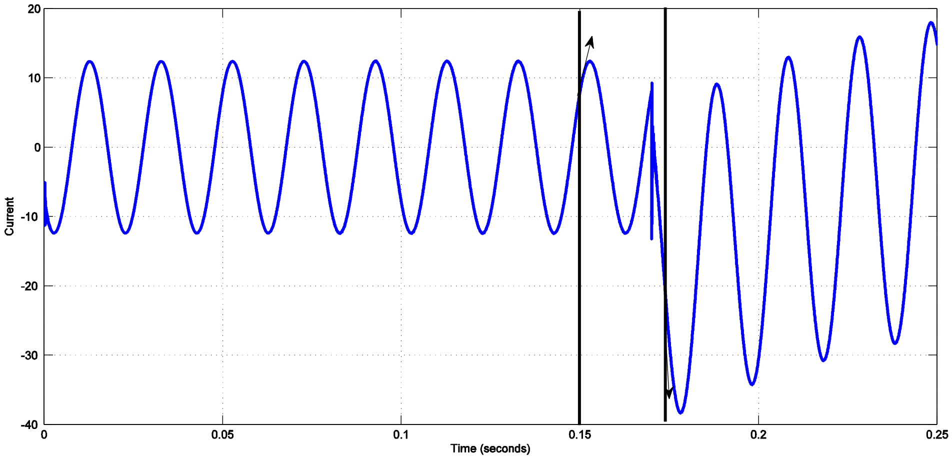

Fig 5.31: Relay D response

Fault at feeder B during third quarter cycle:

