

Optimal Service Restoration of Power Distribution Networks Considering Voltage Regulation

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Abstract—This paper proposes a convex model for the optimal service restoration of power distribution networks after a permanent fault. The proposed method minimizes the out of service area providing the minimum switching actions and the tap position of the on load tap changer (OLTC) placed at the HV/MV substations subject to voltage and capacity limits of the distribution network. The nonlinear constraints of the restoration problem are transformed into second-order cone programming constraints providing a convex formulation for the service restoration problem that can be efficiently solved by commercial branch and bound solvers. The proposed method is applied to an 83-bus power distribution network to verify its effectiveness and robustness.

Index Terms—distribution network reconfiguration, mixed integer programming, power system restoration.

NOMENCLATURE

A. Sets

Ω_{CL}	Set of distribution lines with closed switches.
Ω_L	Set of distribution lines.
Ω_{LS}	Set of distribution lines with switches.
Ω_N	Set of system buses.
Ω_{OP}	Set of distribution lines with open switches.
Ω_{SS}	Set of substation buses.
Ω_T	Set of lines with on load tap changers (OLTC).

B. Parameters

M	Big number.
$P_{d,i} / Q_{d,i}$	Active/reactive load demand of bus i .
r_{ij} / x_{ij}	Resistance/reactance of line $i-j$.
rt	OLTC transformer ratio.
$S_{\max,jj}$	Thermal limit of line $i-j$.
$S_{SS \max,i}$	Maximum substation capacity of bus i .
$t_{0,ij}$	Initial tap position of the OLTC placed between buses i and j .

$t_{\max,ij}$	Maximum steps of the OLTC placed between buses i and j .
$V_{\min,i} / V_{\max,i}$	Minimum/maximum voltage magnitude limits of bus i .
w_1, w_2, w_3, w_4	Weighting coefficients.

C. Variables

$AuxP_i / AuxQ_i$	Auxiliary variable associated with the active/reactive power balance at bus i .
$AuxU_{sqr,i}$	Auxiliary variable associated with the voltage square magnitude of bus i .
P_{ij} / Q_{ij}	Active/reactive power flow of line $i-j$.
$P_{SS,i} / Q_{SS,i}$	Active/reactive power injected from substation at bus i .
$U_{sqr,i}$	Voltage square magnitude of bus i .

D. Integer Variables

t_{ij}	Tap position of the OLTC placed between buses i and j .
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E. Binary Variables

LR_i	Power supply of bus i . It is equal to 1 if load at bus i is supplied; otherwise it is equal to 0.
y_{ij}	Switch status of line $i-j$. It is equal to 1 if line $i-j$ is connected; otherwise it is equal to 0.
z_{ij}	Power flow direction variable. It is equal to 1 if power flows from bus i to bus j ; otherwise it is equal to 0.

INTRODUCTION

A fundamental function of the power distribution network operation is to efficiently deal with the outcome of an outage due to a faulted or overloaded network element. The replacement or repair of the faulted element may last several hours affecting several customers. A service restoration strategy provides the appropriate switching actions in order to supply the part of the distribution network that is disconnected due to the isolation of the faulted area. The main objective of the service restoration is to minimize the number of the non

supplied loads in the shortest time with minimum number of switching actions [1]. During the restoration process, all the operational and technical constraints of the distribution network, such as voltage and capacity limits, must be satisfied. In fact, service restoration is a distribution network reconfiguration (DNR) problem in an emergency condition and it can be modeled as an optimization problem.

The service restoration is a mixed integer non linear programming (MINLP) problem. An extended literature review of service restoration methods can be found in [1], [2]. An enhanced dynamic programming method is used for the restoration of radial distribution networks after an outage in [3]. Another heuristic method based on A* search method is used to solve the service restoration problem in [4]. Even though heuristic methods provide high quality solutions, they cannot guarantee optimality. In [5], the proposed multi-agent system implements the switching operations for the restoration of the distribution system, after the location and isolation of the fault. A two-stage method based on mathematical programming is developed in [6]. In the first stage, an approximate mixed integer linear programming method provides the network configuration, which minimizes the out of service area, and in the second stage, a nonlinear programming method determines the steady state operating points of the network. A mixed integer second order cone programming (MISOCP) method is formulated in [7] in order to determine the appropriate switching actions for the restoration of a distribution network after a bus fault.

