Journal of Operation and Automation in Power Engineering

Vol. 8, No. 2, Aug. 2020, Pages: 152-163

http://joape.uma.ac.ir

Active Distribution Networks Restoration after Extreme Events

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Abstract- *After extreme events such as floods, thunderstorms, blizzards and hurricanes there will be devastating effects in the distribution networks which may cause a partial or complete blackout. Then, the major concern for the system operators is to restore the maximum critical loads as soon as possible by available generation units. In order to solve this problem, this paper provides a restoration strategy by using Distributed Generations (DGs). In this strategy, first, the shortest paths between DGs and critical loads are identified. Then, the best paths are determined by using a decision-making method, named PROMOTHEE-II to achieve the goals. The uncertainties for the output power of DGs are also considered in different scenarios. The IEEE 123-node distribution network is used to show the performance of the suggested method. The simulation results clearly show the efficiency of the proposed strategy for critical loads restoration in distribution networks.*

Keyword: *Critical load, DGs, PROMOTHEE-II, Restoration.*

NOMENCLATURE

Symbol	Description
c_j	The weight of critical load j
Ω_i	Set of restored buses by path i
$ceil(.)$	Function that rounds the input number to the nearest integer greater than or equal to that number
F	Set of feeders
$f_{energy,i}$	Total critical load energy restored by path i
$I_j^{\max}$	Upper limit of current flowing through line j
I_j	Current flowing through line j
N_l	Set of branches
N_b	Set of buses in the energized area
$n_{ops,i}$	The number of switching operations to construct path i
N_{fc}	Number of field crews
$Path$	Set of restoration paths
P_j^N	The nominal active power of critical load j
P_{DG}	Active power of DG
$P_j(t)$	The active power of critical load j at time t
P_j^N	The nominal active power of critical load j
Q_{DG}	Reactive power of DG
$P_{DG}^{\max}$	Maximum active power allowed for DG
$Q_{DG}^{\max}$	Maximum reactive power allowed for DG
P_k , Q_k	Active, reactive power injection of feeder k
R_i	Resistance of line i
RCS	Remote control switch
SW_i	ith switch
S_i^M	Set of manual switches for isolation of path i
$S_k^{Max\ T}$	Upper limit capacity of transformer k
S_i^R	Set of remote-controlledswitches (RCSs) for isolation path i
S^N	Nominal apparent power
T_i^r	Maximum service time for restored critical load i
T_i^{res}	Mean time to isolation of path i
t_{sw}^m	Mean time to operate manual switch
t_{sw}^r	Mean time to operate a RCS
V_i	Voltage magnitude at bus i
$V_{\min}$, $V_{\max}$	Lower and upper limit of bus voltage
X_i	Reactance of line i

Received: 21 Feb. 2019

Revised: 26 Jul. 2019

Accepted: 26 Aug. 2019

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Digital object identifier: 10.22098/joape.2019.5803.1435

Research Paper

1. INTRODUCTION

Despite all efforts to have an uninterrupted power delivery to the distribution customers there are some destructive events like thunderstorms which cause a blackout. According to studies conducted in [1], more than 58% of the power outages in the United States from 2002 to 2012 were due to the severe weather conditions in which more than 50,000 consumers were being out of service.

Thus, network resilience, which describes the network’s ability to withstand and to be recovered from disruptions, becomes a key issue for distribution networks [2]. In this regard, it is very important to re-energize maximum critical loads, such as hospitals and water stations as soon as possible after a blackout [3]. In doing so, the main goals are to increase the restored energy and to reduce the preparing time of the restoration path [4, 5].

After a natural disaster, when access to the main network is lost, the traditional restoration methods for distribution networks are inappropriate [6-8], and there is the need to have advanced methods. One such approach is to use DGs as emergency power sources to feed the critical loads in de-energized areas [9]. Some recent studies have considered utilization of DGs, energy storages and electric vehicles (EVs) for distribution network restoration [5, 10-15]. A multi-stage restoration process for distribution network with DGs which considers all feasible switching operations is presented in Ref. [5]. In Ref. [10], the intentional islanding of DGs with network reconfiguration is used to maximize the restoration of de-energized loads. In Ref. [11], two tabu and node-depth search methods are used to find the best restoration paths. In papers [5], [10] and [11] the restoration process is accomplished without considering uncertainties in DGs. In Ref. [12] a strategy is presented to specify the optimal size, the number and locations of distributed energy resources (DERs) for the efficient distribution network restoration. The main objective functions include System Average Interruption Frequency Index (SAIFI), investment and maintenance costs of DGs, total voltage deviation and total power loss. However, the amount of restored de-energized loads which is very important in restoration is not considered in [12]. The impact of DGs and EVs on the distribution network restoration is discussed in references [13, 14]. In these papers a decentralized multi-agent system (MAS) method is presented to restore maximum loads by minimum switching operations. In this regard, it should be noted that Multi-agent system method needs sequential decision-making of central controller which may slow down the restoration process. A decentralized Multi-Agent System-based technique for radial distribution networks restoration with DGs is presented in Ref. [15]. Expert system rules are used to solve the restoration problem. The main objectives include restored loads and number of switching operations. In this paper only one type of agent is used at each zone of the feeders which simplifies its implementation.

In general, the main disadvantages of multi-agent systems are; 1) a powerful central controller is needed for processing the whole information of the network, 2) a high communication capability is required to communicate with all the agents, and 3) the sequential decision making of the central controller may slow down the restoration process.

