Coordinated Restoration Method for Electric Buses and Network Reconfigurations in Distribution Systems Under Extreme Events

Bo Zhang, *Member*, *IEEE*, Lu Zhang, *Senior Member*, *IEEE*, *IEEE*, Wei Tang, *Member*, *IEEE*, Zhaoqi Wang, and Chen Wang

***Abstract*—Distribution systems are facing challenges in serving lifeline loads after extreme events. Network reconfiguration is a traditional and practical method for power supply restoration, which has strong but inflexible power transfer capabilities influenced by network topology. Multiple failures of utility power under extreme events will further limit the efficiency of network reconfiguration. Electric buses (EBs) can be utilized to achieve power supply considering their discharging capabilities as mobile storage devices. However, the mobility of EBs and the influences of transport systems must be carefully considered to enhance the resilience of distribution systems. Reconfiguration and EBs are complementary in terms of recovery capabilities and location flexibility, and more important loads can be recovered by the coordination between EBs and network reconfiguration. This paper proposes a coordinated restoration method for EBs and reconfigurations considering the influences of transport systems. The post-disaster restoration problem is formulated as a bi-level model, in which the network topology is optimized in the upper-level aiming at maximizing restoration loads through the main grid and EBs, while the traffic paths of all EBs are optimized with the goal of maximizing the restoration loads by the EBs in the lower-level considering time consumption and energy consumption during movement. The PSO and a genetic algorithm are used to solve the proposed bi-level optimization problem. Simulation studies are performed to verify the superiority of the proposed method.**

***Index Terms*—Distribution system, electric bus, extreme event, network reconfiguration, restoration, transport system.**

I. Introduction

ENHANCING the resilience of the distribution system (DS) in urban areas is necessary because of the frequently occurring extreme events and high reliability requirements of lifeline loads [1], [2]. Long-time outages of lifeline loads will cause significant economic losses and even destroy the basic needs of human life [3]. Network reconfiguration is a traditional method of service restoration, which can be used to restore power supply of lifeline loads under extreme events [4], [5]. Moreover, local power sources such as DGs and storage systems can also be effectively utilized for the supply restoration of lifeline loads in distribution systems to enhance the resilience of the power grid [6], [7].

Electric bus (EB) has already been widely used in urban areas to reduce carbon emissions, which shows discharging capability as mobile storage devices, thus are able to provide power supplies after extreme events [8]. Moreover, in bus charging depots there can be several EBs that are charging or on standby with full power energy, which are dispatchable. Therefore, using EB to restore important loads is a possible way to enhance the resilience of distribution systems.

Network reconfiguration is a traditional and more practical method for power supply restoration, which has strong capability but is inflexible due to the limitations of switch positions and operation times. Multiple failures of utility power under extreme events will further limit the flexibility of network reconfiguration. EBs are available to provide power supply after extreme events with flexible energy support locations and limited capacities, which are also affected by the transport system between the original and destination nodes. Reconfiguration and EBs are complementary in terms of recovery capabilities and location flexibility, and better recovery results can be achieved through coordination. Therefore, how to achieve the maximum restoration through the coordination of the reconfiguration and EBs needs to be studied.

Various methods of restoration under extreme events have been proposed in literature. Reference [9] presented a restoration method using photovoltaic (PV) generation systems coupled with battery energy storage systems (BESSs). Since the discharge power of the fixed energy storage system (FESS) is controllable, studies have proposed restoration strategies based on FESSs [10], [11]. However, only local loads are able to be served due to the fixed location of the FESS. Electric vehicles (EVs) have mobile discharging capability during the restoration period [12], but are influenced by user characteristics and vehicles' uncertain locations and numbers. Reference [13] proposed an optimization strategy for network reconfiguration considering the centralized EV charging depots as the black-start power sources. A resilient service

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restoration method was designed utilizing the neighboring networks, distributed energy resources and aggregated vehicle to grid (V2G) capacity when facing an extreme incident with multiple faults [14]. To cope with multiple outages caused by natural disasters, a coordinated restoration model including the routing repair crews, mobile electric vehicles, and soft-open-point networked microgrids is proposed [15]. Reference [16] focused on the pre-hurricane allocation of generation resources in a distribution system for its resilience enhancement, and generation resources including the allocation of diesel oil, electric batteries, and electric buses. In the existing research, the influence of the transport system (TS) is simply modeled as the demand of repair sources [17]. However, the mobility of EVs and the impact of transport system failures on traveling time of EVs under extreme events were not considered. There is also some literature that research service restoration methods based on reconfiguration. Reference [18] proposed a restoration strategy based on network reconfiguration, and results revealed that the strategy restores the load outages and improves the system overall safety and resilience in a very fast manner. A coordinated restoration method of distribution system reconfiguration and islanding operation was proposed in [19].