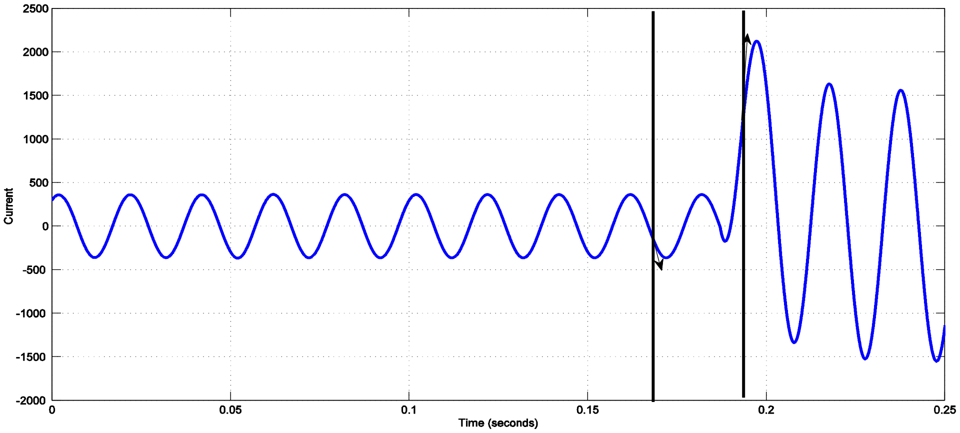

Fig 5.32: Relay A response

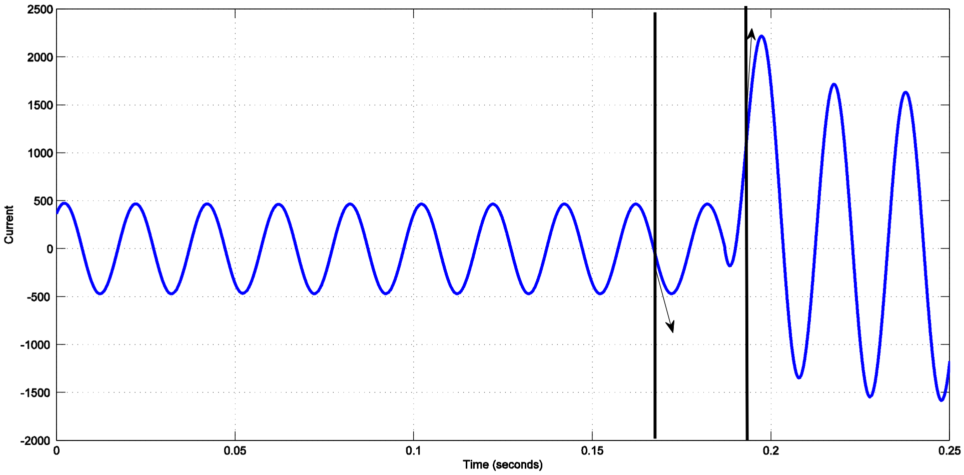

Fig 5.33: Relay B response

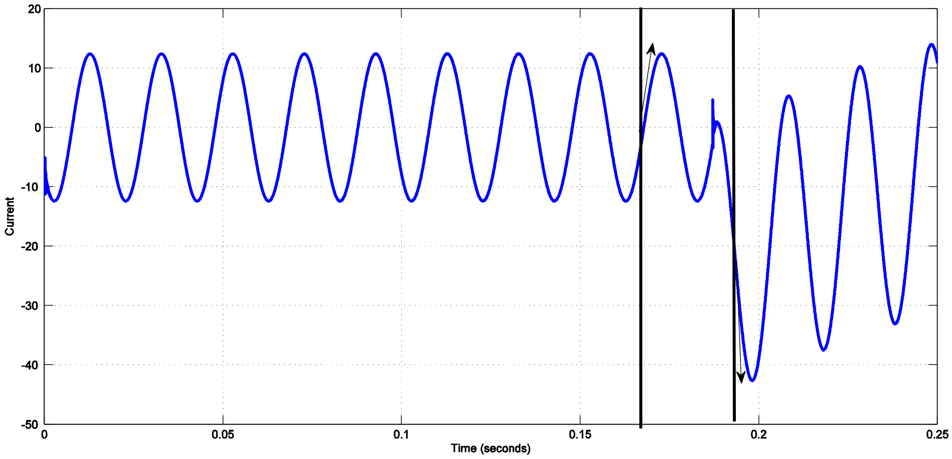

Fig 5.34: Relay D response

Observations:

From figures 5.12 to 5.22, for a fault on the feeder B, the product of the slopes of the relay A and relay B for prefault downward power flow is positive whereas for prefault upward power flow, from figures 5.23 to 5.34 the product of the slopes of the relay A and relay B is negative.

Also from figures 5.12 to 5.22 the response of relay D is just opposite to the relay A and B i.e., product of slopes is negative and from figures 5.23 to 5.34, its response is same as A and B, i.e., product of slopes is negative.

Hence, it is concluded that, the direction of the fault occurrence is identified by finding the product of the slopes of currents and prefault power direction. Here, the product of slopes has been changed for relay A and B but not for relay C because there is no change in direction of power flow in both cases of upward and downward power flow.

5.4 Results and Discussions

Relays Response at different fault locations:

Table 5.1: For prefault downward Power flow

Fault Location	Relay A	Relay B	Relay C	Relay D
Feeder A	Downward (-1)	Downward (-1)	0	Downward (-1)
Feeder B	Upward (1)	Upward (1)	0	Downward (-1)
Feeder C	Upward (1)	Downward (-1)	Upward (1)	Downward (-1)
Feeder D	Upward (1)	Downward (-1)	0	Upward (1)

Table 5.2: For prefault upward Power flow

Fault Location	Relay A	Relay B	Relay C	Relay D
Feeder A	Downward (1)	Downward (1)	0	Downward (1)
Feeder B	Upward (-1)	Upward (-1)	0	Downward (1)
Feeder C	Upward (-1)	Downward (1)	Upward (-1)	Downward (1)
Feeder D	Upward (-1)	Downward (1)	0	Upward (-1)

The Table 5.1 shows the response of all four relays for prefault downward power flow located along four feeders as shown in Fig. 3.3. If fault is located at feeder A, then the three relays A, B and C shows the output value as minus one, which means the fault is in the upward direction. If fault is in feeder B, the two relays A and B shows the output value as one, which means the fault has occurred in downward direction whereas the relay C outputs minus one, which means fault is in downward direction. Similar case can be explained for fault in feeder D. If fault has occurred in feeder C, then the output of relay A and C gives minus one, which means fault is in downward direction and the other relays B and D outputs one, which indicates upward fault.

