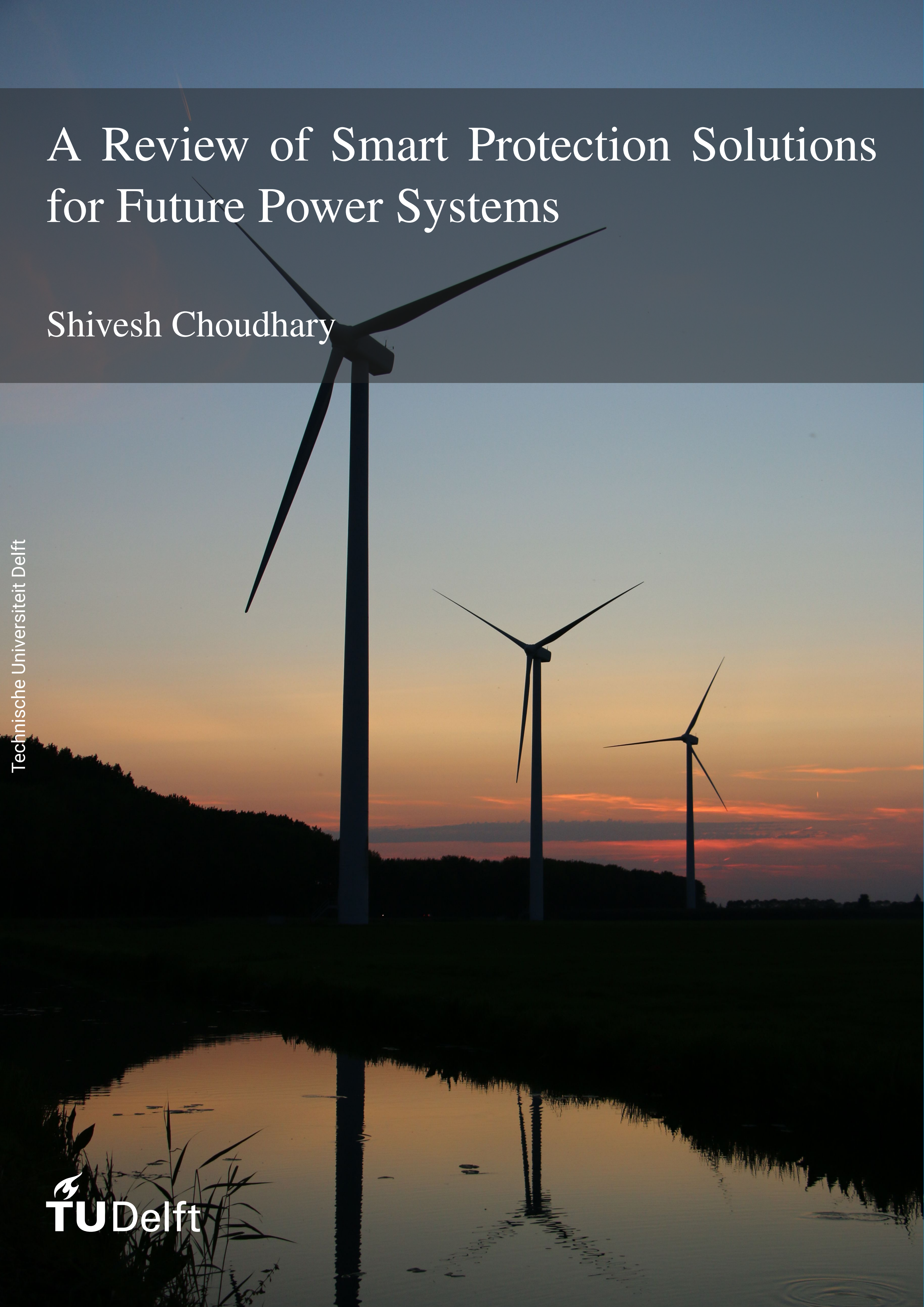
A Review of Smart Protection Solutions for Future Power Systems

Shivesh Choudhary



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A Review of Smart Protection Solutions for Future Power Systems

by

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Abstract

The growing demand for electricity and the importance of decarbonization have forced to transition from fossil fuels to sustainable sources of energy like wind and solar. Currently, the universal power mix remains dominated by fossil fuels but plans are in motion to achieve the target set for the upcoming years. It involves grid expansion and the addition of new elements in the form of Distributed Energy Resources(DERs). This has an influence on the performance of the complete power system. To allow an increasing penetration level of DG(Distributed Generations) without causing protection problems or unacceptable power flows and fault levels, the impact of DG has to be researched for a secured future grid.

The protection system of the power system is an aspect that will be significantly affected by the continuous integration of Distributed generation sources. For this reason, it is crucial to develop and validate smart protection solutions for future power systems in order to avoid catastrophic blackouts. In order to overcome the shortcomings, Synchrophasors systems can be used for real-time wide area protection and control. The real-time implementation reflects a smart protection scheme, using smart hardware such as a Phasor measurement Unit (PMU).By developing a suitable algorithm that can be used for decision-making in case of an event on the transmission lines. It coherently helps in faster restoration of the transmission lines operation. Smart protection solutions will help in strengthening the protection system and will allow more flexibility in the coming years.

Acknowledgement

An eventful, challenging, and memorable phase of University life has come to an end with this thesis. My journey started in the midst of the global pandemic with various challenges, but I am thankful for all of my experiences. The journey would not have been complete without the motivation and support of those who assisted me along the way.

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Shivesh Choudhary
Delft, November 2022

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Introduction

Due to technological advancement, increasing societal concerns, rapid climate change, and dealing with flexibility issues appear to be critical for almost all scientific fields[16]. In the power system department, there is a need to create multilateral collaboration to accelerate global development and deployment of smarter electricity grids. There are various trends such as Deregulation, Decarbonisation, Digitization, and Integration influencing the power systems that have changed the organizational structure of the electricity supply industry and the operation of the power systems[17].

In the process of generation, transmission, distribution, and communication networks, the future power system will require flexibility and adaptability. By definition, flexibility means flexibility in the transportation of energy and adaptability means ẗhe adaptability of a system in response to external influences and maintaining accurate system stability and performance. It is a must for the smart future power system. System performance is defined by functional parameters such as capacity, level of performance, low maintenance, and high profitability. External changes are characterized by the ability to withstand uncontrolled conditions, including fluctuating demand or usage, infrastructure losses, and degradation. Currently, there is a wide range of stakeholders involved in the transformation and development of this matter [16].

In the past decade, the portfolio of renewables has been continuously evolving due to the high rate of power demand. The increasing rate of penetration of renewable resources and variation in generation from these resources has led to rising concerns in both the operational and planning horizons of the power system network. The future of the power system network will comprise energy hubs, multi-energy microgrids, and Virtual

Power Plants(VPPs) [16]. It will enhance the technical, economic, and environmental performance of the power system. Out of all the three, VPPs seem to be more dependent to provide flexibility for future power grids. It will act as a channel to create synergy between electricity and other energy resources system for balancing purposes in presence of fluctuating generations. Due to the energy mix, the future power system should be able to cope with the changing net load [18]. It should be flexible in responding to large fluctuations in demand and supply, meet up scheduled and unforeseen variations, and ramp down the generation when the demand decreases and upward when it increases. This can be achieved by power system flexibility on both the supply and demand sides. The generation plants should be capable enough to accommodate themselves according to the flexible demands. A security measure is implied to prevent undesirable flexibility threats to the power systems.

1.1. Classical Power System Vs Future Power system

The electrical power system is considered to be one of the most outstanding achievements of the 20th century by human mankind. The basic principle of energy generation, transportation, and distribution has remained the same since the first applications of distribution grids[19]. The energy generation was done in power plants using non-renewable resources such as fossil fuel and nuclear energy in masses. The generated electricity was transported through the electrical components involving (cables, OHL, and transformers). It was operated by TSO(Transmission system operator) and further connected to the various distribution networks hubs and operated by DSO(Distribution system operator). It was further connected to the end users like any other commodity which is consumed at the same time.Figure 1.1 illustrates the top(generation) to the bottom(loads) approach of the electrical power system in the past.

In a large classical power system, the "load flow" is defined by the flow of electricity and contributions from each generating unit to the static and dynamic loads. The load flow equations are nonlinear and numerous as it depends on the number of nodes in the power system network. The voltage of the network and system frequency at each node must remain within specified thresholds according to the standards of different countries so that the stability of the grid is maintained [20]. Traditional power systems have limited control over the flow of electricity and centralized generation. Over time, the smart grid has optimized the generation, control, and delivery of electricity to the end users.

Evolution is a slow process that begins with the incorporation of new technologies into

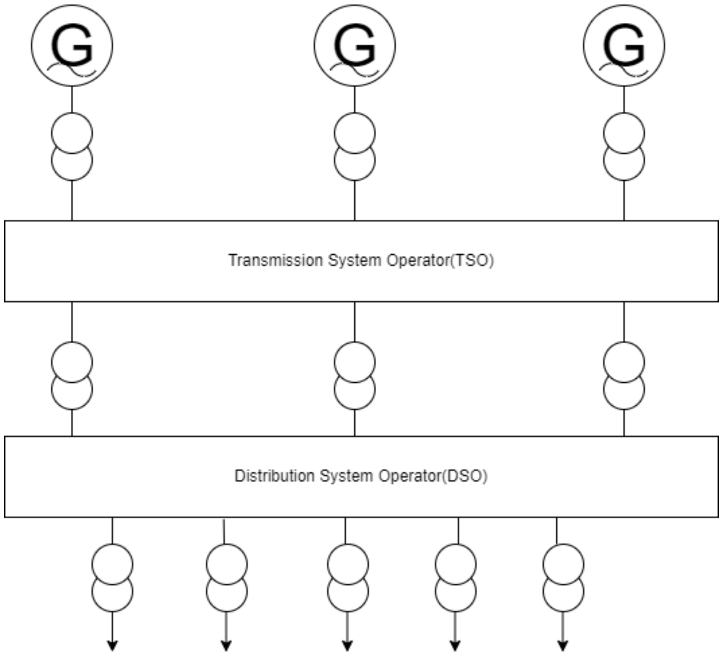

Figure 1.1: Classical Power System

the existing traditional power system. In comparison to the traditional power systems, the distribution grid has transformed from passive to active considering the effect of distributed generation and active demand during the planning and the supervision of the control. There are various trends driving the power systems of the future such as Innovations in Data, intelligence, Renewable Resources cost reduction, Energy Security, Reliability of the system, and Resilience[21]. Cost cutting in renewable energy will be driving continuous deployment and are motivating both power system interdependence and independence.

The future grid does not only produce electricity but the sensors, monitoring devices, and Information technology are rapidly permeating power systems. It results in the prevalence of the energy market and operational data, which provides an opportunity to realize further optimizations of the power systems. A large amount of DERs (Distributed Energy Resources) will drastically increment the complexity of the distributed operation of the network as shown in Figure 1.2.

The future power system will be very indifferent due to the interdependence of information technology and energy technology. It will open pathways for situational awareness and also an opportunity for active management of various resources that can be beneficial for monetizing in energy markets. These data on power systems can enhance performance and reveal investment needs for future grids and operational planning. It is also sharpening and detailing the focus on cyber security, access to customer data, and privacy protection.

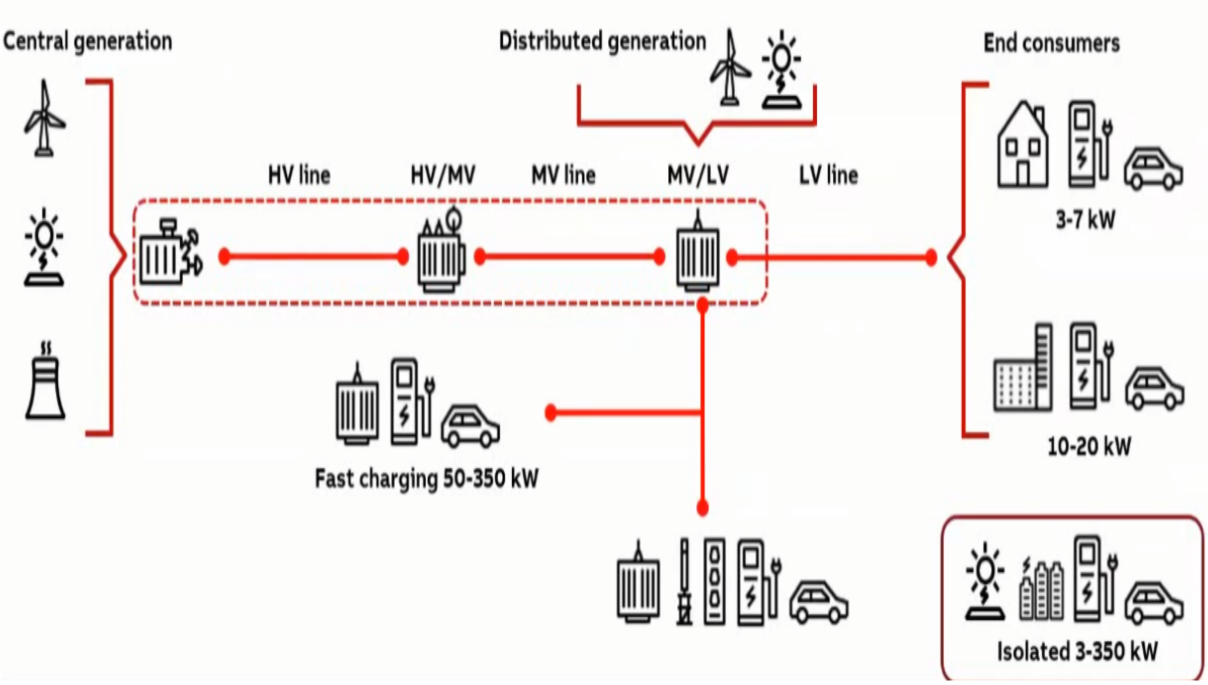

Figure 1.2: Grid Automation for smart power distribution solutions, Adapted from ABB [1]

There is a need of recognizing sustainable models to meet up the growing demand and needs of society. It is estimated that the future grid will face challenging developments such as microgrids, DERs(Distributed energy resources), and an enormous amount of renewable energy will pose various problems to the current power system grid. The DGs in the grid introduces uncertainties in the optimization model which makes resource planning decision very difficult. This gives an opportunity for additional optimization methodology to solve concerns related to the connection and placement of DGs in the future grid [20]. It will also provide grid reinforcement, reduction in losses and on-peak-costs, and better security, reliability, and efficiency of the system.

1.2. Phenomena

The penetration of Distributed Energy Resources has various effects on the power system network. It concerns the protection of the system such as maloperations, mis-tripping, and protection blinding. The challenges that may occur and how they will affect the protection have been briefly discussed below:

1.2.1. Effect of the faults in inverter-based electrical grids

Inverter-based resources such as Wind Turbine Generators(WTGs) produce different fault current behavior compared to traditional synchronous generators. These differences in currents may lead to the misoperation of conventional sequence component-based protective devices which operates under the assumption of a synchronous generator-based power system. The asynchronous speed wind turbine generators (Type- 3) or full ac-dc-ac conversion of power output using power electronic converters (Type 4) exhibit an indifferent behavior under short-circuit fault conditions.

Doubly- Fed Asynchronous Generator(Type 3)

A doubly- Fed Asynchronous Generator also called a Doubly- Fed Induction Generator is an excitation machine and the excitation generated by a power electronic converter has the ability to vary frequency and magnitude. The fault behavior of the traditional synchronous generator and the induction generator is generally linear and the fault currents are proportional to the extremity of the abnormal condition.

