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A New Adaptive Method for Distribution System Protection Considering Distributed Generation Units Using Simulated Annealing Method

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1. Introduction

Distribution systems usually have radial configuration and have unbalanced operation. Distribution system protection is based on a time over current method. This method includes selection of equipment and settings, placement of equipment, and coordination of devices to clear faults with as little impact on customers as possible. Equipment in distribution protection consists of fuses, reclosers and sectionalizers. Also an over current time inverse relay usually exists inside the distribution substation at feeder outset. In distribution system, the main priorities are to prevent further damage to utility equipment, reliability and power quality (Barker & De Mello, 2003).

The installation of small distributed generation (DG) units at distribution system has many advantages such as energy efficiency, environmental considerations and voltage support. A wide range of power generation technologies are currently in use or under development, these technologies includes: small combustion turbines and micro turbines, small steam turbines, fuel cells, small-scale hydroelectric power, photovoltaic, solar energy, wind turbines and energy storage technologies. Also, Insertion of DG in distribution systems may create technical and safety problems (Brahma, 2001). DG may contribute to increased fault currents, cause in voltage oscillations, decrease or increase losses and interfere in voltage control processes. On the other sides the distribution systems are well designed which could handle the addition of DG if proper grounding, transformers and protection is provided. In fact, all analysis about distribution system occurrence should be reanalyzed as the DG impacts are significant for both planning and operation of distribution networks. The problems associated with protection devices operation and coordination requires special review since they may affect the system security and dependability (Brahma, 2004).

A sample distribution system with DG is shown in Figure 1. In such system DG feed adjacent loads and the system doesn't have radial property. So protection devices must have directional sensitivity in systems with several sources. Fuses, reclosers and sectionalizers don't have directional property while over current relays can equipped with directional element. But displacement of fuses and reclosers with directional over current relays is impossible because of economic considerations. So we need a generalized analysis to distinguish coordination problems of fuse-fuse and fuse-recloser in presence of DG.

