Tampere University

MD NURUNNABI EMON

MICROGRID PROTECTION

Master's Thesis
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ABSTRACT

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Designing an overall protection system for the installation of a microgrid is a major technological problem. For both grid-connected and islanded operation, the general specification like sensitivity, reliability, and selectivity must be met by the protection system. Different researchers have proposed different types of protection system for low and medium voltage microgrids. The traditional protective devices that rely on the overcurrent method cannot provide overall protection for the microgrid, so a new protection system is a must. According to the operational mode of microgrid the new protection system must be adaptable as well as sensitive so that it can identify and clear the smallest fault currents. This thesis's main objective is to review AC microgrids' protection issues, and present other available protection systems for AC microgrids developed and recommended. In this thesis, a substantial literature review on the protection and solution of AC microgrid is presented. The conventional microgrid protection challenges are presented, and also, the faults in grid-connected mode and islanded mode are discussed. The protection solution for grid-connected mode, islanded mode, and for both of them is presented. From the review, it is observed that an adaptive protection policy is the most suitable for a microgrid protection solution. The relay settings can be changed, and the necessary protection can be provided in an adaptive protection system with the topological and operational change. An adaptive protection system can solve the protection problem of the grid-connected and islanded mode operation. A communication system is needed for most of the adaptive protection systems in grid-connected and islanded operations, so communication enhancement is significant for the future microgrid.

Keywords: AC Microgrid, distributed energy resources, microgrid, protection issues, islanded mode, adaptive protection.

PREFACE

This thesis has been written to fulfill the graduation requirements of the degree Master of Science (Technology) at Tampere University. I would like to thank my supervisors for their support and suggestions during this process.

I am thankful to my family and my wife for staying beside me and supporting me. I also want to thank my wife for keeping me motivated when I lost interest. Thank you all for your unwavering support.

Tampere, December 2020

Md Nurunnabi Emon

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LIST OF SYMBOLS AND ABBREVIATIONS

CT	Current Transformers
DER	Distributed Energy Resources
DFT	Discrete Fourier Transform
DG	Distributed Generation
DMS	Distribution Management System
DNO	Distribution Network Operator
DSI	Demand Side integration
DSO	Distribution System Operator
EMM	Energy Management Module
EDGE	Electronically Coupled Distributed Generation
FC	Fuel Cells
FCL	Fault Current Limiter
FRT	Fault Ride Through
GPS	Global Positioning System
HIF	High Impedance Faults
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
LC	Load Controllers
LOM	Loss of Mains
LV	Low Voltage
MAS	Multi-Agent system
MC	Microsource Controller
MGCC	Microgrid Central Controller
MPPT	Maximum Power Point Tracking
MT	Micro Turbines
MV	Medium Voltage
OHL	Overhead Line
PCC	Point of Common Coupling
PCCM	Protection Coordination Module
PLC	Power Line Carrier
PMUs	Phasor Measurement Units
PV	Photovoltaics
RES	Renewable Energy Source
SM	Synchronous Machine
TCSC	Thyristor-Controlled Series Capacitor
THD	Total Harmonic Distortion
VSC	Voltage Source Converter
WT	Wind Turbine

1 Introduction

1.1 Background

The society where we live in is fully dependent on a continuous and reliable power supply. A significant amount of research work, attention, and implementation is going on to ensure fast, reliable, standard quality of power supply while on the other hand because of climate change issue investment and practical work is driven towards renewable energy sources. To develop, maintain, and renew the infrastructure a lot of investment is needed. But the energy industry after the Covid-19 crisis will be remarkably different from the energy industry which was before [1]. Already due to the pandemic the investment in energy fall by one-fifth in 2020. The International Energy Agency (IEA) estimates that over the period 2025-2030 the annual average energy investment will be $610 billion [2]. The next-generation electricity grid should be able to change with the need of society, technology, environment, and economy. Technology should also be dependable, cost-effective, and sustainable.

The technological advancement and incentives of the government helped to make significant combination of distributed energy resources (DER) with the traditional “passive” distribution system. The result was the development of an “active” distribution system [3] further evolved into a microgrid [4]. The European Technology Platform of Smart Grids describes the smart grid as “an electricity network that can intelligently integrate the actions of all users connected to it- generators, consumers and others that can play both roles in order to efficiently deliver sustainable, economic and secure electricity supplies”. The European smart grid project now includes 950 projects totalling around 5 billion of investment [5]. Huge advancement is happening at distribution level though the transmission system was always smart so now the distribution system also needs to be smart. That means the distributed system is transferring from passive to active so the decision and control system can be distributed, and the power can flow bidirectional. Such kind of network is helpful for the integration of RES, DG, DSI, and energy storage. Linking the power generation with the demand of the customer and allowing choosing the best option available is the primary function of an active distribution network. For the voltage control, power flow quality, and for the security advanced cost-effective technology is required and communication technology also plays an important role.

The implementation of an active distribution network requires the development of a new system concept, which can be Microgrid, and it is also characterized as the “Building blocks of smart grids”. Microgrid is regarded as a cluster of microsources consisting of a storage unit and to fulfill the local power requirements it operates like a single controllable unit. For the

DSO, the microgrid refers to a controllable cell of the power system network. However, the microgrid is an exceptionally configured system for the customer to ensure quality, efficient, and reliable power supply with the contribution of a system optimizer, distributed protection unit, and micro source controller [6]. A Microgrid can support the future power system in many ways and can be thought of from the outside as a single controllable unit. A Microgrid can be a platform for sharing energy between owners, it can also give support to the DSO in normal operation as well as fault situation, it can also be used as a balancing purpose for market operators or for the electricity producers.

For the practical implementation of the microgrid, one major technical challenge is to create a complete protection system. For grid-connected and islanded mode of operation, the primary protection requirements such as reliability, selectivity and sensitivity must be met by the protection plan. After the birth of the concept of microgrid many researchers proposed different kinds of protection plans for low voltage and medium voltage microgrids. The traditional protective devices which are mainly based on the overcurrent principal are inefficient to make sure of complete protection for a microgrid in both grid-connected and islanded mode of operation and then comes the necessity to develop new protection technique. So, the newly developed protection system should have the ability to adapt to the microgrid during both grid-connected mode and islanded mode of operation. It should also be sensitive so that it can identify and get rid of the minimum amount of fault current in the microgrid in a short time so that it can ensure the continuous supply of power to the customer. In case of a short circuit fault, if the microgrid remains unprotected, then the offered flexibility by the microgrid will be at risk. Various kinds of problems like a thermal limit violation of lines and transformers, local voltage rise, unintentional islanding can be caused by the integration of DERs. As the integration of DER reaches a certain level it also creates control, operational, and safety issues for low as well as medium voltage electrical systems, and the supply networks are not suitable for adding any kind of generation. So, a finely organized, maintained, controlled, and properly designed “Microgrid” can face the new challenges very well. The typically available distribution protective devices like recloser and fuse are not adequately suitable for the protection of microgrids for many reasons; one important reason is that they are dependent on the local current magnitude [7].

The centralized power grid short circuit limit can be higher than the microgrids small DER unit by more than one order of magnitude which makes the level of fault current different in the islanded mode of microgrid and macro grid connected mode. The settings and coordination of available protective devices become difficult and many times unattainable because of the higher differences. In order to organize the large group of interconnected systems as well as devices performing in the electricity network, proper standardization is also needed. In a smart grid, standardization is an essential component to achieve interoperability in the system.

The main objectives of this thesis are as follows:

- Literature review of the concept of microgrid in general and to study their control and properties.
- Finding out various types of faults in a microgrid in both grid-connected and islanded mode.
- Inverter based microgrid protection during island and grid-connected mode.
- This thesis aims to determine the possible protection solution for AC microgrid, which works in grid-connected mode, in islanded mode, and both grid-connected and islanded mode. And to find out the best possible solution.

1.2 Structure of the thesis

There are six chapters in this thesis, arranged below:

In chapter 1 an introduction to the thesis is provided. The primary objective of the thesis is presented in chapter 1.

Chapter 2 provides a broad overview of the microgrid concept. The chapter starts with the microgrid concept and types of the microgrid. Operation and control of microgrids are presented in this chapter.

In chapter 3, protection issues regarding microgrid, and the types of fault occur in grid-connected mode, and islanded mode are presented. Here the role of microgrid configuration in protection is discussed.

Chapter 4 focuses on the protection solution for AC microgrid in grid-connected mode, islanded mode, and for both grid-connected and islanded mode. The goal of this chapter was to discuss protection solutions and their advantages and limitations.

Chapter 5 concentrates on the adaptive protection system, categories of the adaptive protection system, and the adaptive protection system's advancement.

At last, chapter 6 concludes the entire thesis work.

1.3 Relation of microgrid with distributed generation

Over the past few decades, the expansion of distributed generation is happening very significantly. As many countries are trying to reduce greenhouse gas emissions and DGs can perform a role to accomplish this goal. Self-generation and reduction of energy cost, distribution cost, electricity tax, and value-added tax are key motivations for DG. The presence of DG makes microgrids possible, but first, there needs to be profitable DG, then the properties of microgrid might become possible. DGs are mostly situated at the distribution network at the medium voltage (MV) and high voltage (HV) level as well as low voltage (LV) level. The DG can bring benefits for the customer, distribution network operator (DNO), and for the DG owner also when it is allowed to operate during an islanded situation, as it is selling power at the time of main grid outage and the DG owner can get additional revenue. The microgeneration technologies like wind turbine (WT), fuel cells (FC), photovoltaics (PV), and micro-turbines (MT) can be directly combined with the low voltage network. Typically, these sources are located at the user site and they are becoming a very good option to meet the customer requirement and giving importance to the reliability and quality of power supply and also providing economic, technical, and environmental benefits. As the number of microgeneration integration increase in the power network, it faces new challenges and the effect of micro sources on balancing power and grid frequency becomes crucial. A management and control architecture is essential to obtain a proper combination of active load and microgeneration management.

Although the DG microgrid can provide numerous benefits its implementation needs to be considered. Protection challenge is a critical issue regarding the construction of a microgrid. After forming a microgrid, it is very important that the load, lines, and the DG on the island must be protected [8]. During grid-connected mode and islanded mode of operation, the DG should be provided with an islanding detection algorithm. Change may occur in the fault current in the islanded region and may result in misoperation to the currently available protective device [9]. Current sensing protective devices need minimum amount of current to operate but the inverter based DGs are unable to supply required short circuit current level [10]. If the microgrid protective relays are constructed for small fault currents, then it might result in nuisance tripping [11]. Protective devices must also be able to properly decide when a microgrid can function under the various faulty conditions and also for the secure operation of the microgrid required number of fault protection should be provided.

2 Control and management of microgrid

2.1 Theory of microgrid

2.1.1 Microgrid concept

Microgrids consists of low voltage distribution systems with distributed energy resources (DER) like fuel cells, micro-turbines, PVs, and storage equipment, i.e., batteries and energy capacitors, flywheels, and controllable loads [12]. Normally microgrid is considered as a low voltage distribution network situated in small places such as university campuses, buildings, industrial plants, districts, hospital complexes, business centers, etc. Maintaining the schedule and optimal functioning of a microgrid energy management system is essential. In the local distribution network, a microgrid can be considered an integration stage for demand resources (controllable loads), supply-side (microgeneration), and storage. Also, the microgrid concept aims to supply electricity to the nearly available customer. Generally, a microgrid is situated at the LV level. It can have a below MW range of microgeneration capacity, but the exception is for interconnection; some medium voltage network parts can belong to the microgrid.

