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ORIGINAL ARTICLE

Automation in Service Restoration of Distribution Networks Using Scheduling of Multiple Resources

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Abstract

The service restoration (SR) problem has always been one of the most challenging issues in the operation and automation of electrical distribution networks. With the increasing development of the distribution network and the introduction of various new technologies and facilities, and the need for automation of distribution networks, solving this problem requires much more efficient and faster solutions. In this paper, a new method is proposed to solve the SR problem. The distribution network in this study has many resources including mobile power sources (MPS) and repair crew (RC) that are scheduled simultaneously. This article also pays attention to how to incorporate traffic considerations of the transportation network into the problem, which adds to its applicability. The service restoration problem in this paper is modeled as a MILP problem and solved by mathematical solvers. This ensures the achievement of optimal and fast solutions. The proposed method was used on a 33-bus test network and its efficiency was proven.

Keywords: Service Restoration, Mobile Power Source, Repair Crew, Traffic, MILP.

1. Introduction

In recent years, extreme events such as hurricanes, storms, floods, and cyber-attacks, have caused severe damages to the power grids, resulting in large-scale blackouts and significant economic losses (Asadi, Falaghi, and Ramezani 2024)-(Asadi et al. 2024). Consequently, the development of an effective and efficient distribution service restoration strategy is a highly important tasks for utilities.

Numerous studies have examined the service restoration of distribution network. Among them, network reconfigurations are popularly employed for service restoration. For instance, a two-stage network reconfiguration method was proposed for the self-healing scheme of DS in (Asadi, et al. 2021)- (Cavalcante et al. 2016). Ref (Li et al. 2020) introduced a full decentralized multi-agent network reconfiguration method for distribution networks, which can lessen the computational burden of SR. In (Kianmehr et al. 2019), an hourly basis network reconfiguration was adopted to increase the resiliency of the electrical networks.

Very few studies have addressed the impact of traffic conditions on the service restoration process. Also, the method of dispatching maneuver groups is an important issue. In this paper, by introducing a new framework, the service restoration problem has been solved as a MILP problem so that accelerates the service restoration process, also contribute significantly to the automation of this process. The most important contributions of this paper are:

-Considering and scheduling mobile and fixed power sources together

-Considering traffic conditions of the transportation network

-Transforming the problem into a MILP problem

-Specifying the method of dispatching maneuver groups.

2. Load restoration framework

The proposed structure of this paper for service restoration is shown in Figure 1. According to the figure, in this framework, various resources including maneuver groups, mobile power resources (MPSs) and distributed generation resources will be used for service restoration operations. The modeling of each of these resources will be described below by the relevant equations.

2.1. Repair crew scheduling

Equations (1) and (2) guaranty that each repair crew starts and ends its operation at depot node 0. Equation (3) implies that each crew repairs the damaged lines sequentially. Equations (4) and (5) assume that each faulted line is repaired by only one crew. Equation (6) calculate the time when each repair crew leaves the depot location. Equations (7) and (8) evaluate the relationship between the arrival time at faulted line i and the departure time from the depot location. Equations (9)-(10) also denote the relationship of transportation time between two faulted lines i and j. Equation (11) limits the value of the arrival time of each crew. Equations (12)-(14) calculate the repair completion time of faulted lines i. Equation (15) denotes the relationship between the repair state and the available state of damaged line i.

$$\sum_{\mathrm{i}\in\Phi\mathrm{f}} \varkappa_{0\mathrm{i.c}} = 1.\forall c \quad (1)$$

$$\sum_{\mathrm{i}\in\Phi\mathrm{f}} \varkappa_{\mathrm{i}.0.\mathrm{c}} = 1.\forall c \quad (2)$$

$$\sum_{\mathrm{j}\in\Phi\mathrm{f}} \varkappa_{\mathrm{j.i.c}} - \sum_{\mathrm{k}\in\Phi\mathrm{f}} x_{\mathrm{i.k.c}} = 0.\ \forall c\,.\forall i \quad (3)$$

$$\mathrm{R_{i.C}} = \sum_{\mathrm{j}\in\Phi\mathrm{f}} \varkappa_{\mathrm{j.i.c}}\ .\forall c.\forall i \quad (4)$$

$$\sum_{\forall c} \mathrm{R_{i.C}} = 1..\forall i \quad (5)$$

$$\mathrm{T_{0.c}} = t_0\,.\forall c \quad (6)$$

The research flowchart followed in this study is shown in Fig. 1. Three phases—hazard, vulnerability, and risk analysis—were performed, as explained in detail in the subsequent sections. The superposition of different components of the SPRC model with the three phases considered in this study is also illustrated in Fig. 1.

