CHAPTER 1

INTRODUCTION

1.1 PREAMBLE

1.1.1 Distributed Generation

Distribution Generation sources like Photovoltaic, Wind turbines, fuel cells, micro turbines, energy storage technologies, etc. are fast finding their importance today to solve environmental issues and serve as alternates to rising energy demand. A distribution system with DGs can operate with a grid, or without grid as a microgrid, where a microgrid is basically a cluster of loads and DGs micro-sources which operate as a single power system that provides power to its local area loads. A microgrid is a remarkable way of integrating different types of DGs, where it can operate autonomously as an islanding mode with the help of advanced control technologies of power electronics [1]. The protection of a distribution system in both modes is a challenging task, as in both modes, the fault currents' levels are very different [2], [3]. Furthermore, in the presence of multi-sources system and their increasing penetration, the distribution systems are transforming from the commonly radial nature towards a meshed and looped structure to gain various advantages [4]-[5] such as improved voltage profile and reliability, more penetration of DGs, and continuation of the supply during faulty condition by reconfiguration of feeders. Thus, the modern distribution system is a highly interconnected multi-source and multi-meshed system with bidirectional fault currents, protection of such system is one of the challenging and complex tasks. Directional over current relays (DOCR) become a suitable choice since directional relays operate only when the fault current flows in the specific tripping direction, where the inverse-time characteristics of DOCR provide better selectivity by giving different suitable operating times for different levels of fault currents.

1.1.2 Protection issues with Distributed Generations

In the presence of DGs, besides reconfiguration, grid-connected and islanding mode, an operating mode can also become variable due to the connections and disconnections of the DGs in order to effectively meet the sudden increase and decrease in the load demands. Moreover, an operating mode can also become variable during a faulty condition, if in a microgrid, DGs with low short circuit capacities (SCC) are present, as these DGs can get disconnected from the system. Compared to a synchronous based DG which has generally 5 times SCC of its rated value, an inverter-based DG (IBDG) has very low SCC, which is typically 1.5-2 times of the rated value [6]. The variability of the operating mode in modern distribution system possess challenges in designing a suitable DOCR based protection scheme. Thus, it becomes more complex when the proliferation and penetration of the DGs increase due to the various factors such as increasing demand of consumer clients, acquired high efficiency, high power quality, and high reliability. The increasing proliferation of DGs makes the relay coordination problem a multi-objective and a highly constrained problem.

1.1.3 Necessity of a Fast protection scheme

On the other side, the tendency of extracting more profit from the distribution system, with the help of developing new technologies, forces the system to operate near boundary conditions. In this context, the transient stability of the system relatively more sensitive during a fault condition. Moreover, directly connected rotating machines are also very sensitive to lose stability in voltage dip caused by faults, especially in the islanding mode, which get worse if larger disturbance happens [7], [8] Therefore, fast and effective protection scheme is necessary not only to maintain the stability of the system but also to maintain the quality and life of equipment, to isolate the minimal area while clearing a fault, and to prevent the premature faults in other equipment. Moreover, a fast protection scheme avoids the unnecessary disconnection of the DGs with low fault ride through capabilities while copes of with maximum utilization of the DGs.

1.1.4 Need of an Adaptive Protection Approach

Detection and localization of fault, picking up of the relays, allocation of the hierarchies to the relays, determination of the optimal and coordinated relays' settings, all these are the different stages of a protection scheme, which get affected by the inclusion of DGs. A traditional DOCR protection scheme fails to protect the distribution system with DGs as it is designed assuming fixed topology and unidirectional fault currents. Instead of making small amendments in the outdated protection systems, revolutionary changes are required for safe operation [9]- [11]. The adaptive overcurrent protection schemes are one of the promising approaches to protect the variable modern distribution system, where the purpose of this approach is to change the relays settings to match them with the prevailing distribution system conditions [19]- [21].

Various adaptive techniques have been introduced in the protective relay coordination, such as modification of objective functions [2], [13], dual-setting approach [14], formulation of different mathematical models [15]-[17], and inclusion of constraints associated with change in operating mode [18]. The adaptive protection schemes proposed in [19]-[21] are based on the pre-calculated settings which are updated periodically by the central controller with respect to the state of the system's operating mode. In general, most of the existing works devised OCR protection schemes considering either fixed topology, fixed sizes of DGs, fixed number of DGs, only grid-connected mode, and only islanding mode while assuming that all the relays and their communication links will be successful in passing on the relevant information to the processing center in order to take an adaptive decision. Such existing schemes fails to protect the system if any of the above-discussed factors become variable and/or flow of exchanging the relevant information get disturbed. Thus, a protection scheme must be robust, reliable, fast, and adaptive with respect to the changes in the system considering the above-discussed factors.

