Fault Detection, Localization, Isolation and Restoration in Microgrid through Intelligent Relays

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Session 2018-2020

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Dedication

This Research work is dedicated to my beloved late grandmother who has been my financial support during my studies. This work is also dedicated to my family who has loved me unconditionally and invigorated me for hard work. So that I can achieve things that I aspire to accomplish. I would like to dedicate my thesis to my friends who has encouraged me and has been a constant source of support during the MS Degree program.

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Abstract

Micro-grids have encountered several challenges over time from a control and protection perspective. One of the main issues which is faced related to the protection of micro-grids while integrating Distributed Generations (DGs) is to develop a suitable protection technique that can be effective both in grid-connected and stand-alone operation modes. Our traditional protection and control techniques are not well-equipped to address these pertinent issues. Conventional overcurrent protection schemes face selectivity and sensitivity issues during grid and micro-grid faults since the fault current level is different in both cases for the same relay. Adaptive protection is required to change the relay settings according to the current microgrid configuration. The topic of this thesis is "Fault Detection, Localization, Isolation, and Restoration in Microgrid through Intelligent Relays". As microgrids are dynamic in nature, their parametric values change every second. To handle such dynamic systems, a robust protection technique is presented in this thesis. For fast fault detection and to avoid mal-operation, a sequence component-based approach is suggested. Moreover, determining accurate location, Isolation, and restoration by using an intelligent relay system is also part of this research work. The positive and negative sequence components are extracted from local and remote ends to analyze the system parameters. A sequence components-based algorithm is developed to detect, locate and isolate the fault in the Microgrid system. Also, this system protects and controls radial as well as looped micro-grids against different types of faults with the capability of single-phase tripping.

Keywords: *Fault detection; Fault localization; Fault classification; Internal fault detection; Sequence component analysis*

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List of Abbreviations

MG	Microgrid
DT	Decision Tress
KNN	K – Nearest Neighbors
DWT	Discrete Wavelet Transform
AC	Alternating Current
DC	Direct Current
MRA	Multi – Resolution Analysis
ANN	Artificial Neural Networks
CNN	Convolutional Neural Networks
SNR	Signal to Noise Ratio
IEEE	Institute of Electrical and Electronics Engineers
DER	Distributed Energy Resource
FFT	Fast Fourier Transform
STFT	Short Time Fourier Transform
CWT	Continuous Wavelet Transform
CHP	Combined Heat and Power
COE	Cost of Energy
CO2	Carbon Dioxide
CPUC	California Public Utility Commission
DG	Distributed Generation
FERC	Federal Energy Reliability Corporation
GHG	Greenhouse Gases
HOMER	Hybrid Optimization of Multiple Energy Resources
IOU	Investor-Owned Utility
kV	Kilo-Volts
MW	Mega–Watt
NREL	National Renewable Energy Laboratory

O&M	Operation and Maintenance
PV	Photo-voltaic
SCADA	Supervisory, Control and Data Acquisition
STP	Standard Temperature Pressure
T&D	Transmission and Distribution
WECS	Wind Energy Conversion Systems
AI	Artificial Intelligence
AMR	Anisotropic Magneto-Resistive
CML	Customer Minute Lost
GMR	Giant Magneto-Resistive
MF	Magnetic Field
MR	Magneto-Resistive
TMR	Tunneling Magneto-Resistive
MV	Medium Voltage
OFGEM	Office of Gas and Electricity Markets
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency
SC	Short Circuit
TDR	Time Domain Reflectometry

Chapter 1

Introduction

1.1 Energy in global context

It has become impossible to create a balance between energy demand and population growth due to the incessant rise in the world's population. The energy resources are diminishing, and energy demand is exponentially rising due to unprecedented population growth. Urbanization and industrialization have caused a most important drift in energy intake, and it has become challenging to maintain the energy system. The majority of the population lives in urban areas, and the numbers are expected to rise in near future [1]. Energy consumption and demand are increasing day by day while conventional energy sources are diminishing. The worldwide population growth and economic activities have severed impacts on energy demand. The world is majorly dependent on conventional sources i.e., fossil fuels and it will remain the same unless some major changes are made. Globally, fossil fuel consumption is increasing, and it has become very hard to find a new reservoir of fossil fuels. Newly discovered reservoirs are significantly smaller in size than ones that were discovered in the past. Currently, every year we are consuming over 11 billion tons of oil from fossil fuels. On the contrary, crude oil reserves are waning at the rate of 4 billion tons per year. It means our known reserves could run out in just 53 years if we carry on as we are today. Our gas deposits can give us only 52 years if we increase the gas production to fill the energy gap left by the oil. Though we have enough coal reserves, yet they are not sufficient to cope up with the increasing energy demand due to unprecedented population rise, and depleting oil and gas deposits. Our established coal deposits could run out in 150 years if we use coal to make up for depleted oil and gas reserves [2].

1.2 Impact of Fossil fuel on climate

Fossil fuels are adversely affecting climate change and unleashing global warming. The emission of CO2 from fossil fuels stays in the atmosphere which leads to a rise in global temperature. We emit nearly 750 billion tons of carbon if the world burns all known reserves of coal without carbon capture or storage technology. If we want to meet our climate change goals, we must leave two-third of fossil fuels under the ground. Already 1°C temperature has raised. If the temperature rises above 1.5 °C, the sea level will increase. The unchecked emission of greenhouse gases resulted in extreme weather, species extinction, and biodiversity loss, and food scarcity, deteriorating health, and poverty for millions of people. According to the Intergovernmental Panel on Climate Change (IPCC), emissions from fossil fuels are the dominant cause of global warming, 89% of CO2 emissions came from fossil fuels and industry. In fossil fuel, coal is the filthiest fuel as 0.3 °C of the 1 °C increase in global temperature is due to coal, making coal the single largest source of global temperature rise. Oil is another important driver of triggering climate change while oil spills are ravaging our ecosystem [3]. Natural gas is considered a clean energy source as compared to oil and coal but still, it emits carbon into the atmosphere.

1.3 Need a policy shift

In order to address the depleting fossil fuel sources and environmental and ever-growing population issues, we need to revise our policies. We need a policy shift to mitigate climate change and global warming. These goals can only be achieved if we utilize maximum renewable energy resources for power generation. The power generation from renewable energy will reduce global warming by replacing carbon-intensive energy sources. Renewable energy is clean energy derived from natural resources or comes from continually replenished resources. The major types of renewable energy sources are solar energy, biomass, wind, hydropower, and geothermal. The biomass comes from wood and wood waste, Landfill gas and biogas, ethanol, biodiesel, and municipal solid waste. The usage of these renewable energy resources will reduce fossil fuel consumption which will ultimately reduce greenhouse gases emission [4]. All renewable energy sources are not 100% environmentally friendly as large hydropower dams and biomass impact the wildlife, climate, etc. Like biomass and dams, solar technology has its limitation as in the manufacturing of solar plate emission of carbon take place which is not environmental friendly. Wind energy is the cleanest and sustainable renewable source, but it is expensive, and technology is immature. The birds and bats killing due to the collision with wind turbines and disruption of habitats are the drawbacks of wind energy sources. Land required for the installation of a wind plant is also a hindrance and we need to optimize this technology so that minimum land should be used to install wind plants. Wind plants also have impacts on recreational activities, oil extraction, gravel extraction, aquaculture, and navigation. Even 100% renewable energy is not enough to cope up with the emerging environmental challenges, but renewable energy emits fewer greenhouse gases as compared to fossil fuel [5]. Renewable energy is more environmentally friendly as compared to conventional energy sources.

1.4 Integration of DERs and its challenges

Integration of renewable energy sources has been a dire challenge. Renewable energy sources are highly intermittent. Solar can work only in daylight and need a storage system for the night. The wind is highly unpredictable; it needs a 90-backup system whereas for other forms of power generation around 25% backup system is required. The integration of renewable energy sources is not possible in our conventional grid because it faces selectivity and sensitivity issues. The conventional grid is not well equipped to address the protection issues which it faces due to the integration of renewable energy. Energy integration means the method of developing efficient ways to transfer the variable power from renewable energy sources to the grid. Integration should be cost-effective, and it should be reliable and stable [4]. To address the integration issue, we need to understand the conventional grid and the challenges which it faces during the integration of renewable energy.

1.5 Issues associated with conventional system

The top-down grid is outdated because of protection issues. In order to integrate renewable energy, we need bottom-up redesigned grids. The centralized, top-down power grid is outdated. It is a time for a bottom-up redesign, due to climate chaos blackouts are on the rise and the situation is getting worse. In the conventional system, power is generated at large power plants and transmitted through long high voltage transmission lines. The power is dumped at different points from the high voltage transmission line to the distribution system via substation. At substation transformers, the voltage is low so that it does not damage the appliances at the consumer end [6]. Distribution wires carry power from the transmission distribution interfaces in various directions. The voltage is then lowered again by the transformer which is mounted on the power poles. The distribution wire then feeds electricity to the end-users through a meter which is used to measure consumption. In a conventional system, power flows are only in one direction. Conventional grids are like the river, as it flows in only one direction. Renewable energy integration is shaking our traditional grid system. It becomes complicated to manage the grid as solar and wind are highly intermittent. When the sun comes up, tons of power flow from solar panels, but during the night, a backup system or storage system is needed to supply power [7]. Our traditional grids cannot manage such a complicated system. High penetration of renewable energy is causing challenges and increasing the complexity to meet supply demand in real-time. Distribution energy sources (DER) give consumers access to the energy market due to which DERs are increasing in the energy market, but the conventional grid is not ready to cope up with the above-mentioned challenges. To address these issues, we need to modify our traditional system or need a new system to cope up with the above-mentioned challenges.

1.6 Microgrid

To integrate DERs into the grid, we use new and advanced technology. A microgrid is a single governable entity interconnected with different loads and DERs with clearly defined boundaries. It can operate with the gird and can be disconnected in case of islanding. The microgrid also provides backup in case of emergencies, and it helps to cut the cost. It provides power to remote areas and promotes local generation due to this transmission line length required for power supply reduce which ultimately decreases line losses. Microgrids make consumers independent and allow them to control the energy market. It encourages clean energy, provides low cost, and gives efficient energy. It improves the stability, operation, and reliability of the regional grid. The essential infrastructure of the micro grid increases the reliability and resilience of the system and supplies power to critical loads like hospitals and defense units [7]. Microgrid encourages renewable sources and reduces fuel consumption which ultimately reduces the carbon footprint.

1.7 Problem Statement

Electricity is the basic need of life and its demand is exponentially increasing due to the population explosion and extra use of digital services. To meet the energy demand we need to generate extra power. On the other hand, conventional energy sources are shrinking. To maintain a balance between power generation and consumption, renewable energy sources are needed for extra energy generation. Integration of DERs is challenging and it possesses protection issues. Microgrid has many advantages as mentioned above and it is used for energy integration. Despite all these advantages, microgrid faces significant implementation challenges. The integration of DERs in the grid triggered certain issues. Our traditional system is not ready to integrate renewable energy sources as it faces protection challenges. Integration of DERs in the microgrid has created some serious issues. One of the fundamental reasons for these issues is intermittent energy sources. Uneven DERs cause protection challenges in the microgrid. The proper protection of the microgrid is the last hindrance in the implementation of the microgrid. When we integrate renewable sources, the grid faces selectivity and sensitivity challenges. Fault diagnosis becomes challenging due to the critical microgrid infrastructure. Fault localization in a ring system is crucial because of bidirectional power flow. To address the above-mentioned challenges this thesis proposed a novel sequence component-based technique for fault localization and fault diagnosis. Now the primary focus of this thesis is to develop an intelligent protection system for microgrids that will be effective in both grid-connected and islanding mode. This intelligent system will diagnose the fault and its location. Moreover, it will classify the fault type and isolate the faulty part in the minimum possible time to avoid further damage and will continue to supply power to the critical load without any interruptions.

Summary

The growing energy demand around the world and global warming urge us to explore new clean energy sources as an alternative to conventional energy sources to address the environmental issue. Climate change has helped to create awareness against clean energy sources. The demand for traditional energy sources drastically decreased. Renewable energy sources are being encouraged by the government and industries to mitigate climate change. The Microgrid Energy management system is becoming an emerging research topic with the evolving smart grid technology. Energy demand with increasing population in a global context is discussed. The impact of fossil fuels on climate change is briefly analyzed. To address global warming and population issues we need a policy shift. We must have to shift to renewable energy sources if we want to save this planet. Integration of distributed energy sources and challenges associated with it were deeply investigated. Further top-down and bottom-up grid technologies are examined, and their advantages and disadvantages are discussed. A brief introduction of microgrids and related problems were discussed. the challenges to implementing the microgrid technology are briefly analyzed. Microgrid technology is elaborated, and its advantages and disadvantages are discussed. The thesis addresses the main challenges faced by the microgrid in its implementation. A new microgrid protection strategy is developed to address the implementation issues of Microgrid technology.

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Chapter 2

Literature Review

The electrical fault is the abnormal behavior of the electrical circuit, and it occurs due to imperfection of the circuit due to which current deviate from the intended path and flow in an uncontrolled manner. A power system fault is an abnormal condition that damages electrical equipment and disrupts power flow. The fault is caused in the system due to a variety of reasons. The probability of occurring faults in Microgrids is more because they are broadly branched, operate under variable load conditions, and have variable and intermittent Distributed generation sources. Insulation failure between the conductors can cause a power system fault. Excessive short circuit current can cause heavy fire and explosion which severely damage the distribution network. Insulator failures occur due to abnormal voltage and sometimes even at normal voltage due to aging or decline of the insulation. The fault occurred sometimes due to unpredictable incidents like thunderstorms, tree limbs, vehicles colliding with the transmission poles, birds shorting out the lines. Some faults occur due to flashover and mechanical failure in the switchgear. The deregulation in the energy system in the 1980's motivated power utilities to ensure reliability and power quality in the distribution network of electricity [1]. The power system has been disrupted by various types of faults, which have harmed the proper distribution of power. In a distribution system, short circuit currents are very common and almost 40% of faults occur due to short circuit currents. These faults affect the lifetime of insulation and degrade the reliability of the power system. These issues can be addressed by accelerating the restoration and fast fault recovery [2]. The stability of the system and power system apparatus gets affected due to the SC current. Sometimes complete shut-down happened due to excessive SC current. SC cause overheating and aberrant mechanical forces which damage the power system [3]. According to a report by the Office of Gas and Electricity Markets (OFGEM) in the United Kingdom, approximately 75% of faults occurred in the distribution system, making it more vulnerable [4]. The integration of DG sources makes the distribution system more complex and makes fault detection challenging. To restore the system fault fast fault detection is pivotal. Because the fault current varies, fault detection is difficult. In grid-connected mode, the current will be high in the event of a fault, causing overcurrent relays to trip the system, whereas in islanding mode, the current will be low and relays will not trip. To avoid blinding, an intelligent fault detection technique is needed. In microgrid system bidirectional current flows which make complicated to analyze the fault as fault detection schemes used for the radial system do not work for microgrid system. Due to complicated system fault at one feeder many causes tripping of the healthy feeder. Unintentional islanding can also make fault diagnosis difficult. To address these issues, an advanced and intelligent fault detection system is required [5].