In Ref. [16], in order to restore the de-energized critical loads, a resilient microgrid formation strategy is presented. A sequential service restoration framework is given in Ref. [17] to solve the restoration problem after a large-scale power outage. A graphical based algorithm for microgrid priority-based restoration of distribution networks is presented in Ref. [18]. In this paper, MGs are considered as virtual nodes which are connected to the main feeder. Although this assumption will help the method run faster, it reduces its efficiency in practical implementation. In Ref. [19], a combination of reconfiguration with the application of microgrids is proposed to enhance the restoration capability of the distribution network by using spanning tree search strategy to minimize the number of switching operations, total losses and out-of-service loads. In this paper, the uncertainties in MGs outputs are not considered. In Ref. [20], a two-layer algorithm based on a meta-heuristics technique is presented for the optimal restoration of smart distribution networks in self-healing mode. A resilience-oriented approach is presented in Ref. [21] to determine restoration strategies for secondary network distribution systems after a major disaster. In this paper a look-ahead load restoration framework is presented by considering technical issues associated with secondary networks and limits on DG capacity and its operation. A three-Phase Restoration Model considering unbalanced operation of distributed generation is presented in Ref. [22]. This paper provides a plan for microgrid formation that adopts a three-phase network model to represent unbalanced distribution networks. A modeling framework based on resiliency is presented in Ref. [23] for the optimization and evaluation of restoration policies for distribution networks subject to extreme weather events. A mathematical model for the agent-based restoration process is presented in Ref. [24]. In this paper, the uncertainties of measurements are also considered in restoration process. The presented method is self-adaptable and self-updatable. Generally, these agent-based methods need available online sensor measurements and communications modules which increase the complexity of the restoration problem.

The types and status of the network switches (manual or remote-controlled switches) directly affect the implementation time of the restoration plans. In Ref. [25], a heuristic graph-based approach to minimize the de-energized loads and to reduce the switching operations costs of the load restoration in distribution network is presented. The Prim's algorithm is used to find the minimum spanning trees. The effect of upgrading manual switches to remote-controlled switches (RCSs) on network restoration is considered in Ref. [26]. The optimal allocations of switches for the optimal reconfiguration and restoration of distribution networks are presented in Ref. [27]. Because of the importance of the number of switching operations in the operational costs, one of the main objectives in this paper will be to reduce this cost.

Given the above background, this paper proposes a new restoration strategy to restore critical loads after blackout. The major contributions of this paper are as follows:

1) A new strategy for critical load restoration is presented.

2) PROMOTHEE-II technique is used to select the best restoration paths.

3) Both manual and remote-controlled switches are considered in restoration process.

4) The critical loads are restored by considering their priority degrees.

5) Uncertainty in the available energy of DGs is considered in the restoration process.

The IEEE 123-node distribution network in which three DGs and five critical loads are connected is employed as the test system. In this system, the uncertainty in the available energy of DGs after fault clearance, the priority degrees of critical loads and the simultaneous occurrence of several faults are considered in four difference scenarios. Simulation results show the benefits of using the proposed method for critical load restoration in distribution networks with DGs. This paper is organized as follows; Section 2 describes the problem formulation, and Section 3 gives the proposed method. The test system, simulations and comparison results are given in Section 4. Finally, the paper is concluded in Section 5.

2. PROBLEM FORMULATION

After the event of severe natural disasters a part of the network may be isolated from the main network. In this condition, in the isolated area the power sources are unavailable and the only way to restore the critical loads before the fault repair is to use the available DGs. The restoration can be carried out by changing topological states of switches and constructing the proper paths between DGs and critical loads. The network performance associated with an extreme event from the fault occurrence until the network is back to the normal state is depicted in Fig. 1. According to this figure when the fault occurs at t_e , it is isolated at t_{pe} , and at t_r the restoration process is started. During the time between t_r and t_{pr} , the switching operations related to restoration plan are accomplished and during the time between t_{pr} and t_{ir} the loads are energized by restoration plan. At t_{ir} the faulted equipment is repaired and the system can be back to normal conditions. Therefore, for the time period between t_{ir} and t_{pir} , the plan to return the system to the pre-fault situation is done and after time t_{pir} the network works in normal condition. In this paper, the study period of time includes only the restoration time, i.e. t_r to t_{ir} which is equal to T_0 . Distribution network operators will be able to estimate the time period T_0 by studying the network conditions and the type and location of faults [28]. In this paper it is assumed that the time period T_0 is available and estimated carefully.

2.1. Objective functions

Each restoration path is evaluated by the amount of three objective functions, the amount of restored energy with priority, the preparing time of the path and the number of switching operations. The details of calculating these objective functions and the constraints of the problem are discussed below.