1.1.5 Contribution of the Thesis

This work presents a comprehensive adaptive protection approach for the variable distribution system with DGs considering the information loss due to the failure of the relays and/or their communication links. The proposed protection scheme is the consolidation of the algorithms proposed for different stages of protection as mentioned in Section 1.1.4. The relay coordination problem is formulated as a linear programming problem where the objective is to minimize the overall time of operation of relays prevailing primary and backup coordination between the relays. The scheme has been designed using the online information gathered from the relays, where a central unit processes the gathered information as per the proposed algorithms in order to obtain the suitable adaptive action. The following chapters discuss the problems raised in different stages of protection due to the inclusion of DGs and missing information, and then, present individual solutions for different stages, and subsequently present workflow of the complete adaptive protection schemes. This work proposes two different protection schemes, CAPS-1 and CAPS-2. The CAPS-1 is designed for the system where change in an operating mode can happen due to change in the number and/or sizes of DGs during normal conditions. While the CAPS-2 is designed for the system where change in an operating mode can happen due to change in the number and/or sizes of DGs during both normal and faulty conditions.

1.2 TRADITIONAL OVERCURRENT PROTECTIVE RELAYS

1.2.1 Introduction

An Overcurrent Relay (OCR) picks up when it's current exceeds a predetermined threshold value. Overcurrent protection protects electrical power systems against excessive currents which are caused by short circuits, ground faults, etc. Basically, there are two types of OCR: non-directional relay and directional relay (DOCR). A non-directional OCR operates irrespective of direction of flow of current, for example: breaker at generator end. While, directional OCR contains a directional element to sense the direction of fault current, and operates when the fault current flows in a particular direction.

In terms of operational characteristics, there are mainly four types of OCR, as explained below:

1. **Instantaneous OCR**: It operates instantaneously when the current exceeds its pick-up value. Its operating time is constant irrespective of the magnitude of fault current.
2. **Definite time OCR**: In this type, two conditions must be satisfied for operation (tripping), 1. current must exceed the pickup value and 2. fault must be continuous at least a time equal to time setting of the relay. The drawback of this relay is that it

provides same operating time irrespective of the in-feed variation, fault location, and addition of load. Thus, it is generally less suitable for the feeder networks where a proper discrimination between the different levels of fault current is required.

3. **Inverse Time OCR**: In this type of relays, operating time inversely changes with the fault current. It operates faster for the higher magnitude of fault current, and

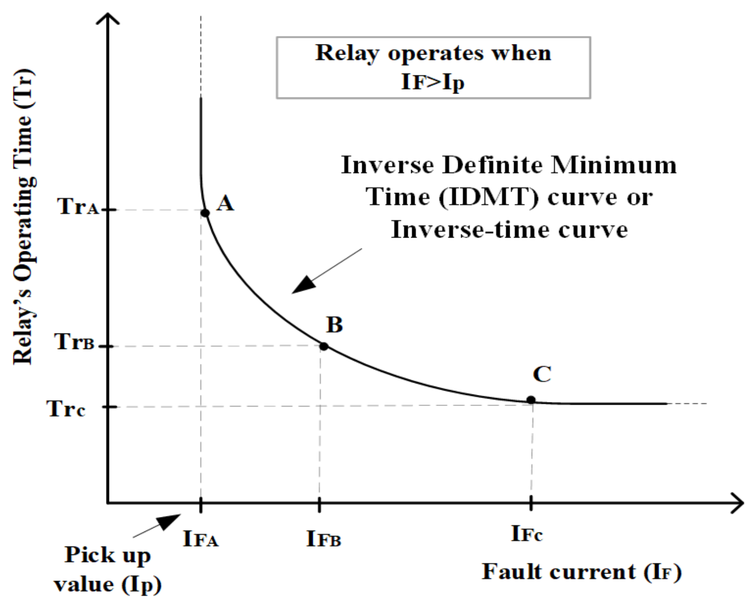

Figure 1.1 Inverse-time overcurrent relay's characteristics curve

comparatively slower for the low magnitude of fault current as shown in the Figure 1.1. There are different types of inverse characteristics such as normal, very, and extreme, that applications depend on the rate of change of the fault current in the network feeder [22]. This relay is widely used for the protection of distribution lines [23] [24]. The fundamentals of the relay coordination problem of an inverse-time OCR is described briefly in the following section.

1.2.2 Relay Coordination in Inverse-time DOCR: A typical inverse time directional overcurrent relay has two values, namely *PMS* and *TMS*, to be setup. The *PMS* defines the relay's sensitivity, and the *TMS* defines the relay's operating time. The conventional formula for calculating the operating time of an OCR (*Tr*) is shown in Equation (1.1). Where, *PMS* is the ratio of the fault current seen by the relay and pickup current of the relay in a particular operating mode as shown in Equation (1.2), where *r* denotes 'P' or 'B' relay, and A, B, and c are the constants for the moderate, very, or extremely inverse characteristics, which can be seen in Table 1.1.

$$\mathrm{T}_r = \left[\mathrm{TMS}_r \times \left\{ \frac{\mathrm{A}}{\left(\mathrm{PMS}_r\right)^c} + B \right\} \right] \tag{1.1}$$

$$PMS_{old} = \frac{I_F}{I_p} \tag{1.2}$$

Table 1.1
Constant and exponent for various relay characteristic from IEEE standards C37.112 [25]

Characteristics	A	B	c
Moderate Inverse	19.61	0.491	2.0
Very Inverse	0.0515	0.1140	0.02
Extremely Inverse	28.2	0.1217	2.0

To isolate the minimal area and to clear a fault safely, a proper coordination of relays settings is required. Where, the coordination problem is to determine the sequence of relay operations for each possible fault location and to provide sufficient coordination margins without excessive time delay [26], [27]. For a proper coordination, if a primary relay fails to operate, then its backup relay should come into action at least after the minimum time interval so that primary protection may take their own time to operate first. This minimum time interval is known as coordination time interval (CTI).

