International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0227

RESILIENCE ENHANCING STRATEGY FOR DISTRIBUTION NETWORK CONSIDERING MICRO-ENERGY GRID

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ABSTRACT

Aiming at the failure with large scale and long lasting time of distribution network(DN) under extreme natural disaster, a strategy of micro-energy grid(MG) and DN improving resilience in coordination in the process of dealing with surface nature disaster is proposed. First, combining the system function curve of DN under extreme disasters, a framework of resilience enhancing strategy during the overall process is proposed. Second, during the stage of DN defending and adapting to disasters, rolling outage management scheme when MG is in islanding state is raised, which considers the relevance among cool, heat and electric load as well as the influence of the remaining capacity in ESS on the next stage. Third, during the stage of fault recovery, robust DN fault recovery model which considers MG's supporting role is established, including raising the master-problem of fault repair plan and the sub-problem of restoration plan of some repair plan; through iteration of the master-problem and sub-problem, the optimal fault recovery strategy is worked out. Finally, the effectiveness of the method proposed in this paper is verified.

Keywords: micro-energy grid, distribution network, resilience, island partition, robust optimization

NONMENCLATURE

Abbreviations	
DN	Distribution Network
MG	Micro-energy Grid
MPC	Model Predictive Control
ESS	Energy Storage System
Symbols	
G	Set of cool, heat and electric load
O	Set of users
T_{ba}	Set of time without load reduction
D	Set of reducted load in DN
T	Scheduling period
IMG	Set of MGs
BA	Set of repair base
DA	Set of fault components
N_{MG}	Set of nodes which MGs are connected to
$\theta_{i,m,t}$	Set of parent nodes of *i*
M	A big number
TRE_e	Repair time of fault component *e*
$TTR_{e,f}$	Travelling time from *e* to *f*
$L(t)$	System Function at time *t*
ω_i	Weight factor of user *i*
$L_{i,j}(t)$	Type *j* load of user *i*
$TL(t)$	Normal system Function at time *t*
T_n	Planned scheduling period
$C_{om}(t)$	Maintenance cost
$C_{fuel}(t)$	Fuel cost
$C_{env}(t)$	Environmental cost
$C_{LS}(t)$	Load Reduction cost
$P_{ESS}(t)$	ESS charging power at time *t*
$E(t)$	ESS remaining capacity
$LS_{i,e}(t)$	Type *j* load reduction of user *i*
$\varepsilon_{i,e,c}$	Correlation coefficient between cool load and electric load of user *i*
$PL_{i,t}$, $QL_{i,t}$	Active and reactive power of loads
$x_{e,f,cr}$	Binary variable indicating whether repair team *cr* moves from *e* to *f*
$cr0$	Repair base of team *cr*
$y_{e,cr}$	Binary variable indicating whether fault component *e* repaired by cr
RES_e	Resources required to repair *e*
CAP_{cr}	Resource capacity of team *cr*

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

$AT_{e,cr}$	Arrival time of *cr* at *e*
$f_{e,t}$	Binary variable indicating the time *e* is repaired
$HL_{e,t}$	Binary variable indicating the fault state of *e*
$v_{i,m,t}$	Binary variable indicating whether node *i* belong to island *m*
$c_{i1,i2,m,t}$	Binary variable indicating the line switching state with i_1 and i_2 as the head node and end node
$SW_{i1,i2}$	Parameter indicating whether there is a switch in line i_1 - i_2
$S_{i,m,t}$	Binary variable indicating the load switching state of node *i*
ge	Node connected to the upper grid
$\overline{P}_{PV,t}$	Forecast output of PV at time *t*
$F_{PV,t}$	Uncertainty adjustment parameter
$P_{G,t}$	Scheduled output of PV
$\Delta P_{PV,t}^{\max}$	Maximum forecast error of PV
γ χ β	Auxiliary variable
z p l	Auxiliary variable

1. INTRODUCTION

Incidents of large-scale power system failure caused by extreme disasters have occurred more and more frequently, which have caused huge economic losses. Therefore, the concept of resilience is introduced to assess the ability of DN to maintain a normal state of power supply under extreme disasters.