A Microgrid can function in both grid-connected mode (normal state) and also in islanded mode (emergency state) [13]. During grid-connected operation mode, the main grid and the micro source sends power to the microgrid. The majority of the load's real power requirements are met by the DGs linked with the microgrid in grid-connected mode, and the rest of the portion and variation is met by the main grid [6] [14]. However, a generation or cutting the power (load shedding) is done to balance the power system in the islanded operation mode. To attain quality power the critical loads are made, and the rest of the loads are for the load shedding [6] [15]. In the future, a large number of the microgrid will function in grid-connected mode. And for a long period of island operation, a microgrid must be able to meet the storage size and capacity requirements of the microgeneration’s and for uninterrupted supply to all load, it also has to meet the demand flexibility. Microgrid and passive grid are different, and the difference is because of the coordination and management of available sources. Microgrid operator performs many functionalities like a network service provider or aggregator of a small generator or a controller of load or can be emission regulator and provide a technical, economic, and environmental benefit. Local utilities can be benefited from microgrid implementation as the system can be repaired without affecting customer load, stress will be lower for the distribution and transmission line, at peak hour condition dispatchable loads can be used. The stress can also increase if the microgrid behaves aggressively at different markets. A problem takes place when in a grid; all microgrids tend to follow market prices (consuming a lot during low price and generating more during high price). In this case, the microgrid behaves in a synchronized way, increasing the peak power in the grid. Independent users are also benefited from microgrid installation. Microgrids are slowly entering into commercialization phases by operating some pilot projects and experiments. Implementing microgrids on a large scale is difficult because storage technology is still expensive. After all, capital investment and pilot projects are also showing many challenges regarding the microgrid's control and operation. These challenges are because microgrid aims to improve power quality and reliability compared to grid connection only.

2.1.2 Types of microgrid

2.2 Formation and properties of microgrid

Classification of the microgrid can be based on the power type, supervisory control, supply phase, and application.

According to the power type, there is AC and DC microgrid. Based on the supervisory control, there are centralized and decentralized microgrids. In the case of operation mode, there are islanded and grid-connected microgrids. Depending on the phase there are single-phase and three-phase microgrids. Furthermore, based on the application, there are residential and municipality microgrids. The Figure 2.1 shows the classification of microgrid.

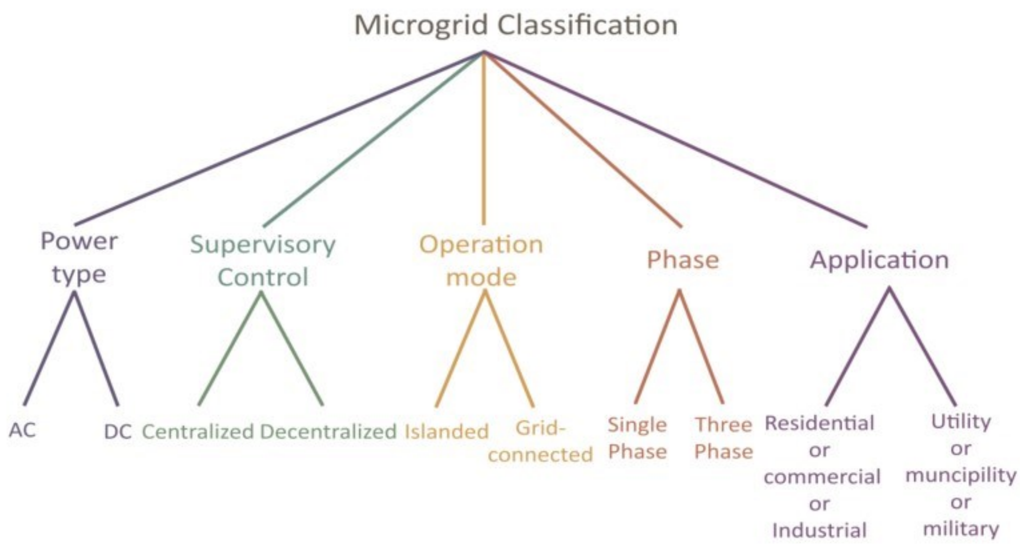

Figure 2.1 Microgrid classification

2.2.1 Microgrid component

There can be various forms of microgrids of different sizes and locations, but the main components are mostly the same. First comes the combination of Distributed Energy Resources, which is essential for microgrid operation. The DER unit can be rotating machine coupled or electronically coupled units. The categorization of the DER unit is important so that the interface medium can find out the characteristic of DER units concerning protection and control. An alternating/direct current voltage source converter supplies the interface medium among the microgrid and the source in the edge unit [16] [17]. The voltage source converter can be single-phase, or three-phase based on the capacity of power generation of the source. There are DG technologies that use voltage-sourced converter (VSC) couplings such as the type-4 wind turbine generator system, battery, solar photovoltaic system, and medium and high-speed gas turbine generator system. The electronically coupled distributed generation (EDGE) unit can be dispatchable as well as non-dispatchable. The maximum power point tracking (MPPT) strategy is necessary to operate and control the primary source of a non-dispatchable unit [18]. The second category of DG unit uses a rotating machine as a coupling medium. This category of DG consists of wind turbine generator unit of type 1 (that uses squirrel cage induction machines), wind turbine generator unit of type 3 (a doubly fed induction machine is used), diesel generator unit that uses field control Synchronous Machines (SMs) and conventional gas turbine generator units (using field control or permanent magnet SMs). Nearly all technologies use a power electronic interface to connect to the grid, which includes an AC/DC rectifier or DC/AC inverter and DC/AC inverter [19]. This converter's primary function is to do the conversion between DC and AC also; conversion between two ACs is also possible.

The second component is the physical layer, which is used to connect customer load, DER, and also the main grid. There are three main topologies such as radial, ring, and mesh configuration shown in Figure 2.2 [20]. There can be a difference between the actual topology and the structural topologies. The network configuration layout is applied based on the voltage level, source type, and geographical location. A radial connection is smooth and straightforward to establish. Moreover, for radial configuration, the most comfortable protection system is needed. The radial configuration is complicated than the ring configuration because it can provide different paths for current flowing, and advanced protection features are needed. The mesh configuration is the most complicated among the three topologies. Mesh configuration provides multiple connection points, and an extensive protection system is needed to provide a stable microgrid operation. Another important term is the point of common coupling (PCC) which refers to such a point where the main power grid network and the microgrid are connected. A microgrid interconnected to the distribution network via PCC: Mainly point of common coupling (PCC) is situated downstream of the main grid transformer and works as a borderline where a microgrid can be disconnected if needed.

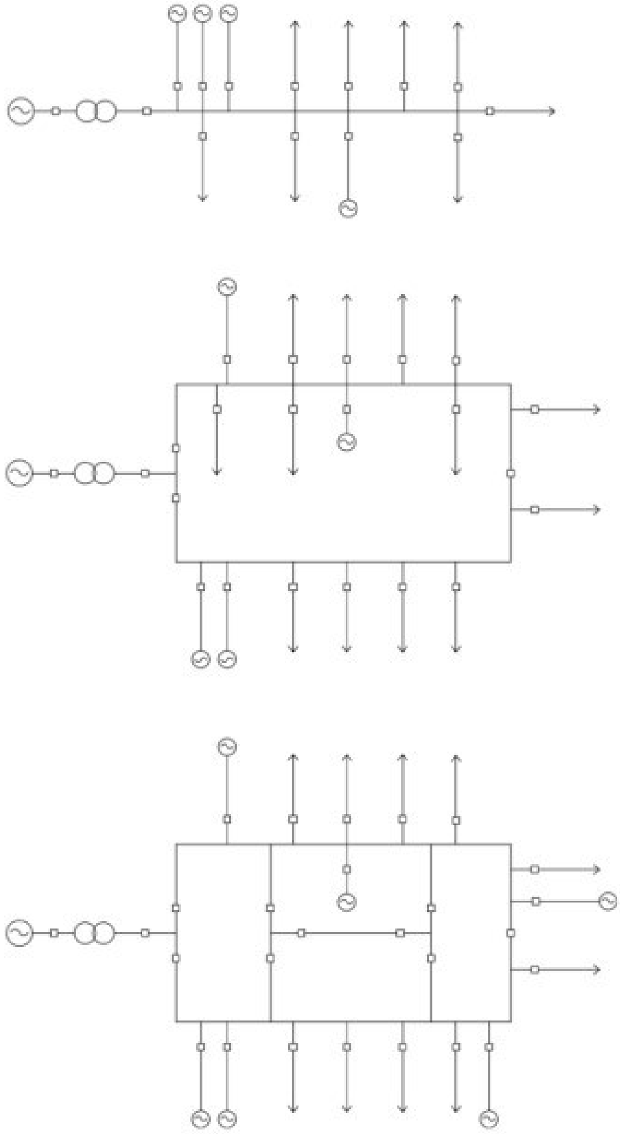

Figure 2.2 Radial, ring, and meshed network from top to bottom

2.2.2 Operation of microgrid

There exist two common microgrids operational mode. Firstly, is the grid-connected mode; in this mode, the Distributed Energy Resources (DER) is connected with the main grid. Second is the standalone mode which also refers to islanding or autonomous mode, where local loads can be feed without using the distribution network [21]. The two microgrid operational mode is described below [22]:

Grid-connected Mode: In the grid-connected mode, the microgrid (MG) is linked to the upstream network. A microgrid may gain energy from the main grid totally or partially which also depends on power-sharing. On the contrary, when there is more production than consumption, the excess quantity of power is sent back to the main power grid.

Island Mode: Sometimes the upstream network can encounter a fault, or intentional action can take place, such as in order to do grid maintenance, so in this kind of situation, microgrid operates in island mode. So, when a microgrid operates autonomously then it is called an islanded mode of operation.

Moreover, the microgrid operation may also depend on the conflicting interest of various stakeholders who are related to electricity supply such as the owners of DG, energy suppliers, DER operators, network/system operators, and also customer or regulatory bodies.

2.3 Microgrid control

In this part, the fundamental microgrid control principal is presented. The typical microgrid management system is shown in Figure 2.3 [20] . Settling the dispute among different stakeholders and making an excellent operational selection is an essential characteristic of the microgrid control. A new control level should be introduced locally at loads and DG so that it can provide the following benefits such as it should be scalable so that it can integrate a large number of users, it should be able to integrate component of various vendors, easy installation of new component and easy to use new functions and business cases. To achieve this goal a hierarchical system control architecture is introduced.

To manage and control storage devices a microsource controller (MC) plays an important role, distributed energy resources, loads, and also an electric vehicle. The microgrid source controller uses the power electronic interface of the micro source. In a microgrid, to monitor and control the frequency and voltage in transient situations, the MC uses local information. For various kinds of micro sources (fuel cell, PV, micro turbine, etc) the MCs have to be adapted. At the controllable loads, the local load controllers (LC) are installed to provide load control capabilities.