$$\mathrm{T_{i.c}} - \mathrm{T_{0.c}} \le t_{0.i.c}^{trip} + M_{\mathrm{big}}\left(1-\varkappa_{\mathrm{j.i.c}}\right).\forall c \quad (7)$$

$$t_{0.i.c}^{trip} - M_{\mathrm{big}}\left(1-\varkappa_{\mathrm{0.i.c}}\right) \le \mathrm{T_{i.c}} - \mathrm{T_{0.c}}\ .\forall c \quad (8)$$

$$\mathrm{T_{i.c}} - \mathrm{T_{j.c}} \le t_{j.i.c}^{trip} + t_{j.c}^{rep} + M_{\mathrm{big}}\left(1 - \varkappa_{\mathrm{j.i.c}}\right)\forall c\,.\forall i.\forall j \in \Phi_f \quad (9)$$

$$t_{j.i.c}^{trip} + t_{j.c}^{rep} - M_{\mathrm{big}}\left(1-\varkappa_{\mathrm{j.i.c}}\right) \le \mathrm{T_{i.c}} - \mathrm{T_{j.c}}\,.\ \forall c\,.\forall i.j \in \Phi_f \quad (10)$$

$$0 \le \mathrm{T_{i.c}} \le M_{\mathrm{big}}\,\mathrm{R_{i.C}}\,.\forall i \in \Phi_f \quad (11)$$

$$\sum_{\forall t} f_{i.t} = 1.\ \forall i \in \Phi_f \quad (12)$$

$$\sum_{\forall t} f_{i.t} \le \sum_{\forall c}\left(\mathrm{T_{i.c}} + t_{j.c}^{rep}\,\mathrm{R_{i.C}}\right) + 1 - \varepsilon.\ \ \forall i \in \Phi_f \quad (13)$$

$$\sum_{\forall c}\left(\mathrm{T_{i.c}} + t_{j.c}^{rep}\,\mathrm{R_{i.C}}\right) \le \sum_{\forall t} t f_{i.t}\ .\forall i \in \Phi_f \quad (14)$$

$$\mathrm{y_{i.t}} \le \sum_{\tau=1}^{\mathrm{t}-1} \mathrm{f_{j.\tau}}\ .\forall i \in \Phi_f \quad (15)$$

2.2. Distributed generation scheduling

Equations (16) and (17) express the start-up and shut-down relationship. Equations (18) and (19) give the minimum up-time and down-time restrictions. The power flow constraints are included in Equations (20) and (21), while the ramp-up and ramp-down limits are given in Equations (22) and (23). Equation (24) define that the active power and reactive power are limited by the maximum capacity of reactive power.

$$\mathrm{x_{g.t}} \le \mathrm{x_{g.t-1}} = \mathrm{u_{g.t}} - \mathrm{v_{g.t}} \quad (16)$$

$$\mathrm{u_{g.t}} + \mathrm{v_{g.t}} \le 1 \quad (17)$$

$$\mathrm{u_{g.t}} \le \mathrm{x_{g.t}}\,.\forall t \le \mathrm{x_{g.t}}\,\tau \le t + t_g^U - 1 \quad (18)$$

$$\mathrm{v_{g.t}} \le 1\mathrm{x_{g.}}\tau\ .\forall t \le\ \tau \le t + t_g^D - 1 \quad (19)$$

$$\mathrm{p_{g.min}\,x_{g.t}} \le \mathrm{p_{g.t}} \le \mathrm{p_{g.max}\,X_{g.t}} \quad (20)$$

$$-\mathrm{S_{g.max}\,x_{g.t}} \le \mathrm{Q_{g.t}} \le \mathrm{S_{g.max}\,X_{g.t}} \quad (21)$$

$$P_{g.t} - P_{g.t-1} \le R_{U.g}\, x_{g.t-1}\, \Delta t + S_{U.g}\, u_{g.t}\, \Delta t \quad (22)$$