The OCR coordination is an optimization problem which can be formalized as a linear (LP) [27] or a non-linear (NLP) problem [28]. In NLP, both settings (*PMS* and *TMS*) are variables, while in LP, one of the settings is variable while another setting is fixed and known. Consequently, compared to the NLP, LP relaxes significant number of constraints that are associated with the known variable. In LP, generally, TMS comes from the optimization, while PMS comes from the analysis of the load and fault currents data and determined by multiplying the maximum load current with a multiplier, which is generally taken as 1.5 in the literature [13].

The relays settings are optimized by minimizing the objective function (OF) in Equation (1.2) subjected to the coordination constraints in Equation (1.3) and the minimum operating time constraints in Equation (1.4). The OF is constituted as the summation of the operating times of *Nr* number of relays which are required to clear a fault completely. In a coordination constraint, given in Equation (1.3), the operating time of a backup relay must be at least minimum *CTI* greater than that of its primary relay. While, the equation shown in Equation (1.4) shows the constraint related to the minimum operating time of a relay.

$$OF = \sum_{r=1}^{N_r} T_r \tag{1.2}$$

$$\mathrm{T_B} - \mathrm{T_P} \geq \mathrm{CTI_{(min)}} \tag{1.3}$$

$$\mathrm{T_i} \geq \mathrm{T_{min\_i}} \tag{1.4}$$

A directional inverse-time OCR is a good option for the system where fault currents could circulate in both directions with a wide range of the fault currents' levels. This relay is the combination of an inverse-time characteristic-based OCR unit plus a directional unit that determines the direction of current flow with respect to a voltage reference [29].

1.3 DISTRIBUTED GENERATION

Distributed Generation (DG) is one of the new trends in power systems used to support the increased energy-demand. Different countries use different notations like "embedded generation", "dispersed generation" or "decentralized generation" for the DG. The DG is defined as small-scale generation and can be interconnected at different load levels (substation, distribution feeder or customer) [30]. Normally a DG are in range of 1 kW ratings to 100 MW [31]. The technologies for DG are generally based on reciprocating engines, photovoltaic, fuel cells, combustion gas turbines, micro turbines and wind turbines [32]. A DG can be classified into two major groups, inverter-based DG (IBDG) and rotating machine or synchronous based DG. Where, larger plants based on water, wind, and steam use the synchronous based generators which are generally directly connected to the grid. While, most of the DGs, especially non-traditional such as PV and fuel cells based DGs use a power electronic converter (inverter) based grid interface to convert the generated power into useful power that can be directly interconnected with the utility grid and/or that can be used for consumer applications [33]. Such DGs are known as inverter-based DGs (IBDGs).

Existing centralized grid system is actively replaced by distributed energy resources located closer to consumers to meet their requirements effectively and reliably [34]. The Microgrid concept is the bringing together of loads and micro-sources operating as a single system with the potential of providing both power and heat [1]. The various energy resources like small capacity Hydro Units, Ocean, wind, PV, energy storages etc. are in MG for electrification mainly rural areas where grid electricity access is not possible due to poor access of remote areas to technical skills. With the help of advanced power electronic and communication technologies, a MG can operate either connected to the grid or islanded from the grid. Where, advanced power electronic interfaces allow DGs to provide increased functionality through improved power quality, improved voltage/volt-ampere reactive (VAR) support and voltage regulation [35]. DGs can be strategically placed in distribution networks for grid reinforcement, reducing power losses and on-peak operating costs, and improving voltage profiles and load factors [36].

1.4 IMPACTS OF DGs ON FEEDER PROTECTION

1. **Bidirectional fault current**:

Conventional overcurrent protection is designed for radial distribution networks considering fault current flows in a unidirection. Whereas the inclusion of DGs into distribution networks changes the singly fed radial networks into complicated ones having multiple sources, causing of which, the flow of fault current is changed from unidirectional to bidirectional [1], [2], [37]. This can be seen in Figure 1.2(a) that in the presence of a DG, the fault F1 at a feeder zone can be fed by both ends of the zone. The bidirectionality of fault currents adversely affects the coordination between relays.

2. Sympathetic Reverse tripping:

When a DG contributes to the fault in an adjacent feeder connected to the same substation, the pickup level of the overcurrent protective relay installed in the DG feeder causing a possible trip of the healthy feeder before the fault is cleared in the faulted adjacent feeder [38]. This can be seen from the Figure 1.2(b) where due to the sympathetic tripping**,** feeder-2 gets unnecessarily disconnected due to the tripping of relay R1.