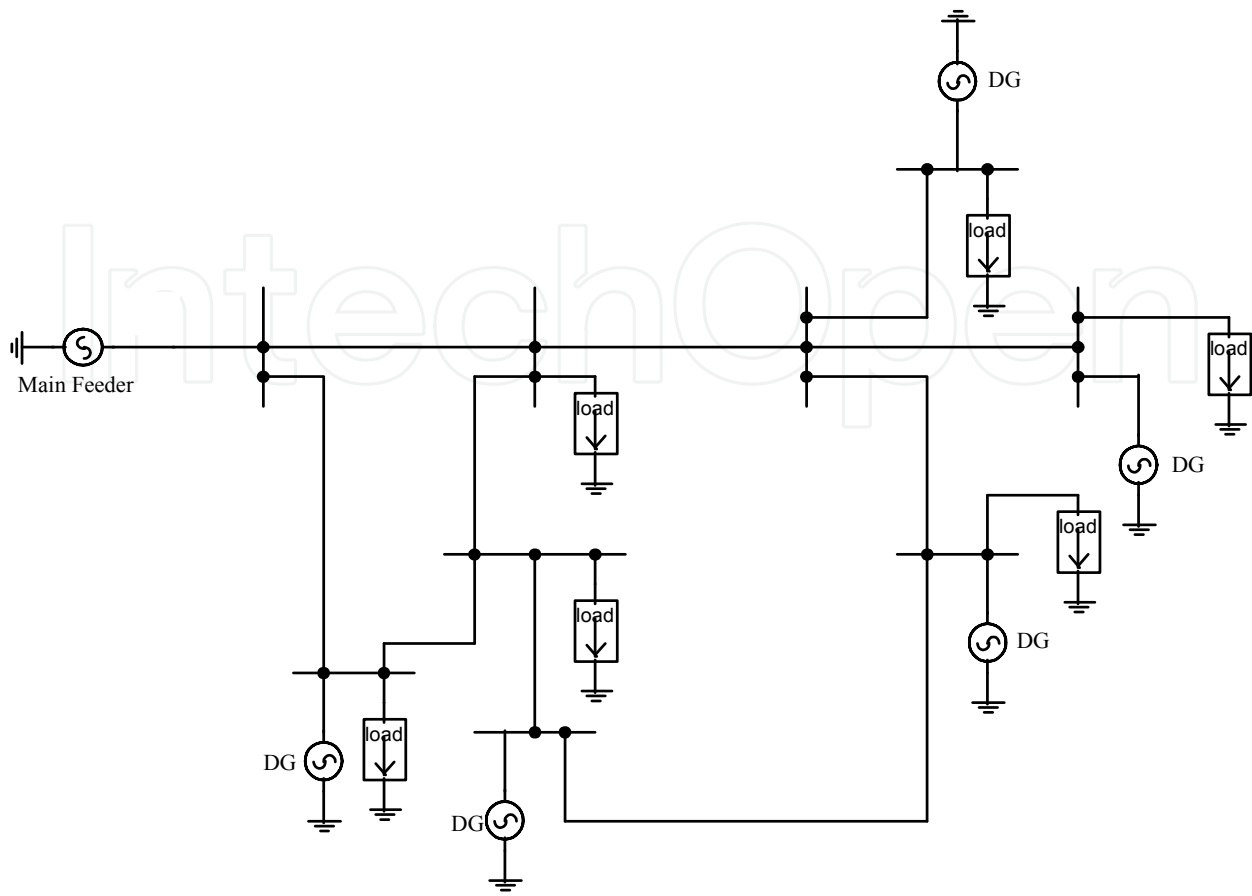


Fig. 1. Sample Distribution System with DG

In this paper, the effect of DG insertion into a distribution network on protection system operation is evaluated by means of short circuit analysis and protective device coordination. In the other words, this paper describes the characteristics of distribution feeder protection and DG interconnection protection, respectively. A new adaptive method is presented based on simulated annealing optimization method for distribution protection considering DG. Simulation results show the effectiveness of the proposed method.

2. Proposed methodology

As it mentioned in previous section, distribution system misses its radial nature in presence of distributed generations. So the protective devices may lose their coordination and proper operation. To keep the coordination of protective devices, it is necessary to separate distributed generations after each fault even for transient fault. The ideal for each protection scheme is that only the faulted section is separated form system and other parts maintain their operations. It should be noted that the coordination of fuse-fuse, fuse-recloser, fuse-relay and relay-recloser diminish considering the loss of radial nature of distribution network after DG insertion. So the best approach is to divide the distribution system into several zones as shown in Figure 2. These zones should be separated by circuit breakers. The breakers must have the ability of system synchronization and frequent switching because of receiving a signal from main relay located in the substation.

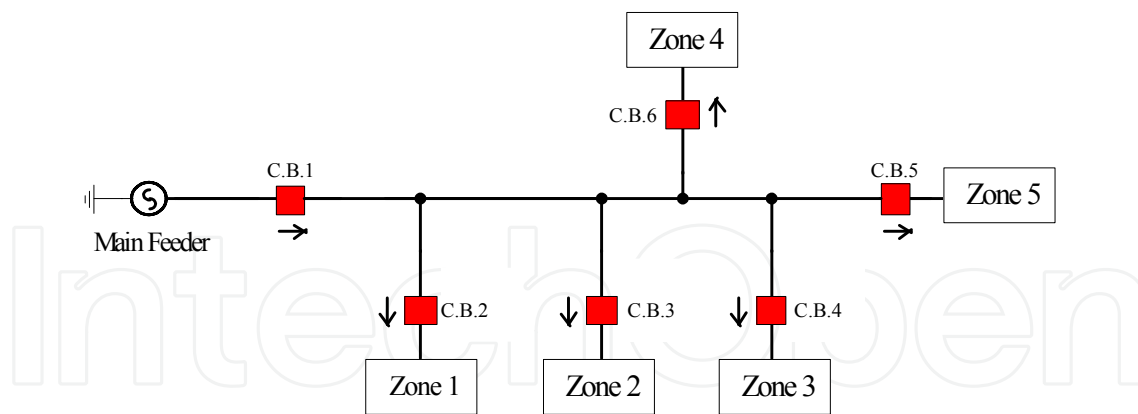


Fig. 2. Distribution system divided into several zones

Outline of proposed adaptive protection method is that first, adaptive relay detects the fault in the system and the fault in DG. If the fault occurred in DG, adaptive relay waits until DG protection system detects the fault and isolates DG from distribution system. Then DG circuit breaker sends a signal to adaptive relay so the adaptive relay will do required analysis for new condition of system. If fault is on the system bus bars, adaptive relay performs online short circuit analysis, detects the fault location and faulted zone and sends a trip command to faulted zone circuit breaker and faulted DG circuit breakers. So only the faulted zone is separated from network and other zones continue their normal operations.

3. Inputs and online calculations

The following measurements are used for the proposed algorithm:

- RMS value of three phase current in each DG and main source.
- A signal indicating the current flow direction in each zone circuit breaker and each DG circuit breaker (Chowdhury & Crossley ,2009).

The current indicating signal reports the status of circuit breakers in each zone and DG to the mail relay so the relay run the adaptive algorithm based on the network situation.

The main principles of proposed adaptive algorithm are that first the distribution system data such as loads, line specifications, generator data, transformer data, busbar voltages, circuit breakers status and measured currents are collected and the following online steps are performed in order to specify the fault type and fault location occurred in DG or system busbars. Then a trip command is issued to separate the faulted zone from the network.

4. Short circuit analysis

This adaptive method is based on short circuit analysis for all types of occurred faults in different phases. Also the contribution of main feeder and each DG for various fault current in each bus must be determined. Short circuit analysis calculations have to be changed and updated after major changes in load, DG or system configuration. So after each change, short circuit analysis is performed online and required information will be send to adaptive relay in order to analysis and Prescription (Sukumar ,2001).