$$P_{g.t-1} - P_{g.t} \le R_{D.g}\, x_{g.t}\, \Delta t + S_{D.g}\, v_{g.t}\, \Delta t \quad (23)$$

$$(P_{g.t})^2 + (Q_{g.t})^2 \le (S_{g.max})^2 \quad (24)$$

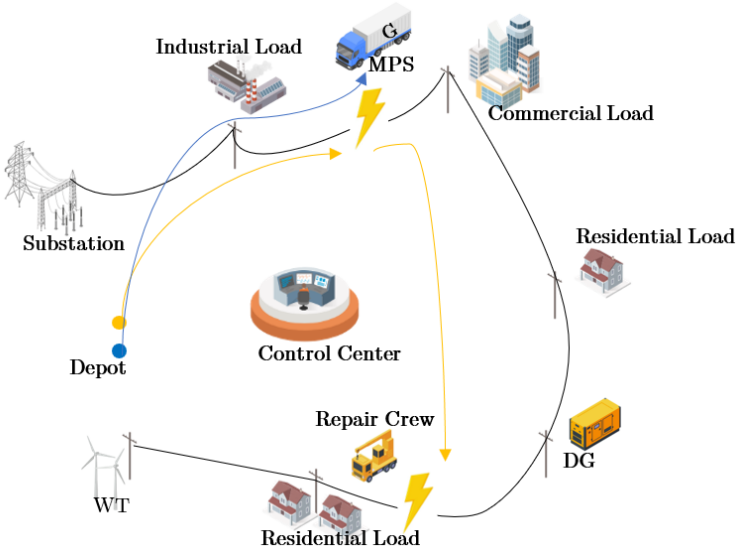


Fig. 1. Schematic of proposed framework for service restoration

2.3. Load flow & network reconfiguration

A linearized DistFlow model is used to model the DS (Zhou et al. 2020) as follow:

$$p_{j.t}^{DG} + p_{j.t}^{MPS} + p_{ij.t}^{D} = \sum_{k \in s_j^{B.d}} p_{jk.t}^{D} + p_{j.t}^{D.L} \quad (25)$$

$$Q_{j.t}^{DG} + Q_{j.t}^{MPS} + Q_{ij.t}^{D} = \sum_{k \in s_j^{B.d}} Q_{jk.t}^{D} + Q_{j.t}^{D.L} \quad (26)$$

$$V_{i.t} - V_{j.t} \le \left(p_{ij.t}^{D}\, r_{ij}^{D} + Q_{jk.t}^{D}\, x_{ij}^{D}\right)/\, V_0 \; + M_{big}\,(1 - \varepsilon_{ij.t}) \quad (27)$$

$$\left(p_{ij.t}^{D}\, r_{ij}^{D} + Q_{ij.t}^{D}\, x_{ij}^{D}\right)/ V_0 - M_{big}\,(1 - \varepsilon_{ij.t}) \le V_{i.t} - V_{j.t} \quad (28)$$

$$V_{i.min} \le V_{i.t} \le V_{i.max} \quad (29)$$

$$-p_{ij.t}^{D.max}\varepsilon_{ij.t} \le p_{ij.t}^{D} \le p_{ij.t}^{D.max}\varepsilon_{ij.t} \quad (30)$$

$$-Q_{j.t}^{D.max}\varepsilon_{ij.t} \le Q_{ij.t}^{D} \le Q_{ij.t}^{D.max}\varepsilon_{ij.t} \quad (31)$$

$$0 \le p_{j.t}^{D.L} \le p_{j.t}^{D.Lmax} \quad (32)$$

$$0 \le Q_{j.t}^{D.L} \le Q_{j.t}^{D.Lmax} \quad (33)$$

$$Q_{j.t}^{D.Lmax}\, p_{j.t}^{D.L} = p_{j.t}^{D.Lmax}\, Q_{j.t}^{D.L} \quad (34)$$

Equations (26) and (27) denotes the nodal equality constraints of active and reactive power. Equations (28) and (29) denotes the relationship of the magnitude of nodal voltage and the branch power flow. Equation (30)

defines the limits for nodal voltage magnitudes. Equations (31) and (32) show that branch power flows are restricted by their capacities and switch states. Equations (33) and (34) give the limits of restored load at node j. Equation (35) shows a fixed ratio between active and reactive restored power at bus j. Equations (36)–(38) give the constraints of the active and reactive power of renewable energies in the distribution network.

