Fault Direction Estimation for DFIG Integrated Distribution System

EMANDI APPANNA

A Dissertation Submitted to

Indian Institute of Technology Hyderabad

In Partial Fulfillment of the Requirements for

The Degree of Master of Technology

भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

Department of Electrical Engineering

June, 2015

Declaration

I declare that this written submission represents the ideas in my own words, and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

E. Appanna
____
(Signature)

____
(E APPANNA)

____
(EE13M1016)

ii

Approval Sheet

This thesis entitled **Fault Direction Estimation for DFIG Integrated Distribution Systems** by **E Appanna (EE13M1016)** is approved for the degree of Master of Technology from IIT Hyderabad.

B Ravikumar
Department of Electrical Engineering
IIT Hyderabad
Supervisor

Siva Kumar K
Department of Electrical Engineering
IIT Hyderabad
Examiner-1

Chandrika Prakash Vysaram
Department of Mechanical and Aerospace Engineering
IIT Hyderabad
Examiner-2

Pradeep Yemula
Department of Electrical Engineering
IIT Hyderabad
Chairman

iii

Acknowledgements

First of all, it is pleasure to thank my supervisor Dr. Ravikumar Bhimasingu for his esteemed guidance in completing my thesis work by his support and advices. I thank all my friends who contributed and extended their valuable assistance to me to learn and understand some of the topics in this study.

I sincerely thank all the research scholars from PE&PS stream of Electrical Engineering, IIT Hyderabad for their extreme support in clearing my doubts related to my thesis work.

I would like to sincerely thank Dr. Zafar Ali Khan, the H.O.D. of Electrical Engineering at IIT Hyderabad for providing necessary support throughout my thesis work.

I would like to extend my gratefulness to Dr. U.B.Desai, Director of IIT Hyderabad for providing necessary facilities in laboratories for my research work.

Finally, I would like to thank my parents for their love and support towards me throughout my life.

Abstract

In Recent years, Distributed energy sources such as wind generators, PV generators, fuel cells have become more attractive to integrate in power system at distribution level because of environmental issues and to replace the fossil fuels which are decreasing day by day. The distributed generation is expected to play a major role in future power systems. The solar and wind energy forms are the two main forms of the renewable energy resources.

But, the presence of these renewable energy resources will change the traditional distribution system in terms of short circuit power, fault current level and the characteristics of fault currents. These will disturb already existing protection system and cause the entire system to become active. The impact will be majorly on short circuit currents, protection and control.

Especially, during fault conditions there will be multiple sources feeding the current to the fault when DG sources are interconnected in distribution system. This lowers the performance of already existing overcurrent relays. This may cause problems like auto-recloser problems, blinding of protection, false tripping, and fuse-recloser mis-coordination. In this type of situations, we need to have directional feature for overcurrent relays.

In this thesis, different techniques have been reviewed to find the directionality for distribution systems integrated with DG units. The DFIG based wind energy system has been simulated using PSCAD. This Thesis addresses the two algorithms that are existed in the literature to estimate the fault direction when DFIG wind system units are integrated into a sample distribution system. These algorithms are the voltage and current information at the relay point during the fault for processing of a directional logic.

In first algorithm, the phase angle change between the post and pre fault positive sequence current phasors is used to estimate fault direction. In second algorithm, the incremental positive sequence impedance diagram is the factor to decide the direction of fault. These two algorithms have been implemented using PSCAD for a radial distribution system. In this thesis, some observations about the two existing algorithms have been addressed and proposed one modification to the positive sequence incremental impedance based algorithm, and listed some advantages. This modified algorithm has been applied to the DFIG integrated distribution system, and implemented in PSCAD. The results of this modified algorithm have been presented in detail in chapter 5.

Nomenclature

WECS : Wind energy conversion system

WTS : Wind turbine system

DFIG : Doubly fed induction generator

FSWT : Fixed speed wind turbine

FCWT : Full converter wind turbine:

DG : Distributed generation

SPV : Solar photo voltaic

CHP : Combined heat power plant

CA : Characteristic angle

NN : Neural networks

ANN : Artificial neural networks

FCL : Fault current limiter

DRG : Distributed renewable generation

IPDS : Interconnected power delivery systems

MV : Medium voltage

MFNN : Multilayer feed forward neural network

PSO : Particle swarm optimization

MM : Mathematical morphology

LP : Linear programming

HAWT : Horizontal axis wind turbine

VAWT : Vertical axis wind turbine

PMSG : Permanent magnet synchronous generator

SCIG : Squirrel cage induction generator

WRIG : Wound rotor induction generator

RSC : Rotor side converter

GSC : Grid side converter

IGBT : Integrated gate bipolar transistor

DC : Direct current

AC : Alternating current

PWM : Pulse width modulation

SFO : Stator flux oriented

PSCAD : Power system computer aided design

LG : Line-ground

LL : Line-line

LLG : Line-line-ground

LLL : Line-line-line

LLLG : Line-line-line-ground

VSC : Voltage source converter

Contents

List of Figures: Page No.

Chapter 1

Introduction

1.1 Distributed Generation: An Overview

Most part of the electric power in the world is produced using conventional sources of energy like coal, petroleum, natural gas etc., which are non-renewable. But, now a day there is a continuous depletion of the conventional energy resources at the same time the demand for energy is increasing rapidly due to rise in population, improved living standards, economic development and more consideration about environmental and climatic problems. This makes the focus to be drawn towards the use of renewable sources of energy like wind, solar, tidal, bio-fuels, fuel cell etc. During last few decades, these Renewable energy resources are attaining more attention at sub transmission or distribution level because of more number of advantages offered by them. This changes the nature of Distribution grids from Passive to Active. This renewable energy forms are also called as Distributed Generation or Dispersed Generation or Decentralized Generation or On-site Generation or Embedded Generation. The main advantages offered by Distributed Generation are as follows [1],

- Quick and easier installation
- Lowering cost by avoiding high voltage transmission
- Environment friendly
- Constant Running cost
- Participation of user-operator because of less complexity

- Simple construction
- Easy operation and maintenance

The most of the DG technologies available in India are related to micro turbines, wind turbines, biomass, and gasification of biomass, solar photovoltaic cells and hybrid systems. However, majority of the plants are based on wind power, hydro power and biomass. The Solar Photo Voltaic (SPV) cells have become more costly. The fuel cells are yet to be commercialized. There are also some internal combustion engines using diesel or natural gas in distributed generation, which are cost effective.

As these are Eco-friendly energy resources, harnessing the power from these sources of energy is the most sustainable way to generate electricity. They also do not create any global warming or toxic pollution problems. These energy sources have become alternatives to conventional sources of energy, because they are capable of generating power at large-scale in a controlled manner.

1.1.1 Integration challenges:

Most of the DG's are generally connected to the utility system at the distribution and sub transmission level. These utility systems are designed to supply radial loads. Islanded operation of dispersed generation to supply utility loads is not allowed for two main Reasons. They are,

- Very difficult to restore power during outage conditions
- Power quality cannot be maintained by the islanded dispersed generators within an acceptable level provided by the utility and that may result in damage to the customer equipment.

However, DG's engagement will change the original distribution system from a radial single-source network, on which the existing distribution protection depends on, to an active network spread with small or medium-sized sources. In many cases, there will be a reverse-power relay connected between DG and distribution system to prevent DG from transporting power into the grid. Along with the increase of DG, the existing protection and automatic devices may not operate correctly. So, we need to pay attention about the Interconnection of DG units into distribution systems.

IEEE Standard 1547 provides necessary information about Interconnection of Distributed Resources with Electric Power Systems.

Large scale integration of DG units in the distribution grid not only affects the grid planning but also has an impact on the operation of the distribution grid.

The following Aspects will be influenced by the connection of DG units into distribution grid [1].

- Voltage control
- Power quality
- Protection system
- Fault level
- Grid losses

The effect of DG units on these quantities strongly depends on the type of DG unit and the type of the network. DG units can be either directly connected to the distribution grid, such as synchronous and asynchronous generators, or via a power electronic converter. Synchronous generators contribute a large short circuit current influencing the protection scheme and the fault level. DG units connected via power electronic converters hardly contribute to the fault current making the effect on fault level and protection system negligible.

1.1.1.1 Voltage control:

For the power system and customers' equipment to function properly the voltage level of distribution grids must be kept within a specific range. This voltage range is well defined in international standards.

The connection of the DG along the feeder may affect proper voltage control of the distribution grid. The impact of the DG on voltage control is dependent on the power flow in the network [1].

The voltage profile is not much influenced when the injected power by the DG is lower than or equal to the load of the feeder. However, when the generated power exceeds the load of the feeder, voltage rise will occur. This voltage rise caused by the reversed power flow is a function of the power generated by the DG and the short-circuit power of the grid at the point of interconnection [1].

1.1.1.2 Power quality:

The effect of the integration of the DG on power quality concerns with three major aspects

- Dips and steady-state voltage rise
- Voltage flicker
- Harmonics

1.1.2 Protection Issues in the Presence of DG Units:

Distribution grid protection consists normally of a simple overcurrent protection scheme since there is only one source of supply and the power flow is defined. The connection of the DG to the distribution grid leads to multiple sources of the fault current which can affect the detection of disturbances. The contribution of the DG to the fault current strongly depends on the type of the DG and the way the DG unit is connected to the distribution grid [1].

The main problems caused by directly coupled DG units on distribution grid protection are as follows,

- Prohibition of auto reclosing
- Unsynchronized reclosing
- Fuse-recloser coordination
- Islanding problems
- Blinding of protection
- False tripping

1.1.2.1 Recloser problems:

Most faults on overhead lines only last for a short period of time. So, switching off the line permanently is not necessary. The automatic recloser switches off the line for a short period of time to allow the arc to extinguish. After a small time delay the line is energized again by the automatic recloser. In case of a permanent fault the line is switched off permanently after three or four unsuccessful reclosing actions In the presence of DG's, during the open time of the recloser, the DG unit still energizes the feeder, thus energizing the arc and making the temporary fault a permanent one. The line will be unnecessary, often switched off permanently [1].

The coordination between fuse and recloser will also be lost in the presence of DG's. Temporary faults will be cleared permanently by the fuse instead of temporarily by the recloser.

1.1.2.2 Blinding of Protection:

When a short circuit occurs at the indicated location in Fig. 1.1, both the grid and the DG unit contribute to the fault current. The division of the current contribution depends on the grid impedance, and power generated by the DG unit. Due to the contribution of the DG unit, the total fault current will increase. However, the grid contribution decreases. This can lead to a poor fault current detection. It is even possible that the short-circuit stays undetected because the grid contribution to the short-circuit current never reaches the pickup current of the feeder protection relay. This mechanism is called blinding of protection as shown in Fig. 1.1 [1].

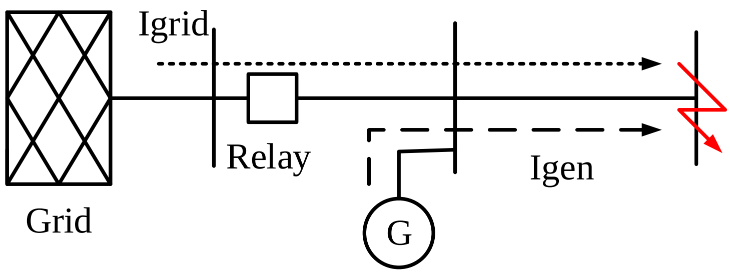

Figure 1.1 Blinding of protection [1]

1.1.2.3 False tripping:

False tripping may occur, when a DG unit contributes to the fault in an adjacent feeder connected to the same substation. The generator contribution to the fault current can exceed the pickup level of the overcurrent protection in the DG feeder causing a possible trip of the healthy feeder before the actual fault is cleared in the disturbed feeder. This is called false tripping as shown in Fig. 1.2 [1].

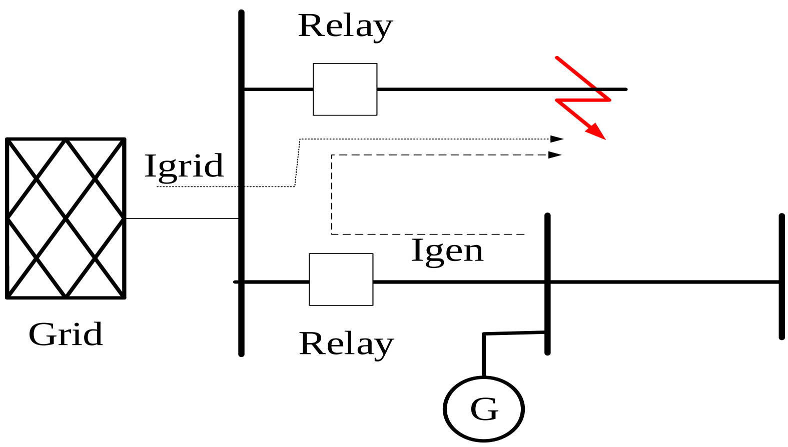

Figure 1.2 False tripping [1]

1.1.3 Need for directionality:

To avoid all the problems mentioned above caused by the interconnection of DG units, we need to employ directional feature for all existing over current relays. Directional over current elements will be necessary to prevent incorrect substation feeder relay tripping for faults on parallel feeders served by the distribution substation.

The fault currents in meshed distribution networks are not limited to one direction. The Overcurrent relays cannot give an indication of the current direction, because they are non-directional. In such conditions, we need to have directional feature for existing overcurrent relays. Both the system voltage and current will be sensed by instrument transformers and they will be supplied as input quantities to the directional overcurrent relay for processing of directional logic.

1.2 Motivation:

Now a day, renewable energy sources such as wind generators, PV generators, fuel cells are most emerging trend at distribution level power systems, because these can give pollution free, eco-friendly energy conversion for rapidly increasing power demand. The distributed generation is expected to play a major role in future power systems.

The wind turbines are mostly used trend today. Double fed induction generators (DFIG) fed by wind turbines are finding more applications, due to its control over power flow in the system. But, the presence of these renewable energy resources especially solar and wind systems will change the traditional protection system in terms of false tripping, blinding of protection, and fuse-relay mis coordination.

These issues caused by the integration of DG units gave the sufficient motivation to develop some algorithms to mitigate the issues. These necessities for fault direction estimation algorithms in DFIG integrated distribution system by using the voltage and current information of fundamental frequency before and after the fault at the relay point.

1.3 Scope of work:

Applications of Distributed renewable energy resources in energy conversion are increasing rapidly now a day. But, integration of these renewable energy resources into distribution systems results in more problems in protection related issues such as false tripping, blinding of protection, fuse-relay mis-coordination, and changes the direction of short circuit currents, especially when DFIG wind units are interconnected. So, we need to have reliable algorithms to identify fault direction of fault current.

According to all these issues, Scope of this thesis work is,

- Study of different methods available in the literature to find the directionality.

- Implementation of two existing algorithms to identify the fault current direction, one is using phase angle difference comparison, and second one is based on positive sequence incremental impedance diagram.
- Modification to the existing positive sequence incremental impedance based algorithm.

1.4 Thesis outline:

This thesis is organized according to the following.

This chapter (**chapter 1**) gives an introduction to distribute generation (DG) units. It also addresses the integration challenges and protection issues caused by the integration of DG units into distribution system. It also specifies the objectives of this thesis and organization of this thesis.

Chapter 2 covers the literature survey on directional overcurrent protection and need to go for it. It also discusses the different techniques to find the directionality function for DG integrated distribution systems. Some of the important techniques available in literature also have been presented in this chapter on directional protection.

Chapter 3 contains the introduction to wind energy conversion systems (WECS). It also addresses the operation, modeling, and control DFIG based wind energy systems.

Chapter 4 explains two existing fault direction estimation algorithms in detail, which are implemented in PSCAD. These two algorithms are based on processing the voltage and current information available at the relay point. It also addresses the modified incremental impedance based algorithm.

Chapter 5 contains the results of the two existing and one modified algorithms as explained in the previous chapter for fault direction estimation in a radial distribution system integrated with DFIG. These results are obtained from the simulations done in PSCAD.

Chapter 6 contains conclusion and future work of this thesis.

Chapter 2

Literature Survey

2.1 Introduction to Protection:

In power systems, it is very much important to limit the impact of a system disturbance in order to prevent accidents, damages, unwanted supply interruptions and financial damage to the system. This objective can be achieved by Power system protection. Protective systems which make use of protection relays are implemented throughout the system to make sure that a fault is removed by isolating the faulted network section from the remaining (healthy) network as quickly as possible [2].

The protective system is required to take decisions quickly, in terms of milliseconds by using the limited information such as the state of the system at the point of disturbance.

The faults in power system usually create very high current levels in the system. With the help of these high currents, protection relays have to determine the presence of a fault and react accordingly. There are several types of relays for this purpose with various design characteristics.

There have been considerable advancements in the development of relay technology over the past few years. The first relays were electromechanical relays and now they have been successively replaced by static, digital and numerical relays [2].

The main protective relay technologies used in sub-transmission and distribution grids are the following.

- Overcurrent protection
- Directional protection
- Differential protection
- Distance protection.

2.2 Introduction to Directional overcurrent Protection:

In meshed or loop network constructions or in networks with multiple connected sources which will be formed by integrating DG units into normal, single source distribution systems, it is very much difficult to achieve selectivity with overcurrent relays only [2].

The fault currents in meshed distribution networks are not limited to one direction. The Overcurrent relays cannot give an indication of the current direction, because they are non-directional.

In such conditions, we need to have directional feature for existing overcurrent relays. Both the system voltage and current will be sensed by instrument transformers and they will be supplied as input quantities to the directional overcurrent relay for processing of directional logic [2].

The directional overcurrent relay contains three operating units named as,

- Overcurrent unit
- Directional unit
- Time restraint

The overcurrent unit is activated during abnormal grid situations when the fault current magnitude exceeds the relay threshold value. Then the directional unit will determine the direction of the fault. When the relay determines that the fault is directed from one side to another side, the directional unit of the relay is activated. At the moment both current magnitude and direction are detected, the relay starts measuring the time. If these conditions continue until the time restraint is exceeded, the relay generates a trip commando to the nearest circuit breaker [3].

The overcurrent unit consists of a current threshold and the pickup current settings of this unit are determined as like for overcurrent relays.

2.2.1 Directional Unit:

The directional protection relay detects the direction of the current, by detecting the sign of the power flow. The inputs to relay are measured system parameters, i.e. the voltage (V) and the current (I) information. The operating torque generated is given by [2],

$$T = k.\phi_1.\phi_2.Sin\,\theta$$

Where, ϕ_1=flux proportional to current

Φ_2=flux proportional to voltage

ϑ= the angle between two fluxes.

When V and I are in phase, the fluxes are out of phase by 90˚ and there will be a maximum torque is generated. The angle of maximum torque defined as the angle for which the displacement between voltage and current produces the maximum torque. This angle is also called the characteristic angle (CA). The characteristic angle plays is very important while determining the direction of the power flow [5].

For relay directional detection the maximum torque can be easily obtained by measuring the current and voltage from the same phase. However, in fact the voltage of the faulted phase might collapse. So, the reference voltage phasor or polarizing voltage vector can be selected from healthy phases.

2.3 Different techniques to obtain the directionality:

The literature provides several techniques to find logic for directional element in directional overcurrent relays. All these techniques use either fundamental frequency data or high frequency transient data of the system voltage and current information and different digital techniques will be applied to that data for further processing to identify a proper logic [3-20].

The different directional techniques are as follows.

- By using Voltage & Current phasors
- Adaptive protection principles
- Application of symmetrical components
- DSP communication based techniques
- Microprocessor based techniques
- High frequency transient data based techniques
- Artificial Neural Network based techniques
- Phase angle comparison techniques
- Numerical based techniques
- Optimization based methods
- Wavelet transform techniques

Because negative- and zero-sequence quantities are usually only present only during unbalanced, faulted conditions on a power system, they are often used to determine the direction of a fault on the system. Negative sequence can be used to detect phase-phase, phase-ground and phase-phase-ground faults. Zero sequence can be used to detect phase-ground and phase-phase-ground faults [43].

2.4 Existing methods in Literature for directionality:

In the presence of distributed generation (DG), it is important to assure a fast and reliable protection system for the distribution network to avoid unintentional DG disconnection during fault conditions. A dual setting directional over-current relay is proposed for protecting meshed distribution systems with DG. Dual setting relays are equipped with two inverse time-current characteristics whose settings will depend on the fault direction. The protection coordination problem for the dual setting directional relay is formulated as a nonlinear programming problem where the objective is to minimize the overall time of operation of relays during primary and backup operation [3].

Directional relaying is one of the most important features of protective relays in situations where the fault current direction is not fixed, such as transmission lines, meshed distribution networks, and modern smart grids, including dispersed generation (DG) units. The application of voltage as a reference quantity for the detection of fault direction is a common practice in transmission lines. But, using pre-fault current, instead of voltage, as a reference quantity, does not need any potential transformers. However, this method requires the voltage for the detection of power-flow direction. This scheme is able to detect the fault direction using only the post-fault current. The efficiency of the proposed scheme has been approved for different operating conditions [4].

Transmission side uses more directional type relays, while distribution systems, e.g., radial and ring-main sub transmission systems use non directional types. The fault direction may be forward (between relay and grid), or reverse (between relay and source), the normal power flow being from source to the grid. Traditional directional overcurrent relays utilize the reference voltage phasor for estimating the direction of the fault. This makes the directional overcurrent relays more costly than non-directional type. This can be avoided, by using current-only directional detection possibility, mainly based on zero crossing points of current waveforms in time domain as well as frequency domain [5].

Neural network (NN) based method for current-only directional detection in an overcurrent relay. Intelligent techniques like NN prove to be computationally less intensive than methods like discrete Fourier transform, Kalman filtering, etc. for phase angle computation which can be used for processing of directional logic [6].

One of the most considerable problems that arise, when DG is used, is destructing efficiency and qualification of the existing protection system. The injected currents of DG to a distribution network lead to not having a radial network anymore, and consequently cause the network faces an inefficient protection system that was formerly designed. With the introduction of the Multi-Agent System (MAS), it can make full use of computer intelligence and the inherent distribution of power system to build a protection system. It designs the communication mechanism between every Agent. This can provide the agent based protection is to accelerate the protection action and isolation the fault section. It is suitable for distribution network protection scheme with DG [7].

Fault section identification in distribution networks is a complicated and important subject. The faulted section can be distinguished with the aid of traveling waves. This algorithm is able to detect the faulty section using voltage signals only and avoid the need for installing current transformers. Fault direction identification method proposed is based on wavelet coefficients of transients generated by the fault. This scheme can work properly in the case of all types of faults, different fault inceptions, different fault locations and fault resistances [8].

A significant increase in the penetration of distributed generation has resulted in a possibility of operating distribution systems with distributed generation in islanded mode. However, 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 [9].

Microprocessor based reclosers and directional elements for feeder relays, can be used for the coordination of protective devices in typical radial distribution networks embedding distributed generation units. It does not require adaptive protective devices. This method also presents the steps taken to characterize the impact of DGs on the protection coordination, for host and neighbouring feeders [10].