In case of normal operation, total flow of all sources (main source and all DG's) is equal to load current. In case of short circuit conditions the current balance equation is written as following:

$$I_F = \sum_{i=1}^N I_{Fi} \quad (1)$$

Where: I_F is total fault current, I_{Fi} is the contribution of each DG in fault current and N is the number of DG's.

In the proposed protective method, if a fault occurs in DG, total source currents are approximately equal to load current according to (1). With the difference that all source currents increased significantly. In this case the protection system of faulted DG sense the fault current and send the trip command to DG's circuit breakers and related zone circuit breaker. But if fault occurs in each part of system, total short circuit currents become significantly higher than load current. Thus the fault in DG is detected from fault in system. If the system fault is transient, first the trip command is sent to DG circuit breaker in faulted zone. This DG's never connected to system until the fault is removed from system. Also adaptive relay performs short circuit analysis and load flow immediately according to new network configuration (without DG's in faulted zone). After about 20 cycles, a reclosing command is sent to faulty zone circuit breaker. In this stage if the transient fault is removed, the adaptive relay send a command to DG circuit breaker after about 2s and after the synchronism operation DG connected to system. After this step, adaptive relay perform the short circuit analysis for going situation. If the transient fault is unresolved in first stage of reclosing, relay sent trip command to zone circuit breaker immediately and the reclosing operation is done until three stages.

5. Fault location determination

In the proposed Adaptive method, a fast detection method is needed for faulted zone diagnosis. So the adaptive relay can send the trip command to each zone and faulted zone circuit breakers. It is necessary to note that faulted zone identification is enough for operation of this method. However if the faulted zone is not specified as precise as possible, much effort will be imposed to maintenance personnel to fault location determination. In order to precise fault location determination, least square method is used. This method is one of the most famous and the most practical methods in system identification theory. There is always a difference between intended structure for modeled system and actual system. Because of nonlinear specification of actual system that be considered linear in modeled system. So there is a difference e_t between measured output and model output at any moment. The objective in the least square method is to minimize the sum of the squared errors ($\sum e_t^2$).

In the presented adaptive scheme for distribution system, there is always a difference between measured current and obtained current from short circuit analysis. Since the contribution of measured currents from measurement devices and short circuit analysis of each source is available online, the adaptive method can use these currents for placement in least square method. For this purpose, a look-up table as shown in Table 1 according to short circuit analysis for each bus in each zone is formed (Dugan & McDermott, 2002).

zone		
Bus		
I _{DG1} - Calculated	Phase 1	
	Phase 2	
	Phase 3	
I _{DG2} - Calculated	Phase 1	
	Phase 2	
	Phase 3	
I _{Source} - Calculated	Phase 1	
	Phase 2	
	Phase 3	

Table 1. A look-up table for fault location determination

After the fault is occurred in distribution system, the adaptive relay synthesizes Table 2 with Table 1. In this table the measured currents for sources (DG's and main source) and measurement error for each source according to (2)-(3) are placed (Kotamarty et al., 2008).

zone		
Bus		
I _{DG1} - measured	Phase 1	
	Phase 2	
	Phase 3	
I _{DG2} - measured	Phase 1	
	Phase 2	
	Phase 3	
I _{Source} - measured	Phase 1	
	Phase 2	
	Phase 3	
E _{DG1}		
E _{DG2}		
E _{Source}		

Table 2. Synthesized table in adaptive relay

$$E_{DG} = \sum_{i=1}^3 \left[(I_i)_{DG- Calculated} - (I_i)_{DG- measured} \right]^2 \quad (2)$$

$$E_{Source} = \sum_{i=1}^3 \left[(I_i)_{Source- Calculated} - (I_i)_{Source- measured} \right]^2 \quad (3)$$

When a fault is sensed in distribution system, adaptive relay forms the Table 2 immediately according to short circuit analysis and direct measurements for all system buses and calculates the error for each bus. The minimum value of error is obtained from the calculated error so the faulted bus is determined. The adaptive relay sends the trip command to faulted zone circuit breaker and prepares Table 2 for new conditions.

6. Proposed adaptive protection scheme algorithm

The proposed method for adaptive protection of distribution system is shown in figure 3. The adaptive relay receives source currents from measurement devices and compares the sum of source currents with load current. If the total current is approximately equal with load current and a fault occurs in a DG, adaptive relay waits until DG local protection system operates. If the total current be more than load current significantly, adaptive relay determines fault location and recalls the look-up table obtained from short circuit analysis. Then calculates the error of calculated current and measured current for each bus of system, considers the minimum error and determines the faulted zone. As it shown in figure 3, if there is a transient or permanent fault in system, sends the trip command to DG circuit breaker that equipped with synchronization system immediately. Then reclosing operation is done on DG circuit breaker in three stages for t_1 , t_2 and t_3 duration time.