2.1.1. Restored energy with priority (f_1)

Because of the limited available energy generated by DGs, after a fault occurrence, a successful restoration plan should be able to restore critical loads that have more priority during the restoration time until the system returns to pre-fault conditions [28]. During the restoration time $(t_r, t_r + T_0)$, the total restored energy by using path x ($f_{energy,x}$) with considering the priority of critical loads is given as follows;

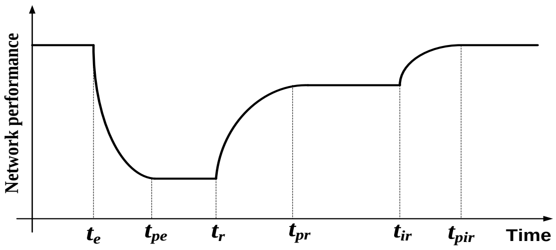

Fig. 1. The network performance associated with an extreme event [28]

$$f_{energy,x} = \sum_{t \in (t_{pe}, t_{pe}+T_0)} \sum_{j \in \Omega_i} c_j P_j(t), \quad x \in Path \tag{1}$$

Where, Ω_j denotes the set of critical loads restored by path *x*, *j* indicates an arbitrary critical load in Ω_j, c_j is the weight of critical load *j* representing its level of priority, $P_j(t)$ is the active power of critical load *j* at time *t* and $f_{energy,x}$ is the restored energy with considering the priority of critical loads by path *x*. It is assumed that path *x* can only supply critical loads for T_i^r hour.

Therefore, $P_j(t)$ is equal to P_j^N for $t \in (t_r, t_r + T_i^r)$ and $P_j(t) = 0$ for $t \in (t_r + T_i^r, t_r + T_0)$. Hence, Eq. (1) is rewritten as follows:

$$\begin{aligned} f_1(x) = f_{energy,x} &= \int_{t_r}^{t_r+T_0} \sum_{j \in \Omega_x} c_j P_j(t)\, dt = \\ \sum_{j \in \Omega_x} c_j \int_{t_r}^{t_r+T_0} P_j(t)\, dt &= \sum_{j \in \Omega_x} c_j \int_{t_r}^{t_r+T_0} P_j^N dt = \\ \sum_{j \in \Omega_x} c_j \left(\int_{t_r}^{t_r+T_i^r} P_j^N \, dt + \int_{t_r+T_i^r}^{t_r+T_0} P_j^N dt \right) &= \\ \sum_{j \in \Omega_x} c_j P_j^N T_i^r & \end{aligned} \tag{2}$$

Equation (2) shows the energy restored by each path. The path with the highest amount of restored energy has a higher priority to be chosen as a restoration path.

2.1.2. Preparing time of path(f_2)

One of the most important issues in critical load restoration is the time taken to isolate the desired restoration path from the rest of the network and to establish the path between DG and critical load. This time includes finding the fault location, isolating it, and the time needed for switching operations to separate the restoration path from the rest of the network. Since the study time period, in this paper, is limited to the time between the fault clearance and the end of the network restoration stage $(t \in (t_r, t_r + T_0))$, the time needed to find the fault location and its isolation is not considered. The time associated with path isolation from the rest of the network and the switching operation depends on the type of switches (manual or remote-controlled switches) and the number of field crews. Therefore, the preparation time of path *x* is considered as the second objective function to be calculated by Eq. (3).

$$f_2(x) = T_x^{res} = \max\{ceil(\frac{S_x^M}{N_{fc}}) t_{sw}^m, S_x^R t_{sw}^r\}, \quad x \in Path \tag{3}$$

The path with the least value of the preparation time has a higher priority to be selected as a restoration path.

2.1.3. Number of switching operations (f_3)

A number of switching operations are required to implement each restoration path. Some of them open the normally closed switches to separate the path from the rest of the network and the others close the normally open switches to establish a direct path between one DG and the considered critical load. As the number of these switching operations is reduced, the cost and the time to set up the path are lessened. Hence, in this paper the number of required switching operations for path *x* $(n_{ops,x})$ is considered as the third objective function to be evaluated and is shown in Eq. (4) [29].

$$f_3(x) = n_{ops,x}, \quad x \in Path \tag{4}$$

The path with the smallest number of switching operations has more chance to be chosen as a restoration path.

2.2. Problem constraints

During the restoration process the following constraints are also to be satisfied.

$$v_{\min} \le v_i \le v_{\max} \qquad \forall i \in N_b \tag{5}$$

$$|I_j| \le |I_j^{\max}| \qquad \forall j \in N_l \tag{6}$$

$$P_k^2 + Q_k^2 \le (S_k^{Max\ T})^2 \qquad \forall k \in F \tag{7}$$

$$P_{DG} \le P_{DG}^{\max}, \quad Q_{DG} \le Q_{DG}^{\max} \tag{8}$$

$$P_i = P_{i+1} + P_{d_{i+1}} + R_i \frac{P_i^2 + Q_i^2}{V_i^2} \tag{9}$$

$$Q_i = Q_{i+1} + Q_{d_{i+1}} + X_i \frac{P_i^2 + Q_i^2}{V_i^2} \tag{10}$$

$$v_i^2 = v_{i+1}^2 + 2(R_i P_i + X_i Q_i) - (R_i^2 + X_i^2) \frac{P_i^2 + Q_i^2}{V_i^2} \tag{11}$$

Eqns. (5) and (6) show the limit voltage of each bus and the current limit for each branch of the network respectively. Eq. (7) shows the capacity limitation of feeders. Eq. (8) considers the active and reactive power constraints of DG. Eqns. (9) to (11) are related to power flows constraints [30]. Another constraint is that the network topology must always be radial. In this paper, the presented method in Ref. [5] is used to check the radially constraint.

3. PROPOSED METHOD

In this section, the proposed strategy for critical load restoration after a blackout is presented. The main three stages of this strategy are; finding all possible restoration paths of critical loads, the assessment of the restoration paths, and selecting the best restoration paths. Each stage is explained in the following subsections.

