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***Abstract*—This study considers the service restoration problem in medium voltage distribution networks that have a meshed topology but are operated radially. A mixed-integer linear program (MILP) is proposed to incorporate technical constraints as well as practical considerations from the Distribution System Operator (DSO). As a result, a sequence of switching steps that need to be done to restore the power supply to the customers is provided. The proposed methodology can assist the decision making of operators in the control center at the DSO. To demonstrate this, a real distribution network is used in a case study.**

***Index Terms*—Contingency assessment, Distribution system, mixed-integer linear programming (MILP), service restoration, switching sequence**

I. Introduction

Distribution system restoration is the process of restoring the power supply to the de-energized sections of the system after an occurrence of a fault. This is achieved through a sequence of switching actions to isolate the fault and to reconfigure the topology of the network. It is important to preserve the technical constraints and maintain the radial topology of the network at each step of the restoration procedure [1].

Several different objectives can be considered during the restoration process. This includes, among others, maximization of the restored affected power demand, minimization of the time and switching actions required to implement the restoration process [1][2]. A combination of objectives with different priorities may also be used, with the resupply of the unserved demand as an imperative.

Various approaches are used for contingency assessment and power restoration. Engineering rules and computational expert systems relying on operator's experience are used both in literature and practice [3][4]. Next, heuristics and graph theory are also applicable as solution techniques. Finally, a large family of methods consists of mathematical optimization models. This can be further divided into meta-heuristic techniques such as genetic algorithms and exact methods using mathematical programming. For a detailed updated review of existing methods for service restoration, please refer to [2].

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Service restoration is a relevant engineering problem since it is directly related to the reliability of the distribution system. In principle, the operation of the Distribution Systems Operators (DSOs) is assessed based on the reliability indices for the networks they operate, more specifically, the System Average Interruption Duration Index (SAIDI) and the related Customer Minutes Lost (CML). Moreover, in the Netherlands, approximately 60% of the CML experienced by end-consumers are contributed by faults in the medium voltage (MV) grid [5].

Therefore, improvements in the restoration process in MV distribution grids can contribute to increased reliability. In this regard, developments in smart grid technologies for distribution networks also play a role. Traditionally, switchgear is operated manually to reconfigure the network, which requires a maintenance crew to be sent on-site. In recent years, the installation of distributed automation equipment such as remotely controllable switchgear and advanced monitoring in the distribution networks, provide opportunities for faster response and switchgear manipulation in the case of an outage [5].

In this regard, there is a rising necessity for service restoration solution methodologies that can incorporate technical and practical constraints, also considering remotely controllable switchgear. An important aspect for service restoration is to provide a switching sequence of intermediate steps that preserve all technical constraints, rather than only a final network topology. Nevertheless, only a small number of existing works present such methods [3][6][7].

Therefore, this study aims to develop a methodology that combines mathematical programming and practical requirements so that the restoration process can benefit from the aforementioned new technologies. Such a new operational paradigm should be easily incorporated in the daily operation of a control center of a DSO for fast and reliable performance. Hence, it is required that the method should be developed based on the available data, measurements, and estimations that can be obtained for a network in operation by the DSO. To this end, a mixed-integer linear programming (MILP) model is proposed for service restoration that combines these requirements. Thus, the contributions of this paper are twofold:

- A service restoration framework that is applicable for use in a DSO control center and takes into consideration

practical operational requirements
- A MILP mathematical model that provides an optimal sequence of switching steps and can be solved with commercially available solvers.

The remainder of the paper is organized as follows: Requirements for contingency analysis and structure of the developed framework are outlined in Section II. The mathematical formulation is presented in Section III. The description of the case study, as well as the corresponding results and discussion, are given in Section IV. Finally, conclusions and the future outlook of this study are presented in Section V.

II. Methodology

A. Contingency analysis in Dutch MV distribution networks

Dutch distribution networks can have both distribution (MV-D) and transmission function (MV-T). MV-D networks connect HV or MV-T networks to residential customers located in LV networks through MV/LV network substations, as well as large industrial/commercial customers in MV networks through MV/MV customer substations, as in Figure 1 [8].