3. Increased fault current level:

When a DG is connected to the network, a fault can be contributed by both main grid and DG. This can be seen in Figure 1.2(a), where relay R2 experiences increased level of fault current. This situation puts components at risk since they were not designed to operate under those circumstances, and disturbs the coordination with other relays.

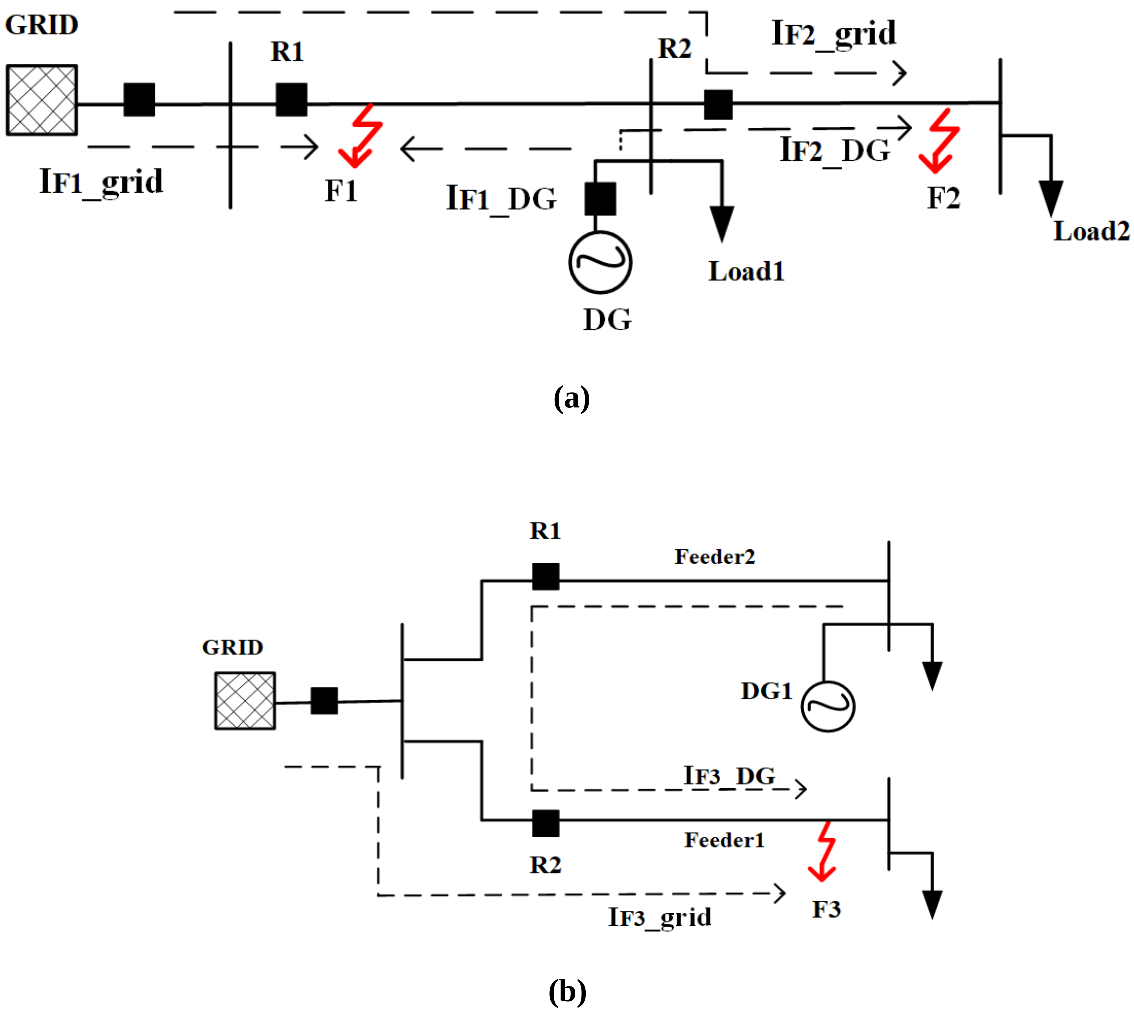

Figure 1.2 Different Protection issues with DGs

4. Low fault current level in islanding:

When a portion of the distribution system becomes electrically isolated from the remainder of the power system and yet continues to be energized by DGs, is known as islanding. [3]. In an islanding mode, a fault is contributed by only DGs. As compared to the main grid, the DGs possess lower short circuit capacities, the level of fault current decreases when islanding occurs. Sometimes, the fault current level is even below or near to the load current, which may result in either delayed operation of an OCR or failure in the picking up of the OCR due to desensitization of the fault [38]. This may result in the prolongation of voltage sag, damage of system equipment, and miscoordination of relays.