During the restoration process, the non supplied loads are connected to the adjacent active feeders. This load transfer may cause higher voltage drops to these feeders and appropriate control actions should be employed in order to maintain the bus voltages within their limits. The voltage regulation of a distribution system is performed mainly by 1) on-load tap changers (OLTC) that are placed at the HV/MV substations, 2) step-up voltage regulators (VRs) and 3) capacitors. The tap positions of the OLTC have a discrete nature and they can be modeled using integer variables. However, in [3]–[7], the voltage of the HV/MV substation is fixed at a certain operation point or the tap position of the OLTC transformer is considered as a continuous variable.

This paper proposes a service restoration method for power distribution networks that determines simultaneously the minimum switching actions and the tap position of the OLTCs in order to minimize the non supplied loads with respect to network operational constraints, i.e., the bus voltage limits, the lines' and substations' thermal capacity. The proposed method transforms the original MINLP formulation into a convex optimization model that is easily solved by classic optimization techniques. The control variables of the proposed optimization method are 1) the load rejection, which is considered as binary variable; 2) the statuses of the network's switches, which are considered as binary variables; and 3) the tap position of the OLTCs, which is considered as integer variable. The objective function minimizes the amount of the non supplied load, the number of switching actions and the number of tap changes for the restoration of the system after the location and isolation of a permanent fault. The

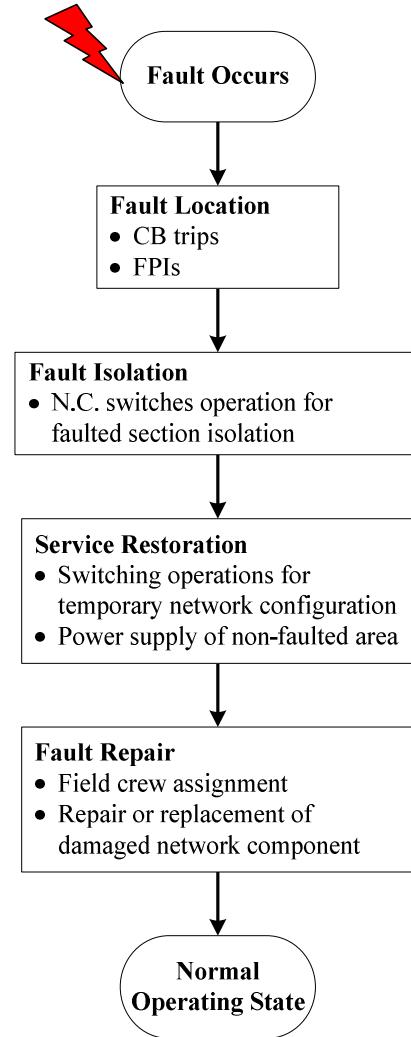


Figure 1. Flowchart of outage management.

proposed method is applied to an 83-bus power distribution system to demonstrate its effectiveness and robustness.

PROBLEM FORMULATION

A. Outage Management

The outage management is one of the most important processes in the distribution network operation and consists of four stages, as shown in Fig. 1 [8]. The four stages are fault location, fault isolation, service restoration and fault repair. When a fault occurs, the circuit breaker (CB), which is usually placed at the source of the feeder, is tripped and the power supply of the distribution feeder is interrupted. Data acquired from the available CBs, fault passage indicators (FPIs) or trouble calls are processed to identify the fault location. At the second stage, the fault isolation is performed by operating the normally closed (N.C.) switches closest to the damaged network component. Then, service restoration defines the appropriate number of operations of N.C. and normally open (N.O.) switches in order to restore power supply to the

maximum possible part of the network. Fault location, isolation, and service restoration (FLISR) are time constraint processes and they should be implemented as soon as possible. At the final stage, the damaged network component is repaired or replaced. Then, the distribution network returns to its initial configuration and the power supply is restored to the whole network.

The level of distribution automation determines the duration of the FLISR process. Currently, distribution networks are not fully automated and FLISR are implemented separately requiring, in some stages, actions by human operators. However, modern power distribution grids are evolving to smart grids, which have advanced automated control and communication capabilities [9]. Self-healing is a prominent function of the smart grids and it can be described as the automatic implementation of the FLISR functions without any human intervention [5]. Thus, the outage time period is reduced and the reliability of distribution networks is improved.