The Table 5.2 shows the response of all four relays for prefault upward power flow located along four feeders as shown in Fig. 3.3. If fault is located at feeder A, then the three relays A, B and C shows the output value as one, which means the fault is in the upward direction. If fault is in feeder B, the two relays A and B shows the output value as minus one, which means the fault has occurred in downward direction whereas the relay C outputs one, which means fault is in downward direction. Similar case can be explained for fault in feeder D. If fault has occurred in feeder C, then the output of relay A and C gives one, which means fault is in downward direction and the other relays B and D outputs minus one, which indicates an upward fault.

Chapter 6

Conclusions and Future work

Conclusions:

The major focus of this thesis has been to evolve a new directional overcurrent-relaying algorithm for grid connected solar photovoltaic energy conversion system with Maximum power point tracking. The main objective was to study, model and simulate a solar energy conversion system with different kinds of faults and to develop an algorithm based on current values only by analyzing the fault current waveforms. A grid-interfaced solar PV energy conversion system was modelled and simulated. The system was implemented without battery at the DC-link of the grid-side converter. An incremental conductance based maximum power point tracking algorithm was implemented and its operation was found to be satisfactory under different operating conditions. This system was integrated with the grid using current controller on the grid side.

The fault direction algorithm has been developed using the slopes concept of both prefault and fault current waveforms. This algorithm gives information about fault direction for all types of faults that is independent of type of fault and fault impedance whereas the sequence current based algorithm, I_2/I_1 is dependent on the positive sequence current, which is nothing but a load current. Since the load current is variable, this algorithm fails during large variation of load. The proposed algorithm does not depends on the load current, which becomes an advantage. The second algorithm, I_2/I_0 is dependent on the neutral impedance i.e., if neutral impedance is high then the zero sequence currents are vey low which leads to the failure of this algorithm. In this proposed algorithm, the direction detection technique is independent of neutral impedance. Also, in this proposed algorithm either there is no need to eliminate DC component or sequence components which makes the fault direction detection task easier.

Future Work:

- Implementations of this proposed algorithm for different DER's for both grid connected and standalone mode.
- One of the following need to be implemented.
  - (i) If Slope value is nearly zero, then previous time step slope should be taken so that more reliable direction detection could be detected during instant of peak fault occurrence.
  - (ii) Zero Crossing detector should be used, so that if fault occurred at approximately 5ms after zero crossing, then the slope calculation can be done by taking present and previous to the previous sample instead of taking present and just previous samples.
- The proposed algorithm should be implemented for different operating modes of microgrid like feeder flow control (FFC) and unit output power control mode (UPC).
- Algorithm depends on prefault power direction i.e., steady state power flow direction. Hence, information about dependency on prefault power direction should be considered from some measurements like load flow delta values available in the feeder so that extra measurements block could be made redundant. Method for identifying the pre-fault power flow direction with only current information can be worked out.
- Generation and load variation should be taken into account and algorithm should be tested for adaptive protection.

References

[1] Vishwakarma, D.N., Moravej, Zahra, “ANN based directional overcurrent relay,” in IEEE/PES Transmission and Distribution Conference and Exposition, Atlanta, GA, pp. 1-5, Nov. 2001.

[2] Nyun-, Thesis on Poly phase Directional Detection for Power System Protection.

[3] K. S. Prakash, O. P. Malik, and G. S. Hope, “Amplitude comparator based algorithm for directional comparison protection of transmission lines,” IEEE Trans. Power Del., vol. 4, no. 4, pp. 2032–2041, Oct. 1989

[4] J. Zhao, Y. Chen, and P. Crossley, “Design and evaluation of a directional relay for use within a distribution network restoration scheme,” Proc. IEEE Power Engineering Society Winter Meeting, vol. 4, pp. 2374–2378, 2000.

[5] Pukar Mahat, Zhe Chen, Birgitte Bak-Jensen, and Claus Leth Bak, “A Simple Adaptive Overcurrent Protection of Distribution Systems with Distributed Generation,” IEEE Trans. Smart grid, vol. 2, no. 3, Sept.2011.