The design and operation of MV-T networks are in a meshed structure, whereas MV-D networks are either ring- or mesh-shaped, but are always operated radially. The goal is to maintain a simple protection scheme and ensure an acceptable level of reliability by reducing the number of customers that can be disconnected in the occurrence of a fault in the MV-D network. The reconfigurability in the topology is enabled through the existence of sectionalizing switchgear, or so-called Normally Open Points (NOP) that can facilitate different supply paths in the case of fault restoration or maintenance operation. Additionally, circuit breakers (CB) are located at the beginning of every feeder connected to the substation [4].

There are multiple reconfiguration options for a single outage for most distribution networks. DSOs usually maximize the number of switching operations to restore power supply. Due to a large number of possibilities, this problem can become computationally challenging, especially if multiple power flow calculations are involved. In the operation phase, this process can be further affected by the current network loading, distributed generation present and the operational status of the network. Furthermore, due to the implementation of monitoring measurement and remote control of the switching operations, the decision for the best sequence for power restoration is not straightforward [5].

B. Framework

The objective of this study is the development of a method that can be incorporated in the daily operation of the control center of a DSO in the Netherlands. To this aim, practical considerations applied in the DSO control center are used as guidelines and constraints. The complete framework is composed of the following steps:

1) *Fault location and isolation* - The first step consists of fault location and isolation, which is considered to take place before the analysis performed for the restoration process. In the case of one or multiple faults, the circuit breaker at the beginning of the feeder automatically opens and isolates the affected feeders up to the NOPs. In practice, DSOs rely on the measurement infrastructure and protection systems as well as customer reports to identify the fault location as accurately as possible.
2) *Preliminary network analysis* - A preliminary analysis of the resulting topology after fault isolation is performed. The islanded zones consisting of buses and lines are identified. Each zone is limited by adjacent switchable lines. Hence, possible restoration paths are determined for each zone.
3) *Service restoration optimization* - In this step, mathematical optimization is performed to determine an optimal restoration sequence taking into consideration operational and topological constraints.
4) *Restoration sequence execution* - The final step consists of the execution of the restoration sequence by remote operation of switches by the operator in the control center and dispatch of maintenance crews to the field if necessary.

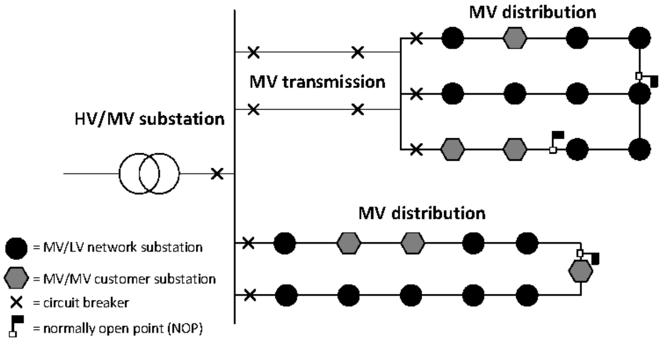

Figure 1. Structure of typical Dutch MV networks (adapted from [4])

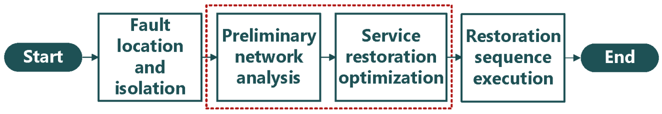

Figure 2. Flowchart for network restoration framework; Main contributions are in the steps enclosed by red-dashed line

The main contributions of this study are incorporated in steps 2 and 3, as indicated in Figure 2. In these steps, the following requirements from the DSO are incorporated as assumptions in the mathematical model. Resupplying zones using distributed generation is not practically possible so all buses must be connected to the main substation at the end of the restoration process [8]. In addition, it is assumed that faults occur in the distribution lines, not in the substations. Last, it is assumed that the system is balanced along the three phases.

