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Service Restoration in Distribution Networks by Optimal Scheduling of Repair Crew and Mobile Power Sources

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ABSTRACT: Power distribution utilities need to have an effective and suitable service restoration (SR) plan to reconnect customers quickly after power outages. This article presents a heuristic bi-stage SR algorithm that first re-energizes some of the loads fast by remote-controlled switches (RCSs) in the first stage and then continues to restore the rest of the network in the second stage with all possible switching actions using RCSs and manual switches (MSs). This study also includes finding the optimal Switching Sequences (SSs) and the estimated energy not supplied (EENS) as an objective function. Moreover, the proposed method is more attractive and practical because it considers the time of occurrence of the failure and the daily load curve, the location of the load transfer capability, and the traffic conditions of the network. In this method, repair crew (RC) and mobile power sources (MPSs) are also important for the restoration process. The heuristic SR algorithm was tested on a standard IEEE 70-bus system in different scenarios. The results showed a significant difference in the solutions to the problem and the ENS in different scenarios. Lastly, it was concluded that this heuristic method would produce optimal, precise, and feasible solutions for SR in distribution networks.

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1- Introduction

Most distribution networks operate by radial configuration today; since it has lower costs, simpler design, easier coordination of protection, and less fault currents than other structures like ring networks. However, radial structure distribution networks are not in the best condition in terms of reliability and resiliency; so, a fault at any point of the network even for a brief time, leads to the loss of energy of its downstream load points [1].

According to statistics, the most common causes of faults in distribution networks are weather conditions, improper equipment operation, and car accidents. According to a recorded statistic, the faults in the United States MV electrical distribution network were the cause of 74% of Customers' Minutes Lost (CML) equal to 20 min./cust.year. Therefore, distribution networks are the most crucial reason for the unavailability of electricity for customers [2, 3].

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 [4]. Also, because conventional restoration strategies cannot recover loads quickly enough, distribution utilities require an advanced strategy for the resiliency of their networks.[5]

After a power outage, the sooner the necessary action is taken, the fewer power outages the customers will experience. The following procedure is followed usually to restore power in the event of a power outage:

- 1- Accurate detection of the fault location
- 2- Isolation of faulty parts of the network
- 3- Power supply to upstream of the fault area (upstream maneuver)
- 4- Power supply to downstream of the fault area (downstream maneuver)
- 5- Repairing faulty equipment
- 6- Returning the status of the switches to the original state (before fault)

In the subject of distribution systems operation, the above set of actions is called service restoration (load restoration).

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 maneuvers 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 [6]. Also, due to the continuous growth

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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 and also achieve a resilient grid.

Studies on the subject of SR have a relatively long history. Perhaps the starting point of these studies goes back to two studies conducted by Aoki et al. At the University of Hiroshima, Japan, about 40 years ago [7, 8]. In these studies, the aim was to reduce the out-of-service areas following a fault by transferring part of the load to adjacent feeders. In [7], referring to the disadvantages of exact optimization methods such as time-consuming implementation, an approximate approach to solve this problem called BLTA was introduced. In [8], besides the network current constraints, voltage constraints are also considered in the load restoration solution. In this paper, two methods are introduced for small and large networks. The second method, which is specific to large and wide electrical networks, only achieves the approximate optimal responses due to runtime considerations. The principle of both techniques is integer programming. This method was implemented on a real network and proved to be practical.

Apart from the proposed method, researchers should pay attention to the details of the problem and consider the aspects affecting the problem; because considering some conditions such as the daily network load curve or the time of fault occurrence, affects the final solution of the problem. 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 of load shedding?

C- Is it considered the possibility to transfer 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 repair crew 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 repair crew considered correctly?

H- For quick restoration, are 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?

K- Did the research consider the Mobile Power Sources?

Table 1 compares the previous studies with the proposed method of this paper (the list is sorted in order of the 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 2, this algorithm has many advantages over many other similar researches. In this heuristic algorithm, many considerations and capabilities, such as network base load, network traffic status, the position of repair crew, the possibility of load interruption, the possibility of load transfer, etc. have been considered. All of the above items affect the final solutions to the problem and maybe more importantly its applicability. In this paper, the concept of expected switching time (ENS) is introduced to estimate the time required to perform a service restoration operation and calculate the amount of ENS. Also, we have introduced a two-stage method for performing service restoration operations. This enables utilities to supply a significant portion of the loads in the fastest possible time after fault occurrence using remotely controlled sectionalizing switches. In the last study, after evaluating the impact of repair crew location on the problem solutions, the best locations for the maneuver group establishment are proposed. The main contributions of this article can be summarized as:

- Proposing a two-stage algorithm to recover part of critical de-energized customers as quickly as possible.
- Estimating the value of EENS by taking into account the switching time.
- Proposing the required switching action sequences.
- Improving restoration process with repair crew and mobile power sources.
- Reducing the dimensions and solution time of the problem using a simplification method.

The rest of the article consists of the following sections: Section II introduces the proposed method. In this section, in addition to providing a flowchart and pseudo-code to explain the proposed method, examples are used to further understand. In section III, numerical studies and analysis of the results obtained with the proposed algorithm are discussed. Section IV and section V deal with conclusions and further studies, respectively.

2- The Proposed Algorithm for SR

As mentioned in the previous section, the proposed heuristic SR algorithm of this article is a bi-stage process that restores part of loads in the first stage using RCSs, and all the switches (RCS and MS) in the network are used to perform a complete SR operation in the second stage. Fig. 1 shows a concept of the proposed SR algorithm. As is seen, after a fault or outage in the distribution network, the required data is entered into the SR program; then it calculates the optimal solution. In the following, the heuristic algorithm used for the SR program will be presented. At first, an example of

Table 1. Comparison between different research in the field of SR

	A	B	C	D	E	F	G	H	I	J	K
[9]		✓						✓	✓		
[10]		✓	✓					✓			
[11]								✓			
[12]	✓								✓		
[13]		✓	✓			✓			✓		
[14]		✓						✓			
[15]		✓									
[16]				✓							
[17]								✓	✓		
[18]		✓		✓							
[19]		✓		✓				✓	✓		
[20]				✓	✓		✓	✓			
[21]		✓						✓			
[22]				✓	✓		✓				
[23]		✓						✓	✓		✓
This Study	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 2. Different objective functions for the SR problem

Objective Function	**Equations**	**Description**
Minimize load not restored [13,14,20]	$\min\,(TLS)=\sum_{l\in\Omega_{LS}} s_L \times w_L$ (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 [10,21]	$\min\,(NSA)$ (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 [12]	$\min\,(ST)=\sum_{s\in\Omega_m} T_{SW}^{s}$ (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 repair crew location.
Minimize Energy Not Restored [20,24]	$\min\,(ENS)=\sum_{s\in\Omega_m} L_{NR}^{s}\times T_{SW}^{s}$ (4)	In this objective function, the initial amount of energy not supplied equals to the energy lost immediately after the fault.
Multi-objective [13,14]	-	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.

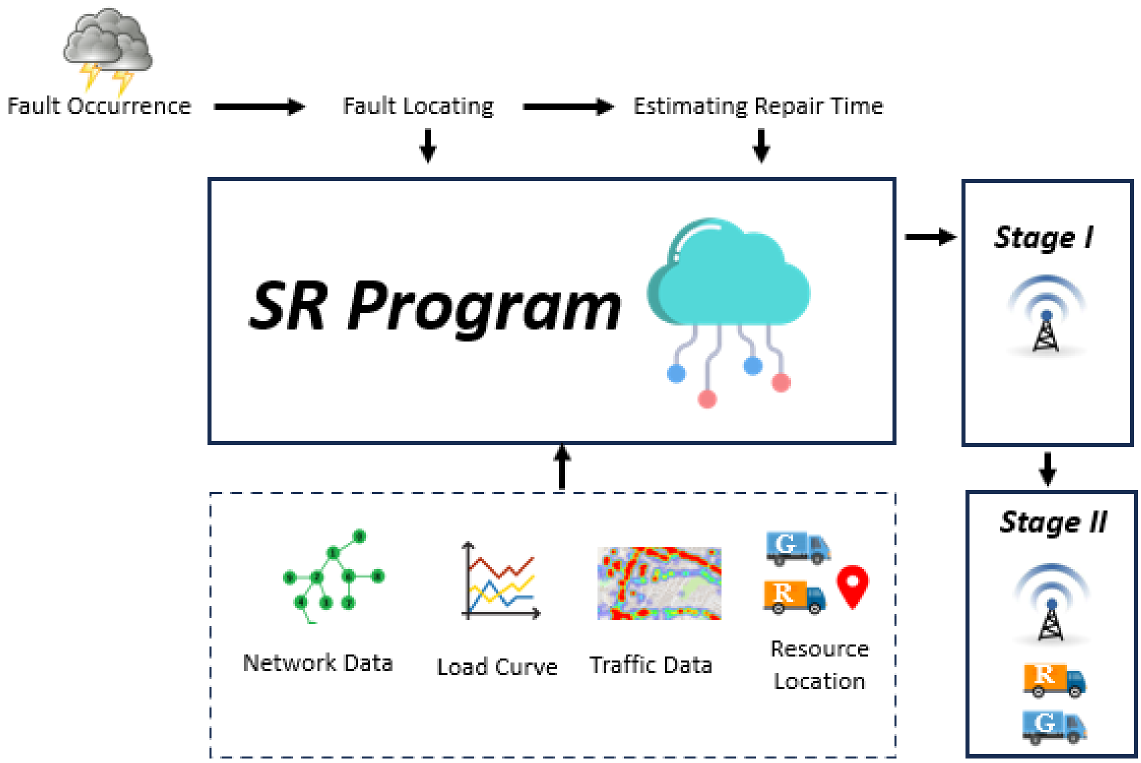


Fig. 1. A concept of the proposed SR algorithm

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

To design an efficient SR program, it is necessary to have a suitable index for the evaluation of the solutions. Table 2 provides the most common objective functions used for the SR problem. The TLS represents the total amount of loads shedded, S_L is the required power of the load L, and w_L is the priority factor of the load. N_s indicates the number of switching actions, T_m is the total time of the SR operation, M represents the set of switches to SR and T_t^s is the time required to change the status of switch s. L_{NR}^s refer to the amount of not restored load before changing the switch's *s* status (s is a member of the solution M).