The fault characteristics of Type 3 and Type 4 turbine generators depend upon the control characteristics. There is a variation depending on the different designs and discontinuous due to discrete actions when the currents and voltages reach their thresholds [22]. The fault behavior of both Type 3 and Type 4 generators are identical as they operate on controlled current sources. The controlled current source characteristic of Type 3 wind turbine is constant for faults not crossing threshold voltage which is 20% - 40% of the rated voltage. Extreme faults may lead to an excessive rise in voltage in the rotor circuit which would influence the voltage of the dc link above the normal level if it is not observed. Every Type 3 wind turbine generators use crowbar technology to bypass the excess induction onto the rotor circuit. This technology is utilized in a number of ways according to the turbine designs such as shorting device connected to the dc link or a chopper-controlled loading resistor connected to the DC link. Another way is by adding a power electronic shorting device implied to the rotor circuit between the wind generator rotor and the converter side of the rotor [22]. A controlled function is added along with the various crowbar implementations. The latest Type 3 wind turbine generators have various LVRT (Low voltage ride through) thresholds. The application and removal of crowbar protection results in discontinuous short-circuit current behavior for Type 3 wind turbine generators.

Full-Conversion Generator (Type 4)

The operating principle of a full conversion wind generator is a back-to-back ac-to-dc and dc-to-ac voltage source converter which allows for operation over a broad range of speeds.

The speed of the wind turbine dictates the frequency of alternating current generated by the synchronous machine. Both Type 3 and Type 4 exhibit different behavior during unsymmetrical faults when compared to synchronous and induction generators. Since the wind turbines are un-grounded due to these they have decoupled positive and negative sequence performance [23].

The short-circuit fault current contribution from a Type 4 generator comprises an initial transient overcurrent, then followed by a controlled injection of a current magnitude according to fault response as inputted into the controls. During a severe abnormal fault condition, the magnitude of the current rises as twice or thrice of the rated value of the current and comes under control after one or two cycles. The fault current injected by a Type 4 wind turbine generator is a combination of real and reactive components as programmed by the controls and it is significantly out of phase with the short-circuit fault current contribution by the grid. The modeling of a Type 4 wind turbine generator for a short-circuit fault current contribution is 2-3 p.u for the upper level of current value which remains for one to 2 cycles and drops around 1.5 p.u thereafter [22].

1.2.2. Effect of System Inertia

In a power system, the inertia comes from the rotation of heavy machines such as steam or gas turbines. It is very evident that the grid with generating units that exhibit low or no inertia is prone to issues such as instability, power quality and unlikely may lead to out-of-step phenomena [24]. A wind power plant is integrated with converters between the induction generator and the grid, in this case, the wind generator is decoupled leading to no contribution of inertia which affects the rate of change of frequency. It is likely that more synchronous generators will be replaced by wind power generators in the future and the grids will face reduced system inertia.

Inertia is a critical factor that determines the acceleration and deceleration of the machine and also influences the transient stability as shown in Figure 1.3. The lowered inertia of the synchronous generator makes the system more prone to disturbances such as transient stability [2]. There are chances due to low inertia that the existing frequency-based protection such as anti-islanding protection and under-frequency load shedding (ULFS) might mal-operate very frequently[25]. The performance of the existing protection can be improved by altering the settings and making it a combination of more adaptive and fixed so that it can handle transient disturbances. This helps in making the protection more dynamic, and optimized and also strengthens the system stability making it ready for the

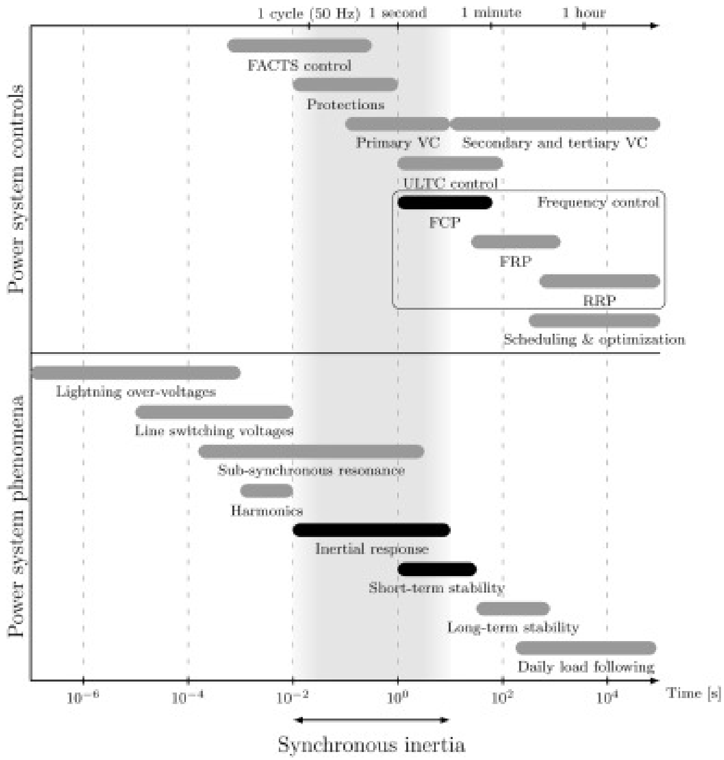

Figure 1.3: Overview of time scales covered by power system phenomena and controls[2]

future power system which will experience more variability of frequency and an unpredictable distributed renewable energy generation to the grid.

1.2.3. Effect of Underfrequency and Undervoltage on the grid

Underfrequency load shedding is a phenomenon that has been used in the past to maintain the balance between load and generation. There are underfrequency relays that are set with intended delays to prevent them from unwanted tripping for source transmission line operations[26]. It does help not only in avoiding a system-wide blackout but serves a greater purpose in protecting the generators online. It is essential to begin shedding load during an underfrequency event so that it does not drop below the frequency levels and affect the operating generators. Load shedding depending on underfrequency UFLS relays may not be enough to save the network during heavy load conditions or when the network is under the impression of loss of main events.

Power systems today are predicted to be more vulnerable to Undervoltage or voltage collapse events when compared to the past since the power has to be delivered a long distance from the generating stations leading to a loss in reactive power [27]. To maintain the voltage level, voltage-based load shedding has to be performed. The response rate of the

Undervoltage load-shedding relay is faster than the frequency since the voltage response is an electrical phenomenon and the frequency response is a mechanical one. Undervoltage relays are deployed in the network to protect the local bus voltages from decaying, it is done by shedding the loads by instructing Undervoltage relays. There are communication-based load shedding schemes utilizing synchronized measurements to transmit voltage signals locally to a control room for decision making which was proposed in [28]. Considering a large amount of intermittent renewable energies penetration, it impacts both voltage and frequency which makes unit protection inside wind turbine trip when the system is impacted by instability. Load curtailment is performed to maintain the system integrity and rescue from instability and disturbances.

1.2.4. Protection Blinding

Due to the penetration of renewable resources, the total contribution of fault current will be reduced in the grid. There is a possibility that the short circuit remains undetected since the grid contribution to the fault current never reaches the threshold current of the operating feeder relay. This blinding may lead the relay protection to become non-functional mostly at the remote end of the feeder including the distributed generation [29]. Overcurrent relays including directional relays depend on their tripping decision on detecting the abnormal current. Therefore all the protective systems protected by those relays can suffer malfunctioning due to the reduced grid contribution of the short-circuit current. This phenomenon is called blinding of protection and is one of the critical issues in power system protection.

The unsymmetrical two-phase fault and also faults with high impedance are more critical. The low fault current contribution to the grid leads to the increased impedance at the fault location and it also hampers the protection function of the distance relay causing protection underreach. It also impacts the definite-time relay blinding as the operation may become blocked when the secondary tripping threshold level is not exceeded. By inverse-time relays the blinding results in slowing the tripping command of protection which further impacts the thermal limits of the equipment and also the lines. Blinding of the protection can be avoided by grid reinforcements or modifications in the type of distributed generation. Finally, it can be further concluded that penetration of distributed generation with a low fault current has a direct impact on the sensitivity and reliability of the protection system.

1.3. Protection Solutions

1.3.1. Protective relaying

In an electrical power system, most of the faults occur on transmission lines resulting from lightning-induced transient high voltage and from falling trees on the line. The most common unsymmetrical faults that occur are Single phase-to-ground faults. There is a need to eliminate these undesirable conditions, Protection is the science that provides maximum sensitivity to faults. It plays a vital role in decision-making procedures by a protective device so as to decide whether the event is intolerable and needs to be isolated or it is a temporary or transient situation that will self-heal. The major role of the protection placed on the equipment is to operate to eliminate the disturbance event quickly with a minimum system disturbance. It must be properly coordinated such that the primary relays operate at the first occurrence of the event in their protective zone and if they fail to pick up the fault in the specified time then the backup protection will operate to clear the disturbance and limit the damage [30]. But there are events where both the protection fails to operate leading to cascading events and blackouts.

In the past, all protective relays were electromechanical types but over the period it has evolved, and now there are digital relays that are adaptive, faster, and communication-based. Protective relaying and Circuit breakers work together for fault isolation, without a circuit breaker it is just an alarming device. The relays using electrical quantities on the AC power system are connected through a current transformer or voltage transformers depending upon the equipment and are associated with a circuit breaker. It is the primary objective of the protection to provide reliability, selectivity, speed of operation, and economical solutions. In a complex power system, the protection should be simple and straightforward as possible to execute the desired goals. The relays can be classified on the basis of performance, function, characteristics, and their operating principles [30]. Protective relays operate on their defined intolerable power system threshold conditions. It is used in all types of equipment of the power network such as transformers, buses, generators, transmission lines, and other devices.

The need for fault study is important for protection applications to determine the directional sensing of the ground faults on the basis of zero-sequence voltage and negative sequence currents. Concerning the open-breaker side of the line, information is extremely important. In the next chapter, different types of relays and their properties will be discussed in detail. It will also provide more information about the changing behavior due to the continuous renewable penetration and its effect on the protection system of the power system network [31].

1.3.2. Application of Synchrophasors in Power systems

Synchrophasors are time synchronized measurements that record electrical measurements which comprise both the magnitude and phase angle of the electrical quantities. The synchrophasor technology has various applications which include wide-area situational awareness and monitoring, state estimation, fault detection, and fault location, topology & islanding detection [32].

Synchrophasor Technology (Phasor Measurement Unit - PMU)

An electronic device that records real-time and accurate data of synchrophasors and frequency for a three-phase AC voltage and current sinusoidal waveforms. It consists of a GPS receiver, phasor-locked oscillator, anti-aliasing filter, digital signal processor, and analog-to-digital converter. It measures the single-phase and three-phase AC waveforms over time synchronized electrical parameters i.e, voltage and current. It has a fixed sampling rate used with a GPS clock. The measure signals are multiplied by the nominal frequency carrier in order to get the real and complex components of the phasors. There are various applications of synchronized technology which are further discussed:

1.Wide Area Frequency Monitoring: Frequency in the power system is the key element for the indication of the load and generation balance in the grid. PMU-based frequency monitoring measurements can be further used for studying post-disturbance and analyzing the root cause. It can provide responses in real and non-real-time in milliseconds [33].

2. Voltage Stability Monitoring:

The term 'Voltage Stability' can be defined as the ability of a power system to maintain voltage stability at all buses in the network after being subjected to a disturbance. The status of the voltages at all the buses helps operators to know how close the network is to voltage collapse or the amount of power that can be supplied to the loads. The outages can be avoided in real-time by using PMU data that helps to predict voltage instability and prepares the operator to take control actions [33].

3.State Estimation: State estimation is widely used in the power system to realize the value of state variables where measurement devices such as voltage & power sensors are not available. It is a tool for online monitoring, analysis, and control of the network. The application of Linear State Estimation has been improved using PMU data to correct for phase biases and current scaling errors [34]. State Estimation based on PMU data has an advantage over the non-iterative process and the linearity of the network by using methods such as Weighted Least squares (WLS), Linear Programming based on least absolute value estimator [35].

4. Fault Location, Identification, and Protective relaying: PMU-recorded data are also used in fault identification and localization. The additional advantage of phase angle measurements by PMU provides an opportunity for making the protection and relaying adaptive. It plays a major role in developing adaptive protection methodology providing fast communication. There are various techniques for transmission line fault detection and identification using PMU data [36]. PMU broadens the scope of research for adaptive protection based on external circumstances and evolving power systems.

1.3.3. Protection Devices against Harmonics

Protection devices are not only defined to attain fast, reliable, and selective tripping. It means that the protection relay shall operate only for in-zone faults. But there are many factors that impact the reliability of the protection and one of those is the harmonics available in the power system during stable operating conditions and during the fault. There are different orders of Harmonics such as 2nd, 3rd, 5th, 7th, and so on. Out of all these 2nd and 5th orders, harmonics are most dominant in the power system while energizing the transformers, it has an inrush current of 2nd order harmonics and during the unbalanced faults [37].

The distortion due to the harmonics can be reduced by implementing Harmonic filters which divert the harmonic currents through low-impedance paths. Filters are tuned to filter the harmonic order without affecting the operation of the power system. The commonly used filter in the power system is the Passive Harmonic Filter used for suppressing multiple harmonics order disturbances in the power line.[38]. A few types of passive harmonic filters are discussed briefly below:

Band Pass Filter

Band Pass Filter also known as a Single-tuned filter is probably the most frequently used shunt filter. The frequency for which it is tuned acts as an extremely low impedance hence effectively shunts harmonic line parameters at that frequency. The resonant peak always occurs at a lower frequency than the frequency for which the filter is tuned due to the source impedance being inductive. Due to the proximity of the resonant frequency, a gradual increase in impedance takes place below the tuned frequency. Adjusting the filter to a frequency below that at which it is desired will provide for enough harmonic filtering action.

High Pass Filter

The high pass filter has the characteristics of low impedance above a corner frequency. This type of filter will shunt the most occurring percentage of all harmonics at or above the defined threshold frequency. There are certain drawbacks to this type of filtering, the shunting of the most occurring percentage of all harmonics using this particular filter may require that filter to be immensely overrated [37].

1.4. Thesis Overview

This section will provide an overview of the different chapters which will be discussed in this thesis.

Chapter 1: This chapter gives an introduction to the review of the need for a future power system and further summarizes the difference between a classical power system and the future power system. The phenomena that will occur in the future power system and their impact on the protection system are presented. In this chapter different sensations such as the effect of inverter-based, low system inertia, Undervoltage & underfrequency, protection blinding, and harmonics in the grids are discussed in detail. In the third segment of this chapter, protection solutions have been analyzed. It discusses protection relaying faults, applications of synchrophasors, and protection devices against filters.

Chapter 2: This chapter is dedicated to Protection relaying and types of protection devices, their advantages, and disadvantages. It introduces the protection relaying devices and explains how these conventional devices can be used for the future protection system. The second chapter ends with a description of the effect of the inverter-based system(Grid forming & Grid following). It provides information about the need to understand its effect on the fault current and malfunctioning protection devices. The advantages & disadvantages of the converter-based power system.

Chapter 3: This chapter addresses the topic of System Integrity Protection schemes. It gives an introduction to the SIPS and the definition of the Synchrophasors. The synchrophasor-based application and its design have been discussed in detail. It also enlightens about Intelligent Network Splitting and the need for network partitioning in future power systems to solve different issues in the network. It ends by explaining the three different types of protection systems to deal with issues such as Undervoltage, underfrequency, and Power swing in the system.

Chapter 4: This chapter starts with an overview of Fault locators. It explains the different types of fault location techniques developed. Further concentrates on different algorithms based on impedance and PMU for fault location have been explained in detail. In the latter half of the chapter, the fault locators' operation has been discussed which involves faulty area detection, faulty line detection, and fault distance.

Chapter 5: This chapter concludes the review and provides an outlook toward possible future work.