3.1. Stage 1: Determining the paths

In the first step, the paths between each DG and critical loads should be specified. Each restoration path starts from one DG and ends with one or more critical loads. If there is more than one DG in a restoration path, the radial constraint of the network is not satisfied and, therefore, that path is removed from the list of candidate paths for restoration.

Several methods such as prim's algorithm [25], Bellman–Ford algorithm [31] and depth-first traversal method [28] have been presented to find restoration paths. In this paper Dijkstra's algorithm is used [3]. This algorithm is simple and is able to find all shortest paths from one source to one target node and also the shortest-path tree from one source to more than one target node. Both of these capabilities are used in this paper to investigate the probability of serving one or more critical loads by one DG. By using this method all the shortest possible paths between each DG and critical loads are stored in the list of candidate paths for critical loads restoration.

3.2. Stage 2: Evaluation of the restoration paths

After finding all possible restoration paths at stage 1, the objective functions presented in subsection 2.1 are calculated for each path to complete the table of restoration paths. This table includes the details of paths and the values of the objective functions for each restoration path.

3.3. Stage 3: Selecting the best paths

After completing stage 2, the best restoration paths should be chosen based on the values of the objective functions. Several multi-criteria decision-making methods such as grey regression method [32], Analytic Hierarchy Process (AHP) [33] and PROMOTHEE-II method [34] have been proposed for solving multi-criteria decision-making problems. In this paper, to find the best restoration paths among all candidate restoration paths according to desired objective functions, the PROMOTHEE-II method [34] has been utilized. The details of PROMOTHEE-II method is presented in the next subsection.

3.3.1. PROMOTHEE-II method

ThePROMETHEE method was developed by J. P. Brans and B. Mareschal in 1983 [34]. When compared to other multi-criteria decision-making methods, the PROMETHEE method is easy to be understood and used. This method provides the opportunity to achieve more precise definition of decision criteria by providing preference functions. The main steps of this method are as follows [34]:

1) Calculate the elements of matrix *A*, where the element $a_{ij} \in A$ $(i = 1,2,...,n\ ,\ j = 1,2,...,k)$ are the values of the j_{th} objective function of the i_{th} path, *n* and *k* are the number of paths and objective functions respectively.

2) For each objective function *j*, define the related preference function p_j.

3) Define the relative weight factor w_i (i ∈ k) for each objective function so that $\sum_{k=1}^{k} w_k = 1$.

4) Calculate the aggregated preference index π for each pair $(a_t, a_{t'} \in A)$ of matrix A as follows;

$$\pi = \begin{cases} A \times A \to [0,1] \\ \pi(a_t, a_{t'}) = \sum_{k=1}^{k} w_k .(p_k(f_k(a_t) - f_k(a_{t'}))) \end{cases} \tag{12}$$

where $\pi(a_t, a_{t'})$ shows that with which degree a_t is preferred to $a_{t'}$ over all criteria.

5) Calculate outranking flows: For each path a_t, two following outranking flows are defined as follows:
The positive outranking flow:

$$\Phi^+(a_t) = \frac{1}{n-1}\sum_{\substack{t'=1 \\ t'=t}}^{n} \pi(a_t, a_{t'}) \tag{13}$$

The negative outranking flow:

$$\Phi^-(a_t) = \frac{1}{n-1}\sum_{\substack{t'=1 \\ t'=t}}^{n} \pi(a_{t'}, a_t) \tag{14}$$

The positive outranking flow expresses how a path a_t is outrankingothers and negative outranking flow expresses how a path a_t is outrankedby others.

6) Partial ranking: The partial ranking is obtained from the positive and the negative outranking flows. Basically, for an alternative, whatever the value of positive outranking flow is greater than negative outranking flow, the ranking of that alternative is higher. In PROMETHEE I, the alternative a_t will be preferred than $a_{t'}$ if one of the following conditions is satisfied:

$$\begin{array}{l} \Phi^+(a_t) > \Phi^+(a_{t'}) \text{ and } \Phi^-(a_t) = \Phi^-(a_{t'}) \quad \text{or} \\ \Phi^+(a_t) > \Phi^+(a_{t'}) \text{ and } \Phi^-(a_t) < \Phi^-(a_{t'}) \quad \text{or} \\ \Phi^+(a_t) = \Phi^+(a_{t'}) \text{ and } \Phi^-(a_t) < \Phi^-(a_{t'}) \end{array} \quad (15)$$

According to Eq. (15), if both positive and negative outranking flows of alternative a_t are higher than $a_{t'}$, the PROMETHEE I cannot specify their ranks. In order to solve this problem, the PROMETHEE II uses the net outranking flow which is described below.

7) Complete ranking: The complete ranking of alternatives is accomplished by net outranking flow presented in Eq. (16).

$$\Phi(a_t) = \Phi^+(a_t) - \Phi^-(a_t) \quad (16)$$

The better alternative has a higher net outranking flow. Then, the path with the highest amount of Φ is the best path.

3.3.2. Preference functions

1) Preference function for restored energy with priority ($p_{f_1}(x)$)

The main purpose of this preference function is to restore the maximum possible energy of the network by considering the priority of the loads. Eq. (17) shows the rules for calculating the preference value of this objective function. Fig. 2 also shows the preference function of restored energy by priorities.

$$p_{f_1}(x) = \begin{cases} 0 & f_1(x) < f_1^{\min} \\ \dfrac{f_1(x) - f_1^{\min}}{f_1^{\max} - f_1^{\min}} & f_1^{\min} \le f_1(x) < f_1^{\max} \\ 1 & f_1(x) \ge f_1^{\max} \end{cases} \quad (17)$$

In Eq. (17) $\mu_{f_1}(x)$ is the membership function of $f_1(x)$, $f_1^{\min}$ and $f_1^{\max}$ are the minimum and maximum possible values of $f_1(x)$, respectively. According to Eq. (17), if $f_1(x)$ is high, the restored energy will be high and a higher membership function value is assigned and vice versa. Also, $f_1^{\min} = 0$ and $f_1^{\max}$ is equal to the maximum possible restored energy during the restoration period.