Table 2.1: Microgrid Protection Issues

Issues	• Bidirectional power flow. Grid connected and blending mode • Change in the magnitude and direction of fault current • Dynamic topology

Table 2.2: Microgrid Protection Challanges

Challanges	• Fault current level variation • Standardrization • Grid code compliance • Choosing of Appropriate Transformer configuration • Auto recloser • Reduction in reach of distance relay • Blinding Protection and Sympatric tripping • Relay interoperability

Table 2.3: Microgrid Protection Solutions

Solutions	• Fault Current Limiter (FLC) • Virtual Impedance • Islanding detection Algorithm (Adaptive, Passive, Hybrid) • Proper Standarization • Fault Detection Algorithm • Adaptive Protection • Intelligent self Healing Schemes • Compatibility and interoperability Test • AI Based Methods

The various fault detection methods can be classified into two categories: a model-based and a data-driven method.

2.1 Model-based methods

Depending upon the fault detection techniques the model-based methods are classified. Model-based methods guarantee that assessed parameters are coherent and match the model. To detect fault different techniques are used which are as followed:

1. Adaptive based technique
2. Centralized based/Decentralized based Scheme
3. Differential based scheme
4. External Device-based
5. Agent-based technique
6. Local Variable based
7. Traveling wave-based
8. Transformation based

2.1.1 Adaptive based

An adaptive system is used to update the system and locate the fault in microgrid system configuration changes by comparing the updated data using the cycle-cycle comparison method. Current and voltage signals are acquired at the relay location using current and potential transformers and compared to diagnose the system fault. There is some limitation linked with adaptive method implementation.

- As the mode of operations changes in MG readjustment in the protection relay setting is needed.
- As the topology changes it gets problematic to calculate the power flows and short circuit
- The communication system, which is costly and complicated, is required for revising system preferences and surveilling purposes.
- Prior knowledge of all MG is required.

2.1.2 Centralized based/Decentralized based Scheme

To detect a fault in the system, both centralized and decentralized base schemes are used. Determining a better protection approach between centralized and decentralized is a difficult task. The centralized method is more reliable and accurate, but there is a significant communication and computation time delay. The decentralized technique, on the other hand, provides a quick response but has the disadvantage of being less reliable and accurate.

2.1.3 Differential based

For fault detection, a differential-based approach examines data from both the local and remote ends. A differential-based scheme has been proposed in [6] for computing the difference on the transformed contours' spectral energy content on both the local and remote sides of the feeder by comparing two-time frequency transformations, S-Transform, and Hilbert Transform.
The main complication associated with differential-based schemes is as followed.

- In case of a communication failure, backup protection is required for MG, which makes the system complicated

- The combination infra-structure is needed which increases the cost of the system.
- The integration of DG or disconnection of DG is challenging. The connection and disconnection of DG can generate transients and load unbalanced.

2.1.4 External Device Based

In the traditional system, conventional protection relays were used but technology evolved and microprocessor-based relays replaced the conventional protection relay. Microprocessor-based technology has progressed to the point where it can now be considered an intelligent electronic device. There are some limits linked with external device-based protection.

- Externally installed devices necessitate a massive investment.
- The widespread use of renewable energy sources has the potential to cause issues.

2.1.5 Agent-Based

The scheme calculates the phase angle through the Phasor measurement unit. Clarks' transformation, over-current, and phase differential-based protection schemes are three versions of agent-based schemes. To achieve high reliability and accuracy, the version and protection scheme were changed. The Agent-based method has its limitation:

- This scheme requires communication between agents that adds to the cost.
- , In the long run, it's difficult to accurately predict agent activity and communication.
- To avoid undesirable conditions and misinterpretation, coordination is required.

2.1.6 Local variable based

To protect the system and detect the fault, the proposed scheme uses local variable current, voltage, and derivatives. There are some drawbacks to using local variables.

- Malfunctioning can cause changes in local variables.
- The proposed scheme is contingent on MG's configuration.
- The time it takes to detect a fault is dependent on the type of fault and the variable magnitude of the fault. As a result of the time delay, performance suffers.

2.1.7 Traveling wave-based

For fault detection, this protection method employs mathematical morphology (MM). MM detects faults by performing addition and subtraction operations. It reduces the amount of computation required, but the performance of the traveling-based method is dependent on high-frequency waves disturbance. Communication failure is a risk in the proposed scheme.

2.1.8 Transformation Based

The wavelet transform (WT) and multi-class support vector machine are used to diagnose the fault in this method. The lowest voltage drop then injects a high-frequency voltage to inspect the others. The threshold is a problem associated with the above-mentioned fault detection method. To keep the MG from being under balanced load conditions, a threshold value must be set.

2.2 Data-Driven based methods

1. Decision -tree-based
2. ANN-based
3. Fuzzy based

2.2.1 Decision tree-based

In the decision tree, method data is extracted and utilized by the decision tree to evaluate the fault. Current at the local end is measured with wavelet transform to detect the fault by the decision tree. The negative, positive, and zero sequences are derived by a sequence analyzer to help assess the system. An inverter-based Microgrids j48 and Naïve Bayes [7], two statistical classifiers are used in the decision tree to categories the fault. DFT is also used in a protection system to extract the data for fault diagnosis.
There are complications associated with the tree-based technique

- For the decision tree training, extensive data is required.
- Prune the algorithm and establish the best split of each tree node is a complicated task.
- Due to a noisy environment, this technique is prone to missed detection.
- The insufficient data leads to miscalculation and false estimation.

2.2.2 ANN-based

In ANN, input signals are used in ANN trained algorithms t detect and localize the fault. A combination of symmetrical components and an adaptive Neuro-Fuzzy interference system is also used in some techniques to identify the faulty phase. Though ANN is an advanced technology to analyze faults and diagnose system issues there are few drawbacks associated with it.

- For the operation, extensive training is required.
- For the large size neuro network, a high processing time is required.
- Limited capability to recognize the possible underlying relation and prone to overfitting.

2.2.3 Fuzzy Based

This technique used fuzzy logic to identify fault, in this technique fuzzy logic combines with wavelet singular entropy is used to analyze fault. Hilbert space power with fuzzy interference processor-based protection scheme is also used for investigating the fault.
There are some issues associated with fuzzy logic-based techniques.

- Finding fuzzy rules and accurate membership functions is difficult.
- Stability is a major concern associated with this technique
- To verify and validate the system extensive testing and hardware are required.

2.3 Fault Location

Fault location in the microgrid is grave to restore the system and ensure reliability. Consumer complaints were used to locate faults in our previous system. This technique used the complaint call location and match with the distribution network line to identify the faulty zone [5]. The field staff (lineman and Headline man) then deployed to restore the system by locating the faulty feeder. In the recent past, Technology has developed, and new advanced techniques have been introduced for the localization of faulted feeders in the distribution system. There are many techniques for the estimation of fault location, but they can primarily classify into three main categories.

- Impedance based fault location technique
- Traveling wave-based fault location technique
- Knowledge-based fault location technique

Researchers have been able to use these techniques for fault detection and classification thanks to the convergence of developments in the domains of signal processing techniques, artificial intelligence, data analytics, and sensor technologies such as the Internet of Things (IoT). These techniques have extended the horizon of traditional protection techniques. The fast growth of interest and improvements in smart grids and related ideas such as microgrids over the last decade has fueled research into establishing an intelligent fault diagnosis system that can accurately categorize and pinpoint fault locations. This section covers key relevant research and does a thorough literature review on fault classification using deep learning algorithms, including a review of previously published material. Data-driven and signal-processing approaches have become increasingly popular in recent years it is used in microgrids to detect and categorize faults. Some of the most commonly used machine learning methods in such investigations are artificial neural networks and various types of networks, support vector machines, decision trees (DT), and K-nearest neighbors (KNN) [8]. It is used to detect and categorize faults in microgrids. Artificial neural networks and various types of networks, support vector machines, decision trees (DT), and K-nearest neighbors are some of the most commonly used machine learning methods in such investigations (KNN). These characteristics are utilized to detect faults and then input into a neural network with gated recurrent units to classify faults. The author put their suggested methodology to the test using the CERTS microgrid testbed using the IEEE-34 bus system, achieving high fault classification accuracy. In microgrids, Jayamaha et al. [9] use similar methods for the detection of the fault. The relative wavelet energy of the signals is recovered using DWT-based Multi-resolution analysis (MRA) of the input signals 5. A simple feed-forward neural network is used to classify the input features. Hagh et al. [10] present a modular artificial neural network (ANN) for fault classification and placement that requires multiple networks to be trained for each type of fault. This strategy helps to reduce network training time and computational complexity because each network only needs to learn one type of failure and does not need to be trained on all available data [11]. This approach, however, only recognizes the four categories of errors and does not identify any others the erroneous stages. Wavelets transformations have been widely used in the field of fault detection and classification because of their ability to improve the differentiability between faulted and non-faulted data by projecting the data in the time-frequency domain. Wavelet transforms have been used in conjunction with machine learning approaches for fault categorization in several studies [12] and [13].

In addition to neural networks, decision trees and K-nearest neighbors are common fault classification techniques. Li et al. [12] used two decision trees to detect and identify problems in transmission lines based on fifteen features retrieved using DWT, and the random forest method achieved a classification accuracy of 94%. The approach also fails to detect the faulty phases. Trees were used to make decisions Jamebozorg et al. [14] utilized them to classify transmission line failures.

Abdelgayed et al. [15] use training decision trees and KNN classifiers to classify faults in transmission and distribution systems, including microgrids, using a semisupervised machine learning strategy that handles both labeled and unlabeled data. The use of convolutional neural networks (CNN) for fault classification is an innovative method in that signals aren't used as direct inputs to the classifier. The signals are usually converted to pictures using extracted features, and then the CNN is trained. In their research, Guo et al. [16] use the Hilbert-Huang transform to generate an energy matrix from the time-frequency pieces. The energy matrix is converted into an image by appropriately translating its values to the color values in a colormap. This method yielded good accuracy, according to the author. In [17] author reported a high accuracy approach to categorize single-phase earth faults. The author Liao et al. [18] used CNN for voltage sag estimation and classification, where matrices of selected variables formed using the concept of the system area mapping were used as inputs to the CNN. Bagheri et al. [19] present a CNN-based technique for voltage dip categorization. For efficient extraction and classification characterization of dip characteristics that are independent of dip duration and sample frequency in a recording, the author used deep learning in a two-dimensional transform domain with a space-phasor model [20].

Other unique approaches to fault classification, in addition to the techniques out-

lined, include as follows. Principal component analysis is used by Alsafasfeh et al. [21] to classify faults based on phase current values in only one-fourth of a cycle. Chaitanya and Yadav [22] investigated how to detect and classify high impedance defects using a fuzzy interference method. In each phase, two different fuzzy interface systems (FIS) are modeled to detect the fault. The first FIS recognizes large fault currents associated with conventional shunt faults, while the second FIS recognizes small fault currents associated with high impedance faults. Mishra and Yadav [23] employed a categorization technique based on Discrete Fourier Transform and fuzzy logic in their research. In [24] author presents a hybrid method based on ANN and wavelets for fault classification and detection. In literature, only a few researchers have paid attention to the quality of simulated signals. Artificial intelligence-based and machine learning algorithms are data-driven. Due attention must be paid to train the network otherwise the performance of the implemented scheme will have a significant difference. To address this issue researchers, need to generate data that should be close to the real world. As a result, in addition to 20 dB SNR, we incorporate Additive Impulse Gaussian Noise (AIGN) to simulate impulses caused by random switching of loads in the microgrid and impulses caused by inverter switching, as reported by Zimmermann and Dostert [25] and Tehrani and Yeh [26].
Different fault location-based techniques are developed which are as followed.

2.3.1 Impedance based approach

This method measured voltage and current of distribution lines and determines the fault location by analyzing line impedance up to the fault point. Radial distribution systems are the most common application for this method. The basic flowchart of the impedance-based method is shown in Figure 2.1. The following is a description of it in more detail.

2.3.2 Single terminal impedance method

The apparent impedance to the fault location is estimated using the voltages and currents from one end of the distribution lines in the single terminal

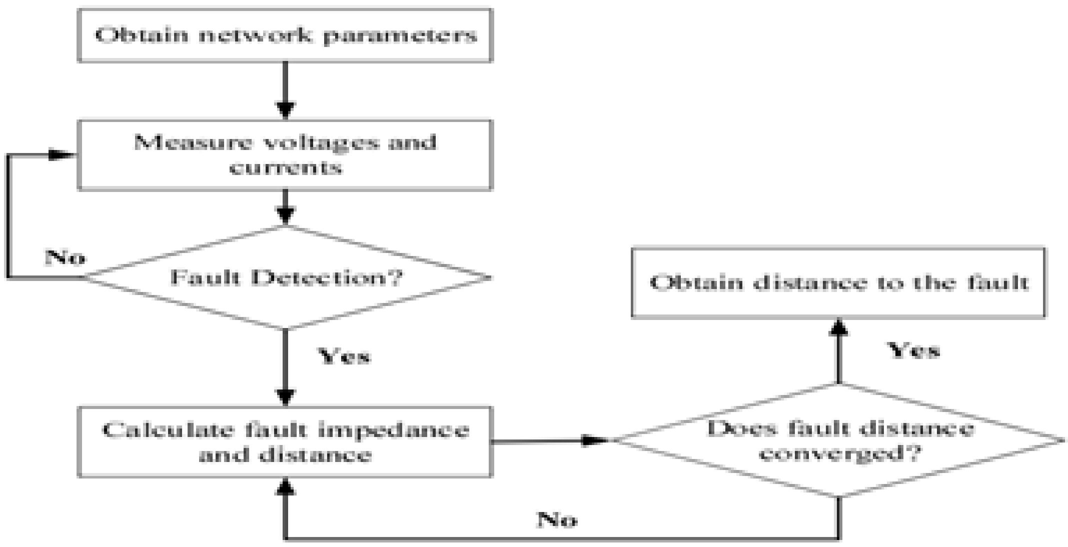

Figure 2.1: Basic flowchart of impedance based method

impedance method. 3-ph current and voltages are measured to find the 7 types of faults [5]. The single line diagram of a three-phase circuit is shown in Figure 2.2. The fault on phase A is a phase-to-ground fault. With an impedance of ZL, the distribution line is assumed to be homogeneous. VS and VF are the terminal and fault voltage respectively and Ia is the current at the terminal.