2

Protective Relaying

2.1. Introduction

Modern society has become heavily dependent upon a continuous and reliable supply of power systems. Power outages that are frequent or last a long time seriously impair daily life in a society that demands greater supply security and reliability. Since the requirement for economy and reliability are largely similar in contrast, designing a power system always involves a trade-off. Power system protection plays a significant role in achieving these tasks and the non-interruption of electricity.

This chapter explains the state of the art of power system protection relaying, its functioning, and its operation. The different types of protection relays, and their advantages & disadvantages will also be discussed in the latter half. Importance is given to its usage with evolving future power systems and its effect on the current protection relaying.

2.1.1. Fundamentals of Protection systems

The main purpose of the power system is to detect an abnormal system condition as fast as possible and conduct an appropriate response to bring the system to a normal steady state. Each protection device is designed to detect a specific system hazard on a system component and can isolate this hazard. The protection system is time bounded as it needs to take necessary actions in a few milliseconds according to [3]. The system is considered in the normal operational state when all the electrical components are operating within their design settings. The occurrence of an event changes the state of the system to abnormal causing a component to exceed its normal operating limits. In this situation, action needs to be taken to relieve the disturbance and prevent irreparable damage as much as possible.

Some scenarios where no action needs to be taken such as lightning and tree flash-overs since the disturbances are temporary and no action needs to be taken. In contrast, when the action is done, this brings the system into an outage state and the faulty component is taken out of service. Under the situation, the system enters a restorative state where the necessary action is taken to repair the faulty component or inspect it so that the system is brought back to its normal operating state. The process is explained below with the help of a flow chart in Figure 2.1.

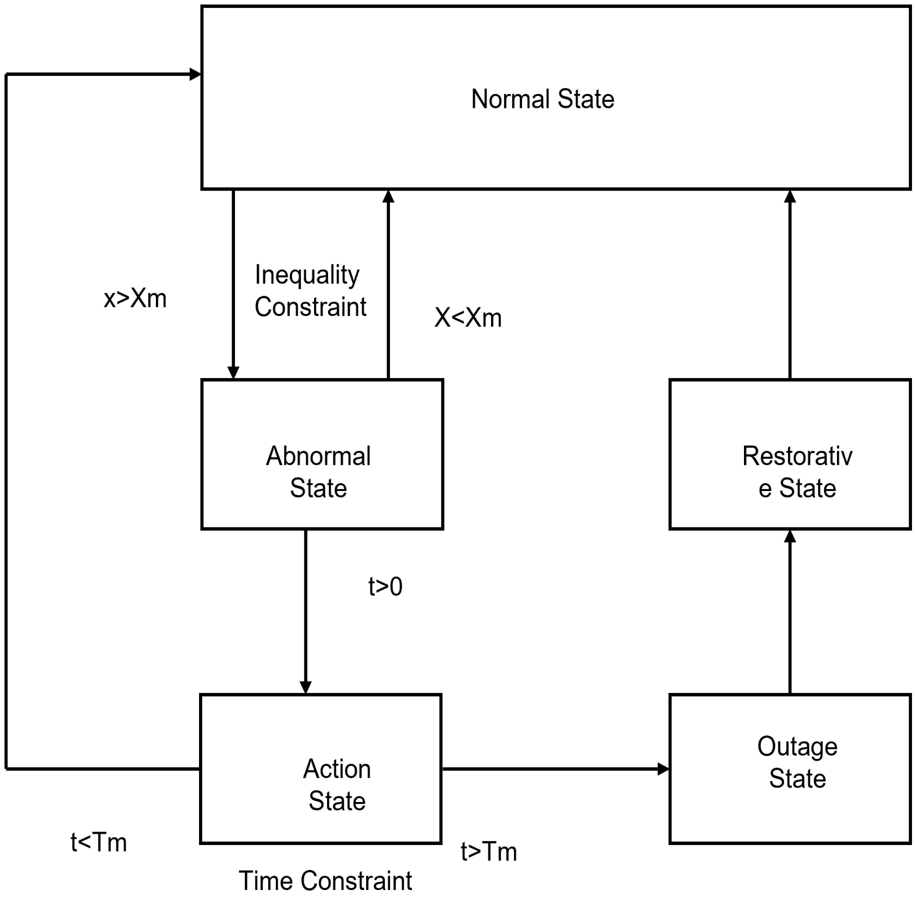

Figure 2.1: Operative states of a protective system[3]

From Figure 2.1it is shown that the two conditions need to be fulfilled to take out the faulty component from the system operation. These conditions are listed below:

1. Violation of the inequality constraint, $x > X_m$
2. Violation of the time constraint, $t > T_m$

Here x is an observed system quantity, and t is the time elapsed from the beginning of the disturbance, and X_m, T_m are certain thresholds.

2.1.2. Protection device Operation

The protection device deals with several functional blocks that are arranged to test the metering system condition, comparing, the decision-making process and functionality of taking the required action. These element blocks are shown in Figure 2.2.

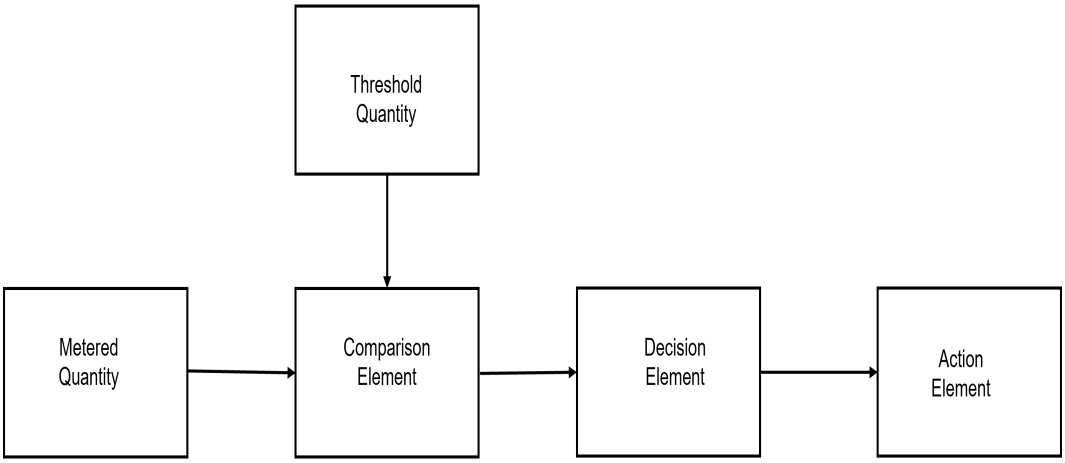

Figure 2.2: Protection device functional elements[3]

The protection equipment always measures certain system quantities such as current, voltage, and frequency. These system quantities or the combination of measure system quantities are compared against the defined threshold settings of the device and when there is a violation observed then the decision element is triggered. In the decision, element timing might be involved to check if the event is temporary or permanent. If all the setting conditions are satisfied then the tripping command is sent to the circuit breaker or fuse on the low-voltage network to remove the disturbance from the system.

The time required to take the corrective decision is called the clearing time and can be equated as follows:

$$T_c = T_p + T_d + T_a \tag{2.1}$$

where
T_c: is the clearing time
T_p: is the comparison time
T_d: is the decision time
T_a: is the action time including circuit breaker operating time.

The clearing time is the most important quantity of a protection device in the network and it has to be coordinated with the device to disconnect the faulty section of the network. The electrical component of the power system is equipped with several protection devices due to which a distinction should be made since all protection devices will observe the disturbance during an abnormal event. It is the foremost duty of the closest protection device to clear the fault. It should also have a restraint time to act and doesn't act immediately after the event.

Clearing time is important because some disturbances such as short-circuit faults must be promptly cleared to bring back the system to stability. Stability preservation also depends upon the type of fault and the location of the fault.

2.1.3. General Definitions used in Grid Protection

There are common terms or concepts used in the field of protection system engineering as defined in [3]. Some of these key terms are definitions are applied in this thesis:

1. Reliability: The ability of the protection device to detect the fault with high accuracy and operate correctly.

2. Security: The ability of the protection device to not respond during undesired operations and remain unaffected during external faults.

3. Sensitivity: The ability of the protection device to pick up an abnormal condition that exceeds the defined threshold value of the device.

4. Selectivity: The ability of the protection device to discriminate the fault closest to the device and trip the nearest circuit breaker to isolate the fault.

5. Backup Protection: The ability of the protection device to detect the uncleared primary fault at a remote location and send a tripping command to remove the fault.

2.2. Protection Devices

In the power system, the protection equipment is often classified in accordance with its construction, function, and also to received input and output signals. They are further divided into primary and backup protection. In distribution grids, they are distinguished on the basis of input signals such as current, voltage, and impedance and named on the basis of functioning such as the differential, distance, and overcurrent relay. It can also be classified according to the technology used i.e, Electromechanical, Static, Digital, and Numeric as discussed in[39].

2.2.1. Overcurrent Protection

Overcurrent relays are the most common form of protection device involved in dealing with the excessive flow of currents on power systems. The operation of this relay depends only on the measured current parameter. When the defined threshold is exceeded by the current, a trip signal is generated and sent to the circuit breaker to act immediately. The overcurrent relay needs to be synchronized with other protections. This is done to ensure sensitivity and selectivity for a wide range of faulted system conditions. TO fulfill this requirement various relay characteristics are added to the Overcurrent relay. The Overcurrent relay can be broadly classified into two major types:

1. Independent or definite-time relay
2. Inverse time relay

Definite-time Overcurrent Relays

The definite time relay allows the settings of the relay to be varied to adjust to different levels of currents with distinct operating times for each level. These settings can be coped so that the circuit breaker nearest to the faulted location should respond to the trip signal in the shortest time. The remaining circuit breakers respond in succession with a gradual time delay as set when moving away from the faulted location towards the source. According to [40], this type of relay is preferred when the source impedance is large in comparison with the impedance of the protected electrical equipment. In that case, the fault current level at the beginning of the protected equipment is almost the same as the fault level at the end of the protected element. In Figure 2.3 a characteristic overview of a definite time-current plot is given.

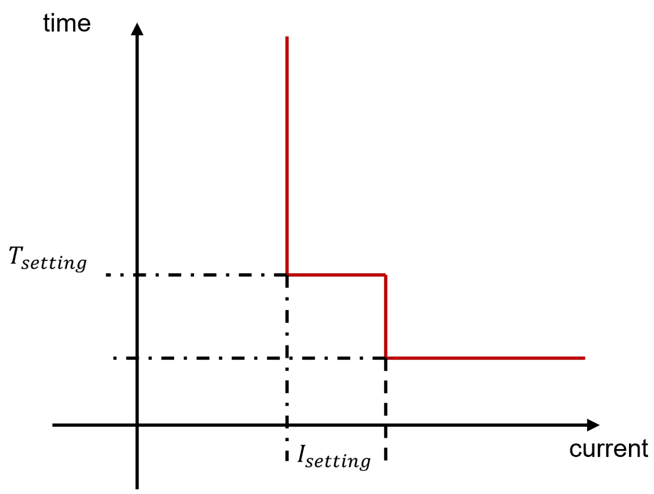

Figure 2.3: Definite-time characteristic of a definite overcurrent relay

Disadvantage:

The disadvantage of using definite-time overcurrent relays is that the fault occurring at the source will have significantly high currents and longer operating times. This can be hazardous since high-level currents should be immediately discriminated against to ensure safety and cascading effect doesn't take place.

Inverse-time Overcurrent Relays

The fundamental functionality of an Inverse-time current relay is that they operate in a time that is inversely proportional to the fault current. The main advantage of this relay over a definite-time overcurrent relay is that they have a short tripping time for extremely high currents. In this way, a shorter tripping definition can be achieved without hampering the selectivity of the protection system. The classification of the Inverse-time current relays can be obtained according to their characteristics curve which is illustrated below as per [3].

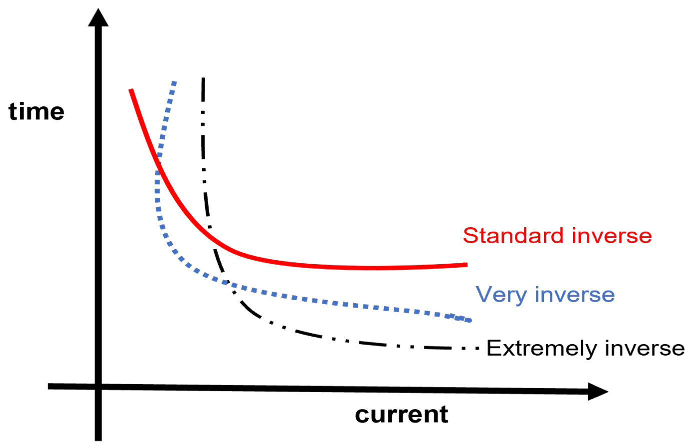

Figure 2.4: Operating Characteristics of an inverse-time relay

General Setting rules for Overcurrent protection

The correct settings of an overcurrent relay involve parameters that include the required time/current characteristics. The setting must be chosen in such a way that the relay does not operate for the rated load current or minimum fault current. An intelligent approach to selecting the parameters so that the protection system operates reliably and selectivity is achieved. This setting of the relay selection involves two major steps defined below:

1. Selection of the pick-up current(PU).
2. Selection of the operating time for current levels.

There are several general rules available for the correct selection of the pick-up current of definite overcurrent relays. All these rules are focused on sensitive relay settings without compromising the security of the protection systems. The threshold of the pick-up current can be defined based on two values:

1. It is between 6 and 10 times the maximum current rating
2. 50% of the line-line fault current at the end.

When selecting the primary value it has to be checked that the pick-up current is 150% of the rated current in order to prevent unnecessary removal of a healthy feeder and that there is no malfunction. In a Medium voltage distribution network, the pick-up current of the definite-time overcurrent relay is usually set as:

$$I_p = 1.5 * I_{rated}, \tag{2.2}$$

where I_{rated} is the rated current of the protected component.

The second important parameter is selecting the operating time of the overcurrent relay. This is done in a way that is well-coordinated with the downstream protection devices. A time grading is done between two successive relays to discriminate fault with a time margin and obtain selectivity of the relays. A time margin is set to prevent loss of selectivity due to breaker opening time and deviation of relay characteristics caused by the manufacturer's tolerance. The operating time is set as low as possible.

2.2.2. Directional Overcurrent Protection

Directional Overcurrent Protection has important characteristics to be able to determine the direction of the flow of power. It also has the ability to restrict the Circuit breakers from tripping when the flow of fault current is in the opposite direction to the setting of the relay. Due to the penetration of renewables in the grid, there is a bi-directional flow of power, which consequently affects the performance of conventional protection devices. [41]. Meshed Distribution systems are protected using directional overcurrent relays. It will allow the nearest relay to pick the fault current circulating in the network due to distributed generation. It will also prevent unnecessary tripping of switchgear and enhance the security of the normal operation of the grid. In the figure below Figure 2.5.

The operating of the breaker takes place when both the overcurrent and the directional block command a trip signal. It has similar operating characteristics and settings as the overcurrent relay. The directional overcurrent relay can be set to operate in the forward or reverse direction of the power flow and sends a tripping command when the power flow coincides with the settings of the directional block [42].