$$\varepsilon_{ij.t} = 1. \forall (i.j) \notin \{\Omega_D \cup \Omega_S\} \quad (35)$$

$$\varepsilon_{ij.t} \le y_{k(ij).t}\,. \forall i\,. \forall j \quad (36)$$

$$\varepsilon_{hs.t} \le y_{k(ij).t}\,. \forall i\,. \forall j. \forall (h.s) \in w_{ij}^{U} \cup w_{ij}^{D} \quad (37)$$

$$\sum_{(i.j) \epsilon B_1} \varepsilon_{ij.t} \le B_i - 1. \forall l \, \epsilon O_l \quad (38)$$

Equations (35)-(38) guaranty the radiality of distribution network.

E-Objective functions

The objective function to be minimized is as follows:

$$f = \lambda_1 f_1 + \lambda_2 f_2 + \lambda_3 f_3 + \lambda_4 f_4 \quad (39)$$

$$f_1 = \sum_t \Big(\sum_t w_f\big(P_{j,t}^{D,Lmax} - P_{j,t}^{D,L}\big) + w_N\big(P_t^{N,max} - P_t^{N,L}\big)\Big) \quad (40)$$

$$f_2 = \sum_t \big(C^{SU}u_{g,t} + C^{SV}v_{g,t} + C^{g}v_{g,t}\big) \quad (41)$$

$$f_3 = \sum_i \big(T_{i,c}\big) \quad (42)$$

In Equation (39) $\lambda_1, \lambda_2, \lambda_3$ *and* λ_4 are weighted coefficient of the function in equations (40)-(42). Setting this equation is on decision of network operators.

E-Transportation network Modeling

The way to consider the traffic situation of the transportation network is briefly shown in Figure 2. According to the figure, first the network traffic information is received online. This information is converted into the form of a transportation graph and then the distance of different points from each other is calculated by Dijkstra's algorithm and finally stored as a simple matrix.

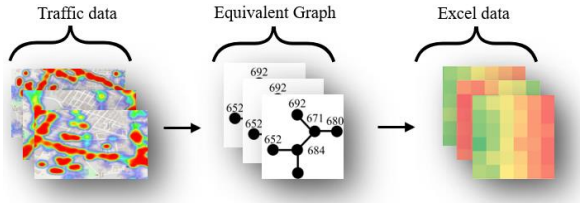


Fig. 2. Schematic of proposed framework for service restoration

3. Case study

A modified version of IEEE 33-bus (Baran et al. 1989) is used to verify the proposed method. The topology structure of the test system and corresponding transportation network is shown in Fig. 3. Also, the daily load curve is depicted in fig. 4. To model the fault conditions, it is assumed that 6 faults have occurred simultaneously on lines 20, 6, 8, 16, 30, and 23. The required repair time for each of the faults is 15, 30, 10, 30, 10, and 45 minutes, respectively. Three diesel generators are located at buses 5,10,15 with capacity of 100kW, 200kW and 400kW respectively. Also, two mobile power sources with capacity of 100kW and 200kW respectively are located at depot spot (bus 1). Moreover, two repair crew group are located at buses 1 and 18.

To solve the problem, the required equations were written as a MILP problem in the MATLAB environment and the problem was solved using the Yalmip Solver. the results are discussed below. The simulation was performed on a PC with Intel(R) Core i3 processor and 8.0 GB RAM. The longest runtime in all cases was 3.21s.

Given that the time of fault occurrence affects the solution of the problem, four different studies have been conducted. In these studies, the time of fault occurrence is considered 05, 10, 18, and 20, respectively. The simulation results are shown in Figure 5. By comparing Figures 5 (a-d) and also according to the daily load curve, it can be seen that as the load increases, the capacity of energy generation by distributed generation sources and MPSs increases. When this extra generation is not sufficient, some loads must be disconnected. Also, Table 1 shows how to dispatch RC to perform repairs and the time required to repair each fault. TABLE I also shows the result for repair crew scheduling. It can be seen that repair crew 1 should repair faults in line 8 and line 6 sequentially and the repair crew 2 should repair lines 16, 30, 20 and 23 sequentially. The full repair operation will need 149 minutes.