III. Mathematical Model

In this section, the mathematical formulation of the optimization model for network restoration is detailed. In principle, service restoration is a combinatorial optimization prob-

Table I
NOMENCLATURE

Sets and indices	
$b(B, B^{SS}, B^O)$	Index (set) of buses, subset of substaion buses subset of outaged buses
i, j	Indices used for buses/zones at the ends of a line
$l(L, L^F, L^{sw})$	Index (set) of branch lines, subset of faulted lines and subset of switchable lines
Ω_l^{to}	Set of receiving buses of line l
Ω_l^{from}	Set of sending buses of bus l
Ω_z^B	Set of buses in zone z
Ω_z^L	Set of lines in zone z
Ω_z^{LSW}	Set of switchable lines adjacent to zone z
$z(Z, Z^O)$	Index (set) of zones, subset of outaged zones
$t(T)$	Index (set) of time steps in restoration sequence
Parameters	
N_b^{cust}	Number of customers per bus
$P_{b,t}^D$	Active and reactive power demand at node b at step t [kW]
$P_{b,t}^{DG}$	Active power from DG at node b at step t [kW]
$Q_{b,t}^D$	Reactive power demand at node b at step t [kVar]
$Q_{b,t}^{DG}$	Reactive power from DG at node b at step t [kVar]
R_l	Resistance of branch l [Ω]
S_l^{max}	Maximum capacity for branch line l [kVA]
$u_b^{B,ini}$	Initial status of bus b
$u_l^{L,ini}$	Initial status of line l
$u_z^{Z,ini}$	Initial status of zone z
V_b^{max}	Max voltage magnitude of node b [p.u.]
V_b^{min}	Min voltage magnitude of node b [p.u.]
V^{max}	Max voltage magnitude allowed [p.u.]
X_l	Reactance of branch l [Ω]
Variables	
$P_{l,t}^L$	Active power flow in line l at step t [kW]
$Q_{l,t}^L$	Reactive power flow in line l at step t [kVar]
$u_{b,t}^B$	Binary variable for bus status at t: 1-on, 0-off
$u_{l,t}^L$	Binary variable for line status at t: 1-on, 0-off
$u_{l,t}^{L,cl}$	Binary variable for closing switchable line l at step t: 1-closed, 0-otherwise
$u_{l,t}^{L,op}$	Binary variable for opening switchable line l at step t: 1-closed, 0-otherwise
$U_{b,t}$	Square of voltage magnitude of bus b at step t
$U_{l,t}^{aux}$	Auxiliary variable for line l at step t [p.u.]
$u_{z,t}^Z$	Binary variable for zone status at t: 1-on, 0-off
$V_{b,t}$	Voltage magnitude of bus b at step t [p.u.]

lem, due to the binary variables used to represent the on/off status of various assets. Moreover, it is a nonlinear problem due to the AC power flow equations [3]. However, multiple linearizations are possible to transform the nonlinear equations to linear approximations with sufficient accuracy. Hence, the model presented in this paper is a mixed-integer linear program (MILP). The main notation used in this paper is defined in Table I. Other symbols and abbreviations are defined when they first appear.

1) Objective function: The objective function of the optimization model is to minimize the number of customers affected by the defect at each step of the restoration process, regardless of the size of the outage, and is expressed by (1). It is an adaptation of the relation for calculation of Customer Minutes Lost (CML) which represents the total interruption times the number of affected customers experienced [5]. The objective function can be extended by adding weights to prioritize specific types of loads or customers.

$$\min \quad \sum_{t \in T} \sum_{b \in B^O} (1 - u_{b,t}^B) \cdot N_b^{cust} \cdot \Delta t \tag{1}$$

$$\text{subject to:} \quad constraints : (2) - (6), (8) - (27)$$

2) Power Flow constraints: Linear DistFlow equations are used to model the power flow [9]. They are primarily used in radial networks as a sufficiently accurate approximation of the power flow equations. Moreover, based on the assumption that non-linear terms are comparatively small to linear terms in radial networks, the non-linear terms can be omitted in the calculations of this model, [9].

