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A Proposed Algorithm for the Self-Healing of Power Distribution Networks

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***Abstract*— The proposed algorithm contributes towards an automated power distribution system, which optimally restores the power supply of the network by changing the existing topology, during an unplanned power outage. By automatic reconfiguration of the network, a fault can be isolated and power can be supplied to customers who are downstream of the fault section. BPSO technique has been implemented, which ensures maximum customer connectivity and minimum power losses while maintaining a radial topology which has acceptable voltage profile, allowable thermal limits and protection selectivity. Simultaneously, new protection settings are generated for the proposed network topology, thus preventing any compromise to grid's integrity. The proposed algorithm was tested for an IEEE 33-bus distribution network on MATLAB simulation platform. The generated network configuration achieved an optimal post-fault topology. The proposed algorithm automates the process of power restoration and thereby reduces the work for engineers and improves the reliability of distribution networks.**

Index Terms—Power system restoration, Power distribution fault, Power system protection, Power system reliability

I. INTRODUCTION

In developed countries, power outages are infrequent events, however, such outages have extreme after effects [1]. The reliability of a power system is determined by two factors: frequency of outages and the duration of power outages [1]. A significant amount of research has been done to reduce the frequency of power outages. However, more methods need to be discovered to reduce the duration of power outages by improving the restoration process.

In radial distribution systems, during an outage, the downstream customers are disrupted during the fault isolation process. Therefore, an efficient self-healing strategy is required for quickly restoring power to the un-faulted sections of the distribution network to minimize the impact of interruption to as few consumers as possible.

Modern distribution systems are embedded with remote controlled sectionalizing switches, which are used to alter the network configuration permitting the distribution engineers to improve load balancing, thus improving the voltage profile and diminishing power losses [2].

The compartmentalising of the distribution network is an effective scheme to improve its reliability. The topology of the network can be reconfigured to provide electricity to the un-served customers in the healthy section of the feeder. However, restoring power through changing the network topology is a combinatorial problem and needs to be solved via optimization.

In this paper, extant methodologies for solving a network reconfiguration problem have been presented. A novel algorithm capable of re-routing the power supply through network reconfiguration, during a fault event, has been proposed. The proposed algorithm aims to maximize the number of customers connected and minimize the associated power losses while all other network constraints are met.

The structure of this paper is as follows: Section II provides commentary on related literature and identifies a research gap, Section III details the methodology for the proposed algorithm, the algorithm is tested in a case study in Section IV and Section V gives the conclusion and recommendations for future work.

II. LITERATURE REVIEW

The aim of this literature review is to study the extant methodologies in the field of network configuration and self-healing. The literature review will highlight the various techniques to implement self-healing and identify the missing link in the existing methodologies: the research gap in the field of self-healing via network reconfiguration.

Nara et al. proposed a re-configuration methodology using a GA in [3]. In the proposed algorithm, arrays contain the list of tie-line switch states of radial topologies. The cost function contains overall power losses and constraint values of voltage deviation and thermal limits. The results indicate that an approximate optimum is found for this optimization problem and that at least a 10% loss reduction is achieved through the proposed algorithm.

In [4], the authors proposed a Tabu search algorithm as a meta-heuristic technique for system reconfiguration to solve multi-target issues in radial distribution systems. The algorithm is tested for IEEE 33-bus system and the simulation results show the effectiveness of the proposed algorithm in reducing power losses.

In [5], a strategy based on modified BPSO is presented for distribution network reconfiguration with the goal of load balancing. As indicated by the characteristics of a distribution network, adaptions have been made to maintain the radial structure and lessen searching requirements. Results for simulations using a specimen network demonstrated that the proposed feeder reconfiguration strategy can adequately achieve load balancing.

In [6], the authors propose a modified Viterbi algorithm for self-healing of distribution networks. The main objective of the cost function is to maximize customer connectivity and to minimize the switching pair commands during the load restoration process. The constraints for the optimization technique are bus voltage deviation, voltage angle limits, thermal capacity and maintaining a radial topology for the network. Load flow analysis is performed for all topologies consisting of one switching pair operation. If the full load recovery is achieved, the switching pair operation is qualified. If more than one switching pair operation achieves the full load restoration, the pair with least bus voltage deviation is selected. Once maximum load recovery is observed, the algorithm stops, thus providing the minimum number of switching operations required to restore power. The proposed algorithm has been tested on different distribution systems and the results obtained through this algorithm are highly satisfactory.