Agent technology can be applied to the protection coordination of power systems integrated with DG units. A multi agent system is proposed with the functions of the agents described. This uses communication to play an important role to provide more information for the relay coordination besides the relay settings. Communication simulation has been carried out on the Java Agent Development Framework platform. A communication protocol enables agents to exchange and understand messages. The behaviour of a multi agent depends not just on its component agents, but also on how they interact. In a multi agent system, each agent would not only need to be able to do the tasks that arise locally, but would also need to interact effectively with other agents. The communication protocols can be regarded as the specification of these interactions. Protocols help in separating the interface between agents from their internal design [11].

Two approaches have been proposed to solve the directional overcurrent relay coordination problem associated with the installation of distributed renewable generation (DRG) in interconnected power delivery systems (IPDS), depending on the existing system protection capability (adaptive or non-adaptive). For adaptive protection systems, one approach introduces a procedure to select the optimal minimum number of relays, their locations and new settings. This is restricted by the available relay setting groups. For non-adaptive protection systems, second approach implements a practice to obtain optimal minimum fault current limiter values (FCL) to limit DRG fault currents and restore relay coordination status without altering the original relay settings. An integration of these two approaches is evaluated for IPDSs possessing both protection systems. Three scenarios are assessed for different numbers of DRGs, and DRG and fault locations using an optimisation model implemented in GAMS software and a developed Mat Lab code [12].

Distributed Generation (DG) will affect the amperage, direction and distribution of fault current. With the penetration of DG, the existing protection and automatic devices may not operate correctly. In accordance with how DG affects the protection of distribution system, the importance of connecting a fault current limiter (FCL) to DG to restrict the fault current is analysed and the detailed algorithm to get the parameters of FCL is presented. The simulations by Matlab/EMTP we proved that FCL with properly selected parameters can effectively restrict DG's fault current, eliminate DG's negative effects and guarantee the original protection's reliability and selectivity [13].

A new high-speed directional relay has been presented using field data, which is based on the current and voltage signals before and after fault occurrence. The voltage signal is compensated and then used as a reference. The relay is used for the directional comparison protection of extremely high voltage transmission lines. An evaluation of this relay is investigated using recorded fault data from the Alberta power transmission system. The real effects of the power system elements, which might have not been completely considered in the mathematical model of the power system, have been included in the recorded real fault data. The performance of the new directional relay is verified in a more realistic environment [14].

A fundamental approach has been proposed for detection of the direction of a power system fault within the first milliseconds following the fault inception. This approach is based on a combined evaluation of the voltage and current deviations generated by the fault occurrence. Design considerations and test results based on numerical simulations and on a transient network analyser are presented. The method solves several problems occurring in conventional relaying and is suitable for use in ultrahigh speed protection systems which employ a fast telecommunication channel between the ends of the protected network [15].

A novel current polarized directional element technique is proposed to determine the fault direction on a transmission line evaluated using fault data recorded in the field. The post-fault current signal and a directional reference current signal are used to derive a directional current element. The directional normal power flow before fault occurrence is also used. The voltage signal is excluded from the study after fault occurrence. It is not affected by the system operating parameters. This technique has a high degree reliability, selectivity and stability for a majority of practically encountered problems [16].

With the rapid developments in distribution system automation and communication technology, a multi-agent based scheme is presented for fault diagnosis in power distribution networks with distributed generators. The relay agents are located such that the distribution network is divided into several sections. The relay agents measure the bus currents at which they are located such that it can detect and classify the fault, and determine the fault location. This technique uses the entropy of wavelet coefficients of the measured bus currents. The performance of the proposed protection scheme is tested for a benchmark medium voltage (MV) distribution system, and practical 66 kV system of the city of Alexandria [17].

Distributed generation (DG) integration necessitates upgrading some distribution system overcurrent relays to directional ones to offer selective protection. The directional feature is conventionally achieved by phase angle comparison between phasors of the fault current and a polarizing quantity, normally a voltage signal. The malfunction of the conventional directional elements during 3-phase short-circuits when a distribution system incorporates DFIG-based wind DG, is due to the exclusive fault behaviour of DFIGs, which affects the existing relaying practices. This also provides accurate fault direction quickly based on wave shape properties of the current. An extensive performance evaluation using PSCAD/EMTDC simulation of the IEEE 34 bus system corroborates the effectiveness of this method [18].

Two algorithms have been proposed using only currents measurements that could be used as a backup protection. These algorithms are based on the symmetrical components (0-zero, 1-positive and 2-negative sequences) of the 3-

phases currents. Due to the power flows generated by the DG the positive sequence current argument is unforeseeable, thus it is not possible to use only the positive sequence. The first algorithm uses I_2/I_0 ratio to locate a phase-to-ground fault upstream or downstream the detector. The second algorithm measures the zero and positive sequence components of the fifth harmonic of the current and calculates the I_{0_5}/I_{1_5} ratio [19].

One problem with micro-grid implementation is designing a proper protection scheme. A protection scheme has been developed using digital relays with a communication network for the protection of the micro-grid system. The increased reliability of adding an additional line to form a loop structure is explored [20].

The design and construction of overcurrent and directional overcurrent relays with ground fault protection for the protection of three-phase sub-transmission and distribution systems is presented here. It uses a 16-bit microprocessor, the Intel 8096BH. The relay obtains the system currents at the rate of 12 samples per cycle and estimates the fundamental frequency components of the current signals using discrete Fourier transform techniques. In the case of the directional overcurrent relay, the direction of the current flow is identified to determine whether the fault current is flowing into its protected zone. For this purpose, several internally stored voltage vectors, corresponding to the different directional element settings are synchronized accurately with the system voltage and used to determine the direction of the power flow. Facilities to change relay characteristics, the time dial and plug settings are provided. The desired operating characteristics are achieved by direct curve data storage in the memory [21].

It is desirable to develop a high speed and accurate approach to determine the fault direction for different power system conditions. To classify forward and backward faults on a given line, neural network's abilities in pattern recognition and classification could be considered as a solution. To demonstrate the applicability of this solution, neural network technique is employed and a novel

Elman recurrent network is designed and trained. Design procedure of this network is presented in one paper. It is suitable to realize a very fast transmission line directional comparison protection scheme [22].

Fault direction discriminator uses an Artificial Neural Network (ANN) for protecting transmission lines. The discriminator uses various attributes to reach a decision and tends to emulate the conventional pattern classification problem. An equation of the boundary describing the classification is embedded in the Multilayer Feed forward Neural Network (MFNN) by training through the use of an appropriate learning algorithm and suitable training data. The discriminator uses instantaneous values of the line voltages and line currents to make decisions. It is suitable for realizing an ultrafast directional comparison protection of transmission lines [23].

When there is a source present at both terminals of the transmission line, the relays protecting the line are subjected to fault current flowing in both directions. Directional relays operate only when the fault current flows in the specified tripping direction. Using the quasi steady state components of the locally measured deviations of the voltage and phase shifted current from their pre-fault values, the direction to a fault is determined. This directional information is exchanged with the relay at the opposite end of the protected zone. If the combination of the locally detected direction and the information from the remote end indicates a fault inside the zone of protection, a trip signal is issued. The deviation signals of the voltage and phase shifted current are determined by subtracting the previous values from the corresponding values in the present cycle. The voltage and current deviation signals contain exponentially decaying dc and high frequency transient components [24].

A novel ultra-high speed directional protection scheme has been developed by using mathematical morphology (MM). The MM technique proposed is used to extract transient features from fault-generated voltage and current wave signals propagating along transmission lines during a post-fault period. Fault direction is determined by two composite relaying signals which are composed of the extracted transient features [25].

The coordination of directional overcurrent relays (DOCR) can be done using particle swarm optimization (PSO), a recently proposed optimizer that utilizes the swarm behaviour in searching for an optimum. PSO gained a lot of interest for its simplicity, robustness, and easy implementation. The problem of setting DOCR is a highly constrained optimization problem that has been stated and solved as a linear programming (LP) problem [26].

The principles of optimization theory can be used to treat the problem of optimal coordination of directional overcurrent relays in interconnected power systems. With the application of this technique, this coordination problem is stated as a parameter optimization problem which in general is of a large dimension, especially when many different system configurations and perturbations are to be considered. Several optimization procedures, including direct methods and decomposition techniques, for solving this large scale coordination problem are described [27].

The fault direction can be obtained by using the traveling-wave directional principle. The algorithm decomposes the voltage signals by using wavelet transforms and calculates the spectral energy, which allows detecting the fault and to choose the phase to make the slope change analysis. This analysis provides a clear indication of fault direction from the comparison of the slope change polarities of the voltage and current at selected phase within a short time. This is able to discriminate the direction for all kinds of faults and is not affected by the change of the fault angle inception [28].

The directional protection has been developed based on real power system data. This method introduces a directional protection technique with phase selection based on measuring the current only. The correlogram function principle is applied on two successive current cycles. The two cycles are based on the pre-fault and post-fault current signals. The sign of correlogram coefficients will give the direction information, while its magnitude is used to identify the faulted phase. It is very much reliable not only to identify the fault direction but also the faulted phase [29].

Chapter 3

Introduction to Wind Energy Conversion Systems

3.1 Introduction to Wind energy Industry:

Wind Energy is gaining interest now days as one of the most important renewable sources of energy due to its eco-friendly nature. During the last decade use of wind energy has raised substantially, and its share in the total energy production has increased to a great extent. The consumption of conventional energy sources has been decreasing now a day. So, the efforts have been made to generate electricity from renewable energy sources such as wind, solar etc. In order to meet power needs, taking into account economic and environmental factors, wind energy conversion is gradually gaining interest as a suitable source of renewable energy. Wind farms have capability to produce large amounts of power (typically of the order of MW-GW's of power). Wind energy is the most preferred renewable energy source around coastal regions and it can be installed onshore or offshore.

A system that transforms the kinetic energy present in the incoming air stream into electrical energy is called Wind energy conversion system.

3.2 Introduction to Wind Turbines:

Wind turbine rotor is the extraction device, which turns under the action of wind stream, thus harvesting a mechanical power. This rotor drives a rotating electrical machine, the generator, which will give electrical output power.

The structure of modern wind turbine system is shown in Fig. 3.1

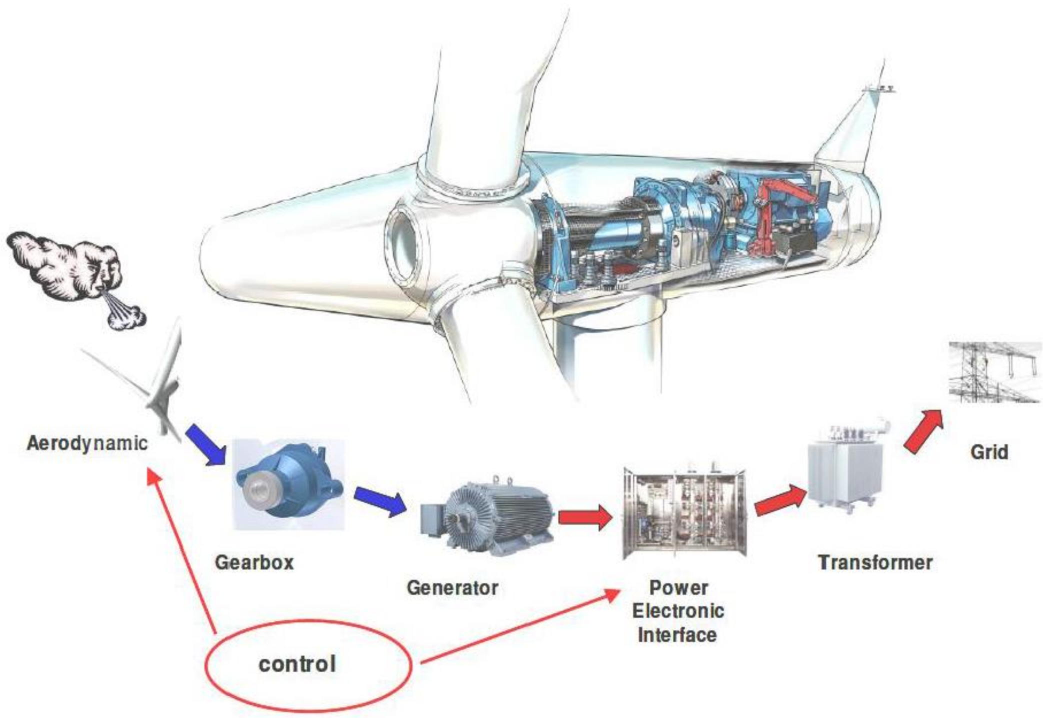

Figure 3.1 Modern wind turbine system components [32]

3.2.1 Classification of Wind turbines:

The wind turbines have been classified based on the direction of rotor axis. They are,

- Horizontal axis wind turbines (HAWT)
- Vertical axis wind turbines (VAWT)

But, today most of the manufacturing wind turbines are Horizontal axis wind turbines with either two or three blades. HAWT is comprised of the tower and the nacelle mounted on the top of the tower.

The energy conversion chain of a wind turbine is organised into four systems.

- Aerodynamic subsystem, consisting of the turbine rotor, which is composed of blades, and turbine hub, which is the support for blades.

- Drive train composed of low-speed shaft, which is coupled with the turbine hub, a gear box and high-speed shaft, which drives the electrical generator.
- Electromagnetic subsystem consisting of the electric generator, which converts the mechanical energy to electrical energy.
- Electric subsystem, which contains the elements for grid connection and local grid. [33]

The nacelle contains the key components of the wind turbine, including the gearbox and the electrical generator. Service personnel may enter the nacelle from the tower of the turbine. The wind turbine rotor, that is, the rotor blades and the hub will present to the left of the nacelle. The rotor blades capture the wind and transfer its power to the rotor hub [33].

Usually, the output voltages of the generator are low, and hence there will be the need for a transformer to step up the generator output voltage for the purpose of directly connecting to the grid. Based on the wind direction, the yaw system will rotate the nacelle to make the wind turbine face into the wind. An emergency mechanical brake is equipped at the high-speed shaft to protect the drive train system from the mechanical stress when experiencing wind gusts.

In addition, there are extensive on-board controllers that can change the pitch angle of the rotor blades, and regulate the yaw system and drive train system as well as power control components. Besides, these on-board controllers can break the rotor in possible runaway situations, such as high wind speeds and power-grid outages [34].

3.2.2 Aerodynamic Model of Wind turbines:

The wind turbine process the conversion of the wind energy into the mechanical energy through a suitable turbine configuration. The wind power P_m extracted by the wind turbine can be defined as,

$$P_m = \frac{1}{2}\rho A V_w^3 C_p$$

$$P_m = \frac{1}{2}\rho \pi R^2 V_w^3 C_p$$

Where,

ρ = Air density (Kg/m^3)

A =Turbine swept area A= πR^2

R =Turbine propeller radius

C_P=Power coefficient which is a function of blade pitch angle β and tip speed ratio λ

V_w=Wind velocity (m/s)

The power coefficient C_P describes the portion of mechanical power extracted from the total power available from the wind, and it is unique for each turbine. This power coefficient C_P is a function of the tip speed ratio λ and blade pitch angle β [7].

The tip speed ratio is the ratio of tip blade speed to wind speed and it is given by,

$$\lambda = \frac{R w_t}{V_w}$$

Where, ω_t represents the rotational speed of the wind turbine.

It says that as wind speed changes, the pitch angle or tip speed ratio is so adjusted to utilize maximum power contained in wind for energy conversion. The power coefficient C_P is a function of the tip speed ratio λ and blade pitch angle β [8]. It is given by,

$$C_p(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_i}} + 0.0068\lambda$$

Where, λ_i is given by,

$$\frac{1}{\lambda_i} = \frac{1}{(\lambda + 0.08\beta)} - \frac{0.035}{(\beta^3 + 1)}$$

3.3 Control techniques of Wind turbines:

There are different control schemes available for wind turbines based on the way how the wind turbine limits or controls the power extracted from the wind.

- Pitch angle control
- Yaw control

3.3.1 Pitch angle control:

In this control, the rotor blades of wind turbine will has the ability to turn around their longitudinal axis. When the power output becomes too high, an order has been send to the blade pitch mechanism, which immediately pitches (turns) the rotor blades slightly out of the wind. As soon as the wind drops again the blades are turned back into the wind. There will be an electronic controller to check the power output of the turbine for pitch controlled wind turbines [12]. On a pitch controlled wind turbine, the computer will generally pitch the blades a few degrees every time the wind changes in order to keep the rotor blades at the optimum angle and maximize output for all wind speeds [13].

3.3.2 Yaw mechanism:

All wind turbines have a mechanism that moves the nacelle such that the blades are perpendicular to the wind direction. This mechanism is called tail vane for small wind turbines or an electric yaw device for medium and large wind turbines [9]. The yaw mechanism is operated by the electronic controller, which senses the wind direction using the wind vane. Normally, the turbine will yaw only for few degrees at a time, when the wind changes its direction. The anemometer and the wind vane are used to measure the speed and the direction of the wind [11].

3.4 Wind energy conversion systems (WECS):

A wind energy conversion system (WECS) transforms the energy present in the blowing wind stream into electrical energy.

Wind energy is transformed into mechanical energy by a wind turbine that has several blades. It usually includes a gearbox that matches the turbine low speed to the higher speed of the generator. Some turbines include a blade pitch angle control for controlling the amount of power to be transformed. The electrical generator transforms mechanical energy into electrical energy. Commercially available wind generators installed at present are squirrel cage induction generator, doubly fed induction generator, wound field synchronous generator (WFSG), and permanent magnet synchronous generator (PMSG) [37].

The electrical power generation structure contains both electromagnetic and electrical subsystems. Besides the electrical generator and power electronics converter it generally contains an electrical transformer to ensure the grid voltage compatibility [37].

The configuration of WECS depends on the type of electrical machine used, its rotational speed, and its interface to the grid. They are,

- Fixed speed WECS
- Variable speed WECS

3.4.1 Fixed speed WECS:

Fixed speed WECS operates at constant speed, determined by grid frequency irrespective of wind speed. This configuration is also known as the Danish concept. A fixed speed WECS consists of a conventional squirrel cage induction generator which, is directly coupled to the grid. It has some superior characteristics such as brushless and rugged construction, low cost, maintenance free, and simplicity in operation. The rotor speed variations of this squirrel cage induction generator are very small, approximately 1 to 2 %, which varies with the amount of power generated. Therefore, this type of topology is called constant or fixed speed WECS.

This system is very simple as shown in Fig. 3.2. However, constant speed turbines must be more mechanically robust than variable speed turbines [33]. Because, the fluctuations in wind speed translate directly into drive train torque fluctuations, causing higher structural loads than with variable speed operation.

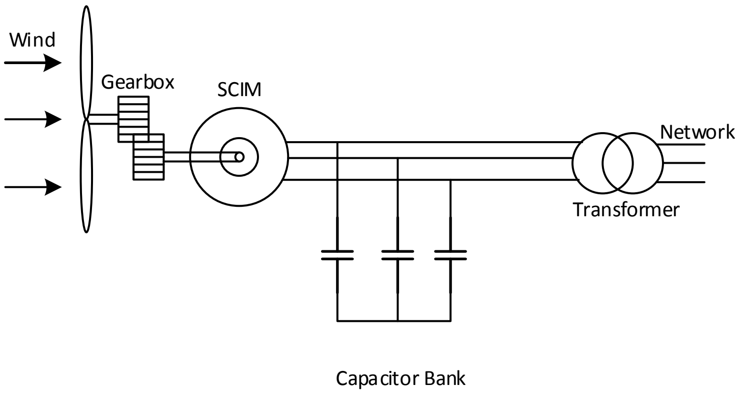

Figure 3.2 Schematic diagram of fixed speed WECS [36]

A squirrel cage induction generator will always consume reactive power, to establish the rotating magnetic field of the stator. In this case, the reactive power must be supplied from the network, which is undesirable particularly for large turbines. Therefore, the capacitor bank will supply the reactive power required by the squirrel cage induction generator to maintain the power factor close to unity [36].

3.4.2 Variable speed WECS:

Variable-speed wind turbines are currently the most used WECS. The variable speed operation is possible due to the power electronic converters interface, allowing a full or partial) decoupling from the grid [33].

One advantage of the variable wind turbines is reducing mechanical stresses in turbines, and also removing gust of wind. These will introduce low power fluctuation, and high power quality, compared to fixed speed WECS.

There are two configurations based on the way of interfacing the power electronic converters and type of induction machine used. They are,

- Full converter variable speed WECS
- DFIG based variable speed WECS

3.4.2.1 Full converter based variable speed WECS:

Squirrel cage induction generator (SCIG) or Permanent magnet synchronous generator (PMSG) can be used in this topology. Generator is coupled to the grid via back-to-back voltage source converter, which is rated to the generator power and its operation is similar to that in DFIG-based WECS [37].

The rotor side converter ensures adjustment of rotational speed over a large range, whereas its grid-side converter transfers the active power to the grid and attempts to cancel the reactive power consumption, especially in case of SCIG equipped WECS [37].

Using full scale frequency converter results in smoother grid connection therefore it will not be necessary to install soft starter [36].

Figure 3.3 shows the schematic diagram of full converter based WECS.

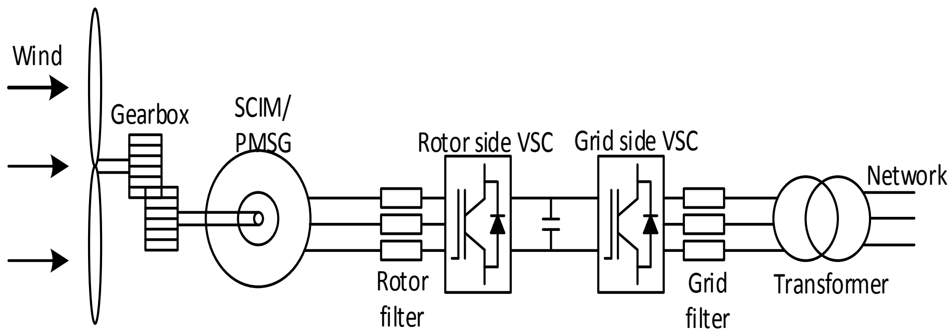

Figure 3.3 Schematic diagram of full converter WECS [36]

3.5 Operation, modeling and control of DFIG based WECS:

3.5.1 Principle of Operation:

With increased penetration of wind power into electrical grids, DFIG wind turbines are largely deployed due to their variable speed feature and hence influencing system dynamics.

The doubly fed induction generator (DFIG) based WECS, also known as improved variable speed WECS, is presently the most used by the wind turbine industry [32].

Figure 3.4 shows the schematic diagram of DFIG based variable speed WECS.

