# An Adaptive Over-current Protection Scheme for MV Distribution Networks Including DG


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*Abstract*- **Conventional electric distribution systems are radial in nature, and are supplied through a main source. These networks have a very simple protection system which is usually implemented using fuses, reclosers, and over-current relays. Recently, great attention has been paid to applying Distributed Generation (DG) throughout electric distribution systems. Presence of such generation units in a network, leads to losing coordination of protection devices. Therefore, it is required to have an algorithm in hand which is capable of protecting distribution systems that include DG, through diagnosis and isolation of occurred faults. In this paper, a new approach for protecting of distribution networks in presence of DGs will be presented. The algorithm is based on dividing an existing distribution network into several zones; each of them is capable of operating in island operation.**

**The proposed scheme has been implemented on some part of a real distribution network and performance of the proposed scheme is tested on it. For simulating the sample network and for implementing the relay algorithm, DIgSILENT Power Factory and MATLAB are used respectively.**



*Index Terms*- **Distributed generation, Distribution system, Protection, Protective device coordination, Recloser**


## I. INTRODUCTION

Traditional electric distribution systems are radial in nature, and are supplied through a main source, therefore it is simple to design protection scheme for such networks. Recently, great attention has been paid to applying Distributed Generation (DG) throughout electric distribution systems, and presence of these generation units results in not having a radial distribution network, consequently raises some problems such as losing coordination of protection devices [1]–[3].

Generally, problems that arise due to application of DGs are: false tripping in feeders, false tripping in generation units, protection blinding, increasing and decreasing short circuit levels, undesirable network islanding and preventing automatic and asynchronous reclosing [4]. Appearance of these problems depends on the characteristics of network and DGs and in most cases network protection scheme must be thoroughly changed in order to avoid the mentioned difficulties. Such changes may be complicated, since it is needed to model whole distribution system including distribution network in addition to DG, consequently obtaining the best protection scheme is still difficult [5].

When DG units are connected to a distribution network, the system will be radial no longer and this means losing the existing coordination among network protection devices. The extent in which a DG affects protection coordination depends on DGs' capacity, type and installation location of them. Due to generation capacity and installation location of DG, there are ranges in which protection coordination is maintained and in some cases no protection coordination can be achieved [5]–[9]. Regarding the influence of DGs on protection of distribution systems, so many researches have been performed so far as well as some researches concerning how to tackle the resultant problems of applying DGs [9]-[16]. In this paper, a new protection scheme for distribution systems in presence of DGs is proposed. In the proposed scheme, systems protection is carried out through a computer-based relay which is installed in sub-transmission substation. The relay determines system's status after it receives the required network data, and in the case of fault occurrence it diagnoses its type and its location and finally issues the proper commands for protection devices to clear the fault and to restore the network.

## II. GENERAL VIEW OF THE PROPOSED SCHEME

The main purpose of a protection scheme in distribution systems is to diagnose the faulty part and isolate it from the rest of the system. In traditional distribution systems, when a fault occurs in a specific part of it, whole downstream network is disconnected from the rest of the system or supplied through network tie lines. Assuming it is impossible to supply through other parts of network and a DG exists in the downstream network of the faulty part, according to conventional protection logic, it will not be possible to utilize the DG any more. This will result in not to be able to utilize DG sources optimally, and amount of ENS (Energy Not Supplied) in network increases so system reliability decreases. Thus, in proposed scheme, general approach is to utilize DGs to the fullest in island operation when fault occurs.

In the suggested scheme, distribution system is divided into several zones in such a way that in each zone there is no DG, or if there is any, balance of generation and consumption in that zone is maintained, regardless of whole generation network, and only using the power generated by DGs that exist in that zone. In other words, distribution system is divided into two categories that have the following characteristics:

1. First category includes those zones which have not DG and their loads are fully supplied through the entire network and other zones of distribution network.
2. Second category includes those zones which have DG; it is obvious that at least one generation unit in each zone

must be equipped with frequency control system in order to be capable of controlling zone frequency in the case that the zone is in island operation state.

As it can be viewed in “Fig. 1,” a number of circuit breakers are placed in network to interconnect the zones. These breakers have fast and consecutive open and close capability as well as receiving remote open and close command. Besides, these breakers must be equipped with check-synchronization function to be able to maintain zones synchronization when it is needed to connect two island zones. To implement the proposed algorithm, a computer-based relay with capability of performing calculations and storing data must be installed in sub-transmission substation. This relay is able to receive required input data (that are provided through measuring some network parameters), to process them, and in the end, to diagnose location and type of fault in order to send proper commands to protection devices.