2) Preference functions for preparing time of path ($p_{f_2}(x)$) and the number of switching operations ($p_{f_3}(x)$)

The main purpose of these preference functions is to restore critical loads by the minimum amount of the preparing time of path and the number of switching operations. Eq. (18) shows the rules for calculating the preference values of these objective functions.

Fig. 3 also shows the preference functions of these two objective functions. According to Eq. (18), if $f_{2,3}(x)$ are low, in other words, these objective functions are more efficient, the higher preference function values will be assigned and vice versa.

$$p_{f_{2,3}}(x) = \begin{cases} 1 & f_{2,3}(x) \le f_{2,3,4}^{\min} \\ \dfrac{f_{2,3}^{\max} - f_{2,3}(x)}{f_{2,3}^{\max} - f_{2,3}^{\min}} & f_{2,3}^{\min} < f_{2,3,4}(x) < f_{2,3}^{\max} \\ 0 & f_{2,3}(x) \ge f_{2,3}^{\max} \end{cases} \quad (18)$$

In Eq. (18) $p_{f_{2,3}}(x)$ are the preference functions of $f_{2,3}(x)$, and $f_{2,3}^{\min}$, and $f_{2,3}^{\max}$ are the minimum and maximum possible values of $f_{2,3}(x)$, respectively. Also, $f_{2,3}^{\min} = 0$ and $f_2^{\max}$ is the maximum amount of time to prepare the longest restoration path and $f_3^{\max}$ is the number of switching operations of the longest restoration path.

The flowchart of the proposed strategy for critical load restoration is shown in Fig. 4.

4. SIMULATION RESULTS

4.1. IEEE 123-node distribution network

Fig. 5 shows the single-line diagram of IEEE 123-node distribution network [28]. It is assumed that there are critical loads at nodes 41, 50, 99, 101, and 114. Three DGs are connected to nodes 54, 62 and 72. Parameters of DGs are given in Tables 1. The details of the network and the proposed method have been implemented in Matlab R2009b environment.

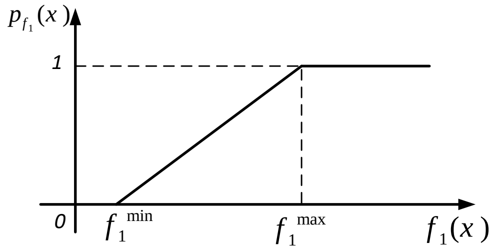

Fig. 2. Preference function for restored energy with priorities

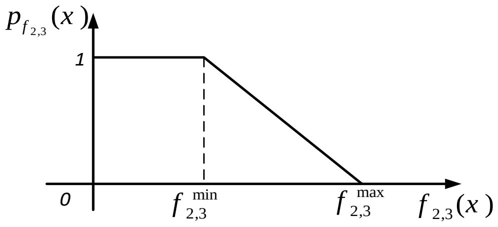

Fig. 3. Preference functions for preparing time of path and number of switching operations

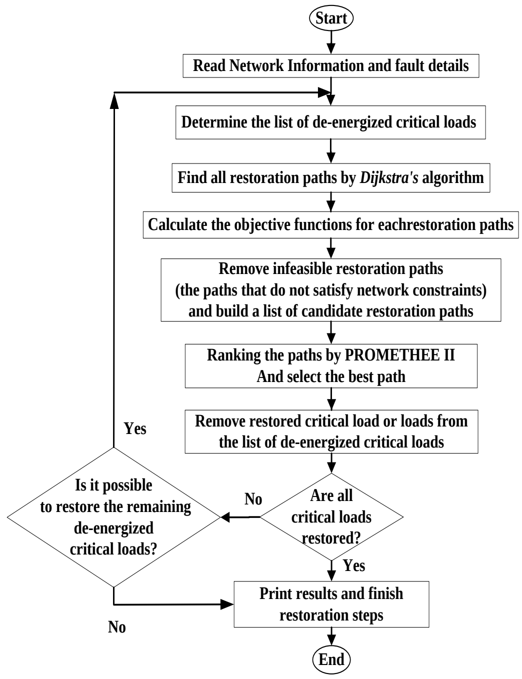

Fig. 4. The flowchart of the proposed strategy for critical load restoration

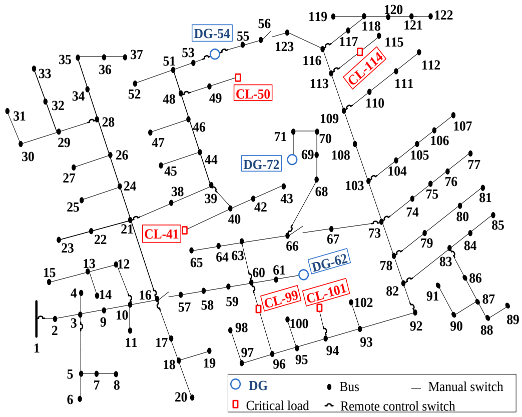

Fig. 5. Single-line diagram of IEEE 123-node distribution network

Table 1. Parameters of DGs

DG #	Node position	$P_{\max}$ (kW)	$Q_{\max}$ (Kvar)	Maximum reserve energy (kWh)
DG -54	54	129.52	89.02	919.12
DG -62	62	92.63	54.56	895.29
DG -72	72	125.33	64.25	780.65