Table 1. Solution of repair crew dispatch

Faults	Time to repair (min.)	
	Repair Crew1	Repair Crew1
Line 20	-	116
Line 6	69	-
Line 8	37	-
Line 16	-	32
Line 30	-	76
Line 23	-	149

4. Conclusion

In this paper, a new method was proposed to solve the service restoration problem. Also, in this method, taking into account network traffic and transportation network status considerations, a framework was proposed that will lead to optimal and efficient solutions by distribution network operators. The proposed method of solving the problem was applied on a test network and demonstrated its effectiveness. However, one of the current challenges is to consider uncertainties in

various values such as network load demand. It is recommended that researchers consider this factor in future studies.

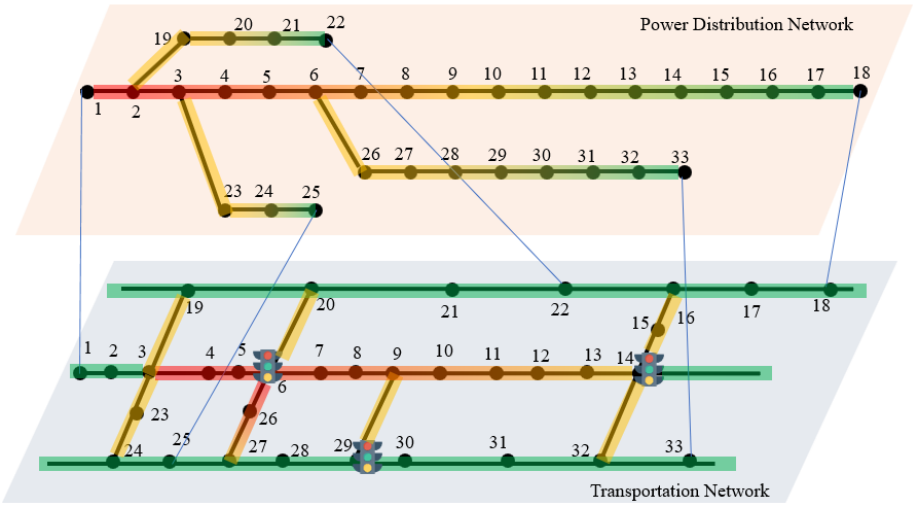


Fig.3. The test network and corresponding transportation network

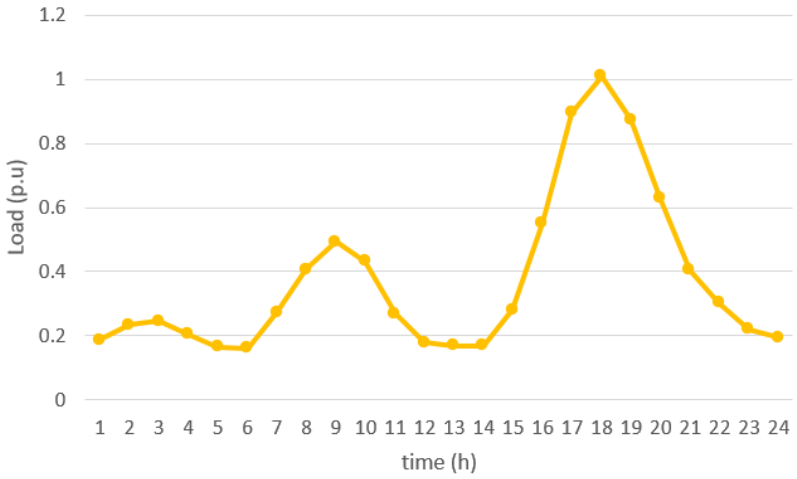
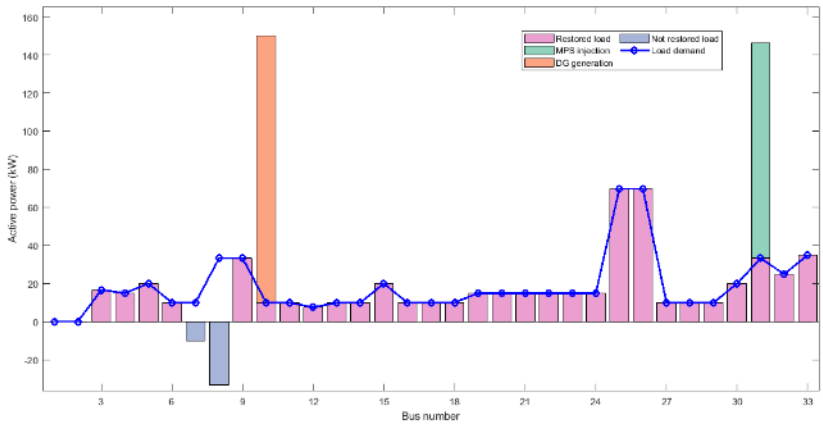
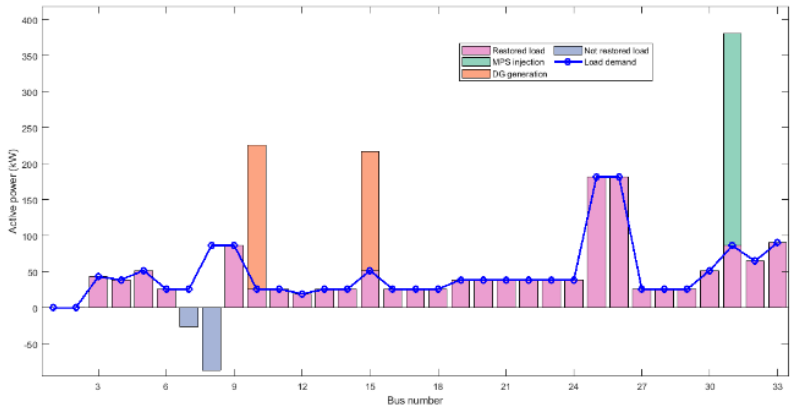