5. Reduce reach of relays or blinding of protection:

Each overcurrent relay device has an assigned zone of protection that is determined by its minimum pick-up value. When a DG is connected anywhere between the feeding substation and fault location, then due to the contribution of the DG, the fault current measured by the feeder relay (R), which is normally located at the start of the feeder, decreases as compared to the situation when no DG is connected to the network. This decrease the range seen by the relay R and reduces the reach of the relay. This may result in failure in the fault detection, delay in the relaying, and miscoordination between the relays.

6. Variable operating modes:

In a distribution system, the connection and sizes of DGs can vary in order to meet the peak or low demands of the loads. Moreover, in the presence of multi-sources with variable connections, the feeder reconfiguration can take place for getting the optimum power supply. Besides these two factors, microgrid's capability of operating with the grid-connection and islanding conditions, make the operating mode of the modern distribution system variable. All these factors change the level and direction of fault currents, and resulting, raises the problem of relays miscoordination.

7. **Uneven distribution of fault currents**:

During a fault, the grid-side relays experience fault current higher than the fault current experienced by the DG-side relays. Also, the synchronous based DG contributes the higher fault current compared to the IBDGs. Due to these factors, the feeder relays are exposed to high as well as low level of fault currents even for a same fault situation and for a same feeder zone. In this environment of uneven distribution of fault currents, coordination between the relays get disturbed and so, the system may remain unprotected.

From the overcurrent protection point of view, all these protection issues basically lead two main problems: 1. Failure in the detection of fault by the relays, and 2. Miscoordination between the relays, which must be considered while designing a adaptive protection scheme for the distribution system with DGs.

1.5 LITERATURE REVIEW

1.5.1 Non-adaptive Protection Strategies

Significant efforts have been carried out on proposing the methods of integrating the DGs without changing the existing protection system.

***Disconnection of DGs*:** To solve the problem of relays miscoordination, earlier, the suggested solution was to disconnect all DGs whenever a fault occurs [37]. The disadvantages of this solution are 1. disconnection of all DGs even during a transient fault, 2. Worsen the reliability of power supply, and 3. Defeat the purpose of the DGs connection.

Storage Devices**:** Some researchers focus on using storage units (flywheels, batteries etc.) to increase the short-circuit power to a desired level (especially in islanding mode) allowing overcurrent protection to operate in a traditional way [39], [40]. But, matching the short circuit level of the grid, by using the storage devices, in order to guaranteed the coordinated protection is a task which require a large investment, costly maintenance, and correct detection of the islanding [41].

Fault Current limiters**:** To retain the existing protection equipment and relays settings without disconnection of the DGs, the fault current limiters (FCLs) has been proposed to connect in series with a DG unit in order to limit the fault current during a fault [42], [43]. FCLs are basically series (resistive, inductive, or compound of them) devices that are considered to be invisible to the system under normal operation, but that help limits the short-circuit current under the fault conditions [44]. In [45], a method that relies on optimally locating fault current limiters to minimize the impacts of DG on protection coordination in radial distribution systems was proposed and solved using particle swarm optimization. The use of TCSC (thyristor-controlled series capacitor) as an FCL has been proposed in [68a]. The FCLs offers various advantages but it has some drawbacks which are as follows. The impedance of FCL increases with increase in the individual DG capacity hence its cost increases. Its cost of replacement and maintenance is high. Also, it requires auxiliary power supplies for sensing and firing. If due to any reason they fail to operate then there is no back up protection which could result in wide spread damage of switch gear [46].

***Penetration control strategy*:** In most of the researches, the relay coordination has been maintained by placing the DGs with optimal location and sizing so that penetration level of DG gets maximized without changing the original configuration of relay protection system. In [47], the rate of change of the DG penetration level with respect to the change in coordination time interval is studied by developing a protection coordination index. This index serves as an effective measure for DGs to find the best location for accommodating the DGs with minimal influence on the protection coordination. Whereas in [48], the DGs' sizing and placement have been optimized by using the Genetic algorithm, where the requirements imposed by the existing relay scheme on allowable short circuit currents are treated as the constraints in the optimization formulation. The penetration level of DGs could be limited by voltage, loss, and protection coordination. In [49] and [50], all three constraints have been considered while optimizing the DGs' placement. In [51], the maximum DG capacity for radial distribution systems has been calculated considering coordination between recloser and fuse to avoid reliability degradation. But, with these solutions, only limited number of penetrations of DGs is possible in the effort of retaining the conventional protection scheme.

1.5.2 Relays and Communication in Protection

Relays are the first line of defense against faults and emergency conditions threatening a disruption in the operation of the power systems. Relays have evolved from expensive and sluggish electromagnetic relays to relatively cheaper and efficient solid-state relays and finally to modern and advanced digital relays. Intelligent Electronics Devices (IEDs) based relays are the modern relays which perform control, automation, and communication functions in addition to their traditional relaying functions. They are programmable, economical, fast, reliable and robust. The conjunction of the modern relays with the advanced communication technologies is the powerful tool that provide opportunity to make the distribution protection smarter and adaptive, and allows a protection scheme to automatically alter relay settings based upon the prevailing conditions of the power system [52]. IEC 61850 is a popular international standard for substation automation, where peer-to-peer communications can be used to perform protection and control functions [53]. The functional elements are the smallest parts of a function that can exchange data. These elements in IEC 61850 are called logical nodes. From the protection point of view, the modelling of a microgrid system with logical nodes provided in IEC61850 and its extension IEC61850-7-420 communication standards have been presented in [54] [55].