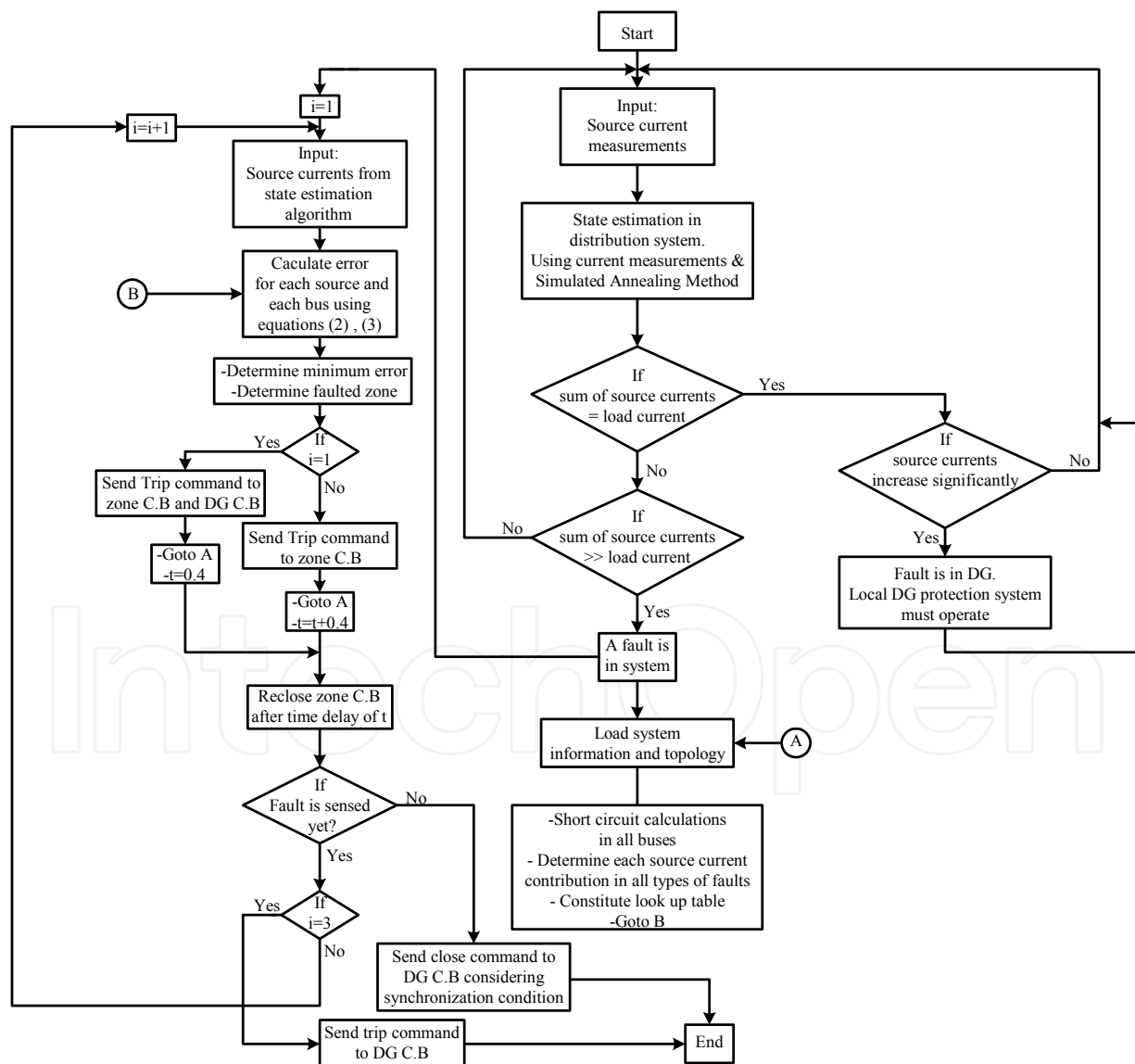


Fig. 3. Proposed adaptive protection scheme for distribution system

7. State estimation and simulated annealing method

The basic idea of the state estimation method proposed in this paper is quite simple (Mori & Saito, 2006). Besides real-time measurements, there exists other information which does not need to be measured. For sub-transmission networks, active power is always drawn from buses connected to the distribution side via transformers. On the other hand, active power taken from the transmission level is injected into a few buses of the sub-transmission portion. In general, it is possible to assert whether the specified real power for each node is less, greater than or equal to zero. This knowledge can be incorporated into the estimation process in the form of inequality constraints. The estimation problem thus becomes that of minimizing a non-linear function subject to non-linear inequality constraints. Mathematically stated:

For a given set of bus-voltage and line-current magnitude measurements, z , related to the vectors of state variables, x , and measurement error, v , by the following equation,

$$z = f(x) + v \quad (4)$$

The estimate \hat{x} is the one which minimizes the scalar

$$\begin{aligned} J(x) &= [z - f(x)]^T R [z - f(x)] = v^T R v \\ \text{Subject to} & \\ C_i(x) &\geq 0 \quad i = 1, 2, \dots, N \end{aligned} \quad (5)$$

In equation (4) the rows corresponding to a voltage measurement are trivial. For a current measurement between nodes i and j the following equation is used,

$$\begin{aligned} I_{ij} &= \sqrt{AV_i^2 + BV_j^2 - 2V_i V_j (C \cos \theta_{ij} - D \sin \theta_{ij})} \\ A &= g_{ij}^2 + (b_{ij} + b_{sh}/2)^2 \\ B &= g_{ij}^2 + b_{ij}^2 \\ C &= g_{ij}^2 + b_{ij}(b_{ij} + b_{sh}/2) \\ D &= g_{ij} b_{sh}/2 \end{aligned} \quad (6)$$

Where g_{ij} , b_{ij} and b_{sh} are the π -equivalent line parameters.

