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Multi-Objective Service Restoration of Radial Distribution System in the Presence of Non-Linear Loads

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Abstract: Most of the power electronic components act as non-linear loads because they draw non-sinusoidal current from the power supply. Due to these non-linear loads, current harmonics are injected in the power network. For normal operation, any power network is equipped with provisions to keep the harmonics level to a minimum value. Whenever a fault occurs in the distribution system, the primary goal is to re-energize the healthy part of the network which got interrupted. It can be done by changing the topology of the network. This method is called as Service Restoration (SR). In this paper, a service restoration strategy is proposed when non-linear loads are present in the radial distribution system. Service restoration problem is formulated as a multi-objective, constrained optimization problem. Three new objectives are included to address the problem of harmonics injection by non-linear loads. Multi-Objective Particle Swarm Optimization (MOPSO) and Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) are used to find the optimal switching sequence for restoration. To test the effectiveness of the proposed methodology, IEEE 33 bus and IEEE 69 bus test systems are taken.

Keywords: distribution automation; meta-heuristic optimization; power quality

1. Introduction

Automation in the electric power sector results in better integration of control and monitoring resources. The presence of automation techniques for the electric distribution system will ensure better service quality and improved investment utilization. Network reconfiguration is the automation technique which can be used to re-route power supply for the healthy part of the system with some fault. Whenever a fault occurs in a distribution network, the first step is to isolate the affected portion of the network by changing the status of surrounding switches. In the case of a radial system, there is a chance of isolation of some of the loads which are present on the downstream part of the affected area. System reliability is highly affected by the number of outages and duration of outages. One of the main objectives of service restoration is to reduce the number of affected customers after a fault occurs in the system. Service restoration can be formulated as a multi-objective, combinatorial, constrained non-linear optimization problem; for such a case finding a robust solution is difficult.

Nowadays with the advancement in the field of power electronics, non-linear loads like adjustable speed drives, electronic ballasts, and switching mode power supplies are connected to the power network. Non-linear loads results in the distortion of sinusoidal voltage and current waveforms. The presence of substantial harmonic frequency elements can cause higher losses in the distribution network. Additionally, the components designed for operation at fundamental frequency will also perform inadequately under the influence of harmonics present in the network. In case of a fault, the service restoration plan should be formed in such a way that the out-of-service area, number of switching operations and harmonic injection from the non-linear loads remain minimum.

Literature survey shows that technique reported in some of the initial work is based on changing the status of switching pairs present in the system (if one switch is closed in a pair, then at the same time the second switch is opened). This kind of technique ensures that the resultant network remains radial and most of the line overloads are alleviated during restoration. The main drawback of this method is that the solution depends on initial system configuration and sometimes it can get stuck in a loop, which results in no solution [1–6]. A fast service restoration algorithm is required for real-time implementation. To reduce time requirement, different heuristic-based algorithms have been reported for SR. Feasible solution for SR is obtained by researchers using different versions of Genetic Algorithm (GA) [7,8], Tabu Search (TS) Algorithm [9], Particle Swarm Optimization (PSO) [10,11], Ant Colony Optimization (ACO) [12,13], Fuzzy Logic [14–16] and Hybrid Algorithms [17–21]. These algorithms are faster than the conventional methods but they can result into local optima in some of the cases where the algorithm fails to explore the complete search space. Expert system [22–24] and multi-agent [25–27] based methods have also been reported in the literature.

In some recent works, SR problem is formulated as convex Optimal Power Flow (OPF) problem, which can be solved using Second-Order Cone Programming (SOCP) or Mixed Integer Convex Programming (MICP) [28,29]. The convex nature of the power flow equation makes this kind of formulation possible. This technique can find the global optimal point with high accuracy but fails to do partial restoration if required.

Power quality improvement by the application of network reconfiguration for a balanced system is reported in [30]. In [31], power quality improvement is taken as one of the objectives of network reconfiguration. It has been found that in the presence of distributed generators, quality of power may decline.

For real-time scenario, network reconfiguration is possible if the node voltages, as well as the power flow in all the branches, are known. Harmonic emission by the non-linear load can also be estimated with the help of measured values of voltages and currents at the Point of Common Coupling (PCC). For Medium Voltage (MV) distribution network, Power Quality Analyzers (PQA) and Phasor Measurement Units (PMU) can provide sufficient data for complete state estimation. But the instrumentation and installation costs for these devices are relatively high. Consequently, some pseudo-measurement techniques along with state estimation algorithms are proposed to make measurement infrastructure economically feasible. In state estimation algorithms, the objective is to place PMUs or smart meters in such a way that the state estimation error is minimum. The placement problem consists of finding the geographical location as well as the number of measurement units. In [32], the authors have proposed a method for load flow analysis with the measured values in the network. This technique uses one measurement at the MV level and rest of the measurements at Low Voltage (LV) level of distribution network using PQAs. As a result, the total cost of the measurement infrastructure is significantly reduced. In the same work, an Artificial Neural Network (ANN) based load power estimation technique has been reported which works for the case when there is temporary unavailability of the load power measurements, in a substation. In another work [33], the same authors have presented an LV measurement technique to limit the number of PQAs placement in order to reduce the uncertainty in the power flow estimation. Optimal allocation of the smart metering system for better state estimation is presented in [34]. The authors suggested a semi-definite programming approach to place smart meters for minimum state estimation error variance. In [35], the placement method for smart meters is determined by the observability of the system and state estimation accuracy. For correct state estimation, a hybrid method which combines Supervisory Control and Data Acquisition (SCADA) and PMU measurements is proposed in [36]. The sampling rate of SCADA is 2–5 s while it is 30–40 milliseconds for PMUs. This hybrid solution ensures better accuracy of data and error reduction caused by bad data.

In this paper, Multi-Objective Particle Swarm Optimization (MOPSO) and Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) are used to solve the SR problem in the presence of non-linear loads. As mentioned before, a proper measurement infrastructure is required for state estimation and harmonic emission by non-linear loads in the network. In this work, the restoration strategy is focused on improving power quality in the network, before and after restoration without actually calculating the values of harmonic emissions at PCC. Service restoration is formulated as a multi-objective constrained optimization problem. The effect of the number and type of non-linear load present in the distribution network is also analyzed. For validating the effectiveness of used algorithms, numerical values of Total Harmonic Distortion (THD) are obtained using simulation in PSCAD software.

The remainder of this paper is organized as follows. In Section 2, harmonic emission by non-linear load and the effect of non-linear load on radial distribution network is demonstrated. Section 3 describes the formulation for service restoration problem in the presence of non-linear loads. Section 4 gives an overview of the optimization methods used in the present work. IEEE 33 bus system and IEEE 69 bus system are taken for the case study with new service restoration formulation. The results for the same are shown in Section 5. The last section of the paper concludes the findings of the work.