Constraints (2) and (3) represent the active and reactive power balance per node respectively, where total power inflow should be equal to the power outflow from the bus. The voltage magnitude difference between the two nodes of an energized line is expressed in (4) and (5), and depends only on the linear terms according to the DistFlow linear model. The two relations are used to account for the two possible directions of the power flow. When the line is not energized, it does not have to fulfill the second Kirchoff's law. Hence, the voltage magnitude difference between the corresponding nodes can vary within the allowed range expressed with the auxiliary variable U_{aux} which is defined in (6).

$$\sum_{l \in L: b \in \Omega_l^{to}} P_{l,t}^L - \sum_{l \in L: b \in \Omega_l^{from}} P_{l,t}^L + P_{b,t}^{DG} = P_{b,t}^D, \forall b, t \tag{2}$$

$$\sum_{l \in L: b \in \Omega_l^{to}} Q_{l,t}^L - \sum_{l \in L: b \in \Omega_l^{from}} Q_{l,t}^L + Q_{b,t}^{DG} = Q_{b,t}^D, \forall b, t \tag{3}$$

$$U_{i,t} - U_{j,t} \leq 2(R_l \cdot P_{l,t}^L + X_l \cdot Q_{l,t}^L) + U_{l,t}^{aux}, \forall l \in L, t \in T \tag{4}$$

$$U_{i,t} - U_{j,t} \geq 2(R_l \cdot P_{l,t}^B + X_l \cdot Q_{l,t}^L) - U_{l,t}^{aux}, \forall l \in L, t \in T \tag{5}$$

$$U_{l,t}^{aux} = (V^{max})^2(1 - u_{l,t}^L), \forall l \in L, t \in T \tag{6}$$

3) Power capacity and voltage limit constraints: Assets in the distribution network are allowed to operate within a given range under certain conditions. The power flow in the lines should not exceed the maximum allowed capacity, expressed through the non-linear, quadratic relation in (7). A polygon-based linearization procedure for convex quadratic constraints is introduced in [10] and it is implemented in this study. Specifically, a hexagon approximation is used to replace (7) with the linear equations (8)-(10). The box constraints for active and reactive power flow that additionally restrict power flow only to energized lines, are shown in (11) and (12). Voltage limits for buses depending on their energization status are presented in (13).

$$(P_{l,t}^L)^2 + (Q_{l,t}^L)^2 \leq S_l^{max}, \forall l \in L, t \in T \tag{7}$$

$$-\sqrt{3}(P_{l,t}^L + S_l^{max}) \leq Q_{l,t}^L \leq -\sqrt{3}(P_{l,t}^L - S_l^{max}) \tag{8}$$

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$$-\sqrt{3}/2 \cdot S_l^{max} \leq Q_{l,t}^L \leq \sqrt{3}/2 \cdot S_b^{max} \quad (9)$$

$$\sqrt{3}(P_{l,t}^L - S_l^{max}) \leq Q_{l,t}^L \leq \sqrt{3}(P_{l,t}^L + S_l^{max}) \quad (10)$$

$$-u_{l,t}^L \cdot S_l^{max} \leq P_{l,t} \leq u_{l,t}^L \cdot S_l^{max}, \forall l \in L, t \in T \quad (11)$$

$$-u_{l,t}^L \cdot S_l^{max} \leq Q_{l,t} \leq u_{l,t}^L \cdot S_l^{max}, \forall l \in L, t \in T \quad (12)$$

$$u_{b,t}^B \cdot (V_b^{min})^2 \leq U_{b,t} \leq u_{b,t}^B \cdot (V_b^{max})^2, \forall b \in B, t \in T \quad (13)$$

4) Topological and sequencing constraints: Throughout the restoration process and in the final configuration, the network topology must remain radial. First, (14) states that should be no loops in the network. This is a necessary, albeit not sufficient condition for radial configuration, as it does not guarantee connectivity of the network [11]. Therefore, additional constraints for the sequencing process are introduced in the model. The faulted lines are kept de-energized after the fault is located, as given in (15). Substation nodes are maintained always on as in (16).