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.

2- 2- An example for the 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 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

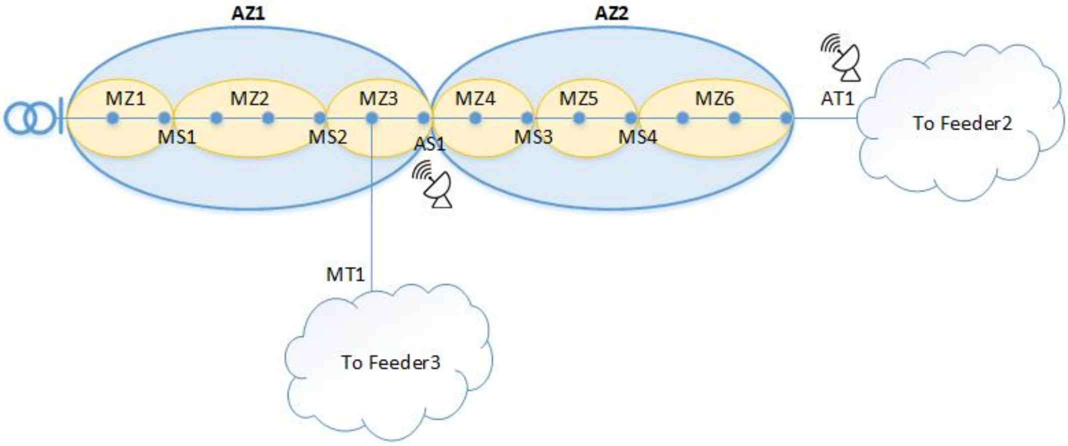


Fig. 2. A sample network for the proposed heuristic algorithm.

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. 3, 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 repair crew must move to its position to close it. MS1 must also be opened before MT1 to isolate the fault zone. So, the final solution would be:

M1 = [AS1, AT1,MS1, MT1]

2- 3- Heuristic method procedure

In general, this algorithm consists of three main stages. Each stage contains its respective steps.

Stage Zero: Receive network data including network load points information, priority customers, lines, protection equipment (circuit breakers, fuses, etc.), switching equipment (maneuver and sectionalizing switches), fault location, daily load curve, fault time, estimated repair time, repair crew location, network operational and loading constraints.

Stage One: Remote Restoration (RR). In this stage, only remotely controlled switches (RCSs) should be used to restore a portion of the out-of-service loads in a very short time. This stage consists of several steps as follows:

1-1- Classification of Automatic Zones (AZs), detection of routes, and final load points.

1-2- Detection of Fault Zone (FZ), fault isolator switches, and healthy out-of-service zones.

1-3- Detection of healthy out-of-service lines, and healthy out-of-service load points.

1-4- Calculating suggested switch combinations and creating the list Ω_{t1}.

1-5- For members of list Ω_{t1}, apply load flow and check network operational and loading constraints.

1-6- Make a list of combinations that meet the network constraints (Ω_{scomb}). If in this step, no combination meets the restrictions, it goes to steps 1-7; otherwise, it goes to 1-8.

1-7- Determining Load Shedding and creating a switching list by considering load shedding and updating the list .

1-8- Sort the list in ascending order based on the objective function (ENS).

1-9- Select the first member of the list to perform the Stage-1 Restoration (RR).

Stage Two: Manual Restoration (MR). At this stage, all possible switches, including RCSs and MSs, are used to perform a complete SR. This stage is similar to Stage One plus one more step as follows:

2-1- Classification of Manual Zones (MZs), detection of routes, and final load points.

2-2- Detection of Fault Zone (FZ), fault isolator switches, and healthy out-of-service zones.

2-3- Detection of healthy out-of-service lines, and healthy out-of-service load points.

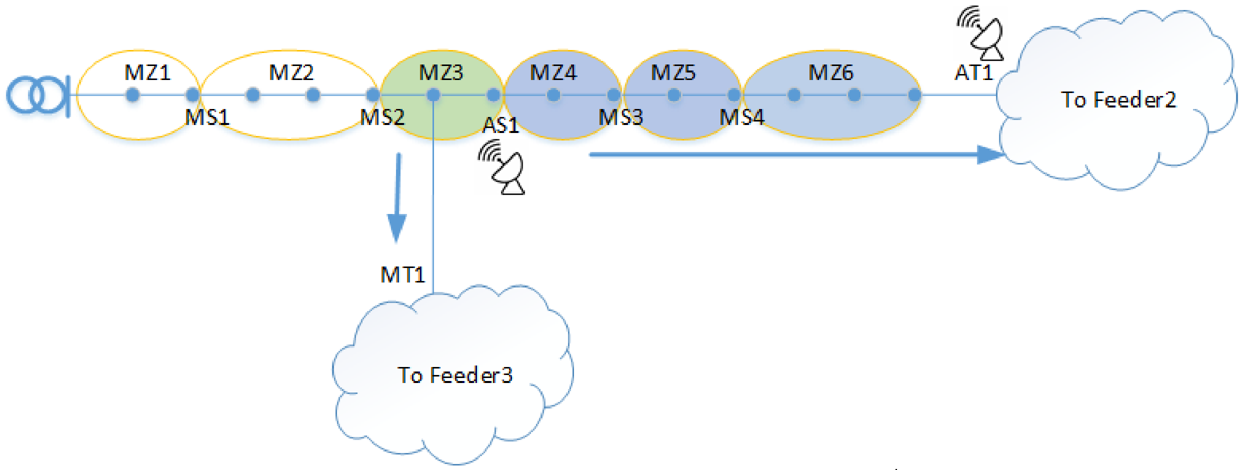


Fig. 3. Network configuration during repair operation (after MR).

2-4- calculating suggested switch combinations and creating the list Ω_{t2}.

2-5- For members of list Ω_{t2}, apply load flow and check network operational and loading constraints.

2-6- Make a list of combinations that meet the network constraints (Ω_{scomb}). If in this step no combination meets the restrictions, it goes to steps 2-7; otherwise, it goes to 2-8.

2-7- Determining Load Shedding and creating a switching list by considering load shedding and updating the list Ω_{scomb}.

2-8- Calculate the best switching sequence and the value of the objective function for each member of the list Ω_{scomb}.

2-9- Sort the list in ascending order based on the objective function (ENS).

2-10- Select the first member of the list to perform the Stage-2 Restoration (MR).

Fig. 4 shows a flowchart of the proposed algorithm. Also, in Algorithm. 1 a pseudo-code for the above stages is presented.

2- 4- Simplification method

The calculation run time for the SR program may not be tolerable in practice due to the introduction of a huge number of variables. Moreover, the increasing the size of the networks may deteriorate this situation; So, so the application of the model may be limited in real applications. It is necessary to use an equivalent simplification of the network for variable reduction. Before describing the simplification methods, some definition needs to be given [26,27].

•Zone: A group of loads/lines surrounded by switching equipment. The presence of a switch inside the zone violates its definition.

•Automatic Zone (AZ): An area where all of its surrounding switching equipment is RCS.

•Manual Zone (MZ): An area where all of its surrounding switching equipment is not RCS (may be RCS or MS) necessarily.

Therefore, in stage A, the SR of the main grid (Fig. 5-a) is performed only by including the automatic zones (Fig. 5-b), and in the second stage (B) by including the manual zones (Fig. 5-c) is summarized and fed into the problem solution.

3- Numerical Studies

In the previous section, the heuristic algorithm for solving the SR problem in distribution networks was described in detail. Using the algorithm introduced in the last section, the service restoration problem will be applied to a sample network. This study will be performed in multiple cases with different considerations. First, the algorithm will be used for the low-loading and heavy-loading conditions of the network. Then a study will be conducted on the effect of the considered base load on the solutions of the problem. As mentioned earlier in this article, load transferring is another feature of SR. Many electrical utilities prefer to use this option for transferring loads from some healthy areas to other areas to deliver more energy to the out-of-service areas; However, other [20] are reluctant to use it; so their policy is based on not disturbing healthy areas. Hence, this item will also be investigated in this section. Next, considering that in different electrical networks, distribution utilities consider different locations for the establishment of the repair crew, the effect of the position of the repair crew on the SR solutions will be investigated. In addition to the above studies, it should be noted that in the electrical networks, there may be some priority customers so that sustainable electricity supply is essential to them, this is also included in the proposed algorithm. The SR algorithm should be such that load shedding, if necessary, involves no priority customers; unless it is the last option.