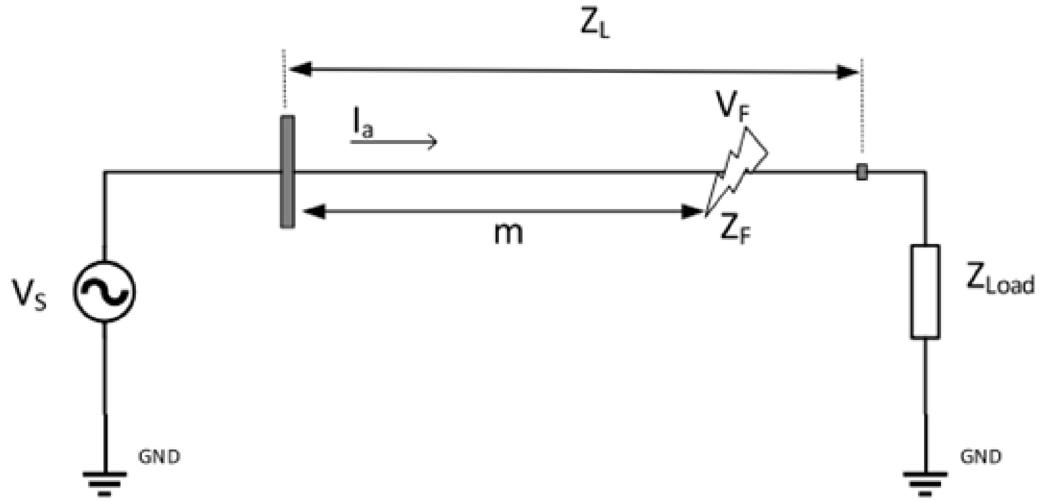

Figure 2.2: Single line diagram of three-phase circuit with fault at phase A and one ended source for distribution line

The fault impedance (ZF) and distance (m) to the fault are given by mathematical equation as follows:

$$Z_F = V_F + mI_aZ_L \tag{2.3.1}$$

Due to fault condition, $I_a = I_F$. Therefore,

$$Z_F = \frac{V_s}{I_F} = R_F + mZ_L \tag{2.3.2}$$

$$m = \frac{V_s}{(Z_L + R_F)I_F} \tag{2.3.3}$$

Estimation of fault location is affected by many factors that are not considered by the above equation 2.3.1.

2.3.3 Double terminal impedance method

It measures voltage and current at both ends of the line. The terminal voltages of the three-phase line are VS and VR, as shown in a single line diagram (see Figure 2.3). On the homogeneous three-phase line of impedance ZL, phase-to-ground faults at phase A are shown to have occurred. The distance (m) between the left terminal and the fault location is calculated using the negative sequence network shown in Figure 2.4. Mathematically, it is represented as follows [5]:

$$m = \frac{V_{2S} - V_{2R} + Z_{1L} * I_{2R}}{Z_{1L} * (I_{2S} + I_{2R})} \tag{2.3.4}$$

The one-ended impedance method is relatively simple and doesn't require a communication channel for data collection at the far end. Accuracy of fault location is affected by several parameters such as reactance effect, mutual coupling due to zero sequence current, improper faulted phase detection, inaccurate line modeling, load unbalances, measurement errors from different devices, etc. On the other hand, the two-terminal method gives accurate results concerning the fault location. However, collecting data from both terminals takes longer, and data synchronization is required on both ends before analysis can begin. Among different techniques suggested for fault location methods, Mora-Flòrez et al. in [27]

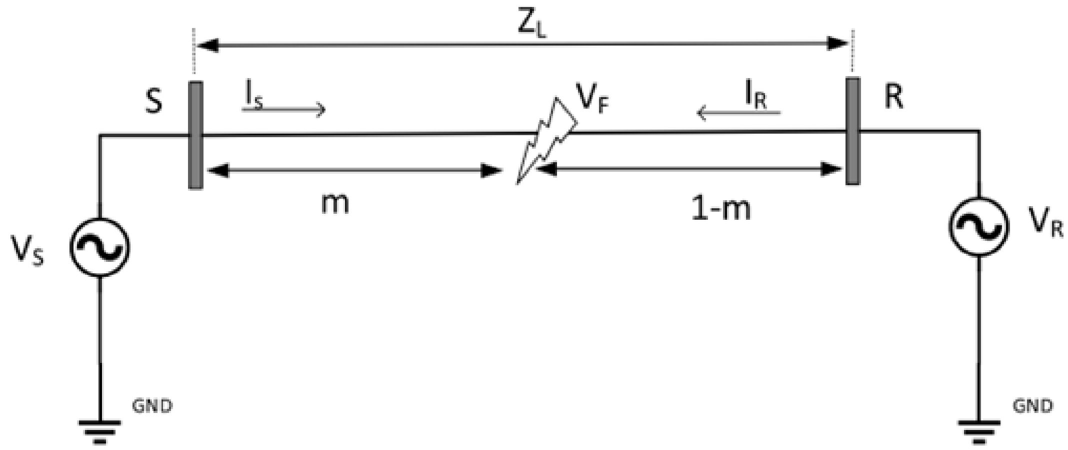

Figure 2.3: Single line diagram of three-phase circuit with fault at phase A and two ended MF source for distribution line

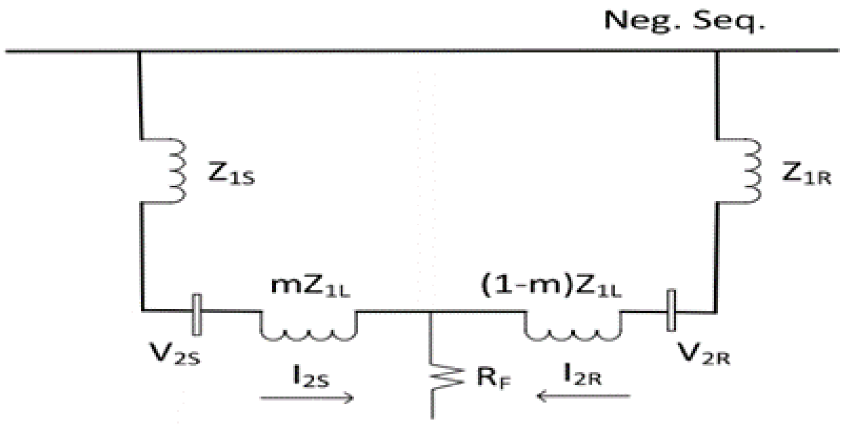

Figure 2.4: Negative sequence network [5]

compared two methods used for the impedance-based technique. In this study, Das et al. [28] proposed a technique that produced better results for double line and double line-to-ground faults. Warrington's technique, on the other hand, suggested greater accuracy for various fault resistance values. After that, a combination of the two techniques was proposed, which performed better for all fault types. For a balanced medium voltage (MV) radial system, Saha 10 et al. [29] proposed a fault location technique that took into account intermediate tapped loads and non-homogenous feeder lines. [30] presented mathematical equations for identifying various types of faults that occurred on the main feeders. Also, the static loads were assumed to be attached to the main feeder. Liao in [31] proposed a general method that reduces the efforts utilized in iterative methods and combined the advantages of SC analysis and bus impedance matrix techniques. The disadvantages to impedance-based fault locations include multiple fault location identification due to the possibility of faults occurring at same distances from the source, load unbalances, inaccuracies involved in line impedance values, measurement errors from various devices and transformer voltage and current errors, the effects due to ground and fault resistances (known as reactance effect), the filter system employed for voltage and current phasors and the time consumed in iterative techniques.

2.3.4 Traveling wave-based approach

In the traveling wave technique, high-frequency waves called surges or impulses are generated [5]. These traveling waves arise due to different reasons. Some of the common causes include faults on overhead lines, switching operations, and lightning strikes. As a result, the resulting surges move with the speed of light. The traveling waves are made up of both voltage and current waves that are linked together by the line's surge impedance (Zo). To provide accurate data, the traveling wave technique requires a standard time reference at both ends of the line. The data could be a precise current or voltage waveform. After that, the fault is located by calculating the wave arrival times at both terminals. The following formula can be used to calculate the fault location (for type A):

$$m = \frac{\Delta t}{2} * v_p \tag{2.3.5}$$

where V_p is the propagation velocity, Δt is the arrival time difference of the traveling waves. Different types of techniques are employed in fault locators based on traveling waves. They are categorized as Type A, B, C, D, and E. They are briefly discussed as follows:

Type A: The fault location is determined using this technique by measuring the time difference between the arrival wave and its reflected wave from a single terminal, as shown in Figure 2.5. Equation 2.3.5 expresses the fault location i.e.

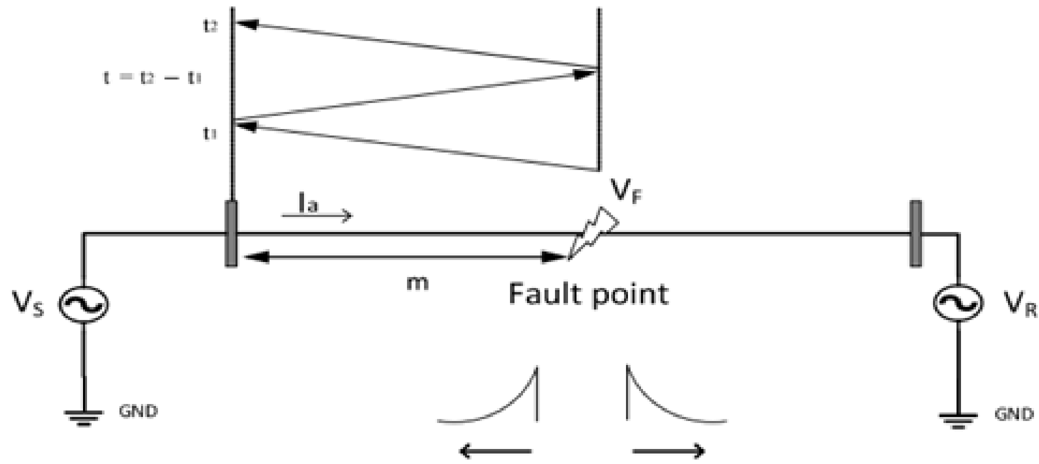

Figure 2.5: Single line diagram of three-phase circuit when travelling waves propagate towards source terminals when fault occurs on any of the three phase

half of the measured time difference.

Type B: The fault location is determined using this method by analyzing traveling waves from both ends of the line. Between the arrivals of the traveling waves at both terminals, the time difference is measured. A timing signal is initiated at the arrival of the traveling wave from the local terminal and continues until a stop signal is received at the terminal at the remote location. Similarly, a stop signal is sent to the data center when the traveling wave is detected at the remote location terminal. The delay time involved in this process is known and it is then subtracted from the total time difference. The resultant time difference is then used to compute the distance to the fault as follows:

$$m = \frac{\Delta t}{2} * \frac{L}{2} * v_p \tag{2.3.6}$$

Type C: In the type C method, an impulse is injected into the transmission line when a fault is detected at some point. The method used is known as time-domain reflectometry (TDM). The time difference between the injected impulse and the arrival of the reflected wave is used to calculate the distance to the fault. After that, the distance to the fault location is calculated in the same way as with the **Type A** method.

Type D: This method requires highly accurate devices to provide timing information at all terminals of the line. The traveling wave arrival at the terminal is time-stamped via a time-synchronized clock provided at all the terminals of the transmission line. The recorded traveling waves are then sent to the data center through communication channels where it is processed. The fault location is determined in several different ways, one of its methods being similar to that used for the **Type B** technique.

Type E: When a line is re-energized after the circuit breakers at one end of the line have reclosing action, a transient is observed. For locating faults in underground cables, this method is similar to the impulse current method. Permanent faults on transmission lines are located using **Type E** methods. The flowchart of the basic traveling wave technique is shown in Figure 2.6.

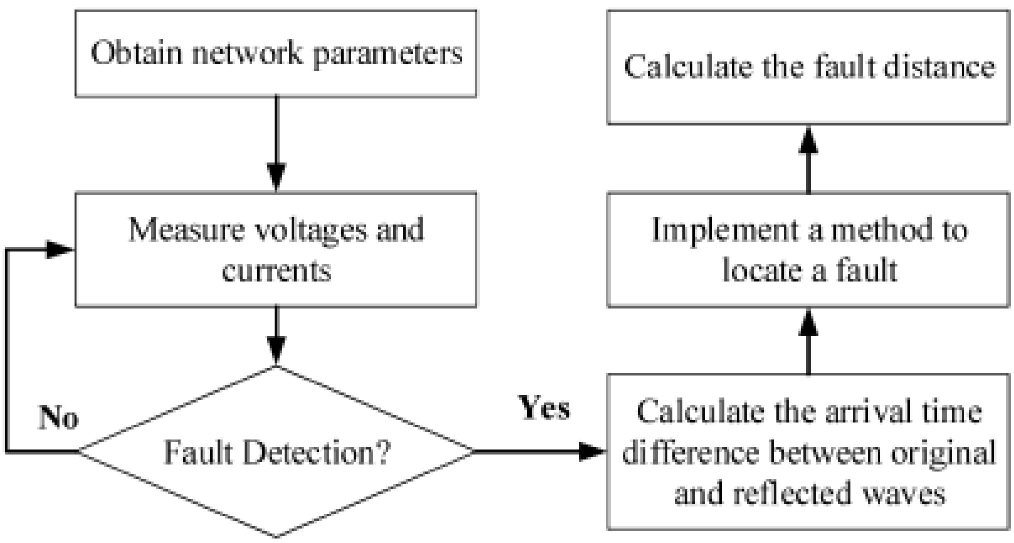

Figure 2.6: Basic flowchart of travelling wave based technique

In transmission networks, the various types of techniques discussed above have been successfully implemented. In [32], the researchers suggest a cross-correlation function for the incident and reflected waves to locate distribution system faults. This method was applied to both single-ended and double-ended systems. The double-ended method was more effective and provide accurate results when fault recorders were installed at two ends of the distribution lines. In [33], Coggins et al. presented a traveling wave-based approach in which fault recorders were installed on a medium voltage (MV) distribution network to analyze capacitor switching events, as well as their preliminary findings. When recording impulses for event fault location, however, the results were less accurate. A novel fault location technique was introduced that utilize the characteristic frequency of recorded traveling wave using digital simulation to locate faults on the distribution network [34]. Other fault location methods using traveling wave-based approach are reported in [35, 36].