B. Optimization Model

The proposed optimization model uses the approximate convex formulation of the *DistFlow* equations [10] presented in [11]. The *DistFlow* equations represent the steady state operation conditions of radial distribution networks. The convex DNR models of [11] are used for power loss minimization, load balancing and minimum voltage maximization and they are intended for planning purposes and not for operational purposes, as this paper does.

The service restoration problem is formulated as follows:

$$\min \left\{ \begin{array}{l} \sum_{i \in \Omega_N} w_1 \cdot (1 - LR_i) \cdot P_{d,i} \\ + \sum_{ij \in \Omega_{CL}} w_2 \cdot (1 - y_{ij}) + \sum_{ij \in \Omega_{OP}} w_2 \cdot y_{ij} \\ + \sum_{ij \in \Omega_T} w_3 \cdot (t_{ij} - t_{0,ij}) \\ + \sum_{i \in \Omega_{SS}} w_4 \cdot (P_{SS,i} + Q_{SS,i}) \end{array} \right\} \quad (1)$$

s.t.

$$P_{SS,i} + \sum_{j \in \Omega_N} (P_{ij} - P_{ji}) - P_{d,i} \cdot LR_i = AuxP_i \quad (2)$$

$$Q_{SS,i} + \sum_{j \in \Omega_N} (Q_{ij} - Q_{ji}) - Q_{d,i} \cdot LR_i = AuxQ_i \quad (3)$$

$$AuxU_{sqr,i} \cdot AuxP_i \geq r_{ij} \cdot (P_{ji}^2 + Q_{ji}^2) \quad (4)$$

$$AuxU_{sqr,i} \cdot AuxQ_i \geq x_{ij} \cdot (P_{ji}^2 + Q_{ji}^2) \quad (5)$$

$$AuxU_{sqr,i} \leq U_{sqr,j} + (1 - M) \cdot z_{ji} \quad (6)$$

$$AuxU_{sqr,i} \geq U_{sqr,j} - (1 - M) \cdot z_{ji} \quad (7)$$

$$U_{sqr,i} \leq U_{sqr,j} - 2 \cdot (r_{ij} \cdot P_{ji} + x_{ij} \cdot Q_{ji}) + (1 - z_{ji}) \cdot M \quad (8)$$

$$U_{sqr,i} \geq U_{sqr,j} - 2 \cdot (r_{ij} \cdot P_{ji} + x_{ij} \cdot Q_{ji}) - (1 - z_{ji}) \cdot M \quad (9)$$

$$0 \leq P_{ij} \leq z_{ij} \cdot M \quad (10)$$

$$0 \leq Q_{ij} \leq z_{ij} \cdot M \quad (11)$$

$$P_{ij}^2 + Q_{ij}^2 \leq S_{max,ij}^2 \quad (12)$$

$$P_{SS,i}^2 + Q_{SS,i}^2 \leq S_{SS,max,i}^2 \quad (13)$$

$$V_{min,i}^2 \leq U_{sqr,i} \leq V_{max,i}^2 \quad (14)$$

$$t_{0,ij} \leq t_{ij} \leq t_{max,ij} \quad (15)$$

$$z_{ij} + z_{ji} = 1 \quad \forall ij \in \Omega_L \setminus \Omega_{LS} \quad (16)$$

$$z_{ij} + z_{ji} = y_{ij} \quad \forall ij \in \Omega_{LS} \quad (17)$$

$$\sum_{j \in \Omega_N} z_{ji} = 1 \quad \forall i \in \Omega_N \setminus \Omega_{SS} \quad (18)$$