## III. Network zoning procedure

The applied procedure in zoning a distribution system is considering one zone for each DG, starting from the beginning of feeder, and each zone extends to the end of feeder as long as the DG within that zone is capable of supplying average load of the zone. When average load of substations located in the zone exceeds generation capacity of zone's DG, zone border finishes, and two circuit breakers are installed in the beginning and in the end of zone points. In the case that there exists a second DG located within the supplying limit of first zone's DG, and as long as zone's average load does not exceed generation capacity of first DG's capacity, while moving towards end of feeder, the second DG is regarded within the same zone and zone border extends as far as the zone's average load does not exceed summation of two DGs' capacity.

The reason to consider zoning procedure from the beginning of feeder to its end is to allow more loads to be supplied through upstream network. This approach increases network reliability and decreases total ENS of the system. Of course, when DG's capacity is higher than the loads of substations located in its downstream network, zone extension border should be considered upward.

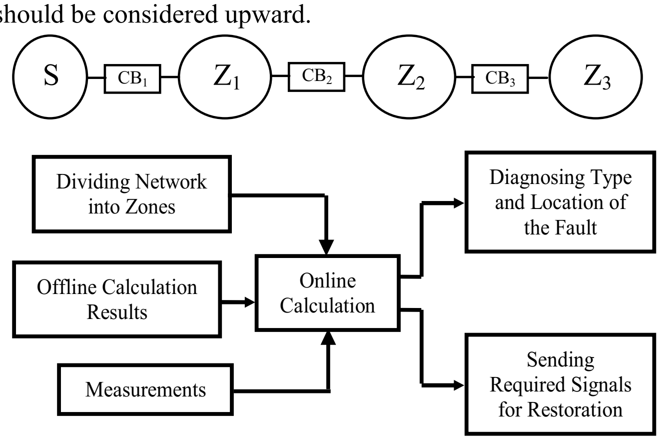


Fig. 1. General view of proposed algorithm

The reason to support the idea of considering average load in zoning is that in distribution systems, daily consumers' loads are variable to a great extent. In other words, hourly curve of consumers loads, and consequently substations loads, have so many maximum and minimum points in such a way that peak load might be four times of base load. Regarding the fact that duration of peak load is short, if zoning is done based on peak load, vastness of zones containing DGs will be very small, and therefore more consumers will face power cut when a fault occurs in the system. On the contrary, if average load is considered as the basis of zoning instead of peak load, vastness of zones containing DGs will increase which will result in giving distribution system consumers more chance of being supplied in the case of fault occurrence. It is required to mention that if this procedure is chosen for zoning; all distribution system loads (i.e. all distribution substations) must be equipped with load break switch. This enables central relay to supply system loads regarding their importance and to disconnect some of them to maintain the balance between generation and consumption in the case of fault occurrence in the peak-load time. Obviously these switches must be capable of receiving remote control commands as well.

## IV. Required input data

The needed input data for correct operation of relay is as follows:

1. Technical characteristics of all network devices such as distribution substations, lines and DGs;
2. Estimated hourly load curve for all loads of network and their degree of importance;
3. Data regarding network zoning;
4. All operational data of the main relay in different faults occurrence;

## V. Required measurements

To implement the proposed protection scheme, it is required to carry out the following measurements and continuously provide the main relay with its results.

1. Synchronized three-phase current vectors flowing through all DGs and through main source;
2. Synchronized three-phase current vectors flowing through laterals, except those branches that have DG;
3. Synchronized three-phase current vectors flowing through zone-forming breakers;
4. A signal which is indicative of current direction flowing through the breakers that form zones;

## VI. Procedure of offline calculations

Offline calculations consist of load flow studies and short circuit analysis for all types of faults and in all points of network. Then for all faults, currents flowing through all DGs, main source and laterals are determined. Also characteristics of Minimum Melting (MM) and Total Clearance (TC) of all fuses in network must be stored. Using the above characteristics and storing them in relay, it is possible to perform software coordination of fuses and the reclosing operation; this will be discussed in section XIII. The time before fuses to be melted is calculated out of MM characteristics and short circuit results. It is also needed to update all calculation results for any network change. For instance, when there is a change in network configuration, like disconnection of a line, it is required to update network admittance matrix and redo load flow and short circuit analysis.