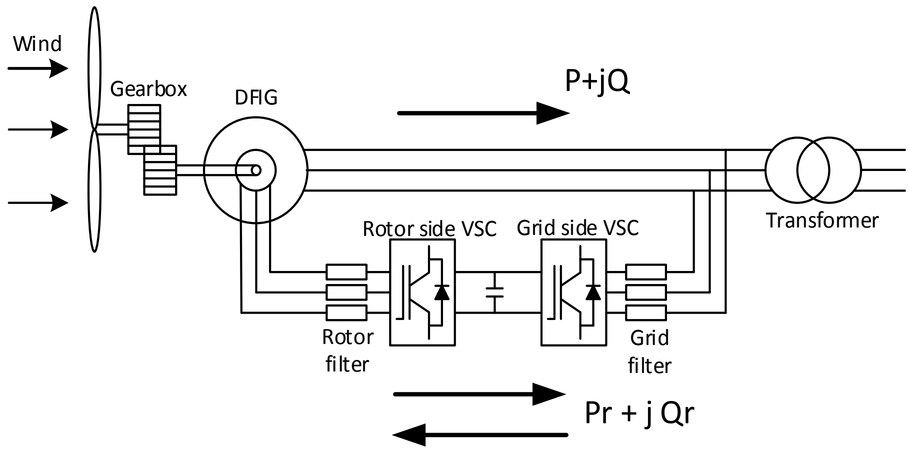

Figure 3.4 Schematic diagram of DFIG based WECS [36].

DFIG has the capability of extracting optimum wind energy over a wide range of wind speeds, which is not possible with fixed speed induction generators.

The DFIG is a Wound Rotor Induction Generator with the stator windings connected directly to the 3 phase, constant-frequency grid and the rotor windings connected to a back-to-back (AC–AC) voltage source converter. This system allows variable-speed operation over a large, with the generator behaviour being governed by the power electronics converter and its controllers [33].

The power electronics converter comprises of two IGBT converters, namely the rotor side and the grid side converter, connected with a direct current (DC) link capacitor. The rotor side converter controls the active and reactive power flow by the generator, while the grid side converter controls the DC-link voltage at a constant value and ensures operation at a large power factor [33].

The stator output power is always flow into the grid. The rotor, depending on the speed of the machine, feed the power into the grid when the slip is negative (over synchronous operation) and it absorbs power from the grid when the slip is positive (sub synchronous operation). In both cases, the power flow in the rotor is approximately proportional to the slip.

The size of the converter is not related to the total generator power but to the selected speed variation range, typically a range of ±30% around the synchronous speed. Therefore, the size and rating of converter is proportional to slip power rating.

DFIG based WECS are highly controllable, allowing maximum power extraction over a large range of wind speeds. The active and reactive power control is fully decoupled by independently controlling the rotor currents. Finally, the DFIG-based WECS can either inject or absorb power from the grid, hence actively participating at voltage control [33].

The main characteristics can be summarized as,

- Limited operating speed range (±30%)
- Small scale power electronic converter (reduced power losses and price)
- Complete control of active power and reactive power exchanged with the grid.
- Need for slip rings and Gear Box (normally 3 stage one)

3.6 Mathematical Model of DFIG:

The mathematical model for wound rotor induction generator is as follows [34].

Stator voltage equations:

$$V_{qs} = p\lambda_{qs} + \omega\lambda_{ds} + r_s i_{qs}$$

$$V_{ds} = p\lambda_{ds} - \omega\lambda_{qs} + r_s i_{ds}$$

Rotor voltage equations:

$$V_{qr} = p\lambda_{qr} + (\omega - \omega_r)\lambda_{dr} + r_r i_{qr}$$

$$V_{dr} = p\lambda_{dr} - (\omega - \omega_r)\lambda_{qr} + r_r i_{dr}$$

Power equations:

$$P_s = \frac{3}{2}(V_{ds} i_{ds} + V_{qs} i_{qs})$$

$$Q_s = \frac{3}{2}(V_{qs} i_{ds} - V_{ds} i_{qs})$$

Torque equation:

$$T_e = -\frac{3}{2}\frac{P}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds})$$

Stator flux linkage equations:

$$\lambda_{qs} = (L_{ls} + L_m) i_{qs} + L_m i_{qr}$$

$$\lambda_{ds} = (L_{ls} + L_m) i_{ds} + L_m i_{dr}$$

Rotor flux linkage equations:

$$\lambda_{qr} = (L_{lr} + L_m) i_{qr} + L_m i_{qs}$$

$$\lambda_{dr} = (L_{lr} + L_m) i_{dr} + L_m i_{ds}$$

3.7 Back-Back Power Electronics converters:

The Converter that is used in DFIG is a back to back voltage source converter. This consists of a bidirectional voltage source converter connecting through the rotor of the generator and the grid as shown in Fig. 3.5. Basically these converters are made up IGBT power electronic switches with body diodes, which permit a bi-directional current flow.

Figure 3.4 shows Back-Back voltage source converter used in DFIG based wind system.

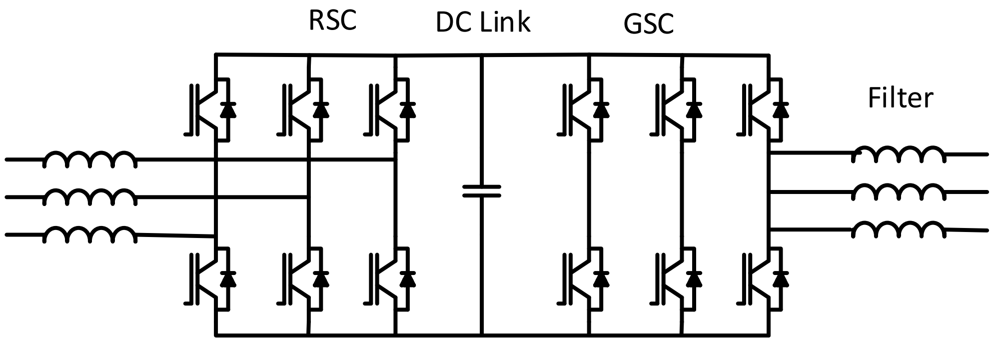

Figure 3.5 Back-Back voltage source converters [36].

The grid side converter is modelled with ideal bidirectional switches. It converts voltage and currents from DC to AC, while the exchange of power can be in both directions from AC to DC (rectifier mode) and from DC to AC (inverter mode). The ideal switch is IGBT with antiparallel diode to allow the flow of current in both directions [36].

The grid side filter is normally composed of at least three inductances (L), which are the link between each output phase of the converter and the grid voltage. The grid voltage is normally supplied through a transformer. This AC voltage is supposed to be balanced and sinusoidal under normal operation conditions.

The rotor side converter along with dv/dt filter is used to supply the rotor of the DFIM. The dv/dt filter is located mainly with the objective to protect the machine from the harmful effects of the voltage source converter, such as capacitive leakage currents [34]. The rotor side converter is connected to the grid side converter by the DC link capacitor.

3.8 DC Link system:

The DC part of the back-to-back converter is typically called the DC link. It tries to maintain a constant voltage at its terminal, by storing the energy in it. It is the linkage between the grid side and rotor side converters [36].

The DC link can be modelled by calculating DC bus voltage as shown below.

$$V_{bus} = \frac{1}{C_{bus}} \int i_c \, dt$$

3.9 Vector control of DFIG wind system:

Vector control of DFIG wind system provides decoupled control of active and reactive power produced by DFIG, by controlling the rotor currents independently. The RSC can realize the decouple control of active and reactive power by adopting the stator flux or voltage control strategy while the GSC can realize the control of the DC link and network power factor by using the grid voltage oriented vector control strategy [38].

3.9.1 Grid side converter control system:

Figure 3.6 shows the vector control system for grid side converter.

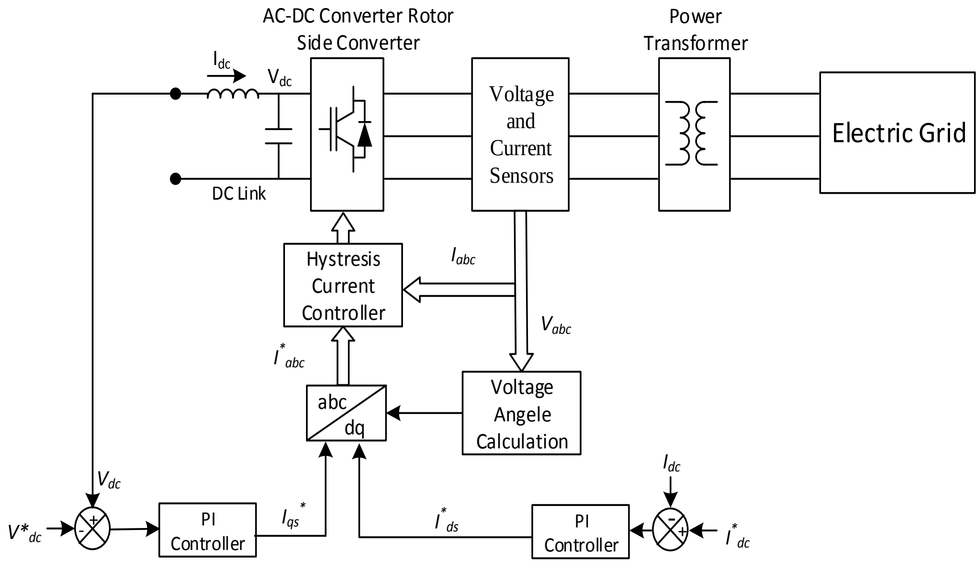

Figure 3.6 Grid side converter control system [38].

The grid-side converter controls the flow of real and reactive power to the grid, through the grid interfacing inductance. The objective of the grid-side converter is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. The vector control method is used as well, with a reference frame oriented along the stator voltage vector position, enabling independent control of the active and reactive power flowing between the grid and the converter. The

PWM converter is current regulated, with the q-axis current used to regulate the dc-link voltage and the d-axis current component to regulate the reactive power.

3.9.2 Rotor side converter control system:

Figure 3.7 shows the vector control system for rotor side converter.

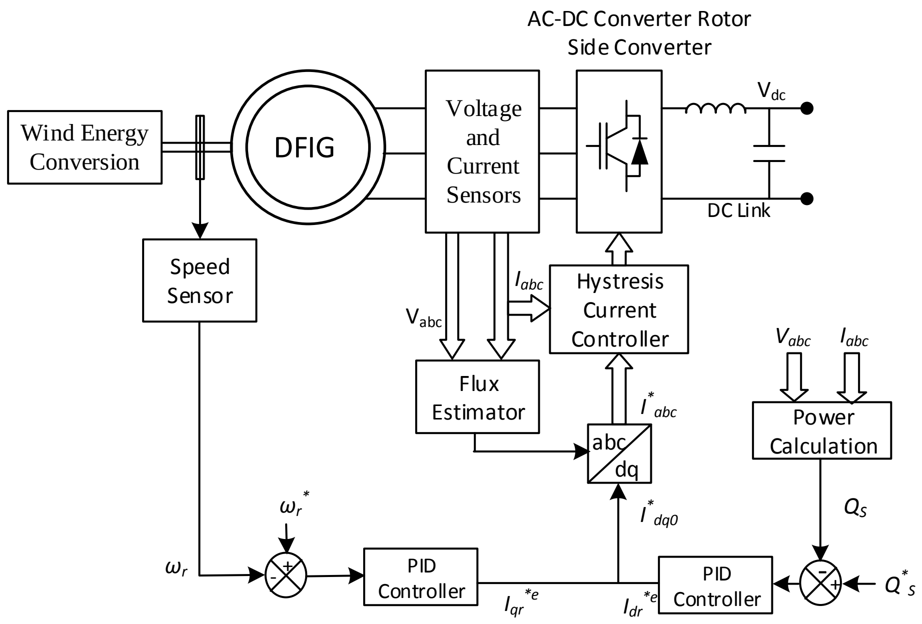

Figure 3.7 Rotor side converter control system [38].

The rotor-side converter (RSC) provides the excitation for the induction machine rotor. With this PWM converter it is possible to control the torque hence the speed of the DFIG and also the power factor at the stator terminals.

The rotor-side converter provides a varying excitation frequency depending on the wind speed conditions. The induction machine is controlled in a synchronously rotating dq axis frame, with the *d*-axis oriented along the stator-flux vector position in one common implementation. This is called stator-flux orientation (SFO) vector control [39].

3.10 Modeling of DFIG based wind system in PSCAD:

This addresses the way of modeling the DFIG based wind system in PSCAD software. Here, the standard components available in PSCAD have been used for wound rotor induction machine, wind turbine. The power electronic IGBT switches with anti-parallel diodes have been used as switches in Back-Back power electronic converter. The firing pulses to the switches have been generated by vector control technique as explained previously. DC link voltage, current is the reference values to generate the firing pulses to the grid side converter, which will maintain the constant DC link voltage. The machine speed, reactive power is the reference value to generate the firing pulses to the rotor side converter, which is responsible for decouple active and reactive power flow. This has been simulated for constant and variable wind velocity. All the protection circuits have been considered in the Back-Back voltage source converter.

The parameters used for different components in the system are listed in Appendix.

Chapter 4

Fault Direction Estimation Algorithms

4.1 Introduction:

In a traditional distribution system, Overcurrent relays are used as primary protection. However, if system contains loop supply schemes or parallel lines, then we need for directional relay for improved performance. When a remote wind farm unit is connected to the utility power system through a distribution line, the overcurrent relay at the common coupling point needs a directional feature.

There are two ways to find logic for directional relay. One is using the power frequency data and the other is using the traveling-wave data generated by the fault. But, the problems with the second one are availability of the short duration of data for decision making and no appearance of a traveling wave if a fault occurs at a voltage inception angle close to zero degrees. This may lead to mis operation and may affect accuracy and reliability.

Hence the method of estimating the power-flow direction by using fundamental frequency data of voltage and current information is mostly used in directional relays.

This chapter explains two existing algorithms for fault direction estimation in detail for DG integrated distribution systems. First algorithm is based on phase angle change in sequence currents. Second algorithm is based on the positive sequence incremental impedance diagram. It also addresses proposed modified algorithm to the second algorithm.

4.2 Algorithm based on Phase change in sequence current [40]:

The direction of a fault on a line can be determined from the phase angles of voltage and current phasors. Generally A polarizing quantity, mostly voltage phasor will be used as the reference. In such an arrangement, the fault current phasors lie in two distinct regions depending on the direction of the fault and pre fault system conditions [40]. These two regions can be shown in Fig. 4.2

Consider a distribution system, for which a DFIG wind DG unit is coupled at the point of common coupling point through a distribution line as shown in Fig.4.1.

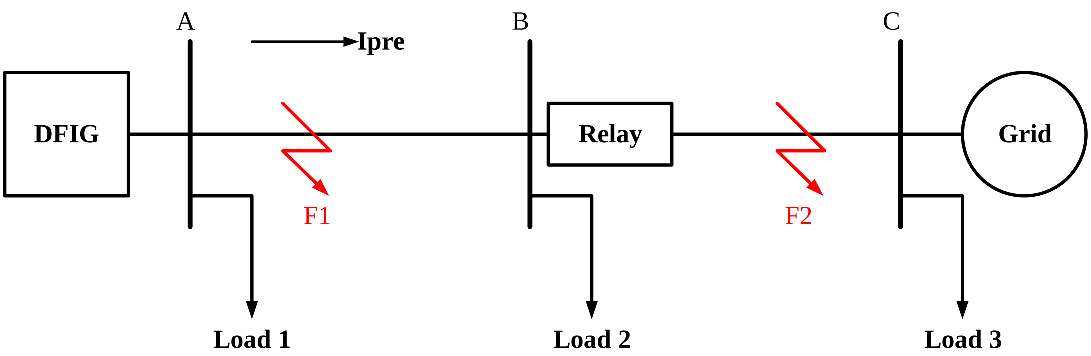

Figure 4.1 Single-line diagram of the three-phase radial distribution system [40].

In this algorithm, authors proposed the fault direction estimation for radial systems based on phase change in current phasor during the fault. This method uses only fault current signals.

Figure 4.1 shows that, DG source at bus A is connected to the distribution system at C through a line. The source at A feeds power to the system and the power-flow direction is always from A to B. At the common coupling point B, the relay is located where direction estimation is required for protection. The upstream and downstream areas in the system correspond to points F1 and F2 in the diagram. If we take the direction of fault into consideration, then fault F2 is referred to forward fault and fault F1 is referred to reverse fault [40].

To illustrate the phase angle of current phasor during upstream and downstream fault conditions, let us consider the following analysis [40].

The pre fault current in line is given by

$$I_{pre} = (V_A - V_C)/Z$$

Where, V_A and V_B are the bus voltages and Z is the total line impedance. For the fault at F_1, the fault component of current at bus B is given by

$$I_{F1} = V_C/Z_1$$

Where, V_C is the bus voltage and Z_1 is the corresponding line impedance from C to F_1. Similarly, for the fault at F_2, the fault component of current at bus B is given as

$$I_{F2} = V_A/Z_2$$

Where, Z_1 is the corresponding line impedance from A to F_2.

During the fault at F1 and F2, the currents at bus B will be,

$$I_1 = I_{pre} - I_{F1} = \frac{(V_A - V_C)}{Z} - \frac{V_C}{Z_1}$$

$$I_2 = I_{pre} + I_{F2} = \frac{(V_A - V_C)}{Z} + \frac{V_A}{Z_2}$$

If V_A and V_C have the same magnitude and phase, $Z=Z_1=Z_2$, then from the equations it is inferred that, I_1 and I_2 are exactly out of phase. This can also be observed from Fig. 4.2.

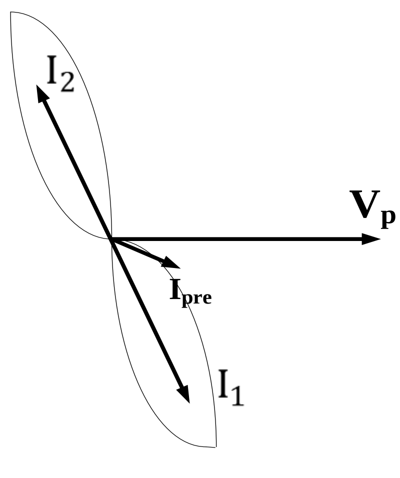

Figure 4.2 fault current regions [40].

4.2.1 Method for 3 phase systems:

From the above analysis, it is observed that fault currents remain in different regions with respect to the pre fault current. Thus, the direction of fault can be identified from the fault phasor position with respect to the pre fault phasor. The phase angle difference of fault and pre fault current phasors for the upstream case (F1) is positive and for downstream (F2), it is negative [40].

In case of 3-phase radial distribution system, the positive-sequence component is estimated for fault and pre fault currents and then the phase angle difference is computed between them to estimate the fault direction. This phase angle difference is positive for upstream or reverse fault and is negative for downstream or forward fault.

The following steps will explain this existing algorithm.

Step 1: Create the fault at F1 or F2.

Step 2: Acquire the current data at the relay point.

Step 3: Estimate the current phasors using Digital filter.

Step 4: Compute the positive sequence components.

Step 5: Compute the phase angle change between pre and post fault current phasors

Step 6: Obtain the fault direction based on sign of phase angle change.

4.2.2 Implementation in PSCAD:

This existing algorithm has been tested by applying to the system shown in Fig.4.1. The system has been simulated in PSCAD for different fault cases such as Line-Ground fault, Line-Line fault, Line-Line-Ground fault and LLL fault by varying the severity of the fault i.e. for different values of fault resistances. The results are presented in next chapter.

4.2.3 Advantages and Improvements:

This existing algorithm is very simple for implementation. But, the drawback of this method is it can't identify the downstream fault of less severity that means with more fault resistance.

Positive sequence Incremental Impedance based Algorithm [43]:

This is an existing algorithm in the literature [43], and it is used to estimate the direction of fault for all conditions. The Positive sequence Incremental Impedance diagram in R-X plane will give the sufficient information to identify the direction of fault either in upstream or downstream.

4.2.4 Principle of operation:

Consider the same system which is used in previous algorithm which is shown in Fig.4.4 to which this algorithm is applied.

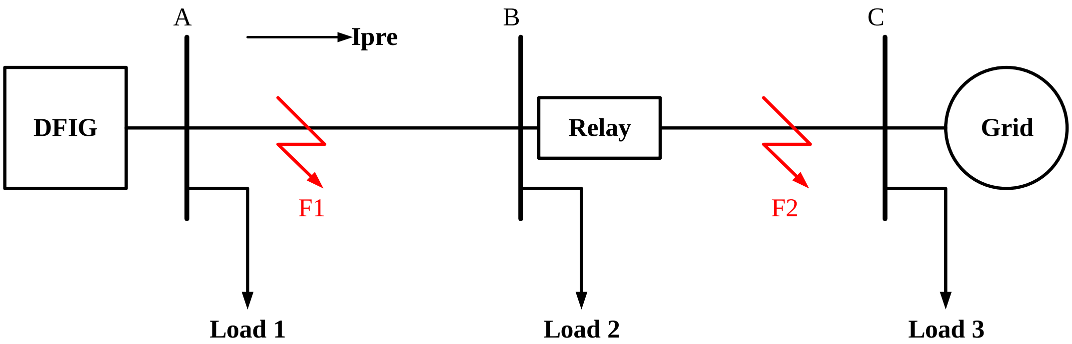

Figure 4.4 Single-line diagram of the three-phase radial distribution system [40].

The voltage and current information which is sensed at the relay point will be used for further processing of algorithm.

The incremental positive sequence voltage and current phasors at the local relay location have been computed which are denoted by the changes ΔV_1, ΔI_1 caused by the application of the fault at location F1 or F2. Now, the positive sequence impedance will be computed using the relationship $\Delta V_1/\Delta I_1$. This impedance will be plotted in R-X plane which will give the useful information. This impedance plot is expected to lie in the third quadrant for a forward fault (F_2) and in the first quadrant for a reverse fault (F_1).

4.2.5 Implementation of Directional logic:

A time delay of 5 cycles has been chosen for the interval between the two phasors to be subtracted to calculate the incremental voltage and current signals. If the fundamental period is T then the incremental positive sequence voltage and current signals are calculated as given below [43], where T_d is the no. of cycles for time delay.

$$\Delta V_1 = V_{1(t)} - V_{1(t-Td)}$$

$$\Delta I_1 = I_{1(t)} - I_{1(t-Td)}$$

The duration of the directional signal is therefore for 5 cycles. Thereafter the $\Delta V_1$and ΔI_1 signals will become very small and the $\Delta V_1/\Delta I_1$ signal is meaningless. In fact, the duration time delay has to be decided by trial and error by changing different values, for which the appropriate logic can be found for different faults such as LG, LL, LLG and LLL faults [43].

4.2.6 Modification to the Existing positive sequence incremental impedance based Algorithm:

A modification has been proposed here for the existing incremental impedance based algorithm by changing the number of cycles for time delay to 2 cycles in directional logic implementation. This will be helpful for the relay to respond quickly.

