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A MULTI-STAGE RECONFIGURATION METHOD FOR RESILIENCE ENHANCEMENT OF DISTRIBUTION SYSTEM

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ABSTRACT

Resilience of power systems has received more and more attention in recent years. In this paper, considering the switching operation time of sectionalizing switches and limited maintenance resources, we propose a multi-stage reconfiguration method for the enhancement of distribution system resilience, where, the preventative network reconfiguration before extreme events is considered to improve load survivability and the network reconfiguration in each stage after extreme events is considered for load restoration. The model is formulated as a MILP problem. Case studies on the IEEE 33-bus system show the effectiveness of the proposed method.

Keywords: resilience, distribution system, multi-stage reconfiguration, load restoration

NOMENCLATURE

Abbreviations	
DG	Distributed Generation
Symbols	
c, C	Index/set of fault scenarios
$(i,j), E$	Index/set of distribution lines
j, B	Index/set of nodes
t, T	Index/set of stages
$\delta(j), \pi(j)$	Set of child/parent nodes of node j
d_j	Binary parameter indicating whether there is a DG at node j (1) or not (0)
$E_{S,t,c}$	Total unsupplied Energy
$f_{ij,c}$	Binary parameter indicating whether there is a fault on line (i, j) (1) or not(0)
g_j	Binary parameter indicating whether node j is a substation (1) or not(0)
$G_{ij}, G_{ij,t,c}$	Reactive power flow on line (i, j)
$H_{ij}, H_{ij,t,c}$	Active power flow on line (i, j)
$k_j, k_{j,t,c}$	Binary variable indicating whether node j is the root node (1) or not (0)
$m_{ij,t,c}$	Binary variable indicating whether the status of line (i, j) can be changed (1) or not (0)
M	Large number
N_{m}	Maximum number of distribution lines whose status can be changed
p_c	Probability of fault scenario c
$P_{\mathrm{DG},j}, P_{\mathrm{DG},j,t,c}$	Active DG output power at node j
$P_{\mathrm{DG},j}^{\max}, P_{\mathrm{DG},j}^{\min}$	Maximum/minimum active DG output power at node j
$P_{\mathrm{L},j}, Q_{\mathrm{L},j}$	Active/reactive load at node j
$P_{\mathrm{S},j,t,c}, Q_{\mathrm{S},j,t,c}$	Active/reactive load curtailment at node j
$Q_{\mathrm{DG},j}, Q_{\mathrm{DG},j,t,c}$	Reactive DG output power at node j
$Q_{\mathrm{DG},j}^{\max}, Q_{\mathrm{DG},j}^{\min}$	Maximum/minimum reactive DG output power at node j
r_{ij}, x_{ij}	Resistance/reactance of line (i, j)
$S_{ij}^{\max}$	Capacity limit of line (i, j)
$U_j, U_{j,t,c}$	Node voltage magnitude of node j
$U_j^{\max}, U_j^{\min}$	Maximum/minimum node voltage magnitude of node j
U_{R}	Reference voltage magnitude
$X_{ij}, X_{ij,t,c}$	Binary variable. X_{ij}, $X_{ij,t,c}$ = 1 indicates that line (i, j) is closed and the virtual flow direction is $i \rightarrow j$, and X_{ij}, $X_{ij,t,c}$ = 0 indicates that line (i, j) is open or the virtual flow direction is $j \rightarrow i$.
$z_{ij}, z_{ij,t,c}$	Binary variable indicating whether line (i, j) is closed (1) or not (0)
Δt_t	Duration of stage t
ω_j	Weight of load j

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1. INTRODUCTION

The power system is one of the most critical infrastructures for modern society. However, recent years have seen many blackouts caused by natural disasters and man-made attacks, such as the 2011 Japan Earthquake blackouts, the 2012 Hurricane Sandy blackouts and the 2013 California terrorist attack blackouts. With an increasing frequency of these extreme events, resilience of power systems is becoming more and more crucial, which focuses on the ability of power systems to anticipate, resist, absorb, respond to, adapt to and recover from extreme events [1].