To have DGs' currents, laterals and main source for all types of faults and in all network buses, a table can be provided and through comparing the above values in this table, it will be possible to diagnose the exact location and type of fault. After diagnosis of location and type of fault, which leads to diagnosis of faulty zone, relay sends disconnection signals to appropriate breakers to isolate the zone from other zones of network and consequently the faulty zone is isolated from network. In brief, procedure of offline calculations can be stated as follows:

1. Receiving network data;
2. Performing load flow calculations;
3. Performing short circuit analysis for all types of faults and in all network buses;
4. Extracting all required fault currents for each type of fault and in each network buses;
5. Extracting the time which is needed network fuses not to be blown, out of MM curves;

## VII. Online diagnosis procedure of fault location

As it was pointed out before, synchronized three-phase current vectors for all DGs and main source are available and summation of these values is always equal to network load. If a fault occurs in some point of network, this summation suddenly increases and is greater than whole network load. In this situation, the main relay installed in sub-transmission substation diagnoses the fault. The situation in which summation of currents is zero shows that the occurred fault is within the protection zone of one of DGs (between DG and the location that its current is measured). In these circumstances, the main relay will not issue any command to let its own protection system isolate it from the rest of network. To detect fault location, currents of DGs, main source and lateral branches are compared with the values of the table that was provided through offline calculations. This idea was introduced in [1] for the first time, but it has some problems in diagnosis of exact location of fault and sometimes encounters error and inaccuracy regarding this issue. However the inaccuracy in detection of fault location decreases when number of DGs increases but in this scheme, currents flowing through lateral branches with no DG are monitored as well, in order to ensure whether the location of fault has been determined correctly. This monitoring has two advantages: first, provides main relay with more quantitative values for doing required comparisons and consequently the error in determination of fault location decreases considerably, second since measurements are carried out in the laterals containing no DG, for those faults that do not occur in these laterals the measured current is equal to load current and this determines that no fault has occurred in laterals. Thus it is possible to increase considerably the accuracy of proposed scheme in [1], through applying this capability.

## VIII. Isolation of faulty zone and network restoration

After relay diagnoses fault location and faulty part of network is detected, it is time to isolate the faulty zone from the rest of network and restore the network. Needed data is available in database to designate those breakers that must issue tripping signals. The general approach is that after detection of faulty zone, the relay sends disconnection signal to its isolating breakers, its downstream network's CBs and all DGs located in the faulty zone. In this situation, upstream network of faulty zone is entirely supplied through main source and its DGs, the faulty zone faces power outage and downstream zones of faulty zone are supplied through DGs within them, if that specific zone has DG or DGs, otherwise faces power outage.

Considering the fact that 80 percent of faults that occur in distribution networks are transient in nature (In this paper, faults lasting less than few seconds are classified as the transient faults.), network must be capable of letting transient faults to be cleared. In conventional distribution systems this is done using reclosers, and in the proposed scheme reclosing operation is carried out using zones isolating switches, through main relay control. The operation procedure is that after isolation of faulty section, reclosing is performed through connecting zone breaker to its upstream network at the command of main relay. After each reclosing operation, relay investigates network status and if the fault still exists, relay issues disconnection command. In the case that fault is transient and is removed during reclosing operation, relay issues reclosing as well as synchronization and restoration commands. To have a successful process, it is required to perform reclosing operation before fuses of network are beginning to melt. Regarding the point that MM curves of all fuses are available in relay database, and the time to avoid fuse blowing has been determined as a result of offline calculations, consequently relay can perform reclosing operation at proper time. Besides, reclosing operation must be coordinated with fuses' characteristics. To achieve this coordination, MM and TC curves of all fuses are stored in relay and relay determines and issues the best disconnection time of related breaker using different types of faults, their respective currents and curves of fuses.

For example, in “Fig. 1,” if a transient fault occurs in $Z_2$, relay first sends disconnecting signal to $CB_2$, $CB_3$ and all DGs located in $Z_2$ and then sends reclosing signal to $CB_2$ to diagnose transient fault. In the end, after clearance of fault, relay sends reclosing signal in addition to synchronization signals to $CB_3$ and all DGs located in $Z_2$ to restore the network completely.

## IX. Load Shedding

There are different methods of load estimation in distribution networks. For instance, among which one can mention installing load recorders in different points of network that measure load at specific times and estimate network load for other times.