In this method, the system has been simulated by applying this algorithm for a time delay of both 5 cycles and 2 cycles. The results have been presented in chapter 5. The results of this modified algorithm show that, it is able to give clear indication of the direction of the fault.

The incremental positive sequence voltage and current signals are,

$$\Delta V_1 = V_{1(t)} - V_{1(t-2T)}$$

$$\Delta I_1 = I_{1(t)} - I_{1(t-2T)}$$

Figure 4.5 shows the implementation of the direction logic for the modified algorithm.

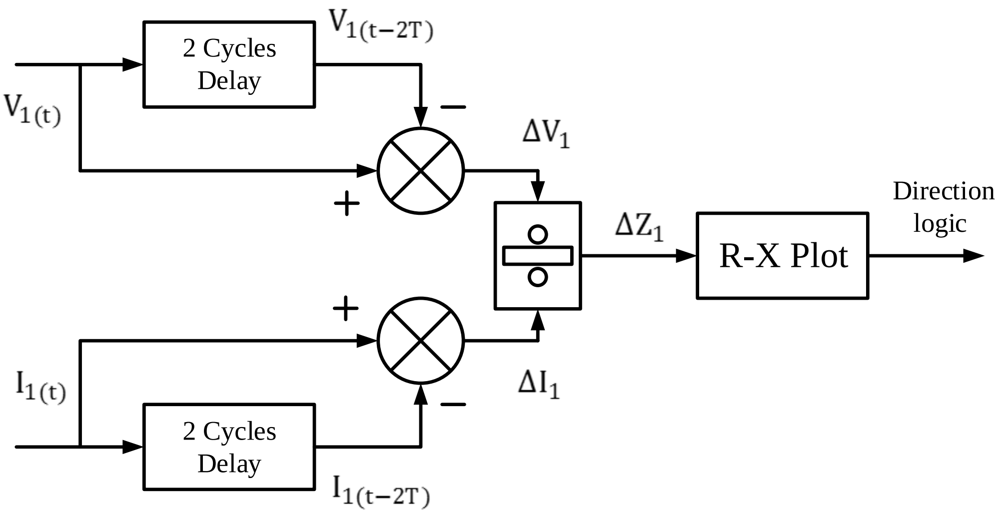

Figure 4.5.Directional element implementation.

4.2.7 Implementation in PSCAD:

The system shown in single line diagram given by Fig. 4.1 has been simulated in PSCAD, by employing this algorithm to it for different fault cases such as Line-Ground fault, Line-Line fault, Line-Line-Ground fault and LLL fault by varying the severity of the fault i.e. for different values of fault resistances i.e. for R_f=0,10,25,100Ω.

The results of this modified algorithm are presented in detail in next chapter.

4.2.8 Advantages:

- This modified algorithm is more efficient for all types of faults even with more resistance.
- This will be useful for the relay to respond quickly.
- This directional element can be integrated into numerical distance relay.

Chapter 5

Results of Algorithms

5.1 Results of Algorithm based on Phase change in sequence current:

This existing Algorithm is based on computing the phase angle difference between the positive-sequence post fault and pre fault current phasors is the proper indication to estimate the direction of the fault.

The single line diagram of the system shown in Fig.4.1 has been simulated in PSCAD for 4 types of faults that are LG, LL, LLG and LLL faults with fault resistance equal to 0, 10, 50, 100,500Ω for both forward and reverse directions. The results show that the phase angle difference is positive for upward (reverse) fault and it is negative for downward (forward) fault. Also it is observed that there is a phase opposition for the reverse fault currents compared to forward fault.

Figure 5.1 shows the results for downward (forward) LG fault for $R_{F=}0$, where channel 'pch' is phase angle difference and Ia1, Ia2 are pre-fault currents before and after relay point respectively. Ia2, Ia3 are post-fault currents before and after relay point respectively.

Figure 5.2 shows the results for upward (reverse) LG fault for $R_{F=}0$, where channel 'pch' is phase angle difference and Ia1, Ia2 are pre-fault currents before and after relay point respectively. Ia2, Ia3 are post-fault currents before and after relay point respectively.

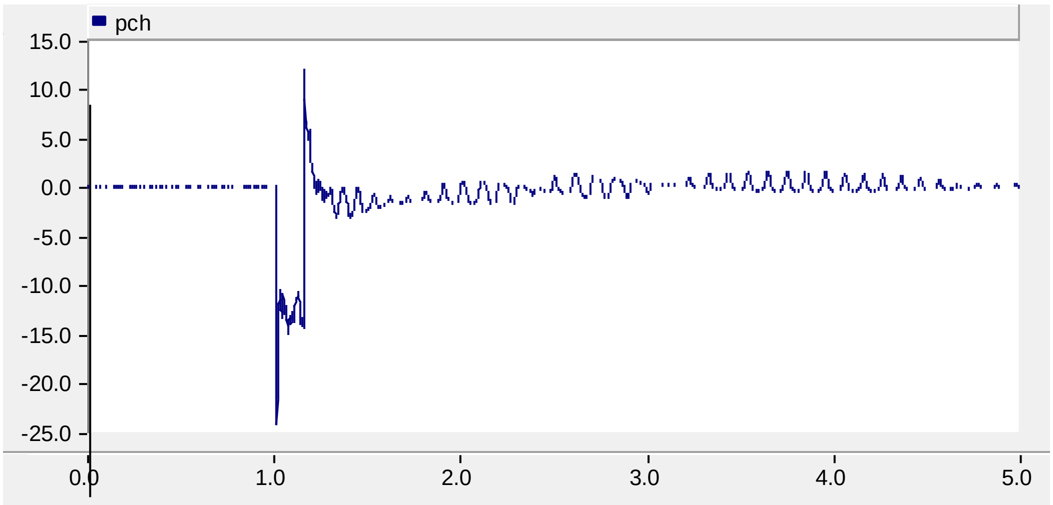

Figure. 5.1 (a) X-axis: time (s), Y-Axis: Angle (degree)

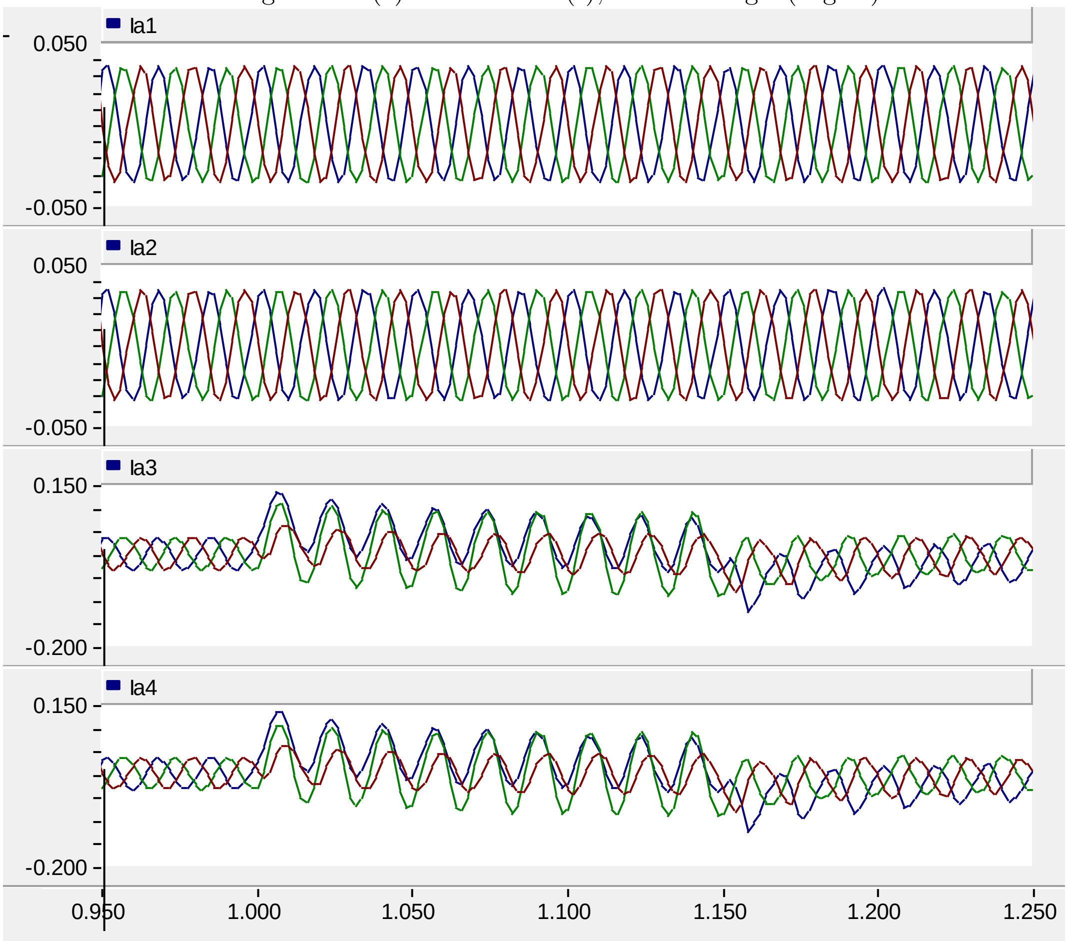

Figure. 5.1 (b) X-axis: time (s), Y-Axis: Current (kA)

Figure 5.1 Phase change and fault current waveforms for forward(downward) LG fault for Rf=0.

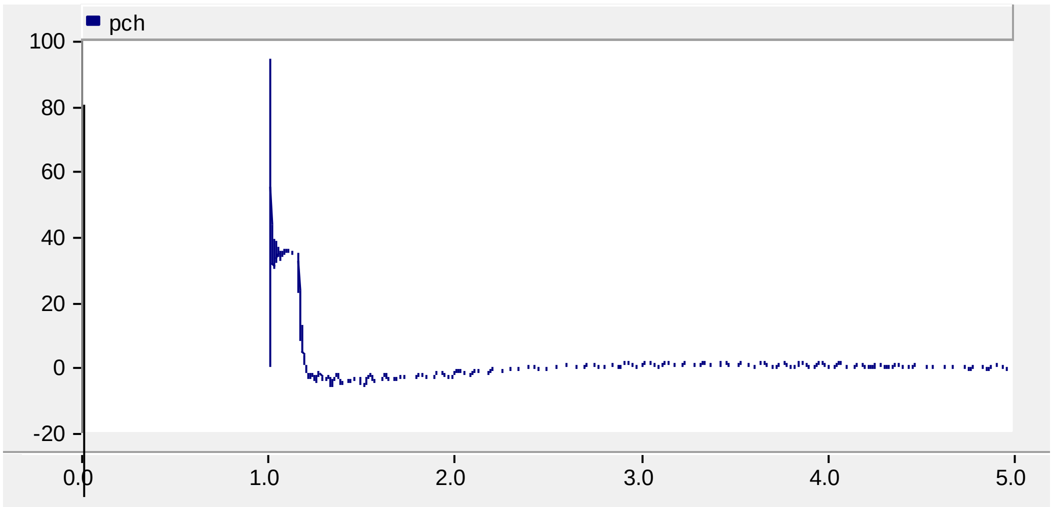

Figure. 5.2 (a) X-axis: time (s), Y-Axis: Angle (degree)

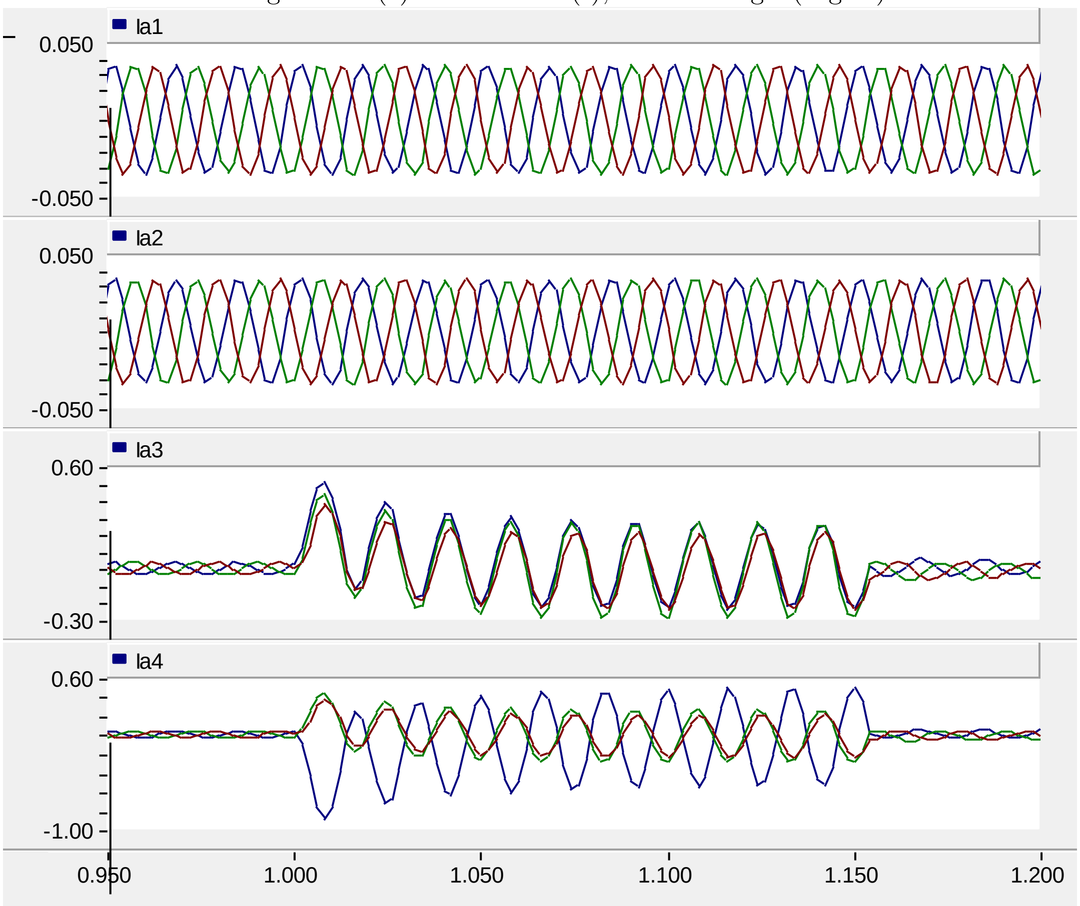

Figure. 5.2 (b) X-axis: time (s), Y-Axis: Current (kA)

Figure 5.2 Phase change and fault current waveforms for reverse(upward) LG fault for Rf=0.

Figure 5.3 shows the results for downward (forward) LL fault for $R_{F=}0$, channel 'pch' is phase angle difference and Ia1, Ia2 are pre-fault currents before and after relay point respectively. Ia2, Ia3 are post-fault currents before and after relay point respectively.

Figure 5.4 shows the results for upward (reverse) LL fault for $R_{F=}0$, where channel 'pch' is phase angle difference and Ia1, Ia2 are pre-fault currents before and after relay point respectively. Ia2, Ia3 are post-fault currents before and after relay point respectively.

Figure 5.5 shows the results for downward (forward) LLG fault for $R_{F=}0$, where channel 'pch' is phase angle difference and Ia1, Ia2 are pre-fault currents before and after relay point respectively. Ia2, Ia3 are post-fault currents before and after relay point respectively.

Figure 5.6 shows the results for upward (reverse) LLG fault for $R_{F=}0$, where channel 'pch' is phase angle difference and Ia1, Ia2 are pre-fault currents before and after relay point respectively. Ia2, Ia3 are post-fault currents before and after relay point respectively.

Figure 5.7 shows the results for downward (forward) LLL fault for $R_{F=}0$, where channel 'pch' is phase angle difference and Ia1, Ia2 are pre-fault currents before and after relay point respectively. Ia2, Ia3 are post-fault currents before and after relay point respectively.

Figure 5.8 shows the results for upward (reverse) LLL fault for $R_{F=}0$, channel 'pch' is phase angle difference and Ia1, Ia2 are pre-fault currents before and after relay point respectively. Ia2, Ia3 are post-fault currents before and after relay point respectively.

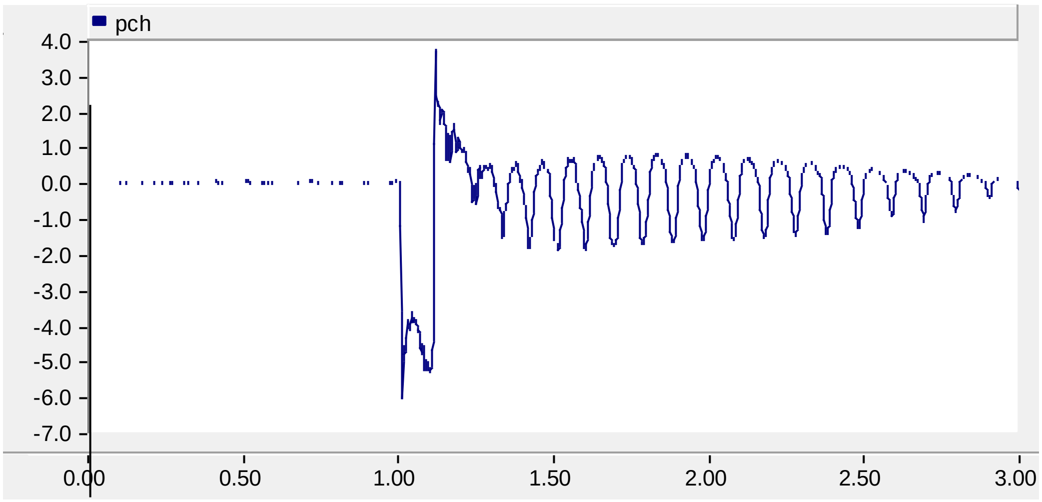

Figure. 5.3 (a) X-axis: time (s), Y-Axis: Angle (degree)

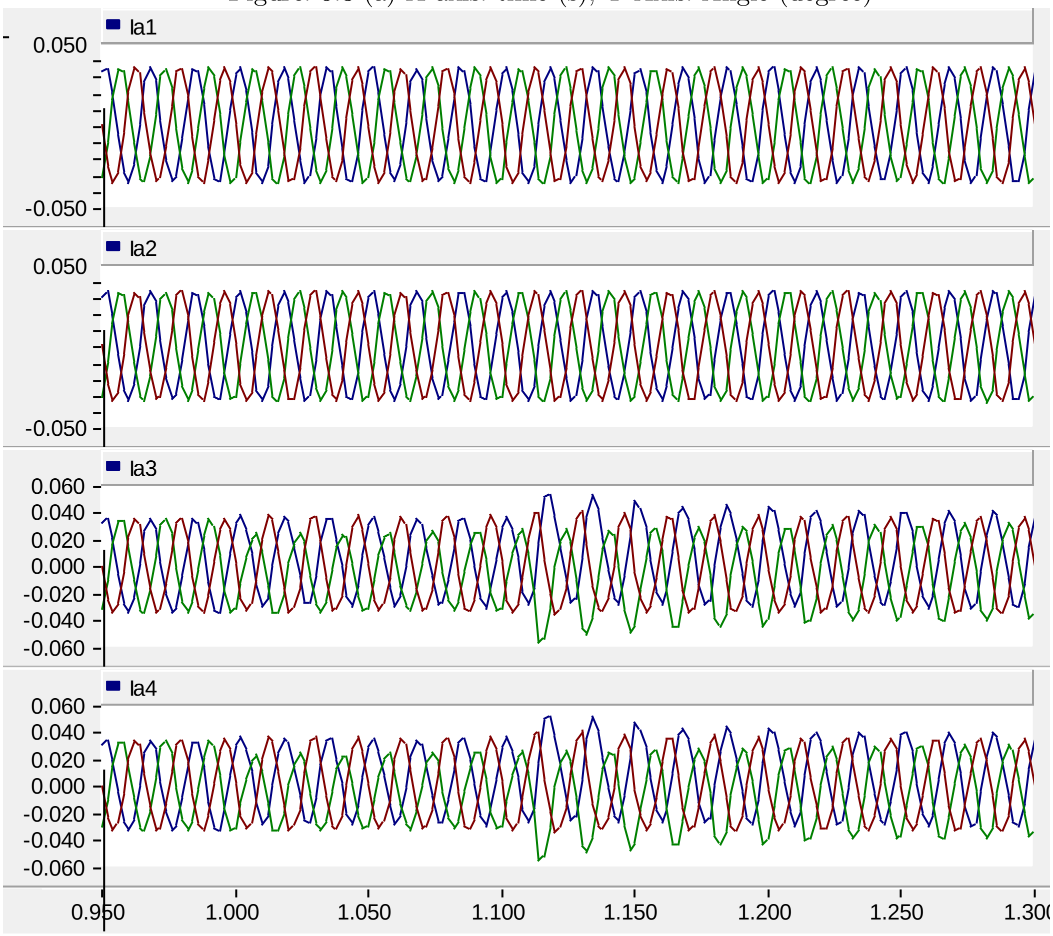

Figure. 5.3 (b) X-axis: time (s), Y-Axis: Current (kA)

Figure 5.3 Phase change and fault current waveforms for forward(downward) LL fault for Rf=0.