Matrix R in equation (5) is the inverse of the measurement covariance matrix. Inequalities are the real components of the well-known Power Flow equations,

$$C_i(x) = \pm \sum_{j=1}^N V_i V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \quad (7)$$

Where, for load buses, the minus sign must be used. Although zero injection buses may be indistinctly regarded as loads or generators, it is advantageous, for accuracy improvement, to treat them as equality constraints. A clear advantage of current and voltage magnitude measurements is the simplicity for a pre filtering to be implemented. Voltage magnitudes

differ more than a certain threshold from 1 p.u. should be discarded. Similarly, ampere measurements at both line ends should be almost equal for lines with negligible shunt susceptance.

In this paper the Simulated Annealing Method (SA) is used in optimization part. Simulated annealing is a method for solving unconstrained and bound-constrained optimization problems (Ingber, 1993). The method models the physical process of heating a material and then slowly lowering the temperature to decrease defects, thus minimizing the system energy. In iterations of simulated annealing algorithm, a new point is randomly generated. The distance of the new point from the current point, or the extent of the search, is based on a probability distribution with a scale proportional to the temperature. The algorithm accepts all new points that lower the objective, but also, with a certain probability, points that raise the objective. By accepting points that raise the objective, the algorithm avoids being trapped in local minima, and is able to explore globally for more possible solutions. An annealing schedule is selected to systematically decrease the temperature as the algorithm proceeds. As the temperature decreases, the algorithm reduces the extent of its search to converge to a minimum. Many standard optimization algorithms get stuck in local minima. Because the simulated annealing algorithm performs a wide random search, the chance of being trapped in local minima is decreased.

8. Simulation results

As it mentioned previous, proposed protective scheme is simulated for a sample distribution network. Short circuit analysis and adaptive protection algorithm must be examined simultaneously and online. PSCAD is used for adaptive algorithm and distribution system simulation and MATLAB is used for short circuit analysis and state estimation using simulated annealing method. After changes in system topology, short circuit analysis results vary. So the short circuit analysis must be shared to adaptive algorithm online and a data transfer link is needed between PSCAD and MATLAB software.

Figure 4 shows the system single line diagram, load specification, fuses and reclosers situation and distributed generations. Total load of system is 2.2 MVA and the system voltage is 20 kV. DG's characteristics are shown in table 3. DG's are modeled as a source and internal impedance and Transformers connection is D/YG 11.

For implementation of proposed method, the network is divided to four zones. Zone 1 clarifies with C.B zone1 circuit breaker and consists of main source and DG2. Zone 2 clarifies with C.B zone2 circuit breaker and consists of DG1. Zone 3 clarifies with C.B zone3 circuit breaker and consists of DG3. Finally Zone 4 clarifies with C.B zone4 circuit breaker and consists of DG4 and DG5.

DG	DG1	DG2	DG3	DG4	DG5
S (kVA)	400	150	400	200	150
R (p.u.)	0.0476	0.0935	0.0714	0.0914	0.0429
X (p.u.)	0.4846	0.6120	0.5244	0.7608	0.5389