2. Harmonic Emission by Non-Linear Load

In practice, various techniques are proposed for estimating the values of harmonic emission by the non-linear component of a load at PCC. Assessment of harmonics is required for two basic reasons, (a) to determine overall and individual harmonic components of various connected loads and (b) to define rules and regulations for power quality maintenance, which will allow effective integration of distributed energy resources and other power electronic loads. Generally, the assessment of harmonics is done at a single stage (at any point of time) or double stage (before and after installation of non-linear load), but ideally, this estimation should be done on a regular basis because of the dynamic nature of the loads. Methods for harmonic emission estimation require measurements at PCC. There are various methods proposed in the literature to determine harmonic injection by non-linear loads. A Voltage Harmonic Vector (VHV) method [37–39] uses a Thevenin equivalent circuit (Figure 1a) to calculate harmonic emissions by load and utility. The Thevenin equivalent network consists of utility voltage source ($\underline{V}_{U-h}$), utility impedance (Z_{U-h}), customer voltage source ($\underline{V}_{C-h}$), and customer equipment impedance (Z_{C-h}) corresponding to a particular harmonic order, as shown in Figure 1a.

$$\underline{V}_{U-h} = \underline{V}_{PCC-h} + \underline{I}_{PCC-h} * Z_{U-h} \tag{1}$$

$$\underline{V}_{C-h} = \underline{V}_{PCC-h} - \underline{I}_{PCC-h} * Z_{C-h} \tag{2}$$

In the VHV method, (1) and (2) can be used, once the Thevenin equivalent parameters are calculated to determine the harmonic emission at PCC ($\underline{V}_{PCC-h}$, $\underline{I}_{PCC-h}$).

Another method used in present times is called IEC voltage phasor method [40]. In this technique, voltage phasor distortion at PCC is calculated before the customer (with non-linear load) is connected to the network; this measured voltage harmonic distortion is called background distortion ($\underline{V}_{background}$). In the next step, the distortion at PCC is measured after the connection of the non-linear load. Consequently, the voltage harmonic distortion injected by the load ($\underline{V}_{emission}$) can be determined using the vector diagram shown in Figure 1b. The vector addition is given in (3).

$$\underline{V}_{emission} = \underline{V}_{PCC-h} - \underline{V}_{background} \tag{3}$$

This method is only valid if background distortion is less than distortion at PCC.

In [41], a harmonic power flow analysis is proposed for the calculation of harmonic emissions. But this method only shows if the harmonic injection is from the utility side or from the customer side at PCC.

A "voltage only" method is proposed by authors in [42]. In this method, distortion injected by the network is taken as a background distortion while harmonic contributions of other customers are taken as separate entities. This method is restricted to planning studies only as it requires analysis of various scenarios of connection and isolation of loads.

All these above-mentioned methods require measuring instruments connected to PCC. In VHV and IEC voltage phasor method, impedance calculations are needed, which again requires some implicit technique like invasive and non-invasive harmonic impedance measurement method. Consequently, all these methods require additional time when they are applied during service restoration. So, in the present work, instead of going for actual calculation of harmonic injection by the loads, the change in power quality is determined in terms of total harmonic distortion at PCC due to change in number, type, and location of non-linear for the radial distribution system.

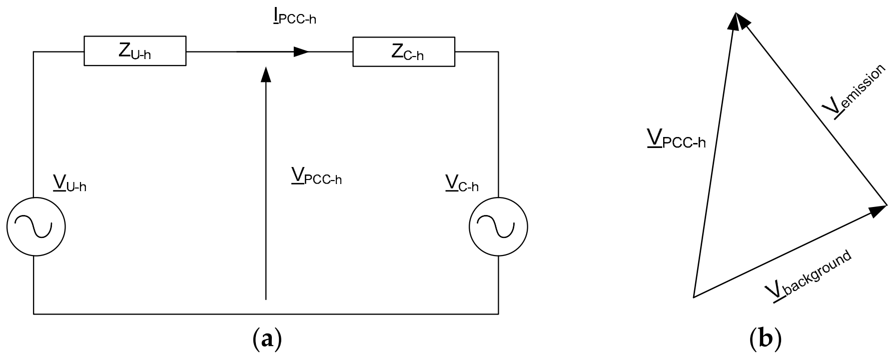

Figure 1. (**a**) Thevenin equivalent circuit for voltage harmonic vector method and IEC voltage phasor method; (**b**) Voltage phasor diagram for IEC voltage phasor method.

2.1. Effect of Non-Linear Load on Radial Distribution Network

The use of power converters is very common in the modern power system. These converters are very useful for various applications as they are capable of converting power from AC to DC, DC to DC, DC to AC, and AC to AC. On the other, hand these converters distort the current waveform by drawing non-sinusoidal current from the supply. Consequently, they inject harmonics to the supply system. Battery chargers, an arc discharge device, electronic ballasts, variable frequency drives, and switching mode power supplies are other examples of non-linear loads which can inject harmonics into the power network.

The harmonics present at a bus i in the distribution network depend on the following factors:

1. The number of non-linear loads present in the path C_i on which bus i is located (since the network is radial in nature, only one path is possible from the source node).
2. Type and rating of the non-linear load in the path $C_{i.}$
3. The distance of bus i from the bus connected to the non-linear load.

To illustrate this concept, a section of IEEE 33 bus system is considered. In this section, a full wave rectifier feeding a resistive load is connected to the radial network. It is assumed that a high Priority Customer (PC) is connected to the system through a bus j. The Total Harmonic Distortion (THD) at this bus j is measured under different scenarios. This demonstration shows that the number, size, and type of non-linear load present on the radial path of priority customer affects THD values.

2.1.1. One Non-Linear Load is Connected at Bus 7, and Priority Customer is Connected to Bus 11

This is the reference case (shown in Figure 2a); the distance of non-linear load (bus 7) is 2.9 km from priority customer (bus 11). The non-linearity in the load is present because of full wave rectifier which is feeding a resistive load of 150 kW connected to the grid.THD for voltage at PCC of bus no.11 is measured. This section is modeled in PSCAD. The obtained THD value is 3.94%.

2.1.2. Two Non-Linear Loads are Connected at Bus 7 and 8

In this case (shown in Figure 2b), a load of the same rating is connected to two buses on the radial path of priority customer. The THD obtained, in this case, is 5.53%. It is evident from THD values of case 1 and case 2 that as the number of non-linear loads increases in the path of priority customer, the value of THD is more.

2.1.3. Non-Linear Load is Connected at Bus 8

A load of reference case is now connected to bus number 8 (shown in Figure 3a), which is connected near to priority customer compared to the reference case. The voltage THD at PCC of bus number 11, in this case, is 4.62%.

Consequently, we can say that as the distance between priority customer bus and non-linear load bus decreases, the value of THD for same load increases.

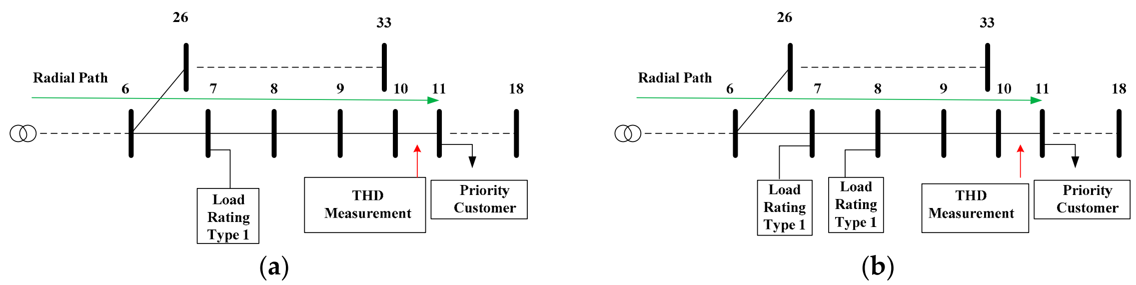

Figure 2. (**a**) Non-linear load connected at bus 7; (**b**) Non-linear load connected at bus 7 and bus 8. THD: Total Harmonic Distortion.