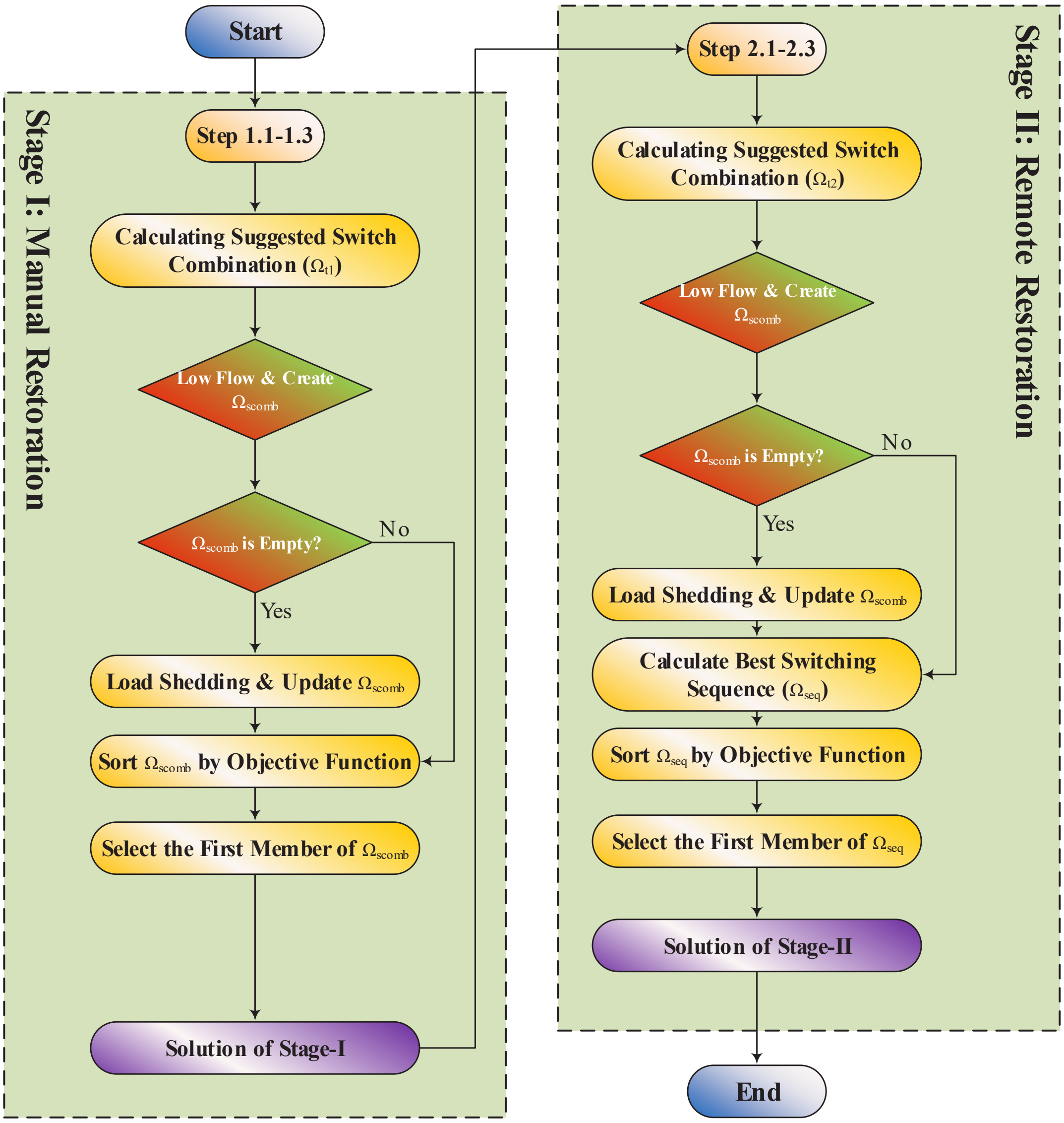
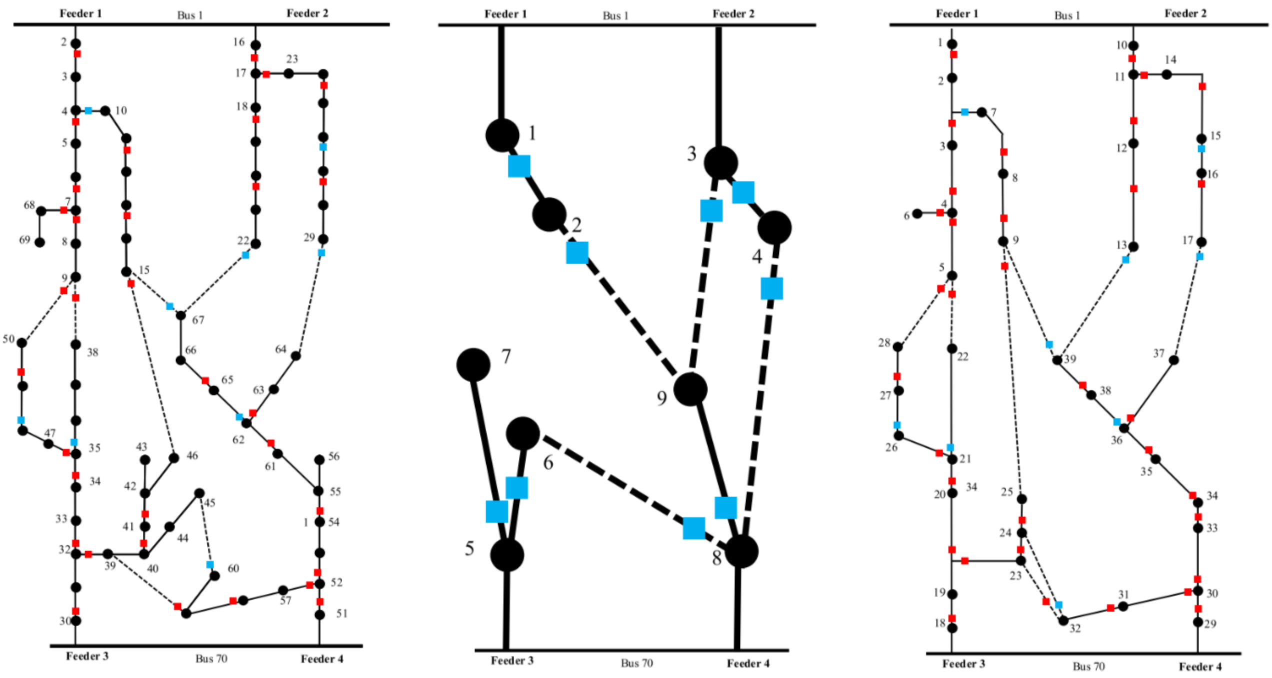


Fig. 4. Flowchart of proposed bi-level SR algorithm.



(a) (b) (c)

Fig. 5. Simplification of the IEEE 70-bus network. (a): main network; (b): simplified network for stage A; simplified network for stage B.

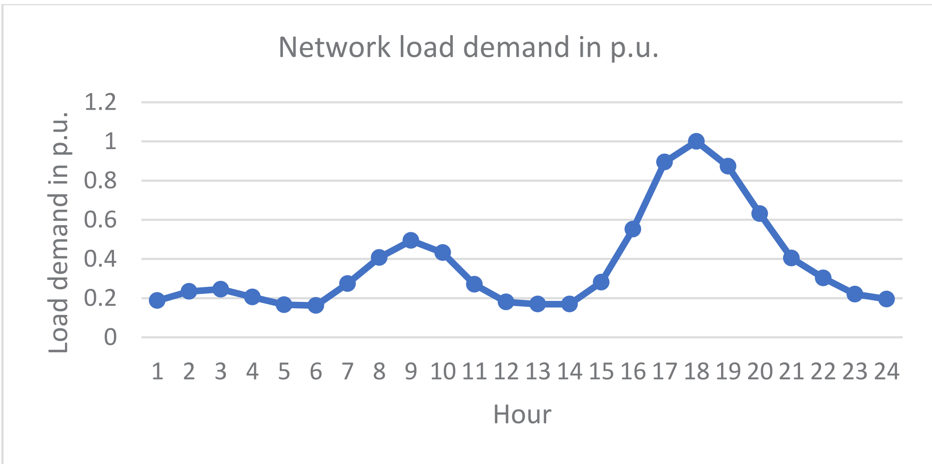


Fig. 6. Daily Load Curve of Network

3- 1- The study network

To implement the proposed method, a 70-bus distribution network has been used [28]. This network has two sub-transmission stations (busses 1 and 70), 4 MV feeders, 68 sections, eight maneuver switches, and 68 load points. Fig. 6 illustrates the daily load curve of the network. Fig. 7 also shows the base configuration of the network, including the position of the switches.