[6] A. T. Johns, “New ultra high speed directional comparison technique for the protection of EHV transmission lines,” Proc. Inst. Elect. Eng., Gen., Transmission, Distribution, vol. 127, pp. 228–239, 1980

[7] EL Khattam W., Sidhu T.S.: ‘Restoration of directional overcurrent relay coordination in distributed generation systems utilizing fault current limiter’, IEEE Trans. Power Deliv., pp. 576–585, 2008

[8] N. Zhang, H. Song, and M. Kezunovic, “Transient based relay testing: A new scope and methodology,” presented at the 13th IEEE Mediterranean Electrotechnical Conf., Torremolinos, Spain, May 2006.

[9] Trung Dung Le; Petit, M. "Directional relays without voltage sensors for distribution grids: Optimal boundaries for fault direction estimation", PowerTech, IEEE Grenoble, pp. 1-6, 2013

[10] E. Trishan, and P.L. Chapman, “Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques,” IEEE Transactions on Energy Conversion 22, no. 2 pp. 439 – 449, 2007 2007

[11] A. Safari and S. Mekhilef, “Incremental conductance mppt method for pv systems,” in 2011 24th Canadian Conference on Electrical and Computer Engineering (CCECE), pp. 345 – 347, 2011.

[12] M. G. Villalva, J. R. Gazoli, and E. R. Filho, “Modeling and circuit-based simulation of photovoltaic arrays,” Power Electronics Conference, COBEP ’09, Brazilian, pp. 1244-1254, 2009.

[13] D. Peftitsis, G. Adamidis, and A. Balouktsis, “A new MPPT method for photovoltaic generation systems based on hill climbing algorithm,” in Proc. ICEM 2008 , pp. 1–5, Sep. 2008.

[14] J. Horak, “Directional overcurrent relaying (67) concepts,” in Proc. IEEE 59th Annul. Protect. Relay Eng. Conf., 2006, p.13.

[15] M. Petit, X. Le Pivert, L. Garcia-Santander, 2010, “Directional relays without voltage sensors for distribution networks with distributed generation: Use of symmetrical components,” Electric Power Systems Research, vol. 80, 1222-1228

[16] Jalilian, M. Tarafdar Hagh and S. M. Hashemi, “An Innovative Directional Relaying Scheme Based on Post fault Current,” IEEE Transactions on Power Delivery, vol No. 29, pp. 2640-2647, Nov.2009.

[17] A. K. Pradhan, A. Routray, and S. Madhan Gudipalli, “Fault Direction Estimation in Radial Distribution System Using Phase Change in Sequence Current,” IEEE Trans. Power Delivery, Vol. 22, pp. 2065-2071, Nov. 2009

[18] John Horak,Member and Walt Babic, IEEE Basler Electric, “Directional Overcurrent Relaying (67) Concepts”, in 59th annual conference for Protective Relay Engineers, pp. 13, Nov. 2006

[19] Zimmerman and D. Costello, “Fundamentals and improvements for directional relays,” in Proc. IEEE 63rd Annul. Conf. Protect. Relay Eng., pp. 1–12, 2010.

[20] H. Teng, “Unsymmetrical short-circuit fault analysis for weakly meshed distribution systems,” IEEE Trans. Power Syst., vol. 25, no.1, pp. 96–105, Feb. 2010.

[21] M. G. Villalva, J. R. Gazoli, and E. R. Filho, “Modeling and circuit-based simulation of photovoltaic arrays,” Power Electronics Conference, COBEP ’09, Brazilian, pp. 1244-1254, 2009.

[22] Blackburn, J.L. 1993, Symmetrical Components for Power Systems Engineering, Marcel Dekker Inc. New York.

[23] J.Holmes, J. M. (2004). Protection of Electricity Distribution Networks. United Kingdom: Power and Energy Series 47

[24] E. Trishan, and P. L. Chapman, “Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques,” IEEE Transactions on Energy Conversion 22, no. 2 (June 2007): 439 – 449

[25] J. Horak, “Directional overcurrent relaying (67) concepts,” in Proc. IEEE 59th Annul. Protect. Relay Eng. Conf., 2006, p.13.