Lots of efforts have been devoted to enhancing distribution system resilience, where network reconfiguration has been widely adopted. For example, the network reconfiguration before and after extreme events are comprehensively considered in [2] for resilience enhancement. In addition, network reconfiguration is often used to form DG islands or microgrids for resilience enhancement, such as in [1] and [3]-[5]. In these studies, the optimal formation of DG islands or microgrids based on network reconfiguration is considered for the restoration of critical loads.

The network reconfiguration after extreme events is considered to be immediately completed in these researches. However, since network reconfiguration is based on the operation of sectionalizing switches, limited by the operation time of sectionalizing switches and maintenance resources, the network reconfiguration after extreme events must be implemented step by step. This is usually neglected in previous studies.

In this paper, we consider the optimal operation sequence of sectionalizing switches and determine the optimal network reconfiguration in each stage after extreme events. And, we also consider the preventative network reconfiguration before extreme events to ensure that the power supply paths to loads are less probable to be damaged by the extreme events, which will improve the survivability of loads. By this multi-stage reconfiguration method, which covers the stage before extreme events and the stages after extreme events, the distribution system resilience will be enhanced.

The remainder of this paper is organized as follows. Section 2 provides the model formulation. In Section 3, the case studies are presented. Concluding remarks are drawn in Section 4.

2. MODEL FORMULATION

The multi-stage reconfiguration model consists of three parts: the reconfiguration model before the extreme event, the reconfiguration model after the extreme event and the objective. In this paper, the impacts of extreme events on distribution systems are represented by the multiple faults of distribution lines. Considering that the faults caused by extreme events are uncertain, the model is formulated as the scenario-based stochastic optimization. Details are shown in Sections 2.1-2.3.

2.1 Reconfiguration model before the extreme event

Limited by the switching operation time of sectionalizing switches, the network reconfiguration after the extreme event cannot be started immediately. Therefore, to ensure load survivability, the preventive network reconfiguration before the extreme event (i.e. before the faults occur) is adopted. New power supply paths are formed, which are less probable to be damaged. The reconfiguration model before the extreme event is formulated as follows.

$$\sum_{i\in\pi(j)} X_{ij} + \sum_{s\in\delta(j)} X_{sj} \le 1 - g_j - d_j k_j, \forall j \in B \tag{1}$$

$$X_{ij} + X_{ji} = z_{ij}, \forall (i,j) \in E \tag{2}$$

$$P_{\mathrm{L},j} - P_{\mathrm{DG},j} = \sum_{i\in\pi(j)} H_{ij} - \sum_{s\in\delta(j)} H_{js}, \forall j \in B \tag{3}$$

$$Q_{\mathrm{L},j} - Q_{\mathrm{DG},j} = \sum_{i\in\pi(j)} G_{ij} - \sum_{s\in\delta(j)} G_{js}, \forall j \in B \tag{4}$$

$$U_i - U_j - (r_{ij}H_{ij} + x_{ij}G_{ij}) / U_{\mathrm{R}} \ge -M(1 - z_{ij}), \forall (i,j) \in E \tag{5}$$

$$U_i - U_j - (r_{ij}H_{ij} + x_{ij}G_{ij}) / U_{\mathrm{R}} \le M(1 - z_{ij}), \forall (i,j) \in E \tag{6}$$

$$-S_{ij}^{\max} z_{ij} \le H_{ij} \le S_{ij}^{\max} z_{ij}, \forall (i,j) \in E \tag{7}$$

$$-S_{ij}^{\max} z_{ij} \le G_{ij} \le S_{ij}^{\max} z_{ij}, \forall (i,j) \in E \tag{8}$$

$$U_j^{\min} \le U_j \le U_j^{\max}, \forall j \in B \tag{9}$$

$$P_{\mathrm{DG},j}^{\min} \le P_{\mathrm{DG},j} \le P_{\mathrm{DG},j}^{\max}, \forall j \in B \tag{10}$$

$$Q_{\mathrm{DG},j}^{\min} \le Q_{\mathrm{DG},j} \le Q_{\mathrm{DG},j}^{\max}, \forall j \in B \tag{11}$$

Where, (1) and (2) are the radiality constraints which ensure that the distribution system is operated radially [2]. Eqs. (3)-(6) are the linearized DistFlow model [6]. Specifically, (3) and (4) are the power balance equations, and (5) and (6) are the power flow equations. Eqs. (7) and (8) are the active and reactive line flow constraints. Eq. (9) is the voltage magnitude constraint. Eqs. (10) and (11) are the active and reactive DG output constraints.