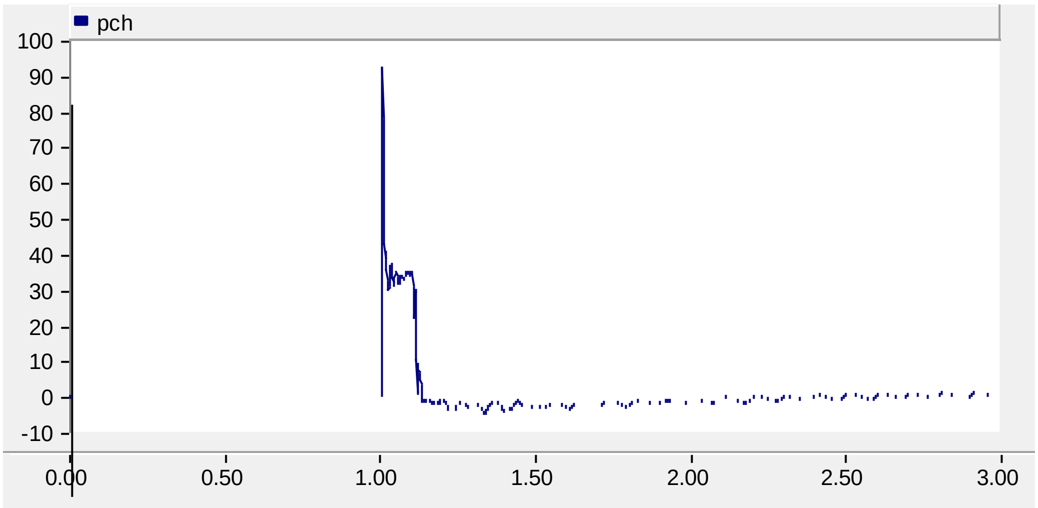

Figure. 5.4 (a) X-axis: time (s), Y-Axis: Angle (degree)

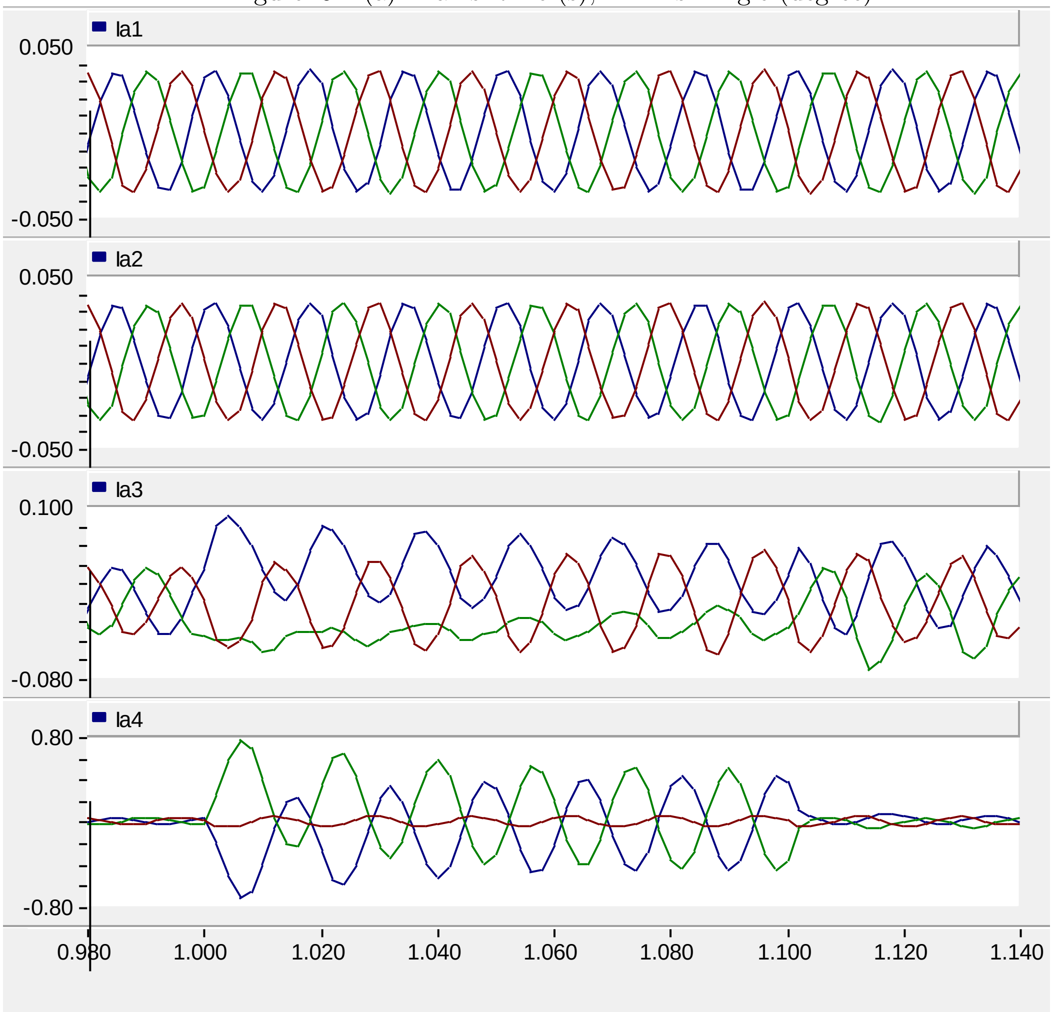

Figure. 5.4 (b) X-axis: time (s), Y-Axis: Current (kA)

Figure 5.4 Phase change and fault current waveforms for reverse(upward) LL fault for Rf=0.

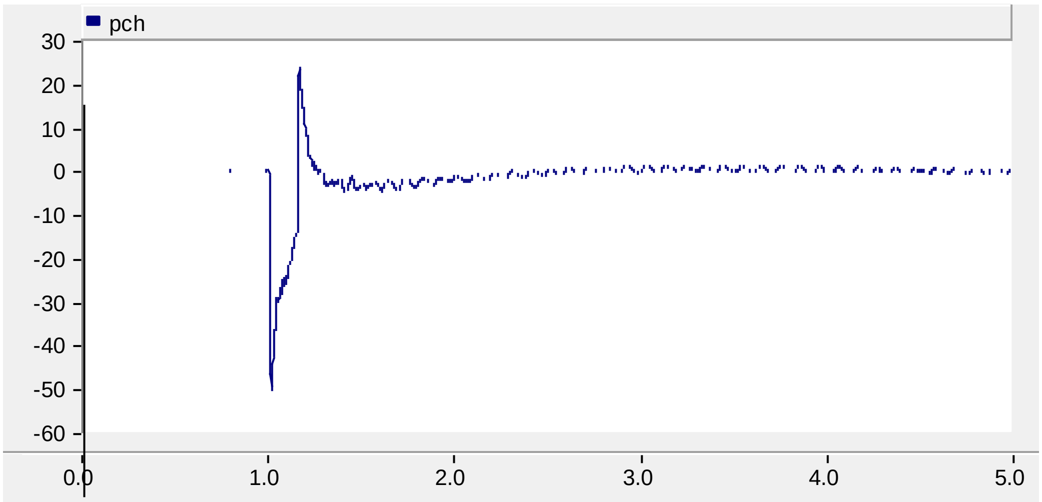

Figure. 5.5 (a) X-axis: time (s), Y-Axis: Angle (degree)

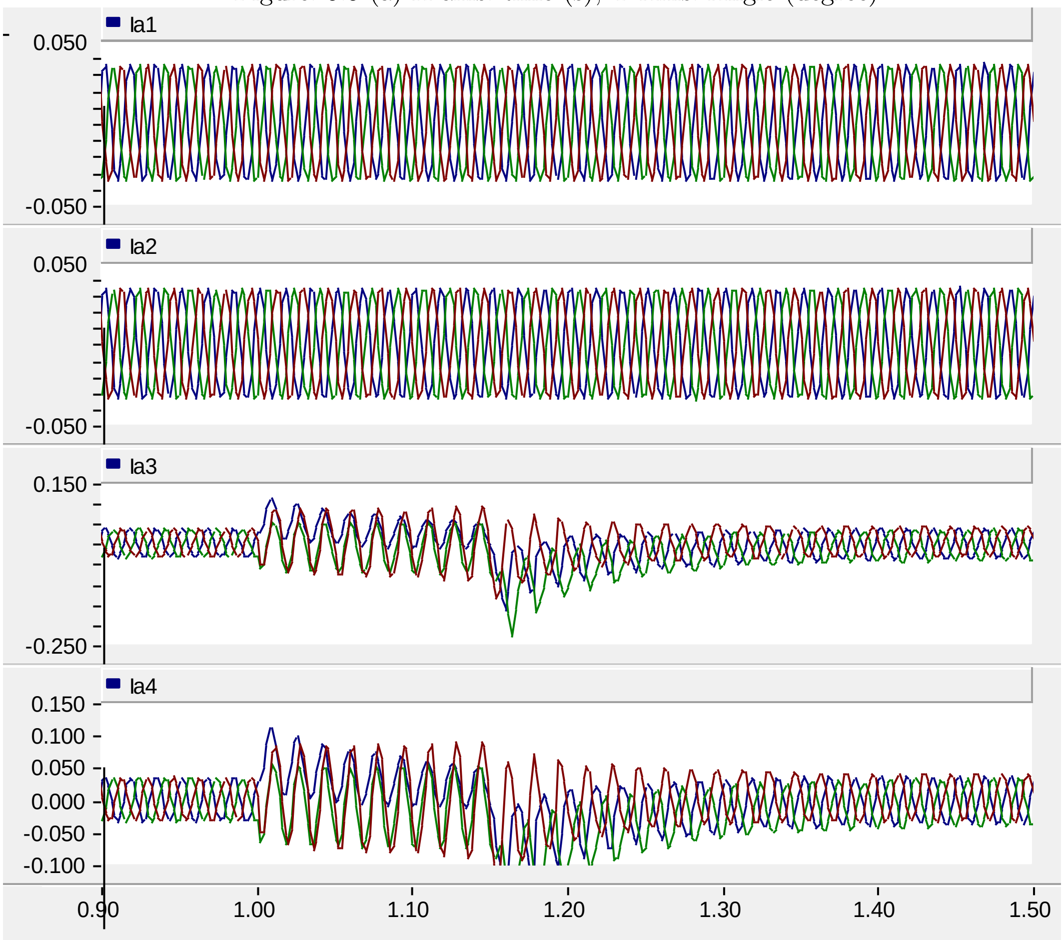

Figure. 5.5 (b) X-axis: time (s), Y-Axis: Current (kA)

Figure 5.5 Phase change and fault current waveforms for forward(downward) LLG fault for Rf=0.

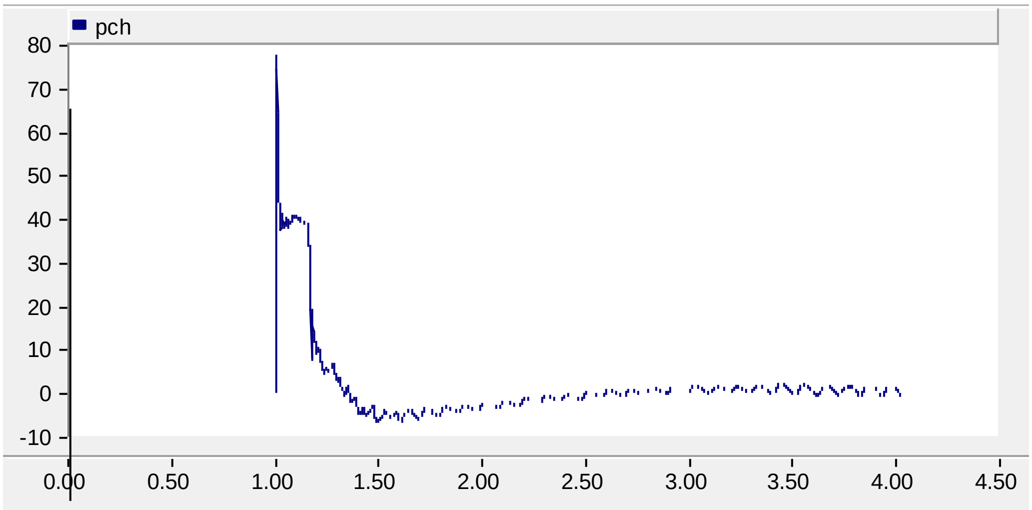

Figure. 5.6 (a) X-axis: time (s), Y-Axis: Angle (degree)

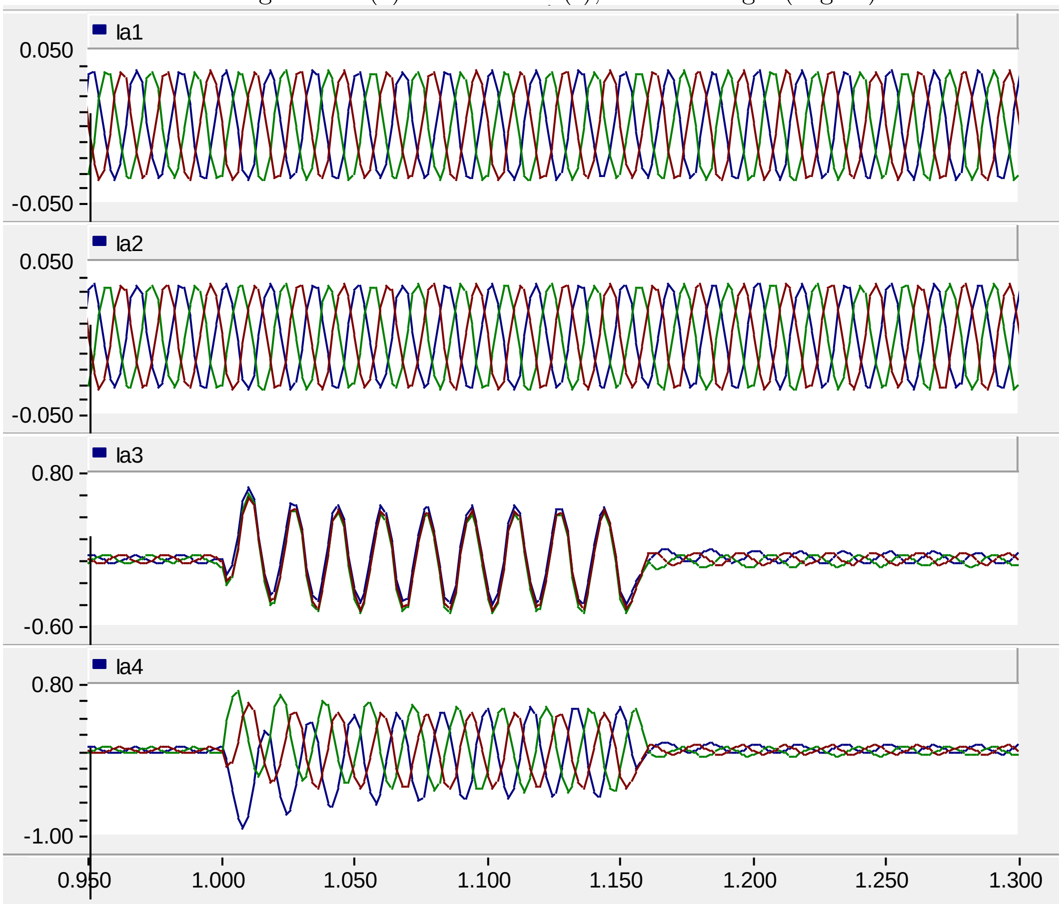

Figure. 5.6 (b) X-axis: time (s), Y-Axis: Current (kA)

Figure 5.6 Phase change and fault current waveforms for reverse(upward) LLG fault for Rf=0.

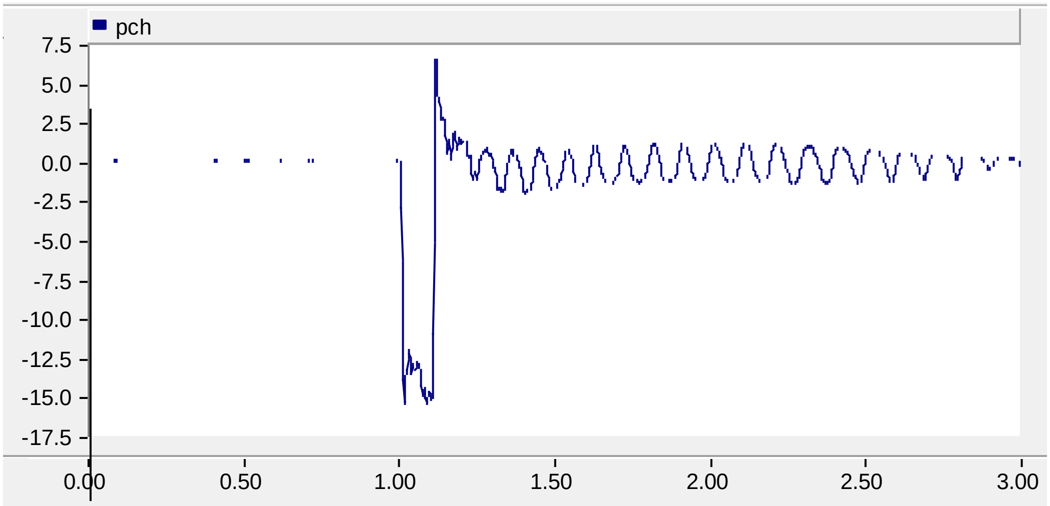

Figure. 5.7 (a) X-axis: time (s), Y-Axis: Angle (degree)

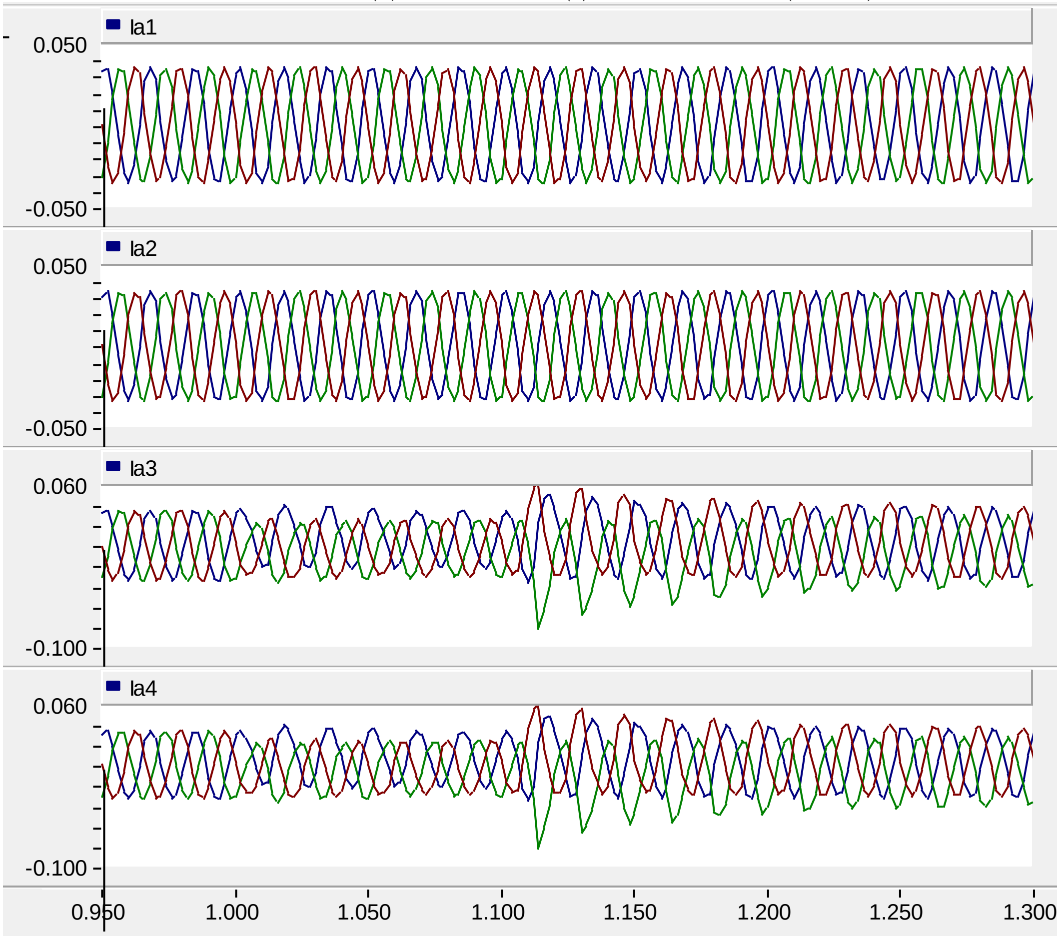

Figure. 5.7 (b) X-axis: time (s), Y-Axis: Current (kA)

Figure 5.7 Phase change and fault current waveforms for forward(downward) LLL fault for Rf=0.

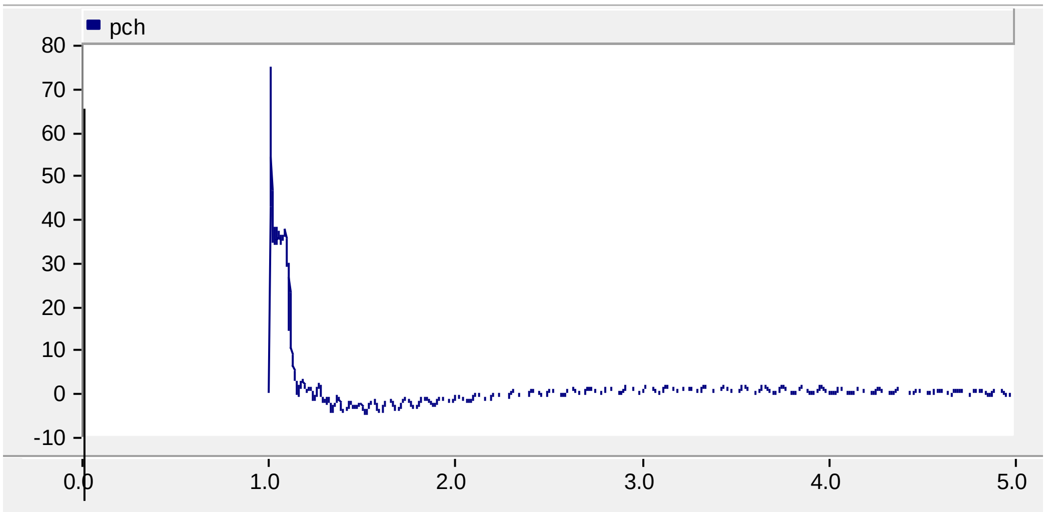

Figure. 5.8 (a) X-axis: time (s), Y-Axis: Angle (degree)

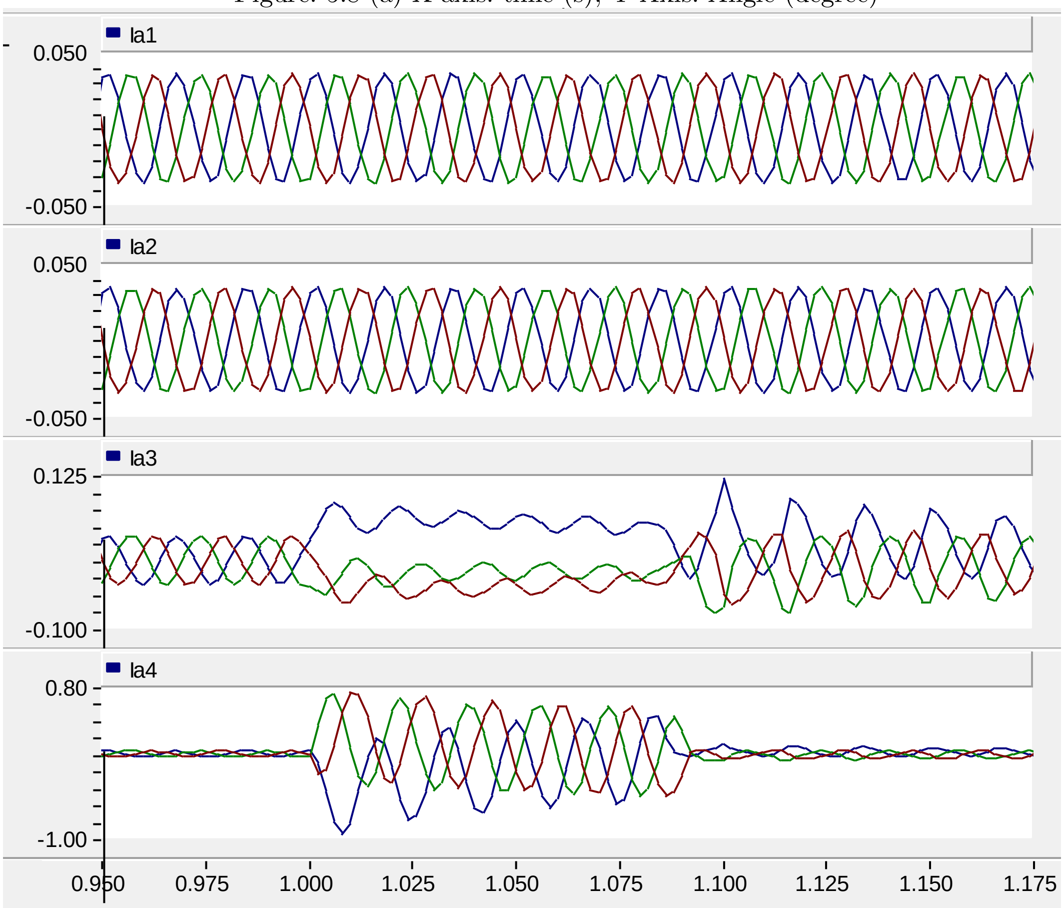

Figure. 5.8 (b) X-axis: time (s), Y-Axis: Current (kA)

Figure 5.8 Phase change and fault current waveforms for reverse(upward) LLL fault for Rf=0.

