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A New Method for Solving Service Restoration Problem in Distribution Networks Considering Expected Switching Time

Qasem Asadi[1], Hamid Falaghi [1*] Ali Ashoornezhad[1], Maryam Ramezani[1]

Faculty of Electrical and Computer Engineering, University of Birjand, Birjand, IR.

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ABSTRACT

With the increasing demand for electricity demand, power distribution utilities must provide an efficient and appropriate Service Restoration (SR) strategy to restore customers as soon as possible after power outages to increase the network resiliency and reliability. The heuristic SR algorithm presented in this article is a bi-stage algorithm that initially re-energizes some loads quickly by remote-controlled switches in the first stage and then proceeds to restore the rest of the network in the second stage. Beside solving the restoration problem in a bi-stage algorithm, determining the optimal Switching Sequences (SSs) and applying the Expected Energy Not Supplied (EENS) as objective function included in this research. Also, taking into account the time of occurrence of the failure and the daily load curve, the position of the maintenance team, load transfer capability and the traffic conditions of the network has increased the attractiveness and practicality of the proposed method. The heuristic SR algorithm was applied on a standard IEEE 69-bus system in various scenarios. The results indicated a significant difference in the solutions of the problem and the ENS in different scenarios. Finally, it was found that using this heuristic method would lead to optimal, accurate, and applicable solutions for SR in distribution networks

Nomenclature

Sets:

Ω_{rcs}	Sets of remotely controlled switches.
Ω_{az}	Automatic Zones
Ω_{fz}	Fault zone
Ω_{t1}	switch combinations
Ω_{scomb}	list of combinations that meet network constraints
Ω_{seq}	list of sequences that meet the network constraints
Ω_{ms}	Sets of manual switches.
Ω_{mz}	Manual Zones
Ω_{t2}	switch combinations
Ω_{at}	Automatic tie
Ω_{mt}	Manual tie
Ω_{br}	Sets of branches
Ω_{fc}	Sets of fault conditions
Ω_{m}	Sets of switches of a solution
Ω_{nfs}	Sets of not feasible solutions
Ω_{LS}	Sets of load shedded

Constants:

$\underline{V}$	Minimum voltage limit
$\overline{V}$	Maximum voltage limit
$\underline{I}$	Minimum current limit
$\overline{I}$	Maximum current limit
n_b	Number of nodes

Variables:

L^{s}_{nr}	Loads not restored
T^{s}_{sw}	time of a changing status (switching) of switches
TLS	Total Load Shedded

* Corresponding author
E-mail address: falaghi@birjand.ac.ir
https:/www./orcid.org/0000-0002-5397-3143
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S_L	Total power of load
w_L	Priority coefficient of load
T^s_{SW}	Time to change status of a switch
LNR	Load Not Restored

Functions:

ENS	Total Energy Not Restored
ST	Total Switching time
NSA	Number of switching actions

1. Introduction

Since the rate of faults in the distribution network is higher than other parts of the electrical grids and also considering that most of today's distribution networks have radial configuration, a service restoration (SR) strategy in post-fault conditions is one of the serious requirements of electrical utilities [1]. Also, because conventional restoration strategies cannot recover loads quickly enough, distribution utilities require an advanced strategy for the resiliency of their networks.[2]

In today's power distribution networks, after each power outage, it usually takes a long time to find the fault location and isolate it from the rest of the network (healthy areas). After separating the fault area, the upstream and downstream manoeuvres also take up a lot of time. So, this process may take up to hours on extended networks. However, in advanced industries or critical customers, including hospitals, water stations, traffic lights, important urban areas, and other infrastructures related to the basic needs of human life, power outages, even for a few seconds, can cause enormous economic and social damages [3]. Also, due to the continuous growth of electrical loads and generations, the size and complexity of distribution systems are increasing dramatically, increasing the probability of fault and the number of customers affected in these networks. Therefore, distribution utilities must provide an effective service restoration program to restore energy to customers as soon as possible.

. Here, the aim is to make a comparison between some previous studies and this article. Many considerations are effective in solving the SR problem. The most important ones have been selected and used for the method introduced in this article. These considerations are:

A- Is it considered the possibility to restore only part of the network loads (partial restoration) in severe loading conditions?