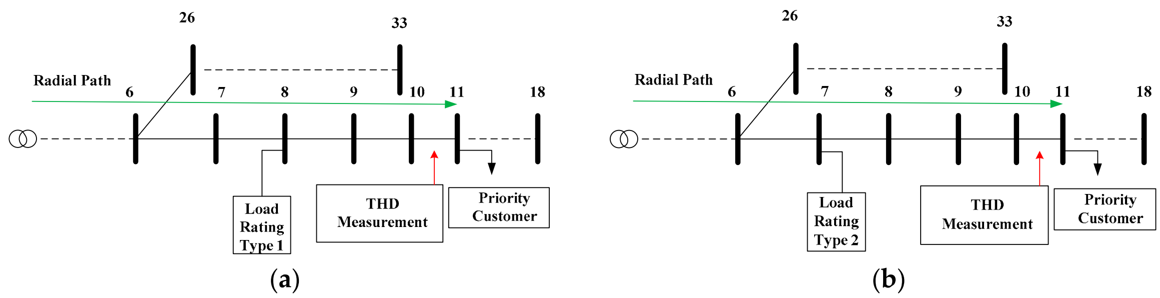

Figure 3. (**a**) Non-linear load connected at bus 8; (**b**) A 200kW resistive load is connected at bus number 7. THD: Total Harmonic Distortion.

2.1.4. Full Wave Rectifier Feeding 200 kW Resistive Load is Connected at Bus 7

When the rating of the non-linear load is changed (shown in Figure 3b) from the reference case, the THD value obtained at bus number 11 is 4.37%. So, it can be concluded that the harmonics injected by the different types of load or different rating of the load will be different.

For a balanced distribution network, the impact of a non-linear load connected to the system can be predicted based on these four cases. The change in values of the harmonics component depends on the distribution line parameters. Typical line data for balanced distribution network includes R and X values. The presence of these passive elements can damp out some percent of substantial harmonic components.

3. Objectives and Constraints of Service Restoration Problem

Whenever a fault occurs in the distribution network, the primary objective of any service restoration plan is to minimize the number of interrupted customers present in the healthy section of the network. This can be possible by changing the topology of the network. By using sectionalizing switches, two sections of the network can be connected or disconnected. In normal operating condition, they are closed. Additionally, tie switches, which are normally open, are also present in the distribution network to control the involvement of tie lines in power transfer between two areas. Based on the capacity of a tie line, it can supply power to adjacent area loads during fault duration. Service restoration problem can be formulated as a multi-objective constrained optimization problem. The number of interrupted customer minimization can be formulated as:

$$f_1 = \min \frac{\phi_{\text{int}}(R)}{\phi_{total}(R)} \tag{4}$$

where Φ_{int} *(R)* represents the total out-of-service area and Φ_{total} *(R)* is the total connected load in the restored network.

Sectionalizing switches and tie switches can be controlled manually or remotely. Operating manually controlled switches is a time-consuming task which can delay the process of restoration. On the other hand, the remotely controlled switch operation is fast but they need proper communication infrastructure in the network and their cost is much higher compared to manually controlled switches. The next objective is to minimize the total number of switching operations in the network.

$$f_2 = \min \frac{\psi_{mcs}(N, R)}{\psi_{mt}} \tag{5}$$

ψ_{mcs} is the total number of switching operation of manually controlled switches in transforming the initial network (N) to the restored network (R). ψ_{mt} represents the total number of manually controlled switches present in the network.

$$f_3 = \min \frac{\psi_{rcs}(N, R)}{\psi_{rt}} \tag{6}$$

ψ_{rcs} is the total number of switching operation of remotely controlled switches in transforming the initial network (N) to the restored network (R). ψ_{rt} represents the total number of remotely controlled switches present in the network.

These are the primary objectives of various strategies proposed for the solution of restoration problem. In this paper, new objectives are formulated when the non-linear load is present in the radial distribution network. The aim of these objectives is to minimize the negative impact of these non-linear loads while selecting the optimal switching sequence for restoration. As discussed in Section 2, THD values in the network depend on the position, number, and type of non-linear loads. Estimating overall harmonics in the system can not exactly predict the THD value at a particular point. Also, as mentioned before, the present work is focused on improving the quality of power as an additional objective of the service restoration plan. So, the exact calculation of harmonic injection is not required. Instead, the governing factors in this work are number, location, and type of non-linear loads present in the radial path of the priority customer. To control the aforementioned entities, statistical technique is used here. The statistical parameters used are the mean and standard deviation. Equation (7) represents the mean of the number of non-linear loads connected in the restored network corresponding to each priority customer. By minimizing this value, it is ensured that the number remains less or the same as the original network, so that power quality improves or remains the same after restoration. Similarly, the second term of (8) represents standard deviation; by restricting this value, the algorithm can restrict abrupt changes in power quality due to service restoration. For example, if in the original network, the number of non-linear loads connected to the radial path of each priority customer is 2 and the total numbers of the priority customers are 4 in the network, then, in that case, mean m_N is 2. But suppose after restoration, 5 non-linear loads are connected to 1 PC and no other non-linear load is present for any other PC, then, in that case, mean m_N value is 1.25, and this value is better than the value calculated for the original network; but for PC with 5 non-linear loads, the harmonic distortion is more than the original network. So, to ensure improvement in power quality at PCC of each priority customer, the standard deviation minimization is introduced in (8). Similarly, for the location of the non-linear load, these two statistical parameters are considered in (10).

$$m_N(R) = \frac{\sum\limits_{i \in \beta_p} NL_i(R)}{PC_t(R)} \tag{7}$$

$$f_4 = \min\left\{ m_N(R) + \left(\frac{1}{PC_t(R) - 1} \sum_{i=1}^{PC_t(R)} (NL_i - m_N(R))^2 \right)^{1/2} \right\} \tag{8}$$

where $ß_p$ represents a set of buses through which priority customers are connected to the system. NL_i (R) represents the number of non-linear loads connected in the radial path of priority customer i for restored network topology. PC_t (R) is the total number of priority customers present in the restored network. m_N (R) represents the average value of the number of non-linear loads connected in the restored network (R) for each priority customer. In the radial distribution system, there will be only one path from a source node to a particular bus. There fore, the NL_i (R) can be easily calculated for a particular topology.

$$m_L(R) = \frac{\sum\limits_{i \in \beta_p} \left(\sum\limits_{j \in NL_i} l_j \right)}{PC_t(R)} \tag{9}$$

$$f_5 = \min\left\{ m_L(R) + \frac{1}{PC_t(R) - 1} \left(\sum_{i=1}^{PC_t(R)} \left(\sum_{j \in NL_i} l_j - m_L(R)^2 \right) \right)^{1/2} \right\}^{-1} \tag{10}$$

In (9) and (10), l_j represents the distance between the buses where non-linear load j is connected from the bus where priority customer is present. m_L (R) represents the average value of the distance of Non-linear Loads (NLL) connected in the restored network (R) from each priority customer. As demonstrated in Section 2, with a decrease in distance between the non-linear load bus and priority customer bus, the THD value will increase for the same type and rating of the load. Equation (10) ensures a maximum distance of non-linear loads from each priority customer. Additionally, it restricts the sum of minimum distance value of all the non-linear loads from a priority customer.

$$f_6 = \min \sum_{i \in \beta_p} \left(\sum_{j \in NL_i} w_j \tau_j \right) \tag{11}$$

The objective mentioned in (11) minimizes the effect of non-linearity based on the type and rating of the non-linear load connected on the radial path of a priority customer. T_j represents the type of non-linear load j, w_j represents weight factor. In this work, weight factor for 200 kW loading is 1 and for 150 kW loading it is 0.8. Additionally, a DC drive load of 2.2 kW is taken for analysis, which is connected to the grid through a delta-star step-down transformer.