Table 2. Numbers of possible restoration paths

Numbers of paths supplying *n* critical loads						
Starting DG	*n*=1	*n*=2	*n*=3	*n*=4	*n*=5	Total paths
DG-54	8	15	15	10	7	55
DG-62	9	21	25	14	3	72
DG-72	10	28	34	19	4	95

It is assumed that after the fault occurs, the power of the main network is not available, and three DGs in the network are in operation and can participate in the restoration process. The operation times of remote control and manual switches are 20 seconds and 30 minutes respectively [29].

It should be noted that the following assumptions are considered.

I. In the restoration process, the non-critical loads can be isolated from the restoration path by using the remote control or manual switches [35]
II. There are 4 field crews ($N_{fc} = 4$)
III. The blackout will last for 10 hours ($T_0 = 10h$)

4.2. Simulation results and discussion

In this section, the efficiency of the proposed method to restore critical loads has been tested in four different scenarios. In the first scenario, only the occurrence of a single fault is taken into account. In the second scenario, for a condition in which a single fault occurs, the priority degrees of critical loads and generation limits of DGs are incorporated in restoration process. In the third scenario, the occurrence of multiple faults which is very likely to happen during the critical situations has been investigated. Finally, for the fourth scenario, the worst condition is considered in which multiple faults occur, the outputs of DGs are reduced and critical loads have different priorities.

First scenario: It is assumed that a fault occurs on line 44-46 and is isolated by opening the switches on both sides of line 44-46. In this scenario, all DGs are available and all critical loads have a priority with a weighting factor of 1.

For this scenario, Table 2 depicts the total number of possible paths starting from each DG, supplying 1 to 5 critical loads. As shown in this table, there are 222 possible paths to restore critical loads. The restoration results for this scenario are shown in Table 3. As expected, critical load CL-50 is restored by DG-54 through the path 54, 53, 51, 48, 49 and 50 for 9.5 hours, because all restoration paths between CL-50 and existing DGs pass through node 54 (the node that DG-54 is connected to it). Due to the radiality constraint of the network, DG-62 and DG-72 could not restore CL-50. Also, MG-54 can restore CL-114 through path 54, 55, 123, 116, 113 and 114 which needs 4 switching operations and 0.5 hour to establish this path. The restored energy and supplying time by this path are 0.1824 MWh and 9.5 hours, respectively.

DG-62 supplied critical loads CL-41 and CL-99 for 9 hours through path 62, 61, 60, 99, 96, 95, 94, 101, 59, 58, 57, 16, 21, 38, 39, 40 and 41 which needs 8 switching operations and 1 hour to construct this path. CL-101 is restored by DG-72 for 9.5 hours through path 72, 71, 70, 69, 68, 66, 67, 73, 78, 82, 92, 93, 94 and 101. Table 4 shows the restoration results for this scenario. According to this table, DG-54 supplies CL-50 for 9.5 hours and DG -62 supplies CL-41 for 9.5 hours. The critical loads CL-99, CL-101 and CL-114 are re-energized for 3.7 hours by DG-72.

By comparing Tables 3 and 4, it can be seen that considering the priority of loads and generation limits in DGs caused the supplying time of critical loads with less priority to be reduced. Like the first scenario the CL-50 is restored by DG-54 and, therefore, the supplying time of this load remains constant. Unlike the first scenario, DG -62 supplies the CL-41 only. Therefore, the supplying time of CL-41 is increased from 9 to 9.5 hours. The supplying time of all three critical loads CL-114, CL-99 and CL-101 are reduced from 9.5, 9 and 9.5 hours to 3.7 hours.

Although the supplying times of critical loads CL-41 and CL-50 either remained constant or increased, the supplying times of other critical loads CL-114, CL-99 and CL-101 are reduced. These differences in the supplying times of critical loads are because of difference in their load priorities. The weighting factors of CL-50 and CL-41 are five times more than the weighting factors of CL-99, CL-101 and CL-114. This causes the CL-50 and CL-41 to be restored first for the maximum possible time of 9.5 hours, and then in the next priority, other critical loads are energized.

The mean re-energizing times of critical loads for the first scenario (a fault occurs on line 44-46) and second scenario (considering load priorities and generation limits) are 9.3 and 6.02 hours respectively. By this comparison it can be said that considering load priority and generation limits have significant impact on the re-energizing time.

Third scenario (multiple faults): In this scenario two faults occur on lines 44-46 and 94-93 and they are isolated afterwards. Here, it is assumed that all DGs are available and all critical loads have a priority with a weighting factor of 1. Table 5 shows the restoration results for this scenario. As shown in this table, critical load CL-50 is restored by DG-54. Loads CL-41, CL-99 and CL-101 are restored by DG-62. Both DG-72 and DG-54 can restore CL-114, but all the available energy of DG-62 is used to energize CL-41, CL-99 and CL-101 and it cannot participate in the restoration of CL-114. The DG-72 can restore the CL-114 by path 72, 71, 70, 69, 68, 66, 67, 73,103, 108, 109, 113 and 114 which needs 7 switching operations and 1 hour to establish this path. The restored energy and supplying time by this path are 0.1728 MWh and 9 hours, respectively. According to Table 5, the values of different objective functions for the restoration path of CL-114 by DG-54 are better than the restoration path of this critical load by DG-72. Therefore, DG-54 restores CL-114, and DG-72 does not consequently participate in the restoration process.