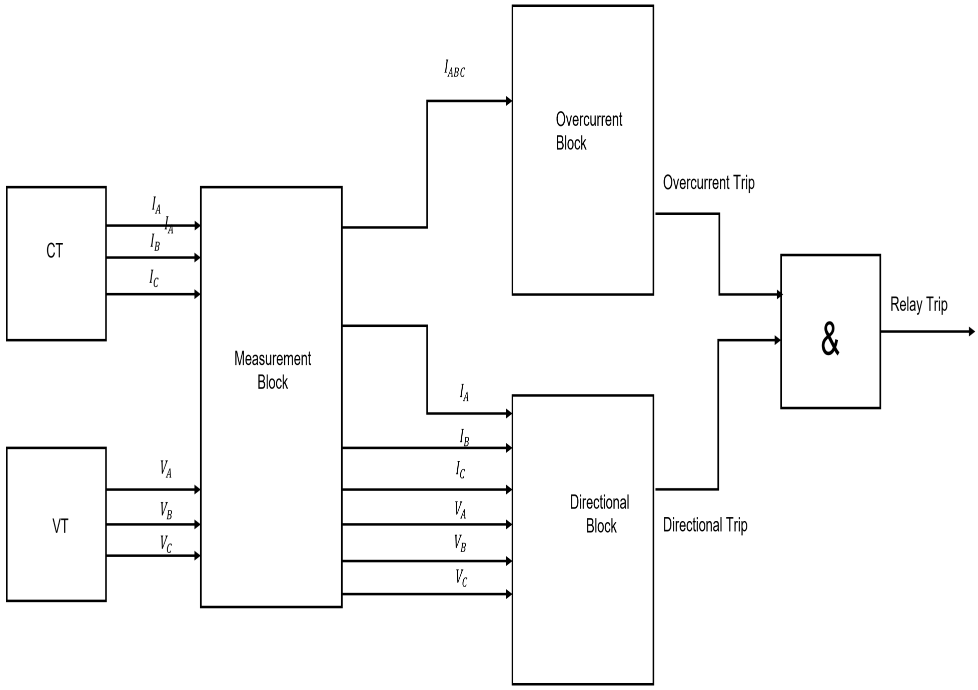

Figure 2.5: Block Diagram of a Directional Overcurrent Protection Relay

Different Optimization techniques have been proposed in the past to determine the settings of the relays in order to solve the protection coordination problems. With the various approaches, the problem of protection is formulated with the coordination of the relay. So the researchers have finally proposed a new approach using heuristic optimization techniques that can be implemented to solve the protection coordination problem [41]. In the future power system, the smart grids will see more integration of Distributed generations which will require numerous changes in protection settings. Accountability needs to be taken to secure protection for future power systems and develop approaches that minimize the frequent changes to the protection settings of the relays.

The major concern of the utility planners is to realize a set of relay settings that is reliable for all future possible Distribution generation capacities. A valid simple algorithm that can sustain varying capacities of Distributed generation between the minimum and the maximal expected capacity.

Advantages of Optimized Directional Overcurrent Relay [43]

1. DOCR(Directional Overcurrent Relay) is widely accepted for meshed and Ring networks.

2. It is adaptive, flexible, and effective to handle the coordination of the relaying settings.

3. It handles the constraint of conventional relaying very well.

4. Implementation of the technique is easy and robust.

5. It has a fast and better rate of convergence.

Disadvantages of Optimized Directional Overcurrent Relay [43]

1. It takes longer computational time.

2. It is difficult to identify the topology of all the power networks.

3. It still produces mis-coordination during some events.

4. It is difficult to compare with other techniques to justify its efficiency.

5. The contribution of distributed generation fault current impacts the reliability and sampling rate.

2.2.3. Differential Protection

Differential protection is the vector difference between the magnitude of two current quantities measured on either side of the protected component in a power system. Under the stable operation of the protected equipment, these currents should be equal. This is the simplest and most frequently utilized type of 'unit protection in transmission and secondary equipment protection. Various network components such as transformers, generators, terminals, cables, or overhead lines can be protected using differential protection. The measurement area is considered everything that lies between the measuring path of the current Transformer(CT), also the CTs are placed at the beginning and end of the protected equipment. The differential relay operates when the given Equation 2.3:

$$\sum_{m=1}^{n} I_m \neq 0 \tag{2.3}$$

Here, I_m is the m^{th} current vector and n is the total number of buses incorporated in the differential protection.

The differential protection works on the theory of Kirchhoff's current law[40] i.e, the sum of the currents entering and leaving the protected zone must always be equal to zero. It also states that the differential protection should not trip on an external fault outside the protected zone. This is also explained with the help of a simplified network illustrating the operation during internal faults in Figure 2.6 and Figure 2.7:

The secondaries of the current Transformers are interconnected on either side and connected to the relay's coil across these. During an external fault or outside the protected

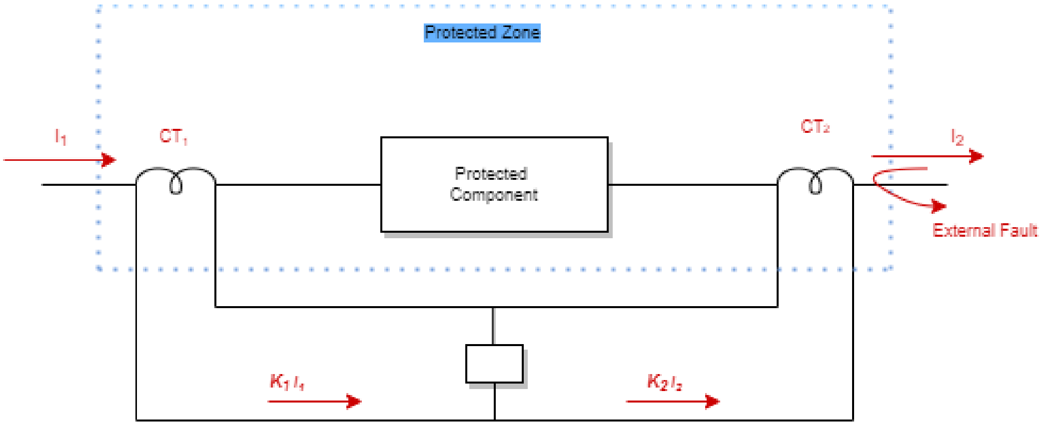

Figure 2.6: Differential relay operation during external or outside protected zone

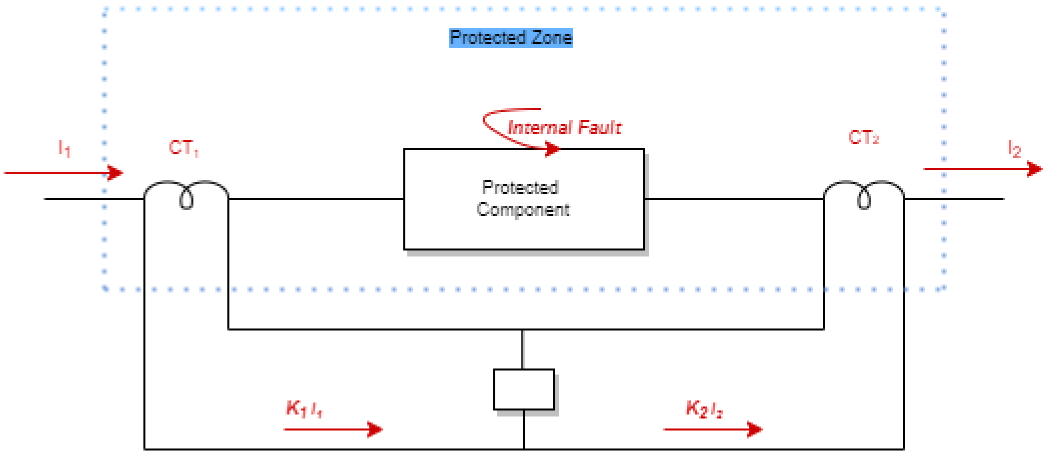

Figure 2.7: Differential relay operation during internal or protected zone

zone, the current will circulate between the two CTs but, it will not flow through the differential relay. During an internal fault, the current flow towards the location from both sides and this makes a difference in current and is detected at the differential relay. The relay picks up the system faults and sends a tripping command.

2.2.4. Distance Protection

Distance Relays are used for primary or backup protection for symmetrical and unsymmetrical faults on transmission, and distribution lines/feeders. This scheme is one of the most straightforward and economical approaches for protecting the lines [44] -[45]. It is faster and more selective than overcurrent protection and is further advantageous due to its fault location function. It is also applicable to radial networks.

The working principle of distance protection is that it determines the fault impedance from the measured short-circuit current and voltage at the device location. The calculated fault impedance is then compared with the transmission line impedance if the measured line impedance is smaller than the inputted line impedance and an internal fault on the line is detected. There are multiple reasons for inaccuracies in the distance measurement caused by CT errors, incorrect line impedance calculation, and a protection setting of 100% reach of the line which is impossible in practical cases. A common setting is 80-85% of the line length is done and fault within this zone is cleared without any delay as shown in Figure 2.8.

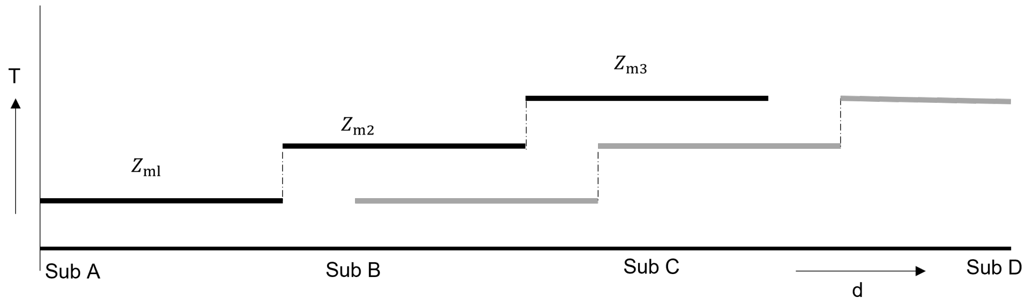

Figure 2.8: Impedance zones of a transmission line protected by distance protection [4]

Fundamentally there are three protection zones where the second zone covers the last 20 % of the line and the next 50% of the second line section. The second zone is used to ensure selectivity and must be time-delayed which is about 250-300ms in case of numerical distance protection.

Since 100% distance protection setting of the feeder length is not possible in practice, the keywords have been defined for different stages:

Under-reaching stage or first zone of the relay: - This zone covers 80-85% of the transmission feeder length and has a security margin of 10-15% from the remote end of the feeder(cable/ overhead lines).

Over-reaching or second zone of the relay: The second zone of the relay covers the remaining 20% of the line and is further extended to about 50% of the adjacent section of the feeder (line/cables).

The working principle of distance protection is easy, and simple but finding the correct settings is a bit complicated. The distance protection in a distribution grid with a short lumped transmission line is not used. It is mostly preferred for a transmission grid for high voltage in a meshed or ring network grid structure.

2.3. Grid Forming Converter

In a closed-loop way, the grid-forming converters are controlled in order to maintain stable ac voltage and line frequency. Their performance is regarded as the ideal ac voltage source. It represents low impedance output. For the successful operation of grid-forming converters in parallel, accurate system synchronization is needed. During an islanded mode operation or in case of grid failure, the grid-forming converters form the grid voltage which is used as a reference voltage for the operational system. An example of a control block diagram for a grid-forming converter is shown in Figure 2.9:

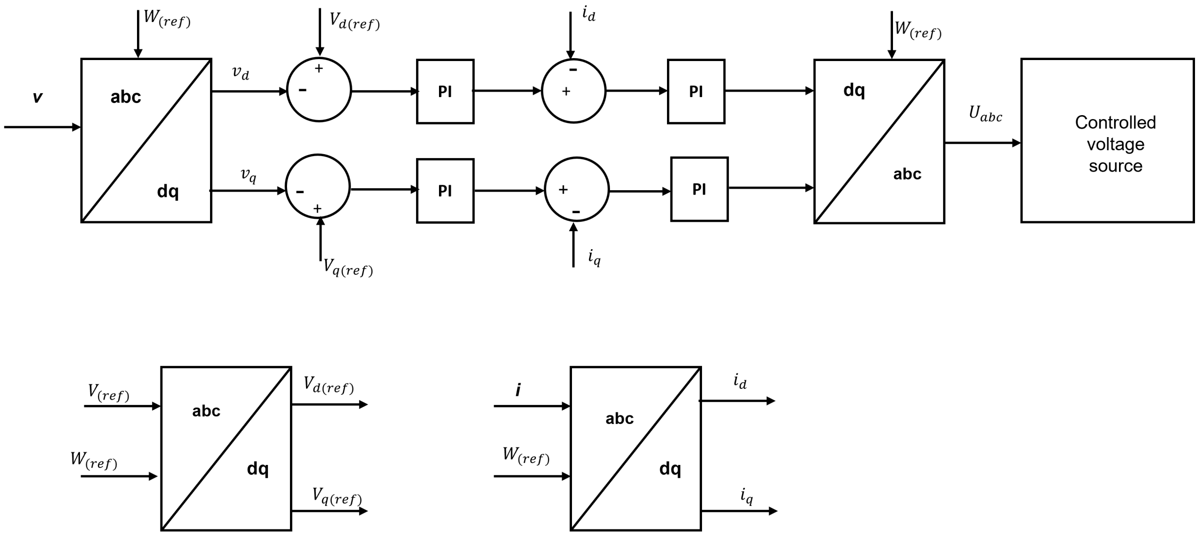

Figure 2.9: (a)Inner loop control structure for grid forming converter
(b)Outer loop control structure for grid forming converter[5]

The block diagram has an inner current control loop and an outer voltage control loop performing specific functions. The two control loop regulates the converter current and voltage as shown in Figure 2.9. The equations are described below for both inner and outer loops of the converter as shown in Equation 2.4

$$v = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad i = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2.4}$$

where, v_a, v_b, v_c are the instantaneous voltages of Phase A, B, C and i_a, i_b, i_c are the instantaneous currents of Phase A, B, C

The inputs to the controllers are provided as three-phase ac voltages. The three-phase voltages are transformed into dq frame voltages v_d and v_q. PI controller block outputs the current reference signal for the inner current loop. The error signal between the current reference and the determined current i_d and i_q again goes through the second PI controller.

Then, the reference frame dq is transformed into abc reference frame which is represented by u_{abc} (where u_{abc} is the controlled three-phase voltages) as explained in [5].

2.3.1. Grid Following converter

The proposed power references are tracked using the grid following converters, the power references are inputted according to the requirements. This type of inverter is suitable for grid following mode. The instantaneous power helps determine the converter's active and reactive power, and the equations are derived below Equation 2.5.

$$
\begin{aligned}
P &= v_d i_d + v_q i_q \\
Q &= v_d i_q - v_q i_d
\end{aligned}
\tag{2.5}
$$

The block diagram of the grid following converter explains in detail about the control blocks as shown in Figure 2.10. In the grid following converter, the input of the converter is

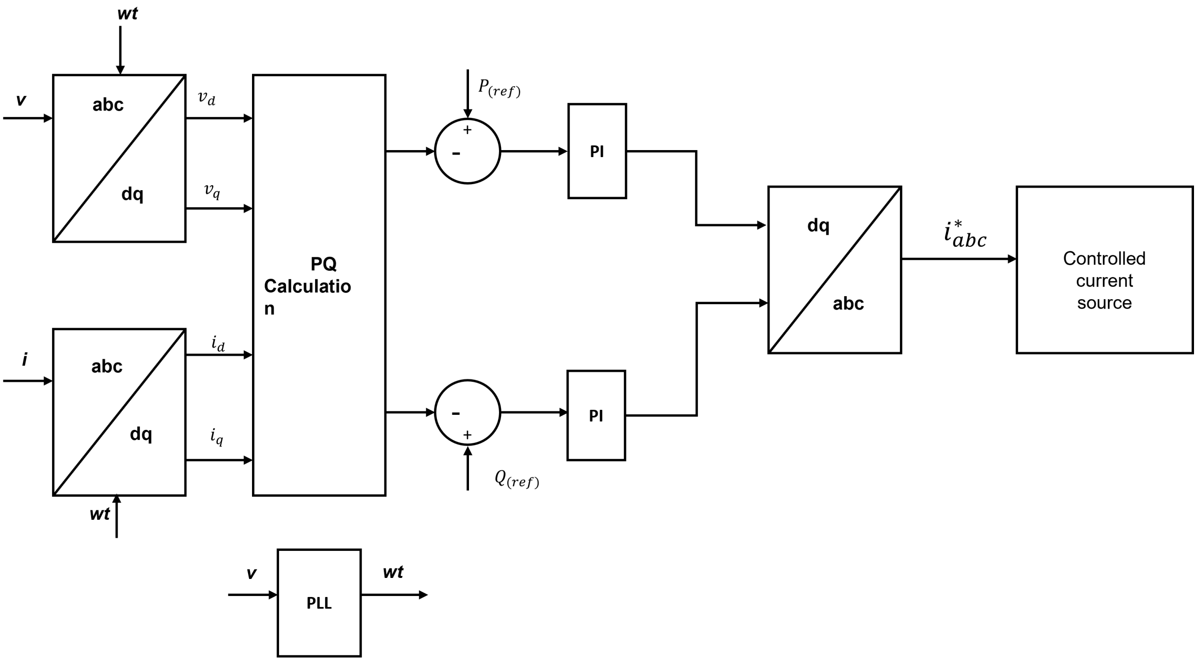

Figure 2.10: (a)Inner loop control structure for grid following converter (b)Outer loop control structure for grid following converter[5]

the difference between the reference values of the reactive and active power and the output of the active and reactive power of the converter. PI controller outputs the current reference signal for the inner current loop, also the error signal passes through the PI controller giving the output of the voltages into dq transformation. In the grid following converter without switching, the current response is fast and disregards the inner current loop when compared to outer loop.