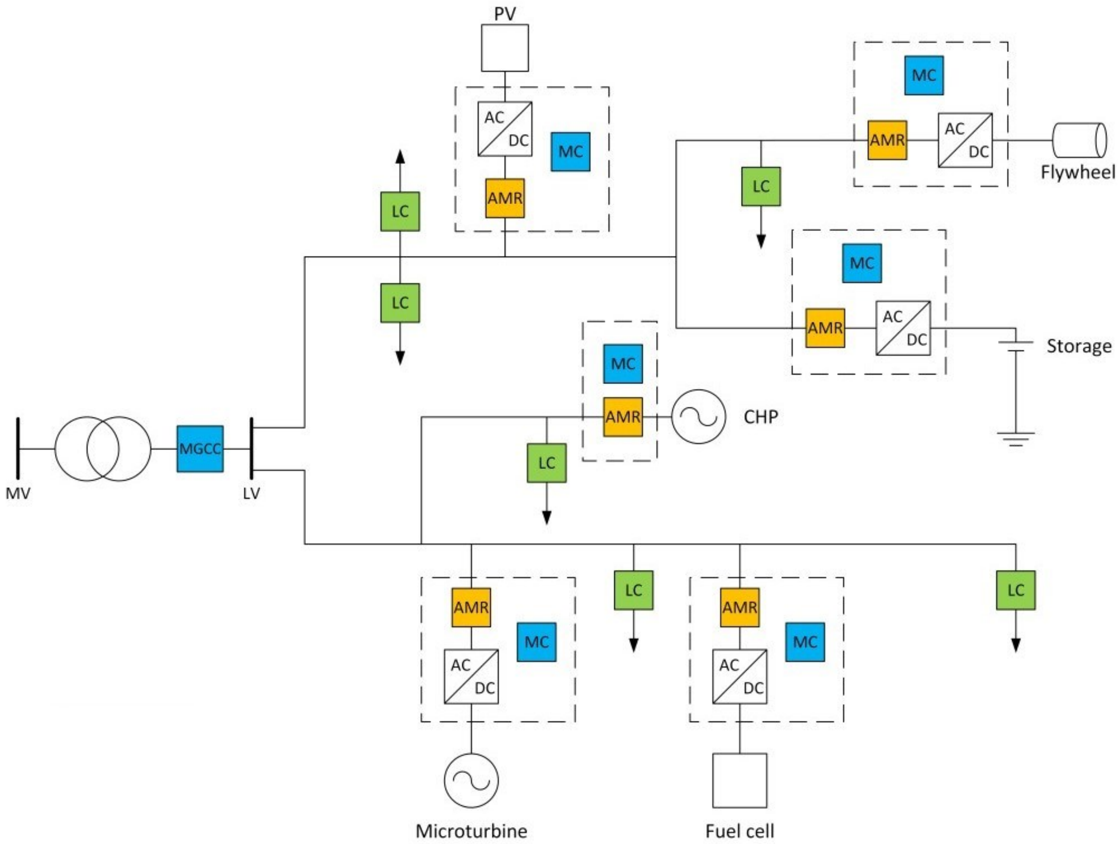

Figure 2.3 Microgrid control structure

In microgrid control, the microgrid central controller (MGCC) contribute a significant role. Interaction between a microgrid and other actors is possible because of MGCC. Most important of them are the local Distribution System Operator (DSO), energy market, and third-party aggregators. The MGCC can perform different roles for the entire microgrid starting from the microgrid value maximizing to the ordinary management of local MCs. For example, it can allocate set-point limit for MCs or it can manage or govern their function. [23].

Data is obtained from the microgrid AMR meters by the meter data management system (MDMS) of the DSO; it also passes on the measurements and alarms to the DMS and sends requests from DMS to the AMR meter. The distribution management system provides a self-healing, smart distribution system and it also helps to develop power quality, power reliability as well as efficiency.

The frequency, voltage, reactive, and active power are the variables that should be managed in a microgrid, and they also depend on the microgrid operational mode. The frequency and the voltage are managed by the main power grid when the microgrid operates in grid-connected mode. But in an islanded situation the microgrid controller is responsible to take care of not only frequency and voltage but also reactive and active power. These control procedures are performed with the assistance of either centralized or decentralized supervisory control. Both of the control strategies include (i) Market operator (MO), (ii) Microgrid Central Controller (MGCC), (iii) Local controller (LC) linked with (a) storage unit (b) load (LC_{load}) (c) DG units (LC_{DG}) [24]. The responsibility of LC_{load} is to make sure that the customer gets a continuous and reliable supply of power. The requirements of the generation of the microgrid are taken care of by the LC_{DG}. To look after multiple microgrid simultaneously, the Distribution Network Operator is used. In the next section, a detailed discussion on supervisory control is presented.

2.3.1 Centralized control

The microgrid central controller maintains a lookup table in the centralized supervisory control system. The lookup table information is updated after a defined interval with respect to present time condition of DG (ON/OFF), the type of DG, generation contribution of DG, at relay point the current and voltage level, operation mode (islanded or grid-connected mode), demand of the network (load).

The microgrid central controller consists of two essential modules they are Energy Management module and the Protection coordination module. In the grid-connected and islanded operational mode for the microgrid protection, the PCM is responsible. This module aims to identify islanding and measure the fault current. To secure and balance the microgrid and the main power grid, the PCM should implement suitable protection settings. As the microgrid network changes dynamically, therefore, an adaptive protection system is needed. Managing the frequency, voltage, and reactive and active power of the microgrid EMM is mainly responsible. Local Controllers (LC) obtains operating values from the EMM. In grid-connected mode, the central controller executes the following functions:

- Managing system parameters described above from load, bus, or DG unit whichever is essential for definite control.
- Plan economic production of reactive and active power of the DGs.
- Reliable as well as stable operation of the network with the main power grid is maintained.

In the islanded mode, the function of the central controller is:

- For the master DG unit, the control command for voltage and frequency is issued, and for the other functioning DG unit control command for real and reactive power is issued.

- A command is provided to the load controllers to separate the loads depending on the load criteria and backup reservoirs.

A substantial communication system is needed among the microgrid central controller and the local controller to establish a centralized supervisory control system, but it is not appropriate for a massive area. If the communication system encounters a fault, then the whole control network can fail [24].

2.3.2 Decentralized control

Implementing the centralized control principle is inappropriate in remote areas due to the long distance between the DGs. Additionally, a comprehensive communication link is needed, which makes it very expensive. The decentralized control principle can be a possible solution in such a case. The decentralized control principle connects more DGs in microgrids, and various service providers can own the DGs.

The Local Controller (LC) responsibility is much greater in a decentralized control system than in a centralized control system. Because of this, the load, as well as DG, have more freedom to operate. The decentralized control system hierarchical structure includes LC, MGCC, and DNO, similar to the centralized control system. The local controller's primary objective is to meet the demand by providing enough production and increasing the overall performance of the microgrid.

For sharing power, every inverter coupled DG units are managed freely. The main power grid manages the frequency and voltage of the microgrid during the grid-connected mode of operation. The DG is formed with the frequency droop features for sharing real power and for sharing reactive power voltage droop features. The aim is to provide the microgrid with reactive and real power in the case of grid-connected mode. The Figure 2.4 presents the characteristics curve of the droop of real and reactive power as $f = f_{max} - m(P - P_{max})$ and $V = V_{max} - n(Q - Q_{max})$ respectively. Here V_{max} and f_{max} represent the maximum voltage and frequency, respectively [24]. The voltage droop coefficient is n, and the frequency droop coefficient is m; on the contrary, the instantaneous value of real and reactive power is P and Q.

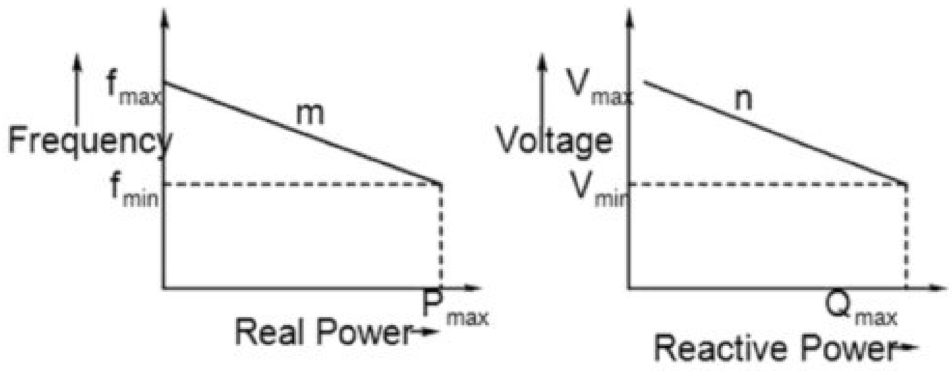

Figure 2.4 Droop curve of real and reactive power

One of the inverters fed DG's duty is to govern the microgrid's frequency and voltage in the islanded mode of operation. These DGs are recognized as the master unit, whose control strategy means to govern only frequency and voltage. The rest of the DG sources operate for balancing power with the reactive and real power droop characteristics. The MGCC provides information to the LC about how many loads need to be served and how many loads need to be disconnected. A fully decentralized control system has some limitations, such as the microgrid central controller (MGCC) is unaware of all the action executed by the LC as depending on the local information, its corresponding LC controls each unit. To get rid of this problem, a hybrid control system is needed in which the microgrid central controller rechecks the actions were taken by the local controllers to find out flaws in control. If the microgrid central controller identifies any lack of control, it provides the local controller with modified control commands.

2.4 Islanding operation of microgrid

Another demanding characteristic of a microgrid is the ability to function in both grid-connected mode and islanded mode. The process of islanding can take place by opening up the upstream switches located at the substation that links the main power grid and microgrid. This shifting can take place due to any kind of disturbance or some intentional reasons. There is some difference between intentional and unintentional islanding. In intentional islanding before the transition, the flow of active and reactive power among microgrid and main power grid is maintained nearly zero so as to keep balanced power inside the microgrid. The transition process is monitored by the microgrid management system actively. If inside the microgrid the power unbalance is small, then the existing control capacity, then only the transition to island operation is possible. The capacity includes control feedback of locally managed DER units, storage of energy strong enough to respond rapidly, and the manageable microgrid loads provided their separation can be made very quickly. So high speed communication among the components and management system can make the transition very easy [25]. In an islanding situation considering quality and safety issues microgrid should be capable to serve as many customers as possible. It should also keep the voltage and frequency in an acceptable range and ensure less load shedding. In an islanded mode the MGCC plays an important role to control and manage all the agents within the system. Some features of MGCC are highlighted, such as [26]:

- Restoring frequency as well as voltage in an islanded mode of operation.
- Determining the connection and separation protocol of the loads.
- Optimizing the function depending on the load profile, energy market price, and report of the weather.
- Management of purchasing and selling power.
- To provide a smooth islanding as well as reconnection process.

Based on the requirement set by DSO a microgrid can have three operational strategies in case of unintentional islanding [20].

Disconnection needed: the microgrid is assumed as an individual generation unit related to the main power grid and so it should be separated from the system to restrain energized islands in the main power grid as per the loss-of-mains protection system of generation units [20].

Disconnection possible: the operator of the microgrid can choose which action to apply. For example, they allow operating the loss-of-mains protection of the DG unit before separating the microgrid from the main grid.