Table 3. DG's and transformers characteristics

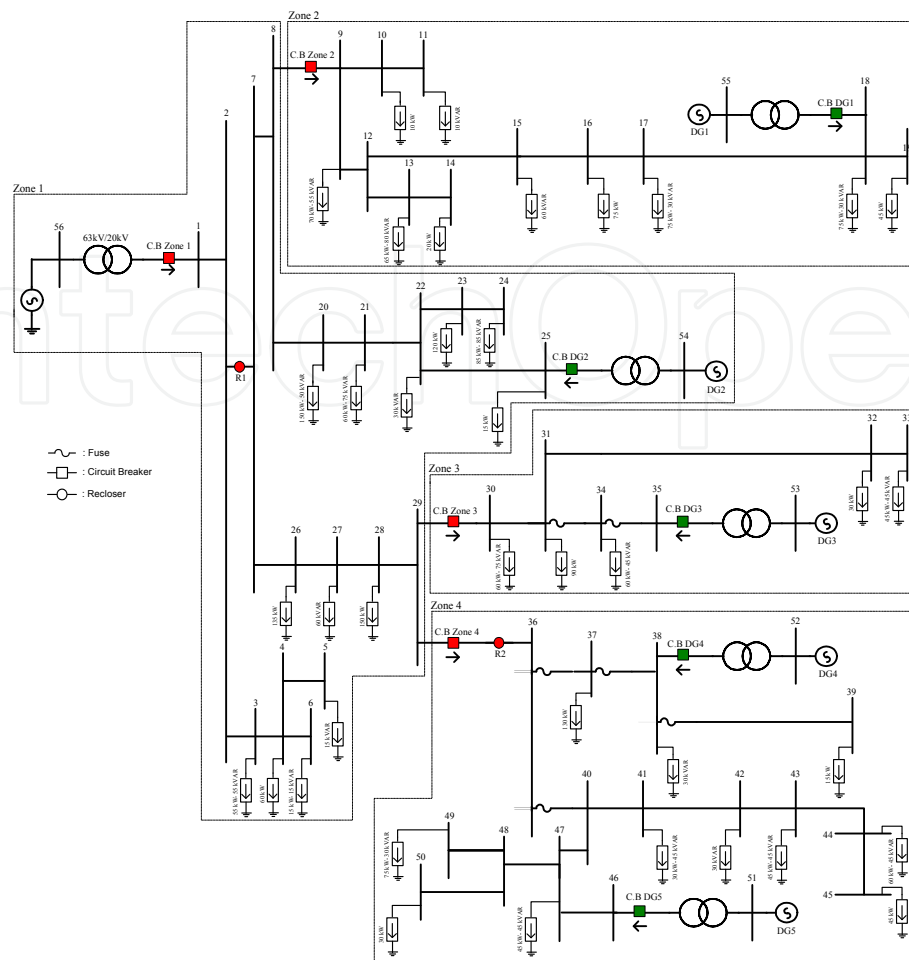


Fig. 4. Proposed adaptive protection scheme for distribution system

The adaptive algorithm is tested under different conditions and faults to ensure of proper performance. These conditions are fault in DG, permanent and transient fault in system buses. The performance of adaptive relay has been studied for some of these faults.

In case of fault occurred in DG, Adaptive relay waits until DG protection system operates and issues the trip command. As it seen in figure 5, while a fault occurs in DG1, current comparator in adaptive relay permits that DG over current relay operates. While a fault occurs in a DG, only the faulted DG must be disconnected from network and the other parts must continue their normal operations as it seen in figure 5.

In case of studying permanent faults in a system bus, it is assumed that a fault occurs in bus 41 in zone 4. This fault occurs at $t=2$ s and the fault duration is 3 s. Figures 6 shows that the adaptive relay sends a trip command to DG4, DG5 and zone 4 circuit breaker immediately. As the fault is permanent, adaptive relays doesn't allow DG's to connect on network, even after clearing the fault. After disconnecting DG4 and DG5, the adaptive relay does a reclosing operation on zone 4 circuit breaker. First reclosing is done on the circuit breaker at 0.4 s after fault occurrence. Second and third reclosing are done 1.2 s and 2.4 s after fault occurrence. This is shown in figure 6. Since the fault is permanent, in each reclosing stage, the adaptive relay senses the fault and sends trip command. After the third reclosing, trip command is sent to zone 4 circuit breaker and zone 4 is disconnected from network.

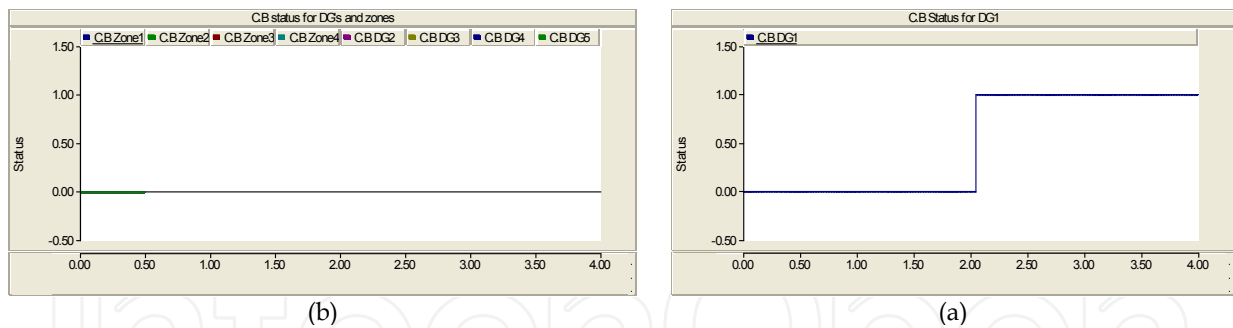


Fig. 5. Fault occurs in DG1. (a) DG1 C.B status. (b) Other DG's and zones C.B status.