As mentioned, the proposed method for solving the service restoration problem in this article is based on a bi-stage method. The first stage, called remote restoration (RR), aims to restore loads as quickly as possible using remotely controlled switches (RCS). In the second stage, called manual restoration (MR), the goal is to restore all healthy out-of-service areas using all available network switches (RCSs and MSs). Fig. 8 shows the automatic zones (AZ) and manual zones (MZ) of the studied network that may be used in the first and second stages of SR, respectively. As can be seen, the network has nine automatic zones (AZ1 to AZ9) and 37 manual zones (MZ1 to MZ37).

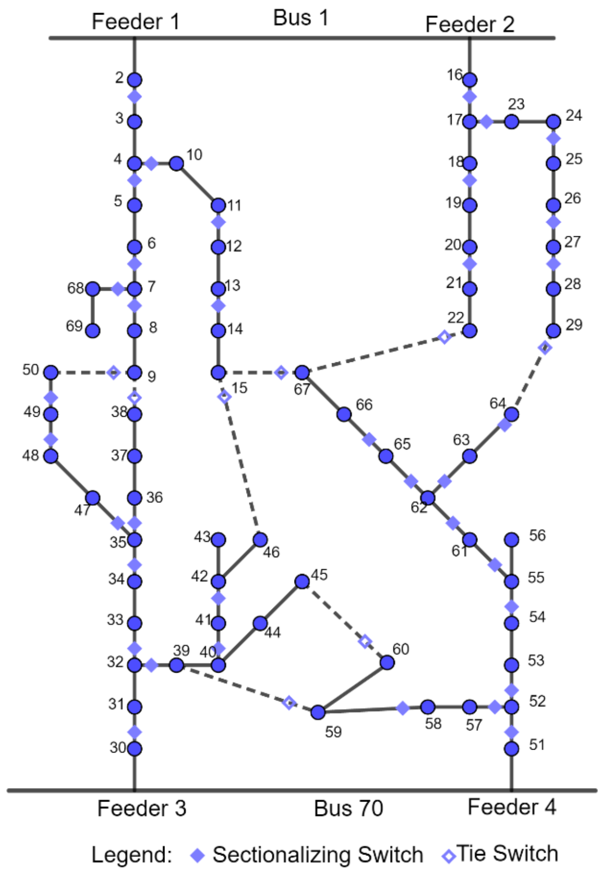


Fig. 7. The Default configuration of the study network

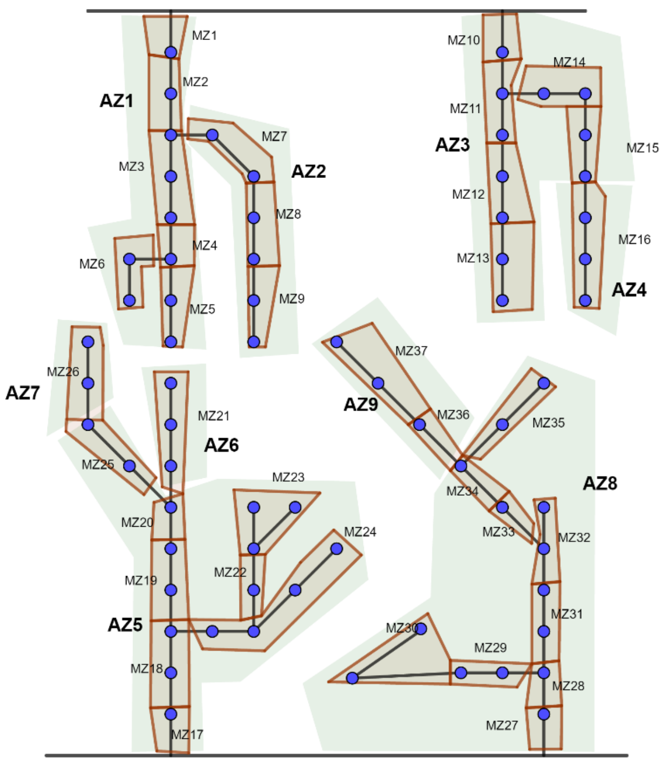


Fig. 8. Automatic/Manual zones of study network

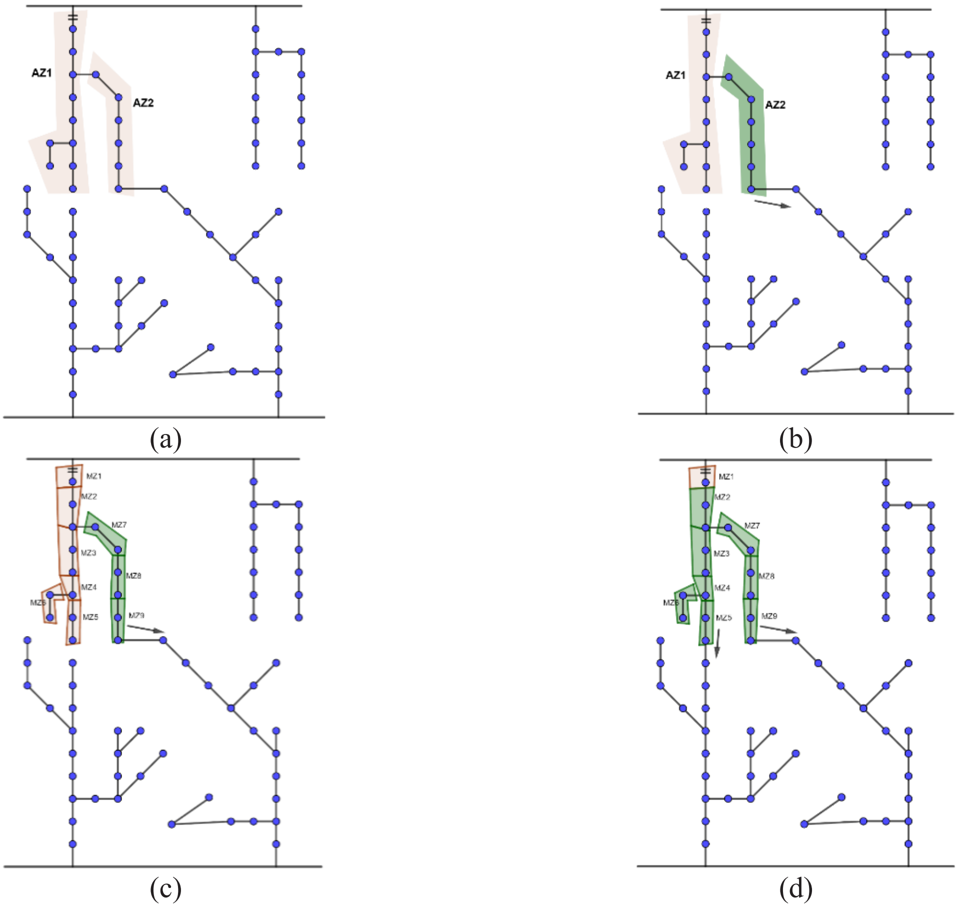


Fig. 9. Network configurations change after different switching actions

3- 2- Time of fault occurrence (TFO)

One of the parameters affecting the SR problem is the time of fault occurrence (TFO). In most previous studies on SR, no attention was paid to the TFO. In this section, the aim is to show the importance of this item. Hence, two different studies have been conducted for SR. In the first study, it was assumed that the fault occurred during the network low-loading condition, and in the latter study, the same analysis was performed for network peak hours (heavy-loading condition).

A: Fault in low-loading condition

In this case, it is assumed that the fault occurred during network low-loading hours. The time 9:00 a.m. is selected for this case. According to the daily load curve of the network (Fig. 6), in this case, the amount of total load is 0.494 p.u.

Fig. 9 shows the process of changing the network configuration after performing the switching action for the occurrence of a fault in line 1-2. In Fig. 9(a) the network configuration after the fault occurrence in line 1-2 is shown. The location of the fault is indicated by the intersection lines. Given that the remote restoration (RR) stage is performed first, it is necessary to identify the automatic zones (AZ). These zones are marked with the letters AZ1 and AZ2. Zone AZ1 is the fault zone, and AZ2 is the healthy zone. Fig. 9(b) shows the network configuration after restoring the AZ2 zone by closing the remotely controlled maneuver switch 67-15. As shown, the loads in the AZ2 area have been transferred to feeder 4. The restored zones are marked in a different color (green) in the figure. This is where the first stage of restoration (RR) ends, and the manual restoration stage must begin. Fig. 9(c) shows the manual zones of the network before performing the manual restoration.

According to Fig. 9(c), it is clear that the manual zones of MZ2 to MZ6 are healthy zones that should be energized. The fault zone is also MZ1. Fig. 9(d) shows the network configuration after restoring the MZ2 to MZ6 zones via the 9-38 switch.