Increasing proliferation of the DGs requires a higher performance (high speed, security and selectivity) of protection [1]. In [38], Generic Object-Oriented Substation Event- (GOOSE) messaging has been used to transmit the high priority information like trip commands or interlocking information. It assists in providing fast protection by reducing the overall fault clearing time. In a large network, a reduction in the communication delay can be achieved by splitting the network into different parts [56]. An adaptive protection scheme based on the clustering of the network into several zones is presented in [2]. [57] proposes a distributed agent-based protection scheme by using IED relays and IEC 61850 communication standard. It presents a selectivity mechanism of the definite-time relays which is based on the feeder characteristics and IED locations. Centralized [54], [58], [59], [60] and decentralized [61], [20], [63], both types of protection schemes are presented in the literature. To connect the relays agents with the protection and control agents, various types of communication links can be used. Since the distances involved are relatively short, the communications could use pilot wires, optical fibers or the Ethernet [64]. An agent-based self-healing reconfiguration scheme has been discussed in [65].

1.5.3 Adaptive Protection Strategies and Methodologies

Various methods, strategies, and relay coordination techniques have been attempted to introduce an adaptive element in the protection system.

Relay Coordination Optimization: A relay coordination problem is a linear, a non-linear, or a mixed integer non-linear problem depending on the pick-up setting variable. Trial and error approaches were used in earlier days for coordination of DOCR relays [66]. Huge computational effort and slow rate of convergence are limitation of these approaches. In [15], [67], [68] the relay coordination problem has been formulated as a linear problem in which the pickup setting is a fixed quantity while TMS setting is a variable quantity which needed to optimize to get the required coordination. In [16], [69], it is formulated as a non-linear problem where coordination has been achieved by optimizing both settings, TMS and PMS, as variables. In the solid-state and microprocessor-based relays, the currents are discrete and digital [70]. Considering this fact, in [16], [71], and [73], the relay coordination problem has been represented as a mixed integer nonlinear problem (MINLP). Different optimization techniques such as Linear [23], non-linear [69], Dual simplex method [75], sequential quadratic programming method [16], non-linear Random Search Technique [76], genetic algorithm (GA) [16] and particle swarm optimization [77], Hybrid GA-NLP [78], and Differential evolution techniques [79] have been used in solving the optimization problem.

Where, nonlinear programming methods are generally complex and time-consuming, while linear programming methods are simple and easily converge to optimal solutions [23].

Adaptive pickup current based strategies: Number of researches are presented in the literature in which the overcurrent-based protection schemes have been made adaptive to the prevailing conditions by adjusting the pickup current settings instead of TMS settings. For this, in [81], a lookup table of pre-determined maximum load current values corresponding to different operating modes have been used as adaptive pickup currents. While [80] reported that such pickup values may lose the protection due to dynamically changes the reach of relays with varying the system operating conditions such as sudden increment in the load and addition of the DGs. In [70], [80]-[82], dynamic pickup setting is taken as a function of load current. In [83], a new formulation is developed where steady-state fault current based pick up settings have been established on the basis of coefficients of reliability and fault type, where these coefficients are pre-determined and based on the offline values. An adaptive overcurrent pickup scheme that updates the OC relay minimum pickup current based on the system fault analysis is proposed in [54]. Every connected DGs has its own fault current contribution impact on the fault current seen by a relay. [54] suggests to determine the matrix of impact factors associated with all the DGs and network relays, and then to determine the adaptive pickup currents for each relay by calculating the cross product of this matrix and DGs' fault currents. In [84], [85], a higher overcurrent pick-up threshold has been selected to avoid the sympathetic tripping on feeders. But, reduction in the fault detection sensitivity is the major disadvantage of increasing the threshold pickup value. Where a reduction in reach increases with the increasing penetration of the DGs [86]. In [86], an adaptive pickup current protection scheme is proposed in which the relays pickup current decreases as the total amount of power injected by all DGs increases. But, this solution conflicts with the solution proposed for the sympathetic tripping [38].