$$z_{ij} = 0 \quad \forall j \in \Omega_{SS} \quad (19)$$

The objective function (1) consists of five terms. The first term of (1) minimizes the rejected load due to constraint violation; the second and third term minimizes the switching actions for the service restoration; the fourth term minimizes the tap changes of the OLTC transformers and the fifth term minimizes the active and reactive power injected through the substations. Equations (2) and (3) represent the active and reactive power node balance, respectively, for all $i \in \Omega_N$. When $z_{ji} = 1$, i.e., when the power flows from j to i , then (4), (6) and (7) represent the active power losses of line $i-j$. Otherwise, when $z_{ji} = 0$, i.e., when there is no power flow from j to i , the constraints (4), (6) and (7) are not activated for big values of M . Similarly, when, $z_{ji} = 1$ then (5)–(7) represent the reactive power losses of line $i-j$; otherwise, i.e., if $z_{ji} = 0$, then (5)–(7) are not activated. Constraints (4) and (5) are hyperbolic constraints, which are considered as convex second order cone programming constraints [11] and they can be recognized by commercial solvers. The voltage drop between buses i and j is calculated by (8) and (9). The direction of the active and reactive power flow of line $i-j$ is determined by (10) and (11), respectively. The thermal capacity limit of line $i-j$ is given by (12). The capacity limit of the substation placed at bus i is given by (13). The limits of the voltage square magnitude of bus i are shown in (14). As shown in (15), during the restoration process, the tap position of the OLTC at line $i-j$ should not take a value lower than its initial one. The distribution network is formulated as a spanning tree. The substation buses are considered as roots of the tree and each bus can have only one bus as parent ensuring network's radicity, as shown in (16)–(19) [12].

The OLTC is modeled as an ideal transformer between buses i and j and is mathematically modeled as follows:

$$U_{sqr,j} = (V_{min,i} + t_{ij} \cdot rt)^2 \quad \forall ij \in \Omega_T \quad (20)$$

It is safe to assume that the minimum voltage magnitude at the HV/MV substations is equal to 1 p.u. and the OLTC transformer ratio (rt) takes very small values, e.g., 0.625%. Using the binomial approximation, i.e., $(1+x)^a \approx 1+ax$ for values of x near to zero, the quadratic constraint (20) is transformed into a linear constraint as follows:

$$U_{sqr,j} = 1 + 2 \cdot t_{ij} \cdot rt \quad \forall ij \in \Omega_T \quad (21)$$

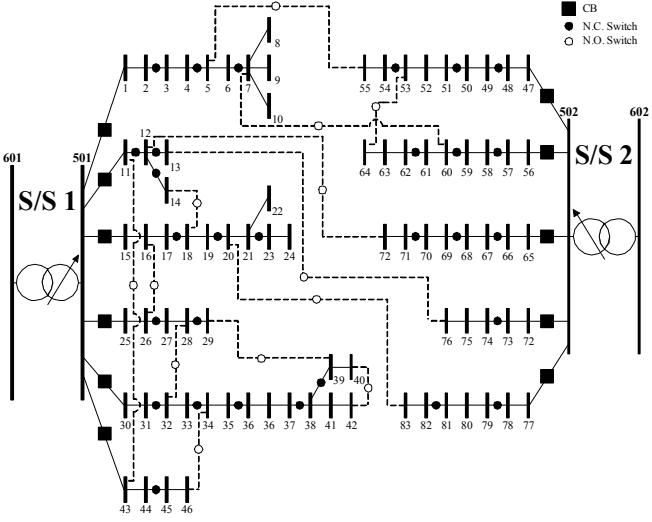


Figure 2. Initial topology of the 83-bus distribution system.

The proposed optimization model minimizes (1) subject to (2)–(19), and (21). It was implemented in GAMS environment and it was solved by CPLEX solver [13].

RESULTS

The proposed method is applied to an 83-bus distribution system to demonstrate its effectiveness. The 83-bus distribution system is an 11.40 kV network with 11 feeders, 2 substations and its topology is shown in Fig. 2. The detailed bus and line data can be found in [14]. As shown in Fig. 2, the network is equipped with 11 CBs, 29 N.C. switches, and 13 N.O. switches. The bus voltage limits are equal to $\pm 5\%$ of the nominal voltage. The capacity of each substation is equal to 25 MVA and the capacity of each line is considered to be equal to 10 MVA. Each substation is equipped with OLTC, which has $rt = 0.625\%$ and $t_{max,ji} = 8$. The voltage magnitude at bus 501 and bus 502 is equal to 1.025 p.u. and 1.0125 p.u., respectively. In the configuration of Fig. 2, the minimum voltage magnitude is equal to 0.956 p.u. at bus 9 and the power losses are equal to 510 kW. All simulations have been carried out on a PC with an Intel Core i7 CPU at 3.40 GHz and 4 GB of RAM.