Fig. 10 shows the trend of variations in the amount of loads not restored (LNR) of the network after performing switching actions for the SR. As mentioned, after the fault occurs, the manual zones of MZ1 to MZ9 are without electricity. The total load of these zones is 416 kW, and they should be without electricity until the first switching action. First, the restoration is performed remotely. After closing the 15-67 switch, after the expected two minutes (1 minute due to opening the remotely controlled switch 4-10 and one

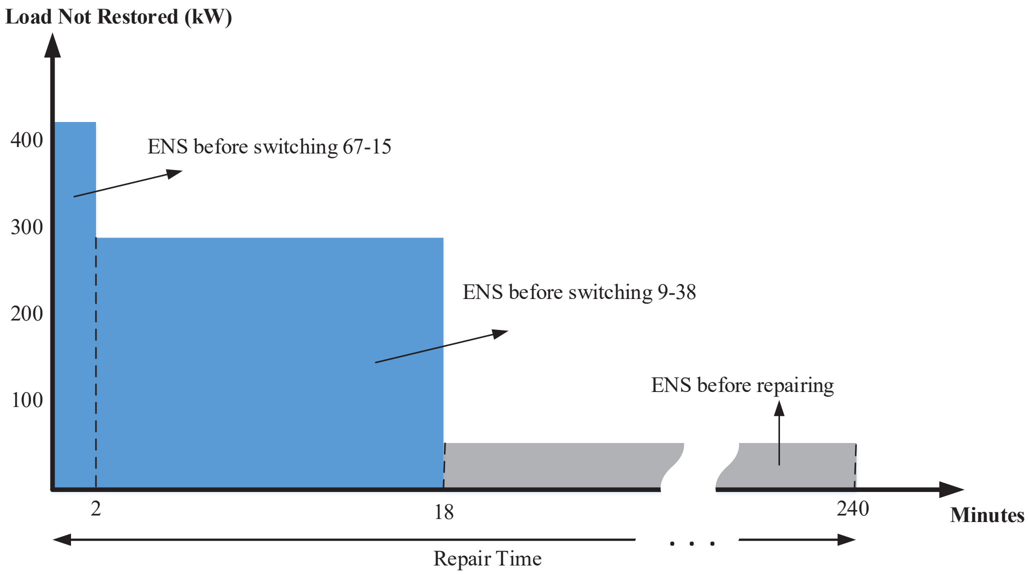


Fig. 10. Changes in the Loads Not Restored (kW) during different switches

Table 3. Service Restoration results for low-loading conditions

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	17-23→24-25→27-28→1-16	0.915	10	3148	-	-
3	34-35	9-38→35-36	35-47→34-35→30-70→9-50	0.938	38	16994	-	-
4	61-62	22-67→62-65	62-63→61-62→70-51→29-64	0.959	28	10621	-	-

minute due to closing the switch 15-67), the remote zone AZ1 is restored, and the LNR value is reduced to 289 kW. At this stage, it is the turn of manual restoration, and the 9-38 switch will be closed 18 minutes from the start of the outage (2 minutes due to the previous switching operation, 2 minutes to move the repair crew from their location to the switch 2-3 and 14 minutes to move the repair crew from switch 2-3 to switch 9-38 location). So, manual zones MZ1 to MZ6 are restored. Now, The LNR value of the network decreases to 49 kW after these switching actions. This value is equal to the MZ1 zone load. This area should be out of service until the repair operation is completed. Also, Fig. 10 shows three different values for the ENS: the ENS value before closing switch 15-67, the ENS value from previous switching action 15-67 until closing switch 9-38, and the ENS value from the closing 9-38 until the repair is completed (after 240 minutes). The total ENS value of the network for this fault condition is equal to the sum of the three mentioned ENS values.

Table 3 shows the results of the SR program in different fault cases. According to the table, it can be seen that for fault case-1, after switching and restoration, the minimum voltage in the network will be equal to 0.926 p.u. All switching operations are expected to be performed in 18 minutes. Fig. 11 also shows the network configuration after manual restoration (restoration completion). Fig. 11(a-d) belong to faults number 1, 2, 3, and 4, respectively. In the table, the sequence of the switching is indicated by an arrow.

B: Fault in heavy-loading condition

In this section, it is assumed that the fault occurred at 7 P.M. Therefore, the base load is 0.873 p.u. Table 4 and Fig. 12 show the results of the SR program for this study. Figures (a-d) belong to fault cases 1, 2, 3, and 4, respectively. Compared with the results of the first case (low-loading condition), it is observed that in this case, because the network is in peak hours, it is necessary to shed (cut off) some loads during the manual restoration stage. Also, for fault case 2 in the first stage (RR), it is not possible to restore any load. Only some loads are provided in the manual restoration stage, and the rest of the load points (24, 25, 26, and 27) must be disconnected. However, for the same fault case in the first study (low-loading condition), first, part of the loads is restored in the first stage of restoration, and the rest is fully restored in the second stage (MR).

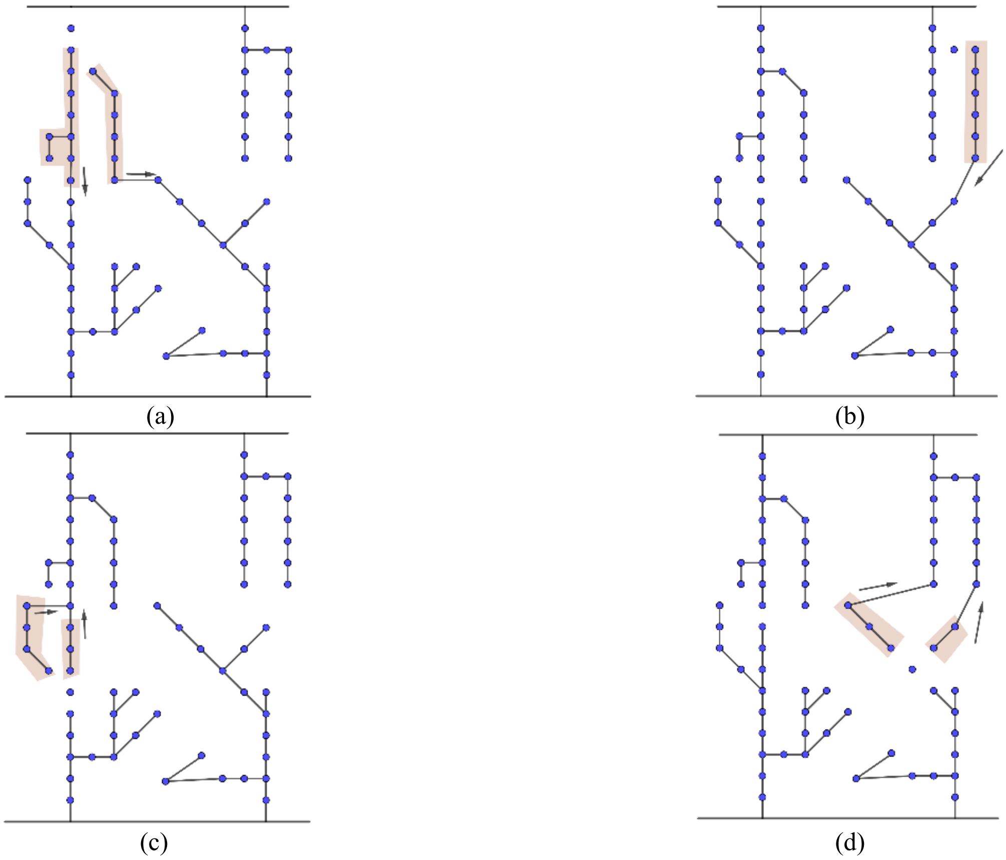


Fig. 11. Final configuration of the network after SR in low-loading conditions. (a) – (d) are related to faults 1, 2, 3, and 4, respectively.

According to what was studied here, it is necessary to consider the time of fault occurrence (TFC) and include it in the SR calculations; because the program's output solutions must be both optimally and technically possible. This means that network load points should be provided as much as possible and also be feasible following constraints like line loading and voltage. For example, if an error occurs during off-peak hours, but the peak-hour load is included in the calculations, the program output will lead to a non-optimal solution; because many loads may be interrupted due to miscalculations. The second point is when the fault occurred during peak hours, but the low-loading condition was included in the calculations. In this case, the program will provide an output that is not technically feasible (due to non-compliance with voltage and current constraints).

3- 3- The effect of the repair crew location (RCL)

Knowing that the switching sequence (SS) has a critical effect on ENS value, one of the factors that may affect the SS is the repair crew location, i.e., the starting point of the switching operation. To examine the importance of the RCL, a study will be conducted in two modes. In the first mode, it is assumed that the RCL 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 RCL is at bus number 70. Table 5 and Fig. 13 show the results of the service restoration program for the first mode (RCL=1). Table 5 and Fig. 14 also show the results of the service restoration program for the second mode (RCL=70). Figures (a-d) belong to fault cases 1, 2, 3, and 4, respectively. By comparing Tables 5 and 6, it can be said that the RCL affects the solutions of the service restoration problem. This is important from two perspectives. First, the RCL must be properly incorporated into the service restoration program to achieve the most appropriate (optimal) switching sequence with the lowest ENS value. Second, due to the importance of the RCL on the service restoration process by reducing or increasing the amount of ENS, an optimal location for the establishment of the repair crew should be selected. So, it can be said that considering the location of the repair crew according to the method of this article is effective in the solution of the service restoration problem and leads to finding a much more suitable solution than the studies that don't consider the RCL.