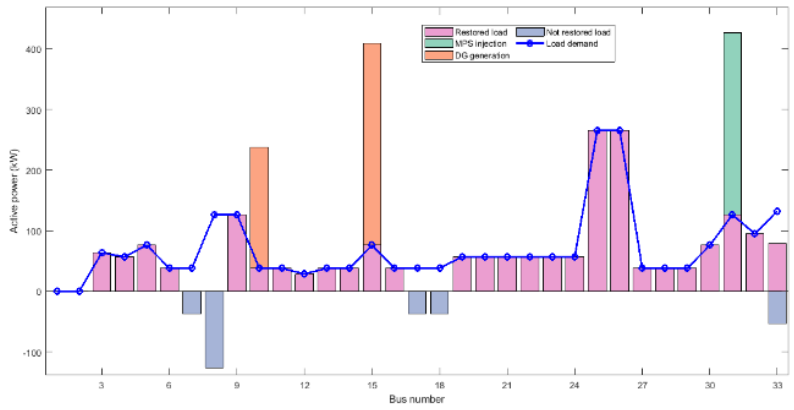
Fig.4. Daily load curve of the test distribution network (p.u.)



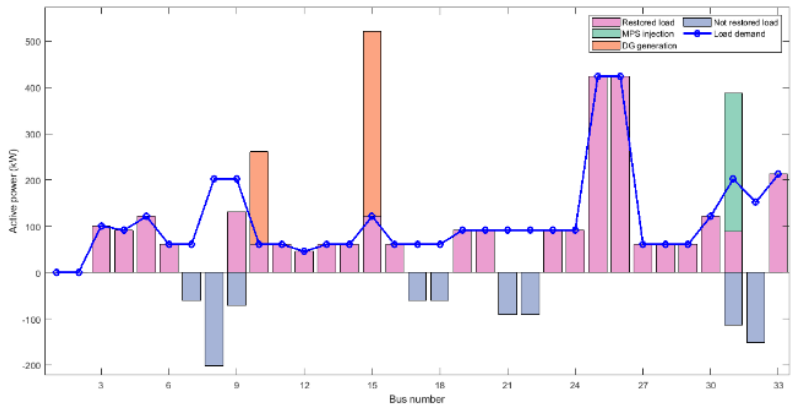
(a)



(b)



(c)



(d)

Fig. 5. Result of service restoration: power exchange in different buses. Run time = 2.01s,3,09s,2.89s and 3.21s for cases a-d.

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