In comparison to the impedance-based technique, the traveling wave-based technique yields more accurate results. Fault resistance, frantic iterative processing, and tapped loads are all addressed by proposing innovative solutions. However, the implementation of the traveling wave-based technique is complex and expensive. It requires the GPS, fault recorder, and diagnostic software. The installation of fault recorders on such a network is inappropriate due to the complexity of the distribution network's configuration. This technique is better suited to long lines and requires high-speed broadband communication channels. Also, the location accuracy predicted by this method is affected significantly by noise in data measurements.

2.4 Knowledge-based approach for fault localization

This is the more advanced category used in a microgrid for fault localization. It is further divided into three sub-categories.

- Artificial intelligence-based fault localization
- Distribution Devices based Method
- Hybrid method

2.4.1 Artificial intelligence (AI) based Fault location

Different artificial intelligence-based techniques have been developed with the advent of the internet and computer technology. These techniques help professionals to perform complex tasks in less time. Human errors are reduced by using artificial neural networks (ANN), fuzzy logic (FL), genetic algorithms (GA), and expert systems (ES) among other technologies [37]. Artificial neural networks and vector machines are the most reliable and widely used for fault localization due to their capability to recognize complex fault patterns. Below Figure 2.7 shows the basic function of the knowledge-based technique.

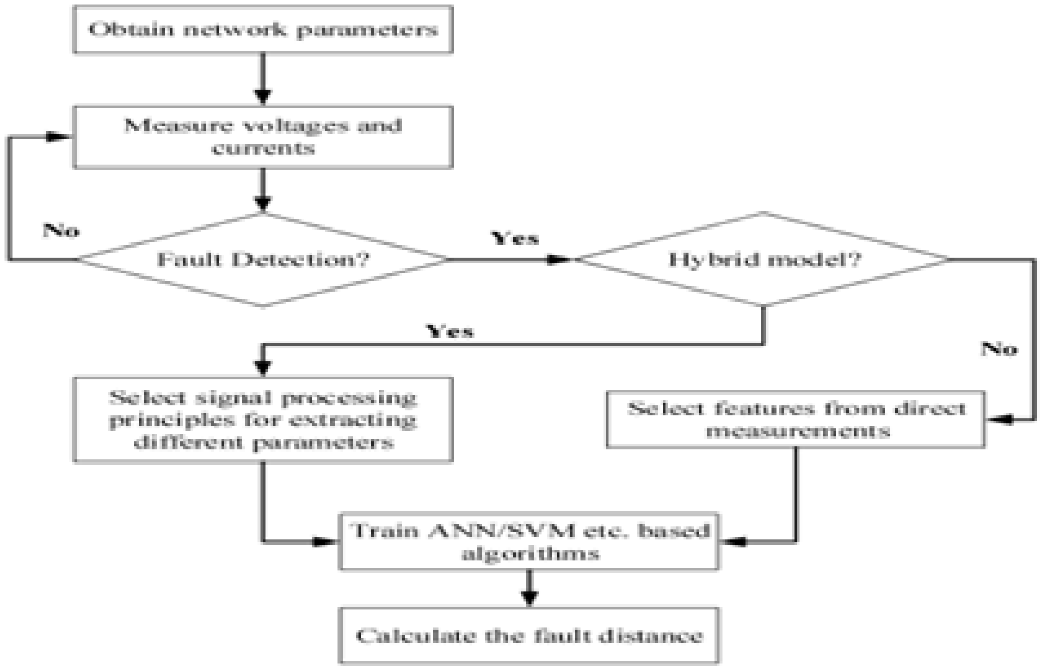

Figure 2.7: Basic flowchart of Knowledge based method

In this method network parameters were obtained for fault location measurement and the results are accurate. At the substation, three-phase currents, voltages, and active powers are measured and fed into ANN. After that, the ANN calculates the distance to the fault.

Some intelligent methods are used for fault location recently. In [38] author used a type-2 fuzzy logic system for fault classification and zone identification. For detection, classification, and fault location identification, the proposed strategy considers a variety of uncertainties related to faults and utilizes 2 distinct fuzzy systems. The fault is detected and classified using the deep brief network scheme is used in Ref. [39]. Discrete wavelet transform identifies the statistical patterns using the data from relays. This data is passed to deep neural networks to detect and locate the fault. In [40] fault detection and localization are done through hybrid technique by using SVM MSVM and wavelet transform WT. In the first step, each DG's voltage detects a problem, and the DG with the greatest voltage collapse injects a 333 Hz harmonic to locate another DG where the fault is located. Finally, the fault is located in a smaller search space using a wavelet transform and an optimized multiclass support vector machine (M-SVM). Ref [41] and [42] use an SVM classifier for detection of fault and then location is estimated based on harmonic injection that fed to MSVM.

The proposed SVM-based approach solves the problem of distinguishing between islanding and grid fault occurrences, allowing for better precision in islanding detection while also accurately detecting grid faults. The CNN scheme was used by the author in [43] for the protection of PV integrated Microgrids. A CNN-based protection strategy for fault detection classification and location is proposed in ref [44, 45]. This strategy takes TP current signals as input and applies convolution and pooling to extract features from input data. The CNNs layers then identify the fault type and location. In ref. [6] data mining intelligent differential scheme uses discrete Fourier Transform for feature extraction, but it is a high computational technique.

2.4.2 Distributed devices-based fault location Method

This scheme calculates fault localization based on simulated and measured data. The proposed technique uses current and voltage measurements from different fault locations [46]. Figure 2.8 illustrates the basic flowchart distributed devices-based data matching techniques for fault location in the microgrid.

2.4.3 Hybrid Methods

This technique is used to analyze transient occurring in the microgrid. The most effective approach that is used for current and voltage analysis in signal processing is based on the hybrid method. The wavelet transforms both continuous and discrete are commonly used in power system fault detection and localization [47].

In presence of variation of load, angle of inception, and fault impedance, the

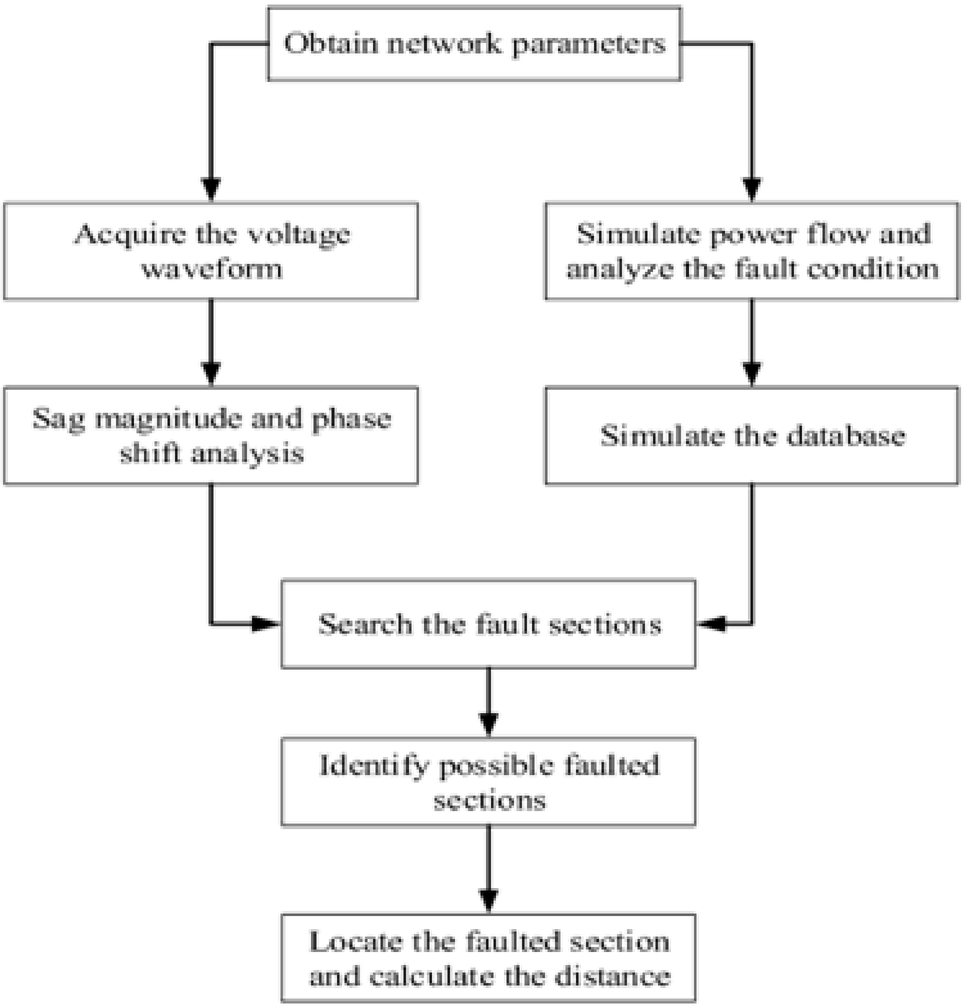

Figure 2.8: Flowchart of Distributed devices based fault location method

proposed method is more effective, and its results are more accurate.

Single point-based fault location techniques are also proposed by using traveling waves (TW), which detect the characteristic frequencies of TW from the fault point in the microgrid. In [48], a fast hybrid method has been presented to locate the fault in distributed generation (DG) systems. Current and voltage measured from the main substation and DG connection points are fed to feedforward artificial neural network (ANN) to calculate fault distances from all sources [49, 50].

It is very simple to implement knowledge-based methods but at the same time, the execution of these methods highly depends on correct data extraction. Inaccurate data obtained from an insufficient number of monitoring or measuring devices have a significant impact on the accuracy of results. The implementation of this method is also hampered by the placement of expensive devices on each node [51].

2.5 Proposed Scheme

This paper proposes a novel protection scheme to address the above-mentioned literature issues and create a protection scheme for the two modes of a microgrid: islanded and on-grid. The positive sequence component of voltage and current, which is extracted from both local and remote buses, is used to detect and classify the fault. Positive and negative sequence components are extracted from the buses to locate faults. To evaluate the efficacy in various modes of operation and topologies, simulations are carried out using MATLAB/Simulink.

2.6 Contribution of Proposed Scheme

The contribution of the Proposed Scheme

1. Defend the system from solid-state and high-impedance faults.
2. The proposed scheme is reliable for fault detection, location, and classification because it is independent of fault type and even works for high and low impedance faults.
3. Both grid-connected and islanding modes of operation are supported.
4. The proposed scheme applies to Microgrid topologies with radial and meshed topologies.
5. Under noisy measurement conditions, protect the system.

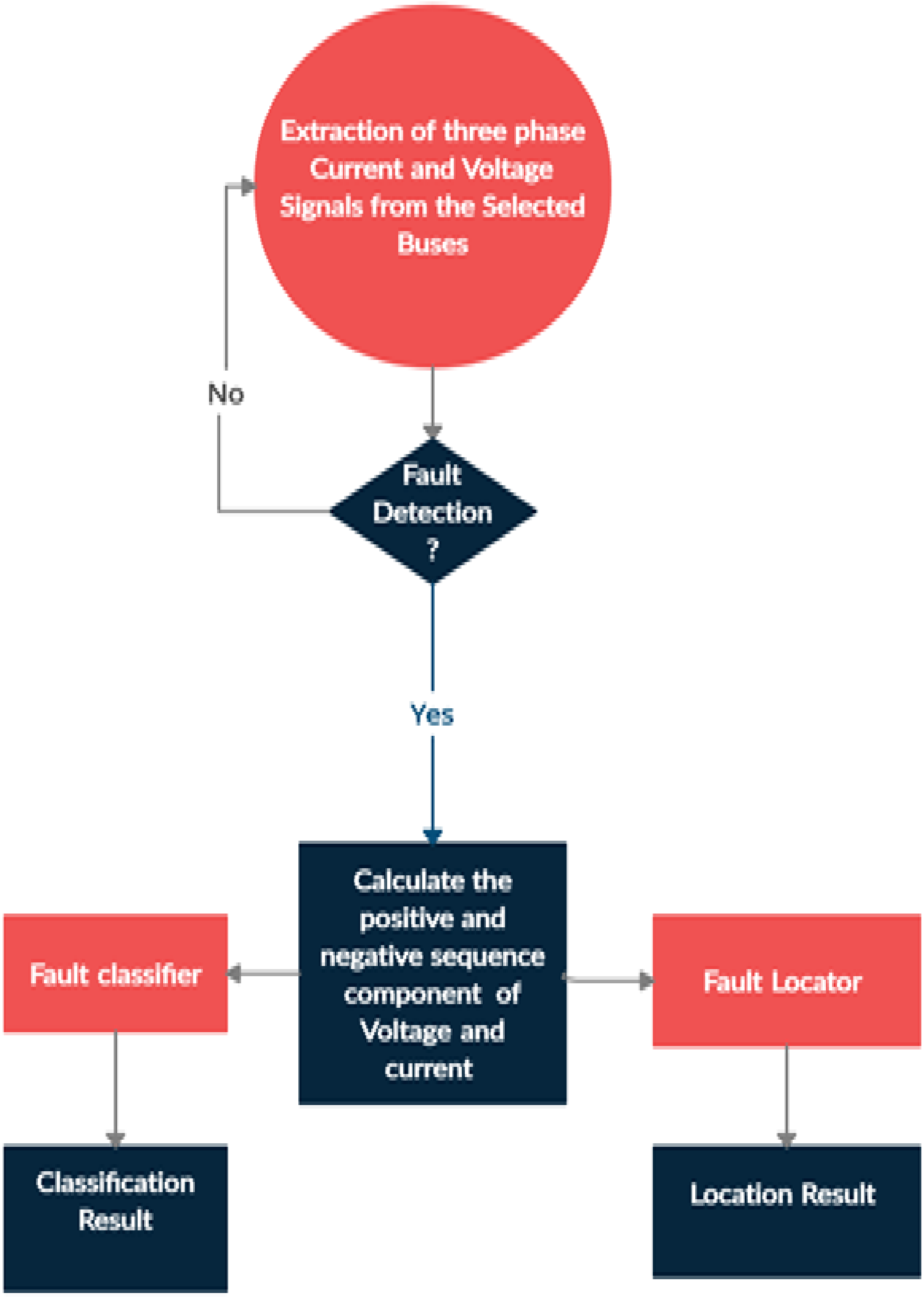

Figure 2.9: Generalized Framework of Proposed Microgrid Protection scheme

Summary

This chapter discusses all available technologies for microgrid protection. The chapter discusses the main categories of fault location techniques used in fault location in a microgrid. The schemes are explained in detail. The previous work carried out in literature has been discussed. The advantages and disadvantages of each technique have been reviewed. Later, a brief description based on new sequence component-based fault detection and location has been elaborated. This chapter provides the foundation for mathematical modeling and Microgrid test system are given in the next chapter addresses the protection issues that need to be overcome to implement the smart grid technology.