Disconnection prohibited: the microgrid will support like normal generation units to the main power grid network in case of fault as per the predefined fault-ride-through requirements. A precise instruction of the power system is required for microgrid.

The breaker at the PCC or the interconnection switch operates to separate the microgrid from the rest of the network and when separated the microgrid adjusted to the fault for the time being. This situation increases the risk of islanding because the fault can simply jeopardize the balance of the microgrid after doing islanding.

Concerning the stability issue there are some very sensitive elements in the microgrid such as induction motors, induction generator, converters of converter-based DG units, and synchronous generator.

2.5 Microgrid resynchronization

The transformation of microgrid from interconnected mode to island mode of operation and vice versa will cause a huge discrepancy in generation and loads, giving rise to voltage and frequency variation [23]. A vigorous grid synchronization plan is needed to make sure that there is no occurrence of interruption in the loads, and the transition should be very smooth and transient free [27].

At microgrid PCC the re-synchronisation equipment should be taken into account so that microgrid can re-establish the connection with the main grid when the grid is ready to connect the disconnected loads of the microgrid. Depending on the system characteristics the re-synchronization and reconnection process can take several seconds to several minutes and can be done manually or automatically [6]. Different kinds of microgrid synchronization plan have been discussed in [28] , and active, passive, and open-transition transfer synchronization are three basic types.

The active and passive synchronization scheme is highly reliable when it is compared with the open-transition transfer synchronization. The active synchronization schemes are complicated as well as uneconomical. Besides passive synchronisation scheme is proposed by using switched capacitor banks and synchrocheck relays for a microgrid with converter based as well as directly coupled DERs [28]. After microgrid islanding, if switched capacitor banks are used to balance the voltage, the result can be slow re-synchronization. For complicated microgrid structure, an automated re-synchronization system incorporated through a microgrid central controller utilizing a communication system is recommended [29].

3 Microgrid protection

3.1 Protection challenges in microgrid

For a large-scale implementation of a microgrid, a major technical problem is to design its protection system. To maintain a reliable, safe, and secure operation of the power system overall protective devices are required which have better flexibility, simplicity, fast operation, selectivity, sensitivity, reliability, various setting opportunities, and low prices must be selected. If there occurs a fault in the main grid or in the microgrid then the protection system should respond to prevent damage to devices and human. In general, there can be two sections for the microgrid protection problem. One is the protection problem in grid-connected mode, and the other one is the protection problem in islanded mode. There are isolation devices (circuit breaker) of microgrid at the point of common coupling, and the protection problems are related to the reaction time of these isolation devices in the grid-connected mode for faults in microgrid and the main power grid. The reaction time of the protective apparatus situated in the microgrid (DER protection and line protection) for faults in the microgrid during grid-connected mode is also considered. The response time of the protective device (DER protection and line protection) installed in the microgrid for faults occurring in the microgrid is also considered, and it relies on the complication in the microgrid during the islanded operation mode. In the islanded mode of operation, the reduced short circuit current level is a major issue because the overcurrent protection device may not function. If the overcurrent protection device operates, then they need more time to operate (seconds needed for operation) [29] [6].

The conventional protection plan outlined for radial flow with high fault current for distribution system will not function satisfactorily to a microgrid as required owing to dynamic characteristics of DGs, bidirectional power flow, sporadic behaviour of the DG, and deviation in fault current [24]. In microgrid protection the major challenges are [30]. In the next chapters 3.1.1, 3.1.2, 3.1.3 and 3.1.4 the challenges are described in detail.

- Dynamics in fault current level
- Loss of Mains (LOM)
- Spurious separation or false tripping
- Blinding protection

3.1.1 Dynamics in fault current level

The DGs connected in the LV network changes the level of fault current to a significant level mostly due to two main mode of operation they are grid-connected mode and islanded mode of operation. The fault current will be very high in the grid-connected mode because the main power grid and the DGs present in the microgrid contribute to the fault current. However, in the islanded mode of operation, the fault current level is very low as the available source feeding the fault current in the microgrid is the DGs with low ability.

Besides, the fault current contribution by the DGs differs according to various types of DGs. The contribution of fault current by synchronous type of DG is five times the rated current, and the inverter-based DG contribute 1.5 times the rated current [31]. The dynamics in fault current level is shown in Figure 3.1 [32] . In the figure, there are two DGs denoted as G1 and G2. When a fault takes place, then the fault currents I_{Gf}, I_{g1f}, and I_{g2f} will be contributed by the main grid, G1, and G2, respectively. So, the fault current will be the summation of $I_f = I_{Gf} + I_{g1f} + I_{g2f}$. So, this is basically the one scenario when this is a grid-connected mode of operation. Now the grid is disconnected from the rest of the network due to the opening of the circuit breaker, which means these two DGs are disconnected from the main grid. So, in this case, the fault current I_f will be the summation of the two current I_{g1f} and I_{g2f}. So, during a fault, the fault current level changes based on the different modes of operation and network configuration.

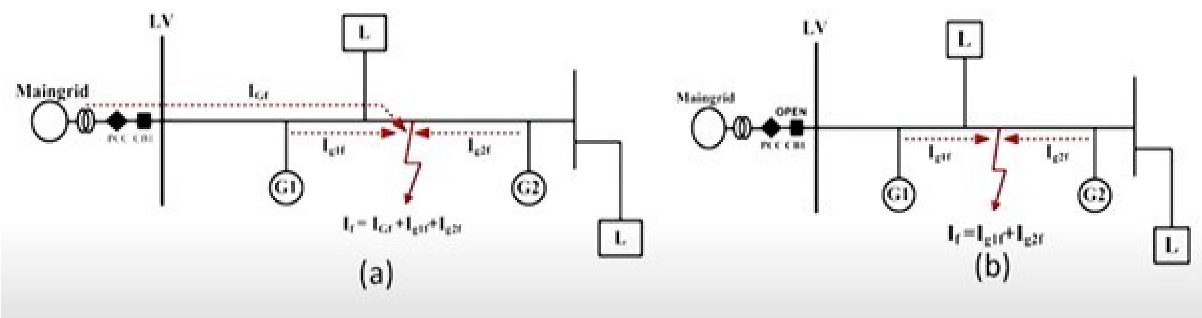

Figure 3.1. *Magnitude of fault current (a) During grid connected (b)Islanded mode*

The DGs which are based on the renewable source is very sporadic in nature, and they only contribute to the fault when they are in ON condition. So, the level of the fault current keeps changing time to time depending on the type of DGs, number of DGs, and on the mode of operation. Therefore, it is very tough to anticipate the fault current precisely [33].

3.1.2 Loss of Mains (LOM)

Loss-of-mains protection scheme of DERs is another important factor for islanded mode of operation. But when the anti-islanding protection is remained turned on, then there is a possibility of having uncontrolled islands in the microgrid because of its fast tripping. So, whenever there is a possibility of forming an isolated microgrid it is sensible to immediately deactivate anti-islanding protection, for this the DERs should have the fault ride-through FRT capability to deal with the frequency and voltage transients created by the islanding [29] [34]. To turn off the anti-islanding protection of DERs, the most dependable and quick technique according to [29], is to provide a trip blocking signal via microgrid central controller with the help of a communication link. However, the trip message will disconnect the DER units, so in this case, block messages can be sent, which will deactivate the LOM protection device. For a balanced operation of a microgrid it is necessary to have a rapid and reliable method to detect islanding. Usually, the islanding detection methods are divided into three sections: Active, passive, and telecom-based [35]. Different types of active and passive loss-of-mains identification methods are presented in [36] [37] [38]. Passive islanding methods are more favoured than active methods because of the aspects like reliability, speed, and power quality. On the other side, telecom-based principal is complicated and uneconomical than passive methods. Although depending on electrical quantities like frequency and voltage, there are some passive islanding detection methods, but they may be unable or can take much longer time to identify islanding if in a microgrid generation and loads become equal [35] [39]. To overcome this problem an alternative passive islanding detection method is proposed in [39]. This method depends on the pattern recognition approach for the extracted voltage, and current transient signals (at Dg terminals) originated during the separation of the main grid. The discrete wavelet-transform and classification strategy (decision-tree (DT) classifier) is used by this method to obtain voltage and current signal energies in the different bands of frequencies. When the value of the detail coefficient goes over the set value then to activate the classifier after a delay of 0.01 seconds, the transient detector is used. This suggested technique has been differentiated with different kinds of passive methods in [35]. For different kinds of islanding situation and DG types, the reaction time of the advised relay is (30-48) milliseconds. But high fluctuation in current and voltage signal can stimulate a decrease in the performance of the proposed relay and also there is no clear declaration about the setting of the threshold value. For Loss-of-Mains detection at either side of PCC, the application of synchronized phasor measurements using global positioning system (GPS) as well as phasor measurement units (PMUs) is mentioned in [36]. This scheme is unprofitable because of the high capital cost of the PMUs [36]. However, there is a probability of loss of GPS signal or deterioration, which can cause clock drift, making PMUs inaccurate less reliable, so PMUs with back-up functionality is needed [40].

3.1.3 Spurious separation or false tripping

False tripping or spurious separation can take place owing to the failure of the PCC device as they cannot distinguish the accurate place of the fault whether the fault is located within the microgrid or on the main power grid side. The issue arises when a DER present in a healthy feeder contributes to a fault occurring on an adjoining feeder. The false tripping in microgrid is shown in Figure 3.2 [32]. The reason behind the spurious separation is not only the breakers and low-priced electromechanical relays but also the complicated microprocessor-based protective equipment, which only works on data present at PCC.

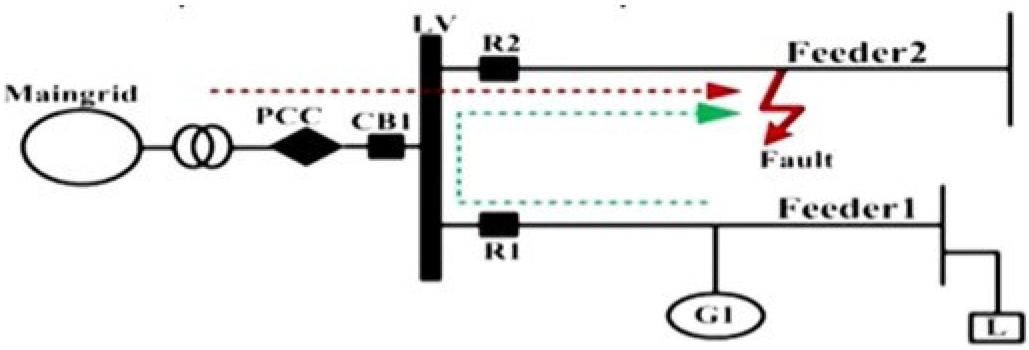

Figure 3.2. False tripping in microgrid

When fault current contribution of the distributed generator G1 exceeds the current setting, then relay1 (R1) will be tripped before the function of faulted feeder relay2 (R2). As a result, the unnecessary power interruption will occur for loads connected to the healthy feeder1. To provide rapid tripping of PCC breaker and to avoid false tripping, a reliable principle is the transfer trip from the main grid substation breaker. If the microgrid is capable enough to get back to its normal operation after separation, then the effect of the spurious separation is very less on the microgrid and main grid operations. Because of spurious separation cost increases as the operation of PCC device increases but its lifetime decreases, and more labour is needed to restore normal operation. Due to false tripping, microgrid faces several problems such as an imbalance in power quality, inappropriate interruption to non-priority loads (detached due to islanding), loss of profit, and duration of over frequency function for exporting microgrid [29] [6].