Constraints of Service Restoration

A set of constraints also need to be satisfied by SR plan. For this problem, constraints can be broadly classified into two categories, (A) Topological Constraint and (B) Electrical Constraints. Distribution system generally operates in radial topology. This kind of network structure ensures less construction cost and better coordination of protection devices. So, restoration must be done in such a way that the resultant network is radial in nature. The operating electrical constraints are as follows:

$$\left|V_j^{\min}\right| \leq \left|V_j\right| \leq \left|V_j^{\max}\right| \forall j \in N \quad (12)$$

$$\left|I_j\right| \leq \left|I_j^{\max}\right| \forall j \in N \quad (13)$$

$$S_k \leq S_k^{\max} \forall k \in N \quad (14)$$

In the above-mentioned equations, V_j is the voltage at bus j, I_j is the current entering at bus j. The power flow in the feeder and maximum power handling capacity of feeder k is represented by S_k and ${S_k}^{max}$, respectively. Load generation balance is another important electrical constraint which is considered in this work. Also, the important constraint for this work is that the priority customers belong to set $ß_p$ must be supplied after restoration.

4. Methodology to Solve Service Restoration Problem

In the conventional deterministic method, SR plan can be obtained by considering all the possible outcomes. Suppose there are "n" switches in a system, which are located downstream to the fault point. Then, there can be 2^n possible combinations for switching operations. To encapsulate all these possible combinations, a matrix can be defined as shown in (15). The status of different switches from S_1 to S_n is represented in the columns whereas possible switching combinations are displayed in rows.

A flowchart for finding SR plan through conventional deterministic method is shown in Figure 4. This process is very accurate, but due to the large size of matrix M, the computation time is more. Consequently, to reduce this computational burden and to make SR plan executable in real time scenario, meta-heuristic optimization techniques are used to solve service restoration problem.

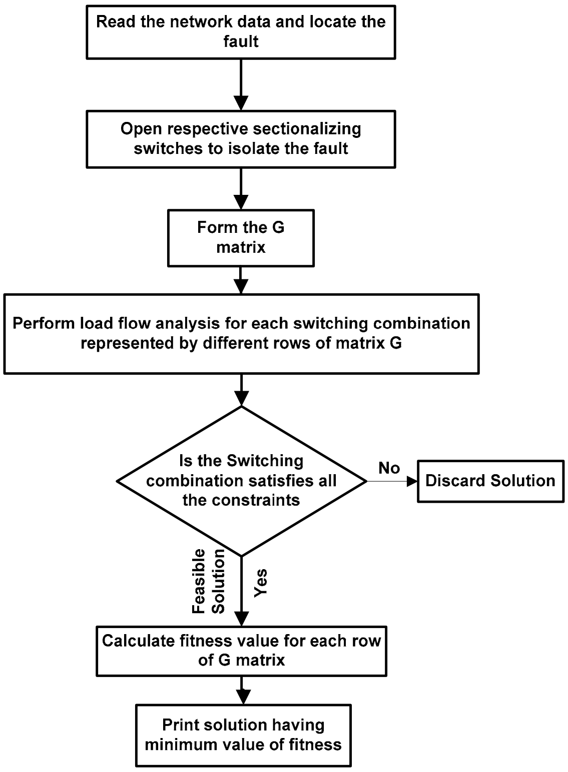

Figure 4. Service restoration through conventional deterministic method.

$$G = \begin{array}{c} \\ P_1 \\ . \\ . \\ P_m \end{array} \begin{array}{c} \begin{array}{cccccc} S_1 & S_2 & S_3 & S_4 & \dots & S_n \end{array} \\ \begin{bmatrix} 1 & 0 & 1 & 1 & \dots & 1 \\ 1 & 0 & 1 & 0 & \dots & 1 \\ 1 & 0 & 0 & 1 & \dots & 1 \\ 0 & 1 & 1 & 0 & \dots & 1 \end{bmatrix} \end{array} \quad (15)$$

The effectiveness of any meta-heuristic optimization algorithm depends on the ratio of exploration of search space and exploitation of potential optimal solutions. In other words, the algorithm should be capable to perform diversification and intensification.

4.1. Multi-Objective Optimization

Service restoration is formulated as a multi-objective optimization problem with constraints. For solving any multi-objective problem, there are two kinds of methods. The first method is the weighted sum approach; in this practice, all the objectives are merged together and formulated as a single equation as shown in (16). Each objective function is normalized, and a weight coefficient is assigned to each objective function. The challenge in this method is deciding the weight values.

$$f = w_1 f_1 + w_2 f_2 + \ldots + w_n f_n \quad (16)$$

The second way to get the optimal point of a multi-objective optimization problem is the direct method. Some optimization algorithm has a characteristic to take care of multiple objectives simultaneously. In this paper, two such methods viz. MOPSO and NSGA-II are used to find a restoration plan for a single fault scenario in a radial distribution network. In any multi-objective optimization problem, simultaneous optimization of different parameters related to various objectives is performed. Generally, the objective functions are contradicting in nature for these kinds of problems. So, the idea of multi-objective optimization is to find a good trade-off solution.

4.1.1. Concept of Dominance

In multi-objective problems, the concept of dominance is applied to compare two set of solutions. For unconstrained optimization problem, a solution 'x' will dominate another solution 'y', if

(a) the solution 'x' is no worse than solution 'y' in all objectives and
(b) the 'x' is strictly better than 'y' in at least one objective.

If anyone of (a) and (b) is violated, then the solution 'x' does not dominate solution 'y' [43].

4.1.2. Pareto Front

A Pareto-optimal solution point is a non-dominated solution present in the feasible region of search space. A set of all points, which are non-dominated and belongs to the feasible region of the search space, is called a Pareto-optimal set. A Pareto front is the solution values corresponding to Pareto-optimal points.

4.1.3. Repository

The best sets of solution are stored in the repository. Any solution present in the repository is not being dominated by any other member of the repository. Another attribute of a repository is that the member with high dispersion is likely to remain the member till the last iteration and can be a potential candidate for optimal solution.

4.2. Multi-Objective Particle Swarm Optimization

The PSO algorithm is inspired by the social behavior of birds. Each bird in a flock is called a particle. There are two kinds of parameters associated with each particle, (a) position of the particle and (b) velocity of the particle. Each particle is having two kinds of experience values, first is the local experience, which is represented by a pbest value, and second is the global experience represented as gbest. The position and velocity updates are governed by relation given in (17) and (18). In this work, a multi-objective variant of PSO is used, which is known as MOPSO.

The MOPSO programming complexity is less, which makes this algorithm faster than the other optimization techniques. As the time consumption is less, this algorithm is suitable for service restoration problem. The MOPSO algorithm starts with random solutions as the initial swarm. The position and velocity are updated just like regular PSO method. But in this method, the concept of pbest and gbest for each particle is different. Each particle has only their best experience value, which is pbest, stored as memory in a repository. After each iteration, this position is compared with the updated position. If the updated position is better than the existing pbest value, then this updated position is the new pbest value; otherwise, pbest for the particle remains the same. Simultaneously, a global best solution is also stored in an external repository, where all the best non-dominated solutions are stored. If the crowding distance between two non-dominated solutions present in the external repository is less, then the probability of selection of that solution as the final optimal solution is also less. A Roulette Wheel Selection (RWS) method can be used to select the Pareto fronts. Good "trade-off" solutions can be obtained from MOPSO that represent the best possible compromises among the objectives [44]. The objective is to find a Pareto optimal set which consists of feasible solutions.