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Chapter 3

Methodology

This chapter outlines the general assumptions associated with the micro-grid protection, followed by the general setup of equations and equipment pertaining to those assumptions and parameters. Afterward, the proposed scheme is implemented on the test model in MATLAB/Simulink to check the accuracy of the scheme [1]. The chapter provides an overview of the proposed scheme to detect, classify the faults and locate the pinpoint location of the fault in microgrids using the sequence component technique. This scheme is designed such that it addresses the challenges posed by microgrids as discussed in the literature review. The proposed scheme is adaptive and viable for both modes of operation. In case of a fault, it detects, classifies, and locates the fault with high accuracy and confidence. The goal of the scheme is to provide a reliable method for fault identification, classification, and localization [2]. To address the problem statement a new sequence component-based approach is introduced in this thesis.

The proposed microgrid protection scheme develops a new indicator for fault detection named "Fault Index (FI)". The term FI is defined as the ratio of the sum of fault complex power at both buses divided by complex power at the local end minus complex power at the remote end. In this research work, the positive sequence component of the fault voltage and fault current is extracted from both ends of the line. The FI is calculated from these extracted positive sequence data. KVL equation between bus 1 and 2 is applied [3].

First, the proposed scheme segregates internal and external fault for fault detection. Later, the fault localization algorithm estimates the fault distance. Afterward, the fault classification algorithm classifies all types of faults e.g., Single Line to ground fault, Line to line fault, Double line to ground fault and triple line to ground fault, etc. Afterward, a faulty zone is isolated through relay tripping.

3.1 Fault Identification

For identification of fault in the microgrid a threshold-based algorithm is developed. Complex power from local buses and remote end is extracted to formulate Fault Index (FI). In this thesis, positive sequence of current and voltage are considered for fault detection [4].

$$\widetilde{V}_{p_1} - l_z.\widetilde{I}_{p_1} = \widetilde{V}_{p_2} - (\overline{(1-l)z}.\widetilde{I}_{p_2})$$

$$\widetilde{V}_{p_1} = \widetilde{V}_{p_2} + l_z.\widetilde{I}_{p_1} - (\overline{(1-l)z}.\widetilde{I}_{p_2}) \tag{3.1.1}$$

Complex power at bus 1 and 2 is represented by Equation 3.1.2 and Equation 3.1.3.

$$\widetilde{S}_{p_1} = \widetilde{V}_{p_1} \times (\widetilde{I}_{p_1})^* = (\widetilde{V}_{p_2}.\widetilde{I}_{p_1}) + (lz.(|I_{p_1}|^2)) - (\overline{(1-l)z}.\widetilde{I}_{p_1}.\widetilde{I}_{p_2}) \tag{3.1.2}$$

Similarly,

$$\widetilde{S}_{p_2} = (\widetilde{V}_{p_1}.\widetilde{I}_{p_2}) + (\overline{(1-l)z}.(|I_{p_2}|^2))) - (lz.\widetilde{I}_{p_1}.\widetilde{I}_{p_2}) \tag{3.1.3}$$

The sum and difference of complex power at Bus 1 and Bus can be obtained from Equation 3.1.2 and Equation 3.1.3.

$$\widetilde{S}_{p_1} + \widetilde{S}_{p_2} = (\widetilde{V}_{p_1}.\widetilde{I}_{p_2} + \widetilde{V}_{p_2}.\widetilde{I}_{p_1}) + lz.(|I_{p_1}|^2 - |I_{p_2}|^2) + l.\widetilde{I}_{p_2}.(\widetilde{I}_{p_2} - \widetilde{I}_{p_1}) = K_1 \tag{3.1.4}$$

$$\widetilde{S}_{p_1} - \widetilde{S}_{p_2} = (\widetilde{V}_{p_2}.\widetilde{I}_{p_1} - \widetilde{V}_{p_1}.\widetilde{I}_{p_2}) + lz.((\widetilde{I}_{p_1} + \widetilde{I}_{p_2})^2) - l.\widetilde{I}_{p_2}.(\widetilde{I}_{p_2} + \widetilde{I}_{p_1}) = K_2 \tag{3.1.5}$$

$$= (\widetilde{V}_{p_2}.\widetilde{I}_{p_1} + (lz.(|I_{p_1}|^2)) - (\overline{(1-l)z}.\widetilde{I}_{p_1}.\widetilde{I}_{p_2})$$

As shown in Equation 3.1.6, FI value is formulated from Equation 3.1.4 and Equation 3.1.5

$$FI = \frac{|\widetilde{S}_{p_1} + \widetilde{S}_{p_2}|}{|\widetilde{S}_{p_1} - \widetilde{S}_{p_2}|} = \frac{K_1}{K_2} \tag{3.1.6}$$

In case of fault, sequence components are formed, positive sequence current component at both the terminal can be expressed mathematically as.

$$\widetilde{I}_{p_1} = \frac{\widetilde{V}_{p_1} - \widetilde{V}_{p_2}}{z} \tag{3.1.7}$$

$$\widetilde{I}_{p_2} = \frac{\widetilde{V}_{p_2} - \widetilde{V}_{p_1}}{z} \tag{3.1.8}$$

Complex power at Bus 1 and Bus 2 can be obtain by using Equation 3.1.7 and Equation 3.1.8.

$$\widetilde{S}_{p_1} = \widetilde{V}_{p_1} \times (\widetilde{I}_{p_1})^* = \widetilde{V}_{p_1} \times (\frac{\widetilde{V}_{p_1} - \widetilde{V}_{p_2}}{z}) \tag{3.1.9}$$

Rearranging Equation 3.1.2 and Equation 3.1.3 will give,

$$\widetilde{S}_{p_1} = \frac{(V_{p_1}^2 - V_{p_1}.V_{p_2})}{z} \tag{3.1.10}$$

Similarly,

$$\widetilde{S}_{p_2} = \frac{(V_{p_2}^2 - V_{p_1}.V_{p_2})}{z} \tag{3.1.11}$$

Both the difference and the sum of sequence components of the complex power at Bus 1 and Bus 2 can be obtained as

$$\widetilde{S}_{p_1} + \widetilde{S}_{p_2} = \frac{V_{p_1}^2 + V_{p_2}^2 - 2V_{p_1}.V_{p_2}}{z} = \frac{(V_{p_1} - V_{p_2})^2}{z} \tag{3.1.12}$$

$$\widetilde{S}_{p_1} - \widetilde{S}_{p_2} = \frac{V_{p_1}^2 - V_{p_2}^2}{z} \tag{3.1.13}$$

Using Equation 3.1.12 and Equation 3.1.13, FI value has been formulated in the Equation 3.1.14

$$FI = \frac{|\widetilde{S}_{p_1} + \widetilde{S}_{p_2}|}{|\widetilde{S}_{p_1} - \widetilde{S}_{p_2}|} = \frac{|V_{p_1} - V_{p_2}|}{|V_{p_1} + V_{p_2}|} \tag{3.1.14}$$

Here FI is the fault index, it is a threshold that detects the faults occurring in the system. When a fault occurs from both ends of the line, FI and positive sequence voltage and current components are estimated. In grid-connected and islanded mode, whenever a fault occurs, the FI value will cross the threshold [5]. Along with the fault detection in the system, this will identify the faulty line as well. It will segregate internal and external faults. For internal fault, both values of current and voltage will vary as FI is a function of positive sequence components of both voltage and current, so in case of fault FI will cross the threshold and fault will be identified. Hence, for internal fault, the FI value will cross the threshold and will identify the faulty line. For external or no-fault conditions, the voltage will not drop much and the FI value will not cross the threshold. From Equation 3.1.14 and Equation 3.1.6 it can be observed, FI for internal fault is always greater than no-fault or external fault condition because in Equation 3.1.14 it can be observed that FI for no fault or external fault is the function of voltage only [6]. In case of no-fault or external fault voltage records, both the buses will almost be the same hence numerator will yield a very small quantity. FI value for these is close to zero or very small. On the other hand, the FI value for internal fault is the function of both voltage and current as shown in Equation 3.1.6. FI value has been studied for a wide range of faults.

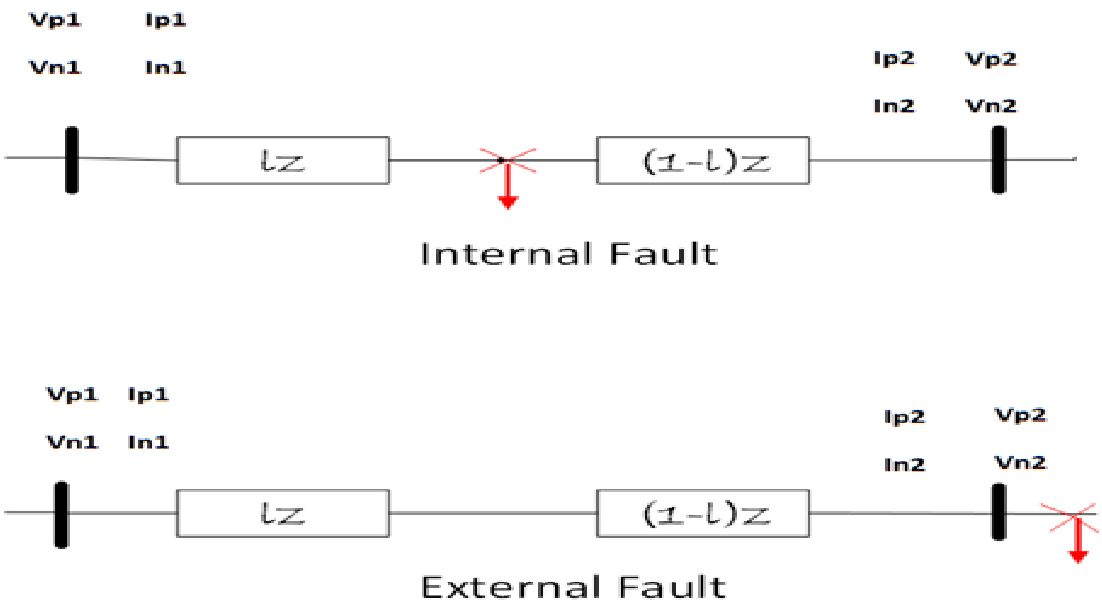

Figure 3.1: External and Internal Fault in Microgrid

3.2 Fault location algorithm

The proposed fault location algorithm makes use of both positive and negative current and voltage components for localizing the fault location. Under a faulty condition in grid-connected and islanding mode, positive and negative components are formed which are further used by the proposed algorithm to inspect the fault location [**?**]. Rearranging Equation 3.1.1

$$\widetilde{V}_{p_1} - \widetilde{V}_{p_2} = l_z.\widetilde{I}_{p_1} - (\overline{(1-l)z}.\widetilde{I}_{p_2}) \tag{3.2.1}$$

Similarly, KVL eq. for negative sequence network can be represented as:

$$\widetilde{V}_{n_1} - \widetilde{V}_{n_2} = l_z.\widetilde{I}_{n_1} - (\overline{(1-l)z}.\widetilde{I}_{n_2}) \tag{3.2.2}$$

Solving Equation 3.2.1 and Equation 3.2.2 will give

$$lz = \frac{(\widetilde{V}_{p_1} - \widetilde{V}_{p_2}).\widetilde{I}_{n_2} - \widetilde{V}_{n_1} - \widetilde{V}_{n_2}.\widetilde{I}_{p_2}}{\widetilde{I}_{p_1}\widetilde{I}_{n_2} - \widetilde{I}_{p_2}\widetilde{I}_{n_1}} \tag{3.2.3}$$

$$(1-l)z = \frac{(\widetilde{V}_{p_1} - \widetilde{V}_{p_2}).\widetilde{I}_{n_1} - \widetilde{V}_{n_1} - \widetilde{V}_{n_2}.\widetilde{I}_{p_1}}{\widetilde{I}_{p_1}\widetilde{I}_{n_2} - \widetilde{I}_{p_2}\widetilde{I}_{n_1}} \tag{3.2.4}$$

Hence, the distance at which the fault occurs can be calculated by using the following equation.

$$l = \frac{lz}{lz + \overline{(1-l)z}} = \frac{(\widetilde{V}_{p_1} - \widetilde{V}_{p_2})\widetilde{I}_{n_2} - (\widetilde{V}_{n_1} - \widetilde{V}_{n_2})\widetilde{I}_{p_2}}{(\widetilde{V}_{p_1} - \widetilde{V}_{p_2})(\widetilde{I}_{n_1} + \widetilde{I}_{n_2}) - (\widetilde{V}_{p_1} - \widetilde{V}_{p_2})(\widetilde{I}_{p_1} - \widetilde{I}_{p_2})} \tag{3.2.5}$$

3.3 Proposed Microgrid Test Model

To check the validity and efficacy of the proposed scheme extensive simulation have been performed in MATLAB/Simulink Software using sequence components of current and voltage. The test system used in this research work for implementation and detail testing of prospered technique is stated as "Standard international

Electro-Technical Commission IEC 61850-7-420 Microgrid Test Model [7]. The microgrid test model has a variety of operation setups. A single line diagram of IEC Microgrid with Six Buses is illustrated in Figure 3.1 A synchronous generator with four invert-based distribution sources is connected to the microgrid test model through step-up transformers. Using IDER's a control strategy has been established. There are five distribution lines in the system that are (DL1 to DL5). The test model has eight buses (B1 to B8) and a point of common coupling which connects the main grid to a microgrid. The network parameters and load are acquired from the Ref. with the operating voltage 25KV. For operating, a microgrid test model in grid-connected and Islanding mode circuit breaker at PCC is used. For radial and loop topological structure of microgrid operation, CB 1oop-1 loop and CB-2 loop are used [8].