B- Is it considered the possibility to load shedding?

C- Is it considered the possibility of transferring part of the load from healthy areas to other feeders (Load transferring)?

D- Is the sequence of different switching actions precisely considered? This switching also includes the Circuit Breaker at the beginning of the feeder (i.e., upstream restoration).

E- Considering the real expected switching time (EST) is one of the factors affecting the objective function value and has a significant impact on the final solution. Is the EST, which includes the time of displacement of the maintenance team from one point to another, considered?

F- Is it considered the time of occurrence of the fault and its effect on the network loading conditions?

G- Is the position of the maintenance team considered correctly?

H- For quick restoration, is priority customers considered?

I- The presence of manual switches (MS) and remotely controlled switches (RCS) is a requirement of today's networks. Are both of these suitably considered?

J- Traffic conditions in the area are another factor influencing the final solution. Has this been considered?

Table I compares the previous studies with the proposed method of this paper (the list is sorted in order of year of publishing the articles). The last line expresses the considerations included in this article.

In this paper, we present a new algorithm for efficient service restoration in distribution networks. As compared in Table I, this algorithm has many advantages over other similar researches.

The main contributions of this article are as follow:

- A bi-stage algorithm for increase speed and effectiveness of restoration
- Including different considerations and factors effecting the final answer
- Determining final switching sequences
- Considering different switching types
- Analysing the effect of manoeuvre team location

	A	B	C	D	E	F	G	H	I	J
[4]	-	✓	✓	-	-	✓	-	-	✓	-
[5]	-	-	-	✓	✓	-	✓	-	-	-
[6]	-	✓	-	-	-	-	-	✓	✓	-
[7]	-	✓	-	✓	-	-	-	✓	✓	-
[8]	-	-	-	-	-	-	-	✓	✓	-
[9]	-	✓	-	-	-	-	-	✓	-	-
[10]	-	-	-	✓	✓	-	✓	✓	-	-
[11]	-	✓	✓	-	-	-	-	✓	-	-
[12]	-	-	-	-	-	-	-	✓	-	-
[13]	✓	-	-	-	-	-	-	-	✓	-
[14]	-	✓	-	-	-	-	-	-	-	-
[15]	-	-	-	✓	-	-	-	-	-	-
[16]	-	✓	-	✓	-	-	-	-	-	-
[17]	-	✓	-	-	-	-	-	✓	-	-
This Study	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

- **Table I.** Comparison between different researches in the field of SR

The rest of the article consists of the following sections: Section 2 describes the proposed method. In section 3, numerical studies and analysing the results obtained with the proposed algorithm are discussed. Section 4 deal with conclusions and further studies.

2. The proposed algorithm for SR

Fig. 1. show a concept of proposed SR algorithm. As is seen, after a fault or outage in the distribution network, the required data entered to the SR program; then it calculates the optimal solution. In the following, the heuristic algorithm used for SR program will be presented. At first, an example for SR operation will be performed to provide an overview of the used method. The proposed method will be described later. This method includes several steps, the most important of which are finding the proper switching combinations to SR and finding the best switching sequence (SS). Before beginning to introduce the proposed method, at the beginning of the section, a comparison will be made between the various objective functions in the SR problem.

2.1. Objective functions of SR problem

To design an efficient SR program, it is necessary to have a suitable index for the evaluation of the solutions. Table 3 provides the most common objective functions used for the SR problem. The TLS represents the total amount of loads shedded, SL is the required power of the load L, and wL is the priority factor of the load. Ns indicates the number of switching actions, Tm is the total time of the SR operation, M represents the set of switches to SR and Tts is the time required to change the status of switch s. LNRs refers to the amount of not restored load before changing the switch s status (s is a member of the solution M).

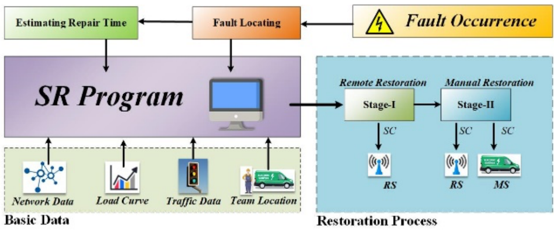


Fig. 1. A concept of proposed SR algorithm

Among the various objective functions introduced, ENS is more in line with SR objectives; because it is a combination of both the Load Not Restored (LNR) and the Switching Time (ST). In addition, this function considers the sequences of switching actions. So, in this paper, the objective function of the Energy Not Supplied (ENS) is used.