To highlight the advantages and the performance of the proposed method, two cases are analyzed for different fault scenarios. These two cases are as follows:

- *Case A*: The service restoration problem is solved considering substation voltage magnitude fixed to its initial value.
- *Case B*: The service restoration problem is solved by the proposed optimization model, which considers voltage regulation by the OLTC.

C. Fault in Line 1–2

When a fault occurs in line 1–2, first the CB in line 501–1 is triggered leaving the buses 1–10 without power supply. Then, the N.C. switch between bus 2 and bus 3 opens to isolate the faulted area, as shown in Fig. 3. The buses 1 and 2

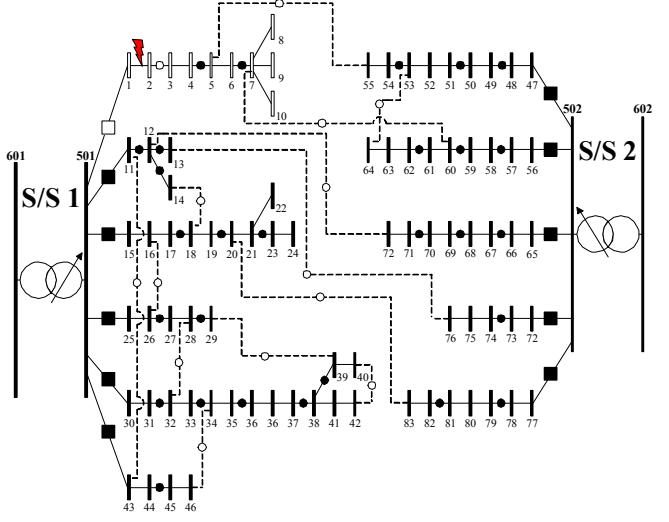


Figure 3. Topology of the 83-bus distribution system after fault location and isolation in line 1–2.

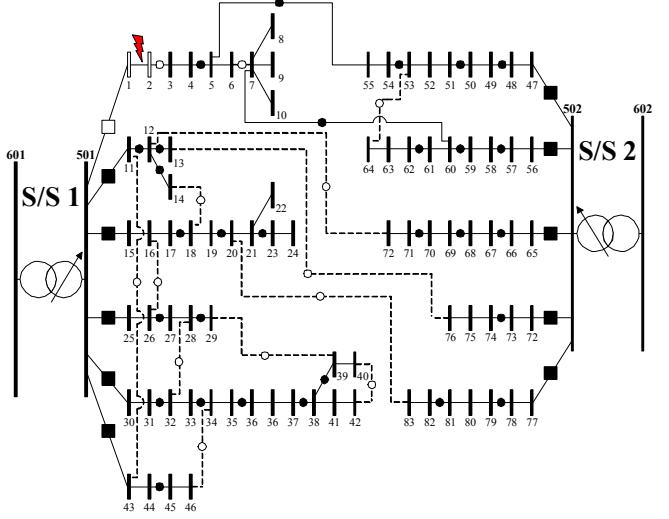


Figure 4. Topology of the 83-bus distribution system after service restoration due to fault in line 1–2 for Cases A and B.

will stay out of service as long as the damaged line is repaired or replaced.

1) *Case A*: Fig. 4 shows the restored network topology considering $|V_{501}| = 1.025$ p.u. and $|V_{502}| = 1.0125$ p.u.. In the service restoration plan of Fig. 4, the switch between buses 6 and 7 opens, while the switches between buses 5 and 55, and buses 7 and 60 close. In this case, the loads of bus 3 and bus 4 are rejected in order to guarantee the operation of the network within its technical limits. In fact, the load of bus 3 and bus 4 is rejected due to voltage constraint violation. The minimum voltage magnitude is equal to 0.951 p.u. at bus 6. The computation time is equal to 4.14 s.