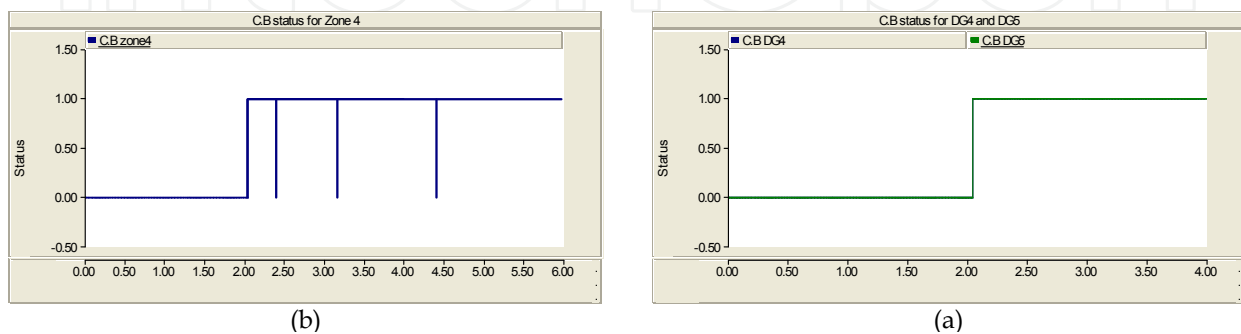


Fig. 6. Fault occurs in zone 4. (a) DG4 and DG5 C.B status. (b) Reclosing on zone4 C.B.

In the proposed method, only the faulted zone and DG's in that zone are disconnected from network and therefore the other zones can continue their normal operation. In order that the faulted zone returns to network as soon as possible, it must be detected precisely so that the fault could be cleared from the zone. Figure 7 shows the adaptive relay operation in precise fault location determination.

Finally, adaptive relay operation in case of transient fault in system has been investigated. The fault duration is considered in three cases so that we can study the adaptive relay operation at three stages of reclosing. In this simulation, first stage of reclosing is done 0.4 s after the fault occurrence, second stage of reclosing is done 0.8 s after the first reclosing and third stage of reclosing is done 1.2 s after the second reclosing.

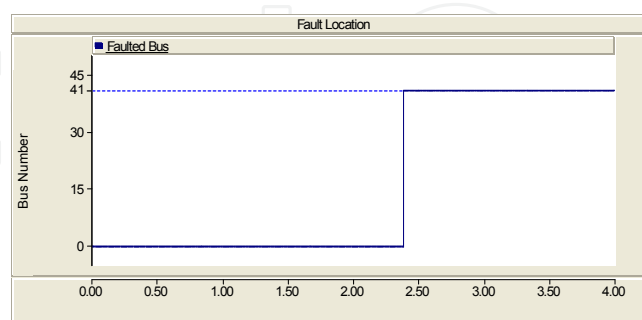


Fig. 7. Fault location determination in case of permanent fault

The fault location is in bus 32 in zone 3, fault duration is 0.3 s, time to apply fault is $t=2$ s.

As it seen in figure 8, adaptive relay sends the trip command to zone 3 and DG3 circuit breakers. After 0.4 s, a reclosing operation is done on zone 3 circuit breaker. As the fault duration is 0.3 s, after the first reclosing, adaptive relay doesn't sense the short circuit

current in the network and since a close command is sent to zone 3 circuit breaker. It is needed that DG be connected to network after fault clearing. So that synchronization operation must be done on DG3 circuit breaker. As it seen in figure 8, adaptive relay permits DG3 circuit breaker to close after 3 s, so that synchronization could be done.

It must be noticed that adaptive relay does reclosing operation only in faulted zone and other zones can continue their normal operation.

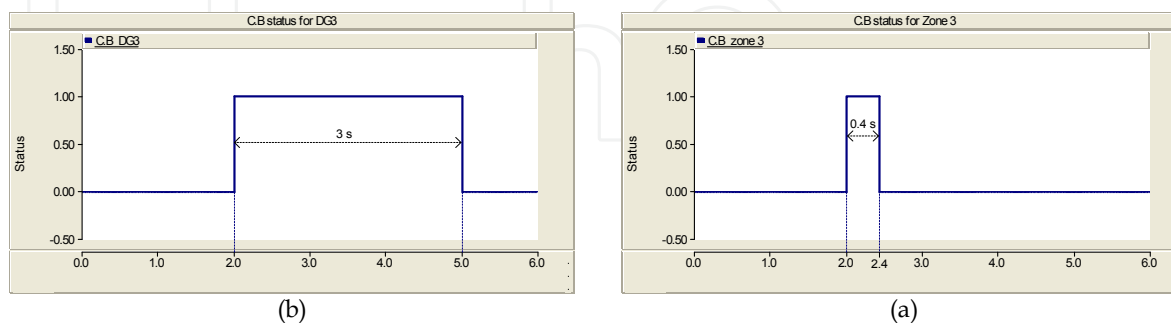


Fig. 8. Adaptive relay operation while clearing fault before first reclosing. (a) Zone 3 C.B status. (b) DG3 C.B status.

The fault location is in bus 34 in zone 3, fault duration is 0.6 s, time to apply fault is $t=2$ s.

In this case, after the fault is sensed with adaptive relay in network, the trip command is sent to DG3 and zone 3 circuit breakers immediately. As it seen in figure 9, does the first reclosing on zone 3 circuit breaker. According to the fault time that is more than 0.4 s, relay senses the fault in first reclosing and sends trip command to zone 3 circuit breaker instantaneously. Adaptive relay send a close command to zone 3 circuit breaker 0.8 s after the first reclosing. Since the fault time is 0.6 s, relay doesn't sense the fault in second reclosing and permits zone 3 circuit breaker to close. Moreover adaptive relay permits DG3 circuit breaker to close 2 s after second reclosing by the synchronization operation. In the explained situation, other zones should operate normally in network.