A greedy heuristic is proposed in [7] to help find a near optimal solution to the weighed set cover problem. The proposed algorithm operates in a polynomial time computational efficiency and consists of a logarithmic estimate index to the maximum loaded regions present in a feeder. Through updating the selected switches, maximum load recovery is achievable. The test results, from simulation, demonstrate that the presented technique produces a reasonable approximation to the optima.

The protection system of the distribution network is an integral part of the power system and should not be neglected. A two-step protection methodology is presented in [8] for auto-updating the protection settings after reconfiguration. In the first stage, off-line fault studies are computed to calculate appropriate protection settings for each possible network configuration; these settings are stored in the relay's memory. Secondly, the on-line state detection algorithm detects the running state of the feeder and the protective devices adjust to suitable settings determined by on-line identified states. A central controller assists for protective implementation to detect reconfiguration of networks in order to update the new protection settings. The results from simulation show the effectiveness of the proposed algorithm for achieving optimum protection settings. However, it is important to verify the selectivity of protection settings for the primary and secondary relay after reconfiguration.

The IEEE 33-bus feeder has been used by most researchers to study the problem of network reconfiguration for various purposes. In the extant literature, it has been identified that the potential challenges associated with network reconfiguration are maintaining a radial topology and ensuring an acceptable voltage profile and allowable thermal limits. However, in the existing literature, little evidence is found that the researchers attempted to the ensure protection selectivity and discrimination for adequate running of the protection system. It is indisputable that, as the network topology of the distribution system changes, fault levels of the branches and power flow direction changes as well [8]. Therefore, the research gap in the field of self-healing via network reconfiguration is identified to be the neglect of protection considerations when altering the network topology. In response, this research gap is addressed in the proposed methodology for achieving a self-healing algorithm which provides a post-fault network topology with maximum number of customers connected and minimal power losses without violating any network constraints identified in the scientific literature: maintaining radial topology, ensuring acceptable bus voltages and branch currents without comprising the protection system of the grid. BPSO has been adopted due to its effectiveness in optimizing problems which have discrete solution space.

III. Methodology

A. Proposed Procedure

The proposed algorithm relies on the presence of remote-controlled switches, which is a crucial element in automating the process of network reconfiguration. The proposed algorithm will be running at a centralized controller located at the zone substation. All the data regarding the feeders connected to the zone substation will be fed into the program, including the operating voltages, thermal ratings, impedances of the network, existing protection settings and load distribution. At the time of fault, the system control and data acquisition (SCADA) will send a signal to the computer program identifying which circuit breaker has been tripped. The computer program will isolate the section of the tripped breaker in the simulation parameters and run in order to find the optimal solution of re-routing power supply to the affected downstream and upstream customers. Upon finding an optimal solution, the program will send commands to sectionalizing switches via SCADA and reconfigure the network topology. New protection settings will also be sent to the relays to be updated. For instance, when a fault occurs at branch 5 of the network shown in Fig. 1, relay 3 will trip the breaker, disconnecting the all the customers upstream and downstream the fault section.

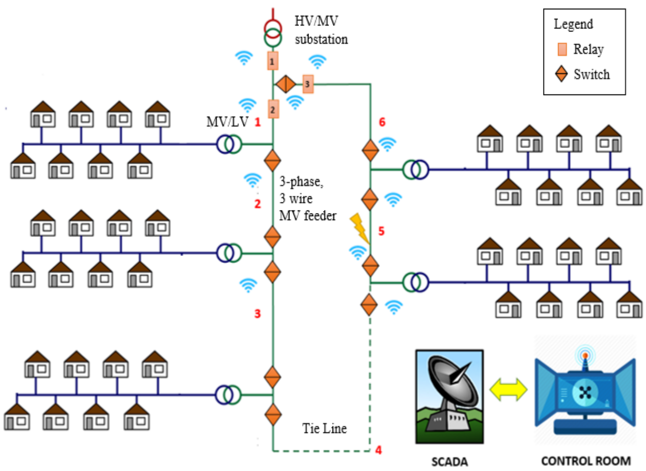

Figure 1. Structure of the automated protection system

When the proposed algorithm receives the fault location, it will isolate the section of the faulted branch in a simulation and then quickly and accurately determine the switching actions that will re-route power to the un-faulted feeder sections, opening the normally closed (NC) switches on branch 5 and closing the normally open (NO) switches on tie-line branch 4. Switching commands for the switches are sent via SCADA. Simultaneously, the protection settings of the protection relays will be calculated by the proposed algorithm in the computational phase. These protection settings from the computer system will be sent via SCADA to the respective protection relays.