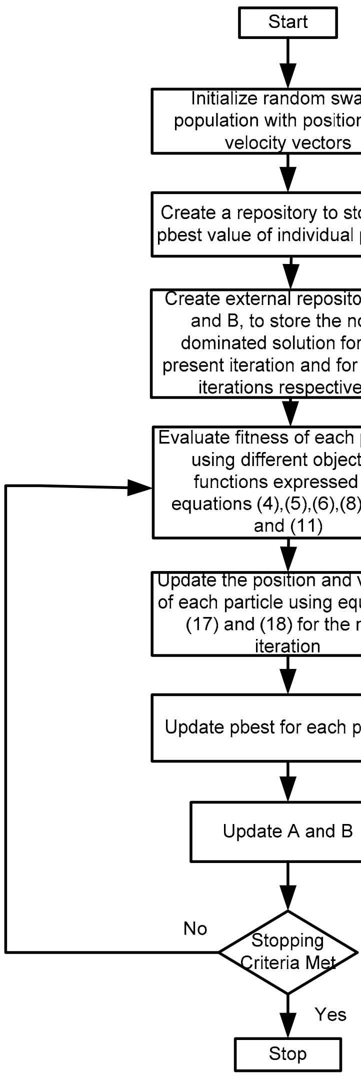

Figure 5. Flow chart for multi-objective particle swarm optimization.

For service restoration problem, this technique can be applied through the following steps (Figure 5):

(a) Initialize the swarm population with random particles (all constrained must be fulfilled by each particle). For the present problem, the particle represents the switching status of the network.
(b) Evaluate the fitness values $f_1, f_2, f_3, f_4, f_5,$ and f_6 for each candidate in the swarm population.
(c) Create an external repository to store the set of non-dominated solutions having the best fitness values from the initial population.
(d) Select a leader for each particle in the population randomly. The leader fitness value is more than that of particle fitness value.
(e) Calculate new position and velocity of particles from basic PSO formulation given in (17) and (18).
(f) Again form the Pareto optimal set for the new obtained population by evaluating the fitness of each particle.
(g) Repeat the steps from (b) to (f) for 100 iterations.
(h) Print the Pareto optimal set.

$$v_i^{k+1} = w_i v_i^k + c_1 rand_1 * \left(pbest_i - x_i^k\right) + c_2 rand_2 * \left(gbest - x_i^k\right) \tag{17}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{18}$$

In the above equations, ${v_i}^k$ and ${x_i}^k$ represent the velocity and position of an i^{th} particle in the k^{th} iteration, respectively. c_1 and c_2 are constriction factors. w_i is the inertia weight factor, and it is used to control the balance between exploration and exploitation for the algorithm; $rand_1$ and $rand_2$ are two random functions in the range of [0–1].

4.3. Non-Dominated Sorting Genetic Algorithm-II

The performance of the genetic algorithm is good for the combinatorial optimization problem. Due to the combinatorial nature of the SR problem, the results obtained from GA are very promising. The main drawback of using basic GA version is the requirement of the longer time for the evaluation of feasible points in the search space. Also, GA revisits the same search point many times that again increases the overall runtime for the algorithm. An improved version of GA known as NSGA-II can be very effective for service restoration problem [8]. Normal GA is valid for a single objective problem, but in some cases, it can also be applied for multi-objective problems through a weighted sum approach. The main difficulty in this method is the calculation of weights for different objectives. So, to counter this problem, Non-Dominated Sorting Genetic Algorithm (NSGA) and NSGA-II are proposed. These two variants of GA can be directly used for multi-objective problems. The objective is to find a Pareto optimal set (just like MOPSO optimization method) which consists of feasible solutions. To form this set, the concept of front formation, sharing function, niche count, crowding distance, Pareto front, and selection methodology can be used.

Steps of NSGA-II optimization for service restoration problem (Figure 6):

(a) The initial requisite for implementing NSGA-II is that the pre-fault configuration and system data should be known.
(b) Generate initial population ${P_s}^1$ randomly. A string consisting of switching sequence represents parents in the initial population. All the candidates must satisfy the electrical and topological constraints.
(c) Evaluate the fitness values $f_1, f_2, f_3, f_4, f_5,$ and f_6 for each candidate in the parent population.
(d) Generate offspring population ${O_s}^1$ from parent population using single point crossover and mutation operators. A mating pool must be formed for O_s using Crowded Tournament Selection Operator (CTSO).
(e) Merge the two matrices ${P_s}^1$ and ${O_s}^1$ to form a new matrix ${R_s}^1$. It is evident that if the size of parent and offspring population is N, then the size of R_s will be 2N.

(f) Divide the candidates present in the R_s into different fronts based on the fitness values.
(g) Form new parent population from the fronts obtained in step (f). The size of the new population should also be N.
(h) Repeat the steps (c) to (g) for further iterations.
(i) After the end of the 100th iteration (which is the convergence criteria here), print the candidate with the best fitness present in the R_s^{100} matrix.

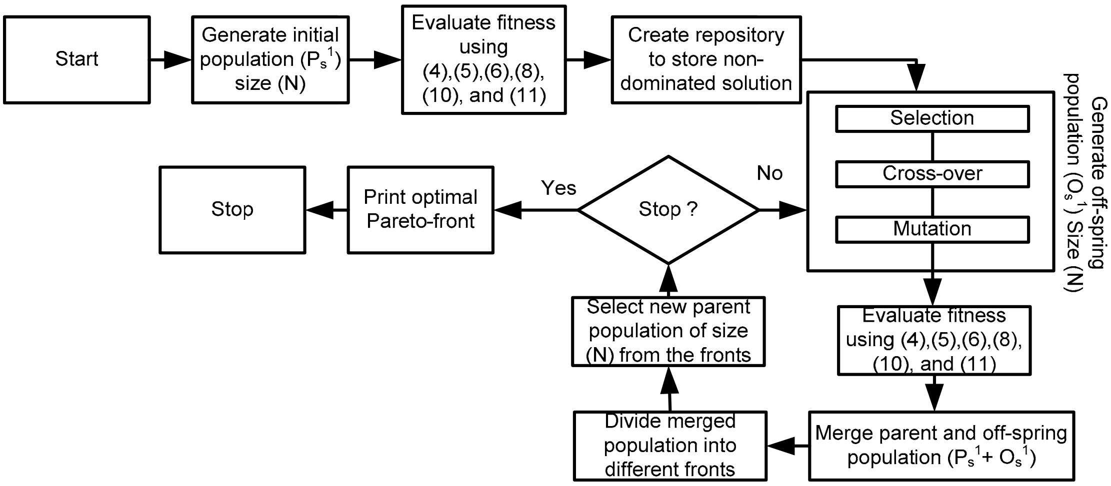

Figure 6. Flow chart for non-dominated sorting genetic algorithm-II.

5. Results and Discussion

In this paper, two meta-heuristic optimization algorithms are applied to solve the service restoration problem. IEEE 33 bus [45] and IEEE 69 bus test systems are taken for case study. It is assumed that some priority customers are present in both the networks. The radial distribution network is modeled in PSCAD, and THD values are measured at the bus through which priority customers are connected. But these measurement values, which are shown in this section, are to validate the effectiveness of service restoration algorithms. The advantage of the proposed approach is that the power quality of the system can be improved as an additional objective of service restoration problem. A comparison has been made between the THD values of each priority customer in the initial network and in the restored network. The exact value of THD is calculated in PSCAD through the modeling of a radial distribution system.