Table 4. Service Restoration results for heavy-loading condition

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→22-67→67-15	2-3→4-5→9-38	0.906	20	4507	3, 4	4-5
2	17-23		17-23→16-1→62-65→22-67→27-28→29-64	0.926	13	5270	24, 25, 26, 27	27-28
3	34-35	36-35→38-9	35-47→34-35→30-70→48-49→50-9	0.914	39	26575	47, 48	48-49
4	61-62	62-65→22-67	62-63→61-62→70-51→64-29	0.925	28	18769	-	-

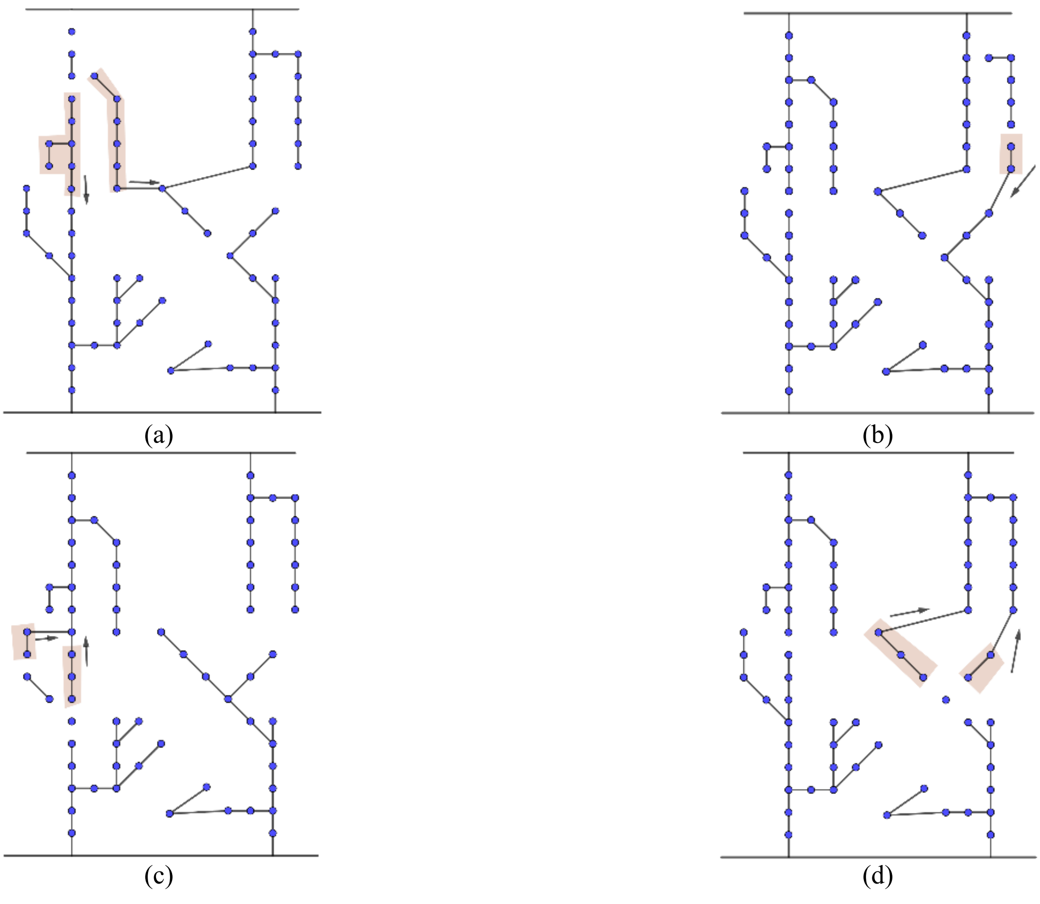


Fig. 12. Final configuration of the network after SR in heavy-loading conditions. (a) – (d) are related to faults 1, 2, 3, and 4 respectively.

Table 5. SR results in the case of RCL=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	-	-
3	34-35	35-36→9-38	35-47→34-35→30-70→9-50	0.938	38	16994	-	-
4	61-62	62-65→67-22	62-63→62-61→51-70→29-64	0.959	28	10621	-	-

Table 6. SR results in the case of RCL=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	-	-
3	34-35	35-36→9-38	34-35→30-70→35-47→9-50	0.938	23	8272	-	-
4	61-62	62-65→22-67	62-61→51-70→62-63→29-64	0.959	18	6022	-	-


(a) (b)


(c) (d)

Fig. 13. Network Configuration after SR in the case of RCL=1

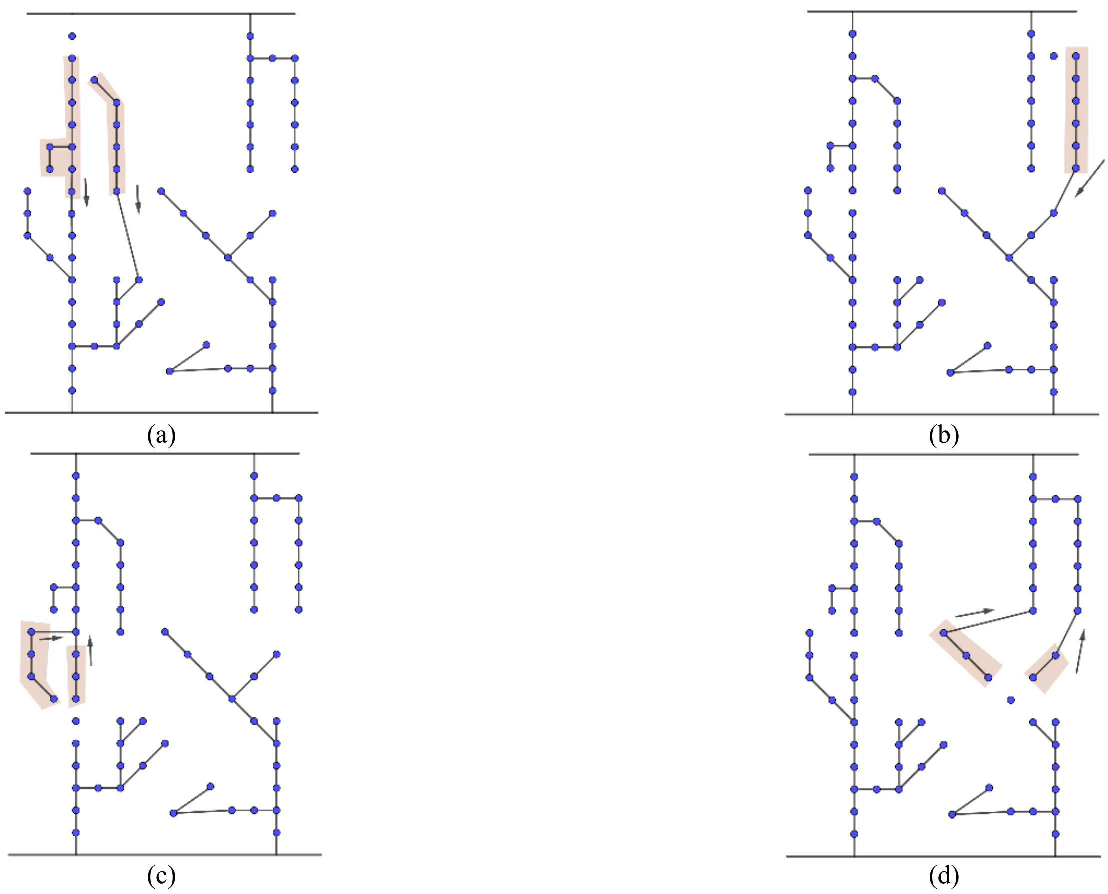


Fig. 14. Network Configuration after SR in the case of RCL=70

3- 4- Optimal placement of the repair crew

In the previous sections, the effect of the repair crew location on the solution to the SR problem, and the value of ENS as the objective function of the problem, were investigated. Due to the significant impact of the RCL on the ENS, in this section, the goal is to find the best place for the repair crew base. In this study, all network buses are candidates for repair crew locations. For this purpose, objective functions should be defined as follows [29]:

$$\min(ENS) = \min\{\sum_{b\in\Omega_{br}}\sum_{f\in\Omega_{fc}}\sum_{s\in\Omega_m} L_{NR}^{s}\times T_{SW}^{s}\} \quad (5)$$

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

s.t.