There are two main shortcomings of the existing research.

(1) Under extreme events, network reconfiguration has a large restoration capability but is not flexible enough. EBs can restore loads at any point because of their mobility but restoration capability is limited. Reconfiguration and EBs carry out load recovery without coordination which may result in waste of resources and lead to the situation that the load location after reconfiguration is difficult to reach for EBs. Since network reconfiguration and traffic paths of EBs influence each other, it is necessary to coordinate reconfiguration and EBs. However, most of the existing restoration methods are based on EBs or reconfiguration only, and lack coordination between them.

(2) EBs need to travel before reaching the destination for important load supply restoration. However, traffic congestion may occur after extreme events and worsen the restoration effects of important loads, because the traffic paths and the required time of EBs are influenced. The traffic paths determine the energy losses of EBs, while the time of travel determines the restoration period of important loads. Therefore, the traffic paths and time must be considered in a restoration optimization.

In this paper, a coordinated restoration method of network reconfiguration and EBs under extreme events is proposed, considering the mobility of EBs as well as the influences of transport systems. Although the SOCP relaxation method can solve the network reconfiguration problem [20], this paper formulates the post-disaster restoration problem as a bi-level model which maximizes the restoration amounts of important loads, considering the interaction between reconfiguration and EBs restoration strategy. In the upper-level, the network topology is optimized aiming at maximizing the restoration amounts of loads by the main grid and EBs. In the lower-level, traffic paths of all EBs are optimized with the goals of maximizing the restoration amounts of loads by the EBs considering time consumption and energy consumption during movement. After repeated iterations, the optimal network structure and the traffic paths of EBs are completed, which will achieve the maximum supply restoration of important loads.

The rest of this paper is organized as follows. Section II describes the restoration problem. Section III presents the proposed bi-level optimization model of restoration. Section IV introduces the optimization algorithm of the bi-level model. Section V verifies the effectiveness of the proposed restoration method. Finally, conclusions are presented in Section VI.

II. Problem Description

Figure 1 shows an urban distribution system with 5 feeders. After an extreme event, some power lines are destroyed. The main network can restore part of the load through network reconfiguration. However, the remaining two normal lines cannot restore all the loads. Moreover, there are several EB depots, in which some of the EBs are fully charged and can be used to restore important loads. However, the mobility of EBs and the influences of transport systems must be considered, such as time consumption and energy consumption during the movement. Network reconfiguration and EBs can complement each other in terms of capacity and flexibility, and better recovery results can be achieved through coordination.

In order to make full use of the recovery capacity and flexibility of the main network and EBs, a coordinated restoration method in urban distribution systems for reconfiguration and EBs is proposed in this paper based on the following assumptions.

1) The shortages of the distribution system and the congestions of the transport systems under extreme events are known. And the restoration period is known due to the constant repair ability after extreme events [21].
2) The main network can realize the restoration of the load in the non-fault area through reconfiguration.
3) All EBs strictly follow their schedules before extreme events thus the state of charge (SOC) of the spare EBs at charging depots can be obtained.
4) After extreme events, EBs can only move to nodes with V2G ability for point-to-point load restoration [22]. And it is assumed that some nodes in the distribution system are installed with V2G charging piles.

The bi-level programming model is appropriate to model problems in which the upper-level optimizes its objective function with consideration that the lower-level will react by optimizing its own objective function [23], [24]. In this paper, the restoration strategy of EBs is dependent on the network topology after reconfiguration, and will further affect the reconfiguration results of the main grid in turn. The interaction between reconfiguration and EBs restoration strategy is consistent with the bi-level optimization model. Therefore, the proposed restoration method is formulated based on a bi-level optimization model.