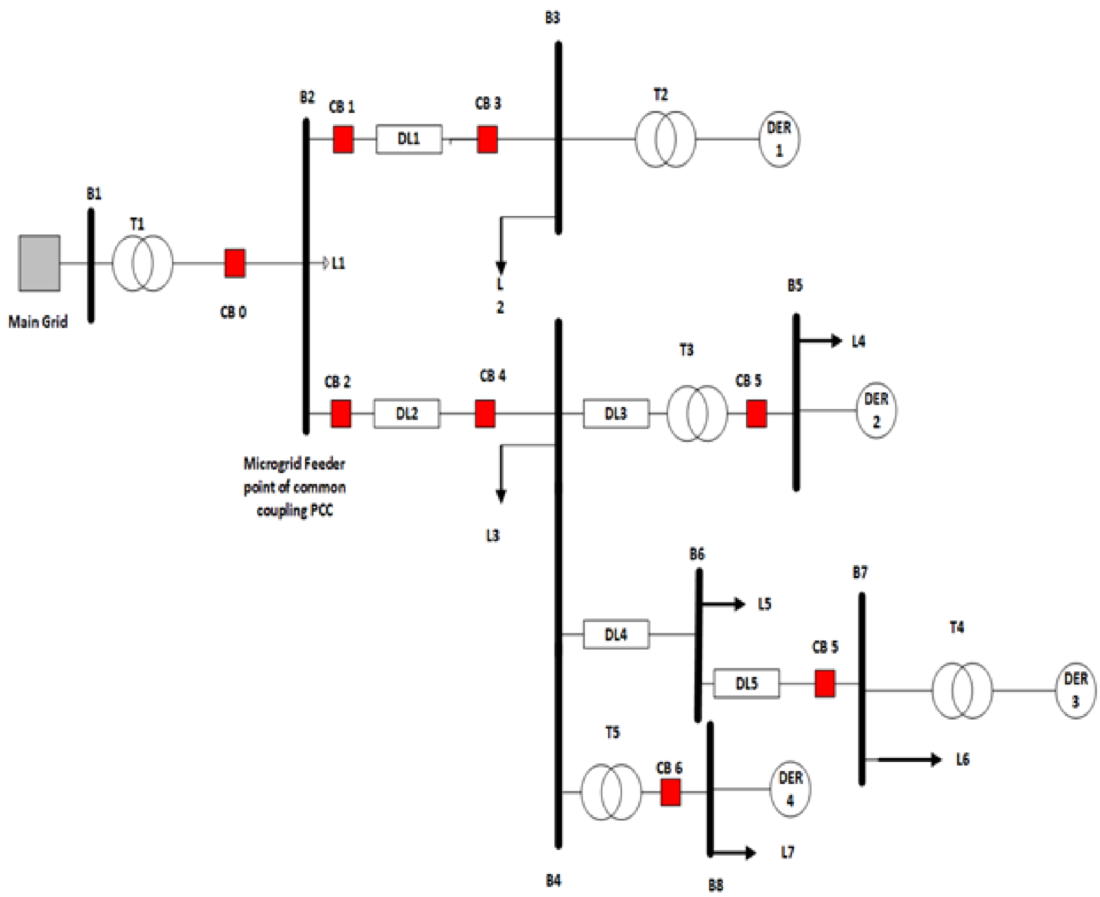

Figure 3.2: Standard International Electro Technical Comission IEC Microgrid Test Model

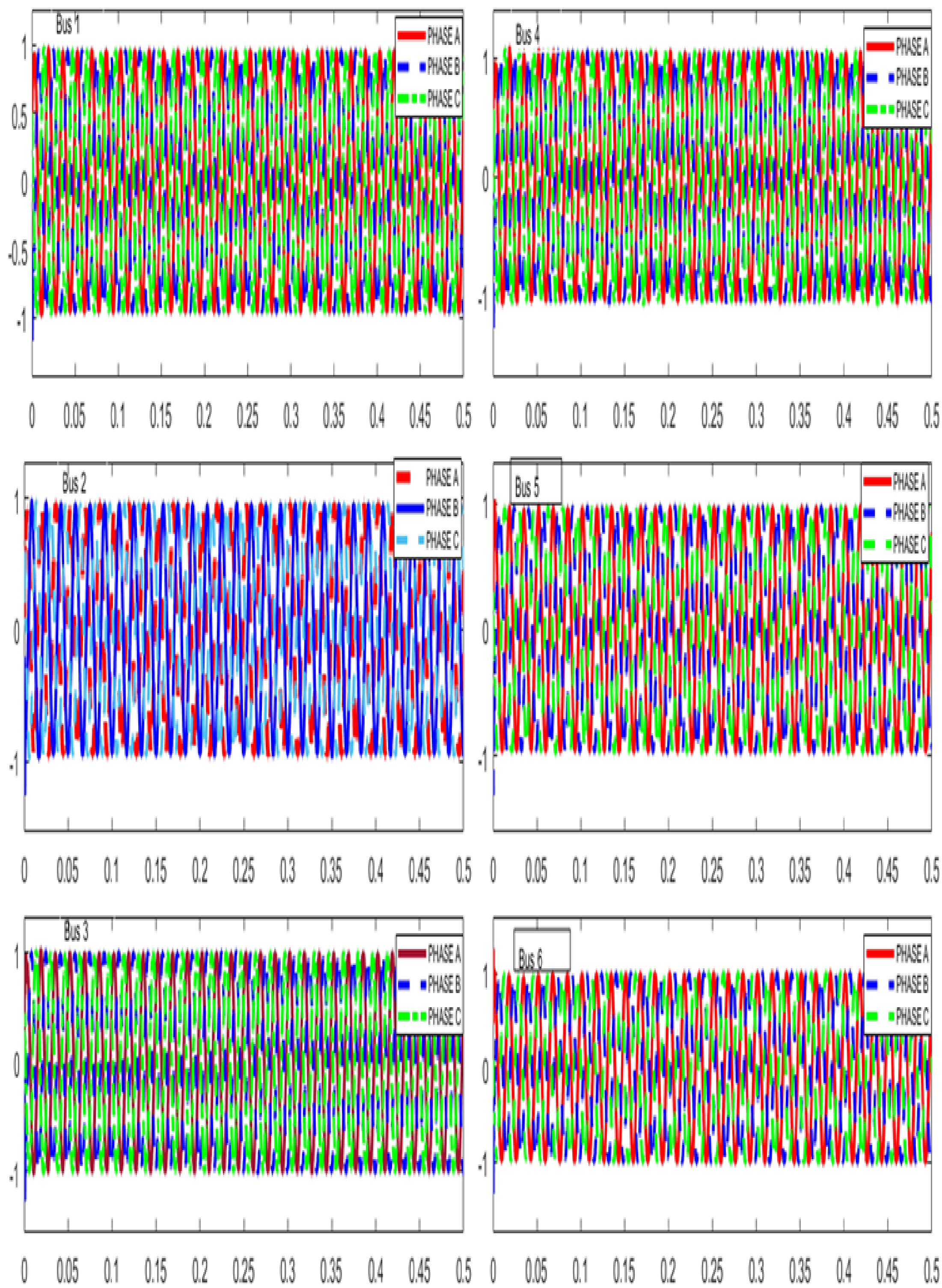

Figure 3.3: Measured three phase voltages at all six buses for no fault Condition

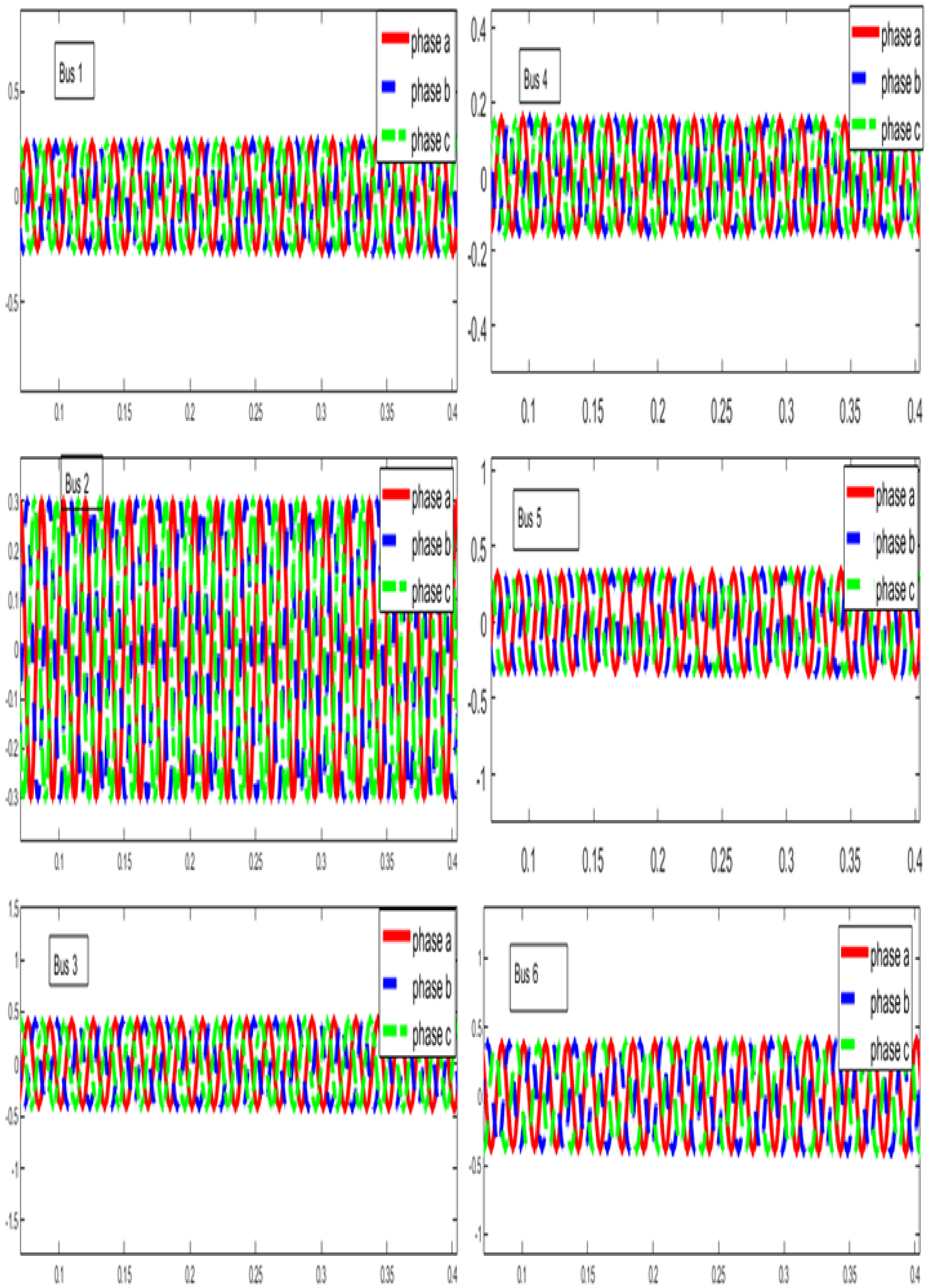

Figure 3.4: Measured three phase Current at all six buses for no fault condition

3.3.1 Fault Detection in Microgrid

- Sequence components are extracted from both ends of the distribution line.
- Current and voltage values are initially extracted at normal condition and then the fault is injected and again sequence components of current and voltage are extracted.
- A threshold is developed by using the extracted complex power from both end buses.
- In case of fault, FI will cross the threshold. Hence fault is detected.
- Each phase is analyzed to classify the fault type.

3.3.2 Fault localization in Microgrid

- After fault detection, both positive and negative sequence components are extracted from both ends of the line.
- Impedance is calculated using sequence component of voltage and current.
- Above mentioned algorithm by using impedance and sequence components of current and voltage estimate the distance of fault.

The proposed algorithm is implemented and verified for different types of faults. It is noticed that the proposed technique is viable for all types of fault and it is less complex and has a low computational load [9].

Summary

The mathematical modeling of the proposed scheme for Microgrid is presented in this chapter. The performance of the proposed scheme is analyzed by mathematical modeling and a Microgrid test system. The first fault detection algorithm is proposed. From both remote and local ends, sequence components of voltage and currents are obtained. The proposed technique is based on the location algorithm also used for locating faults in the microgrid. The proposed method is further clarified with the help of flowcharts and Figures. This chapter provides the support to simulate the proposed protection scheme on MATLAB/Simulink.

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Chapter 4

Results and Discussion

4.1 Fault Analysis

An extensive analysis of fault in the Microgrid test system is executed to check the validity and accuracy of the proposed scheme. IEC Microgrid Test model is implemented in the MATLAB/Simulink 2019b software for data generation which is further used in different case studies to detect and locate the fault. Fault under different case studies includes a single line to ground fault, the line to line fault, triple line to ground fault, three-phase fault, and high impedance fault. In this research work, all types of faults are almost covered, in different operating scenarios, distribution lines, various resistances, load, and fault locations [1]. Above all, backup protection is also provided to avoid further damage in case of primary relay failure. In addition, a large number of no-fault cases are simulated in different constant and load varying conditions [2].

To check the accuracy of the proposed scheme a fault is injected on phase A between 0.15s to 0.30s. Figure 4.1 show that when a fault is initiated on phase A the value of current at Phase will shoot and on the other two phases current signals will not show any abnormality. Figure 4.2 shows when a fault is initiated at phase A between the 0.15s-0.30s voltage at phase A will drop and the voltage of remaining phases will normal. So the proposed scheme show in case of fault current will increase and voltage will decrease.