It should be noted that (3) and (4) indicate that there is no load curtailment due to the normal operation of the distribution system before the extreme event. Controllable DGs are also considered in the model.

2.2 Reconfiguration model after the extreme event

After the extreme event, the network reconfiguration is adopted for load restoration. Considering the switching operation time of sectionalizing switches and limited maintenance resources, the load restoration process can be divided into several stages. The duration of each stage is depended on the switching operation time, and the number of sectionalizing switches which can be operated is depended on the maintenance resources (i.e. the number of maintenance teams). The optimal operation sequence of sectionalizing switches and network reconfiguration in each stage should be determined. The reconfiguration model for each stage in each fault scenario (i.e. $\forall t \in T \cap t \geq 1, \forall c \in C$) is formulated as:

$$\sum_{ij \in E} m_{ij,t=1,c} = 0, \forall c \in C \quad (12)$$

$$z_{ij,t=0,c} = s_{ij}, \forall (i,j) \in E, \forall c \in C \quad (13)$$

$$\sum_{ij \in E} m_{ij,t,c} \leq N_{\mathrm{m}} \quad (14)$$

$$z_{ij,t,c} \geq (1 - f_{ij,c})(z_{ij,t-1,c} - m_{ij,t,c}), \forall (i,j) \in E \quad (15)$$

$$z_{ij,t,c} \leq (1 - f_{ij,c})(z_{ij,t-1,c} + m_{ij,t,c}), \forall (i,j) \in E \quad (16)$$

$$\sum_{i \in \pi(j)} X_{ij,t,c} + \sum_{s \in \delta(j)} X_{sj,t,c} \leq 1 - g_j - d_j k_{j,t,c}, \forall j \in B \quad (17)$$

$$X_{ij,t,c} + X_{ji,t,c} = z_{ij,t,c}, \forall (i,j) \in E \quad (18)$$

$$P_{\mathrm{L},j} - P_{\mathrm{S},j,t,c} - P_{\mathrm{DG},j,t,c} = \sum_{i \in \pi(j)} H_{ij,t,c} - \sum_{s \in \delta(j)} H_{js,t,c}, \forall j \in B \quad (19)$$

$$Q_{\mathrm{L},j} - Q_{\mathrm{S},j,t,c} - Q_{\mathrm{DG},j,t,c} = \sum_{i \in \pi(j)} G_{ij,t,c} - \sum_{s \in \delta(j)} G_{js,t,c}, \forall j \in B \quad (20)$$

$$U_{i,t,c} - U_{j,t,c} - (r_{ij} H_{ij,t,c} + x_{ij} G_{ij,t,c}) / U_{\mathrm{R}} \geq -M(1 - z_{ij,t,c}), \forall (i,j) \in E \quad (21)$$

$$U_{i,t,c} - U_{j,t,c} - (r_{ij} H_{ij,t,c} + x_{ij} G_{ij,t,c}) / U_{\mathrm{R}} \leq M(1 - z_{ij,t,c}), \forall (i,j) \in E \quad (22)$$

$$-S_{ij}^{\max} z_{ij,t,c} \leq H_{ij,t,c} \leq S_{ij}^{\max} z_{ij,t,c}, \forall (i,j) \in E \quad (23)$$

$$-S_{ij}^{\max} z_{ij,t,c} \leq G_{ij,t,c} \leq S_{ij}^{\max} z_{ij,t,c}, \forall (i,j) \in E \quad (24)$$