Table II. Different objective functions for the SR problem

Objective Function	Equations	Description
Minimize load not restored	$\min(TLS) = \sum_{l\in\Omega_{LS}} s_L \times w_L$ (1)	This function only is useful when some loads need to be shedded. Hence, a priority coefficient is defined for each load, and the aim is to minimize the amount of load interruption by considering the priorities.
Minimize switching actions	$\min(NSA)$ (2)	The aim is to minimize the number of switching actions. Depending on the study, there may be differences between the manual and the remotely controlled switches.
Minimize switching time	$\min(ST) = \sum_{s\in\Omega_m} T_{SW}^s$ (3)	The value of the objective function is the time required to change the status of each switch. Restoration time can be a function of switch type, area traffic conditions, and maintenance team location.
Minimize Energy Not Restored	$\min(ENS) = \sum_{s\in\Omega_m} L_{NR}^s \times T_{SW}^s$ (4)	In this objective function, the initial amount of energy not supplied equals to the energy lost immediately after the fault.
Multi-objective	-	The objective function can be a combination of the above functions. This problem can be solved by weighting the target functions or by using the Pareto front.

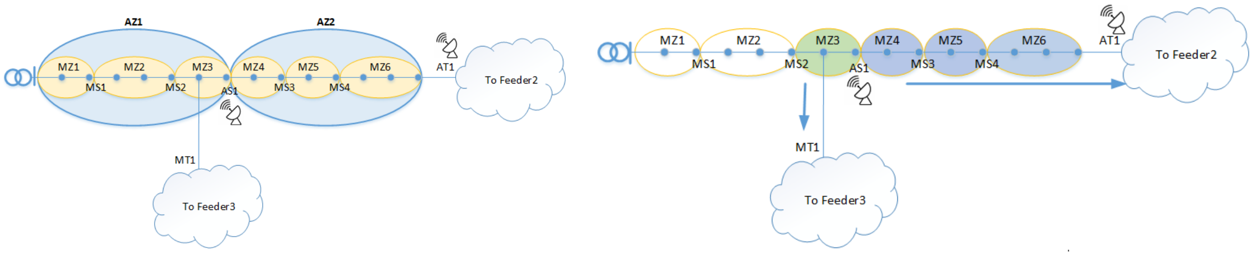


***Fig. 2.** A sample network for the proposed heuristic algorithm. (a) Befor restoration. (b) After restoration*

2.1. An Example for Heuristic Method

In this section, the proposed SR algorithm will be introduced by an example. In this method, according to the location of the RCSs and MSs, Automatic Zones (AZ) and Manual Zones (MZ) are defined as follows:

Zone: A set including one or more load points and lines surrounded by switches. The presence of a switch inside the set (Zone) violates its definition.

Automatic Zone (AZ): An area where all of its surrounding switches are RCS.

Manual Zone (MZ): An area where all of its surrounding switches necessarily are not RCS (may be RCS or MS).

Fault Automatic Zone (FAZ): An AZ that includes the faulty section.

Fault Manual Zone (FMZ): A MZ that includes the faulty section.

Path: A set of sections providing a feeding route between two points (for example, from a distribution substation to one load point).

Fig. 2-(a) shows the Automatic Zones (AZ1 and AZ2) and Manual Zones (MZ1 to MZ6). The remotely controlled sectionalizing switch is named AS1, and the remotely controlled maneuver switch is marked as AT1. The manual sectionalizing switches are also shown by MS1 to MS4 and the manual maneuver switch by MT1. The Cloudy area includes the rest of the network feeders. Now assume that a fault occurs in the manual zone MZ1, i.e., the beginning of the feeder. Therefore, AZ1 is the Automatic Fault Zone, and MZ1 is the Manual Fault Zone. Following this fault, all manual zones downstream of the FMZ, i.e., MZ2 to MZ6, or the AZ2 automatic zone, will be without power. As mentioned in the proposed algorithm, the restoration process is done in two stages. In the first stage, remote restoration should be completed using remotely controlled sectionalizing switches and maneuver switches. At this stage, the aim is to restore some customers as soon as possible. In the next stage, the restoration should be completed manually. This stage may be done using all sectionalizing and maneuver switches of the network (either manual or remotely controlled types). So, in the first stage, the AZ2 automatic zone is early restored using the AT1 remotely controlled maneuver switch. However, to isolate the fault zone, the AS1 switch is opened first, and then the AT1 maneuver switch is closed. These two switching operations are performed remotely by the utility operators. Here the first stage of restoration (remote restoration) ends.