The coordination of relays in the presence of DGs is the most vital step for making a protection scheme adaptive. In the conventional methods, the relays settings have been optimized by minimizing the objective function consisting of summation of operating times of relays, where OF is subjected to the constraints which are related to the operating modes with DGs. In [63], a selection process of optimal settings has been presented where TMS boundaries of primary and backup relays are plotted as a square area, named as possible solution area (PSA), while the related coordination constraint is plotted as a straight line. In this method, a feasible solution area (FSA) has been discovered by using the PSA and constraint line to locate the pickup values within the FSA. The objective of this method is to avoid the violation of some selectivity constraints and to provide the fast relay's operating time by selecting a minimal value of TMS. [88] proposes the addition of fault current direction constraint to the formulation of the optimal directional inverse overcurrent relays coordination. This additional direction detection constraint in the formulation assures that every OCR in the backup scheme will detect the short circuit current in its forward zone or otherwise it will be excluded. To prevent the blackout due to maloperation of the relays in non-fault transient conditions, and in turn, to prevent the penalty compensation to the affected users, [89] develops an impact severity curve for digital overcurrent relay by quantifying the impact of the different transient currents in the presence of DGs. This curve assists in selecting the characteristics constant and pick up current setting of the relay and demonstrates the border for the coordination between the two setting of relays. [90] takes advantage of the user defined curves option available in the modern digital relays and formulates the coordination problem by taking two more settings parameters, characteristics constant A and B, besides PMS and TMS. But this multi-variable approach will eventually get complicated and time consuming with the increasing number of DGs. In [91], a new protection adaptive approach for the meshed distribution system has been demonstrated. This approach uses the combination of three types of protection relays, namely overcurrent (OC), directional (DOC), and differential relays (DIF), where the first two relays deal with the unidirectional and bidirectional flow of fault currents while the third relay assists in quick fault clearance with minimal area isolation. [60] proposes a definite time-based time grading protection strategy for both grid-connected and islanding operating modes by utilizing the communication systems. Where, the localization of the short circuit fault is performed by using the predefined chart of the fault current directions. OCR coordination in industrial plants are complicated as these plants contains various types of loads on different buses. In [92], a modified formula of relay curves has been presented such it can adapt various characteristics of OCR to deal with various types of loads.

To protect the modern distribution system from the short circuit faults, several protection approaches have been developed by using the differential protection technique. As, this protection technique is based on the difference value between the currents measured at both sides of a feeder. It works independently of the magnitude of fault current, and thus a suitable protection methodology, especially for the islanding mode where the detection of the fault by using the fault. However, such scheme has its own limitations; it generally raises the need of accurate time-synchronization as well as a separate backup protection scheme, and sometimes are not suitable for the MV networks where capacitor-charging and CT's saturation are prominent [93]. In [94], directional OCR are used in conjunction with the FCLs in series with every DGs in the system.

In [56], [64], and [95] voltage-based protection schemes are proposed for the modern DS, as the overcurrent-based schemes are sometimes insufficient to detect the short circuit fault current in the feeders due to the absence of the main grid and/or low output current limit of IBDGs. This method is based on monitoring the output voltages of IBDGs, where it extracts the fault disturbance information by using the abc-dq voltage transformation. In [97], By utilizing the extensive communication, comparative voltage protection is used as a secondary protection when instantaneous differential protection fails to protect the system due to failure of the relays and communication links. This scheme utilizes some of the principles of synchronized phasor measurements and multifunctioning feature of the microprocessor relays to detect all types of fault conditions. In [98], a multi-criteria-based loss of main detection algorithm has been presented. It uses the passive local measurements of voltage unbalance and voltage total harmonic distortion.

1.6 PROBLEM STATEMENT

Distribution Generations are fast finding their importance today to solve environmental issues and serve as alternates to rise in the energy demand with various prominent benefits. These benefits can only be fully exploited when the modern distribution system is secured and safe with a fast and robust protection scheme. While, designing a protection scheme for a distribution system with DGs, the following points must be taken into account:

1. Unlike the traditional distribution system, in the modern distribution system, the network configuration is no more radial and the direction of fault current is no more unidirectional.
2. In addition, the operating mode is also no more fixed because of the changing connections and capacities of DGs, feeder-configurations, grid-connected and islanding mode.
3. As the proliferation of DGs will increase, the number of operating modes in which a system may appear will also increase. , where these numbers can increase sharply as the proliferation increases.
4. Moreover, with the increasing proliferation of DGs, a system is becoming relatively more dynamic and unpredictable, due to which, a system may appear in an unknown operating mode.
5. In addition, meshing of the distribution network in the presence of DGs is transforming the system into a complicated network, due to which, number of fault currents path are also increasing.
6. On one side, deployment of the communication system in protection is increasing to monitor and collect the information to make the protection adaptive. However, on the

other side, the flow of information may loss if the relays and/or their communication links get failed.

In this research work, the problem statement is defined as to how to achieve the coordinated protection in such intricated, variable, and unpredictable network by the approach of adaptive protection and coordination study.

1.7 OBJECTIVES OF THE THESIS

The main objective of this research work is to design a fast and robust comprehensive adaptive protection scheme (CAPS) for the modern distribution system mainly considering the following protection factors 1. Variability of the operating modes and 2. High proliferation of variable size DGs, and 3. Information loss due to the pre-fault failures of relays and/or their communication links. In order to accomplish this goal, the research work further sectionalized in the following objectives:

1. The first objective is to develop an effective approach for coordinating the relays with the aim of prevailing the coordination irrespective of the changes in the operating modes. Where, this objective is achieved by proposing a novel constraint reduction relay coordination method, which relaxes a significant number of constraints while optimizing the comprehensive settings for relays.
2. The second objective is to develop a method for sensing the fault irrespective of the level and type of the fault current and operating modes including grid-connected and islanding mode. To achieve this objective, a hybrid approach has been developed in which a hybrid pickup multiplier setting (HPMS) has been proposed for the system

relays. Where this setting is obtained by using the magnitudes of more than one-line parameters besides the phase current magnitude.