The mean re-energizing times of critical loads for first scenario (single fault) and third scenario (multiple faults) are 9.3 and 8.72 hours respectively. This comparison clearly shows that the restoration time of critical loads has an inverse relationship with the number of faults.

Fourth scenario (considering load priorities and generation limits): In this scenario, like the third scenario faults occur on lines 44-46 and 94-93, but the available generation resources of DG-54, DG-62 and DG-72 are reduced to 75%, 60% and 40%, respectively. Among critical loads, CL-41 and CL-50 have a higher priority with the weighting factor of 5 and CL-99, CL-101 and CL-114 have a lower priority with weighting factor of 1.

Table 6 shows the restoration results for this scenario. As depicted in this table, CL-50 and CL-114 are restored by DG-54 for 9.5 and 5.8 hours respectively. DG-62 restores CL-99 and CL-41 for 8.4 hours. The loads CL-101 is restored by DG-72 for 6.8 hours.

Table 3. Restoration results for the first scenario

Load	DG #	Nodes on paths	Restored Energy * c_j (MWh)	Path prepare Time (h)	Number of Switching	Critical loads Serve time (h)
CL-50	DG -54	54,53,51,48,49,50	0.5776	0.5	3	9.5
CL-41 CL-99	DG -62	62,61,60,99,96,95,94,101,59,58,57,16,21,38,39,40,41	0.5760	1	8	9
CL-101	DG -72	72,71,70,69,68,66,67,73,78,82,92,93,94,101	0.4332	0.5	6	9.5
CL-114	DG -54	54,55,123,116,113,114	0.1824	0.5	4	9.5

Table 4. Restoration results for the second scenario

Load	DG #	Nodes on paths	Restored Energy * c_j (MWh)	Path prepare Time (h)	Number of Switching	Critical loads Serve time (h)
CL-50	DG -54	54,53,51,48,49,50	2.888	0.5	3	9.5
CL-41	DG -62	62,61,60,59,58,57,16,21,38,39,40,41	2.128	0.5	8	9.5
CL-99 CL-101 CL-114	DG -72	72,71,70,69,68,66,67,73,103,108,109,113,114,78,82,92,93,94 ,101,95,96,99	0.3108	1.5	12	3.7

Table 5. Restoration results for the third scenario

Load	DG #	Nodes on paths	Restored Energy * c_j (MWh)	Path prepare Time (h)	Number of Switching	Critical loads Serve time (h)
CL-50	DG -54	54,53,51,48,49,50	0.5776	0.5	3	9.5
CL-41 CL-99 CL-101	DG -62	62,61,60,99,96,95,94,101, 59,58,57,16,21,38,39,40,41	0.8918	1	10	8.2
CL-114	DG -54	54,55,123,116,113,114	0.1824	0.5	4	9.5

Table 6. Restoration results for the fourth scenario

Load	DG #	Nodes on paths	Restored Energy * c_j(MWh)	Path prepare Time (h)	Number of Switching	Critical loads Serve time (h)
CL-50	DG -54	54,53,51,48,49,50	2.888	0.5	3	9.5
CL-99 CL-41	DG -62	62,61,60,59,58,57,16, 21,38,39,40,41,99	2.0429	0.5	8	8.4
CL-114	DG -54	54,55,56,123,116,113,114	0.1114	0.5	4	5.8
CL-101	DG -72	72,71,70,69,68,66,67,73,78,82,92,93,94,101	0.3101	1	6	6.8

Moreover, a DG can supply one or more critical loads based on the restoration path. If for any restoration path that is started from a DG, there is more than one critical load, for instance, CL-41 and CL-99 supplied by MG-62, as shown in the second row of Table 6, all critical loads are supplied for the same time. As another case, if a DG supplies more than one critical load with two different paths such as critical loads CL-50 and CL-114 which are restored by MG-54 (shown in Table 6), based on the priority and the power demand of both critical loads the supplying time may be different. This difference shows that the proposed method has also considered the priorities of critical loads.

By comparing Tables 5 and 6, it is obvious that the generation limits in DGs have significantly reduced the supplying times of critical loads (e.g., the supplying time of CL-114 is reduced from 9.5 to 5.8 hours). Also, taking into account the priority of critical loads has caused the critical loads with less weighting factors to be restored for the shorter times. For example, the supplying time of critical load CL-50, which has the weighting factor of 5, remains constant (9.5 hours) in both third and fourth scenarios and also the supplying time of critical load CL-41, which has the weighting factor of 5, has been increased from 8.2 to 8.4 hours. However, the supplying time of CL-101 with the weighting factor of 1 in two scenarios, as expected, has been reduced (1.4-hours reduction in supplying time).

As shown in the above scenarios, different combinations of single/multiple faults, uncertainties in the generation of DGs and the priority degrees of critical loads have been considered. The results confirm the efficiency and the robustness of the proposed method in critical load restoration for various cases, especially in the worst condition in which the network faces with multiple faults and loss of generation.

4.3. Performance Comparison

In order to demonstrate the efficiency of the proposed method, the obtained results are compared with the method presented in Ref. [36]. For this purpose, the modified 123-node network given in Ref. [35] is used. Network information including parameters of Distributed Energy Resources (DERs) and critical loads are given in Tables 7 and 8, respectively [35].