$$U_j^{\min} \leq U_{j,t,c} \leq U_j^{\max}, \forall j \in B \quad (25)$$

$$P_{\mathrm{DG},j}^{\min} \leq P_{\mathrm{DG},j,t,c} \leq P_{\mathrm{DG},j}^{\max}, \forall j \in B \quad (26)$$

$$Q_{\mathrm{DG},j}^{\min} \leq Q_{\mathrm{DG},j,t,c} \leq Q_{\mathrm{DG},j}^{\max}, \forall j \in B \quad (27)$$

$$0 \leq P_{\mathrm{S},j,t,c} \leq P_{\mathrm{L},j}, \forall j \in B \quad (28)$$

$$0 \leq Q_{\mathrm{S},j,t,c} \leq Q_{\mathrm{L},j}, \forall j \in B \quad (29)$$

Where, (12) indicates that the network reconfiguration cannot be started immediately right after the extreme event (i.e. t = 1), because the switching operation time is needed. Eq. (13) defines the network topology before the extreme event (i.e. s_{ij}) as the network topology when t = 0 after the extreme event (i.e. $z_{ij,t=0,c}$). Eq. (14) is the maintenance resource limit. Eqs. (15) and (16) indicate that, if there is a fault on the distribution line, the line will be open. And if not, the line can be operated for network reconfiguration when the sectionalizing switch is operated by the maintenance team. Eqs. (17) and (18) are the radiality constraints. Eqs. (19)-(22) are the linearized DistFlow model. Eqs. (23) and (24) are the active and reactive line flow constraints. Eq. (25) is the voltage magnitude constraint. Eqs. (26) and (27) are the active and reactive DG output constraints. Eqs. (28) and (29) are the active and reactive load curtailment constraints.

It is worth noting that, when t = 1, the network topology is only determined by the network topology before the extreme event and the faults caused by the extreme event.

2.3 Objective and resilience metric

The unsupplied energy for each stage in each fault scenario is formulated as (30).

$$E_{\mathrm{S},t,c} = \Delta t_t \sum_{j \in B} \omega_j P_{\mathrm{S},j,t,c} \quad (30)$$

To obtain the optimal network reconfiguration in the stage before the extreme event and in the stages after the extreme event, the expected total unsupplied energy is minimized, which is formulated as (31).

$$\min \sum_{c \in C} p_c \sum_{t \in T} E_{\mathrm{S},t,c} \quad (31)$$

Based on the proposed method, the percentage of supplied loads is introduced to reflect the system performance in each stage after the extreme event, as formulated in (32).

$$R_{\mathrm{L},t,c} = 1 - \sum_{j \in B} \omega_j P_{\mathrm{S},j,t,c} / \sum_{j \in B} \omega_j P_{\mathrm{L},j}, \forall t \in T, \forall c \in C \quad (32)$$

Besides, the percentage of supplied energy of the entire restoration process is introduced to comprehensively reflect the resilience level of the distribution system, as formulated in (33).

$$R_{\mathrm{D}} = 1 - \sum_{c \in C} p_c \sum_{t \in T} E_{\mathrm{S},t,c} / (\sum_{t \in T} \Delta t_t \sum_{j \in B} \omega_j P_{\mathrm{L},j}) \quad (33)$$

3. CASE STUDY

The IEEE 33-bus system is adopted to verify the proposed method. The topology can be found in [1]. There are 3 controllable DGs at nodes 10, 20, 30. The capacity of each DG is 300kW. The voltage magnitude is within [0.95, 1.05]p.u.. The total system load is 3.715MW + 2.300MVar. 10 scenarios are randomly generated. Each scenario is assigned with a probability p_c=1/10. The time needed for completely repairing the faults is 2.28h, and the switching operation time is 0.46h. Therefore, there are 5 stages after the extreme event, where Δt_1, Δt_2, Δt_3,

Δt_4=0.46h and Δt_5=0.44h. The number of maintenance team is set to be 1. The proposed model is formulated as a MILP problem and solved by MATLAB with CPLEX.