The second stage is manual restoration. At this stage, the rest of the healthy areas of the network must be restored by other available switches. Here, Manual zones are considered. According to Fig. 2-(b), there is only one other maneuver switch in the network (MT1). Now it is possible to use the MT1 switch to restore the rest of the areas, i.e., MZ1 to MZ3. Since the MT1 switch is manual, the maintenance team must move to its position for closing it. MS1 must also be opened before MT1 to isolate the fault zone. So, the final solution would be:

M1 = [AS1, AT1,MS1, MT1]

3. Numerical studies

In the previous section, the proposed heuristic algorithm for solving the SR problem in distribution networks was described by an example. Using the algorithm introduced in the previous section, the service restoration problem will be applied to a sample network. This study will be performed in multiple cases with different considerations. To implement the proposed method, a 70-bus distribution network has been used [18]. This network has two sub-transmission stations (busses 1 and 70), 4 MV feeders, 68 sections, eight manoeuvre switches, and 68 load points. Fig. 8 illustrates the daily load curve of the network. Fig. 9 also shows the base configuration of the network, including the position of the switches.

3.1. The effect of base load

One of the most potentially serious parameters affecting the solutions of the SR problem is the amount of load in different parts of the network. This part discusses the importance of how to include this parameter in the problem. The fault is assumed to occur at 2 PM. Three different modes are considered for the base load of SR problem calculations. In the first case, according to many previous works, the network peak load is the basis of problem calculations. In the latter case, the daily load curve is included in the calculations, i.e., the amount of load at the time of fault occurrence is considered as the basis. In the third case, the peak load of the repairing period is considered as the base load of calculations. For example, if the repairing time is predicted to be four hours, the maximum load of these four hours will be considered as the basis for the calculations. Fig. 15 shows values in two cases of daily load curves and repairing peak as base loads for the calculations.

- A: Daily load curve

In this case, the network load at the time of fault occurrence (2 PM) is equal to 0.169 p.u. The results for this case are given in Table III. It can be seen that in this case, since that the network is in low-loading condition and the amount of load base of the calculations is 0.169 p.u., in all of the fault cases, there is no need to load shedding. The final structure of the network after performing the switching actions is depicted in Fig. 3. Figures (a-b) belong to fault cases 1 and 2 respectively.

- B: The peak load of the repairing period

Here, considering that the fault occurred at 14:00 and the peak load of the repairing period must be considered in the calculations if repair time is estimated four hours, the base load for the calculations will be equal to 0.895 p.u. The results for this case are given in Table VI. In this study, in two fault cases, it is necessary to load shedding. The final structure of the network after all of the switching action is shown in Fig. 4. Figures (a-b) belong to fault cases 1 and 2 respectively.

Table III. SR results in case of considering daily load curve as the base of calculations

Case	Fault Location	Remote SR Sequence	Manual SR Sequence	Min. Voltage (p.u.)	EST (Min.)	ENS (kWh)	Load Shedding	Load Shedding Switch
1	1-2	4-10→15-67	2-3→9-50	0.962	16	710	-	-
2	17-23	27-28→29-64	17-23→24-25→27-28→1-16	0.972	10	1076	-	-

Table IV. SR results in case of considering maintenance peak load as the base of calculations

Case	Fault Location	Remote SR Sequence	Manual SR Sequence	Min. Voltage (p.u.)	EST (Min.)	ENS (kWh)	Load Shedding	Load Shedding Switch
1	1-2	4-10→62-65→67-22→67-15	2-3→7-8→55-61→29-64→22-67→62-65→4-10→9-38	0.933	74	1089	-	-
2	17-23	-	23-17→16-1→27-28→65-62→22-67→29-64	0.924	13	5403	24, 25, 26, 27	27-28