3.1.4 Blinding protection

When a fault takes place at the lower end of the feeder in a microgrid then not only the main power grid but also the DG contribute to the fault current. At the faulted point, the Thevenin's impedance increases then the traditional network because of the impedance offered by DG. The blinding protection in microgrid is shown in the Figure 3.3 [32].

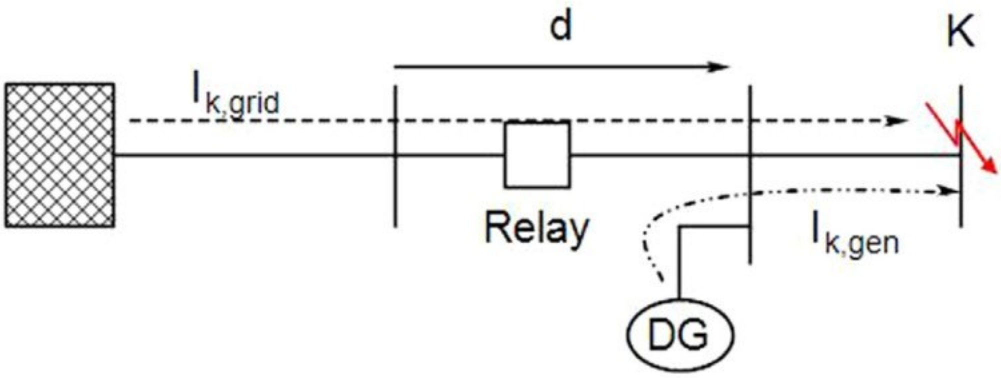

Figure 3.3. Blinding of protection in microgrid

In the figure Figure 3.3, the distance is d, after which a DG is linked. The maximum fault current in the individual phase for a fault is

$$I_k = \frac{V_{th}}{\sqrt{3}\, Z_{th}} \,, \tag{1}$$

Here V_{th} = the pre-fault voltage at the faulted point and Z_{th} = Thevenin's impedance

If Z_g= impedance of DG, Z_s= impedance of main grid source, and Z_L = transmission line impedance then the thevenin's equivalent circuit of the network can be presented as Figure 3.4. Thevenin's impedance is

$$Z_{th} = \frac{(Z_s + l.Z_L).Z_g}{(Z_s + l.Z_L + Z_g)} + (1 - l)\, Z_L \,, \tag{2}$$

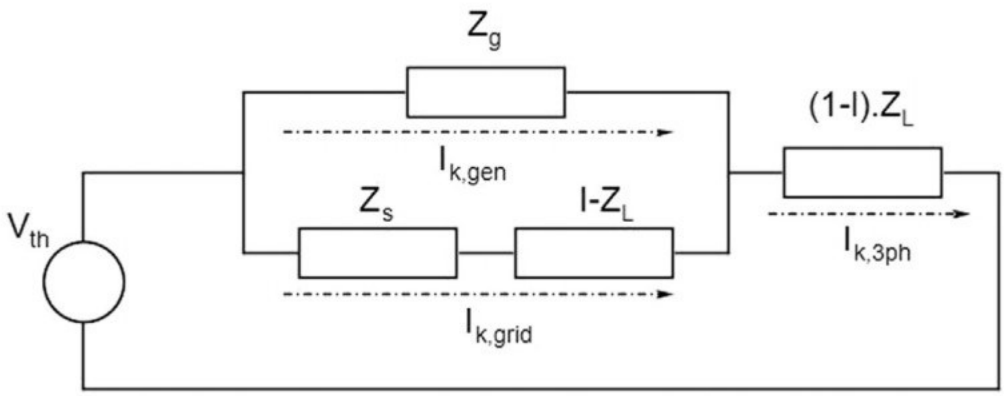

Figure 3.4 Thevenin's equivalent circuit

Therefore, the thevenin's impedance at the fault location rises owing to the impedance contributed by DG.

The main grid contribution to the fault current is

$$I_{grid} = \frac{Z_g}{(Z_s + l.Z_L) + Z_g} . I_K \ , \tag{3}$$

The fault current contributed by the main grid is nonlinear with the size and location of DG [24]. The grid impedance will be equivalently large as the DG impedance for a fault at the lower end of a feeder; thus, the short circuit current will be below the pickup current in the LV network. For this situation, the relay is unable to detect a fault, and the whole protection system can malfunction.

3.2 Protection switch & device selection

The selection of the protective equipment relies on the desired level of voltage, operational speed, and also on the presence of fault current. The protective device can be moulded case circuit breaker or can be a high-speed solid-state switch. The requirement of the microgrid PCC switch (breaker) reaction speed against a fault on both sides of the main grid transformer mostly relies on the sensitivity of the load attached with the microgrid [29] [6]. The microgrid loses its stability owing to a fault within the microgrid or on the main grid, and so the high-speed protective device is needed when the directly coupled DGs are linked with the microgrid because they are susceptible to voltage dips because of the fault and can jeopardize the stability of the microgrid [41].

3.3 Grid-connected mode faults

In normal operation when a fault occurs at the main grid, the duty of the protective devices of individual DERs (anti-islanding protection) is not to trip before the PCC protection device trips and DERs should carry on its operation while the PCC device performs its sensing and switching. All DERs should have fault ride through (FRT) capability to authorize this [34]. In normal operation, during a fault within a microgrid the responsibility of feeder/line protection is to disconnect the faulty part from the entire system as soon as possible and the process is based on the features and complexity of microgrid and used protection strategy [42]. Non-fault cases can take place which may result in low voltage at PCC such as unbalance of voltage and non-fault open phases this is hard to identify and can probably create risk for sensitive loads, microsources, etc. To avoid such kind of situation some protection mechanism must be developed [29].

3.4 Faults in islanded mode of operation

In the islanded mode of operation, the character of problems turns out to be entirely different from the grid-connected mode. To trigger traditional overcurrent protection equipment's higher magnitudes (10 to 15 times the full load current) of fault current are supplied by the main grid in the grid-connected mode. But on the other hand, in the islanded mode of operation, the fault current of about 5 times the full load current is available [29]. If the microgrid is connected to a substantial number of converter based DERs then the fault currents of only 2-3 times of the full load current (or maybe less based on the control method of the converter [43]) are available [44]. The traditional overcurrent protection devices are mainly programmed to operate at 2-10 times the full load current. Therefore because of the radical decrease of fault level, there occurs a disturbance in the time current coordination of OC protective equipment's; the overcurrent devices which have highly inverse characteristics such as fuse and the high-set instantaneous overcurrent devices are mainly affected.

3.5 Duty of microgrid architecture in protection

The formation of the microgrid can change owing to several types of control operation such as load-shedding when needed or an increase in local production for exporting power to the grid for flawless and economical operation. With the change in microgrid configuration to change the protection relay settings, an adaptive protection system is needed. With the adaptive protection system, both centralized and decentralized control operations can be executed, but both of them need a separate communication structure. For the adaptive protection technique, the centralized control structure is the standard method. A central controller is responsible for managing the protection settings. If the central controller fails, then there will be a loss of adaptive protection settings. The centralized communication structure supports different types of information exchange protocol such as DNP3, IEC 60870-5-101/104, Modbus, IEC 61850. The decentralized control system is based on the information interchange among distributed intelligent electronic devices (IEDs). The IEDs operate independently when they acquire information from another IED about changing the active setting. Currently, IEC 61850 is used as a standard protocol for the decentralized communication. An ethernet network or bus is needed for the establishment of decentralized communication but it can also be established with the help of PLC or with 4G wireless network [23]. Although the conventional single setting microgrid protection devices are providing safe and sound functioning of microgrid in both islanded and grid connected mode of operation, but the previous research analysis tells that these protective devices are unsuited for microgrid protection principles. Therefore, an alternate method for fault identification and isolation has become compulsory which can operate evenly for both grid-connected and islanded mode of operation and so the protection scheme should be adaptable [29] [42] [45] [46]. The new protection system should be able to deal with the reduction of the fault level and also the possibility of bidirectional current flow in some feeders [29]. Also, communication links should be used by the new protection system to provide swift and steady operation.

4 Microgrid protection scheme

4.1 Grid-Connected mode protection scheme

There are various types of protection schemes recommended to be used in a microgrid operation system. Usually, there are mainly three types of classification: some schemes are formulated for the grid-connected mode of operation, some schemes are only for the islanded mode of operation. and some are designed for both grid-connected and islanded mode of operation.

To minimize high fault clearing times and to widen up DG connections to MV distribution network, a protection coordination system is presented which relay on over current principal and time-dependent characteristics of current [47]. Because of this approach, it is possible to operate a closed-loop network with converter-based DGs (C-DGs) and large-scale radial networks with directly coupled DGs (D-DGs). If there is a large number of relays, then this scheme is very efficient but uncertain for high impedance faults (HIF). For the MV feeder, an adaptive overcurrent pickup system with C-DGs and radial overhead line (OHL) is recommended in [48]. By analysing the fault of the system this scheme refurbishes the OC relay minimum pick-up current. If there are some disconnected DGs in the network, then this scheme is more effective. A protection technique is proposed, which uses traditional OC relays with definite time grading for an LV microgrid with both D-DGs and C-DGs connected to OHL and cable networks [49]. The above protection technique is inexpensive because there is no need for communication, and without changing the existing protection scheme, it can be used. Another protection scheme based on an intelligent agent for both radial OHL distribution system connected with DG and closed-loop system disconnected from DG is presented in [50]. Between the IEDs peer to peer, communication takes place in this scheme. Extremely fast speed of backup protection is provided by this scheme than the traditional protection system, modification of parameter and monitoring system automatically but it needs the high speed of communication. To reduce the fault current supplied by DG during an event the fault current limiter (FCL) is connected in series with the DG unit and thus the system can return to its original condition as if there was no DG connected to the system, and this scheme is proposed in [51] [52]. Hence without separating the DG, the initial OC relay settings can be used. The thyristor-controlled series capacitor TCSC, has been used as an FCL in [53]. There are many benefits of FCLs such as using initial relay settings, no separation of DG, prevention of modification of equipment for dealing with large current. But the cost rises as with the increase of the capacity of each DG the impedance of FCL also increases. On the other hand, the transient response of FCL is another topic to be taken care of. Protection system for the islanded mode and protection system for both the islanded and grid-connected mode is presented in the next few sections briefly, and also their summary is presented accordingly in Table 1 and Table 2 .