B. Binary Particle Swarm Optimization

BPSO was adopted as the optimization algorithm to solve the reconfiguration problem for the purpose of self-healing. The BPSO algorithm arranges the trajectories of a population of "particles" through a problem space on two pieces of information, its own former best performance and the former best performance of any neighbouring particle. The algorithm operates on discrete binary variables and trajectories are a random number ranging between '1' and '0' [9]. Since the optimum of network topology is a combination of open or closed switches, a '0' signifies an open switch and a '1' signifies a closed switch.

Two goals are measured in this proposed algorithm. The first is to maximize the number of customers connected achieving higher customer satisfaction and second is to minimize the total power losses during normal operation. The proposed algorithm contains constraints which ensure a radial topology, allowable thermal ratings, acceptable voltage profile and a fully functional protection system.

The BPSO algorithm is initialised by determining the number of loops which can be formed by closing all the switches in the network. The number of loops in the network provides the number of dimensions for the search space. For each dimension, the sample space is defined by inputting the labels of tie-switches for each loop. A random (gbest) vector and a random initial velocity matrix are created. A (pbest) matrix is generated by creating a swarm matrix for the algorithm. The maximum number of iterations is set depending on the time constraints and complexity of the network. The tie-switch on the faulted branch is always kept in an open state in order to isolate the faulted branch. Then one switch from each of the different dimensions is opened each time to form a new topology. Any topology which violates any of the network constraints is discarded. The optimal post-fault topology restores service to maximum numbers of customers and ensures healthy operation of the network without compromising the integrity of the grid for higher customer satisfaction and increased reliability of the distribution system.

C. Problem Formulation

To obtain an optimal post-fault configuration, the network will be reconfigured by testing different switching combinations and selecting the topology which ensures maximum customer connectivity and minimal power losses by satisfying a number of objectives with constraints.

<u>Customer Connectivity</u>

Customer connectivity is the primary objective defined by the number of buses connected to the zone substation through any path. Customer connectivity can be ensured by opening only one switch from each dimension.

<u>Power Losses</u>

Power losses are the secondary objective. If two or more configurations have the same customer connectivity, then select the topology with least power losses. The power losses are calculated using the results from a load flow program.

<u>Bus Voltage Deviation</u>

$$V_{min} \leqslant V \leqslant V_{max} \quad (1)$$

The voltage range given is a constraint, where V_{min} and V_{max} are the minimum and maximum allowable rms voltages at a given bus, respectively. The values V_{min} is 0.9 per unit and V_{max} is 1.1 per unit are adopted [2].

<u>Thermal Limits</u>

$$| I | < I_{max} \quad (2)$$

Another constraint, where I is the magnitude of the current passing through any given branch, and I_{max} is the maximum allowable current through a branch, which is defined by the conductors used in the network [10].

<u>Radial Topology</u>

Distribution line protection design philosophy relies on radial power flow. Hence, an important constraint is to preclude loops in the network. Therefore, at least one switch in each of the identified loop has to be opened.

<u>Protection Selectivity</u>

$$1.1I_{peak} \leqslant | I_B | \leqslant 0.5I_{fault} \quad (3)$$

The final constraint is related to protection selectivity. I_B is the pick-up current setting for breaker B, I_{peak} is the peak current passing through breaker B, I_{fault} is the minimum fault current which will be seen by breaker B. It is essential for the relay to distinguish between half the minimum fault current and 110% overload current (extra 10% to include load forecasting) to ensure healthy protection selectivity [10]. This is one of major contributions of the proposed research methodology.

In the existing literature, most of the researchers have used a load flow algorithm in order to determine the voltage profile, branch currents and associated power losses for different network topologies. An optimization algorithm then uses these results to find the best re-route path out of all possible configurations. The proposed methodology also uses the Newton-Raphson load flow algorithm to achieve the same objective. Subsequently, fault currents at the points of interest are computed in order to ensure protection selectivity for the configuration. Based on the calculations for different topologies, the BPSO algorithm converges to an optimal post-fault network configuration.

D. Flow Diagram

The flow diagram illustrated in Fig. 2 shows how the post-fault optimal topology is found. The first step is to input the maximum number of iterations to be tested along with a random array of open switches. The algorithm starts by changing the combination of switches and generating load flow data for each combination. Upon reaching the maximum number of requested iterations, the algorithm presents the optimal solution. New protection settings are generated and updated accordingly to the required switching actions.