2.3.2. Difference between Grid forming and Grid following converters

The differences between grid forming and grid following converters are summarized in the Table 2.1

Table 2.1: Comparison between Grid Forming and Grid Following Converters

Grid Forming Converter	Grid Following converter
1. It adjusts the modulated voltage with respect to the operating voltage of the grid at PCC [46]	1. It adjusts the injected power with respect to the operating voltage of the grid at PCC[46]
2. It doesn't rely on external grid voltage to maintain stable power production. It can operate with or without synchronous generators	2. It requires a voltage reference signal from other generators to operate.
3. It operates as the controlled voltage source [47].	3. It operates as the controlled current source[47].
4. It has a slow response due to large inertia.	4. It has a fast response to intermittent renewables.

2.4. Effect of Grid forming & Grid Following on fault currents

The continuous appeal for reducing the carbon footprint has encouraged an increment of renewable resources. This has led to significant changes in the dynamics of the power system. One of the major impacts of this transition is a low-inertia power system encountering stability challenges. To handle the low-inertia issue, the grid forming and grid following control strategies are developed for the power electronic converters [48]. In future power systems, the grid-forming converters will play a key role. It will allow a transition from connected grid operation to islanding a part of the grid during emergencies or faults. It has the ability to generate voltage and frequency independently of an islanded system [48].

2.4.1. Influence on the fault currents & Protection System

The fault characteristics of Inverter Based Resources are different from conventional synchronous generators. It depends on the control structure of the inverter implemented in the network according to industry standards. The short-circuit capacity of the Inverter based Resources is rated lower than Synchronous Generators due to the thermal limits of the semiconductor switches [49]. The inverter-based resources will impose majorly two challenges to distribution system protection.

1. It will impact short circuit fault current and its duration on coordination of the distribution protection system.
2. When the Distributed generator is isolated from the network due to the ground fault,

an overvoltage can occur.

In a semi-conductor-based inverter, there are two control techniques voltage control and current control technique. Both techniques are used to regulate the active and reactive power of the system. An open or closed-loop voltage control technique is used to regulate the voltage magnitude whereas a current control technique regulates the current directly. For an accurate and non-misleading fault analysis, nonlinearities have to be adequately modeled. It is possible to estimate the fault characteristics and their effect on the protection system on the basis of specific application requirements.

In recent years there have been changes in the energy landscape and a shift toward Inverter based resources. These changes have affected the reliability and security of distance protection. Several occasions where maloperation of the relay took place due to Inverter based resources as discussed in [50]. Grid-forming inverter control is gaining attention due to various studies showing that it has promising features and advantages. An investigation has been carried out in [50] to address the effect of different grid-forming control designs on the performance of the distance protection relay. Its impact on the directional element of the distance protective relays. The grid-forming control has an influence on the fault impedance computation of traditional distance protection. The author proposes two Grid forming control architecture which is built on a synchronous *(dq)* frame and an advanced control architecture in a stationary frame($\alpha\beta$) which has the capability of tackling unbalance fault conditions.

The first frame which is a Synchronous-frame grid forming control architecture has an inner-current loop and an outer-voltage loop with a current-reference saturation limiter with the purpose of preventing currents from exceeding the maximum allowed rating of the currents. Another advanced control architecture is based on $\alpha\beta$ frame to expedite the flow of negative sequence currents during asymmetrical faults. It also employs proportional resonant controllers to track the reference frame. In this control, the gain does an equal scaling of line currents in the abc frame when one of the phase currents exceeds the threshold of the maximum rated currents. The equation of all the mentioned frames is discussed in [50].

2.4.2. Advantages & Disadvantages of Grid forming and Grid Following

Grid-following Inverter- Advantages [51]

1. Simple control and fast response time.
2. It is available in rotating and stationary frames.

3. It limits current during faults.

Disadvantages:

1. Phase locked loop loses system frequency during faults.

2. It does not contribute to grid strength and requires grid robustness.

Grid Forming Inverter- Advantages:[51]

1. It can run in stand-alone mode and also in weak-grid mode.

2. It handles load variation without disturbances.

Disadvantages:

1. The grid desynchronizes during faults.

2. The grid-forming inverters with voltage stabilizer inner loops are stiff to work with DG and the existing grid.

2.5. Conclusion

In this chapter, an overview of the protective relaying was given. First, an introduction about the relaying technology and then types of Protection relays and their importance in the power system of the future is discussed. It also explains how this conventional protection system can be developed so that it can be used for future power systems. The various protection relays and their advantages and disadvantages have been reviewed. The final section of the chapter emphasizes the effect of the inverter-coupled(grid forming & grid following) converters on the power system. A conclusion has been made that inverter-coupled distributed generations do not contribute enough to the fault current which has a significant impact on the protection system.

3

System Integrity Protection schemes

3.1. Introduction

SIPS (System Integrity Protection Schemes is a new concept of utilizing local and remote locations and extracting appropriate network information to the nearest processing site to counteract the propagation of extreme disturbances in the power system. With the development of advanced technologies, fast communication, and synchrophasor-based measurement technologies, intelligent technologies have been developed at the local level to improve network monitoring and overall response [52]. The security and local supervision of the network can be enhanced using a SIPS-based algorithm according to power system response.

The SIP encircles Special Protection Scheme(SPS), and Remedial Action Schemes(RAS) additionally extended to Underfrequency, Undervoltage, and Out-of-step(OOS) protection. This type of protection scheme is implemented in the overall power system network in order to maintain power system stability, monitor topology correctness, and observe the system to avoid network equipment damage due to critical events. The SIPS can be classified into different categories as shown in Figure 3.1

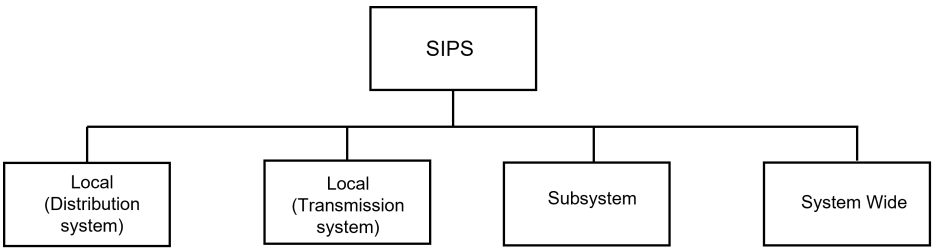

Figure 3.1: SIPS classification [6]

Architecture of SIPS

There are mainly two types of architectures in SIPs: flat and hierarchical. These architectures are designed so as to take corrective action in case of failure or the SIPs fail to operate or undesired operation of the SIP also disturbs the balanced operation of the power system network. It is important to have redundancy or backup in the system to have additional security in the system. In flat Architecture, the measurements and decisions of operating elements are in the same location. Whereas in Hierarchical Architecture the local measurement or predetermined variable at different locations is transported to various control locations. Depending upon the motive of the scheme, necessary actions can be initiated or further analyzed for a corrective response as shown in Figure 3.2.

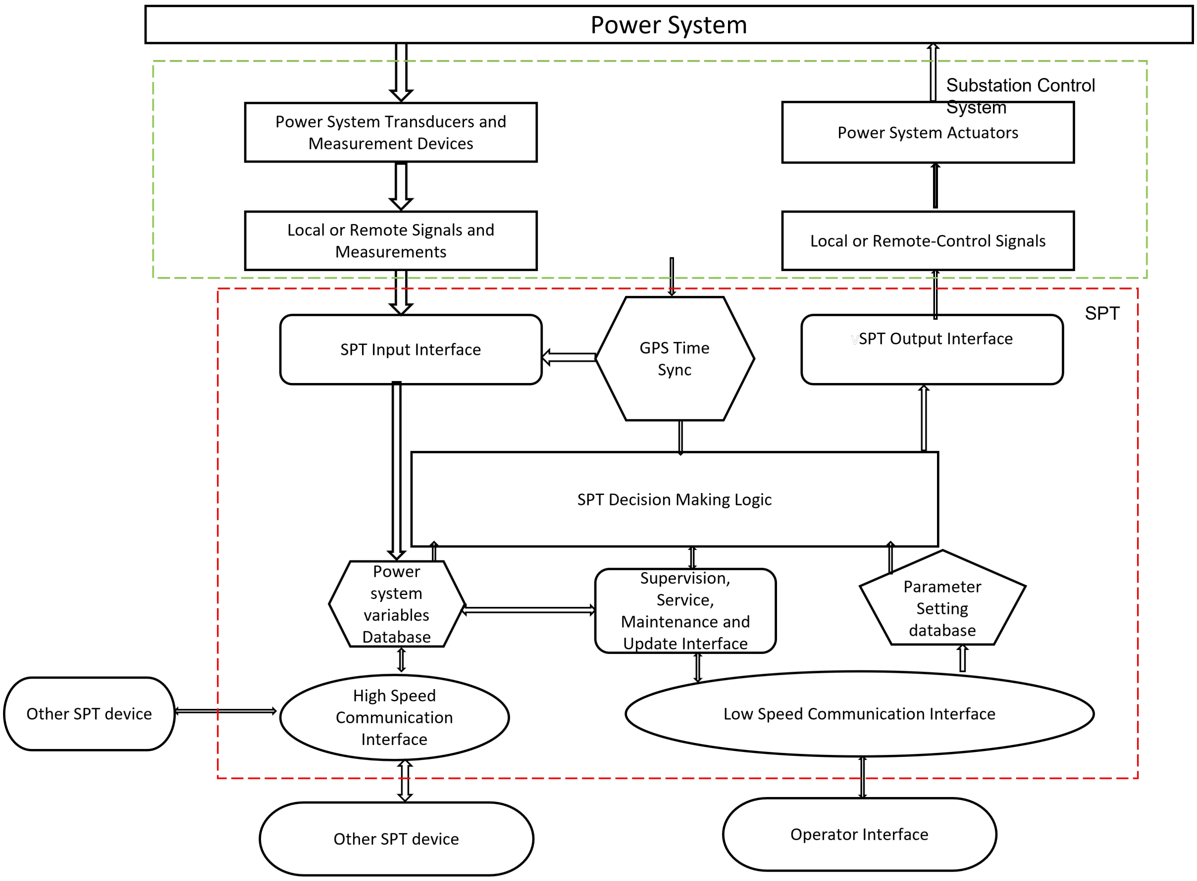

Figure 3.2: System Protection Terminal [7]

In this Figure 3.2, the design is addressing all the standard requirements for the protection terminals. Subsequently, the protection terminal is connected to the substation control. It is GPS-based and time-synchronized at the substation terminal so that the data can be transferred between the terminal and the specific substation. The substation has a decision-making algorithm to decide the impact of the event and control signals such as circuit breakers to provide trip commands. The SCADA system has different functions such as OPF(optimal Power flow), emergency load control, etc. The operator at the SCADA room has access to the terminal, parameter setting, load shedding, maintenance, supervision, and disturbance recorder data collection.

3.2. Synchrophasor Design and Applications

The introduction of the Phasor Measurement Unit in the power system represents a remarkable change in security, power measurements, monitoring, and control [53]. PMUs utilize synchrophasor measurements to retrieve the system state's information from the sample data and are collected to form the network which is called a Wide-area Monitoring system (WAMS). Basically, synchrophasors are the representation of the mathematical method by the phasor complex values of the sinusoidal waveforms in power systems. The measurement retrieved from the synchrophasor technology is called synchronized measurement. The various electrical parameters such as bus voltage, line sequence quantities including (magnitude and angle), and the frequency of the power system network can be measured directly using a synchrophasor [8]. The data provided by PMUs are accurate and help the system to investigate and analyze or post-mortem the exact sequence which led to undesired events.

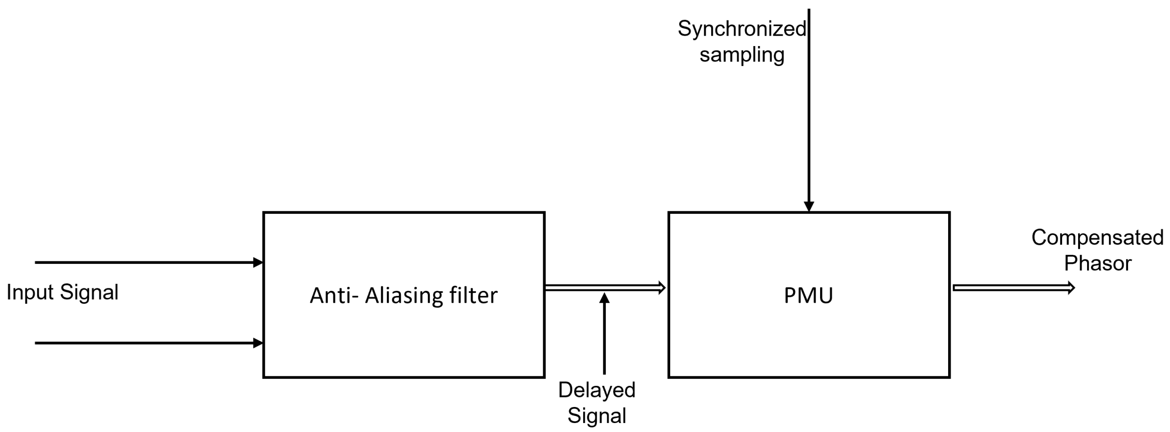

Figure 3.3: Compensating for signal delay introduced by anti-aliasing filter [8]

Synchrophasor is a terminology to define the phasor estimate which has been estimated at a particular instant using a GPS clock with the timestamp of the synchrophasor. In order to collect simultaneous measurements of phasors across the interconnected power system, it is important to synchronize the timestamp of all the PMUs, so that the measurements recorded simultaneously consist of the same timestamp. The anti-aliasing filter present in the PMU produces a phase delay depending upon the characteristics of the filter type. The delay in the PMU is a function of the signal frequency as shown in Figure 3.3.

The synchronization of the sample data is succeeded by using a sampling clock which is phase-locked logic to the one-pulse per second input signal provided by a fast communication GPS receiver. The GPS receiver is inbuilt into the PMU. The timestamp is at intervals and there are multiple intervals of a cycle of the rated power system frequency. A schematic design of synchrophasor with Phasor Data concentrator is shown in Figure 3.4. A PDC has three modules: an input module, Data Processing Module, and an output Module. The brief details about the three modules are explained in the literature [9]. The implementation of a PDC faces challenges such as various PMUs data may be located at different locations resulting in latency or data may be lost/arrive late. Another issue is time synchronization of PMUs can be lost.