4.2 Islanded mode protection scheme

4.2.1 Protection based on THD

In the case of an islanded microgrid by observing the harmonic content of C-DGs a protection scheme is proposed in [54]. Discrete Fourier Transform (DFT) calculation is used in this protection system, and at each DG unit, it monitors the harmonic distortion (THD) of the inverter terminal phase voltage resulting in separation when the THD overshoot the set pick-up value. The main grid distribution network performs as a low impedance in normal operating conditions and at the inverter terminal, low THD of voltage is maintained by the voltage source. During the transition of the microgrid to islanded mode, since only the load and local network stay connected the impedance at the terminal rises, at the inverter output current harmonics will give rise to voltage harmonics in the terminal voltage [54]. There are two-part of the proposed scheme. In the first part to determine the fault type the magnitude of the fundamental frequency of each phase is put in use. Simulation results shows that in a faulted phase the fundamental frequency amplitude will drop remarkably compared to the healthy phase and this differentiation helps to detect single phase, phase to phase, and three-phase fault. In the second part, the THD values of all phases is compared to determine the faulted phase, as the faulted phase will have higher harmonic content and the healthy phase will have a lower harmonic content. To govern tripping the THD values needed to be shared among the DGs and therefore a communication link is needed. The relay which has the highest harmonic content is considered situated in or near the fault zone and it should be tripped. The simulation result was for two uniform converters based DGs and the author mentioned that if there are two different DGs then theoretically the concept will be effective but another type of protection may need to be used if any one of the DGs has zero harmonics distortion. Trip failure may result because of the existence of various dynamic loads in a microgrid and the plan is recommended as supporting or backup for the main protective devices [54]. But there is some limitation such as complexity in assessing THD threshold value for various types of fault and also sensitivity issues with varying fault impedances [55].

4.2.2 Protection based on voltage

For the islanded microgrid with converter based DGs, a voltage-based protection system is presented in [56]. This protection scheme is dependent on calculating and converting the DG output voltages to DC quantities in the synchronous rotating d-q frame of reference based on the dq0 or Park transformation [57]. Disruption in the d-q quantities can be recorded as a network fault. Disturbance signal V_{DIST} is computed and a comparison is done between the measured and references three-phase balanced d-q values to filter out a value. The calculated values match the reference values in normal condition and the disturbance signal V_{DIST} value is zero. When a fault happens based on the type of fault, the disturbance voltage shows different behaviours.

V_{DIST} is absolutely DC voltage, in case of a three-phase fault, V_{DIST} includes a DC signal with ac ripple in case of a two-phase fault, V_{DIST} will be a fluctuating signal between the maximum and a zero value. So, the type of fault can be detected. A communication link is used among the relays in this protection scheme to compare the mean average value of the disturbance signal. This information helps to detect inside the zone and out of the zone faults and trips the correct relay. Simulation is performed at different locations for different faults in a test microgrid to verify the protection scheme and is recommended to serve complimentary protection to traditional OC relaying in low fault current conditions [56]. The sag of voltage is considered by enduring the voltage amplitudes of 50% for 200 ms, 70% for 0.5 s, and 80% for 1 s. But in a microgrid, the voltage drop can still be a cause of misoperation [58]. But the designated FRT for the system sets the boundary necessary for voltage sag tolerance and also clarify exact operation. Some other limitations are the disability to identify high impedance faults (HIF)and relying on a specific microgrid configuration, which has a test outcome. In a review of AC microgrid protection solutions, the authors mentioned that the single-pole tripping and the high impedance faults (HIF) are not taken care of [55].

Table 1. Only islanded mode protection system

	Protection system	Applied principle/functions	Faults	Benefits/restrictions
I.	Protection system based on harmonic content [54]	Frequency and THD measurement of converter voltages, communication link among relays	LLG	For various fault type it is problematic to evaluate THD threshold values, relays may fail to trip if more dynamic loads are linked or if few DGs with pure voltage output, problems regarding sensitivity with different fault impedances
II.	Protection based on voltage [56]	abc-dq0 transformation of DGs output voltages and communication network among relays	LLL, LL, LG	High impedance faults and single-pole tripping are not taken into account, tripping decision relies on the communication link
III.	Residual current and symmetrical component-based scheme [59]	OC relays, at PCC static switch PCC, zoning method	LG, LL	Communication link is not needed, and overall protection is provided for LL and LG faults. But three phases, tripping of single pole and high impedance faults is not taken into account
IV.	Adaptive protection scheme [34]	IEDs (current, voltage, directional OC measurements with interlocking), zoning, high speed communication network.	-	Very much dependent on communication system and adaptable to microgrid mode of operation, simulation results for specific fault types are not discussed

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4.2.3 Residual current and symmetrical component-based protection

Depending on the method of residual current and symmetrical component for the microgrid islanded operation, a protection scheme is presented in [59]. In this method, the term differential current is employed, and the technique is the same as common residual current devices. Residual current devices are used as the primary protection of LG faults for the territory upstream the faults and zero sequences current as of the primary protection of LG faults for the territory downstream the fault. In the case of LL faults, the negative sequence current is used as the main protection system. For the LG and LL faults, the I^2t protection is used as the main backup protection, and as the secondary protection under-voltage is used if I^2t fails because of inadequate current levels [55].

4.2.4 Adaptive protection scheme

Depending on telecommunication technologies and the latest protection relays or IEDs, an adaptive protection system for a microgrid with C-DGs is presented in [34]. This protection principle is applied to an MV feeder split into four protection zone, and a circuit breaker is connected in the middle of each zone, which is coordinated by an IED. The DGs are also connected with IEDs. High-speed communication is used to connect all the IEDs. Information related to voltage, current measurement, and directional OC protection functions is provided to the IEDs. In the proposed method to determine a fault, voltage measurement is used, and the current direction is used for determining fault location. The selectivity and speed of the whole system is achieved through fault direction alteration and interlocking information among IEDs with the help of communication depending on IEC 61850.

4.3 Grid and islanded mode protection scheme

4.3.1 Adaptive protection scheme

Depending on the method of network zoning an adaptive protection scheme is presented in [60]. In this method Suitable balance is maintained when zoning the feeders like maintaining the balance of DG and load with DG capacity a bit larger than load. The biggest DG is provided with the load frequency control ability in each zone. Right after the zoning, few rapidly operating switches are installed between each of the two zones which are provided with synchronization-check relays and they have the ability to obtain remote signals from the sub-station breaker. A computer/based relay having a large storage capacity, better processing power, and ability to communicate with DG relays and zone breaker is installed at the subtransmission sub-station. The duty of the relay is to identify fault through online and has to isolate the faulted area by tripping the correct zone breaker as well as DG related to the zone. A system which has the low DG penetration is not appropriate with this scheme and the scheme mainly relay on centralized relay and communication links. But this scheme is expensive because of the necessity of continuous measurements of synchronised current at every DG site and circuit breaker using PMU and GPS.

An adaptive protection system is proposed in [61] by applying numerical directional OC relays with directional interlocking ability for microgrid with both D-DGs and C-DGs. This system is dependent on the microgrid central controller and it updates the protection settings with respect to the operational mode of the microgrid with the help of an enhanced communication link providing fast tripping.

By using a wavelet transform method a multi-agent-based protection system for the distribution system with DGs is presented in [62]. The network is divided into various sections and at interconnection points among these sections, relay agents are positioned. The relay agents communicate with the neighbouring agents which helps them to detect and isolate the fault. At the interconnected branch, current transformer (CTs) is located, and they can calculate the current leaving the node and sends a feedback signal which determines the faulted zone. From the transient currents, the wavelet transform coefficients are computed. A fault can be detected as external or internal by the wavelet transform coefficients sign. The fault is considered as an internal fault if the wavelet transform coefficients of the currents calculated at all positions have a uniform sign, if they are different then it is an external fault. When a fault is recognized by a relay agent on its bus bar, then to clear the fault, all circuit breaker related to the bus bar is tripped, and other relays get the message as well. For MV smart grid a new adaptive protection system is presented which is dependent on a multi-agent approach [63]. Multi-agent refers to a cluster of software and hardware agent scattered in the network, and they also operate together to obtain a universal goal. The suggested method is dependent on distributed intelligence, but it is possible to make it adaptable via centralized intelligence.

In [64], a differentiation is made between distance protection and directional overcurrent protection using PSCAD simulation. It proposes that distance protection functions better than directional overcurrent protection. but it has certain limitations in some use cases. But each of these schemes can be improved with adaptivity as because adaptivity can integrate very nicely with other protection schemes and also with the technique. So, for the grid-connected mode, an adaptive protection system dependent on directional OC protection is suggested and for islanded mode, adaptive protection based on distance protection is proposed.

4.3.2 Differential protection scheme

A protection scheme dependent on differential protection is proposed in [65]. This protection system uses communication assisted digital relays which works on the method of synchronised phasor measurements for MV microgrids integrated with both C-DGs and D-DGs. For the primary protection system, an instantaneous differential protection system is used. If the breaker fails, then as a backup protection adjacent relays are used. But if there is a failure in the relay or communication then comparative voltage protection is used as a tertiary protection system. This scheme has also the ability to detect HIF. It is noted that the proposed scheme is not economical to establish and needs modern technical features such as better relay and breaker performances. In [55] [66] it is noted in the literature review that this scheme is expensive and needed beyond state-of-the-art high-tech equipment like very sensitive and without error current transformers (CTs). Besides, it is noted in [58] that the differential protection scheme may face problems because of the unbalanced systems and transients during connection and disconnection of DG units. A relay and sensor placement optimization algorithm is proposed in [67] which can lower the equipment expense and system disruption. And this scheme can save expenses almost 50% in sensor and relay compared to the scheme in [65]. Depending on the theory of differential current and using conventional OC relays as well as communication, a protection scheme is proposed in [65] for MV microgrids consisting of both D-DGs and C-DGs. The proposed scheme is not suitable for an unbalanced load, but it offers economical benefits.

In [68] a differential protection system is proposed as the main protection for MV microgrid with C-DGs as well as closed-loop OHL in case of the grid-connected and islanded mode of operation. If there is a breaker or communication link failure, then as a backup, this method uses OC and under-voltage-based protection. For the feeder and bus protection, current differential relays are used and the DGs are protected with the help of reverse power flow, over-voltage, under-voltage, and synchronism check relays. Because of the unbalanced load and switching transients, this protection scheme may also face problems.

Table 2 Grid connected and islanded mode protection system

No.	Protection system	Applied principle/functions	Faults	Benefits/restrictions
I.	Adaptive directional overcurrent protection [61]	Consists of Inverse-time admittance- based protection scheme	LLL, LL, LG	Installation cost is high, only D-DGs have simulation results, HIF is not examined, for protection settings centralized control is used and communication is necessary.
II.	Differential protection scheme [69]	Communication link and OC relays	LG, LLL	Cost effective (conventional OC relays and available communication link), but inefficient for unbalanced loads.
III.	Current travelling waves based scheme [70]	For fault identification bus bar voltages and for fault location current travelling waves		No simulation result is available but uninfluenced by power flow, fault current, load unbalance, plug-and-play generators and independent of Microgrid operational mode
IV.	Multi-agent protection schemes [62]	Network zoning, IEDs, communication link, wavelet coefficients of transient current for fault location	LG, LLG-HIF	Efficient for all types of fault including HIF, no voltage transformers, no time synchronized measurements, less calculations, no central data processor, needs medium to differentiate among fault and switching transients to avoid false trips, high speed communication is needed
V.	Inverse-time admittance-based protection scheme [71]	Communication system, IEDs, network zoning, wavelet coefficients of transient current for fault location	LLL, LL, LG, LLG	No need of communication link, for high impedance fault slow tripping, errors in calculations because of fundamental extraction due to harmonics, transients, and decomposing dc components
VI.	Inverse-time admittance-based protection scheme [72] [73]	Spectral energy contours, time-frequency transform (S-transform), calculation of differential energy	LLL, LG, LL, LLG, LLLG HIF	Vigorous than available differential scheme, resistant to noise and not so much fragile to synchronisation error, utilizes both frequency and time information (takes more data for making decision), suggested for protecting a wide area.