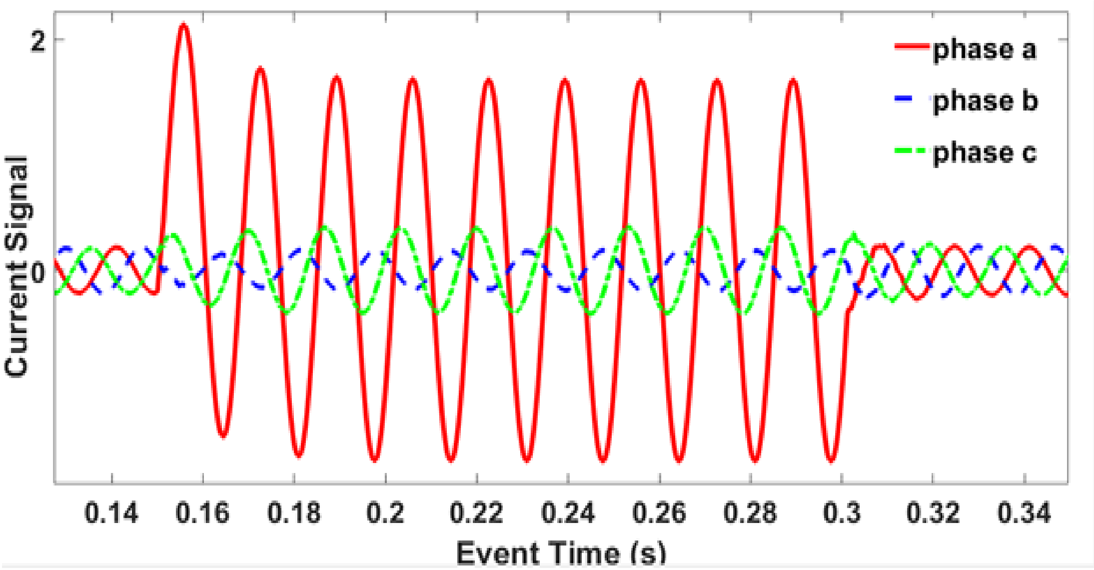

Figure 4.1: Current Signal in case of fault at phase A

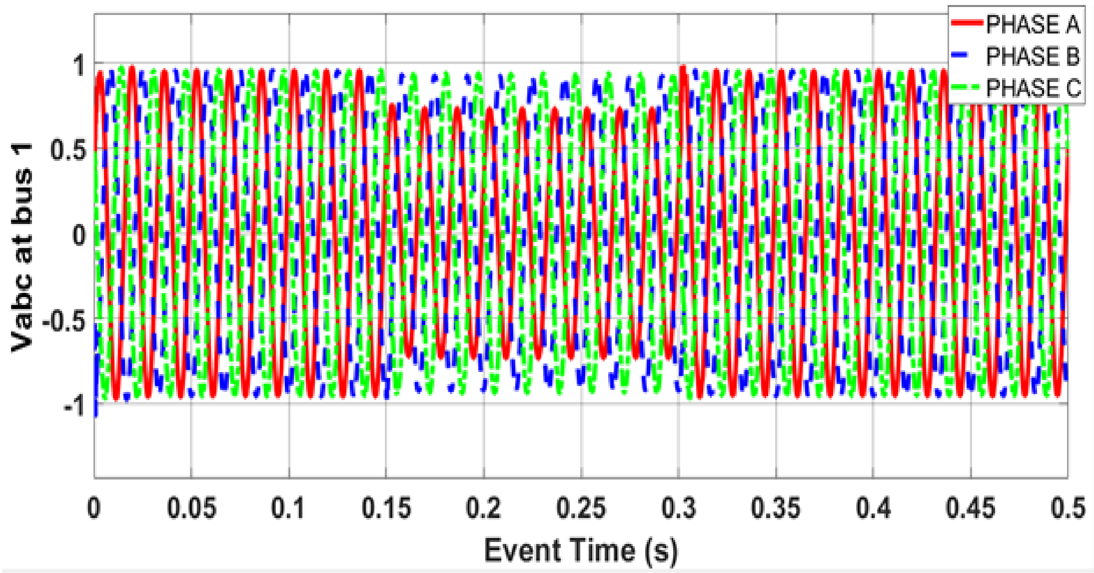

Figure 4.2: Voltage Signal in case of fault at phase A

4.1.1 External Fault

The Proposed scheme has the capability of identifying the faulty zone. In case of external fault, the FI value measured at both ends of the transmission line will remain below the threshold [3]. By analyzing the FI signal, a fault zone can be detected. When there is no fault or in case of external fault FI value will be zero or very small.

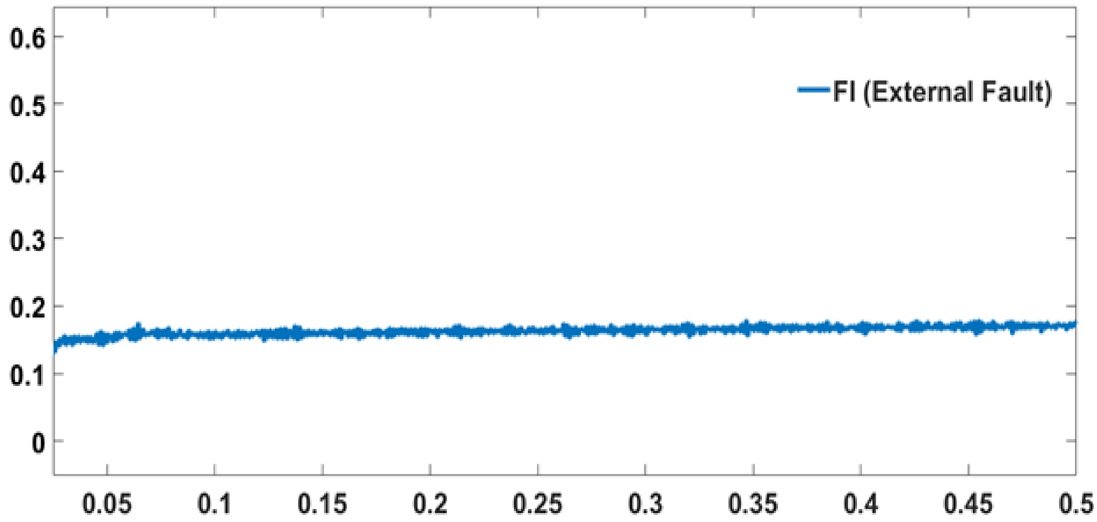

Figure 4.3: FI Value for External Fault

4.1.2 Internal Fault

When a fault is inside the transmission line, FI measured at both the end of buses will cross the threshold and will detect the fault. FI signal analysis will show either fault is internal or external [4]. A fault is injected between bus 1 and bus 2 between 0.15s to 0.30s. FI signals measured at both crosses the threshold limit which shows that fault is in between Bus 1 and Bus 2. The below result shows the efficacy of the proposed scheme.

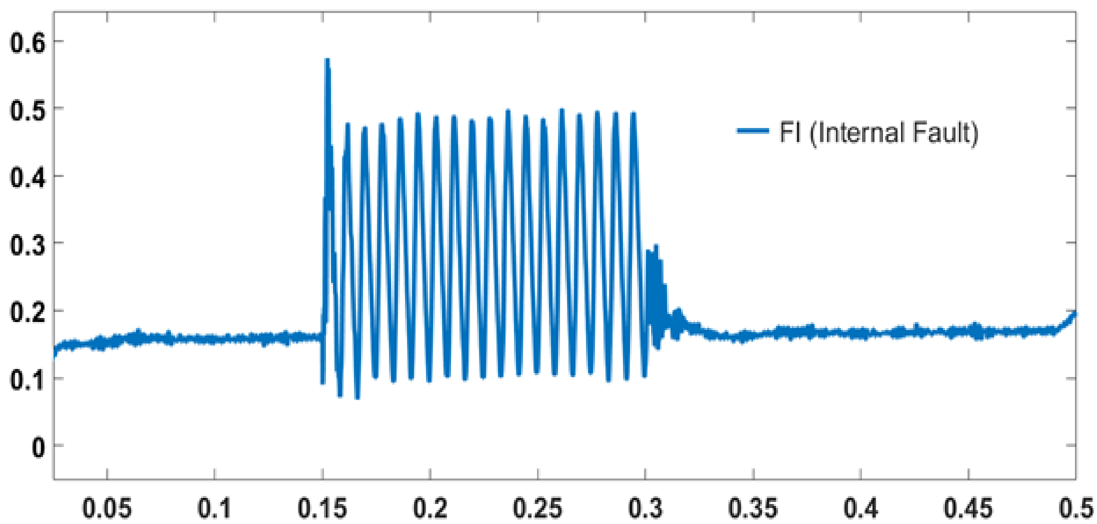

Figure 4.4: FI value for internal fault

4.1.3 Single Line to Ground Fault

In this case study, the fault is initiated on phase A, measured current and voltage signal will give the value of FI more than the Threshold. As shown in Figure 4.5 FI reaches 0.6 while the threshold is 0.2. The fault period is 0.15s to 0.30s and during this period FI value remains above the threshold. Hence, the proposed technique is viable for single line to ground fault [5].

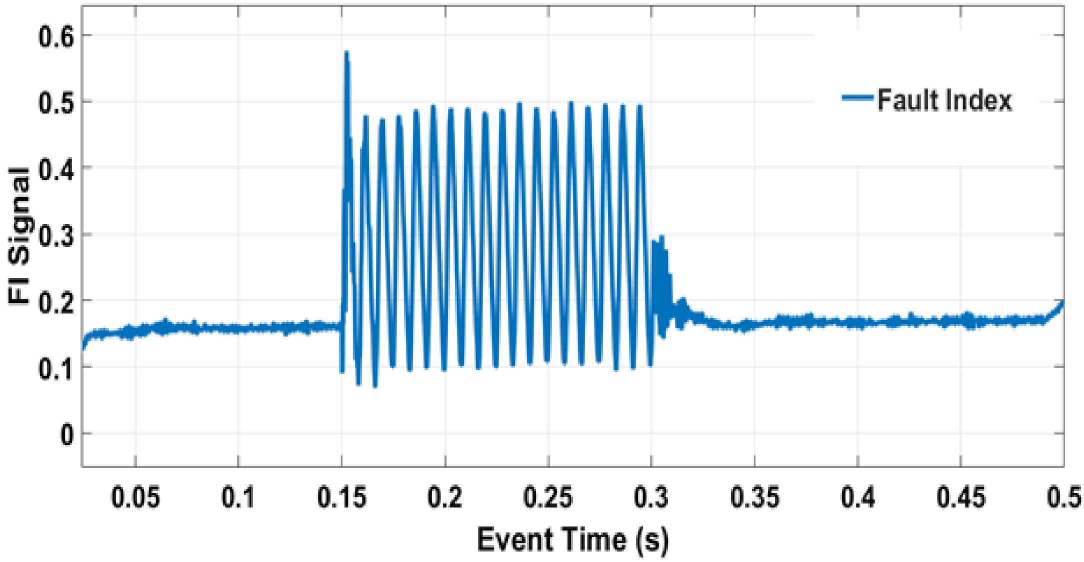

Figure 4.5: FI value for Single Line to Ground fault

4.1.4 Phase to Phase fault and Double line to ground fault

When a fault is injected on two phases or double line to ground, the proposed scheme successfully detects the fault. Figure 4.6 shows FI value for phase-to-phase fault while Figure 4.7 shows FI value for double line to ground fault. The fault is introduced between 0.15s to 0.30s and for that period FI signal shows it crosses the threshold at 0.15s and clears the fault at 0.30s.

4.1.5 Triple line to ground fault

In this type of fault, a three-phase fault is injected into all three phases [6]. Each phase is analyzed and the result shows that in each phase, current increases and voltage drops. FI value will shoot to 1.5 which is eight times higher than the threshold value.

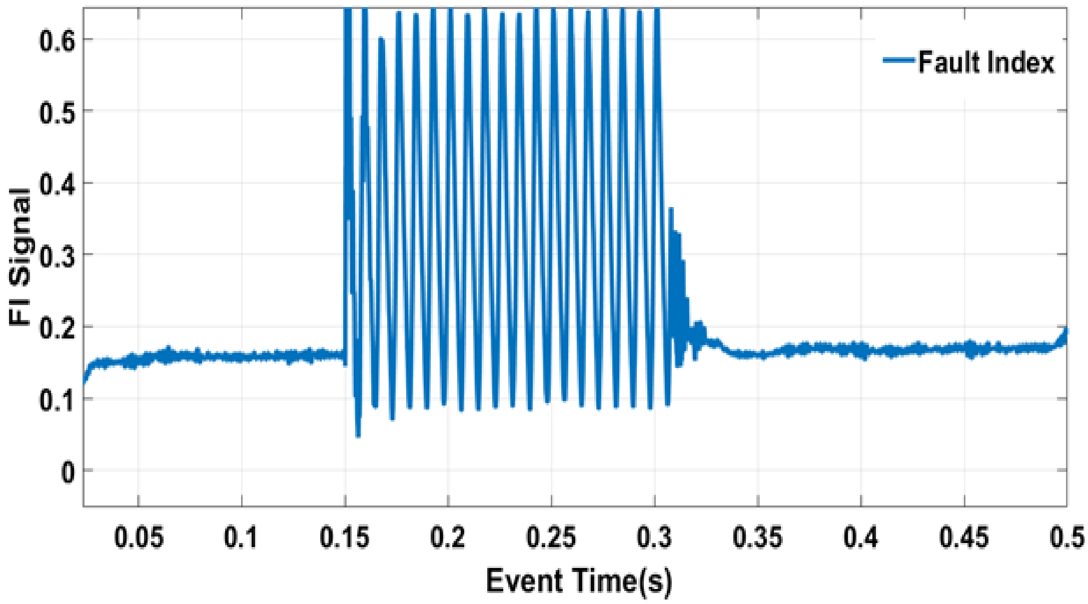

Figure 4.6: FI for Line-to-Line fault

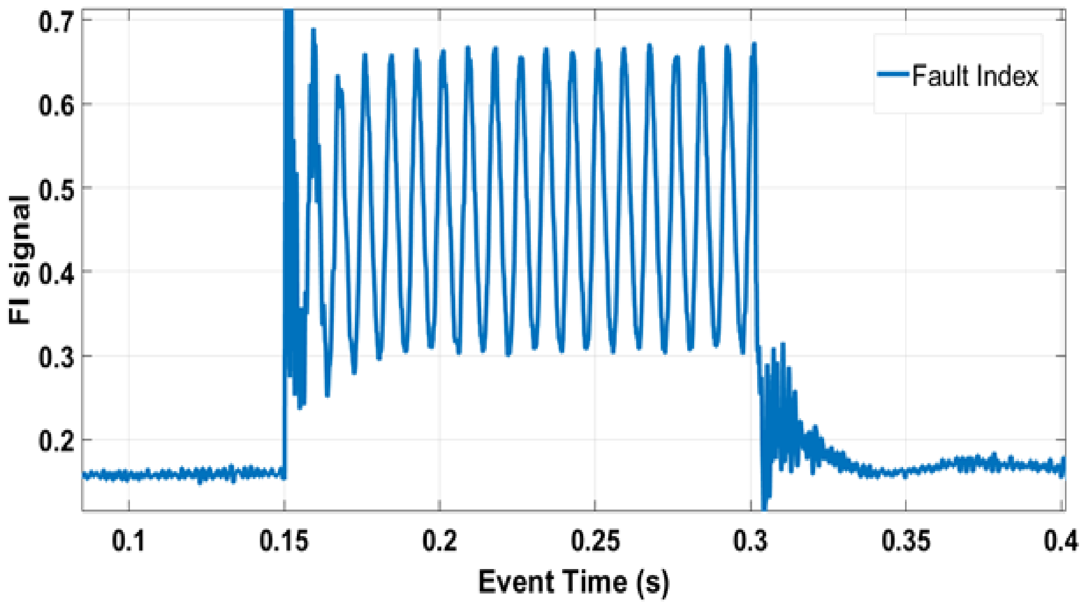

Figure 4.7: FI for Double line to ground fault

4.2 Fault Classification

In general, faults can be classified into two broader types. Some faults occur due to insulation failures or degradation of insolation which results in a short circuit between two live conductors such faults are called shunt faults. These faults occur due to sudden over-voltage or overstressed conditions. The faults which lead to the interruption of current flow are called series faults or open