2) *Case B*: The network topology after service restoration is presented in Fig. 4 and the switching actions are identical to Case A. However, the voltage magnitude of bus 502 is equal to 1.03125 p.u., which means that the tap position of the OLTC, installed at the substation of bus 502, has changed

TABLE I. SUMMARY OF RESULTS FOR CASES A AND B DUE TO FAULT IN LINE 1–2

	Case A	Case B
$ V_{501} $	1.025 p.u.	1.025 p.u.
$ V_{502} $	1.0125 p.u.	1.03125 p.u.
Switching operations	Open: 6–7 Close: 5–55, 7–60	
Load rejection	Buses 3, 4	None
Minimum voltage magnitude	0.951 p.u. at bus 6	0.954 p.u. at bus 3
Computation time	4.14 s	3.22 s

TABLE II. POWER FLOW ANALYSIS RESULTS FOR THE NETWORK TOPOLOGY OF FIG. 4.

	Proposed	MATPOWER [15]
$S_{SS,501}$	16.67 MVA	16.67 MVA
$S_{SS,502}$	19.66 MVA	19.65 MVA
Minimum voltage magnitude	0.954 p.u. at bus 3	0.955 p.u. at bus 3

from its initial position. Moreover, the OLTC installed at bus 501 did not change its initial status. As a result, there is no load rejection and the power supply was restored to the maximum possible part of the network. In this case, the minimum voltage magnitude of the restored topology is equal to 0.954 p.u. at bus 3. The total computation time is equal to 3.22 s.

The comparison and summary of the results for Cases A and B are presented in Table I. Overall, the proposed service restoration method determined 3 switching actions and 3 tap changes within a negligible computation time in order to satisfy the maximum possible load demand subject to the technical constraints of the distribution network. Furthermore, it should be noted that the proposed optimization model is an approximate convex MISOCP model. Table II presents representative power flow analysis results calculated by the proposed method and MATPOWER [15] for the network configuration of Fig. 4 in order to validate the accuracy of the proposed optimization model in the computation of power flow. As shown in Table II, the proposed optimization model and MATPOWER provide almost identical power flow results.

D. Fault in Line 11–12

The fault in line 11–12 is simulated. First, the CB in line 501–11 is tripped and the power supply of buses 11–14 is interrupted. To isolate the damaged network component, i.e. line 11–12, the N.C. switch in line 11–12 is opened, as shown in Fig. 5. The load demand of bus 11 will not be satisfied until the repair of line 11–12.

1) *Case A*: The network topology after service restoration is presented in Fig. 6(a). The service restoration plan determines the opening of the switch of line 12–13 and the closing of the switches of line 13–76 and line 14–18. In this case, there is no load rejection and the load demand of buses 12–14 can be transferred to the adjacent feeders without violating any operational constraint. The minimum voltage

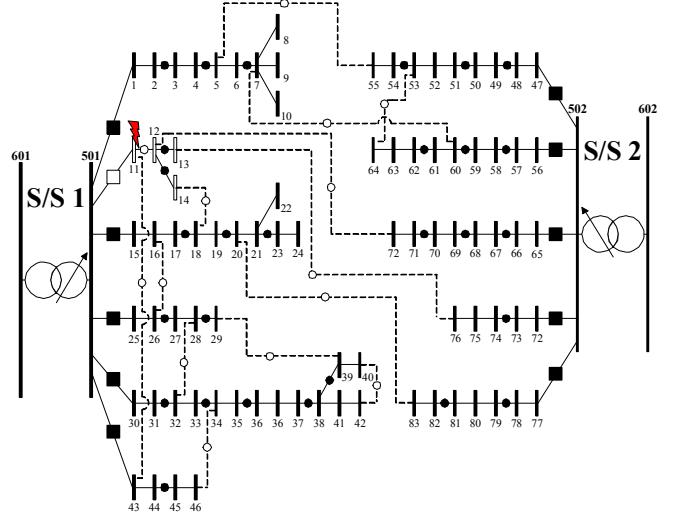


Figure 5. Topology of the 83-bus distribution system after fault location and isolation in line 11–12.

TABLE III. SUMMARY OF RESULTS FOR CASES A AND B DUE TO FAULT IN LINE 11–12

	Case A	Case B
$ V_{501} $	1.025 p.u.	1.0375 p.u.
$ V_{502} $	1.0125 p.u.	1.0125 p.u.
Switching operations	Open: 12–13 Close: 13–76, 14–18	Close: 14–18
Load rejection	None	None
Minimum voltage magnitude	0.955 p.u. at bus 9	0.954 p.u. at bus 13
Computation time	4.60 s	1.93 s

magnitude is equal to 0.955 p.u. at bus 9. The computation time is equal to 4.60 s.