At present, several studies on enhancing DN resilience with DG[1-4] and microgrid[5-8] have been carried out. The strategy to coordinate failure recovery of DG with two-stage method is proposed in [1]. [2] raises a kind of linear model, which could guarantee power supply of critical load by forming microgrid with DG. A synthetic model is introduced in [4], which integrates the service restoration model and the crew dispatch model based on a universal routing model. A multi-microgrids hierarchical power outage management scheme is developed to coordinate power transmit between microgrids under extreme disasters in [5]. A method for fault recovery of distribution network using grid-connected microgrid is proposed in [7], and the advantages and disadvantages between centralized and decentralized control of microgrid are compared.

All the studies mentioned above made operation strategies from the single stage of DN defending in disaster or recovery after disaster, without considering the relevance between these two stages. With the development of MG, more and more MG will be connected into DN and coupling between multi-energies would keep deepening; therefore, the conception of resilience would not be limited to power load any longer but extend to the scope of terminal energy demand. Meanwhile, underground facilities usually have powerful resistance to surface disasters and most natural gas pipeline systems adopt buried design; so the MG with natural gas system as energy resource has great potential to improve resilience.

Aiming at the problems mentioned above, this paper makes the following contributions:

1. DN resilience evaluation index is constructed from the perspective of terminal energy demands and the research framework of DN overall process resilience enhancing strategy considering MG is proposed.

2. During the stage of DN defending and adapting to disaster, relevance of user's cool, heat and electric load and the influences of ESS remaining capacity on the next stage are considered and MG rolling blackout management scheme is put forward.

3. MG's supporting role to DN is taken into consideration, and a robust DN fault recovery model considering fault repair is established.

2. FRAMEWORK

2.1 DN resilience evaluation index

In DN containing MG, the system function shall meet the demands of cool, heat and electric loads, especial the demands of critical load. The system functions at some moment and DN resilience index are as shown in the following formula:

$$L(t)=\sum_{j\in G}\sum_{i\in O}\omega_i L_{i,j}(t) \tag{1}$$

$$AR=\frac{\int_0^T L(t)\mathrm{d}t}{\int_0^T TL(t)\mathrm{d}t} \tag{2}$$

The index shows the proportion of system functions maintaining normal state under disasters.

2.2 Framework of resilience enhancing strategy

In the first stage, once the MG is powered off due to a fault, the MG immediately enters the island state; the micro-source output is dispatched according to the preset power outage management scheme, and the means of multi-energy complementary is adopted to power the critical load. At this moment, MG is at decentralized control mode and the agent is MG operator. After the disaster, it enters the second stage after DN operators have completed investigation of fault location and causes. Since MG has a controllable distributed power supply, it is considered to use MG to supply power to the critical load of DN. By signing the agreement in advance, MG is in centralized control mode and the agent is DN operator. MG operator transmits the micro-source and load information to DN operator, who will formulate the fault recovery plan uniformly. The process framework for this strategy is shown below:

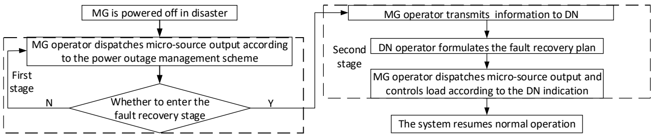


Fig 1 Framework of DN resilience enhancing strategy

3. MG OUTAGE MANAGEMENT SCHEME

3.1 MPC based MG rolling scheduling method

In disasters, uncertainty of renewable energy output increases, and the two-stage transition time of the system is also highly uncertain. Therefore, an MPC-based MG rolling optimization scheduling method is proposed to enable MG to respond to unforeseen circumstances.