The result of network reconfiguration before the extreme event is shown in Fig.1, and the value of R_D is 50.33%. The optimal operation sequence of sectionalizing switches under each fault scenario is listed in Table 1. If the distribution lines listed in the 3rd-6th rows are opened before the extreme event, they will be closed in the corresponding stage after the extreme event. Otherwise, they will be opened. It is worth noting that, when the fault occurs on a distribution line, the line will be damaged whether it is closed or not. However, the faults which occur on the open lines will not affect the existing power supply paths to loads, which will help improve the load survivability.

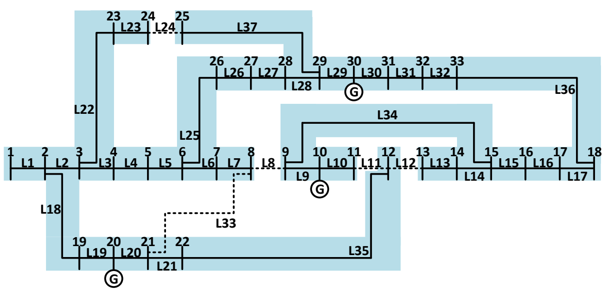

Fig 1 Result of the network reconfiguration before the extreme event

Table 1 Optimal operation sequence of sectionalizing switches under each fault scenario

Fault Scenario	Faulted Line	Optimal operation sequence			
		t=2	*t*=3	*t*=4	*t*=5
1	L1, L3, L23, L33, L37	L8	L12	L14	-
2	L20, L21, L29, L31, L35	L8	L33	L11	-
3	L2, L4, L6, L7, L8	L12	L24	L33	-
4	L13, L14, L23, L33, L34	L24	L12	-	-
5	L12, L25, L27, L35, L37	L8	L24	L11	-
6	L9, L11, L18, L24, L25	L8	L33	L20	-
7	L16, L19, L20, L22, L27	L33	L8	-	-
8	L3, L19, L22, L25, L33	L8	L12	L11	
9	L13, L14, L16, L31, L35	L11	L8	L12	L19
10	L5, L8, L11, L16, L24	L33	L12	-	-

Taking fault scenario 3 as an example, the percentage of supplied loads ($R_{L,t,c=3}$,t=1,…,5) is shown as the solid line in Fig. 2. Comparison results are also shown in Fig. 2, where,

Case 1: the proposed method is adopted, and N_m=2;

Case 2: the proposed method is adopted, and N_m=1;

Case 3: only the network reconfiguration after the extreme event is adopted, and N_m=1.

When comparing Case 1 with Case 2, it is obvious that adequate maintenance resources will contribute to faster load restoration. It should be noted that, the results of network reconfiguration before the extreme event under Case 1 and Case 2 are different. That is why the percentage of supplied loads under the two cases are different when *t*=1.

Compared with Case 2, the load restoration under Case 3 is slower. And, the percentage of supplied loads is much lower than that of Case 2 during the entire restoration process. It can be concluded that the network reconfiguration before the extreme event can not only improve the survivability of loads but also contribute to faster load restoration.

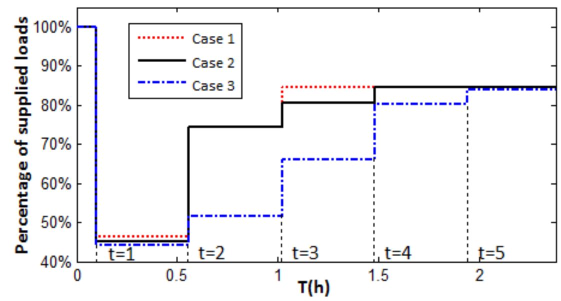

Fig 2 Percentage of supplied loads in each stage

4. CONCLUSION

In this paper, a multi-stage reconfiguration method for the enhancement of distribution system resilience is proposed and verified. Results show that the proposed method is effective in improving load survivability and ensuring the optimal network reconfiguration in each stage for load restoration, thus it can enhance the resilience of distribution systems.

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