Due to the vastness of load estimation topic in distribution systems, this paper has not dealt with it, and for network zoning and operation of load shedding it is assumed that hourly load curves for all substations of distribution network have been estimated before, and are available for performed studies.

When it came to zoning issue, it was stated that operation of load shedding must be performed when network faces two conditions. First, a fault occurs in a zone where there exists at least one zone in its downstream network, including one or more DGs, and the zone goes into island operation status due to the disconnection command issued by relay and consequent operation of the circuit breakers. Second, a fault occurs when the load of an island zone is higher than the generation capacity of DG or DGs within that zone, in other words the load is higher than zone's average load. In these conditions if disconnection of load does not happen, frequency of the zone operating in island status drops considerably and this leads the zone encounters power cut problem.

To perform load shedding accurately, it is required to have all loads of substations at each time as well as their degree of importance, in order to be able to determine priority of loads disconnection and maintain the balance between generation and consumption. This needs precise loads monitoring of each and every single of the existing substations in a distribution network, which is very costly and is practical in no network. Thus, it is required to apply some approximate approaches and monitoring of currents in the most appropriate points of network to make the best decision, regarding facing the lowest possible power cut in zones as well as maintaining the balance between generation and consumption. In this paper, this algorithm has been implemented using continuous monitoring of currents flowing through circuit breakers that form zones. This is done using the fact that at each time the whole load of each zone can be calculated using (1):

$$P_L = \sum_i P_{CBi} + \sum_j P_{DGj} \quad (1)$$

In this equation $\sum P_{CBi}$ indicates the whole power flows into zone and $\sum P_{DGj}$ indicates the whole power of all DGs placed in that zone. It is obvious that negative value of $\sum P_{CBi}$ for a specific zone shows that generation in that zone is higher than load of that zone and the zone exports energy to other zones. Considering the point that at each time relay monitors powers following through DGs and isolating breakers of zones, it can determine instantaneous difference between generation and load of each zone, through calculating instantaneous $\sum P_{CBi}$. Therefore, when network faces a fault, relay can determine whether there is shortage or excess of load in zones including DG, using these values for the time exactly before occurrence of fault. For those zones that must operate in island status and their generation is more than their consumption, relay does not shed any loads and lets zones' DGs maintain the balance between generation and consumption through frequency control system existing in each zone. But, relay performs load shedding operation when there is overload within the zone. Relay sends disconnection command to load break switches of loads through considering a safety factor (for instance 1.1), and also considering importance of loads as well as the estimated values of loads at the time that fault occurs. The following equation shows the load that must be disconnected in each zone:

$$P_{cut} = SF \times \sum_i P_{CBi} \quad (2)$$

It might be possible to implement this idea through modeling only some part of network loads and placing load break switches for those loads (The loads that have lower importance and their summation is equal to the difference of peak and average loads of each zone). Obviously, this is simpler and regarding economic considerations, it has lower costs. But, it is important to note that through placing load break switches for all loads of those zones that contain DG, flexibility of protection scheme increases considerably, in such a way that if generation capacity of DGs of a zone decreases (for any reason) or even if DGs go out of operation (due to forced outage or for maintenance), there is no need to change the protection algorithm of relay and the designed protection system will be still effective. For instance if there are two DGs located in one zone, and one of them goes out of operation, it is possible the remaining DG not to be able to supply load, even in minimum load regime. In this situation, the main relay disconnects loads till the balance between generation and consumption is achieved. Of course, for this situation, and for the situation in which there is only one DG in a zone, and the DG has gone out of operation for any reason, it is needed to update network data and redo offline calculations for the new network in order the relay avoids wrong diagnosis of fault location. Apparently, for the situation in which there is only one DG in a zone and that DG has gone out of operation, the zone can be regarded as second type of zone (zones without DG) to be needless of operation of load shedding in that zone.

"Figure 2" illustrates the load shedding algorithm of the main relay.