Fig. 3. SR results in case of considering daily load curve as the base of calculations

Fig. 4. Network Configuration after SR in case of considering Maintenance peak load as the base of calculations

Table V. SR results in the case of MTL=1

Case	Fault Location	Remote SR Sequence	Manual SR Sequence	Min. Voltage (p.u.)	EST (Min.)	ENS (kWh)	Load Shedding	Load Shedding Switch
1	1-2	4-10→15-67	2-3→9-38	0.926	18	1286	-	-
2	17-23	27-28→29-64	23-17→25-24→27-28→1-16	0.915	10	3148	-	-

Table VI. SR results in the case of MTL=70

Case	Fault Location	Remote SR Sequence	Manual SR Sequence	Min. Voltage (p.u.)	EST (Min.)	ENS (kWh)	Load Shedding	Load Shedding Switch
1	1-2	4-10→15-46	2-3→9-38	0.922	49	8744	-	-
2	17-23	27-28→29-64	24-25→27-28→23-17→1-16	0.915	36	9920	-	-

(a) (b)

Fig. 5. Network Configuration after SR in the case of MTL=1

(a) (b)

Fig. 6. Network Configuration after SR in the case of MTL=70

3.2. The effect of the maintenance team location (MTL)

Knowing that switching sequence (SS) has a critical effect on ENS value, one of the factors that may affect the SS is the maintenance team location, i.e., the starting point of the switching operation. To examine the importance of the MTL, a study will be conducted in two modes. In the first mode, it is assumed that the MTL is in bus number-1. All previous studies in this article were based on this assumption. In the second mode, it will be assumed that the MTL is at bus number 70. Table V and Fig. 5. show the results of the service restoration program for the first mode (MTL=1). Table VI and Fig. 6. also show the results of the service restoration program for the second mode (MTL=70). Figures (a-b) belong to fault cases 1 and 2 respectively. By comparing Tables V and VI, it can be said that the MTL affects the solutions of the service restoration problem. This is important from two perspectives. First, the MTL must be properly incorporated in the service restoration program to achieve the most appropriate (optimal) switching sequence with the lowest ENS value. Second, due to the importance of the MTL on the service restoration process by reducing or increasing the amount of ENS, an optimal location for the establishment of the maintenance team should be selected. So, it can be said that considering the location of the maintenance team according to the method of this article is effective on the solution of service restoration problem and leads to finding a much suitable solution than the studies don't consider the MTL.

3.3. Optimal placement of the maintenance team

In the previous sections, the effect of the maintenance team location on the solution to the SR problem, and the value of ENS as the objective function of the problem, was investigated. Due to the significant impact of the MTL on the ENS, in this section, the goal is to find the best place for the maintenance team base. In this study, all network buses are candidates for maintenance team location. For this purpose, objective functions should be defined as follows:

$$\min\,(ENS) = \min\,\{\sum_{b\in\Omega_{br}}\sum_{f\in\Omega_{fc}}\sum_{s\in\Omega_{m}} L_{NR}^{s}\} \quad (5)$$

$$\min\,(ST) = \min\,\{\sum_{b\in B}\sum_{f\in FC}\sum_{s\in M} T_{t}^{S}\} \quad (6)$$

s.t.