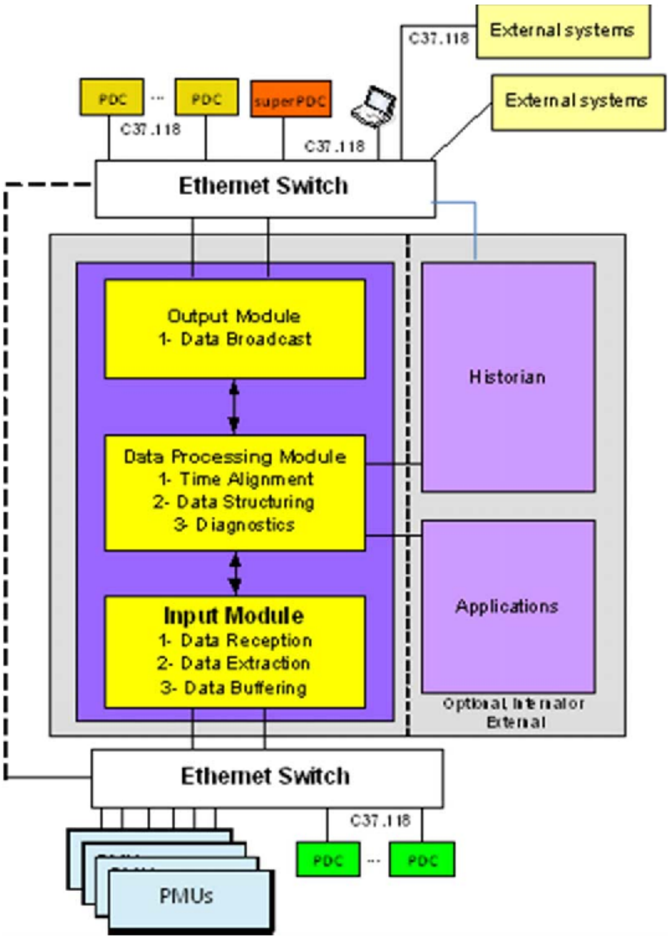

Figure 3.4: Design of a synchrophasor Data concentrator[9]

3.2.1. Application of Synchrophasors in Distribution System Network

This section discusses the different applications of synchrophasor in the distribution system network [54]:

Voltage Stability Monitoring: The monitoring of the voltage at all the buses is one of the major applications of synchrophasor measurements.PMU placements are done in such a way that it measures voltages on both ends of the buses. In a distribution system due to a large number of renewable resources voltage monitoring is crucial to have a good knowledge of the reactive power flow.

Angle/Frequency Monitoring: Using PMU for angle and Frequency monitoring is a generic function by the operator to uplift the observability of the power system network. The dynamics of the distribution network are continuously evolving by fluctuating renewable generation (wind, photovoltaic), and monitoring of angle/frequency used to determine the power balance in a distribution network of the grid.

Post Event Analysis: There are cases where analysis is carried out after the major fault to understand the root cause so the recorded measurements from synchrophasors are very valuable. It also allows documentation of the event on request of the authorities in an easier process. It is beneficial for the distribution network.

Power System Restoration: In case of complete or partial separation of the network from the grid, the network can be restored quickly with the help of synchrophasor measurements. Having PMU on a network provides information on electrical parameters such as voltage, currents, and frequency so the re-closure of the circuit breaker can be decided based on available information during the event.

Power system Protection & Control Synchrophasor measurements have effectively improved the protection function which has a relatively slow response time. The latency of communicating information between the remote substation and the locally placed PMU does not have significant delay issues. PMUs have improved the security and reliability of the protection system in the grid as compared to traditional protection relaying. The measurement data offers the possibility of improving the control of remote locations. The advantage of having angle information of both currents and voltages helps in detecting instabilities and taking switching controls in an attempt to take advanced actions so that events can be mitigated.

3.3. Intelligent network Splitting

Intelligent network splitting or partitioning is a concept of power system networks introduced frequently in advanced control, operations, and protection technique of the network. Network splitting is also used for intentionally controlled islanding and determining coherent generators. An important approach for partitioning power systems is Spectral Clustering. It is also used for studying power system dynamics and operational uncertainty [55]. This paper proposes to choose the number of clusters for Intelligent network splitting and develop a robust & time-efficient algorithm. Another algorithm is designed on transformed eigenvectors that split the power system into a well-structured network [56]. The proposed algorithms show high efficiency and splitting quality also ensuring the connectedness of the resulting clusters. There are clusters having equal nodes and the high-speed clustering framework of the algorithm makes real-time decision-making faster.

Spectral Clustering Algorithms

In the Spectral Clustering algorithm, each row of an eigenvector is assigned to a fixed cluster. It is referred to as the eigenvector discretization procedure and the results are also considered as a conversion of a real-valued eigenvector matrix into a discrete matrix. One of the drawbacks of this algorithm is to not account for the graph interconnection of the structure that is encoded in the matrix. It results in obtaining disconnected network clusters consisting of various graph-connected components. This constraint cluster connectedness can be resolved by defining the distance as the shortest path in the graph. It is equipped with new edge weights that are equal to the Euclidean distance in spectral embedding between the edge of each end node [57]. However, it was observed that spectral distances have a very negligible influence on the splitting results [10]. The overall representation of the power system partitioning has been shown in Figure 3.5. Detailed information can be found in the dissertation of [10].

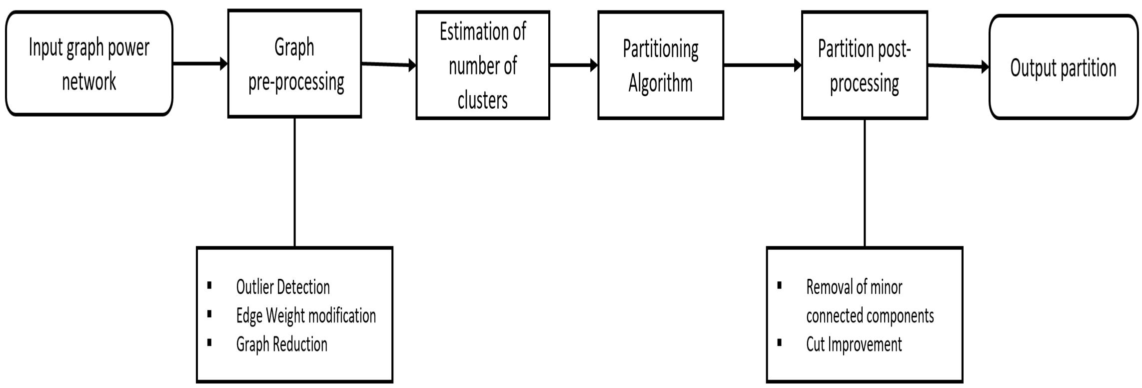

Figure 3.5: Generic graph partitioning framework(adapted from[10])

Eigenvector Alignment Based Splitting

The axes-aligned spectral embedding is an important input to the partitioning of the network, apart from providing valuable indicators to define the number of clusters. In this algorithm, each eigenvector is sorted to find out which row has the highest a large magnitude. A threshold is defined to check that no two or more normalized eigenvectors can assign the same row to their clusters. Then the expansion of the cluster core is updated by adding each next node and the final cluster core is found by observing the set of nodes with the least achieved expansion. In some cases, the largest connected node can be accounted as the core. After estimating all the cluster cores, the algorithm defined in the research is used to improve in the decreasing order of their expansion as referred to in [56].

The refined estimated clustered core is collapsed into single nodes. The new network should consist of k and the left-out nodes that were not assigned to the cluster cores are partitioned by recursive bisection. This is done so that the left-out nodes are assigned to a cluster. It ensures that network partitioning is connected and cluster cores are also connected, here partitioning is done by computing the s-t cut. The minimal s-t cuts divide the graph into two connected parts. The step-wise explanation of the process is discussed in detail in [56].

3.4. Undervoltage and Underfrequency Protection

3.4.1. Undervoltage Protection

In the past Undervoltage fault protection was used to protect the alternator, and generator from low-voltage operation. It is also rarely used for other protection functions such as field failure protection or unintended energization protection where the events may be directly or indirectly detected and can lead to an Undervoltage condition [39]. In a transmission system, Undervoltage conditions may arise due to insufficient reactive power generation to retain the balanced system voltage level and this situation must be handled to avoid the leading effect of network voltage collapse.

The most occurring case of Undervoltage protection is necessary for a generator supplying an independent power supply or meeting the demand of the utility companies. This situation is due to overloading or failure of the AVR(which governs the stability of the system). The Undervoltage protection is activated when the voltage drops below 85%-90% of the rated system voltage. The protection setting of the Undervoltage protection should be chosen with a gradual delay to avoid misoperation during the inevitable voltage sags concerning power system faults or associated with induction motor starting. Transient drop in voltage fall to 80% or lesser may be faced during motor starting. Undervoltage protection is commonly used to disconnect the motor from operating for a longer voltage dip than intended [39].

The motors fed by switch have in-built Undervoltage protection, with a definite time

Undervoltage element used. An interlock is required with the starter to block relay operation when the starter is in open condition else a start will never happen. The delays are considered by the motor so that the temporary occurring events such as transient faults or starting of a motor can be avoided. A motor starting can depress the voltage to 80% of its rated system voltage. So the devices are manufactured in such a way that they can handle voltage dip for a specific time as set in the protection device [58]. The progressive and successive penetration of decentralized renewable energy sources into the power system challenges the system's protection. The new concept of directional reactive power Undervoltage protection will improve reliability and ensure the security of the grid during faulted conditions.

3.4.2. Underfrequency Protection

Underfrequency Protection is required to protect the generator from prolonged overloading due to excessive generation or during periods of operation when the unit is isolated from supplying due to equipment failure in the power system network. This type of protection is advantageous to the generation-load imbalance sensitivity and its relatively simple approach to the protection system [59].

One of the major indicators of underfrequency is power deficiency which needs to be corrected otherwise the system may result in failure. There are corrective measures taken to deal with power deficiency such as scheduled load shedding which is intentionally dropping demanded amount of power upon detecting power deficiency. The local frequency of the network can be monitored throughout the operation of the system, underfrequency load shedding protection can automatically sense the power drop and higher demand at the load side, and open circuit breakers so that the balance of the system can be retained and system collapse can be avoided. The underfrequency load shedding relay protection works on the principle when the preset value of the frequency decreases beyond it. The underfrequency load shedding scheme has constraints which are circuit breakers operating on the threshold value of frequency alone.

In the future power system, there is a risk of islanding renewable energy sources due to the conventional load shedding protection schemes because of the high penetration of photovoltaic and wind plants in the medium and low voltage network. It is necessary to develop a new technique for underfrequency load shedding protection for future intelligent grids [60].

3.5. Out of Step Protection

During normal operations of the systems, the power system is introduced to a wide range of small and large disturbances. There are certain disturbances that cannot be handled leading to the loss of synchronism between the generator and the interconnected power system of the utilities. The phenomenon of out-of-step relaying protection is simple and straightforward. It prevents the relay from tripping during stable swings and protects the power system during unstable conditions. When two areas of a power system or two interconnected lose synchronism then an instant action should be initiated to separate from each other to avoid electrical equipment damage or interruption of supply to the major part of the system [61].

The main functionality of the out-of-step condition is to detect stable and unstable swings by using the electrical parameter variation of voltage and current. A power swing condition is an electromechanical transient phenomenon with a time constant considerably longer than short-circuiting faults. During a power swing, the rate of change of positive sequence impedance is much slower than in a short-circuited fault. It also depends on the frequency. When δ approaches 180 ° which is the power angle during OOS(Out of swing), the positive sequence impedance reaches the operating zone of a distance relay for the line. Since positive sequence impedance itself is not enough to distinguish between an Out of step swing or a short-circuit fault on the line. The rate of change of apparent impedance is the discriminating factor for transmission line fault and power swings[39].

Basically, there are two major functions related to unstable swings which are out-of-step tripping that discriminates between stable and unstable power swings and islanding the affected area. The next function is Out of Step blocking which distinguishes between a short-circuit fault on the line and stable or unstable power swings. It is always recommended to complement the Out-of-Step tripping with Out-of-Step blocking to prevent unnecessary relay operations and rescue systems from being damaged. It is noticed that OST(Out-of-Step tripping) takes place where the relay is located and islanding is done at the same location but there are cases when islanding is essential where the OST relay system is not located. Another important aspect of the Out-of-step protection relay is to not initiate tripping when the angle between the system is almost 180 °. It is because the system is under high stress and can cause re-strike and circuit breaker damage.

3.6. Conclusion

In this chapter, the general concept of a System Integrity protection scheme is discussed. The design and applications of Synchrophasors in the distribution system are explained in detail. It can be concluded that synchrophasors play a vital in the power system and with an increasing amount of renewables penetration in the network. It is used for monitoring, analysis, decision-making for system restoration, and controls. The future protection of the power system can be developed using synchrophasors and a fast communication network. To enhance operations, monitoring & advanced controls, Intelligent network Splitting is a concept that has been introduced into the power system. It is useful for controlled islanding and partitioning the network into clusters so that the dynamics of the system can be studied with much ease and the computational burden decreases. Several algorithms have been explained in detail for partitioning the network. In the final section, the working principle and functionality of the Undervoltage, Underfrequency, and Out of step protection have been studied. It also explains the usefulness of the protection system in the future power system with increasing Distributed generations.

4

Fault Locators

4.1. Introduction

The rapid development and demand for power supply have led to a large increase in the number of transmission and distribution lines. Coherently, these feeders experience faults that must be repaired to restore them to operation. The restoration of service can be done faster if the location of a fault is known or can be located with reasonable accuracy [62]. Fault locators in the power system are used to measure the distance to a fault location on a transmission line. Conventionally, there were methods based on surge voltage due to a fault on both sides of the transmission line connected to the buses. The time difference of the surge detected between the two buses determines the fault location [63]. In calculating the distance from the fault location, it has been noticed that using the voltage and current data from both buses is beneficial.

There are various research and methods proposed for the location of a fault on transmission lines. These methods can be subdivided based on the estimation of the voltages and currents at one end of the bus or both ends. It is further categorized based on traveling waves, methods using high-frequency components of currents and voltages, & and there are methods based on fundamental frequency voltages and currents of a line. Lastly, they are also methods based on impedance consisting of calculating transmission line impedance observed from the terminals. With the recent advancement in technology and research, there are methods of fault location using PMU(Phasor Measurement Unit). The method proposed using fundamental frequency and voltage can be used for rural distribution feeders [64]. In this chapter, various methods will be discussed in detail and followed by fault locator operators consisting of (faulty area detection, faulty line detection, and fault distance).

4.1.1. Fault location on line

Method based on Travelling wave

Automatic and accurate fault location methods for lines will not reduce the search area for technicians in the field but also help in the restoration of the network. A very simple method has been adapted for fault location on transmission lines & cables based on traveling waves using Park's Transformation theory for unbalanced fault detection. The method is advantageous since the sampling of one voltage sample per phase at a time and monitoring of transient phenomena in all three phases can be conducted simultaneously by analyzing one signal voltage i.e, the direct axis voltage[11].

The traveling wave method provides a higher accuracy as a function of the sampling frequency of DFRs (Digital Fault Recorders). It is often referred to that the traveling wave being highly reliable and providing an estimation of the maximum expected error as a function of sampling frequency. The reliability of any algorithm of fault estimation is directly proportional to the estimation of fault location at any instant. The key feature mentioned in this approach is that the fault location method is based on analyzing voltage waveforms recorded by Digital fault recorders at the two ends of the terminals.