## X. Simulation Results

Proposed algorithm in this paper has been implemented using MATLAB and a software application has been provided to implement designed protection scheme and to simulate operation of main relay installed in sub-transmission substation. The distribution network that the proposed scheme implemented on it, is a radial 20kVdistribution feeder with a 4.9 MVA diesel generator and is simulated using DIgSILENT Power Factory. For each load a three-step hourly load curve is considered, which is shown in "Fig. 3". The peak load for all loads is 2 MW and power factor for all of them and in every time is 0.92. Performing zoning procedure on this network causes to have 3 zones that one of them includes DG and has the capability of island operation. “Fig. 4,” shows single line diagram and zoning approach of simulated feeder. To make sure the main relay operates accurately; its operation has gone through detailed investigation with different faults but in this paper the operations of the main relay in the case of following three scenarios are presented:

- ✓ Single-phase fault on the line connecting buses 7 and 8;
- ✓ Two-phase fault on the line connecting buses 3 and 4;
- ✓ Three-phase fault on the line connecting buses 5 and 6;

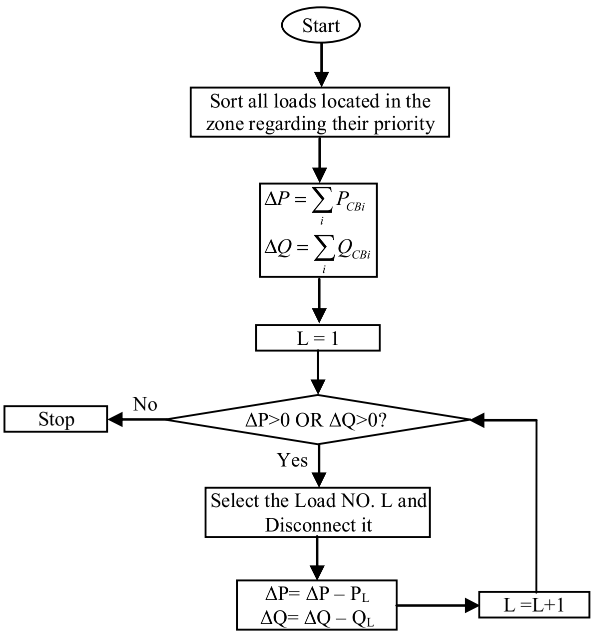


Fig. 2. Load shedding algorithm of the main relay

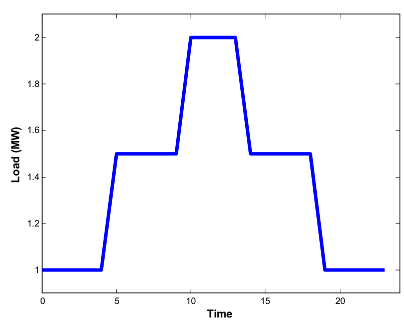


Fig. 3. Hourly load curve of the simulated feeder's loads

### *A. Single-phase fault on the line connecting buses 7 and 8*

In this situation, the relay sends disconnection commands to $CB_1$, $CB_2$, and $CB_3$ immediately after it diagnoses fault type as well as it determines fault occurrence in the first zone ($Z_1$). Thus, $Z_1$ and $Z_3$ face power cut and $Z_2$ go on operating as an electric island. Then, to diagnose whether fault is transient reclosing operation is done by $CB_1$, this operation is also coordinated with $F_1$ by the main relay. Obviously, there is no need to synchronize the network, since $Z_1$ has faced power outage. If the fault is permanent, $F_1$ cuts the faulty branch and during slow reclosing operation, $Z_1$ is supplied with power and then closing signals are sent to $CB_2$ (in parallel with network synchronization operation) and $CB_3$. However, in the case if $F_1$ is not able to isolate the faulty section, $CB_1$, $CB_2$, and $CB_3$ remain open. Also, if the fault is transient and is cleared during reclosing operation, the network must be restored. To make restoration, first, connection signal is sent to $CB_1$, then, $CB_2$ is closed with network synchronization operation, and finally connection signal is sent to $CB_3$.

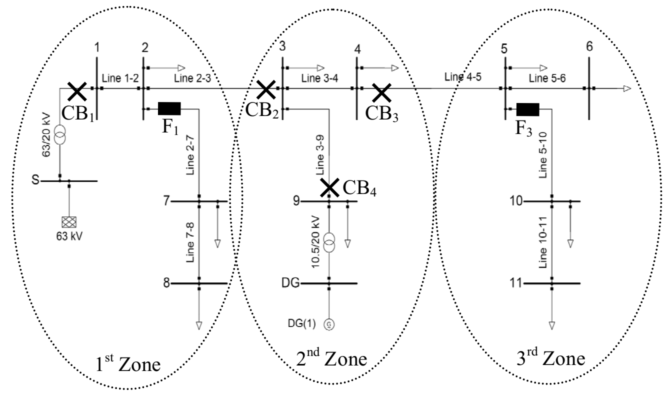


Fig. 4. Single line diagram of the studied distribution feeder and its zoning after connection of DG