2) *Case B*: The restored network topology, when voltage regulation of the OLTCs is considered, is shown in Fig. 6(b). In this case, only the closing of the switch in line 14–18 is required to restore the power supply to the healthy part of the network without any load rejection. Furthermore, the voltage magnitude of bus 501 is equal to 1.0375 p.u., while the voltage magnitude of the substation of bus 502 did not change from its initial value. The minimum voltage magnitude is equal to 0.954 at bus 13. The total computation time is equal to 1.93 s.

The results calculated by the proposed method for Cases A and B are summarized in Table III. As shown in Table III, the service restoration plan that considers voltage regulation by the OLTCs, i.e., Case B, requires less switching actions than Case A. Thus, the FLISR process and the process of returning the system to its pre-fault configuration become less complicated and less time-consuming.

CONCLUSION

This paper proposes a convex optimization model for the solution of the service restoration problem after a permanent fault. The proposed method considers the voltage regulation provided by the OLTCs installed at the HV/MV substations to

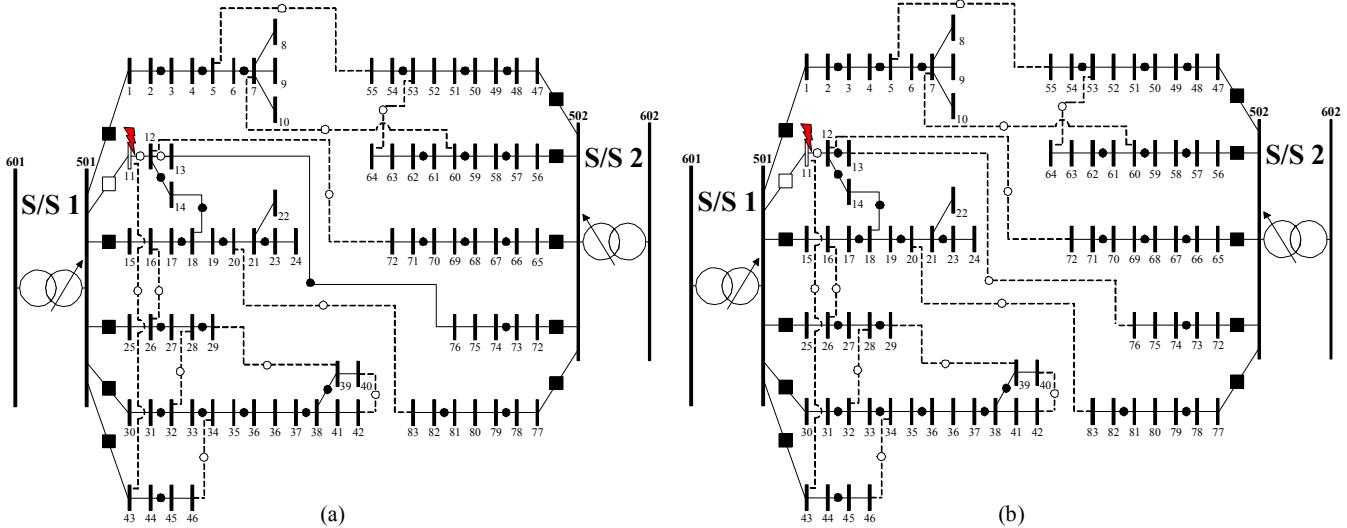


Figure 6. Topology of the 83-bus distribution system after service restoration due to fault in line 11–12: (a) Cases A and (b) Case B.

determine the optimal service restoration plan. The objectives of the optimization procedure are the minimization of load rejection, switching actions, tap changes and power injection through the substations. The service restoration problem is modeled as MISOCP problem, which can be easily solved by commercial branch and bound solvers.

Results show that if the substation voltage magnitude is set at a fixed value, the solution of the service restoration problem may lead to load rejection in some fault cases. On the contrary, including the control of the OLTC in service restoration plan can eliminate this load rejection. Furthermore, the proposed problem formulation leads to service restoration solutions that require less switching actions significantly facilitating the FLISR process. It should be also noted that the consideration of OLTC into the optimization procedure did not increase its computation time, making the proposed method a practical and efficient approach.

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