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4.3.3 Distance protection scheme

For the microgrid with C-DGs, a distance protection scheme is proposed in [74]. For the unbalanced faults (LL, LG, LLG) in a radial feeder, the operation of distance relays having Mho characteristics have been assessed by using MATLAB computation and PSCAD simulation. To keep the converter current within the limit a converter control method is presented by decreasing the voltage at the faulted phase and by not changing the voltage of the healthy phases. Based on the features of Mho the consequences of load and fault resistance are considered. It is found that in case of a ground fault, relay located downstream to the fault function needlessly. This situation happens when the low impedance is present at the fault point and when downstream to the fault star-connected load is present. Adding directional features to the distance relay is advised to mitigate this problem. Inspection on a negative sequence impedance is done at every distance relay location to solve the problem in [75]. To differentiate forward and reverse faults successfully for radial networks with C-DGs the reactive part of the negative sequence impedance can be used.

For a radial distribution system consisting of numerous C-DGs, an inverse time admittance dependent relay is presented in [71]. The fault current can be identified by the proposed scheme even with the minimum magnitudes. In this proposed scheme, at first, a normalized admittance is achieved, then to achieve an inverse time-tripping features of relay this normalized admittance is used. If the normalized admittance reaches higher than 1.0 or if the calculated admittance turns out to be higher than the total admittance of the protected line segment, then the relay operates. Each relay consists of two protection zone such as zone 1 and zone 2 and the inverse time characteristic of an individual zone is related to the value of admittance of that particular zone. Therefore, the upstream relays provide backup to the closest downstream relays. To distinguish between forward and reverse faults the use of directional features is proposed by the scheme. Besides figuring out high resistance/impedance faults a third zone namely zone 3 for each relay is also presented. Each relay consists of two tripping features for zone 3, the first one is for the forward faults and the second one is for reverse faults.

4.3.4 Pattern recognition protection scheme

For the MV microgrid consisting of loop/radial network and C-DGs applying time-frequency transform technique S-transform, a differential energy-based protection system is presented in [72] [73]. At first, from the corresponding buses, currents at both ends of the faulted line are picked up then they are refined via an improved S-transform as well as their time-frequency curves are created. At first, a calculation is carried out to find the spectral energy content of time-frequency curves of fault current signals, and then the differential energy is determined. In a microgrid for the identification of the fault sequence, a vital indicator is the differential energy of time-frequency curves of fault currents. For various fault events in a microgrid, a tripping signal is issued based on a pre-set threshold value on the differential energy. In a faulted phase the differential energy fluctuates significantly compared to a healthy phase and so it is very easy to identify a faulted phase.

4.3.5 Other diverse protection schemes

Depending on the current traveling waves principle a brand-new protection technique is presented in [70]. To identify a fault, local bus bar voltage is used by this scheme and current traveling waves to detect the fault location. If a fault takes place in any feeder then based on the fault type, there will be a variation in power frequency voltages of the bus connected to that feeder. To measure the traveling waves current transformers are used. For the disintegration of the traveling waves, wavelet multi-resolution analysis is used. For the identification of the faulted feeder differentiation of amplitude and polarity of initial traveling waves are used.

Another protection system is presented in [76] for LV microgrid consisting of D-DGs, C-DGs, and unbalanced loads which is based on programmable microprocessor-based relays with directional components. In the islanded mode of operation to detect solid faults voltage-based relays and instantaneous OC relays are used, to detect medium impedance faults negative as well as zero sequence components of fault currents are used, to detect HIF the energy level principle is proposed in [77]. To abstain from false tripping caused by low magnitude fault currents a negative sequence directional component is used along with the three directional components. False tripping can also be avoided by directional component using another method namely current-magnitude comparison. In an islanded mode of operation to find out ground faults of the MV side of the transformer, a neutral voltage displacement operation is also proposed. It is suggested to use the traditional OC protection devices like fuses and relays with inverse time characteristics and relays based on a microprocessor without communication in case of the grid-connected mode of operation. The proposed scheme is remarkably independent of the microgrid mode of operation, fault current magnitude, and type and size of DERs. Neither adaptive protection devices nor communication is required for this scheme and facilitate single-pole tripping.

Table 3 [78] presents a summary of the microgrid protection systems.

Table 3. Summary of microgrid protection schemes

Protection system	Devices used	Method of operation	Advantage	Disadvantage
Current based (Conventional)	OC	Current symmetrical component	Simple, Cost effective	Management is difficult in meshed distribution system, Problems with unsymmetrical loads due to the single-phase DGs
Current based (Modification)	DOC	Current symmetrical component	Coordination is easy in meshed distribution system, Selective	Expensive than OC
	FCL	Current symmetrical component	Short circuit current reduction	Expensive
Voltage based	UV, OV, UF, and OF	Voltage symmetrical component	Load shedding designing and blocking blackout system	Cannot detect HIF, very poor accuracy in grid-connected mode, error due to voltage drop
Impedance based	Distance	Measured impedance with threshold value	Much easier than DOC for coordination in the meshed distribution system	Harmonics and transients affect accuracy, Because of fault impedance there is error, Ineffective for short-range lines
Differential current	Differential	Comparison of input and output current of a zone	Speed and sensitivity are high, Very simple, Very high performance for HIF.	Difficulty because of transients and unbalances, Dependent on communication channel.
Harmonic content	IEDs device	Voltage components	Utilized for inverter-based system	Fails to trip in various dynamic loads
Adaptive	Any relay	Relay setting changes according to network state	Online system, Compatibility relay setting with power system conditions	Network upgrading is needed, Post knowledge is needed for configuration, Needed communication, Calculation of fault for relay settings

5 Adaptive protection system methodologies

5.1 Theory of adaptive protection system

One kind of online protection scheme is adaptive protection, and adaptive protection can change the fault response with respect to the system condition. Various techniques are available for applying the adaptive protection system. However, for grid-connected and islanded mode, the easiest and ideal approach to use an adaptive protection system is having two sets of set values of the relay. The settings of the relay can be updated with the changing status of the microgrid. Mainly the characteristic curve of the relay shifts to keep up with the changing fault current. Some other variations of adaptive protection systems are discussed in section 5.3. Among other protection systems, adaptive protection is less complicated, and the installation cost is affordable, thus making it a beneficial solution. Previous knowledge on the configuration of microgrids is needed by the adaptive protection system so that calculation on short circuit and power flow can be done to determine perfect relay setting. A communication method is also needed to update the relay settings.

Because of the development of the digital relaying idea, the modernization of the adaptive protection system was also possible [79]. Tomas Liacco presented a proposal in 1967 where the relay adapts its settings according to the changing of the system condition [80]. The purpose of previous versions of the adaptive protection system was only to enhance the general protection features such as selectivity, sensitivity, and speed. In 1989, the adaptive protection system was recommended for the transmission protection system [81]. A summary of the adaptive protection method is given in Table 4 and they are also discussed in the section 5.3 briefly.

5.2 Adaptation by changing the network

A technique which consists of intentional islanding is proposed by Nikkhajoei and they thought to introduce the protection system to grid-connected and islanded mode of operation [59]. A static switch situated at the point of common coupling (PCC) is opened upon the detection of a fault and the fault clearing method is applied in order to clear the fault and so there will be no high fault currents. Since the load requirements will not be fulfilled by the DG all the time so this technique is not sensible for the present state of the art microgrid.

Because of the dynamic impedance features of the Fault Current Limiters (FCL), they are implemented in the microgrid for fault protection. In the grid-connected and the islanded mode of operation to keep the relay setting equal an optimization problem is developed for the ideal value for the Fault Current Limiter [82]. A suitable outcome is obtained by testing ideal overcurrent relays (OCRs) settings in meshed and in the radial system. As this scheme primarily targets the DGs with Conventional Synchronous Generator so it is a leading drawback for this scheme. The contribution of the fault current is higher by the synchronous type of DG if it is compared with Induction type DGs and PE interfaced DGs. To become suitable for the microgrid having energy storage and for the PE interfaced DGs this method needs a problem remodification. The Fault Current Limiter (FCL) is proposed to integrate with the microgrid where the inverter plays the key role by using a method named as the Virtual-impedance-based fault current limiter [83]. The proposal was to place the Fault Current Limiter ability in the inverter control loop so that there is no need for any extra hardware. Although this recommended method is verified in software as well as in hardware-in-loop simulation but in order to execute this method in the real network there is a need for exceptionally developed DG combined with the manageable inverter. Research has been done on adding fault current in the network as well. A Fault Current Source (FCS) is used to add additional fault current in islanded mode to cope up with the grid-connected operation [84]. The battery, flywheel, and super capacitor is proposed as the Fault Current Source (FCS) by the researcher. There is a need for an exceptional amount of investment for this kind of energy storage method. If this method, fails to cope up with the short circuit level of the grid-connected mode then it may not be able to clear the fault rapidly.

5.3 Advancement of adaptive protection settings

To solve the protection problem, a method is proposed by Brahma and Girgis. Their method was focused on a microgrid containing high DG penetration in every zone to maintain a balance between load and generation [60]. Each area consists of a remotely operated circuit breaker and a frequency controlling generator. This method needs synchronized current measurement at every DG and main grid as well as the current direction among zones. For all types of scenarios, the method performs short circuit analysis and off-line power flow. In order to overcome the temporary faults this method includes auto reclosing, and with the addition of more DG the accuracy also increase, and it is proven in the simulation result. The main drawback in this method is that it is not suitable for low DG microgrids, it depends on the communication channels and the cost is high for the phasor measurement units.

A digital relay based adaptive protection system is also proposed so that it can reform and review its parameter with the help of the modern communication system [61]. In this method, an off-line short circuit investigation is performed which includes DERs condition and an event scenario table is prepared. In case of a fault updated values are taken by the controller and the status is recorded in the event table and then uploads the settings in the active devices. Moreover, a 'follow-me' kind of hardware connected operation is introduced in this system so that the selectivity can be enhanced. The directional numerical overcurrent relay is the main disadvantage of this method and the whole microgrid structure should be known in advance because of the follow-up table. However, if there are any changes regarding the topology or new addition, then the whole calculation must be repeated, including relay parameter and short circuit.

Depending on the impedance of the system an adaptive protection method is proposed in 2010 by Han et al. [85]. Utilizing the fault current and voltage component the impedance of the system is calculated and it is achieved through the Fourier filter method. The settings of the relays are updated via the impedance comparison. The major disadvantage of this system is that it is not appropriate for the backup protection, but it can quickly clear the fault.

An adaptive protection method is proposed with improving reliability and selectivity in 2011 by Dang et al. [86]. By comparing the zero-sequence impedance angle, mode discrimination is executed by the protection devices. In the islanded mode of operation to detect the fault the voltage dq0 transformation is applied on the other hand at the grid connected mode the conventional overcurrent protection method is performed. By identifying the zero-sequence current which flows through the Protection Devices, additional protection planning is achieved. But there is no simulation available for this method only the method is established.

