ABSTRACT

Protective relaying is the first line of defense against fault in the power system. Inverse time overcurrent relay (OCR) is considered as the backbone of the protection strategies in a distribution system and their coordination plays an important role in the selective operation of OCRs during a fault. The OCRs' coordination can be achieved by adjusting their two main settings, namely pickup multiplier setting (PMS) and Time Multiplier Setting (TMS). In recent years, due to increased energy demand and lower dependence on fossil fuels, there is a significant momentum in the penetration of distributed generation (DG) to meet the increase in demand. The design of protection systems associated with the distributed networks has traditionally been based on the assumption of unidirectional power flows, which get tremendously affected in protecting the distribution networks with DGs. It is because the interconnections of DGs typically changes the radial structure of the network and the magnitude and direction of the currents in the feeders during a fault. This aggravates a number of protection issues against the OCR protection of the system, such as false tripping by back feeding (sympathetic tripping), blowing of the fuse, bidirectional power flow, blinding of protection, reduced reach of relays, and limited short circuit level in islanding of the network. Where in the islanding scenario, the grid supply is disconnected and the connected DGs continue to power the local loads. All these discussed protection issues mainly lead to the problem of either miscoordination between the relays or prolongation of the fault in the presence of low level of fault currents or both. These problems get more complex and challenging when the operating mode of the distribution system becomes variable due to the connections and disconnections of the DGs, feeder reconfiguration, grid-connected and islanded mode of the system. During a normal condition, DGs can be connected or disconnected to meet the high or low load requirements respectively. Moreover, during a fault condition, DGs may get disconnected due to their

low fault ride-through capabilities. Hence, the modern distribution system needs an intelligent and adaptive protection scheme where the relay can automatically configure its settings corresponding to change in the status of the operating modes and can assist in the faster clearance of a fault. Therefore, a protection scheme must be designed considering the impacts of the DGs as well as the variability of the operating modes, to utilize the different aspects of the distributed generation in a secure environment.

The inclusion of communication technologies into the protection schemes opens doors in many ways to make the overall scheme adaptive with respect to the changing nature of the operating modes. By utilizing the advanced technologies, the protective relays are becoming more compact, intelligent, and multitasking. These relays are commercially available with various advanced features such as the acquisition of data, self-checking, data storing, data communication, and numeric calculations. Exchanging and sharing of the information between the relays and the central processing agents is one of the major parts of the communication based adaptive schemes. In this context, if a relay or its communication link fails to operate before the occurrence of a fault, then, it may not be able to exchange the relevant information between the agents. As a matter of fact, the protection scheme may fail to take a suitable and adaptive protection decision. Thus, it is worthy to mention, a protection scheme for the modern distribution system must be designed considering not only the variable operating modes but also information loss due to the pre-fault failure of relays or/and their communication links.

In documented literature, most of the existing works have proposed OCR protection schemes which are designed 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 communicating the relevant information to the processing center in order to take an adaptive decision. These

existing schemes are generally based on the pre-calculated settings stored in a look up table, where relays' protection settings are updated periodically by the central controller with respect to the state of the system's operating mode. But, if any unknown operating mode or any information loss happens, then these schemes may fail to maintain the relays coordination and, consequently, may fail to protect the system.

The contribution of the work being carried out presents a comprehensive adaptive protection approach for the DGs-distribution system with the aim of not only providing the adaptive relay settings but also makes adaptive the rest of the intermediate protection-stages considering the variability of the operating modes and information loss. Further the work presents individual algorithms and methods for each protection stage (as mentioned below) and presents comprehensive adaptive protection schemes. The brief detail about the work is mentioned as follows.

a) **Coordination of the relays:** The addition of a new set of constraints corresponding to each of the possible operating modes in the relay-coordination study provides the adaptive relays settings for the variable distribution system. Thus, the present investigation realizes that an increase in the proliferation of DGs makes the relay coordination problem a highly-constrained optimization problem, and further, changes in the number of DGs make the problem more complex. In addition to the above fact, a novel relay coordination method, named as constraint reduction-based relay coordination (CRRC) method, is introduced. This method selects a small set of constraints out of a large set of constraints while determining the optimal relays settings, and thus releases the unnecessary burden of constraints and provides improved performance of relays.

b) Detection of a faulted zone: Locating the faulted zone by using the fault current direction is the method which is independent of the magnitudes of fault currents. This method is an effective approach for the system where fault currents change its level due to variable operating modes. Apart from that, to detect the fault location, a modern relay sends the information of the current's direction to the relevant agents after sensing of the fault. But, in the presence of low magnitude of fault current, a relay sometimes fails to detect the fault and hence fails to send the directions and relevant information to the agents. Similarly, if relays sense a fault, but due to some mal-functioning in them and/or their communication links, they fail to send their direction information to the associated agents, then, subsequently the conventional fault-detection method may fail to find the faulted zone in the presence of incomplete information. In this work, a new direction-based Fault Zone Detection method with an algorithm (DFZD_algo) is introduced, which is capable of detecting the faulted zone, in a variable operating mode even in the presence of missing information.

c) Selection of the relays-hierarchies: A different operating mode requires a different set of relays hierarchies to clear a fault. For this, the conventional schemes use pre-determined relays hierarchies prepared for the known set of operating modes. But, if any operating mode is unknown or goes through an unplanned change such as disconnection of a DG or a feeder during a fault condition, the conventional scheme may fail to find the appropriate hierarchy levels for coordination. In this work, an algorithm (RHs_algo) is proposed which determines the relays hierarchies by using the online information and provides adaptive relays hierarchies irrespective of the variable operating mode and missing information.

d) Sensing of the fault and relays pickup: In the presence of variable operating modes, the distribution feeders are exposed to the fault currents of different characteristics with a wide range of levels. Even for the same fault situation, the grid side relays experience

higher magnitudes of fault currents while the DG side relays experience lower magnitudes of fault currents, and sometimes, even, the magnitude of fault current is very near to and lower than the normal current, especially in islanding conditions. As a result, in most of the faulty situations with DGs, the conventional relay's pick up setting, which is based on the overcurrent parameter, fails to sense the fault or picks up the relay. In this context, 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.

Thus, the main objective of this research work is to add the self-adaptive feature to each stage of the protection and to propose comprehensive adaptive protection schemes (CAPS) for the varying operational status of the distribution system with DGs considering the information loss. The performances of the proposed schemes have been tested and validated on the IEEE 38-bus test distribution system in a MATLAB simulation and coding environment. The results show that the proposed schemes not only provide the optimal relay's coordination in varying operating modes but also effectively reduces the protection latency due to the pre-fault failures of the relays and communication links, and due to the low level of the fault currents.