5.1. Case 1: IEEE 33 Bus Test System

For this test case, the non-linear loads are connected at bus no. 4,7,17,19,24,31(Figure 7)

- Priority Customers (PC) are assumed to be present at bus 16 (PC1), bus 20 (PC2), and bus 32 (PC3)
- The switch between two buses A and B is represented as S (A, B)
- Full wave rectifier supplying a resistive load of 150 kW is connected to bus 17,24,31
- Full wave rectifier supplying a resistive load of 200 kW is connected to bus 4,7,19

5.1.1. When the Fault Occurs Between Bus 10 and 11

A single point fault is considered in the present case. The first step for power restoration is to locate and isolate the fault point and then deploy the restoration plan obtained through MOPSO and NSGA-II. This study is carried out in the MATLAB environment. The total computational time for the restoration plan should also be less. MOPSO and NSGA-II have less computational complexity compared to the other multi-objective optimization techniques. Table 1 shows the switching operations that need to be done for the restoration through MOPSO and NSGA-II algorithms when the fault occurs between bus 10 and bus 11.

Table 1. Sequence obtained when the fault occurred between bus 10 and 11.

Optimization Algorithm	Switching Sequence	
	On Switches	**Off Switches**
MOPSO	S(12,22),S(9,15)	S(13,14),S(9,10),S(11,12),S(14,15)
NSGA-II	S(12,22),S(33,18),S(9,15)	S(16,17),S(9,10),S(11,12),S(12,13)

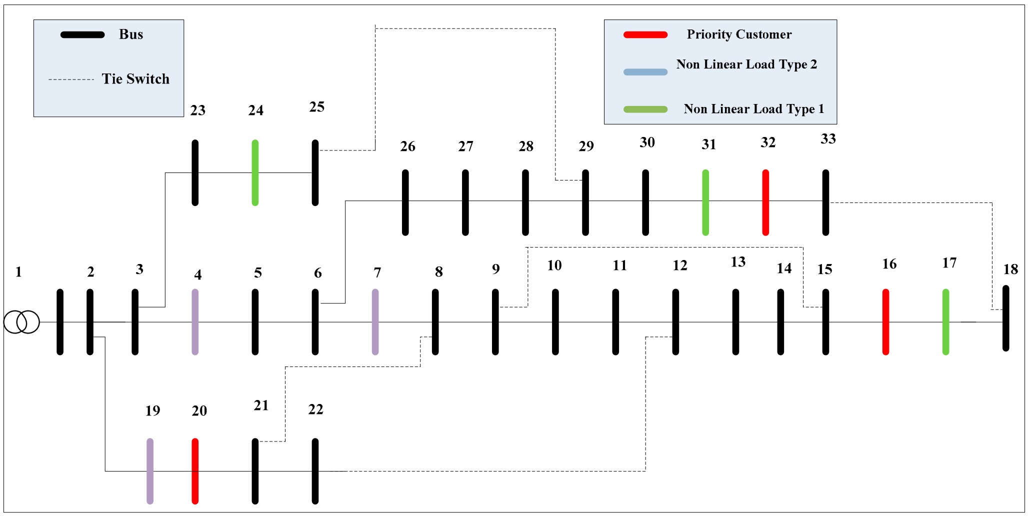

Figure 7. IEEE 33 bus test system.

Service Restoration through MOPSO

Figures 8 and 9 show the components of harmonics present at different priority customer buses when MOPSO is applied for the restoration in the present scenario of fault location.

When the aforementioned restoration plan is simulated for validation of the proposed methods, THD values are obtained for both the restoration plans. Through MOPSO, the THD values at PCC of PC1 and PC3 are shown in Figures 8 and 9 respectively. Odd harmonic component values and fitness of each objective through MOPSO plan is shown in Table 2. The important aspect of the service restoration algorithm is to minimize the out-of-service area and perform the restoration as quickly as possible. In the restoration scheme obtained from MOPSO, only one customer connected at bus 14 is out-of-service. Also, the total number of switching operations is six which directly relate the amount of time required for the deployment of service restoration scheme.

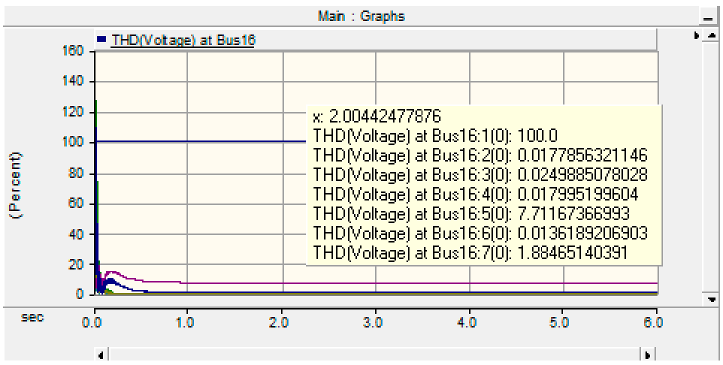

Figure 8. The harmonic components at the point of common coupling of the priority customer connected to bus no.16. THD: Total Harmonic Distortion.

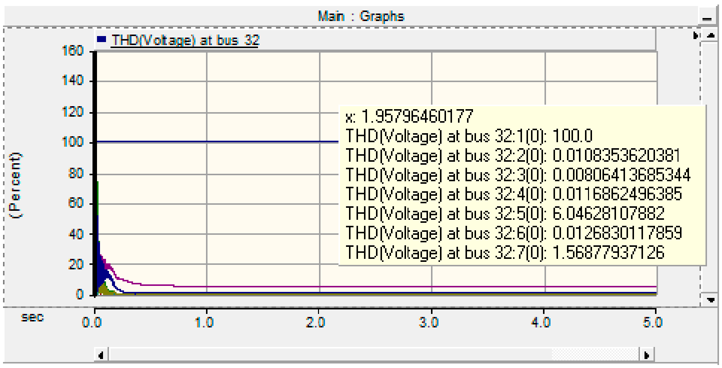

Figure 9. The harmonic components at the point of common coupling of the priority customer connected to bus no.32. THD: Total Harmonic Distortion.

Table 2. Optimal values through Multi-Objective Particle Swarm Optimization (MOPSO) after restoration.

Out of Service Area Buses		14
Manually Controlled Switching Operations		4
Remotely Controlled Switching Operations		2
THD (%) at Bus No. 16	3rd Harmonic Component	0.02
	5th Harmonic Component	7.17
	7th Harmonic Component	1.88
	Total THD at Bus 16	9.94
THD (%) at Bus No. 32	3rd Harmonic Component	0.01
	5th Harmonic Component	6.04
	7th Harmonic Component	1.51
	Total THD at Bus 32	6.25
THD (%) at Bus No. 20	3rd Harmonic Component	0.00
	5th Harmonic Component	0.91
	7th Harmonic Component	0.85
	Total THD at Bus 20	1.24

As mentioned before, the number of non-linear loads in the radial path of the PC directly affects the THD value. Also, the number of non-linear loads in the restored network should remain as minimum as possible for each priority customer, mentioned in (8). These numbers are calculated for the original network and restored network as shown in Table 3. It can be clearly observed that there is no drastic change in number due to the restoration. For normal operating conditions, there are proper arrangements to maintain the quality of power. So, in the present work, the power quality of the original network is either improved or maintained in the restored network. Also, only odd order harmonics are shown in the results because of the half-wave symmetry of the sine wave.

Table 3. The total number of Non-Linear Loads (NLL) connected to the radial path of the Priority Customer (PC) bus in the initial topology (without fault) and in the restored network topology.