5.1.1 Observations:

The system model was simulated also for different fault resistance values that is R_F=10, 50,100, 500Ω. From the results it is observed that the algorithm is unable to identify the forward (downward) faults for R_F≥50Ω.

For example Fig. 5.9 show the results for downward (forward) LG fault for $R_{F=}$50, where channel 'pch' is phase angle difference and Ia1, Ia2 are pre-fault currents before and after relay point respectively. Ia2, Ia3 are post-fault currents before and after relay point respectively. Phase angle difference is around zero from observation.

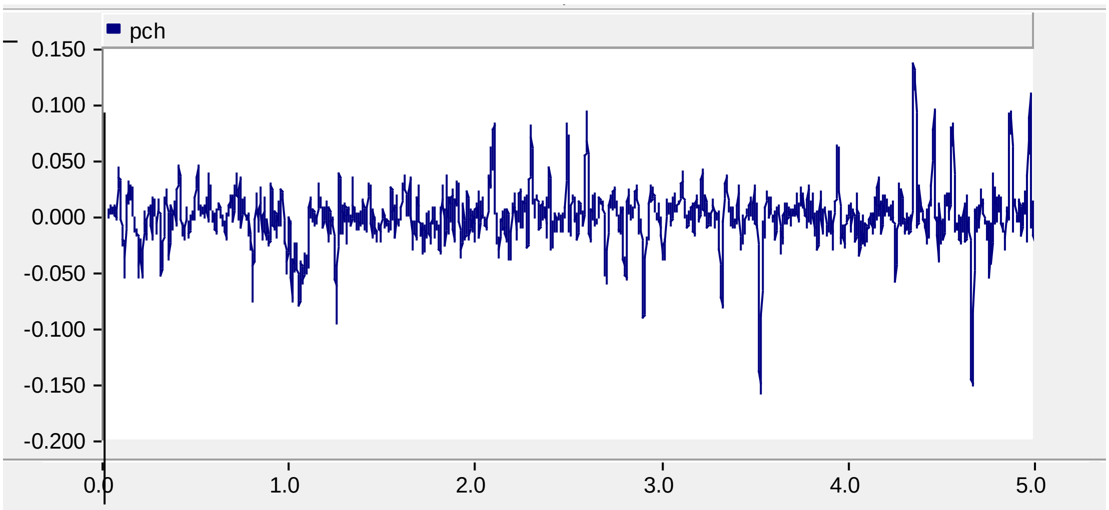

Figure. 5.9 (a) X-axis: time (s), Y-Axis: Angle (degree)

Figure 5.9 Phase change for downward (forward) LLL fault for Rf=100.

5.2 Results of Incremental impedance based Algorithm:

This existing Algorithm is based on computing the positive sequence incremental impedance diagram for the voltage and current phasors and its plot in the R-X plane will give the decision about the direction of fault.

The single line diagram of the system shown in Fig.5.1 has been simulated in PSCAD for 4 types of faults that are LG, LL, LLG and LLL faults with fault resistance equal to 0, 10, 25, 50 and 100Ω for both forward and reverse directions for a time delay of 5 cycles.

The results shows that the plot of incremental positive sequence impedance diagram (crowd of points during fault) in R-X plane is in third quadrant for forward (downward) fault and it is in first quadrant for upward (reverse) fault. Otherwise the distance between crowd of points of plot during fault and pre-fault conditions is more for forward (downward) fault. At the same time it is very less for upward (reverse) fault.

Figure 5.10 shows the results for downward (forward) LG fault for $R_{F=}0$, where plot indicates the plot of incremental positive sequence impedance diagram (crowd of points during fault) in R-X plane. It is clearly observed that plot lies in third quadrant or distance is more between the crowds of points.

Figure 5.11 shows the results for upward (reverse) LG fault for $R_{F=}0$, where plot indicates the plot of incremental positive sequence impedance diagram (crowd of points during fault) in R-X plane. It is clearly observed that plot lies in third quadrant or distance is more between the crowds of points.

Plots from Fig. 5.18 to Fig. 5.25 shows the results for 4 types of faults i.e. for LG, LL, LLG and LLL faults for both the directions for R_F-50, by employing a time delay of 5 cycles to show the advantage of the proposed algorithm for faults with high resistance.

Plots from Fig. 5.26 to Fig. 5.33 shows the results for 4 types of faults for R_F=0, by employing 2 cycles time delay in direction logic implementation, which will useful for relay to react fast. Results show that this algorithm is giving good identification of fault direction.

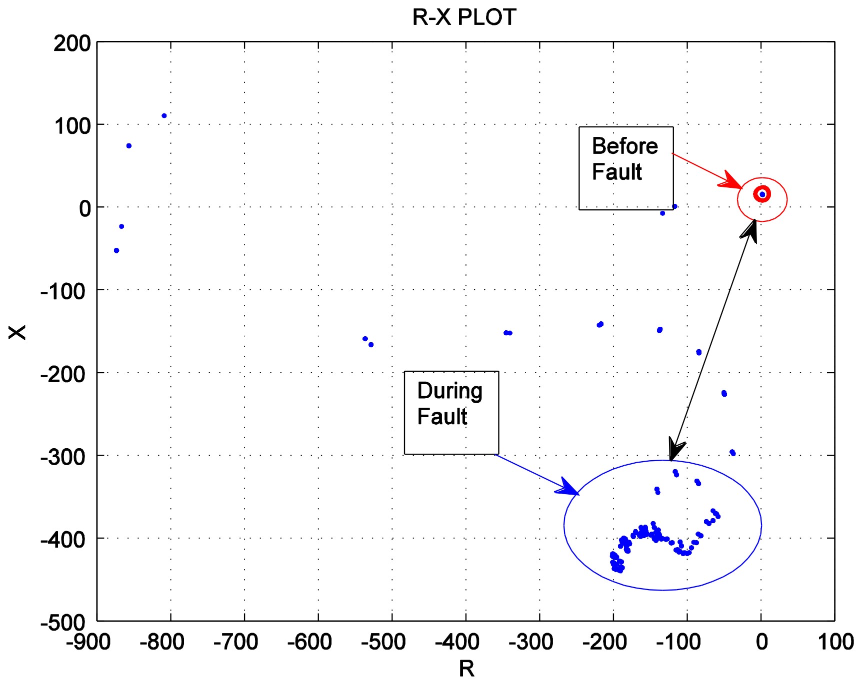

Figure 5.10 R-X Plot for downward (forward) LG fault for $R_{F=}0$, T_d=5 cycles

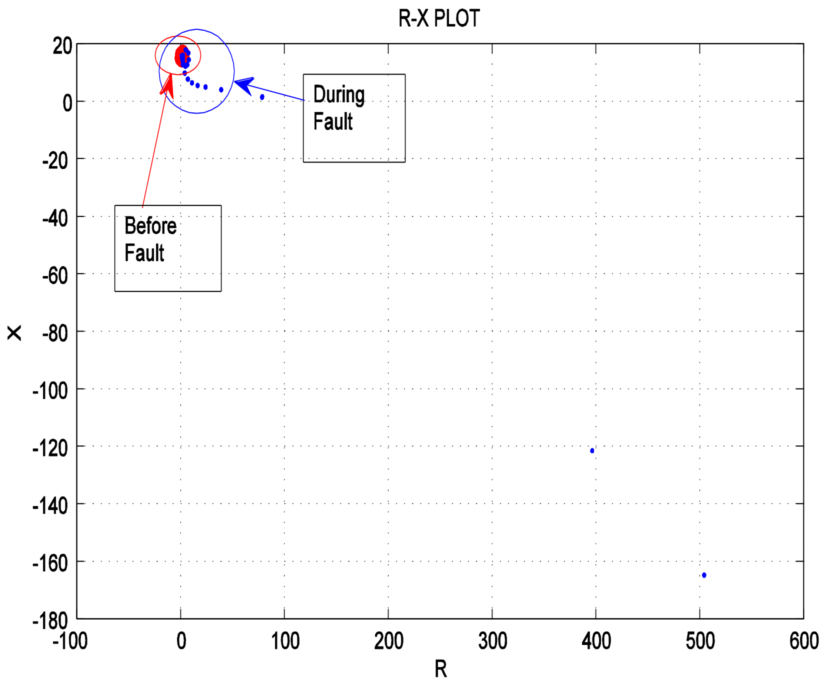

Figure 5.11 R-X Plot for upward (reverse) LG fault for $R_{F=}0$, T_d=5 cycles

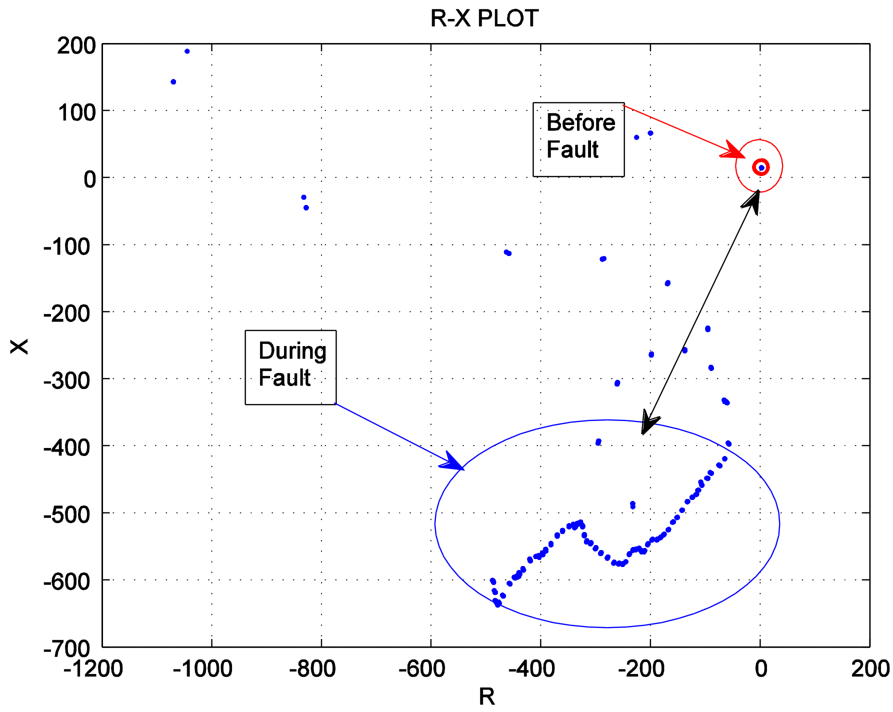

Figure 5.12 R-X Plot for downward (forward) LL fault for $R_{F=}0$, T_d=5 cycles

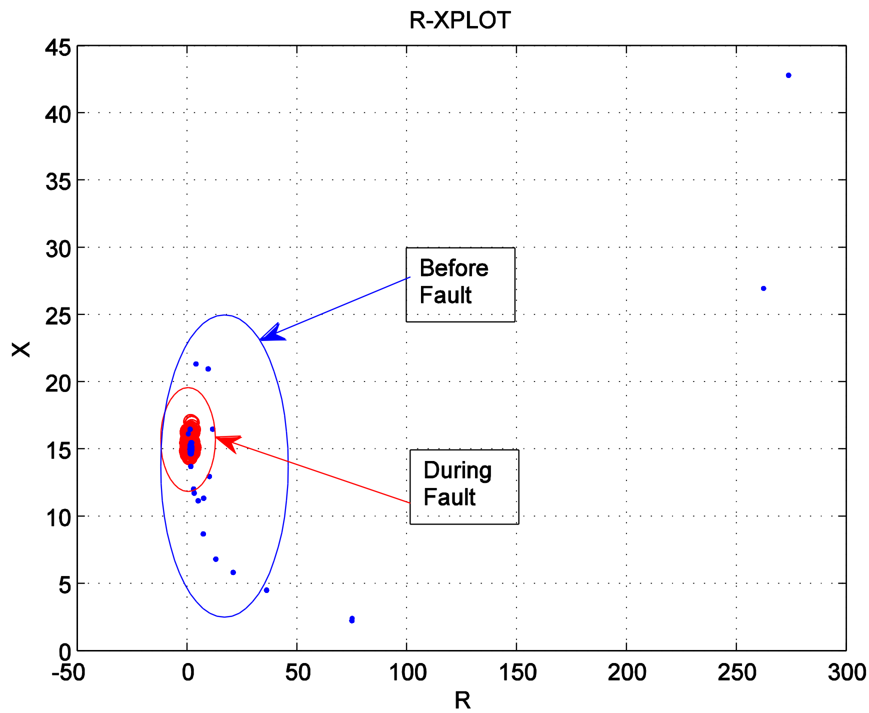

Figure 5.13 R-X Plot for upward (reverse) LL fault for $R_{F=}0$, T_d=5 cycles

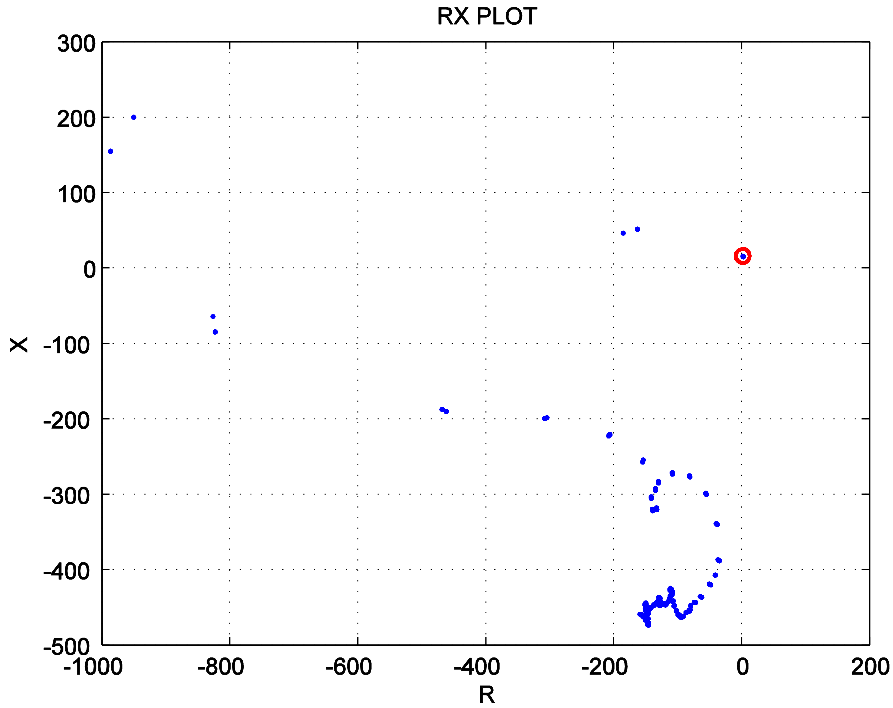

Figure 5.14 R-X Plot for downward (forward) LLG fault for $R_{F=}0$, T_d=5 cycles

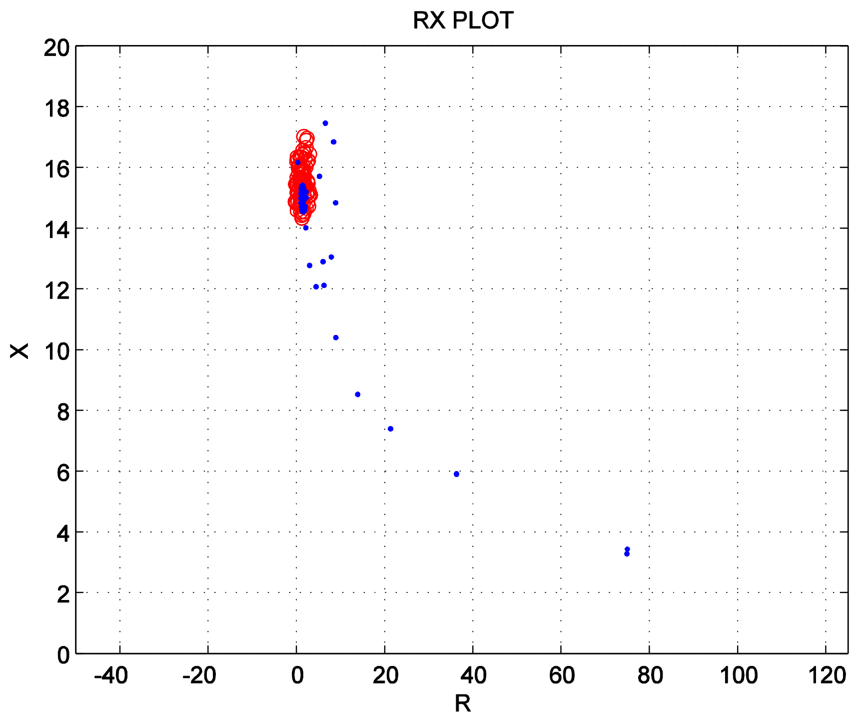

Figure 5.15 R-X Plot for upward (reverse) LLG fault for $R_{F=}0$, T_d=5 cycles

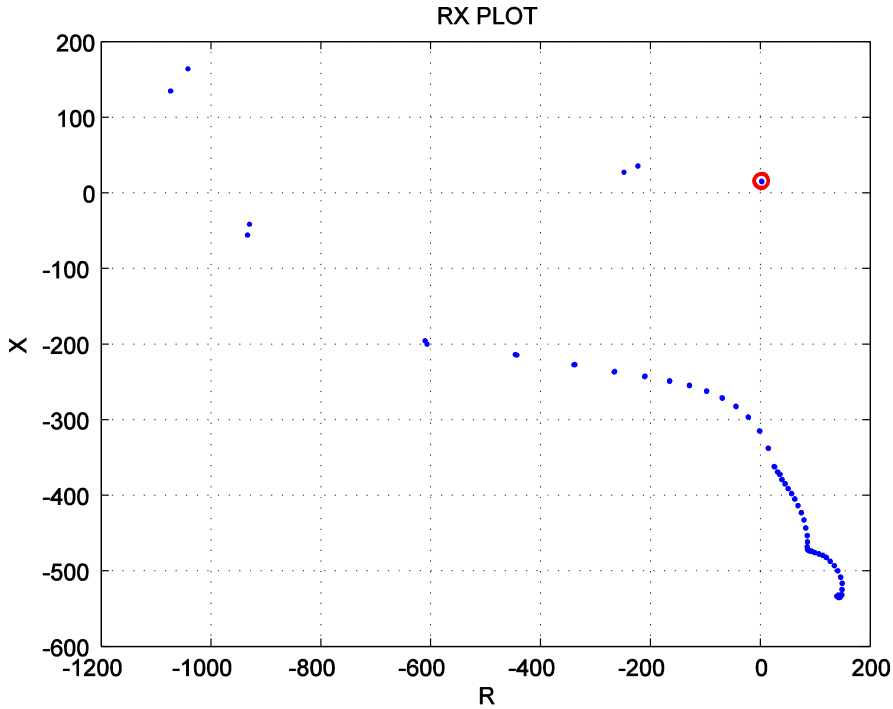

Figure 5.16 R-X Plot for downward (forward) LLL fault for $R_{F=}0$, T_d=5 cycles

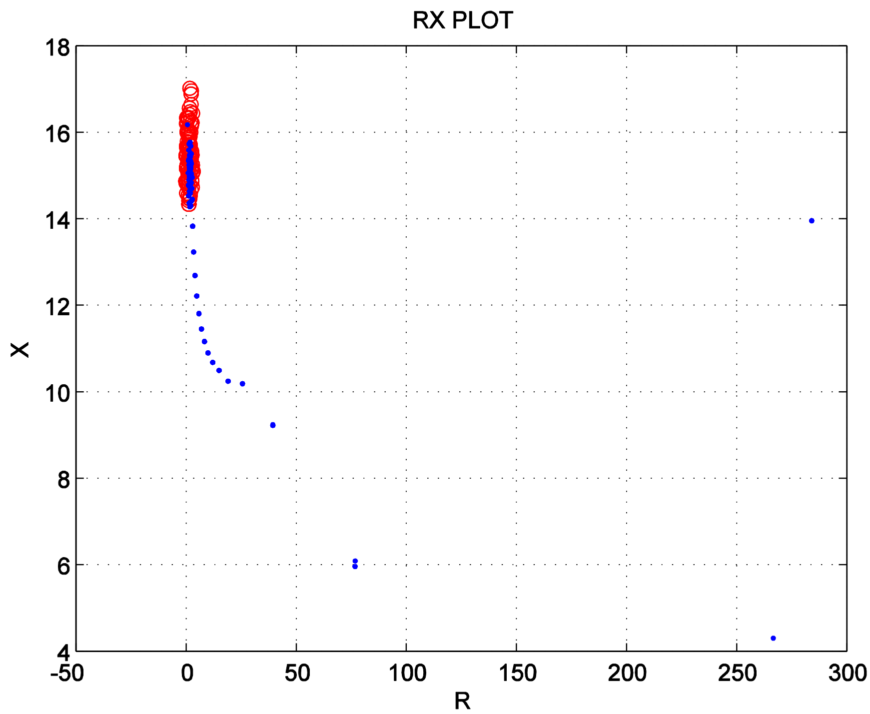

Figure 5.17 R-X Plot for upward (reverse) LLL fault for $R_{F=}0$, T_d=5 cycles

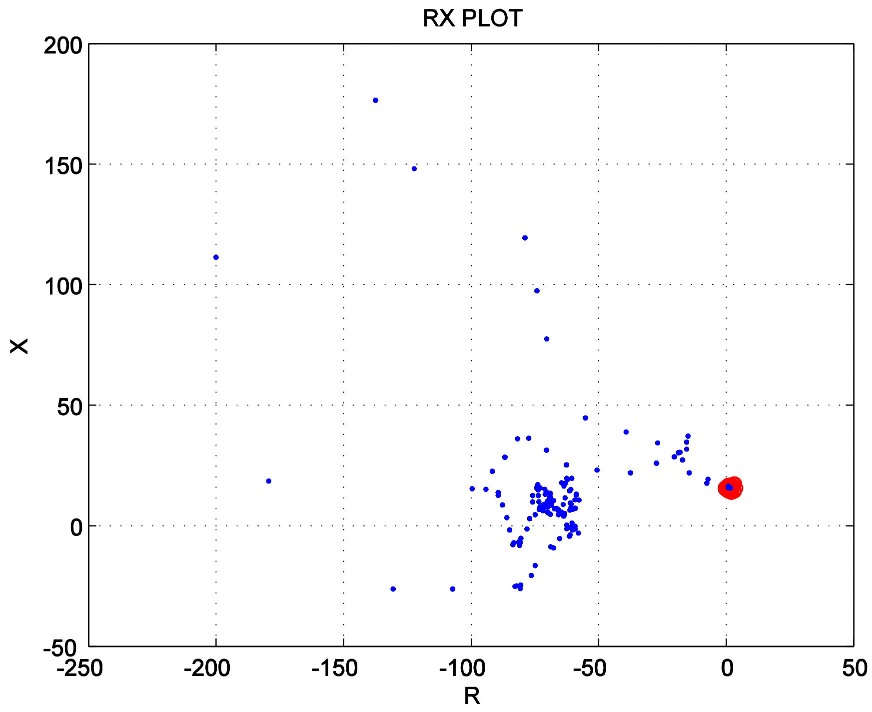

Figure 5.18 R-X Plot for downward (forward) LG fault for $R_{F=}50$, T_d=5 cycles