The rolling optimization method can be concluded into the following steps: 1) At current time *t* and state *x*(*t*), predict future state of the system based on the prediction model. The scheduling schemes at *n* periods in the future could be obtained based on the established scheduling model; 2) The scheduling personnel implement only the scheduling scheme at time *t*; 3) At time *t*+1, the system state is renewed as *x*(*t*+1) according to the scheduling at time *t*; repeat the above procedures.

3.2 Objective function

The objective function is to minimize the total cost.

$$\min f=\sum_{t=1}^{T_n}[C_{om}(t)+C_{fuel}(t)+C_{env}(t)+C_{LS}(t)] \tag{3}$$

The formula for calculating the above cost can be found in [9].

3.3 Constraints

The balance constraint of cool, heat and electric power in MG and the constraints of micro-source output can also be found in [9].

In the first stage, if the remaining capacity of ESS is sufficient, redundancy of DN in the second stage will be improved, which is beneficial to DN fault recovery. Therefore, in this paper, ESS in MG is set to be in a state of charge in case there is no critical load reduction. The constraints are as follows:

$$P_{ESS}(t)=\min\left\{P_{ESS,\max},E_{\max}-E(t)\right\} \quad \forall t\in T_{ba} \tag{4}$$

This constraint ensures that ESS is charged fully at the moment with no critical load reduction.

The MG operator could determine the amount of load reduction for the user, and the user also has the right to adjust his/her own behavior of using energy. The degrees of correlation among cool, heat and electric loads of different users' vary also, which determines the actual load reduction of users. Therefore, the load reduction constraint expressed as follows:

$$\frac{LS_{i,e}(t)}{L_{i,e}(t)}=\varepsilon_{i,e,c}\frac{LS_{i,c}(t)}{L_{i,c}(t)}=\varepsilon_{i,e,h}\frac{LS_{i,h}(t)}{L_{i,h}(t)} \quad \forall i,t \tag{5}$$

4. ROBUST DN FAULT RECOVERY MODEL

Robust DN fault recovery model includes the master-problem and the sub-problem[11]. The master-problem is to minimize the total value of load reduction during this stage, and to formulate the best fault repair plan and pass it to the sub-problem. Its objective function is to be calculated by the sub-problem. To prevent frequent operation of the switch, the sub-problem forms an island with the MG as root node by adjusting the switch state when the fault component is repaired, and dispatches the micro-source output and maintains stable operation of the island with load control until all the fault components are fixed.

4.1 Objective function

Both the master-problem and the sub-problem are to minimize the total value of the load reduction.

$$\min f=\sum_{t\in T}\sum_{i\in D}\omega_i PL_{i,t}+\sum_{t\in T}\sum_{n\in IMG}\sum_{i\in O}\omega_i LS_{n,i,t} \tag{6}$$

4.2 Constraints

4.2.1 Master-problem constraints

$$x_{e,f,cr}=x_{f,e,cr}=0 \quad \forall e\in BA/\left\{cr0\right\},f,cr \tag{7}$$

$$\sum_{\forall cr}\sum_{\forall e\in DA}x_{cr0,e,cr}=\sum_{\forall cr}\sum_{\forall e\in DA}x_{e,cr0,cr}=n_{cr0} \quad \forall cr0 \tag{8}$$

$$\sum_{\forall cr}\sum_{\forall e\in DA\cup BA}x_{e,f,cr}=1 \quad \forall f \tag{9}$$

$$y_{e,cr}=\sum_{\forall f\in RA\cup DA}x_{f,e,cr} \quad \forall e,cr \tag{10}$$

$$\sum_{\forall e\in DA}y_{e,cr}\bullet RES_e\le CAP_{cr} \quad \forall cr \tag{11}$$

Constraints (7) and (8) represent that each repair team can only start from the repair base where it is located, and shall return to the base after the task is completed; constraint (9) indicates that each fault can only be repaired by one repair team; constraints (10) and (11) indicate that the sum of the resources required by the fault component repaired by a repair team shall be no more than the resource limit that the team can carry.