Configuration / **PC**	**Initial Network Topology Total Number of Non-linear Load Connected**			**Restored Network Topology Total Number of Non-linear Load Connected**		
	150 kW Load	**200 kW Load**	**Total NLL**	**150 kW Load**	**200 kW Load**	**Total NLL**
PC at Bus 16	1	2	3	1	1	2
PC at Bus 32	1	1	2	1	0	1
PC at Bus 20	0	1	1	0	1	1
Fitness Value f_4	3			1.9107		

The distance of non-linear load from each priority customer is shown in Table 4. The fitness of the objective function f_5 (given in (10)) is calculated for the initial network and the restored network.

Table 4. Comparison of the total distance of non-linear loads from the priority buses in the initial network and in the restored network obtained through Multi-Objective Particle Swarm Optimization (MOPSO) plan.

PC / Non-Linear Load	Initial Network			Restored Network		
	PC at Bus 16	**PC at Bus 32**	**PC at Bus 20**	**PC at Bus 16**	**PC at Bus 32**	**PC at Bus 20**
Distance of non-linear load at Bus 4 from	8000 m	5200 m	X	X	X	X
Distance of non-linear load at Bus 7 from	6650 m	X	X	X	X	X
Distance of non-linear load at Bus 17 from	1300 m	X	X	1300 m	X	X
Distance of non-linear load at Bus 19 from	X	X	1500 m	4500 m	X	1500 m
Distance of non-linear load at Bus 24 from	X	X	X	X	X	X
Distance of non-linear load at Bus 31 from	X	300m	X	X	300 m	X
Fitness value f_5		0.0709×10^{-3}			0.184×10^{-3}	

By looking at individual fitness value, it is not possible to predict the nature of the solution as it is a multi-objective problem. But we can say from the above observations that the power quality in the restored network is as good as the original network. The fitness values of f_4, f_5 and f_6 have a direct impact on the harmonics experienced by priority customer.

Service Restoration through NSGA-II

For the same scenario (fault between bus 10 and 11), the results obtained from NSGA-II are shown below.

Table 5. Optimal values obtained through Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) restoration plan.

Out of Service Area Buses		17,18
Manually Controlled Switching Operations		4
Remotely Controlled Switching Operations		3
THD (%) at Bus No. 16	3rd Harmonic Component	0.03
	5th Harmonic Component	5.80
	7th Harmonic Component	1.19
	Total THD at Bus 16	5.25
THD (%) at Bus No. 32	3rd Harmonic Component	0.07
	5th Harmonic Component	10.12
	7th Harmonic Component	2.95
	Total THD at Bus 32	7.73
THD (%) at Bus No. 20	3rd Harmonic Component	0.00
	5th Harmonic Component	0.89
	7th Harmonic Component	0.85
	Total THD at Bus 20	1.24

Odd harmonic component values and fitness of each objective through NSGA-II plan is shown in Table 5. The out-of-service loads are connected to bus no.17 and 18. Compared to MOPSO restoration plan for which the out-of-service load is connected to bus no.14, this value is more. Also, the total numbers of switching operations are 7 through NSGA-II plan and it is 6 through MOPSO restoration plan. The THD values obtained after restoration is similar with both the techniques.

A comparison of THD values (at the PCC of the priority customers) in the initial network and restored network is shown in Table 6.

Table 6. Comparison of Total Harmonic Distortion (THD) values.

PC \ Configuration	Initial Network Topology THD(Percent)	THD (Percent) by NSGA-II in Restored Network	THD (Percent) by MOPSO in Restored Network
PC at Bus 16	8.06	5.25	7.94
PC at Bus 32	6.52	7.73	6.25
PC at Bus 20	1.24	1.24	1.12

Service restoration plan through both the algorithms is very effective, and this is validated by the tabular results. It can be noted from the results in Table 6 that the power quality is improved for PC1, PC2, and PC3 in the restored network when compared to the original network in almost all the cases.

Total number of non-linear loads connected to each priority customer for the network in different configurations is shown in Table 7.

Table 7. Total number of Non-Linear Loads (NLL) connected to the radial path of the priority customer buses in the plan obtained through Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO).

PC \ Configuration	Restored Network Topology By NSGA-II			Restored Network Topology By MOPSO		
	150 kW Load	200 kW Load	Total NLL	150 kW Load	200 kW Load	Total NLL
PC at Bus 16	1	2	2	1	1	2
PC at Bus 32	1	1	2	1	0	1
PC at Bus 20	0	1	1	0	1	1
Fitness Value f_4	1.9107			1.9107		

The second parameter mentioned in the objective function for the power quality improvement is the distance of non-linear loads from PC. In Table 8, the distance of non-linear load from each priority customer is shown.

Table 8. The total distance of non-linear loads from the priority buses for Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO).

Non-Linear Load \ PC	Network Topology By NSGA-II			Restored Network Topology By MOPSO		
	PC at Bus 16	PC at Bus 32	PC at Bus 20	PC at Bus 16	PC at Bus 32	PC at Bus 20
Distance of non-linear load at Bus 4 from	5800 m	X	X	X	X	X
Distance of non-linear load at Bus 7 from	X	X	X	X	X	X
Distance of non-linear load at Bus 17 from	1300 m	X	X	1300 m	X	X
Distance of non-linear load at Bus 19 from	X	X	1500 m	4500 m	X	1500 m
Distance of non-linear load at Bus 24 from	X	X	X	X	X	X
Distance of non-linear load at Bus 31 from	X	300 m	X	X	300 m	X
Fitness value f_5	0.1517×10^{-3}			0.184×10^{-3}		

The Fault Occurs Between Bus 10 and 11 for the Case When DC Drive Load of 2.2kW is Connected as Non-Linear Load in the Network (At Buses 4, 7, 17, 19, 24, and 31)

The switching sequence obtained in this case is shown in Table 9.

Table 9. Switching sequence obtained when the fault occurred between bus 10 and 11 for the DC drive load case.

Optimization Algorithm	Switching Sequence	
	On Switches	Off Switches
MOPSO	S(12,22),S(9,15)	S(13,14),S(9,10),S(11,12),S(14,15)
NSGA-II	S(12,22),S(33,18),S(9,15)	S(16,17),S(9,10),S(11,12),S(12,13)

In this case also, the switching obtained from both the algorithms remains same as shown in Table 1. Results obtained are shown in Table 10 when MOPSO is applied for service restoration; and in Table 11 when NSGA-II is applied for service restoration.

Table 10. Optimal values through Multi-Objective Particle Swarm Optimization (MOPSO) restoration plan when DC drive load is present.

Out of Service Area Buses		14
Manually Controlled Switching Operations		4
Remotely Controlled Switching Operations		2
THD (%) at Bus No. 16	3rd Harmonic Component	0.02
	5th Harmonic Component	3.68
	7th Harmonic Component	2.56
	Total THD at Bus 16	4.44
THD (%) at Bus No. 32	3rd Harmonic Component	0.03
	5th Harmonic Component	4.52
	7th Harmonic Component	3.25
	Total THD at Bus 32	5.62
THD (%) at Bus No. 20	3rd Harmonic Component	0.01
	5th Harmonic Component	2.29
	7th Harmonic Component	1.64
	Total THD at Bus 20	2.87

Table 11. Optimal values through Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) restoration plan when DC drive load is present.

Out of Service Area Buses		**17,18**
Manually Controlled Switching Operations		**4**
Remotely Controlled Switching Operations		**3**
THD (%) at Bus No. 16	3rd Harmonic Component	0.02
	5th Harmonic Component	3.09
	7th Harmonic Component	2.10
	Total THD at Bus 16	3.74
THD (%) at Bus No. 32	3rd Harmonic Component	0.06
	5th Harmonic Component	4.52
	7th Harmonic Component	3.21
	Total THD at Bus 32	5.55
THD (%) at Bus No. 20	3rd Harmonic Component	0.03
	5th Harmonic Component	2.31
	7th Harmonic Component	1.68
	Total THD at Bus 20	2.87

In this case also (when DC drive load is present), it can be clearly concluded from the results in Table 12 that the power quality is improved for PC1, PC2, and PC3 in the restored network when compared to the original network.