$$v_{n,\min} \le v_n \le v_{n,\max} \quad (7)$$

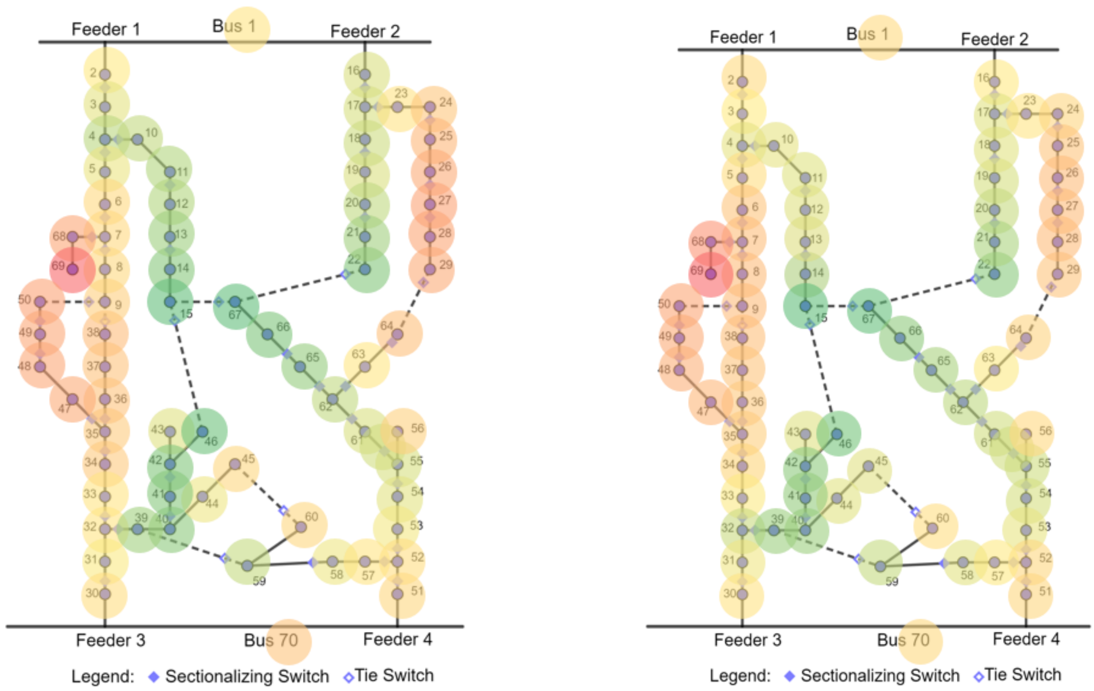
$$I_n \le I_{b,\max} \quad (8)$$

$$M = n_b - 1 \quad (9)$$

$$S \notin \Omega_{nfs} \quad (10)$$

Objective functions (5) and (6), respectively, are the minimum value of ENS and the minimum switching time, constraints (7) and (8) are related to voltage and current limitations, respectively. constraint (9) is related to the radiality constraint of the distribution network and (10) is selected so that the solution meets the technically and safely constraint of the network. By implementing the objective functions and constraints mentioned above in the SR program, ENS and expected switching time (EST) values for each candidate point were calculated and compared with each other.

Fig. 7. shows the heatmap of the network sections in terms of the passage of the maintenance team. For example, the route from bus 4 to bus 15 has the highest number of references for switching operations. Examining these results can also be helpful for better planning the placement of the maintenance team.



(a) (b)

Fig. 7. Heatmap diagram of the candidate points based on the objective functions of the minimum ENS (a) and the minimum EST (b).

4. Conclusion

In this paper, an innovative heuristic algorithm for solving the service restoration SR problem in electrical networks was presented. The proposed algorithm was applied to a sample network. At first, the importance of considering the time of fault occurrence was studied. Due to the differences in the solution in two different cases, including low-loading and high-loading conditions, the necessity of considering this item in the SR program was proved. In the second study, the impact of base load on the final solution of the SR problem was proved. In the third study, the impact of the difference in maintenance team location (MTL) on SR solution was investigated. In the last study, by examining the different candidate points for the establishment of the maintenance team, optimal locations were suggested. Considering the energy not restored (ENS) as the objective function in the proposed algorithm and the use of the Bi-Stage SR method to reduce ENS, the proposed SR algorithm can achieve optimal and practical solutions satisfying network operation constraints. some suggestions for future studies in this field are provided as follows:

-Nowadays, the presence of distributed energy resources (DERs) in distribution networks has become very prevalent. So, the expansion of these resources in different types of wind, solar, geothermal, etc., is increasing day by day. The presence of these resources in distribution networks has brought many advantages and, of course, challenges. The issue of service restoration may be affected by these resources. Since this issue has not been addressed in this article, it is suggested that the service restoration problem with distributed generation sources be considered more effective.

-In this paper, it was assumed that only one maintenance team perform service restoration switching actions. Some companies may use multiple maintenance teams simultaneously for different switching actions for various reasons, including restoring faster loads after faults. Coordination between these groups, in turn, is a significant issue that, if addressed properly and effectively, may reduce ENS value.

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