It is assumed that multiple faults occur on lines 29-30, 21-16, 55-56, 95-96 and 60-63 and they are cleared by opening the faulted lines. In this case, as assumed in references [35, 36], all critical loads are equally important and the network restoration time (T_0) is not specified and the objective is to restore the maximum possible critical loads for the maximum possible time. It is also assumed that all non-critical loads are removed from the network during the restoration period [36]. The method given in Ref. [36] does not include tie-lines in the restoration problem formulation.

Table 9 shows the results obtained by the proposed method and the method presented in Ref. [36]. In both methods, the critical loads CL-30 and CL-109 have not been restored, because in the restoration process there is no way to restore these loads. The presented method in Ref. [36] has also failed to restore the critical load CL-99, while the proposed method restored this load by DER-6 for 8.48 hours. The other difference between the obtained results by the proposed method and the ones given in Ref. [36] is in restoring the critical loads CL-36, CL-41 and CL-50. In Ref. [36], DER-29 supplied loads CL-36 and CL-41 by 7 switching operations for 10.19 hours and DER-48 supplied CL-50 by two switching operations for 32.42 hours. However, the proposed method restored CL-36 by DER-29 with 3 switching operations for 13.23 hour. Also, the critical loads CL-50 and CL-41 are restored by DER-48 with 5 switching operations for 22.7 hours. The supplying times of critical loads CL-36 (13.23 hours) and CL-41 (22.7 hours) obtained by the proposed method are more than the ones attained by the method given in [36] (10.19 hours). Other critical loads of CL-93, CL-72 and CL-85 are restored by the same paths in both methods.

Moreover, as can be seen in Table 9 the supplying time of CL-50 obtained by the proposed method (22.7 hours) is less than the one given by Ref. [36] (32.42 hours). For this case it should be noted that there is a large difference between this time (32.42 hours) with other supplying times acquired by the method given in Ref. [36] for other critical loads. Since the importance of the critical loads is considered to be the same, this large difference in the supplying times of these loads must be minimized as much as possible. It is clear that while this goal has not been accomplished by Ref. [36], it has easily been achieved by the proposed method given in this paper. In order to show this advantage the variance of the supplying time can be used as an index. The method which gives a lesser variance value, gives a more desirable performance. The supplying time variances of the restored critical loads for the method given in Ref. [36] and the proposed method are 60.114 and 50.93 respectively. Therefore, it can be said that the proposed method is better than the method presented in Ref. [36].

Table 7. Critical loads parameters

Critical load	Node position	P (kW)	Q (kVar)
CL-12	12	52.43	12.43
CL-19	19	19.588	9.568
CL-30	30	44.65	24.63
CL-36	36	40.788	20.288
CL-41	41	12.14	21.14
CL-50	50	28.35	18.65
CL-72	72	20.35	17.31
CL-85	85	14.56	42.52
CL-93	93	26.75	44.56
CL-99	99	20.08	14.25
CL-109	109	33.71	13.25

Table 8. DERs parameters

DER	Node position	$P_{\max}$ (kW)	$Q_{\max}$ (KVar)	Maximum reserve energy (kWh)
DER-6	6	125.33	64.25	780.65
DER-29	29	196.23	86.52	539.78
DER-48	48	129.52	89.02	919.12
DER-92	92	101.63	152.89	550.23
DER-66	66	92.63	54.56	895.29

Table 9. Obtained results by proposed method and method in Ref. [36] for modified 123-node distribution network

DERs	Method	Critical loads	Nodes on paths	Number of switching operations	Critical loads Supplying time (h)
DER-6	Method in Ref. [36]	12,19	6,5,3,9,10,12,16,17,18,19	7	10.83
	Proposed method	12,19,99	6,5,3,9,10,12,16,17,18,19,57,58,59,60,99	10	8.48
DER-29	Method in Ref. [36]	36,41	29,28,34,35,36,26,24,21,38,39,40,41	7	10.19
	Proposed method	36	29,28,34,35,36	3	13.23
DER-48	Method in Ref. [36]	50	48,49,50	2	32.42
	Proposed method	50,41	48,49,50,46,44,39,40,41	5	22.7
DER-92	Method in Ref. [36]	93	92,93	3	20.57
	Proposed method	93	92,93	3	20.57
DER-66	Method in Ref. [36]	72,85	66,68,69,70,71,72,67,73,78,82,83,84,85	5	25.65
	Proposed method	72,85	66,68,69,70,71,72,67,73,78,82,83,84,85	5	25.65

5. CONCLUSIONS

In this paper, a new strategy for multi-objective restoration of the critical loads using distributed generations after extreme events causing a complete blackout is proposed. This new restoration strategy includes three stages; finding all possible paths to restore critical loads, evaluating the restoration paths, and selecting the best paths. The objective functions include the restored energy, the preparing time of the path and the number of switching operations. In order to solve the restoration problem, the decision-making method, PROMETHEE II, has been used. The uncertainties in the available energy of DGs, priority degrees of loads, impact of both manual and remote-controlled switches and multiple faults were considered. The suggested method is implemented on IEEE 123-node distribution network and various conditions such as multiple faults, loads priorities and generation resources limits of distributed generations have been considered.

The comparison results showed that the proposed method restored one more critical load with the less variance of the supplying time when compared with another paper.

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