$$AT_{cr0,cr}=0 \qquad \forall cr0,cr \tag{12}$$

$$0 \le AT_{e,cr} \le y_{e,cr}M \qquad \forall e,cr \tag{13}$$

$$\begin{cases} -(1-x_{e,f,cr})M \le AT_{e,cr}+TRE_e+TTR_{e,f}-AT_{f,cr} \\ AT_{e,cr}+TRE_e+TTR_{e,f}-AT_{f,cr} \le (1-x_{e,f,cr})M \end{cases} \forall e,f,cr \tag{14}$$

$$\begin{cases} \sum_{\forall t} f_{e,t}=1 \\ \sum_{\forall t} t\cdot f_{e,t} \ge \sum_{\forall cr}(AT_{e,cr}+y_{e,c}\cdot TRE_e) \\ \sum_{\forall t} t\cdot f_{e,t} < \sum_{\forall cr}(AT_{e,cr}+y_{e,c}\cdot TRE_e)+1 \end{cases} \qquad \forall e \tag{15}$$

$$HL_{e,t}=\sum_{\tau}^{t-1} f_{e,\tau} \qquad \forall e,t \tag{16}$$

Constraint (12)-(14) is about the calculation method of $AT_{e,cr}$; constraint (15) is about the calculation method of $f_{e,t}$; constraint (16) shows that the fault component is upgraded into non-fault state at the following time after the repair is completed.

4.2.2 Sub-problem constraints

$$\sum_{m} v_{i,m,t} \le 1 \qquad \forall i,t \tag{17}$$

$$v_{r,m,t}=1 \qquad r=N_{MG}(m) \qquad \forall m,t \tag{18}$$

$$v_{i,m,t} \le \sum_{k\in\theta_{i,m,t}} v_{k,m,t} \qquad \forall i,m,t \tag{19}$$

$$\begin{cases} c_{i_1,i_2,m,t} \le v_{i_1,m,t} \bullet v_{i_2,m,t} \quad c_{i_1,i_2,m,t} \le HL_{e,t} \\ c_{i_1,i_2,m,t} \ge (1-SW_{i_1 i_2})HL_{e,t} \end{cases} \forall i_1 i_2,m,t \tag{20}$$

$$\sum c_{i_1,i_2,m,t} = \sum v_{i,m,t}-1 \qquad \forall i,m,t \tag{21}$$

$$v_{i,m,t+1}-v_{i,m,t} \le \sum_{\forall e\in DA} f_{e,t} \qquad \forall i,m,t \tag{22}$$

$$\begin{cases} \gamma_{i,m,t}=\chi_{i,m,t} \,\|\, \beta_{i,m,t} \\ \chi_{i,m,t}=v_{i,m,t}\bullet s_{i,m,t} \\ \beta_{i,m,t}=v_{i,m,t}\bullet v_{ge,m,t} \\ s_{i,m,t} \le s_{i,m,t-1} \end{cases} \forall i,m,ge,t \tag{23}$$

$$\begin{cases} PL_{i,m,t}=\gamma_{i,m,t}PL_{i,t} \\ QL_{i,m,t}=\gamma_{i,m,t}QL_{i,t} \end{cases} \forall i,m,t \tag{24}$$

Constraint (17) indicates that each node can belong to only one island; constraint (18) indicates that the node where MG is connected must belong to the island; constraint (19) shows that if the node *i* belongs to the island *m*, there must be at least one parent node of node *i* belonging to the island, so that the channel from node *i* to the MG could exist; constraint (20) is the constraint of the distribution line; constraint (21) is the island radial constraint; constraint (22) indicates that the DN will re-distribute island whenever a fault component is repaired; constraints (28) and (29) indicate that the load of node *i* can be restored only in the following two cases: the first is node *i* belongs to some island and the load switch is closed; the second is node *i* is connected with the upper grid.