To evaluate relay's load shedding algorithm, the above fault has to be simulated for two conditions, peak load and minimum load conditions. Simulation results indicate that at minimum load condition, relay's load shedding unit sends no command, but at peak load condition sends disconnection command to load break switch of substation 4 in order to maintain the balance between generation and consumption in $Z_2$ with considering. Output result of relay simulation software application is as follows:

```
>>
The fault is single-phase fault.
The faulted section is section 3 which connects bus 7 to 8.
The faulted zone is zone 1.
CB1 ==> Opened
CB2 ==> Opened
CB3 ==> Opened
CB1 ==> Reclosed
For transient fault:
    CB2 ==> Closed
    CB3 ==> Closed (with synchronizing function)
For permanent fault:
    CB1 ==> Opened
    CB1 ==> Reclosed
    If F1 removed the fault then:
        CB2 ==> Closed
        CB3 ==> Closed (with synchronizing function)
    If F1 did not remove the fault then:
        CB1 ==> Opened
        Load 4 ==> shed
>>
```

### *B. Two-phase fault on the line connecting buses 3 and 4*

In this situation, the relay sends disconnection commands to $CB_2$, $CB_3$, and $CB_4$, immediately after it diagnoses fault type as well as it determines fault occurrence in the second zone ($Z_2$). Therefore, $Z_2$ is isolated thoroughly. Thus, $Z_1$ is supplied by the main source and $Z_2$ and $Z_3$ face power cut. Then, to diagnose whether fault is transient reclosing operation is done by $CB_2$. Obviously, there is no need to synchronize the network, since $Z_2$ has faced power outage. If the fault is permanent, $CB_2$, $CB_3$, and $CB_4$ remain open. But, if the fault is transient and is cleared during reclosing operation, the network must be restored. To make restoration, connection signals are sent to $CB_3$ and $CB_4$, as well as network synchronization operation. Output result of relay simulation software application for this scenario is as follows:

```
>>
The fault is two-phase fault.
The faulted section is section 5 which connects bus 3 to 4.
The faulted zone is zone 2.
CB2 ==> Opened
CB3 ==> Opened
CB4 ==> Opened
CB2 ==> Reclosed
For Transient Fault:
    CB3 ==> Closed
    CB4 ==> Closed (with synchronizing function)
For Permanent Fault:
    CB2 ==> Opened
Load Shedding is not required in this situation.
>>
```

### C. *Three-phase fault on the line connecting buses 5 and 6*

In this situation, the relay sends disconnection command to $CB_3$, immediately after it diagnoses fault type as well as it determines fault occurrence in the third zone ($Z_3$). Therefore, only $Z_3$ faces power cut and $Z_1$ and $Z_2$ are still supplied through main source. Then, to diagnose whether fault is transient reclosing operation is done like what was done for previous situations, except that this time relay assigns this task to $CB_3$.

If the fault is transient and is cleared, relay sends reclosing signal to $CB_3$ to supply $Z_3$ through its upstream network. If the fault is permanent, $CB_3$ remain open and $Z_3$ faces power outage. Output result of relay simulation software application for this scenario is as follows:

```
>>
The fault is three-phase fault.
The faulted section is section 8 which connects bus 5 to 6.
The faulted zone is zone 3.
CB3 ==> Opened
CB3 ==> Reclosed
For Transient Fault:
    No signal is needed.
For Permanent Fault:
    CB3 ==> Opened
Load Shedding is not required in this situation.
>>
```

## XI. Conclusion

In this paper, an algorithm for protection of distribution networks in presence of DG was proposed. The algorithm uses network zoning approach, in which each zone is an independent section, capable of island operation whenever needed. In the proposed algorithm, after dividing distribution system into several independent zones, computer-based relay that has been installed in sub-transmission substation, diagnoses exact fault location through making comparison between needed measured currents and results of offline calculations and sends required commands and signals to protection devices in order to isolate the faulty zone from the rest of network.

Besides, the algorithm has the ability to perform reclosing operation as well as coordination with fuses of network using software procedures. In the end, when fault is cleared, network restoration in addition to synchronization operation is done through sending reclosing commands to circuit breakers.

In the end, the proposed algorithm was implemented on a distribution network and performance of the main relay was tested.

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