[26] F. Liu, S. Duan, F. Liu, B. Liu, and Y. Kang, "A Variable Step Size INC MPPT Method for PV Systems," IEEE Transactions on Industrial Electronics 55, no. 7 (July 2008): 2622-2628

[27] Paul C. Krause, Oleg Wasynczuk, and Scott D. Sudhoff, Analysis of Electric Machinery and Drive Systems, IEEE Press Power Engineering Series, 2nd ed. reprint, 2013.

[28] T. S. Sidhu, et al "Design, Implementation and testing of an Artificial Neural Network-based Fault Direction Discriminator for Protecting Transmission Lines", IEEE Trans. On Power Delivery, Vol. 10, No. 2, April. 1995, pp.1002-1011

[29] S. Bin, D. Xinzhou, S. Yuanzhang, Z. Q. Bo, and H. Jiali,"New principle of high-speed directional relay," in Proc. IEEE Power Engineering Society Summer Meeting, vol. 1, 2002, pp. 387–392

[30] Murtaza, A.F.; Sher, H.A.; Chiaberge, M.; Boero, D.; De Giuseppe, M.; Addoweesh, K.E. "Optimization of the perturb and observe maximum power point tracker for a distributed photovoltaic system", Multi Topic Conference (INMIC), 2013 16th International, On page: 77 – 82

[31] J. Upendar, C. P. Gupta, G. K. Singh, and G. Ramakrishna, "PSO and ANN-based fault classification for protective relaying," Inst. Eng. Technol. Gen., Transm. Distrib., vol. 4, no. 10, pp. 1197–1212, 2010

[32] Abouzar Rahmati, Member, IEEE, and Reza Adhami. "A Fault Detection and Classification Technique Based on Sequential Components," in Proc. IEEE Power Engineering Society Summer Meeting, vol. 1, pp. 257–61, 2005.

[33] B. Mahamedi and J. G. Zhu, "Fault classification and faulted phase selection based on the symmetrical components of reactive power for single-circuit transmission lines," IEEE Trans. Power Del., vol. 28, no.4, pp. 2326–2332, Oct. 2013.

[34] S.K. Salman and S.F.Tan, "Comparative study of protection requirements of active distribution networks using radial and ring operations," IEEE Power Tech, Lausanne, pp. 1182 –1186, 2007.

[35] T. Ghanbari and E. Farjah, “Unidirectional fault current limiter: An efficient interface between the microgrid and main network,” IEEE Trans. Power Syst., vol. 28, no. 2, pp. 1591–1598, May 2013.

[36] Trung Dung LE, Marc PETIT. “Performance of Directional Relays without Voltage Sensors: Impact of Distribution Generation Technologies,” in Electricity Distribution, 22nd International Conference, pp.1-4, 2013.

[37] Chunguang Yu , Zhencun Pan，Wei Cong , Wei Wang, “The study on Fault Directional selection system for Distribution system under high DG penetration level,” in Rural Electric Power Conference (REPC), IEEE Stone Mountain, May 2013

[38] D. Yuan, X. Dong, S. Chen, Z Q Bo, B R J Caunce and A Klimek, “A New Directional Comparison Scheme For Distribution Line protection” Universities Power Engineering Conference, 2006.

[39] Abhisek Ukil, Senior Member, IEEE, Bernhard Deck, and Vishal H Shah, “Current-Only Directional Overcurrent Protection for Distribution Automation: Challenges and Solutions,” IEEE Transactions on Smart Grid, Vol. 3, No. 4, December 2012.

[40] T.D. Le and M. Petit, "Directional relays for distribution networks with distributed generation," in Proc. 2012 IET International Conference on developments in Power Systems Protection, pp. 1-6, 2012.

[41] Premalata Jena and Ashok Kumar Pradhan, “A Positive-Sequence Directional Relaying Algorithm for Series-Compensated Line”, IEEE Transactions on Power Delivery, Vol. 25, No. 4, October 2010.