$$\sum_{l \in L} u_{l,t}^L = \sum_{b \in B} u_{b,t}^B - 1, \forall t \in T \quad (14)$$

$$u_{l,t}^L = 0, \forall l \in L^F, t \in T \quad (15)$$

$$u_{b,t}^B = 1, \forall\ b \in B^{SS}, t \in T \quad (16)$$

$$u_{l,t}^L - u_{l,t-1}^L = u_{l,t}^{L,cl} - u_{l,t}^{L,op}, \forall l \in L^{SW}, t \in T \quad (17)$$

$$u_{l,t}^{L,cl} + u_{l,t}^{L,op} \leq 1, \forall l \in L^{SW}, t \in T \quad (18)$$

$$u_{z,t}^Z \leq \sum_{l \in \Omega_z^{L^{SW}}} u_{l,t}^L, \forall z \in Z^O, t \in T \quad (19)$$

$$u_{l,t}^L \leq u_{i,t-1}^Z + u_{j,t-1}^Z, \forall l \in L^{SW}, t \in T \quad (20)$$

$$u_{l,t}^L = u_{z,t}^Z, \forall l \in \Omega_z^{L \setminus (L^{SW} \cup L^F)}, t \in T \quad (21)$$

$$u_{b,t}^B = u_{z,t}^Z, \forall b \in \Omega_z^B, t \in T \quad (22)$$

$$u_{l,t}^L \geq u_{l,t-1}^L, \forall l \in L \setminus L^F, t > 1 \quad (23)$$

$$u_{b,t}^B \geq u_{b,t-1}^B, \forall b \in B, t > 1 \quad (24)$$

$$u_{z,t}^Z \geq u_{z,t-1}^Z, \forall z \in Z, t > 1 \quad (25)$$

$$u_{b,t}^B = 1, \forall\ b \in B, t = T \quad (26)$$

$$u_{l,t}^L = u_l^{L,ini}, u_{b,t}^B = u_b^{B,ini}, u_{z,t}^Z = u_z^{Z,ini}, t = 1, \forall l \in L, \forall b \in B, \forall z \in Z \quad (27)$$

The status of the switchable lines at each moment of the sequencing procedure, given in (17) depends on two auxiliary variables, $u_{l,t}^{L,cl}$ and $u_{l,t}^{L,op}$, representing the process of closing and opening a switch between steps, respectively. At each sequencing step, only one switching action can be performed as given in equation (18).

The status of a de-energized zone depends on the status of the adjacent switchable lines as in (19). Moreover, equation (20) determines that a switchable line can be energized at step t only if one of the zones it connects was already energized in the previous step. When a zone is energized, the nonswitchable lines and buses that belong to it are also energized as given in (21) and (22), respectively.

After a line, bus or zone is energized, line tripping and bus or zone shedding is not allowed as expressed through equations (23)-(25). At the end of the restoration process, the power supply must be restored to all buses as in (26). Finally, the initial status of buses, zones and lines are set by (27) to be equal to the network status after the fault is cleared by the circuit breaker which is determined during preliminary network analysis.

The topological constraints (14)-(27) ensure that the radial topology of the network is maintained throughout the restoration process, without relying on the power flow constraints. This is the case with some existing models, which can result in inefficient solution procedure as elaborated in [11].

IV. Case study and results

A. Description of case study

The developed method is applied to a real-world, ring-shaped, medium voltage network, provided by a Dutch DSO, depicted in Figure 3. It is operated at 10 kV and consists of underground power cables. There are 8 industrial/commercial customers connected to the MV network, whereas the remaining 22 substations are MV/LV network substations. In addition, there are 8 distributed generators in the network. The network has 3 circuit breakers, on lines 1, 2, and 3 and two NOPs on lines 11 and 21 that can be used in the restoration process. Detailed data for the network and asset parameters, including the allowable loading of assets and voltage limits during service restoration can be found in [8].

A fault occurring on line 15 is simulated. The isolated zones can be restored through switches in line 2 and line 11 or 21. Moreover, the following two cases, relevant for the DSO are considered in the simulation [8]:

1) Case I - Dominance of load (load: 100 %, DG: 0 %)
2) Case II - Dominance of DG (load: 25 %, DG: 100 %)

The mathematical model was implemented in Python 3.6 and the optimization problem was solved in Pyomo [12] using the Gurobi solver[13].

B. Results and discussion

The results for the switching sequence are presented in Table II. The computation time for the two cases is in the range of several seconds. The network can be restored by performing two switching actions in addition to the isolation of the faulted line. The procedure favors the larger group of unsupplied customers to be restored first in both cases. However, the switches that are involved in the two cases differ, depending on the loading conditions of the network. Thus, in the first case, the second group of buses is restored through closing NOP at line 11, whereas in the second case the same group is restored through line 21.