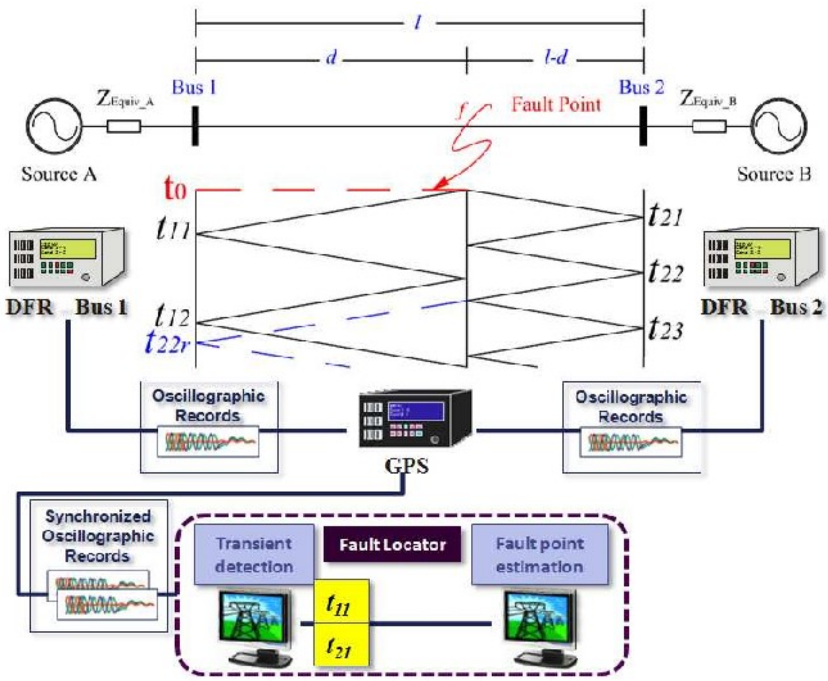

Figure 4.1: Double-ended fault location scheme based on traveling wave[11]

In this method, the incident wave is considered for detecting the fault location, and reflected waves are ignored, making the approach more reliable. To synchronize the DFRs measurement with the voltage sample so that they are coordinated over the same timebase, a GPS is used. To synchronize the DFRs measurement with the voltage sample so that they are coordinated over the same timebase, a GPS is used. A synchronization error of plus and minus 1 microsecond is also considered. The principle of traveling wave methods with two DFRs placed at two ends of the buses is shown in Figure 4.1. The algorithm is two stepped, the first step is transient detection and the next step is fault localization. The process of transient detection is based on Park's Transformation (Tdq0). It is a very popular methodology used in electrical engineering for synchronous machines. In the Park transformation, the direct and quadrature axes are calculated during transients and oscillatory signals are obtained. Both these signals can be used for transient detection but in this research one Direct axes has been considered as it has high attenuation during high impedance faults.

The implementation of the proposed method is carried out in five steps: (a) voltage data acquisition using DFRs at both ends of the line (b) an orthogonal voltage phasor calculation in a static reference frame (c) an orthogonal voltage phasor calculation in a rotating reference frame (d) ascertainment of the initial transient instants (e) fault location. This sub-division of implementation can be broadly studied in the literature [11].

In the final step, fault location is estimated from the voltage signals at the two ends of the transmission lines using the equation as derived in literature [11]. Having the information of the detected first transients, line length, and the propagation velocity of the aerial modes is used to calculate the fault point location. The method can automatically determine the fault location quickly after the occurrence of the fault on the transmission line.

Method based on Impedance

Transmission lines are often exposed to numerous faults due to various factors and they are either temporary or permanent. To restore the system to normal and improve system reliability, impedance-based algorithms are popularly accepted in the power system due to their straightforward to implement and estimate of the fault location. Over time numerous impedance-based fault location algorithms have been developed for the transmission network. Single-ended algorithms or two-ended algorithms by recording data from both ends of a terminal having specific input requirements and certain assumptions when calculating the distance to a fault. The single-ended terminal is advantageous because no data is required from the other end of the terminal whereas Two-ended terminal methods are accurate and unaffected by the fault resistance and also have a higher precision of fault location than single-ended [12]. In this literature [12], the author developed two types of algorithms i.e, Parameter dependent and the other is parameter-free fault locator which is discussed in the next part.

Parameter-Dependent Algorithm

The author has two types of approaches for fault location algorithms on an impedance-based. Using Telegrapher's equation from a single-line network in the literature [12] and then Clarke's transformation is applied to extract the variables the $\alpha\&\beta$ from the original phasors. The equations that have been referred to in the research are derived from the work [65]. In the equation, the information from the sending and receiving ends is used along with the total length of the transmission line. Clarke's transformation provides an extended solution to a three-phase of the transmission line. The accuracy of the faulted location can be determined through the selection of the appropriate mode and the type of fault that has occurred.

Parameter-Free Algorithm

As mentioned about two different approaches in the previous paragraph, the author developed a Fault locator Algorithm that does not require prior knowledge of the line parameters and it is more flexible and reliable in comparison with more conventional impedance-based algorithms. It uses only the fundamental phasors of voltages and currents sampled at the end of the transmission line and isn't affected by the line parameter such as line loading or bad weather conditions, arcing resistances, and fault impedances. It can locate both symmetrical and unsymmetrical faults using positive and negative sequence voltage and current quantities.

To extract the sequence quantities from the voltage and current phasors, the fast Fourier transformation is used. The parameter-free algorithm for fault locator can locate all types of symmetrical and unsymmetrical faults without time-synchronized devices and utilization of pre-fault data. Using the Fortesque symmetrical component technique, the sequence components of the asymmetrical three-phase circuit can be extracted per phase. The algorithm is also not affected by zero-sequence coupling. The equivalent circuit from which the equation has been originally derived is in the literature [12]. A flowchart representing the whole approach of the two procedures in fault location algorithms is represented in Figure 4.2.

Since the algorithm is sequence component dependent and has discarded fault resistance in the development of the algorithm. It is not affected by mutual zero-sequence coupling and fault resistance. There are cases of faults with extremely high resistance with low current measurements that can create inaccuracy due to errors in current measurements. The research concluded that a parameter-free algorithm provides more accurate fault locating estimation than a parameter-dependent. Also, a parameter-dependent algorithm

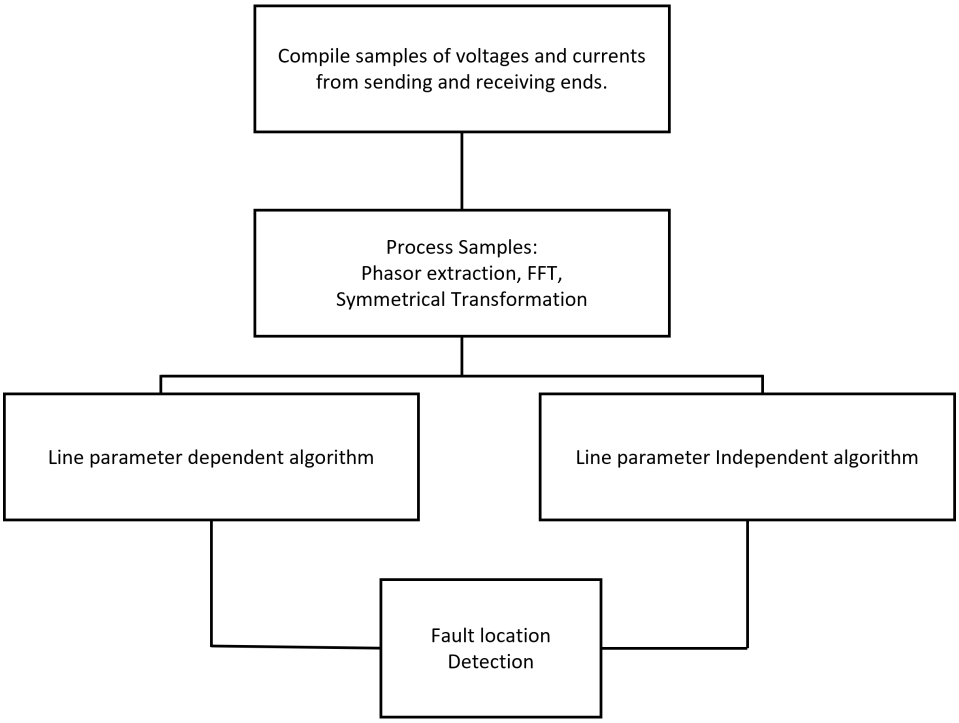

Figure 4.2: Flowchart depicting approach used in fault location algorithm[12]

has high error current measurement data when the fault location is near the sending end of the line.

Method based on PMU

Wide-area Protection algorithms based on PMU are classified as very accurate for fault location and enhancing the performance of the protection system on the transmission line. The accuracy also depends on the placement of PMUs in the network, the placement should be done so that the system is fully observable with fewer PMUs. The data recorded from PMU can be erroneous and lose their way to the control room. Therefore researchers have developed some techniques to handle data corruption which is proposed in [66] - [67]. Since the positive sequence quantities can be obtained from the PMUs placed on the network. The algorithm is developed using the positive sequence quantities which are available during all types of faults.

In the pre-fault state, the impedance matrix is calculated, and during the fault, F is treated as an additional current-injection bus which leads to the calculation of the new matrix which is represented in the proposed literature [13]during the fault. The impedances from the fault bus to the other buses help determine the fault and estimate the fault line's location. The injected current can be calculated from the two PMUs placed at the end of two buses by the equation given in [13]. A fault locator factor has been determined which is dependent on voltage change and transfer impedance and also the fault function variable

x which is during the fault.

The flowchart of the proposed method as represented in Figure 4.3 for the fault locating algorithm comprises two stages: fault region identification and exact fault location. In a large transmission network, detecting the faulted line is difficult and it's time-consuming. So the faulted area identification accelerates the narrowing down of the search region and saves time. During high impedance faults in a large power system, some bus voltages can be very low which results in inaccurate estimation of fault location. Therefore partial PMUs data are used for measuring changes in voltage. To eliminate the effect of erroneous measurements and computational errors, a few suspicious buses are selected according to the matching degree close to the minimal matching degrees. After identifying the faulted area, stage two is finding the faulted line and the exact fault location. The fault location can be done using at least two PMUs in the power system network. The step-wise implementation of the approach has been discussed in the proposed literature [13].

4.2. Fault Locators Operation Method- I

The fault locator information involves three stages i.e, the faulty area is located thereafter the faulty line is detected, and finally fault distance is determined. The research addresses the topic of Wide area backup protection using synchrophasor data based on two techniques namely the delta algorithm and the least square estimator. The advantage of this method is that it successfully detects the faulted line by identifying the fault type and estimates the distance within the time limit of the defined local backup protection.

Faulty Area detection

In the first stage, PMU collects data from the full network and a modified Delta current method(DCM) is used to locate the event area using voltage data. It is performed using PMU placed to the nearest buses in the network. It takes actual current data. Here, the phasor voltage is compared with the previous voltage using Euler's numerical differentiation [68]. It is done since the previous timestamp of the voltage phasor provides information about the stability before the fault occurrence. The disturbance in the network is detected when it exceeds the threshold of the defined DCM method. However, the current method is modified to work with the phasor voltage amplitude signals.

Furthermore, unsymmetrical ground faults are detected by using the zero sequence delta voltage phasors and the abnormal line is detected. After the fault detection, the directionality module comes into action, where negative and zero sequence currents along with positive sequence voltage are used as polarization. The PMU provides the advantage

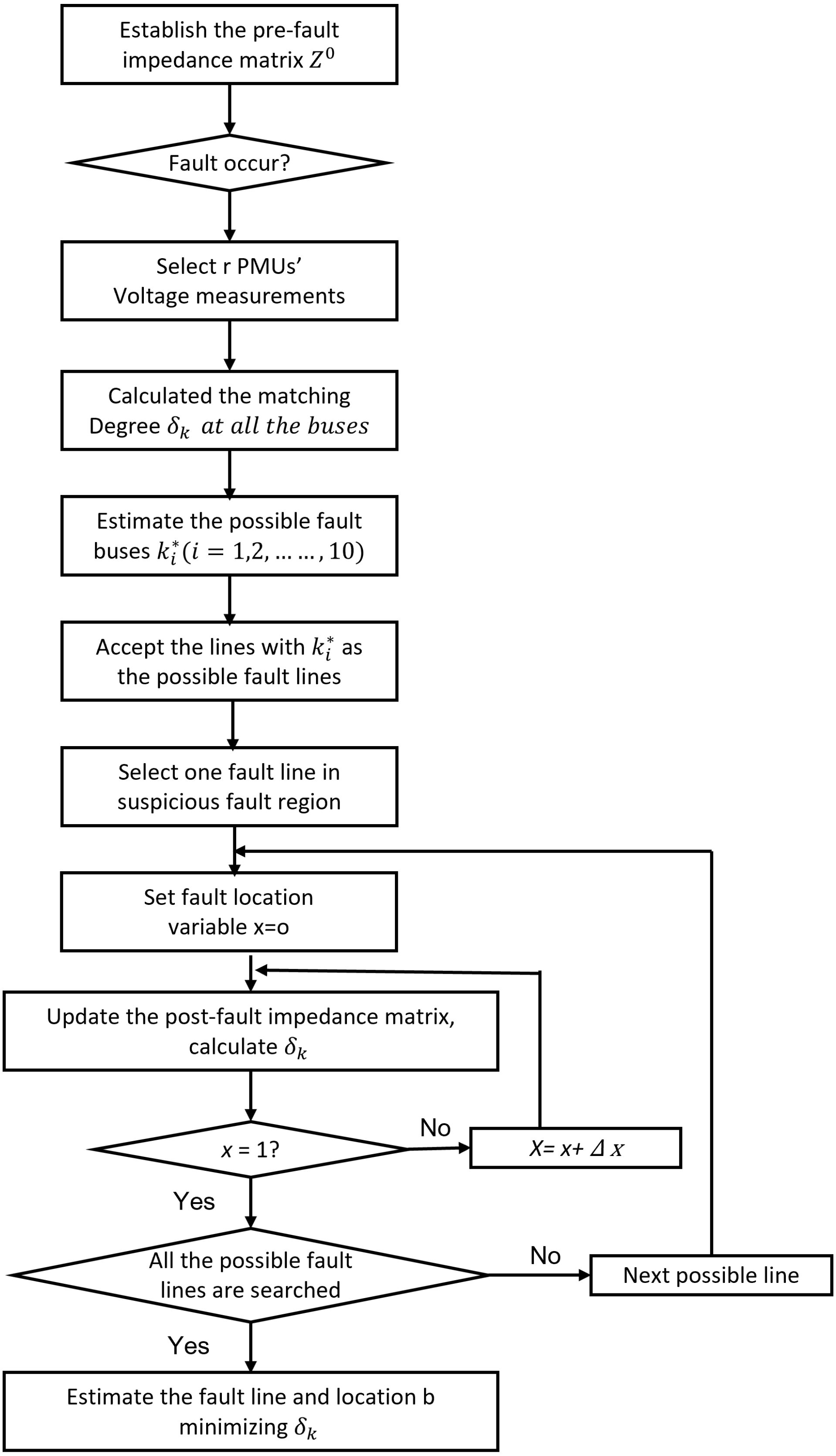

Figure 4.3: Flowchart of proposed fault location algorithm[13]

of sequence signals computed with the same timestamp signals. The function of the directionality module in PMU escalates the fault to determine the faulted area as shown in Figure 4.4. The advantage of using this method is its ability for fast detection and low computational burden.