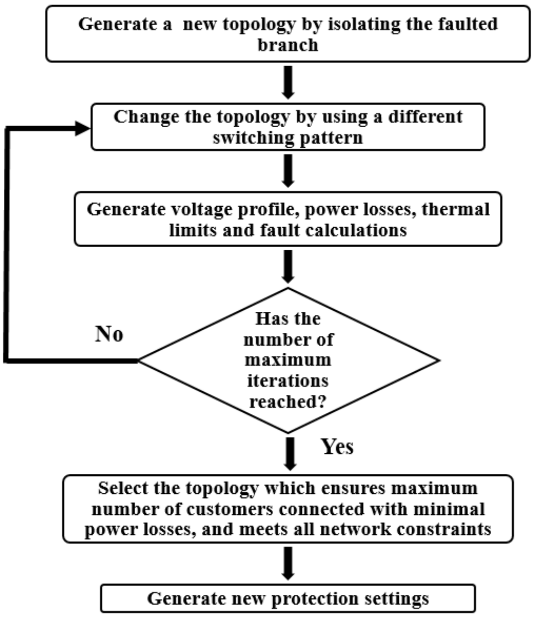

Figure 2. Flow diagram of the proposed algorithm

IV. TEST & RESULTS

To test the proposed algorithm, an IEEE 33-bus test feeder was used [11]. The test feeder is illustrated in Fig. 3. The operating voltage of the network is 12.66 kV. In this network, there are thirty-two NC switches (1-32) and five NO switches (33-37). The thermal limits for the branches are 300 A. The fault level for the system at the start of the feeders is 80 MVA. The protection system for the feeder consists of five relays: Main Relay and Branch Relays 1-4.

In order to compare the proposed BPSO algorithm with other optimization techniques, the reconfiguration problem was solved without implementing the protective constraints for the 33-bus test feeder. The optimal network topology aimed to minimize power losses and produce a better voltage profile. The results from BPSO and other optimization techniques, used by previous researchers [12], have been summarised in Table I. It was realised that BPSO produced a similar topology to the other optimization techniques. However, it was realised that BPSO converges to the near optimal solution faster than the other techniques.

TABLE I. COMPARING DIFFERENT OPTIMIZATION TECHNIQUES

Optimization Technique	Open Switches	Power Losses (kW)	Min. voltage (p.u.)
BPSO	7,9,14,32,37	139.5	0.9375
GA	7,9,14,28,32	139.9	0.9413
PSO	7,9,14,32,37	139.5	0.9375
Cuckoo-search	7,9,14,32,37	139.5	0.9375
Fire-work	7,9,14,28,32	139.9	0.9413

To test the proposed algorithm with protective constraints, a fault on branch 8 was placed in the simulation. When the algorithm was run on MATLAB, the program isolated the faulted branch and started computing the load flow analysis and fault currents for different switching combinations in order to test for bus voltage deviation, thermal limits and protection selectivity. The topologies which violated any of the constraints were discarded and out of all the technically feasible topologies, the topology with 100% load recovery and minimal power losses was selected. The post-fault optimal network topology had open switches 7, 8, 14, 32 and 37 and closed switches 33, 34, 35 and 36. The power losses associated with this configuration were 145.6 kW. The algorithm converged finding an optimal solution in 37.1 seconds. The proposed topology has been illustrated in Fig. 4.