Constraints in MG and flow constraint in DN shall also be satisfied. A robust peer-to-peer model for PV and WT output constraint is established using KRO theory[10]:

$$\begin{cases} -\overline{P}_{PV,t}+P_{G,t}+z_{PV,t}F_{PV}+p_{PV,t} \le 0 \\ z_{PV,t}+p_{PV,t} \ge \Delta P_{PV,t}^{\max} l_t \\ -l_t \le P_{G,t} \le l_t \\ z_{PV,t} \ge 0, p_{PV,t} \ge 0 \end{cases} \qquad \forall t \tag{25}$$

Constraint (20) and (23) and flow constraint can be linearized with the method in [2].

5. CASE STUDY

5.1 Overview of the case

The case adopts modified PG&E69 node DN. MG considers three types of users, i.e., hospital, business, and residents, among which hospital is critical load while business and residents are non-critical loads. The correlation coefficient of the cool and heat loads of the commercial user is set to 1 and that of the hospital and the resident user is 0. The weight factors for critical and non- critical loads are 100 and 1 respectively. Considering the typhoon disaster scenario, the typhoon continues from 18 o'clock to 4 o'clock of the next day. Since 20 o'clock, 10 faults occur one after another. Suppose the required repair time for each fault is 3 hours, and the travel time between the faults varies from 10 to 30 minutes. Fault recovery stage begins at 6 o'clock.

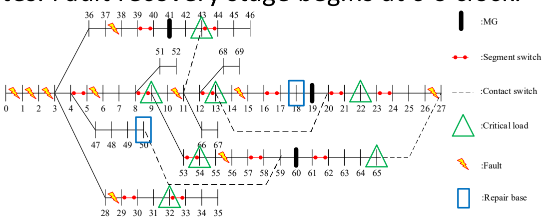


Fig 2 Framework of DN resilience enhancing strategy

5.2 MG outage management scheme

MG1 outage management scheme is taken as the example. Power supply from the upper grid to this MG is shut down at 20 o'clock due to fault of line 14-15, when SOC of ESS is 0.2. During the power outage, the controllable micro-source output and load reduction are shown in the following figure. The electric boiler output and the reduction of hospital load are 0 during the power outage, which is not shown in the figure.

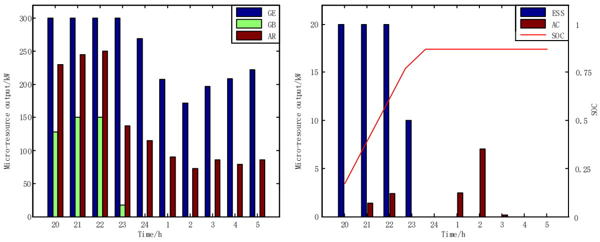


Fig 3 Output of various micro-sources

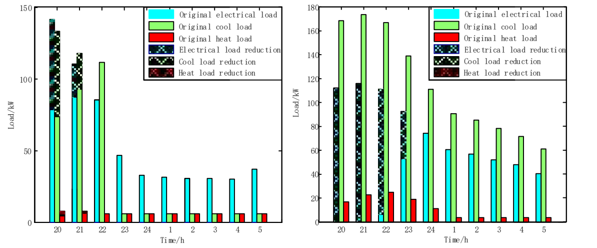


Fig 4 Reduction of the loads

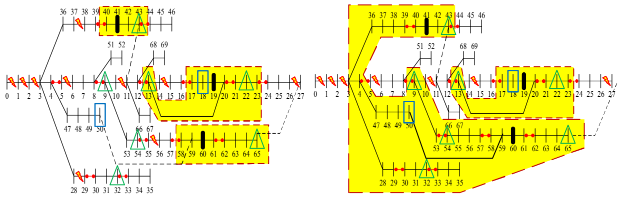
It could be seen from Fig. 3 and Fig. 4 that continuous supply of critical loads could be guaranteed by scheduling the output of each micro-source, and by the means of multi-energy complementation and reduction of non-critical load. Power shortage is the most serious in MG, so gas engine output has been at a high level; moreover, the outputs of electric boiler and air-conditioning are reduced, and gas boiler and absorption refrigerator are used mainly for heating and cooling. ESS will be charged at 20-23 o'clock because of constraint (4), and SOC reaches the upper limit of 0.9 at 24 o'clock, which could enhance the redundancy of DN in the fault recovery stage. Residential electric load is reduced with priority due to the limitation of constraint (5). If commercial power load is reduced in priority, the commercial heat load and cool load will be reduced in equal proportion and could cause unnecessary load reduction and increase cost of MG power outage management.