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

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

-

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

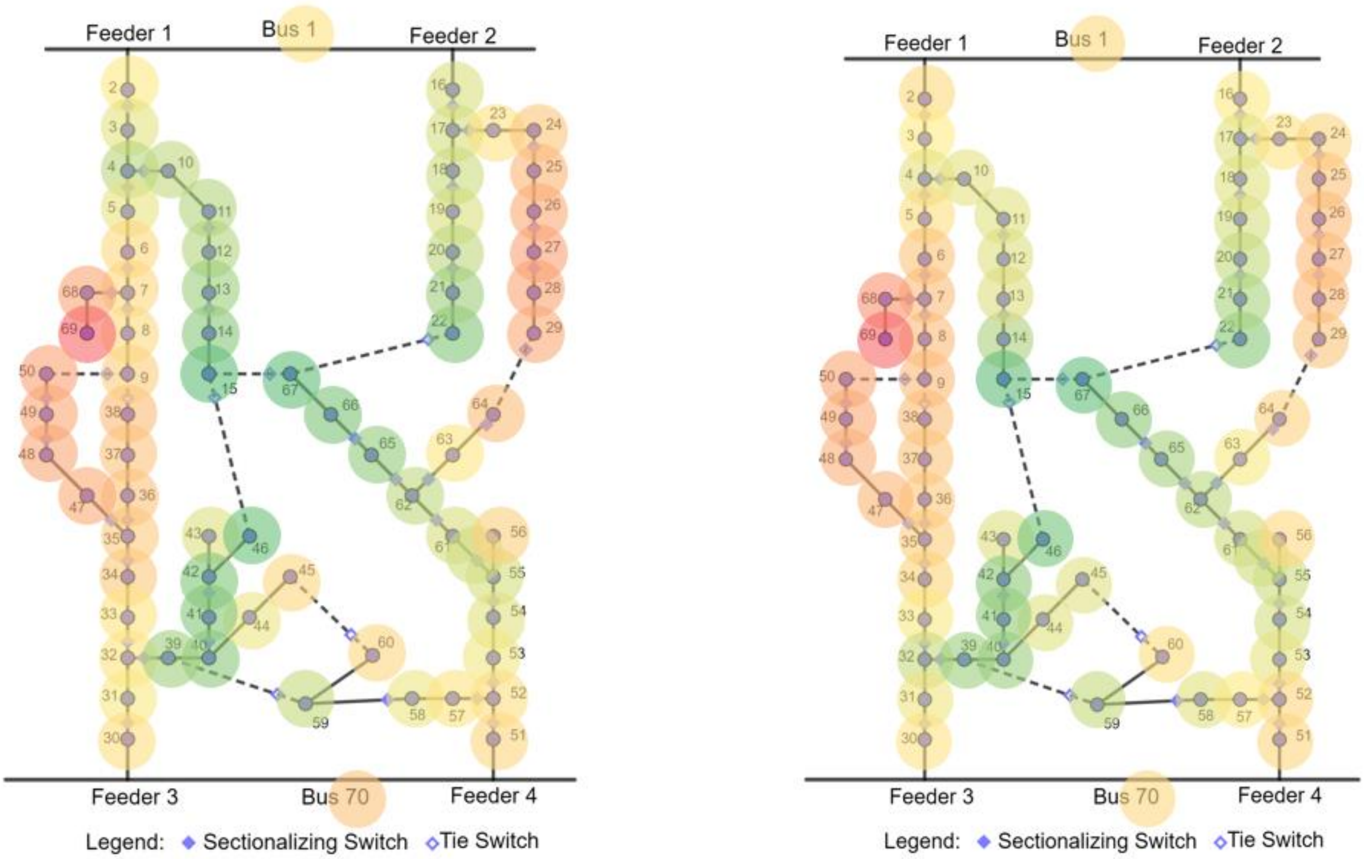
$$S \notin \Omega_{nfs} \quad (10)$$

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 technical and safety constraints 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. These results are shown in Fig. 15. It can be seen that the best candidate point in terms of the objective function (minimum ENS) is bus number 15 with a value of 195613.1 kWh and the worst candidate point is bus number 69 with a value of 302619 kWh. Also, considering the objective function as the minimum EST, bus 67 with 839 minutes and bus 69 with 1154 minutes are the best and worst candidate points, respectively.

Bus No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
ENS (kWh)	245279	244612	236698	229887	243642	253847	259400	260732	260740	229821	228344	228048	224839	210787
ST (Minutes)	986	981	954	916	960	1000	1002	1004	1016	924	910	910	892	872
	15	16	17	18	19	20	21	22	23	24	25	26	27	28
ENS (kWh)	195613	237485	228508	225749	225594	221799	214887	206169	239746	247000	256374	260344	260520	259845
ST (Minutes)	840	945	942	933	946	922	894	868	988	1028	1048	1063	1074	1070
	29	30	31	32	33	34	35	36	37	38	39	40	41	42
ENS (kWh)	255919	240343	232451	222246	235250	247793	251155	253379	256149	258878	210497	208408	207544	206645
ST (Minutes)	1064	997	973	931	986	1024	1020	1032	1032	1040	895	877	871	867
	43	44	45	46	47	48	49	50	51	52	53	54	55	56
ENS (kWh)	228064	228453	241500	201075	263036	265865	268576	271132	246597	237064	230489	225470	223788	245585
ST (Minutes)	949	963	1005	849	1064	1068	1068	1076	1005	997	967	953	942	1013
	57	58	59	60	61	62	63	64	65	66	67	68	69	70
ENS (kWh)	235804	229167	221394	243477	224030	219561	235522	248089	214121	207281	196580	281009	302619	246299
ST (Minutes)	987	963	925	1005	943	923	984	1038	884	863	839	1072	1154	1029

Fig. 15. ENS and switching time (ST) values for different repair crew candidate locations



(a) (b)

Fig. 16. Heatmap diagram of the candidate points based on the objective functions of the minimum ENS (a) and the minimum EST (b).

Fig. 16 shows the heatmap diagram of the candidate points based on the objective functions of the minimum ENS and the minimum EST. By comparing the two figures, a meaningful relationship is observed between the ENS objective functions and the minimum EST.

3- 5- Mobile Power Sources

In this section, we will examine the importance of Mobile power sources (MPSs) presence in the network. For this purpose, two different studies will be conducted. In the first study, the network is low-loading, and in the second, the

Table 7. Service Restoration results in low-loading conditions.

Case	Fault Location	Remote SR Sequence	Manual SR Sequence	Mobile Resource	Min. Voltage (p.u.)	EST (min.)	ENS (kWh)	Load Shedding
1	1-2	4-10→15-67	2-3→9-38	-	0.926	18	1286	-
2	17-23	27-28→29-64	17-23→24-25→27-28→1-16	-	0.915	10	3148	-
3	34-35	9-38→35-36	35-47→34-35→30-70→9-50	-	0.938	38	16994	-

Table 8. Service Restoration results for heavy-loading condition.

Case	Fault Location	Remote SR Sequence	Manual SR Sequence	Mobile Resource	MG Buses	Min. Voltage (p.u.)	EST (min.)	ENS (kWh)	Load Shedding
1	1-2	4-10→62-65→22-67→67-15	2-3→4-5→9-38	-	-	0.906	20	4507	3, 4
2	17-23	-	17-23→16-1→62-65→22-67→27-28→29-64	26	25, 26, 27	0.926	13	4150	-
3	34-35	36-35→38-9	35-47→34-35→30-70→48-49→50-9	48	47, 48	0.914	39	25875	-

network is heavy-loading. We will see that in heavy-loading situations when the network is facing a huge amount of load demand, the presence of MPSs can greatly help restore the service.

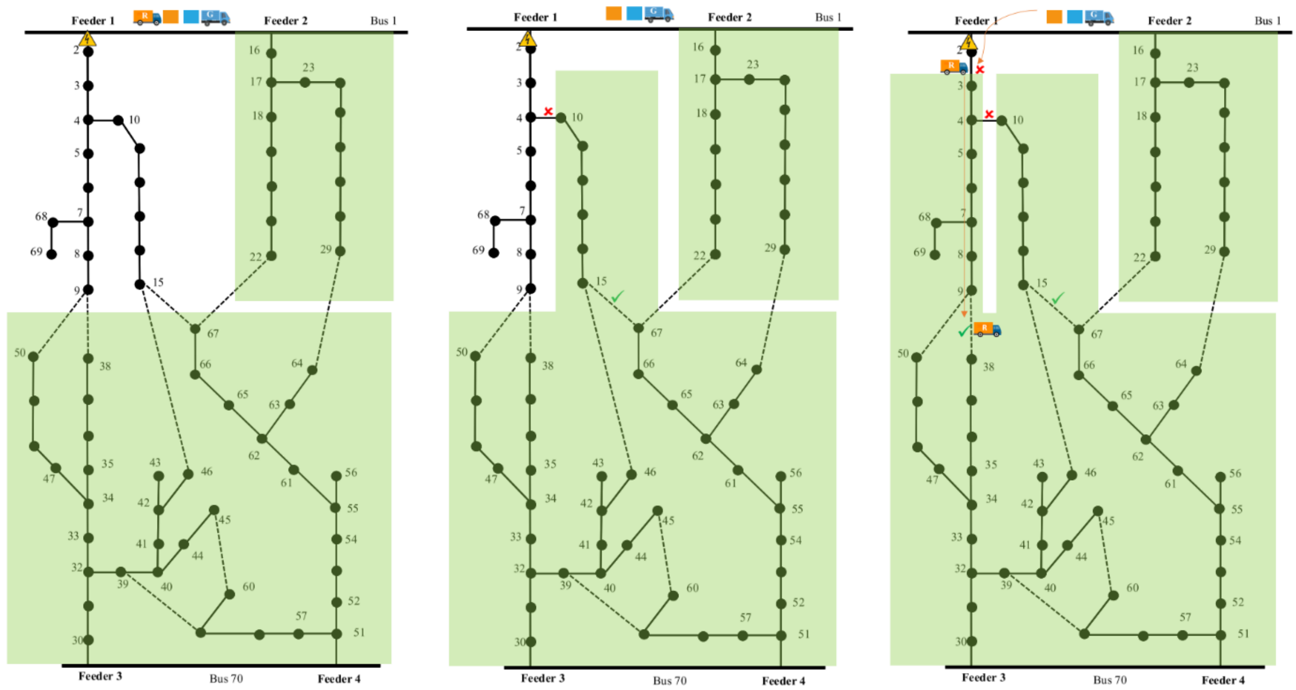
A-Low-loading conditions

Fig. 17 illustrates the load restoration process for the first case as listed in table 7. (Fig. 17-a) shows the state of the network after fault occurrence. It is comprehensible that in this situation, the load points 2-15 and 68-69 are without service. The highlighted parts show the restored loads. In (Fig. 17-b), using remote control switches 4-10 and 15-67, most of the outaged loads are recovered. In (Fig. 17-c), first, the maneuver repair crew dispatched to switch 2-3 and changed its position to open and then referred to switch 38-9 and closed it. At this stage, other outaged load points are also restored. Only load number 2 remains without electricity service because it is located in the faulty area. As mentioned in Table 7, this process takes 18 minutes to complete and the amount of ENS will be equal to 1286 kWh.