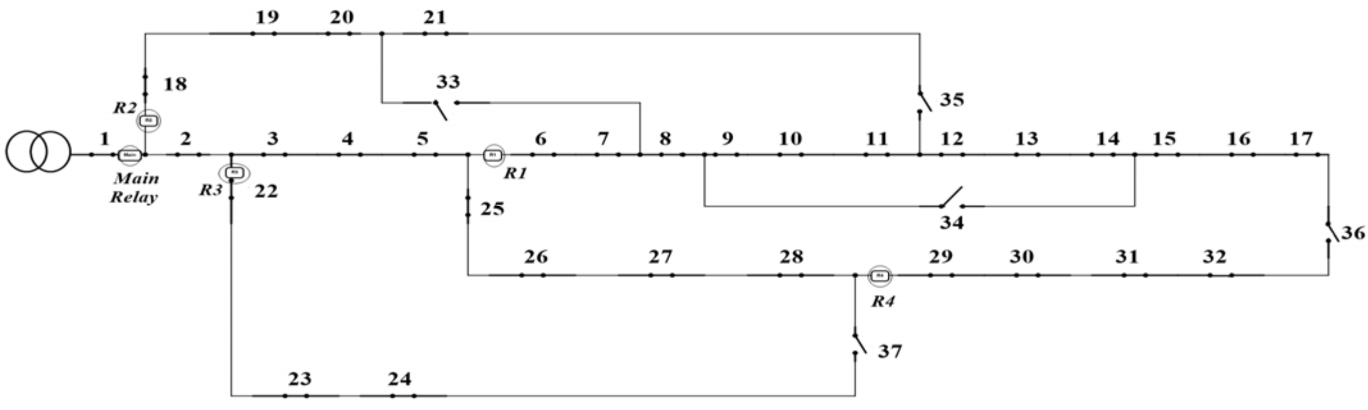

Figure 3. IEEE 33-bus tester feeder in the actual configuration

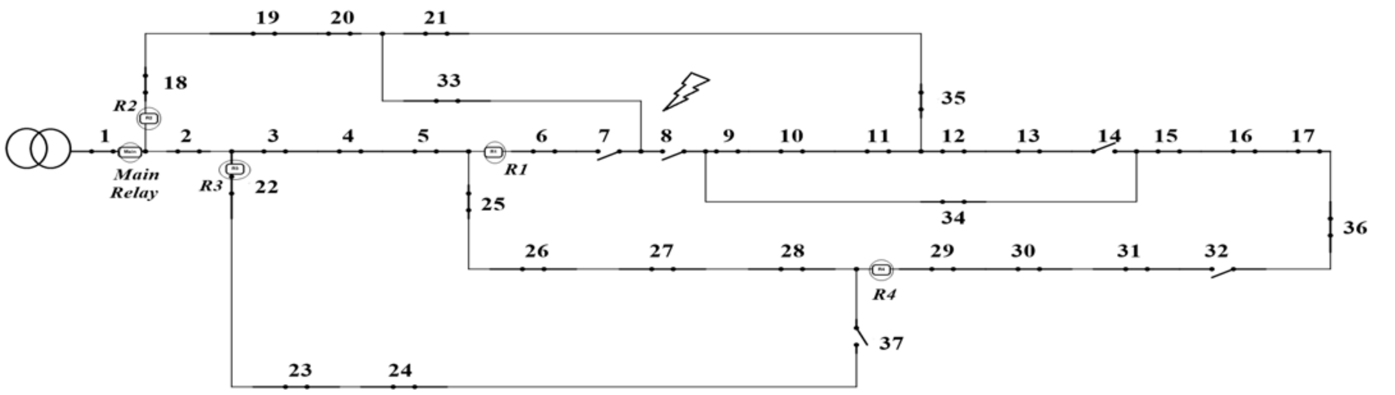

Figure 4. Post-fault network topology

The post-fault topology successfully isolated the fault and selected the topology that had the maximum number of connected customers; associated power losses were also minimal. The network was tested for constraints and the results showed an acceptable voltage profile, allowable thermal limits and protection selectivity was established. Moreover, the algorithm also generated new over-current (OC) protection settings for each protective relay. The new OC settings were compared to the old OC settings as shown in Table II. It is evident from Table II that if the protection settings of the OC relays are not changed, the protection system will not work adequately. For instance, if the protection settings of Relay 1 are not changed after reconfiguring the network, the relay fail to detect a fault current and the breaker will not trip; thus, compromising the integrity of the grid.

TABLE II. THE OLD AND NEW PROTECTION SETTINGS

Relay	Old OC Setting (A)	New OC Setting (A)
Main Relay	230	230
Relay 1	70	20
Relay 2	25	80
Relay 3	60	60
Relay 4	60	55

V. CONCLUSION & FUTURE WORK

In this paper, a preliminary algorithm for the self-healing of distribution networks has been proposed. When a fault takes place in a distribution network, the entire downstream section is isolated, potentially interrupting the power supply for healthy sections of the network. The healthy sections are restored by changing the topology of the network, opening the appropriate normally closed switches and closing the normally open switches. In the light of extant literature, BPSO was adapted in order to solve the combinatorial problem in MATLAB and satisfying results were achieved by applying the algorithm to an IEEE 33-bus feeder network.

Future work is necessary to verify the accuracy of proposed algorithm and fault analysis techniques. A limitation of this work is the absence of any real-world network for conducting case studies to substantiate the practicality of the presented algorithm. The next step in developing a fully functional self-healing algorithm would be to determine the appropriate time-dial settings for the respective protection devices. In future, there can be studies exploring the post-fault network topology for faults at multiple locations within the distribution network.

It can be concluded, from the work completed so far, that the problem of self-healing via network reconfiguration can be solved through compartmentalizing of the distribution network. The results from the conducted work show that the presented algorithm is an effective scheme for restoring power to healthy sections of the network without any human intervention.

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