5.3 MG outage management scheme

According to the DN fault recovery model, the repair plan is as shown in Table 1. The general rule is to repair the path between MG and the critical load first, then to repair the path between DN and upper power grid, and finally, to repair other fault components. The total time taken is 13.21 hours. The result of DN island division of is as shown in Fig. 5. MG is used to supply the critical load by adjusting the switch state. During the islanding period, all non-critical load switches of DN are in disconnect state, because MG recovers the internal non-critical load preferentially; after 12 o'clock, all loads are restored to power supply because repair of the path between DN and the upper grid is completed, island state of DN ends.

Table 1 Repair plan of fault components

Repair team	Repair path
1	Node 50, 28-29, 0-1, 5-6, Node 50
2	Node 50, 37-38, 1-2, 10-11, Node 50
3	Node 18, 55-56, 2-3, 14-15, 26-27, Node 18



(a) 6-9 o'clock (b)10-12 o'clock

Fig 5 Division results of islands

Four scenarios are set to illustrate the effectiveness of the proposed method. Scenario 1 does not consider the supporting role of MG to DN. Scenario 2 adopts the method proposed in this paper. Scenario 3 adopts traditional fault repair strategy, that is, the fault is repaired within the shortest time. Scene 4 does not consider constraint (4) in stage 1. Comparison of the normalized function curves of the DN system in each scenario is shown in Fig. 6.

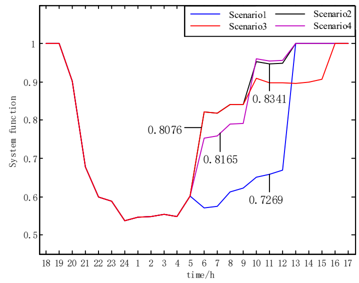


Fig 6 Comparison of different scenarios

Compare scenario 1 and scenario 2. Long-time outage of critical load in DN could be caused in case the supporting function of MG to DN is not considered, which could result in low system resilience. The resilience evaluation index of scenario 1 is 0.7269, which is smaller than 0.8341 in scenario 2.

Compare scenario 2 and scenario 3. Although all the faults can be repaired quickly according to the traditional repair sequence, long-time outage of critical loads, such as loads 9 and 32, could be caused due to failure to consider coordination with the fault recovery; therefore, the function curve of the system at 10-12 o'clock is much lower than in scenario 2. Meanwhile, line 2-3 in scenario 3 is repaired at 15:21 and the system function is restored to normal until 16 o'clock, which is three hours later than in scenario 2, resulting in low system resilience. The resilience evaluation index of scenario 3 is 0.8076, which is smaller than that of scenario 2.

Compare scenario 2 and scenario 4. The initial SOC of ESS in stage 2 of scenario 4 is 0.1. Because the critical load in MG1 is large, PV output is small, and it is impossible to recover critical loads 13 and 22 of DN relying only on gas engine and WT, smaller critical load 22 could not be recovered during this period, causing the system function curve is lower than in scenario 2 and the system resilience is low. The resilience evaluation index of scenario 4 is 0.8165, which is smaller than that of scenario 2.

6. CONCLUSION

A resilience enhancing strategy for DN is proposed and the following conclusions are obtained:

(1) The resilience enhancing strategy could improve efficiently DN resilience with MG during the stage of DN defending and adapting to disasters as well as the fault recovery stage, meanwhile considering that coordination between two stages could exert fully the functions of time sequence elements like ESS.

(2) Although traditional fault strategy could complete the repair of the fault components in the shortest time, long-term power outage of the critical load could be caused due to the failure to coordinate with restoration, thereby reducing the resilience of DN.

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