The demand and DG output restored at each step of the procedure are given in tables III and IV for Case I and Case II respectively. The total load and DG restored in the second step of the restoration is larger than the one restored in the first step. This is due to the objective function used in the model, which is based on CML as a practical consideration from the DSO and not the amount of restored load. Same behavior will be observed in the case of multiple faults in

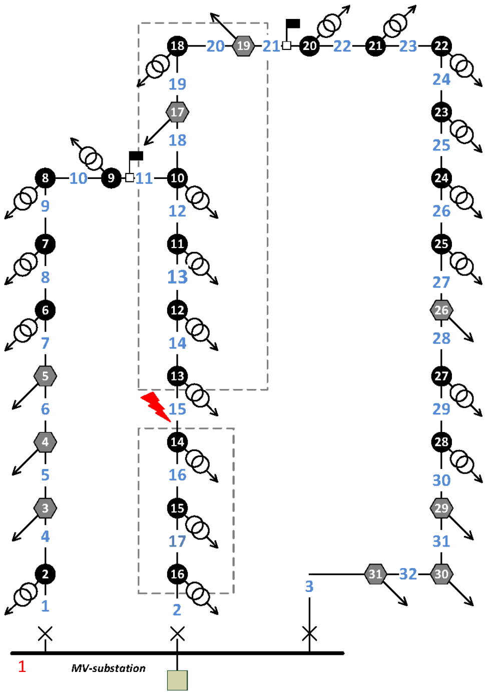

Figure 3. Network topology used in case study; NOPs are marked with flag, CBs with cross, MV/LV network substations with circle, MV/MV industrial customer substations with hexagon; faulted zones with dashed rectangles

Table II
SWITCHING SEQUENCE AND RESTORED BUSES AND CUSTOMERS

T	Sequence		Buses restored	N^{cust} restored
	Case I	Case II		
1	2	2	14, 15, 16	503
2	11	21	10, 11, 12, 13, 17, 18, 19	500

the same low voltage network. If necessary, the model can be adjusted to include priority for a certain load, for example, industrial/commercial customers.

In the two cases, the voltage level is within the allowed range, including the DG dominant case II. The maximum line loading measured in both cases is within the allowed range for emergency situations, which is $1.3 \cdot S_l^{nom}$. The lines are more loaded in case I, when no local DG is available, which is a situation that can occur during the night or in case of low wind. In this case, if the network was assessed based on the nominal line loading, some of the lines would be loaded above that level.

Table III
CASE I (LOAD DOMINANCE) - RESTORED DEMAND AND DG, AND ASSET LOADING AT EACH STEP

T	P^D [kW]	Q^D [kVar]	P^{DG} [kW]	Q^{DG} [kVar]	S/S_{em}^{max} [%]	S/S_{nom}^{max} [%]	$Vmin$ [p.u.]	$Vmax$ [p.u.]
1	718	378	0	0	49.23%	64.00%	0.9	0.911
2	1734	811	0	0	78.05%	101.47%	0.9	0.924

Table IV
CASE II (DG DOMINANCE) - RESTORED DEMAND AND DG, AND ASSET LOADING AT EACH STEP

T	P^D [kW]	Q^D [kVar]	P^{DG} [kW]	Q^{DG} [kVar]	S/S_{em}^{max} [%]	S/S_{nom}^{max} [%]	$Vmin$ [p.u.]	$Vmax$ [p.u.]
1	179.5	94.5	0	0	29.22%	37.99%	0.9	0.908
2	433.5	202.75	2940	597	47.66%	61.96%	0.9	0.924

V. CONCLUSION

In this study, a mixed-integer linear model (MILP) model for obtaining the switching sequence of the restoration process in meshed- structured but radially operated medium voltage distribution networks was introduced. The model incorporates constraints and practical considerations that are not accounted for in the existing literature. The proposed framework is intended to support the decision making process of operators in the control center of a DSO during an outage, foreseeing implementation of distributed automation and more varying load and DG in the networks. The applicability of this method is demonstrated on a case study with a real MV network.

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