Faulty line and distance estimation

In the complete fault identification process, locating faults is one of the critical parts so that the power system can be restored to operation. In this section using the fault location formula from the proposed method in [14] is used at each of the superimposed sequence networks. The formulated equations are derived briefly in the proposed work by [14]. The proposed methodology has been tested on an RTDS and the placement of PMUs is decided where there are three or more lines connected in a network. The proposed method uses the synchrophasor concept to detect the faulty area location, faulty line, and distance estimation. This methodology also detects other important power system events such as stable power swing, load switching, etc. It results to be a better approach than the classical protection system.

4.3. Fault Locators Operation Method- II

The synchrophasor-based protection method has an edge over simulation-based fault location which is substantially detected by matching waveforms carried out in [69, 70]. In this research, fault location and identification are carried out in a hierarchical manner, where the faulted area is first identified by locally placed PMUs, next the suspected faulty transmission lines are diagnosed and finally, the fault location is located along the line. It is possible to identify and locate the faulted line even if the PMU is not placed on either terminal.

The paper addresses the identification of the faulted line and locating the fault location along it by utilizing the synchronized measurements of voltage and current signals pre-fault and post-fault. Measurements are recorded by the wide-area measurement system consisting of various PMUs placed so that the network is completely observable. It is time synchronized by the global positioning system signal. An IEEE 9-bus network with three generators and two PMUs for fault diagnosing with complete observability as shown in Figure 4.5

In a power system, when a fault occurs the voltage and current phasors vary depending upon the location and type of the fault. The main concept of this method is to match the measured phasors by PMUs and compare the behavior of the phasor after the fault as

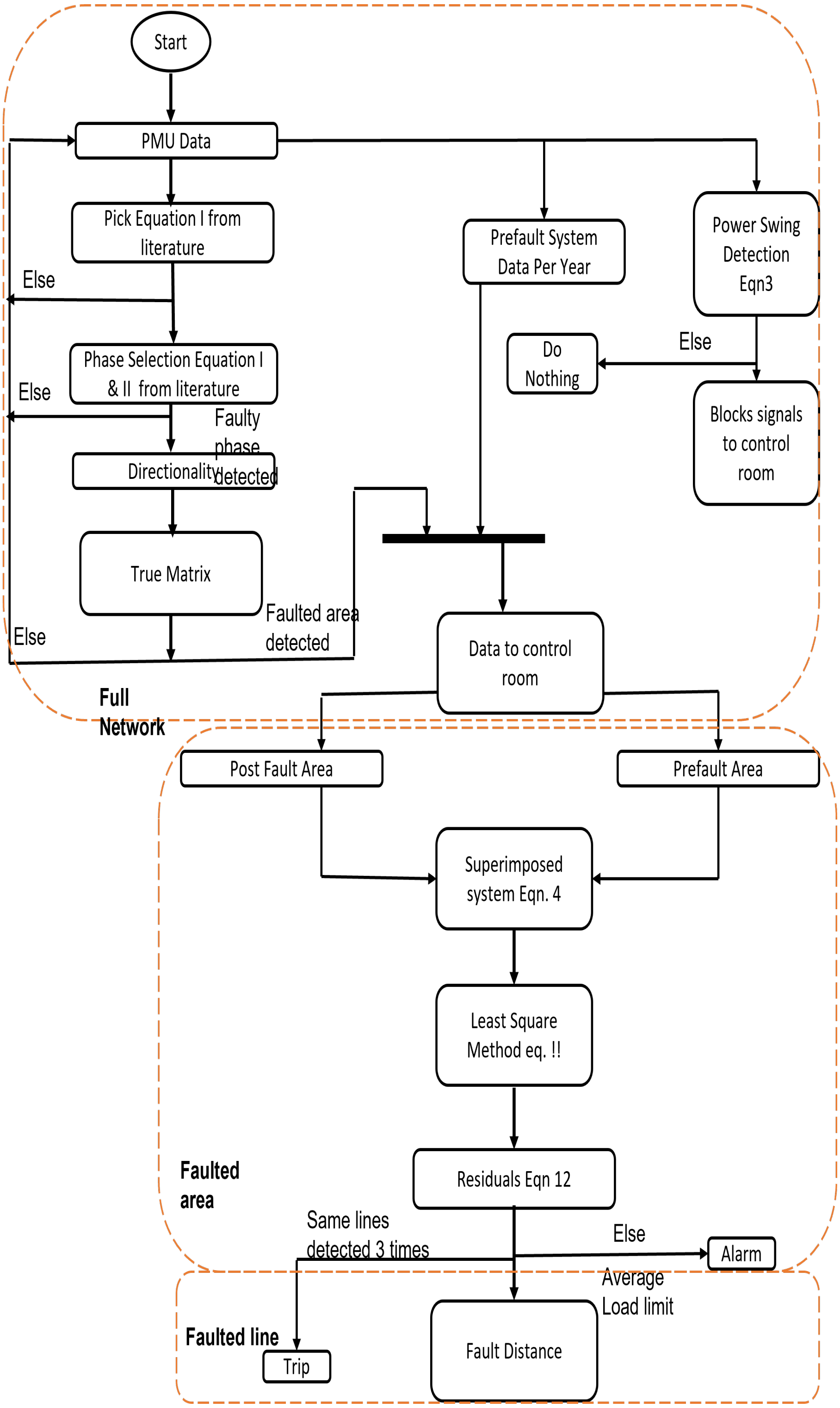

Figure 4.4: Flowchart proposed methodology in three stages[14]

expected of the system. Using this pattern, the ideal fault point, and fault type is diagnosed.

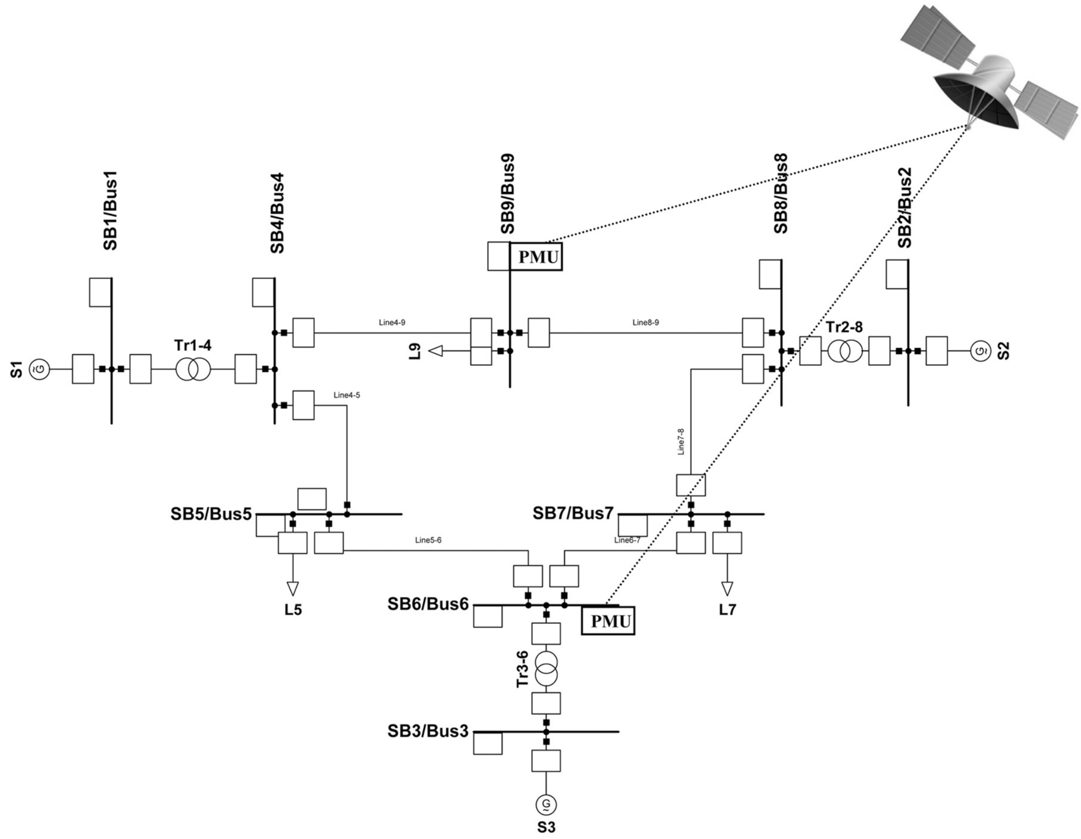

Figure 4.5: Single line diagram of IEEE-(bus with PMU[15]

4.3.1. Transmission Line Fault Operation

Power system experience the most number of faults on the transmission line. Therefore, it is important to clear the fault so that the system can be restored back to normal operation. The fault locator operation involves three-stage so that the maintenance operator can speed up the restoration process. The steps will be discussed briefly in the next paragraph [15].

Diagnosis of Fault area

Power system faults lead to a significant rise in current and a drop in bus voltages across the fault area. Therefore the method proposed in [71] is used for identifying the faulted area by comparing the recorded values of positive sequence voltage magnitude. This is decided by determining the bus with a minimum voltage value that indicates the area nearest to the fault.

Finding Suspected Fault lines

In this method, the midpoints of transmission lines in the fault area are considered fault estimation points. When a fault occurs on the transmission line, the estimated fault midpoint will have the least value as calculated in [63]. The fault current in the estimated midpoint and actual fault point will have similar fault currents in both cases. There are numerous factors that provided errors in fault detection such as a short line connected to a long transmission line or a fault occurrence near the bus. A second level diagnosis is proposed by the author as shown in Figure 4.6.In the first stage, a transmission line is suspected to be faulty so a diagnosis is carried out again to determine the exact fault location and distance.

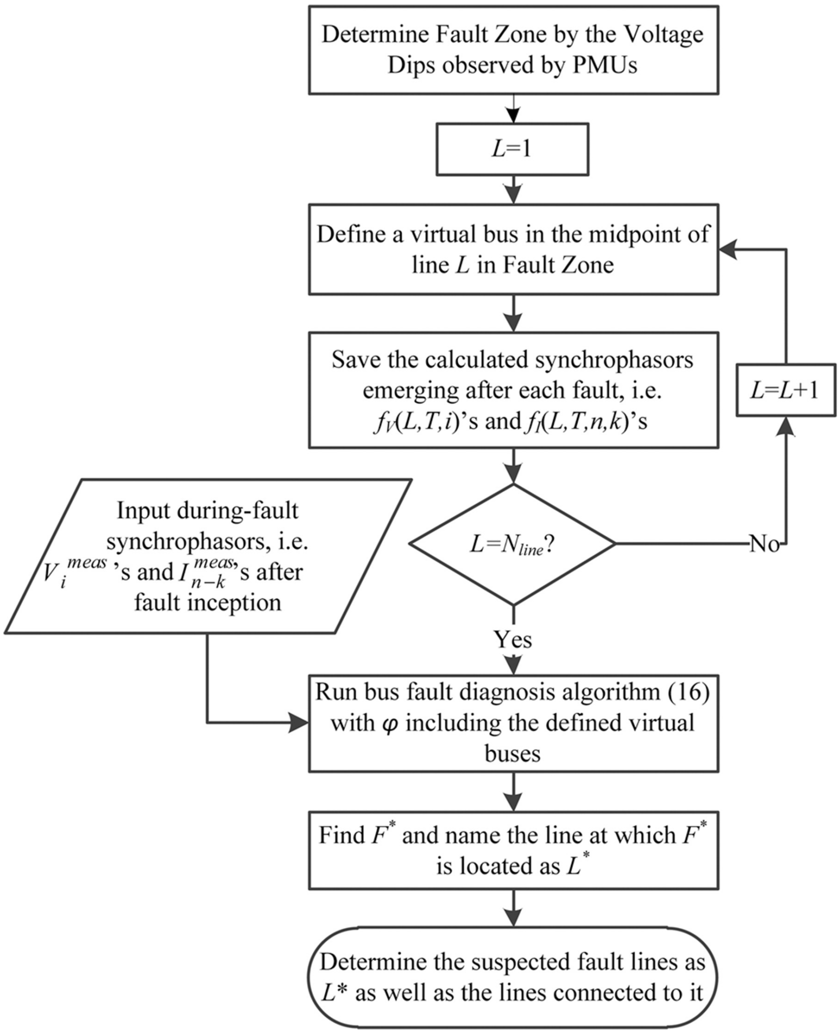

Figure 4.6: Proposed fault diagnosis to determine suspected fault lines[15]

Diagnosis fault location

An expected fault location is calculated in the first stage of the iteration in order to determine the fault. An iterative method of gradient descent has been utilized to locate the fault point. The initial value of fault is the midpoint of the expected fault point and gradient descent incorporates the injected fault bus in the impedance matrix by the algorithm in [72]. The focus of this research is not aimed at the protection system moreover focuses on the fault location and diagnosis. The computation time is minimum with respect to the limits of the protection standards. Hence, it can be implemented in the practice.

4.4. Conclusion

The focus of this chapter is Fault locators and their operation. An introduction to fault locators and their importance in the power system has been discussed. The methodology based on the Travelling wave, impedance, and PMU(Phasor Measurement Unit) for the accurate fault location on the transmission lines has been explained. The fault location is very important for both the operators and the power system so that the system can be restored back to normal operation without much delay and interruption. In order to speed up the fault locating, it involves step-wise Fault locators Operation i.e, Faulty area detection, faulty line detection, and distance estimation. The Wide area measurement system consisting of PMU(Phasor Measurement Unit) along with fast communication and GPS has proved to be one of the best technology for carrying out all three steps using the algorithm developed using current & voltages magnitude and angles. Hence it can be concluded that the fault locators' operation significantly accelerates the restoration process and also helps the maintenance worker to locate the distance easily.

5 Conclusion

The topic of this review is Smart protection solutions for future power systems. The concept of Smart grids is gaining attention with the many leaders and stakeholders ambitious about accelerating the energy transition. Globalization and demand have forced the traditional generation approach to evolve. In this decade, the portfolio of distributed generation has increased immensely due to the growth in demand. The changing portfolio has led to issues in the grid and the need for the development of a protection system for a secure and reliable power system.

The review is organized into several chapters covering different topics focusing on the need for Smart Protection solutions for future power systems. The first chapter discusses the emerging need for a reliable and smart power system in the future. It summarizes the difference between a classical and a futuristic power system. Concerns relating to phenomena that will occur due to distributed generation and its impact on the protection system of the grid that is available. Further, different protection solutions have been analyzed against the phenomena that take place due to the protection systems.

The second chapter explains different relaying protection systems that are currently available in the power system. Its working principle and applications on different voltage levels of the grid have been elaborated on in detail. The second half of the chapter is focused on the Grid forming and Grid following converters and the difference between the two types of converters. The two types of converters influence the short-circuit fault current contribution. As the fault characteristics of Inverter based converters are different from synchronous generators. It also impacts the protection pickup current settings and isolating the network leads to an overvoltage of the system.

The future power system will rely upon more network information to counteract the propagation of extreme events in the power systems. Synchrophasors based measurements have become very popular which helps in network monitoring and overall response of the grid. It processes information from remote and local substations as well and is further useful in post-morterm or finding solutions. Research has been conducted to develop smart protection based on synchrophasors and its other applications are voltage stability monitoring, and angle/Frequency monitoring. Also, network partitioning is a new concept introduced in the power system in advanced control, operations, and system protection. It is used for intentionally controlled islanding and determining coherent generators.

The most important is the Fault locators in the power system. It helps in faster restoration of the power system network. Determining the distance to the location of the fault on a transmission line helps the maintenance operator to fix the fault early. Due to the development of the network, the possibility of faults has increased eventually. Various algorithms have been developed based on impedance, traveling waves, and PMU(phasor measurement unit) to locate the distance to the fault. The fault locator's operation involves three steps i.e, faulty area identification, faulted line, and the distance to the fault location. PMU-based algorithms are very suited for carrying out the whole operation of fault locators. The information on voltage and current phasors helps in developing the algorithm. The application of PMU technology is very promising since it makes the protection advanced and controls the network effectively.

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