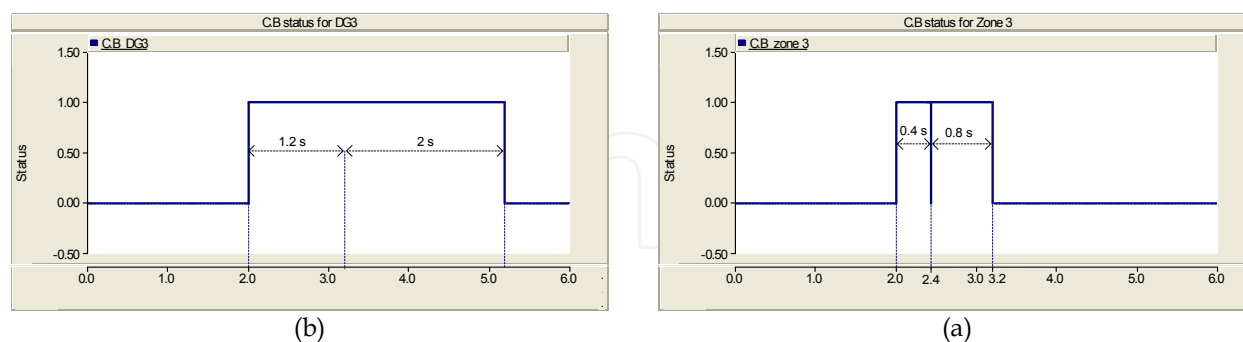


Fig. 9. Adaptive relay operation while clearing fault before second reclosing. (a) Zone 3 C.B status. (b) DG3 C.B status.

9. Conclusion

Distributed generations have possible characteristics for system operation enhancement. Using DG's in distribution systems has many benefits such as system reliability improvement, power loss reduction, development costs decrease, power quality

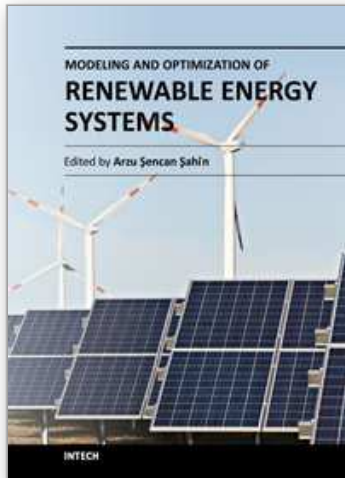
improvement and load peak clipping. Also using DG's in systems has disadvantages such as interaction with protective systems, voltage control problems and DG islanding.

While a DG is inserted in distribution system, some parts of system lose their radial characteristics and protective devices coordination is lost. If the influence of DG be intensive, then coordination of protective devices with usual method is impossible. The proposed adaptive protection scheme does short circuit analysis online and whenever system configuration varies, this analysis execution is done and a look up table is conformed. The adaptive scheme diagnoses fault location, faulted bus and faulted zone by the discussed method.

If the fault is permanent, adaptive relay disconnected only the faulted zone and DG's in that zone and other zones continue their normal operation. If the fault is transient, adaptive relay sends trip command to faulted zone and its DG's circuit breakers and then does a reclosing operation in three time stage. If the fault be cleared in each stage, relay sends close command to zone circuit breaker and sends close command to DG circuit breaker after 2 s or 3 s for synchronization operation. Adaptive relay disconnects DG's in faulted zone whether the fault is permanent or transient.

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Modeling and Optimization of Renewable Energy Systems

Edited by Dr. Arzu Şencan

ISBN 978-953-51-0600-5

Hard cover, 298 pages

Publisher InTech

Published online 11, May, 2012

Published in print edition May, 2012

This book includes solar energy, wind energy, hybrid systems, biofuels, energy management and efficiency, optimization of renewable energy systems and much more. Subsequently, the book presents the physical and technical principles of promising ways of utilizing renewable energies. The authors provide the important data and parameter sets for the major possibilities of renewable energies utilization which allow an economic and environmental assessment. Such an assessment enables us to judge the chances and limits of the multiple options utilizing renewable energy sources. It will provide useful insights in the modeling and optimization of different renewable systems. The primary target audience for the book includes students, researchers, and people working on renewable energy systems.

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Hamidreza Akhondi and Mostafa Saifali (2012). A New Adaptive Method for Distribution System Protection Considering Distributed Generation Units Using Simulated Annealing Method, Modeling and Optimization of Renewable Energy Systems, Dr. Arzu Şencan (Ed.), ISBN: 978-953-51-0600-5, InTech, Available from: <http://www.intechopen.com/books/modeling-and-optimization-of-renewable-energy-systems/a-new-adaptive-method-for-distribution-system-protection-considering-distributed-generation-units-us>

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