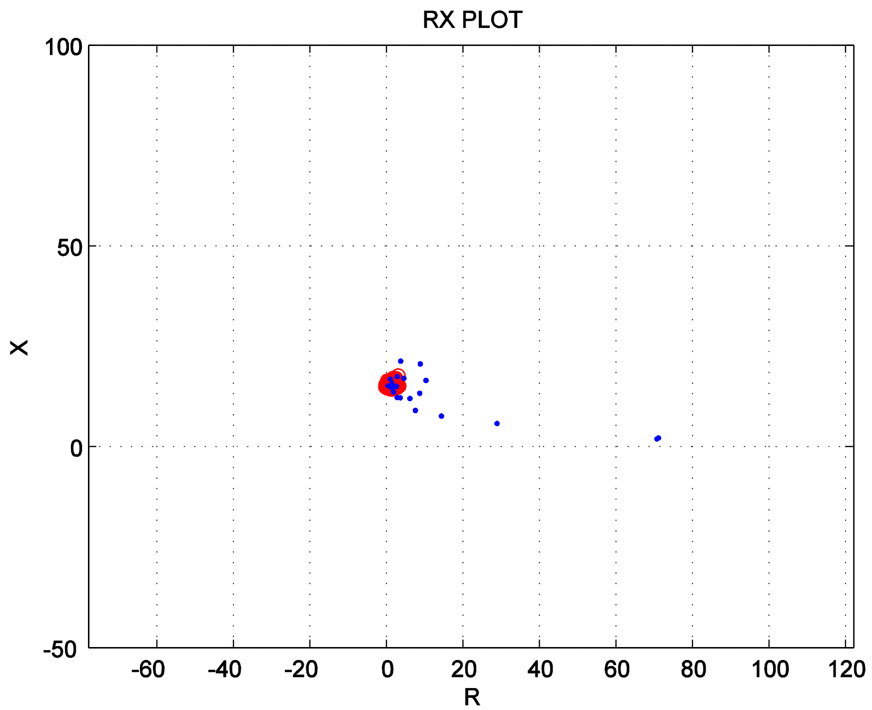

Figure 5.19 R-X Plot for upward (reverse) LG fault for $R_{F=}50$, T_d=5 cycles

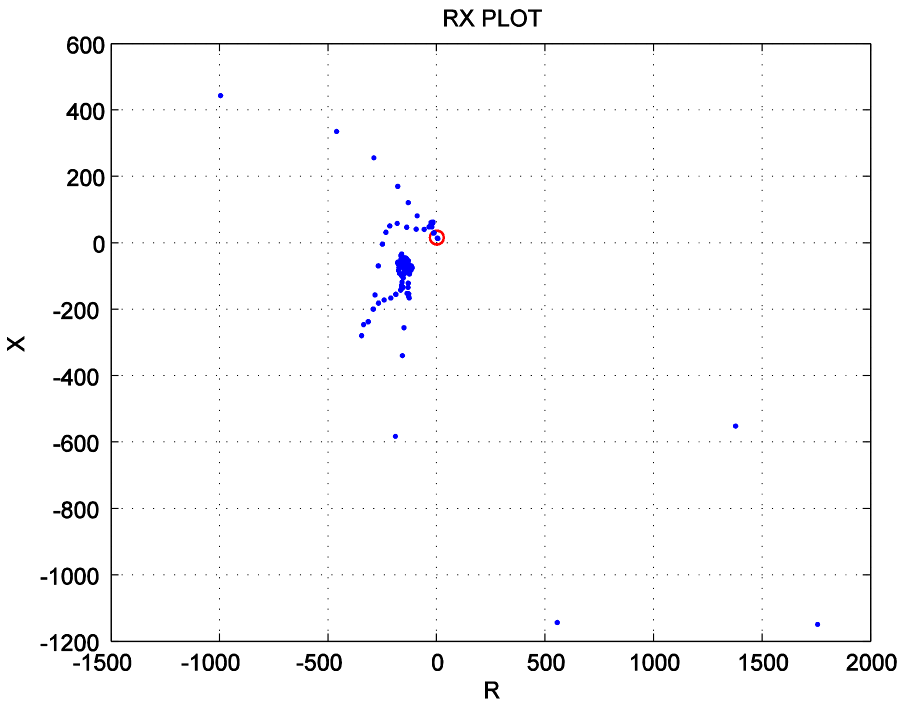

Figure 5.20 R-X Plot for downward (forward) LL fault for $R_{F=}50$, T_d=5 cycles

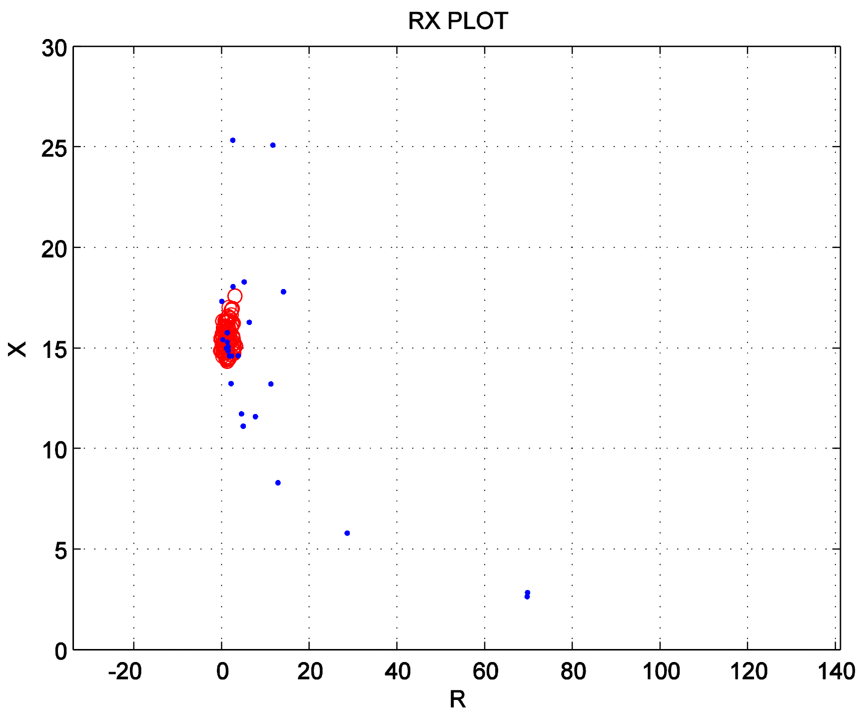

Figure 5.21 R-X Plot for upward (reverse) LL fault for $R_{F=}50$, T_d=5 cycles

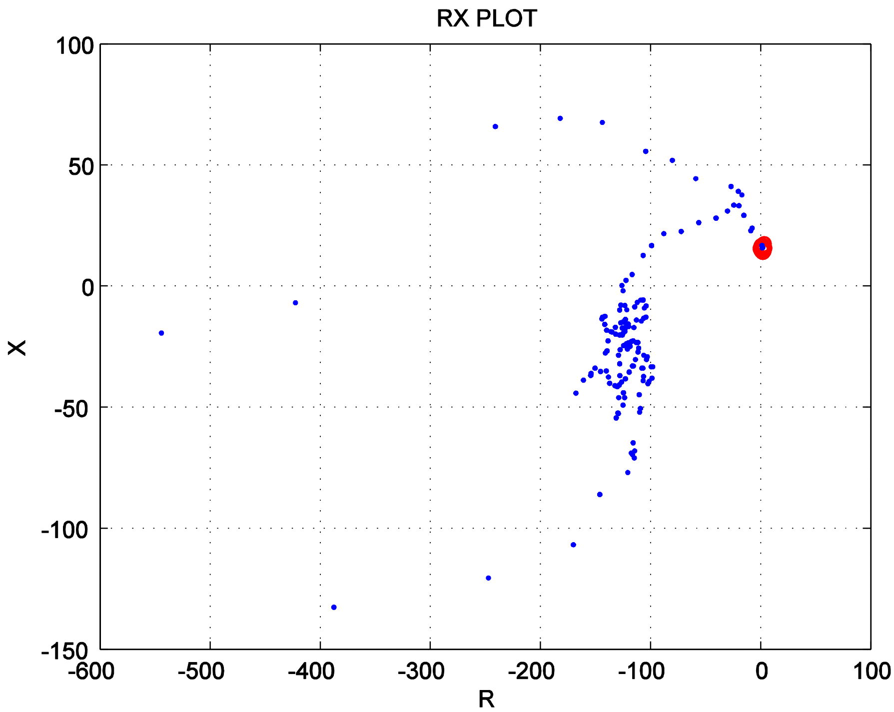

Figure 5.22 R-X Plot for downward (forward) LLG fault for $R_{F=}50$, $T_d=5$ cycles

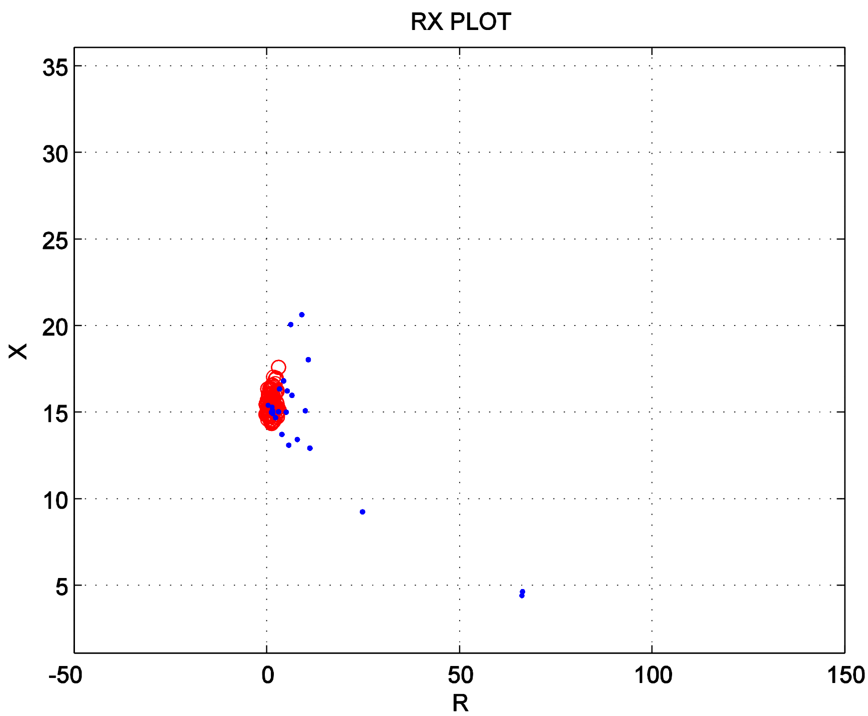

Figure 5.23 R-X Plot for upward (reverse) LLG fault for $R_{F=}50$, $T_d=5$ cycles

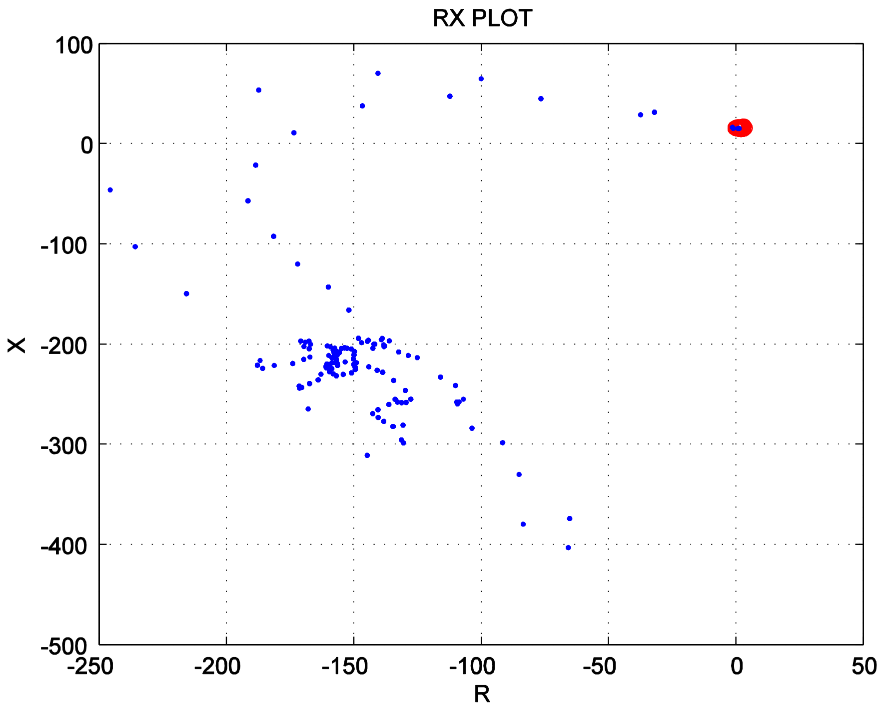

Figure 5.24 R-X Plot for downward (forward) LLL fault for $R_{F=}50$, T_d=5 cycles