Table 12. Total Harmonic Distortion (THD) values when DC drive load is present.

Configuration / **PC**	**Initial Network Topology THD(Percent)**	**THD (Percent) by NSGA-II in Restored Network**	**THD (Percent) by MOPSO in Restored Network**
PC at Bus 16	4.67	3.74	4.44
PC at Bus 32	5.66	5.55	5.62
PC at Bus 20	2.87	2.87	2.87

5.1.2. When the Fault Occurs Between Bus 7 and 8

For the fault location between bus 7 and bus 8, the results are presented in Table 13.

Table 13. Total Harmonic Distortion (THD) values through Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO) algorithm service restoration plan when the fault occurred between bus 7 and 8.

Algorithm	Out-of-Service Buses	MCS	RCS	PC Bus No.16 THD (%)	PC Bus No.32 THD (%)	PC Bus No.20 THD (%)
MOPSO	17,18	3	1	4.11	5.44	1.19
NSGA-II	9,10,11	3	1	6.13	5.44	1.67

A comparison of both the meta-heuristic algorithms is shown in Table 14.

Table 14. Comparison of Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO) algorithms (complexity basis).

Algorithm	Advantages	Drawbacks
NSGA-II	• Can be used to solve the multi-objective optimization problem without using weight coefficients.	• The high computational complexity of non-dominated sorting • Lack of elitism • Need for specifying the sharing parameter
MOPSO	• Short convergence times • Low computational overhead • Comparatively less computational complexity	• Need the addition of a crowding operator to improve the uniformity of the solution distribution

5.2. Case 2: IEEE 69 Bus Test System

- For this case study, non-linear loads are connected at bus no. 17,33,42,49 (Figure 10)
- Priority customers are present at bus 23,45,61
- Switch between two buses A and B is represented as S (A, B)
- Full wave rectifier supplying a resistive load of 150 kW is connected to bus 33,42
- Full wave rectifier supplying a resistive load of 200 kW is connected to bus 17,49

In case of 69 bus system also, the fitness of all the objectives are calculated as shown in Table 15.

Table 15. Restoration plan through Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO) algorithms when the fault occurred between bus 12 and bus 13.

Algorithm	Out-of-Service Buses	MCS	RCS	PC Bus No.45 THD (%)	PC Bus No.23 THD (%)	PC Bus No.61 THD (%)
MOPSO	25,26,27	3	1	4.782	5.901	0.069
NSGA-II	18,19,20,21	4	2	4.833	0.068	0.069

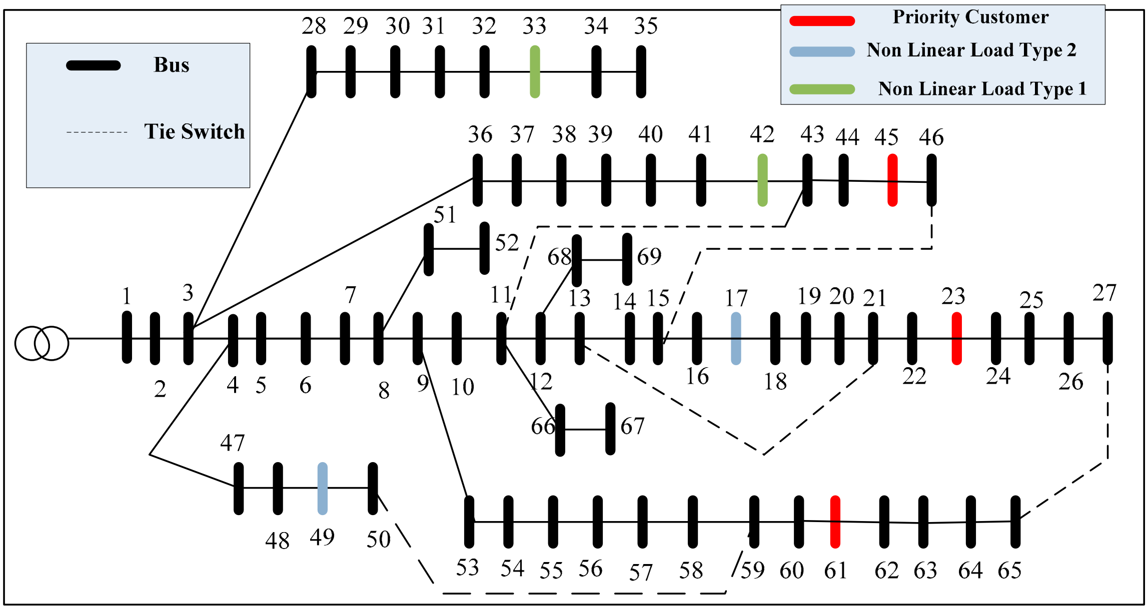

Figure 10. IEEE 69 bus test system.

The case when the fault occurs between bus 56 and 57 is shown in Table 16.

Table 16. Restoration plan through Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO) algorithms when the fault occurred between bus 56 and bus 57.

Algorithm	Out-of-Service Buses	MCS	RCS	PC Bus No.45 THD (%)	PC Bus No.23 THD (%)	PC Bus No.61 THD (%)
MOPSO	60	3	1	3.654	4.197	3.789
NSGA-II	64,65	3	1	3.663	4.674	2.471

Results of the IEEE 69 bus test system also suggest that the service restoration plans obtained through MOPSO and NSGA-II are very effective in minimizing all the objectives of the restoration problem.

6. Conclusions

Service restoration algorithm is formulated as a multi-objective optimization problem in the present work. New objectives for the restoration problem are proposed to address the issue of harmonics when non-linear loads are present in the radial distribution network. The idea is to select an optimal radial path for each priority customer such that THD values are minimized through topological changes. Power utilities have limited time to restore the power during outage condition, and they mainly focus upon restoring as much load as possible. Most of the service restoration algorithms proposed in the literature deal with the time constraint by minimizing the number of switching operations and with the reliability constraint by minimizing the out-of-service area. In the present paper, these two objectives are addressed along with the additional objective of improving power quality when network topology is changed for restoration of power. The optimization algorithms are selected in such a way that this multi-objective optimization problem can be effectively and quickly solved. In the results shown, the out-of-service area customers are very few, and the switching operations required to perform the restoration are also less. For normal operating conditions of any distribution network, there is a requirement of measurement devices (smart meters, PMUs), which need to be optimally placed in the network at different locations, and a proper harmonic emission measurement method like VHV, IEC voltage phasor measurement or voltage only method is required to estimate the quality of power. But in the present work, a novel idea is proposed which directly relates the THD values at the PCC of priority customers to the number of non-linear loads in the radial path of priority customer, the distance of non-linear loads from priority customer, and type of non-linear loads. So, there is no need for the actual calculation of harmonic emission values. As this is a relative power quality measurement technique, it is applicable for the real-time scenario as well because there is no need to actually measure the parameters of power quality. MOPSO and NSGA-II are applied to find the optimal switching sequence for the restoration of power. To validate the effectiveness of service restoration plans, the values of THD are calculated using PSCAD model of the test distribution networks (IEEE-33 and IEEE-69 bus systems). The results obtained from both cases suggest that the power quality (in terms of harmonic distortion) is improved in most of the scenarios and remained the same for the remaining cases.

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