B-Heavy-loading conditions

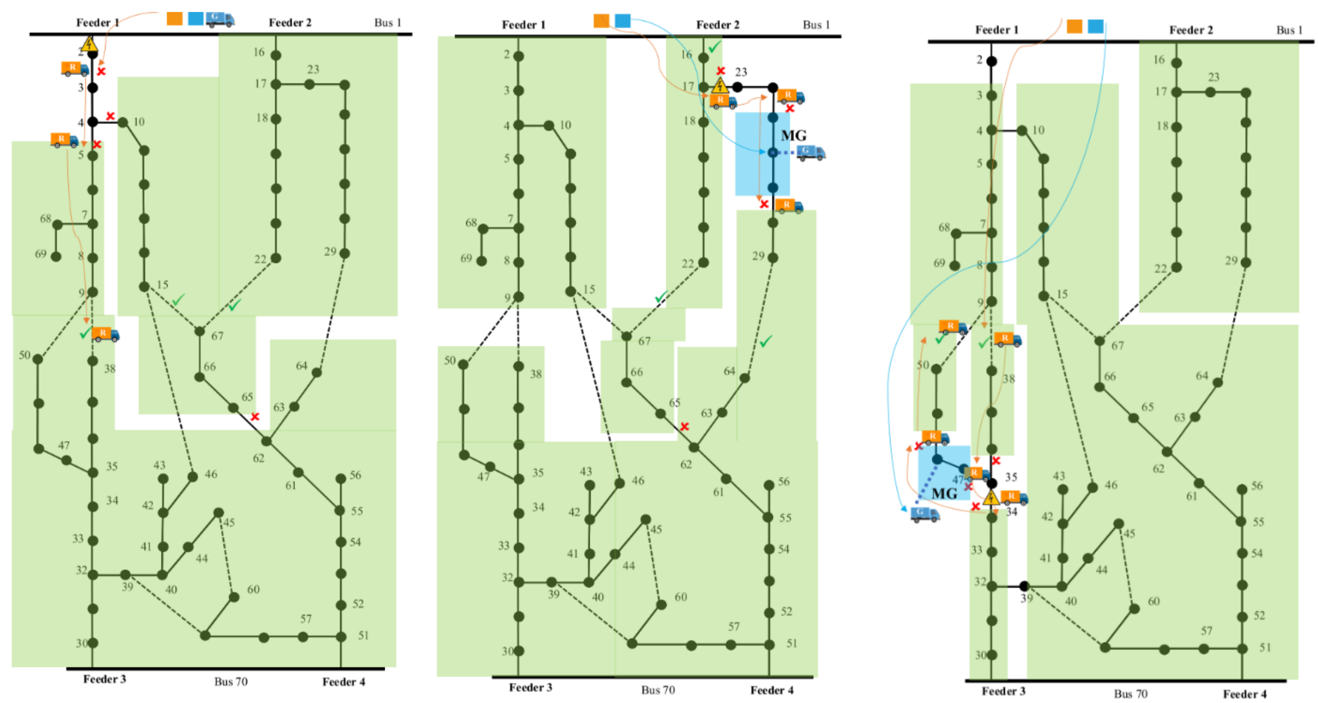
In the following study, we assumed that the fault occurred when the grid was in heavy-loading hours. The results of this study are presented in Table 7 and Fig. 18. According to Table 8, in fault case 1, loads 3 and 4 should be interrupted so that it is possible to recover the rest of the loads. In fault case 2, loads 25-27 have been supplied by a mobile power source (MPS) and forming a microgrid. The rest of the loads have been supplied through the main grid. In fault case 3, the MPS is connected to bus 48 and supplies a microgrid including loads 47 and 48. The rest of the loads will be recovered from the main network after 39 minutes. Fig. 18 shows the ultimate configuration of the network after the service restoration operation for each of the fault cases. The each of highlighted areas connected is served from the same substation.

In Fig. 19 profiles of voltage for fault case 1 in four different situations are depicted. It is clear that in all fault cases, the voltage values in all buses of the network remained within the allowed range (for example here 0.9-1.05 p.u.); except the interrupted buses (with voltage =0).



(a) (b) (c)

Fig. 17. Load restoration process for fault case 1 in low loading conditions



(a) (b) (c)

Fig. 18. Ultimate configuration of the network after the restoration process (during repairing process). (a): fault case 1; (b): fault case 2; (c): fault case 3.

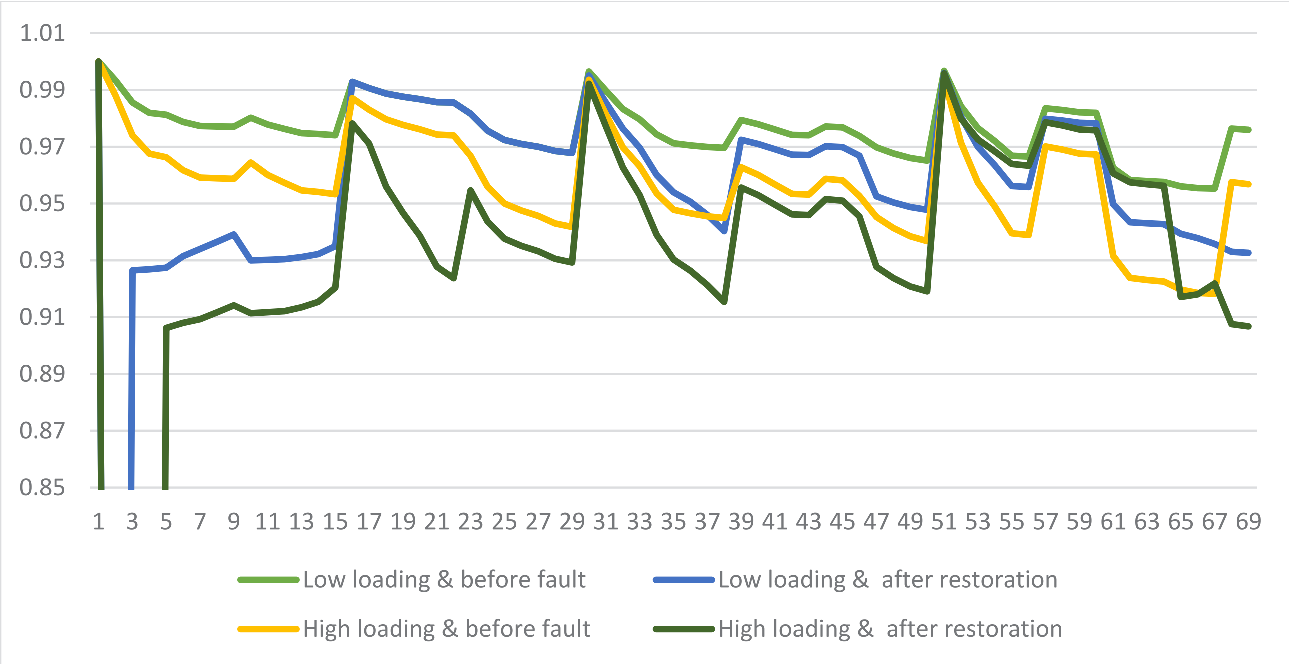


Fig. 19. Profile of voltage (p.u.) for fault case 1 in different scenarios

4- Conclusion and Future Works

This paper introduced a novel heuristic algorithm for the service restoration (SR) problem in electrical networks. The algorithm was tested on an IEEE benchmark distribution network. The first study investigated the impact of the time of fault occurrence on the solution. It showed that this factor was essential for the SR program, as it led to different solutions in low-loading and heavy-loading scenarios. The second study evaluated various potential locations for the repair crew and recommended optimal ones. The proposed algorithm used the energy not supplied (ENS) as the objective function and the Bi-Stage SR method to lower ENS. It could obtain optimal and feasible solutions that met the network operation constraints.

The following are some possible future research directions in this area:

1- Distributed energy resources (DERs) are widely used in distribution networks nowadays. The use of these resources in various forms, such as wind, solar, geothermal, etc., is growing rapidly. These resources have many benefits and challenges for distribution networks. They may influence the service restoration issue. This paper did not address this issue, so it is advised that the SR problem with distributed generation sources be studied more effectively.

2- This paper assumed that only one repair crew carried out the service restoration switching actions. Some companies may employ multiple repair crews at the same time for different switching actions for various reasons, such as restoring loads faster after faults. The coordination among these crews is an important issue that may reduce ENS value if handled properly and efficiently.

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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
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 Supplied
ST	Total Switching time
NSA	Number of switching actions

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