An advanced communication system integrated with the Central Protection Unit (CPU) is proposed to detect the connection/disconnection of DGs as well as microgrids [87]. In this method the DGs are capable to notify its condition, its fault contribution as well as rated current and the settings of the relays are modified by the algorithm based on interruption. Via the communication channel the relays and the DGs of the microgrid is linked with the CPU. The Central Protection Unit (CPU) should also be capable enough to provide fast data accession.

In 2012 a multi -agent-based adaptive protection using distributed intelligence is presented for an MV level microgrid by Kauhaniemi and Voima [88]. There is no detailed discussion for this method as it is still in the primary phase. This method admits that a collapse in the communication can endanger the system and it presents a scheme to manage the telecommunication system and previously planned backup protection system. Creating a huge island during a fault is its primary objective and this way it allows a foundation for self-healing function for the operation of a smart grid.

Table 4 Categorization of the adaptive protection methods

Method	Characteristic			Comments
	Type of fault	Communication link	Voltage level	
Adaptivity based on PMU [60]	All	Yes	LV	Error-free only for high DG integration, Zoned approach, Only calculation
Numerical Directional Overcurrent with Central control [61]	ALL	Yes	LV	Event table based on Offline analysis, Directional interlock, Simulation by calculation
Fault Component extraction (Based on impedance) [85]	L-G, L-L-L-G	No	LV	Only works with IIDG, not appropriate for backup protection, Only Simulation
IED based Multi-agent [63]	All	Yes	MV	Decentralized communication, conceptual design only
Microgrid CPU with WiMAX [89]	-	Yes	LV	Communication latency is the center of attention, Centralized
Distance & Directional adaptive [64]	L-L-L	Yes	MV/LV	Protection method changing among distance and directional
PMU based adaptive distance [90]	All	Yes	MV	Based on event-table, examined on real system
EC-DER embedded protection [91]	All (Simulated for L-L-G)	Yes	LV	For low fault impedances, Auto reclosing function, only simulation

Before the implementation of wireless technology for the power system application the main communication principle was the Power Line Communication (PLC). But now-a-days there are many protocols such as WiMAX, ZigBee, cellular communication, and WLAN which are used in the power system network. An adaptive protection system is developed in 2013 and it was based on WiMAX [89]. In this method, in order to achieve data on the direction of fault current, condition of DGs and to modify the relay settings, the bidirectional communicational ability among the CPC and DG is used. The cost of the installation and maintenance is reduced by using the WiMAX communication technology. In order to check that the communication broadcast latency remain under 40 ms a simulation is also performed as the main goal of the study was the communication structure.

A hybrid active protection system is proposed based on the outcome of the study on distance and directional protection in 2014 by Kauhaniemi et al. [64]. It is observed that in islanded mode of operation distance protection function very well but on the contrary directional protection needs to be modified otherwise fails to function. Another adaptive protection method is proposed which has improved sensitivity and selectivity characteristics [90]. To evaluate the state of the network advanced IED are used and PMU is linked into the IED, the adapted decision is performed via the active devices by the control center. The distance protection system based on Mho features is combined with three protection section and simulation also proposes that it performs very well.

To establish an adaptive protection scheme Sitharthan et al. in 2016 used Electronically coupled Distributed Energy Resources (EC-DER) for example: the fuel cell, solar, the battery, wind [91]. An algorithm is created for all microgrid condition individually and after that is put together to obtain the adaptive protection system. Negative sequence current is used to detect the fault and for the communication purpose the Microgrid Communication Medium (MCM) is used. In the grid-connected and islanded mode of microgrid operation simulation is performed in PSCAD and it shows that the operation time is reduced. In addition, an Auto Recloser Module (ARM) is used to add the fault ride-through ability for the temporary faults.

5.4 Computational intelligence based adaptive protection

The Computational Intelligence (CI) principal can also be summarized as Machine Learning, Data mining and Nature-Inspired Algorithms (NIA). To develop adaptive protection solution, techniques have been used by the researcher from all the mentioned categories. Computational Intelligence (CI) is beneficial in three notable areas such as protection device setting calculation, detecting topology operating by current and rule-based application of the settings. The efficiency can be improved by the Neural network approach and Data mining and the difficulty of calculation can be reduced on the phase of network topology detection. In the future microgrid Data mining which is also known as 'Big Data' can contribute a key role. In every phase of a microgrid such as on transmission, distribution, consumption, and generation a huge amount of data is produced. Sensors as well as the smart meters which are installed in the microgrid are responsible to evaluate the data. In a year, a batch of one million smart meters can collect a huge amount of data and it can be 35.04 billion [92]. In order to prepare a significant record of data the huge amount of data goes through the data mining process. To implement CI for the protection of microgrid the data records act as the base. Another type of adaptive protection is presented which is based on the Decision tree (DT) [93]. The current signals are exposed to the wavelet transformation and the DT model is prepared from the outcome in various transients [94]. There are two type of DTs one is for the detecting presence and another one is for the designation of the fault. The system is prepared very nicely for the faults in various operational condition. The exact value for fault identification was 97% and fault categorization was 85%.

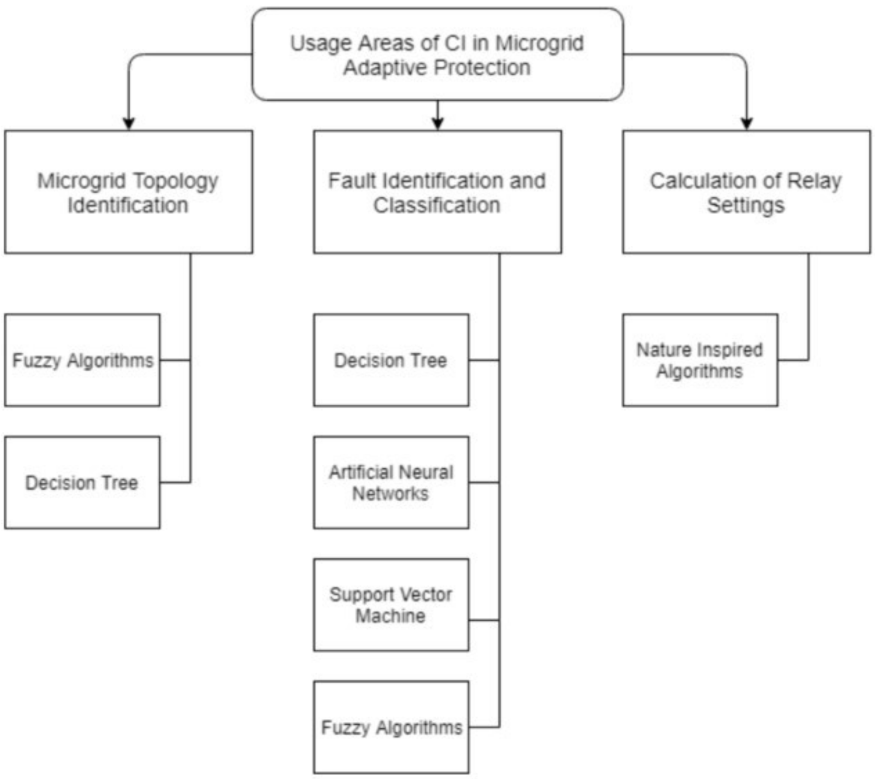

Figure 5.1. Application structure of CI

In microgrid adaptive protection, there are three usage areas of CI. They are microgrid topology identification, fault identification and classification, and calculation of relay settings.

The microgrid topology identification can be made based on fuzzy algorithms and decision tree. For fault identification and classification decision tree, artificial neural networks, support vector machine, and fuzzy algorithms can be used. And nature inspired algorithms can be used for the calculation of the relay settings. The application structure of CI is shown in the Figure 5.1 [94].

To implement adaptive overcurrent protection in 2018 DT method was used [95]. In this method for determining the system status Simple Binary DT is used and the adaptive relay settings are prepared using ANN model. Ordinary calculations and data mining are done by IEDs placed in the network, and the centralized controller is responsible for doing other calculations. For different systems simulation is performed and the outcome was very well for various operating condition.

Depending on the synchronous phase calculation principle as well as ANN, an adaptive overcurrent protection scheme is proposed [96]. Therefore, there are two ANN model one is for the identification of fault status, and the second was for finding the actual location of the fault. To make and execute a decision the approximate location of the fault and the updated result from the active field device is compared. For making the AI more accurate and skilful the action taken during the event is recorded. The drawback of the method is that it needs significant amount of power to process the operation but there is only a simulation result is presented which need further investigation.

Further an adaptive protection system is proposed depending on Fuzzy by Chaitanya [97]. Fault phase identification and fault categorization was also taken into account is this method. Microgrid goes into islanded mode and carries on its function for a fault in the main grid but when the fault is in microgrid it does not disconnected from the grid and the protection system detects and clears the phase. The method shows a faster operating time in case of dynamic operating condition and it is proven by the simulation results.

By using the machine learning principle significantly, a protection system is presented [98]. To determine the existence of the fault ANN model is used and for the fault location a Support Vector Machine (SVM) is used. In simulation the SVM showed error less than 1 %. But the accurateness is less in ANN model and can drop to 77.5% and 80.5%.

Recently, the researchers are concentrating more on calculation of relay settings by NIA. It allows very fast calculation process and provides a better result. NIA method can help to do the calculation very comfortably in case of the adaptive protection system. To calculate the relay setting, Gravitational Search Algorithm and depending on Particle Swarm Optimization (PSO) a Hybrid algorithm is proposed [99]. Compared with other algorithm the hybrid algorithm gives a well-optimized operating time.

6 Conclusion

The existing electricity network is changing from the passive network to the active smart grid because of using renewable energy resources, including distributed energy resources in the distribution network. Microgrid which is a part of the smart distribution grid having islanding operation is the future of the electrical power system. For an AC microgrid major protection issues and currently available protection solution presented in the up to dated scientific literature have been discussed and a critical analysis of proposed protection systems for AC microgrid has been constructed. The critical analysis is dependent on the fundamental protection principle of microgrid in both islanded and grid connected mode of operation to ensure secure and reliable operation. The protection systems are classified based on their importance for specific operational modes of microgrid and on the topology of the network.

This thesis presents a review of microgrid protection system research. The behaviour of microgrid protection system is very challenging and there are different protection solutions proposed by researchers each having their own advantages and disadvantages. An adaptive protection solution is an ideal system for a microgrid because of the uncertain and dynamic characteristic of the microgrid. In order to create an overall protection solution an adaptive protection solution is the most comfortable one to be combined with. These protection schemes may be centralized as well as decentralized and presence of communication is necessary rather than mandatory. In this paper the advancement of the adaptive protection system is reviewed from the time it was first introduced and discussed about various microgrid protection problems and their possible solutions. Because of the short life period, many protection schemes could not develop into a mainstream protection solution and main reason was the rapid enhancement in the technologies.

To ensure the protection of a specific type of AC microgrid in islanded and grid/connected mode of operation, there is a need for an adaptive protection system. But the adaptive protection principle is based on interchanging information in the form of system parameters (current, voltage, phase angle) and among various protection agents interlocking signals and direction are given through a communication link. Recently for many researchers the center of focus is the CI methods. The protection system operation became very simple and it permits to integrate complicated features because of the CI method. With the help of IEDs, the network data is collected, and the relay operation is changed by the machine learning model and can directly control the circuit breaker for clearing the fault accurately.

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