3. The third objective is to propose an online algorithm (DFZD_algo) for detecting the faulted zone considering the information loss due to the pre-fault failure of the relays and /or their communication links. The information about the fault current directions in the form of binary bits has been used to detect the faulted zone. This method also helps to discriminate whether the relays get picked up due to the faulty condition or non-faulty condition.
4. The relays hierarchies assigned prior to the previous operating mode may disturb the relays coordination in the changed operating mode. In this context, the fourth objective deals with developing a method for determining the adaptive relays hierarchies which can function independent of the known or unknown operating modes. An online algorithm (RHs_algo) has been proposed which takes only a few binary bits information from the relays and provides adaptive relays hierarchies without any human calculations.
5. The fifth and foremost objective is to design protection schemes, with the amalgamation of these different protection stages, for two different scenarios: In the first scenario, it is assumed that the number of DGs can only change during normal conditions while it will be constant during the faulty conditions due to the presence of DGs with high fault ride through (FRT) capabilities. Whereas, in the second scenario, it is assumed that the number of DGs can change during both normal and faulty conditions due to the presence of DGs with high or low FRT capabilities.

Thus, overall, the objective of this research work is to investigate the problems with respect to the mentioned protection factors and to add the self-adaptive feature to each stage of the protection. So that a fast and robust comprehensive protection scheme can be developed such that it can function independently of the considered protection factors without any need of the switching into different protection schemes.

1.8 ORGANIZATION OF THE THESIS

The work embodied in the present thesis is organized into seven chapters. The organization of the same is as follows:

Chapter 1 gives a general introduction to the problem and sketches an outline of the thesis. An essential survey of literature covering the development of the overcurrent protection scheme for protecting the distribution feeders of the variable distribution system with DGs is presented. It discusses merits and shortcomings of different existing protection strategies.

Chapter 2 starts with discussing the development of the existing comprehensive relay coordination approach for the distribution system with variable operational status due to changes in number and sizes of DGs. Moreover, it investigates the performance and finds the shortcomings of the existing method considering the increasing proliferation of DGs. Then, it proposes a novel relay coordination method to determine comprehensive settings with the aim of overcoming the discussed shortcomings and providing the fast and optimal protection. The proposed relay coordination has been tested and validated on the IEEE 38-bus test system.

Chapter 3 starts with a brief discussion on the various factors causing of which a system is exposed to different levels of fault currents in the presence of variable operational status of the distribution system with DGs. It also discusses the limitations and demerits of the conventional existing approaches for picking up the relays in such variable environment, and then proposed a new approach named hybrid approach with the aim of sensing of the fault irrespective of the fault current's level. The proposed hybrid method has been tested and validated by using the test system results.

Chapter 4 starts with investigating the performance of the existing method of detecting the faulted zone by using the current's direction, in the absence of some information flow due to failure of the relays and/or its communication links. Then, it presents a new fault detection method with the aim of detecting the faulted zone in the presence of one or more than one such failures. The performance of the proposed method has been investigated for different possible failure events by using different examples and MATLAB coding results.

Chapter 5 starts with discussing the incapability of the pre-determined based relays hierarchies in the variable environment and missing information. Then, it presents an algorithm for determining the relays hierarchies which makes the determination of RHs free from manual calculations and independent of the variable operational status of the system. The algorithm has been developed in the MATLAB coding environment, and the impact of the proposed relays hierarchies on the performance of relays have been investigated by using the test system results.

Chapter 6 presents applications of the methods, proposed in the previous chapters, in designing the protection schemes. It presents two different comprehensive adaptive protection schemes for a distribution system that operational status can change due to any of the following events: grid-connection, islanding, connections and disconnections of DGs, increment and decrement in the sizes of DGs, and feeder reconfiguration. The first scheme (CAPS-1) is designed for the system where change in an operating mode can happen in only normal conditions not in faulty conditions. While the second scheme (CAPS-2) is designed for the system where change in an operating mode can in both normal and faulty conditions. The performance of the individual protection schemes has been investigated on the test system. Moreover, the individual contribution of each of the proposed algorithms in making the protection schemes faster is also shown by using the test system results.

Chapter 7 summarizes the main conclusions and significant contributions of the thesis. It also discusses its future scope and suggests some points on which further investigations may be carried out.

1.9 CONCLUSION

This chapter briefly gives the overview of overcurrent relays coordination, distributed generation, and impact of the DGs on the relay coordination. This section also discussed the required literature review. Finally, this chapter concludes with the research objectives and outline of the present thesis.