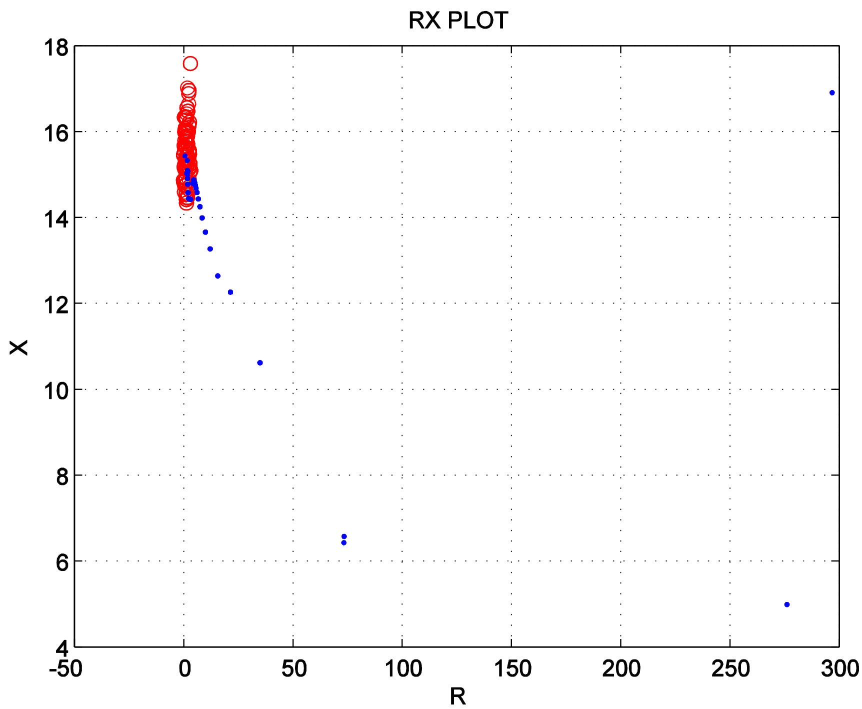

Figure 5.25 R-X Plot for upward (reverse) LLL fault for $R_{F=}50$, T_d=5 cycles

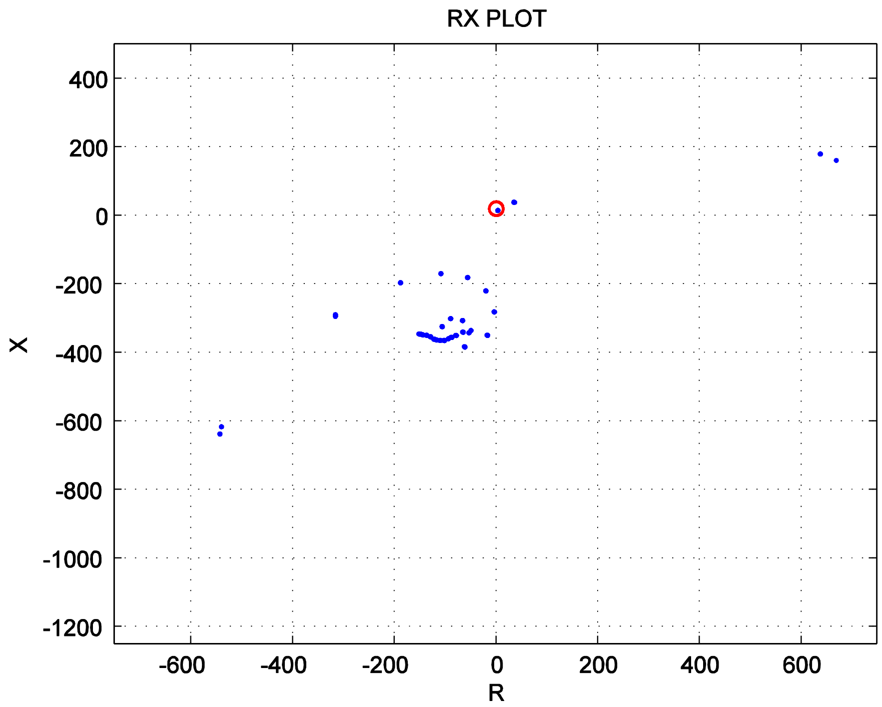

Figure 5.26 R-X Plot for downward (forward) LG fault for $R_{F=0}$, T_d=2 cycles

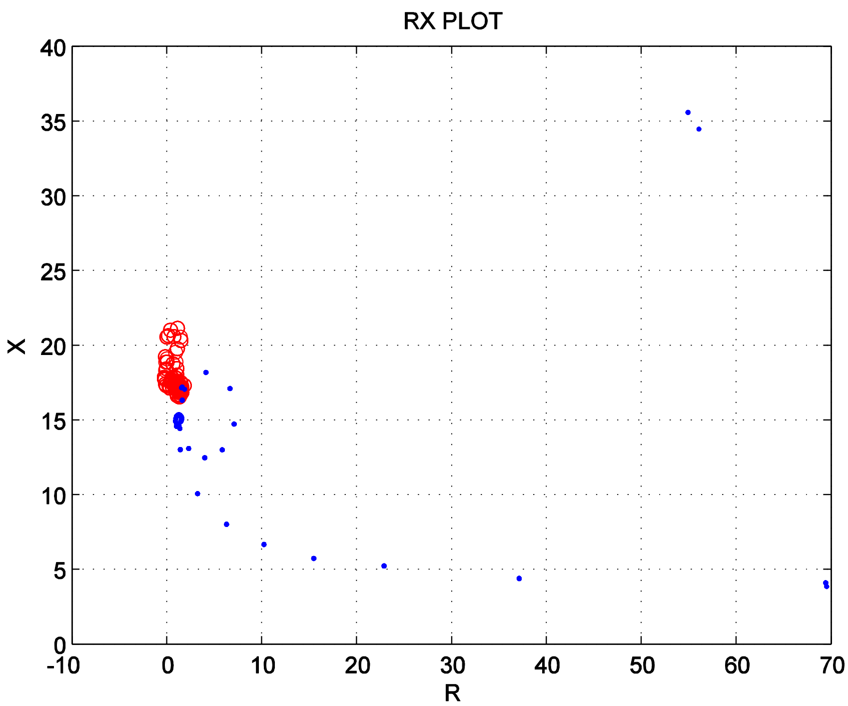

Figure 5.27 R-X Plot for upward (reverse) LG fault for $R_{F=0}$, T_d=2 cycles

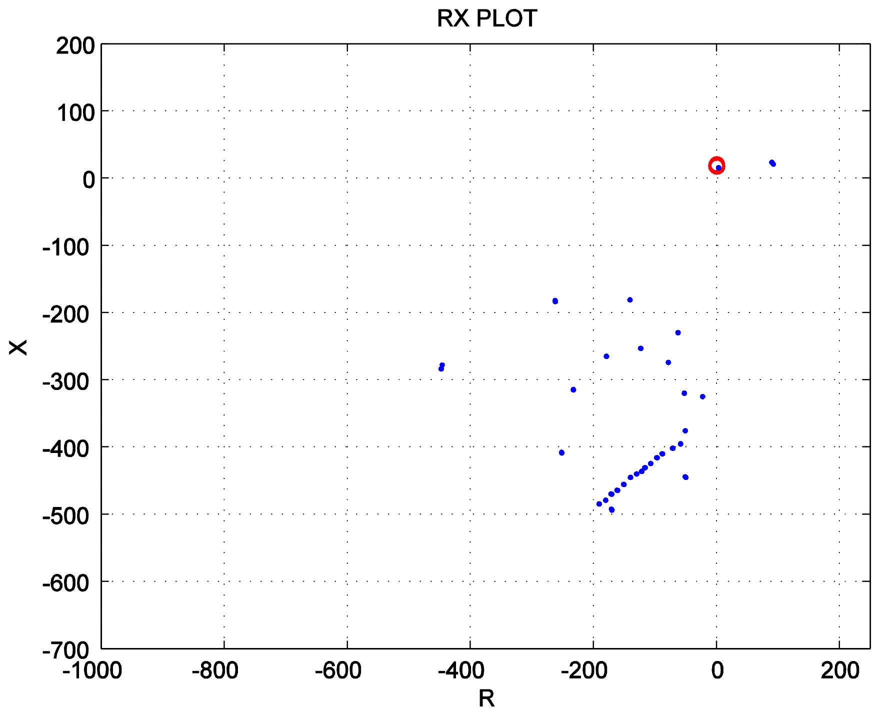

Figure 5.28 R-X Plot for downward (forward) LL fault for $R_{F=}0$, T_d=2 cycles

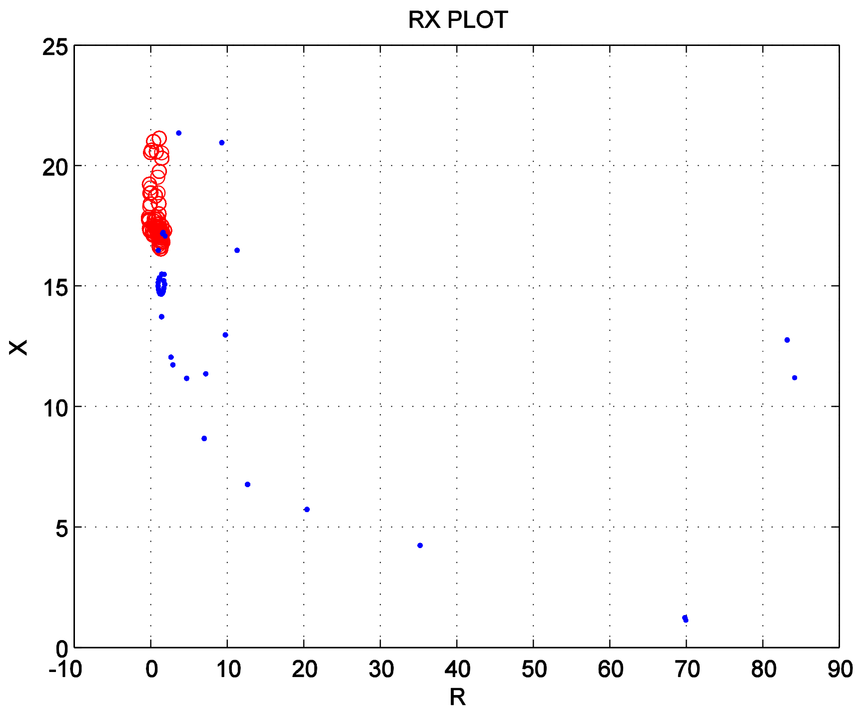

Figure 5.29 R-X Plot for upward (reverse) LL fault for $R_{F=}0$, T_d=2 cycles

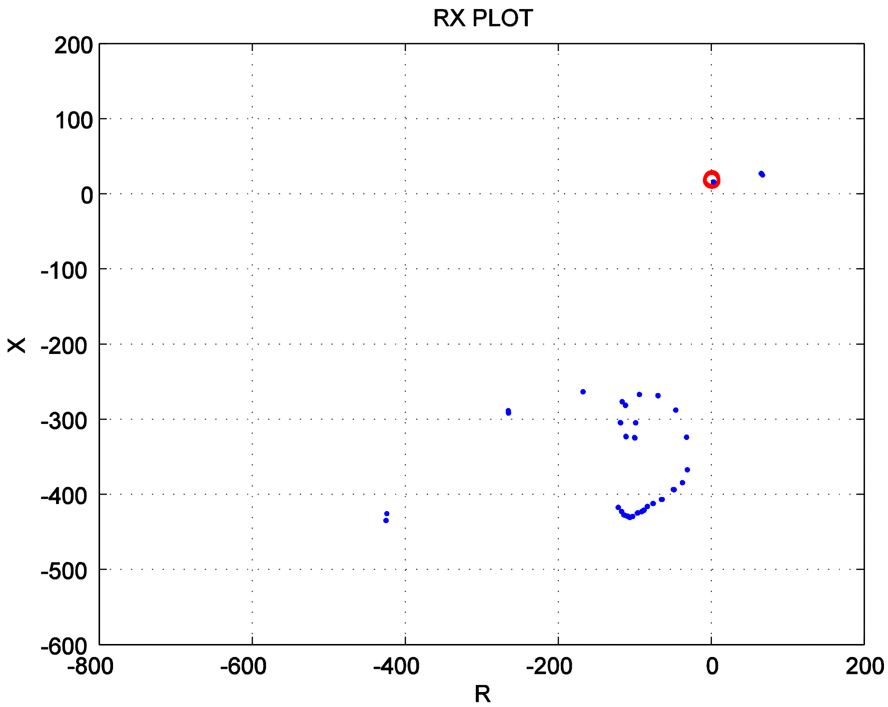

Figure 5.30 R-X Plot for downward (forward) LLG fault for $R_{F=}0$, T_d=2 cycles

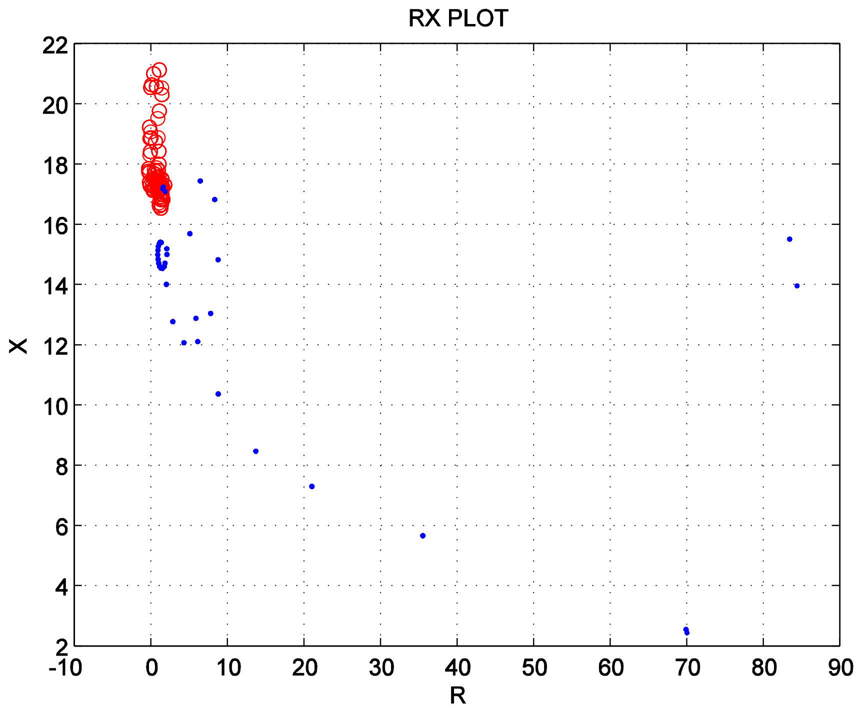

Figure 5.31 R-X Plot for upward (reverse) LLG fault for $R_{F=}0$, T_d=2 cycles

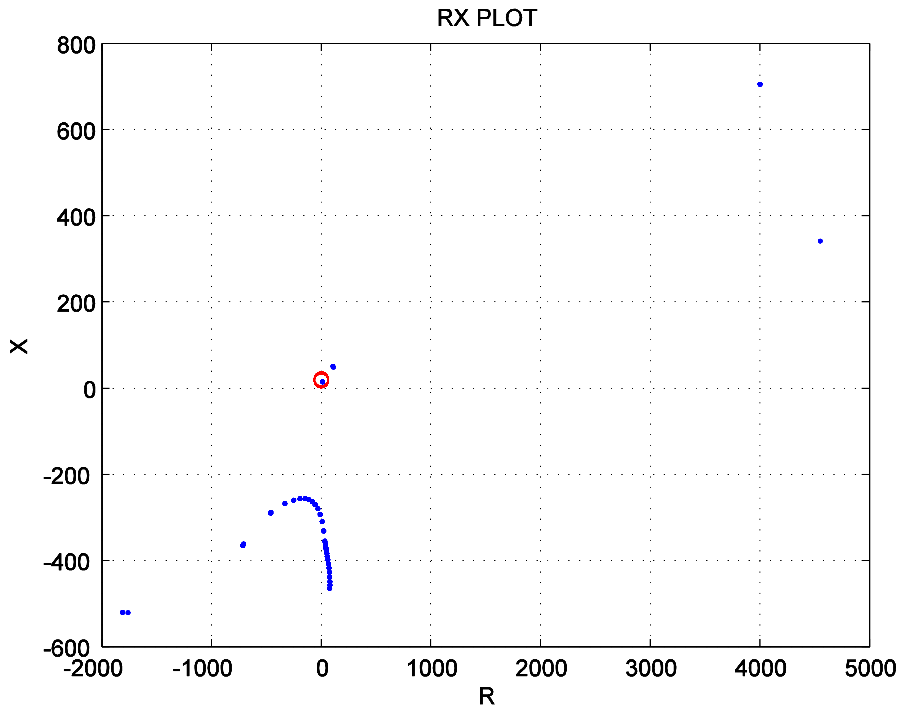

Figure 5.32 R-X Plot for downward (forward) LLL fault for $R_{F=0}$, T_d=2 cycles

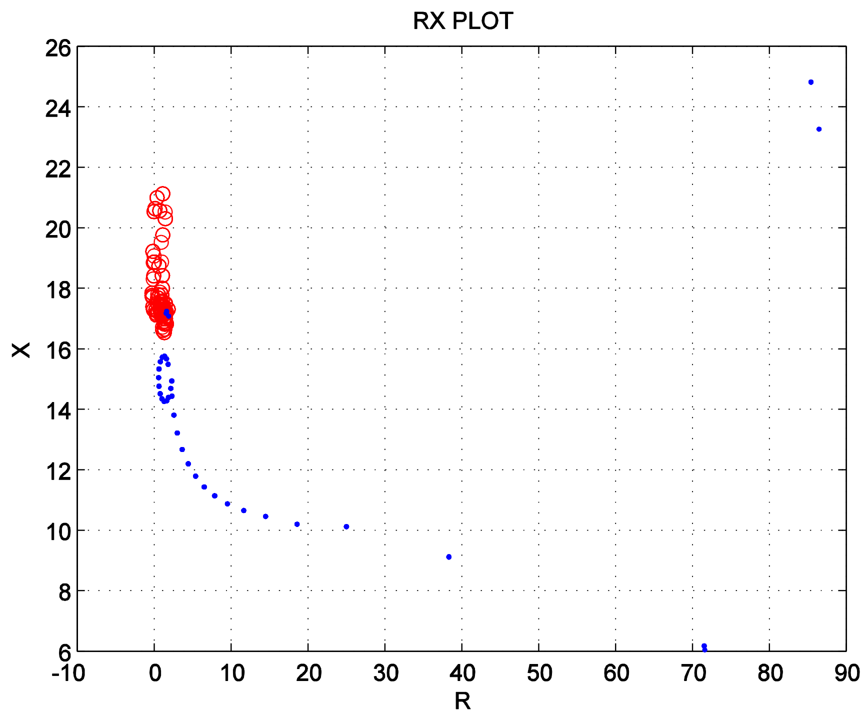

Figure 5.33 R-X Plot for upward (reverse) LLL fault for $R_{F=0}$, T_d=2 cycles

Chapter 6

Conclusion and Future Work

The increasing demand for electricity and changing regulatory and infrastructure requirements present a significant opportunity for distributed generation. However, standard overcurrent protection schemes for passive radial systems, which assume single direction current flow, do not permit DGs to take their advantages.

In this thesis, the different techniques have been studied to find the directionality in distribution networks with distributed generation units. The modeling of DFIG based wind energy system has been simulated in PSCAD. Two algorithms have been implemented to estimate the direction of fault in a DFIG Integrated radial distribution system. These algorithms use the voltage and current information at the relay point for processing of the directional logic to identify the direction of power system fault.

Scope for Future work:

- The algorithm, which uses phase angle change in sequence currents can be improved by employing some new logic to estimate the direction of downstream fault of less severity that means with more fault resistance.
- The integration of this directional element into numerical distance relays can be done as extension to this work.
- These algorithms can be tested for big meshed loop distribution systems.

References

[1] Edward J. Coster, Johanna M. A. Myrzik, Bas Kruimer, and Wil L. Kling, "Integration Issues of Distributed Generation in Distribution Grids," in *Proc. IEEE,* Vol. 99, No. 1, Jan. 2011.

[2] Evita N. Parabirsing*, Analysis of Protection Malfunctioning in Meshed Distribution Grids*, M.Sc thesis, Delft University of Technology, Nov. 2010.

[3] H. H. Zeineldin, Hebatallah M. Sharaf*,* Doaa K. Ibrahim,and E. El-Din A. El-Zahab, "Optimal Protection Coordination for Meshed Distribution Systems With DG Using Dual Setting Directional Over-Current Relays," *IEEE Trans. Smart grid*, 2014.

[4] A. Jalilian, M. Tarafdar Hagh, and S. M. Hashemi, "An Innovative Directional Relaying Scheme Based on Post-fault Current," *IEEE Trans. Power Delivery*, 2014.

[5] Abhisek Ukil, Bernhard Deck, and Vishal H Shah, "Current-Only Directional Overcurrent Protection for Distribution Automation: Challenges and Solutions," *IEEE Trans. Smart grid, vol. 3, no. 4, Dec. 2012.*

[6] Abhisek Ukil, and Akarsha Ramesh Kamala, "Current Only Directional Overcurrent Protection for Distribution Automation Using Neural Network," *IEEE sensors journal*, 2010.

[7] Qin LiJun, Wang Ying, HAO Cuijuan, and LI Meng, "Multi-Agent System Wide Area Protection Considering Distributed Generation Impact," in *Proc. IEEE Int. Conf. on Advanced power system automation and protection,* 2011.

[8] S. Milad Tayebi, and Ahad Kazemi, "A Transient Based Protection Scheme for Fault Direction Discrimination in Distribution Networks," in *Proc. IEEE Int. Conf. on Applied Superconductivity and Electromagnetic Devices*, Australia, Dec. 2011.

[9] 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.*

[10] Amin Zamani, Tarlochan Sidhu, and Amir Yazdani, "A Strategy for Protection Coordination in Radial Distribution Networks with Distributed Generators," *IEEE Transaction*, vol.10, no. 2, 2010.

[11] Hui Wan, K. K. Li, and K. P. Wong, "An Adaptive Multi-agent Approach to Protection Relay Coordination With Distributed Generators in Industrial Power Distribution System," *IEEE Trans. Industry Applications, vol. 46, no. 5, Sept. 2010.*

[12] W. El-khattam, and T.S. Sidhu, "Resolving the impact of distributed renewable generation on directional overcurrent relay coordination: a case study," *IET Renew. Power Generation,* Vol. 3, No. 4, pp. 415–425, Jan. 2008.

[13] Hui Wang, "A new method to eliminate negative effects on the existing distribution network protection," in *Proc. IEEE 20th Int. Conf. on Electricity distribution*, prague, June 2009.

[14] M.M. Eissa, "Development and Investigation of a New High-Speed Directional Relay Using Field Data," *IEEE Trans. Power Del., vol. 23, no. 3, July 2008.*

[15] M. Vitins, "A fundamental concept for High Speed Relaying," *IEEE Trans. Power Apparatus and Systems*, Vol. PAS-100, No. 1, Jan. 1981.

[16] M.M. Eissa, "Evaluation of a New Current Directional Protection Technique Using Field Data," *IEEE Trans. Power Del., vol. 20, no. 20, April 2005.*

[17] M. Petit, X. Le Pivert, and L. Garcia Santander, "Fault diagnosis in distribution networks with distributed generation," *Elect. Power Syst. Res.*, vol. 81, pp. 1482–1490, 2011.

[18] Ali Hooshyar, Maher Abdelkhalek Azzouz, and Ehab F. El-Saadany, "Three-Phase Fault Direction Identification for Distribution Systems With DFIG-Based Wind DG," *IEEE Trans. Sustainable energy.*, Vol. 5, No. 3, July 2014.

[19] M. Petit, X. Le Pivert, and L. Garcia Santander, "Directional relays without voltage sensors for distribution networks with distributed generation: Use of symmetrical components," *Elect. Power Syst. Res.*, vol. 80, pp. 1222–1228, 2010.

[20] Eric Sortomme, S. S. Venkata*,* and Joydeep Mitra, "Microgrid Protection Using Communication-Assisted Digital Relays," *IEEE Trans. Power Del.,* Vol. 25, No. 4, Oct. 2010.

[21] Zhijun Gan, S. Elangovan, and A.C. Liew, "Microcontroller based overcurrent relay and directional overcurrent relay with ground fault protection," *Elect. Power Syst. Res.*, vol. 38, 1996.

[22] M. S. Pasand, and O. P. Malik, "High Speed Transmission System Directional Protection using an Elman Network," *IEEE Trans. Power Delivery*, Vol. 13, No. 4, October 1998.

[23] T.S. Sidhu, H. Singh, and M.S. Sachdev, "Design, Implementation and Testing of An Artificial Neural Network Based Fault Direction Discriminator for Protecting Transmission Lines," *IEEE Trans. Power Delivery*, Vol. 10, No. 2, April 1995.

[24] K. S. Prakash, O. P. Malik, and G. S. Hope, "Amplitude Comparator Based Algorithm For Directional Comparison Protection of Transmission Lines," *IEEE Power Engineering Review*, October 1989.

[25] Q. H. Wu, J. F. Zhang, and D. J. Zhang, "Ultra-High-Speed Directional Protection of Transmission Lines Using Mathematical Morphology," *IEEE Trans. Power Delivery*, Vol. 18, No. 4, October 2003.

[26] M. M. Mansour, Said F. Mekhamer, and Nehad El-Sherif El-Kharbawe, "A Modified Particle Swarm Optimizer for the Coordination of Directional Overcurrent Relays," *IEEE Trans. Power Del.,* Vol. 22, No. 3, July 2007.

[27] A. J. Urdaneta, Ramon Nadira, Luis G. P. Jimdnez, and Universidad, "Optimal coordination of directional overcurrent relays in interconnected power systems," *IEEE Trans. Power Delivery*, Vol. 3, No. 3, July 1988.

[28] Carlos Aguilera, Eduardo, and Giuseppe, "Directional Traveling-Wave Protection Based on Slope Change Analysis," *IEEE Trans. Power Del.,* Vol. 22, No. 4, Oct. 2007.

[29] M.M. Eissa, and M.M.A. Mahfouz, "New high-voltage directional and phase selection protection technique based on real power system data," *IET Gener. Transm. Distrib.,* Vol. 6, No. 11, pp. 1075–1085, 2012.

[30] A.H.A. Bakar, H. Mokhlis, H.A. Illias, and P.L. Chong, "The study of directional overcurrent relay and directional earth-fault protection application for 33 kV underground cable system in Malaysia," *Electrical Power and Energy Systems,* vol. 80, pp. 113–119, 2012.

[31] Walid El-Khattam, and Tarlochan S. Sidhu, "Restoration of Directional Overcurrent Relay Coordination in Distributed Generation Systems Utilizing Fault Current Limiter," *IEEE Trans. Power Del., vol. 23, no. 2, April 2008.*

[32] *Grid Connected Doubly Fed Induction Generator Based Wind Turbine under LVRT* by Subramanian Chandrasekaran, University of Bologna.

[33] I. Munteanu, A. I. Bratcu, and N. A. Cutululis, *Optimal Control of Wind Energy Systems towards a global approach*, XXII, 2008.

[34] Branislav Dosijanoski, *Simulation of Doubly-Fed Induction Generator in a Wind Turbine,* XI International PhD Workshop OWD, 2009.

[35] Preeti verma, N. Jaiswal, and P. Gupta, "PSCAD Modelling and Simulation of DFIG and PMSG based WECS," in *Proc. Int. Conf. Electrical, Electronics & Computer Science Engineering*, India, May 2013.

[36] R. Abari, T. Chen, O. Malik, et.al. *Doubly Fed Induction Machine,* IEEE Press Editorial Board.

[37] *Modelling and Simulation of a Grid Connected Doubly Fed Induction Generator for Wind Energy Conversion System,* A Thesis Submitted for the degree of Master of Technology, IIT Rourkela, May 2014.

[38] Adel A.A. Elgammal, "Optimal Design of PID Controller for Doubly-Fed Induction Generator-Based Wave Energy Conversion System Using Multi-Objective Particle Swarm Optimization," *Journal of Technology Innovations in Renewable Energy, Vol. 3, pp. 21-30,* 2014.

[39] Md. Arifujjaman, M. T. Iqbal, and E. Quaicoe, "Vector control of a DFIG based wind turbine," Trans. Electrical and Electronics Engineering, Vol. 9, No. 2, 2009.

[40] A. K. Pradhan, A. Routray, S. Madhan Gudipalli, "Fault direction estimation in radial distribution system using phase change in sequence current," *IEEE Trans. Power Delivery*, vol. 22, no. 4, pp. 2065–2071, 2007.

[41] M. M. Eissa, "Evaluation of a New Current Directional Protection Technique Using Field Data," *IEEE Transactions Power Delivery*, vol. 20, no. 2, pp. 566–572, 2005.

[42] T. S. Sidhu, H. Singh, M. Sachdev, "Design, Implementation and Testing of An Artificial Neural Network Based Fault Direction Discriminator for Protecting Transmission Lines," *IEEE Transactions Power Delivery*, vol.10, no. 2, pp. 697–706, 1995.

[43] P.G. McLaren, E. Dirks, R.P. Jayasinghe, and I. Femando, "A Positive Sequence directional element for Numerical distance relays," IEE Conf. Publication, No. 434, March 1997.

[44] Amit Kumar Jindal, Aniruddha M. Gole, and Dharshana Muthumuni "Modeling and Performance Analysis of an Integrated Wind/Diesel Power System for Off-Grid Locations," in *Proc. 15th National Power systems Conf.,* India, Dec. 2008.

[45] *IEEE Recommended Practice for Interconnecting Distributed Resources with Electric Power Systems,* IEEE Standard 1547.2, 2008.

[46] S. Vanukuru, and S. Sukhavasi, "Active and Reactive Power Control Of A Doubly Fed Induction Generator Driven By A Wind Turbine," *International Journal of Power System Operation and Energy Management*, pp. 2231–4407, Vol. 1, Issue. 2, 2011.

APPENDIX:

Parameters of different components used in the system

The parameters of the Induction machine used in the DFIG wind system are mentioned below as shown in Table 1.

Table 2 will give the information of system parameters.

Table 1 Induction Machine Parameters

Machine quantities	Values
Base angular frequency	376.99 rad/s
Rated power	0.9 MAV
Rated terminal voltage	0.69 kV (L-L, rms)
Stator/Rotor Turns ratio	0.3
Angular moment of Inertia (J)	0.85 s
Mechanical damping	0.0001pu
Stator resistance	0.0054pu
Wound rotor resistance	0.00607pu
Stator leakage inductance	0.10pu
Rotor leakage inductance	0.11pu
Magnetizing inductance	4.5pu

Table 2 System Parameters

System quantities	Values
Base angular frequency	376.99 rad/s
Three phase transformer	100 MVA, 0.69/20 kV
Fixed Load	0.5 MVA, 20 kV (L-L, rms)
Wind speed (V_w)	11.5 m/s
Rotor blade radius (R)	40 m

Pole pairs	3
Machine rated MVA	0.9 MVA
Initial pitch angle	10 degrees
Air density (ρ)	1.225kg/m^3
Gear ratio (GR)	90.5
Gear box efficiency	97.9%
Grid voltage	20 kV (L-L, rms)
Grid frequency	60 Hz