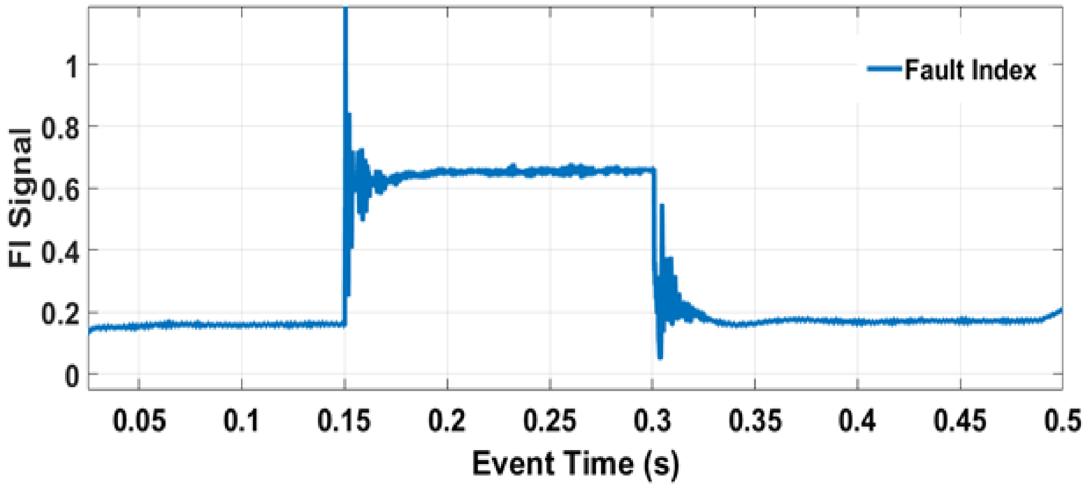

Figure 4.8: FI for Triple line fault

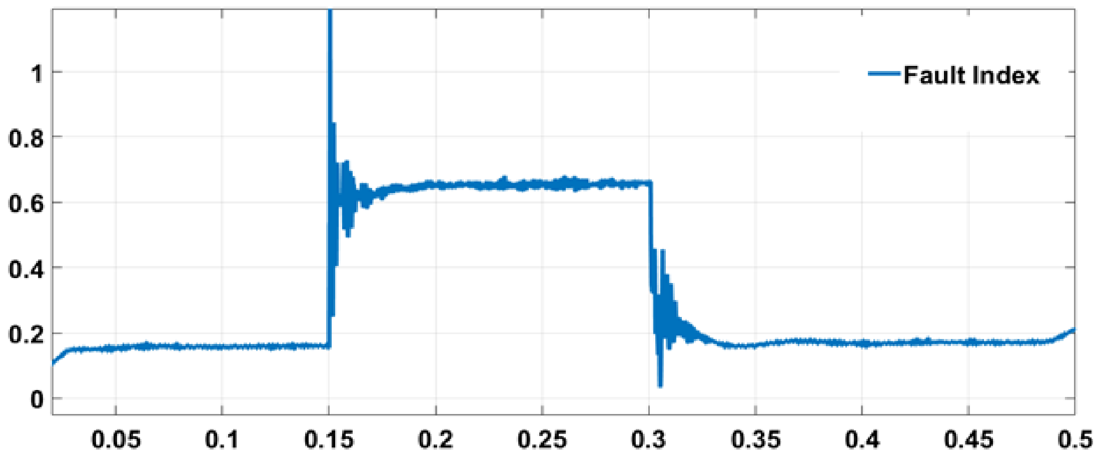

Figure 4.9: FI for triple line to ground fault

circuit faults. Shunt fault which involves all three phases, or three phases, and ground are called symmetrical faults [7]. In LLL and LLLG faults all phases are affected. Shunt faults that occur due to short circuits involve Single line to ground fault, the line to a line fault, or double line to ground fault and these faults are called unsymmetrical faults. In such faults phase balance is disturbed and which results in unsymmetrical current components. The waveforms of three-phase current during single line to ground fault are shown in Figure 4.10. A three-phase current waveform for double line ground fault is shown in Figure 4.11 and a triple line to ground fault waveform is shown in Figure 4.12 Sometimes there may occur two or more faults at a time such faults are called simultaneous faults.

These faults may be of the same type or may be of different types and maybe these faults occur at a different location not at the same location. Whenever an overhead distribution line broke it is simultaneously a single-phase short circuit and single-phase open-circuit fault at the same location [8]. The protection system must make sure that the microgrid gets isolated in case of a fault in the main grid and in case of a fault in the microgrid a minimum number of consumers should get affected. There are few challenges associated with the protection system of Microgrid.

- High penetration of inverter-based distribution sources results in a smaller and intermittent fault current magnitude.
- Different levels of fault current in different modes of Microgrid.
- Topological changes in microgrid due to isolation or reconnection of load, DGs, and storage system.
- Assessing the level of fault current is challenging in Microgrid due to the intermittent nature of DERs.

Thus, to address such issues a data-driven technique combined with signal processing is developed. As the proposed scheme is adaptive and analyzes signals with more accuracy. Using the proposed technique fault can be detected and classified even with the smallest change in the voltage and current. Hence, it reduces our dependence on the large magnitude of fault current. In this thesis we consider the classification of fault, given the condition that fault has occurred, the aim is to identify the faulty phase. This will help the control system to trip the only faulted phase which will avoid unnecessary Islanding of Microgrid, and further isolation of faulty zone and restoration of the power system will become easy. Fault is initiated at different phases and below Figure 4.10,4.11 and 4.12 shows the efficacy of proposed scheme. Each phase is classified and in case of fault, each phase shows abnormal behavior. By analyzing the waveform of measured current at each phase classify the type of fault.

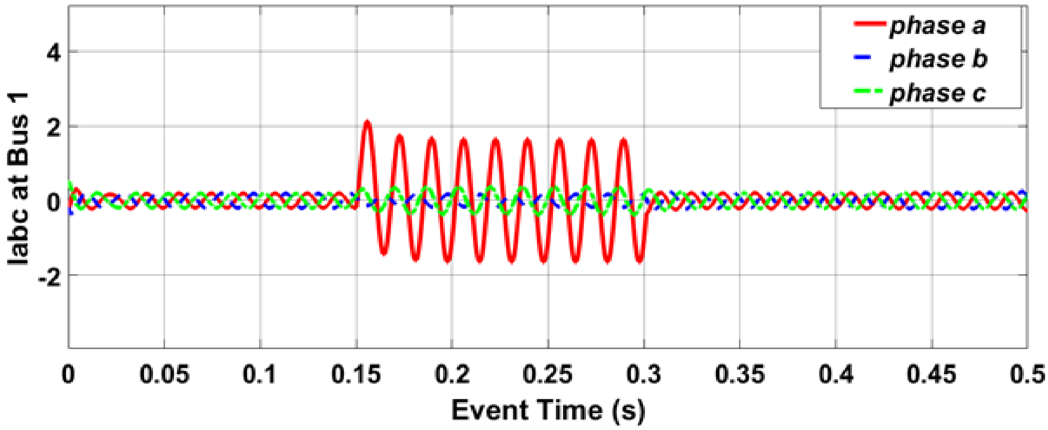

Figure 4.10: Fault Classification for Phase A fault

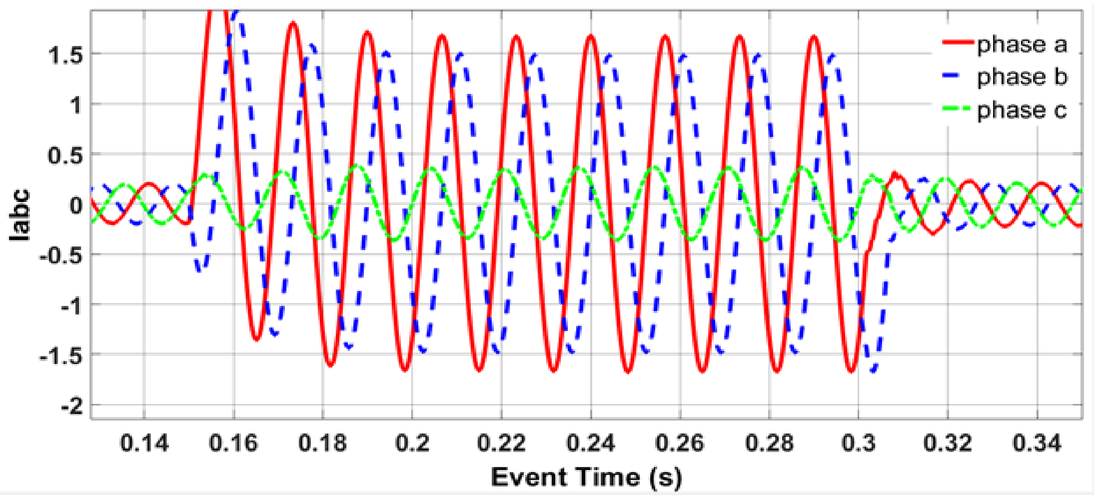

Figure 4.11: Fault Classification for Line-to-Line fault

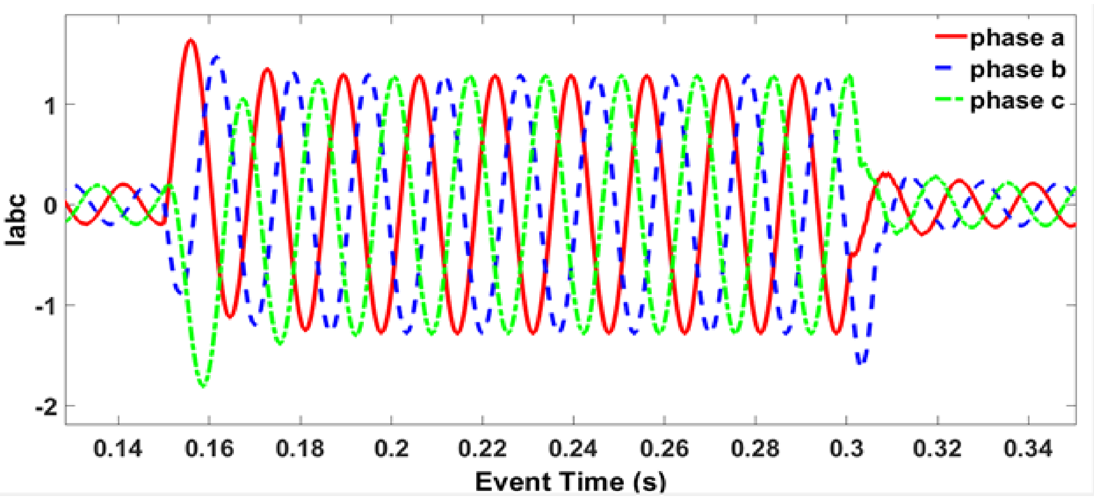

Figure 4.12: Fault Classification for triple line fault

Summary

The chapter verifies the efficacy and validity of the proposed scheme by simulating it in MATLAB/Simulink. The chapter presents the description of numerical simulation. On the Microgrid test system simulations were performed. The different case studies related to the model are being performed and evaluated. Algorithm results obtained from simulation are discussed in detail. The simulation result shows that the proposed scheme is fully trained to address protection issues. The proposed technique detected and located the fault with 100% accuracy.

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Chapter 5

Conclusions and Future Work

5.1 Conclusions

To meet the power quality and reliability concerns this thesis proposed an optimal way to address these issues. Microgrid faces many challenges due to the dynamic transition between grid-connected and islanding mode. Microgrid protection scheme designing is the main challenge and it is the last hindrance in the implementation of Microgrid technology. This thesis proposed a sequence-based technique for the protection of Microgrid. Firstly, the proposed scheme uses the positive sequence-based algorithm for fault detection and classification. Secondly, both positive and negative sequence components are extracted to locate the faulty section. Pinpoint fault location is obtained by the proposed algorithm. Results obtained from measurements were compared with the simulated results of MATLAB/Simulink. Extensive simulations were performed in MATLAB/Simulink to validate the efficacy of the proposed scheme. Mathematical results and simulation results match well which shows the validity of the Proposed scheme. The proposed scheme doesn't need any adaptive relay setting in different modes of operations i.e., grid-tied and islanding mode. The simulation results of the proposed scheme demonstrate the great potential of the proposed protection scheme both for radial and mesh scenarios and for gird connected and islanding modes. We conclude that the proposed technique is efficient and fast enough to detect, locate and classify the fault.

5.2 Future Work

It should be ensured that no extra barriers such as high costs, technical difficulties, lack of standards, etc., exist against the use of DR. The future fault detection techniques will comprise of new technologies such as Global position system, PMU, and advanced communication infrastructure. Hardware I loop is one of the best concepts for real-time implementation. It represents real-time simulators like Real-Time Digital Simulator, RT Lab, dSPACE, Hybrid Real-Time (HRTSim), etc. to build assurance on their performance and to check the advanced detection techniques. In future use of Solid-state Transformer, z-source CB, IEDs, etc., these emerging protection devices in the Microgrid integrated system will enhance the fault detection technology. To achieve the future scenario, the internet of things (IoT) can act as the next target in the vision of protective devices sending data to cloud-based functions working coordinately. It uses to provide value during big data analytics. In the future, considerable research work is needed to address the response time issue. Considering the level of the desired SNR, the validity of the measurements needs to be checked. Response time for fault detection needs more research in the future. The application of optical wireless networks and 4G networks of cellular wireless services can promise high reliability, low latency, communication optimality energy efficiency, and flexibility.

Appendix A- Publication

The following paper is published (or under publication process) from the work described in the thesis

Sequence Based Approach for Fault Diagnosis, Localization, and Classification in Microgrids

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