III. Optimal Restoration Method

The diagram of the proposed bi-level model is shown in Fig. 2. In the upper-level, the network topology is optimized

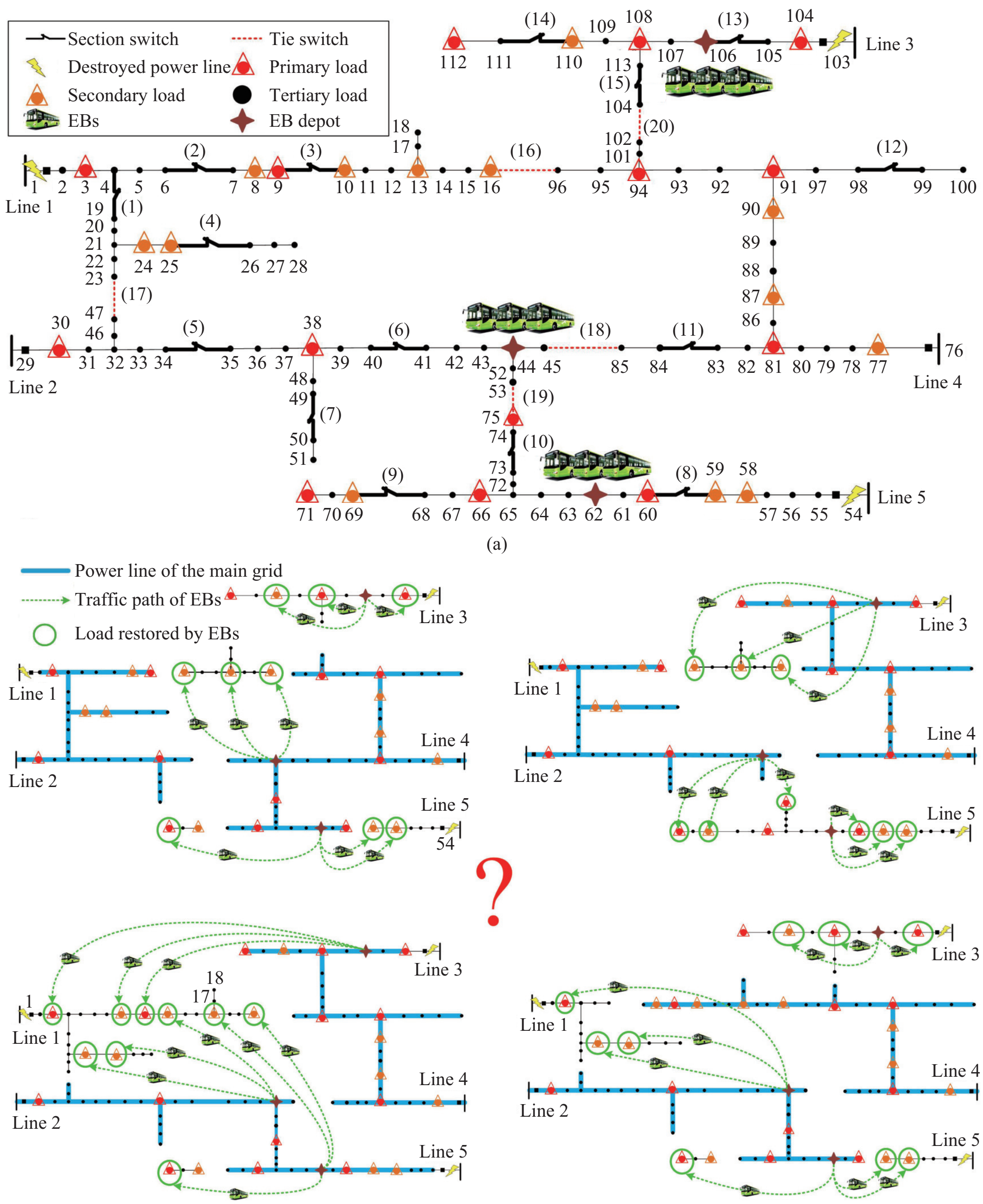

Fig. 1. 5-feeders urban distribution system. (a) Failure diagram. (b) Coordinated restoration of EBs and reconfiguration.

with the objectives of maximizing restoration amounts of important loads by using the main grid and EBs. In the lower-level, traffic paths of all EBs are optimized with the goals of maximizing the restoration amounts of important loads by the EBs. First, the upper-level initializes network topology subjected to the constraints of the upper-level and transfers them to the lower-level; secondly, the lower-level optimizes traffic paths of all EBs, and returns the traffic paths of all EBs and corresponding objectives to the upper-level; then, the-upper-level evaluates the restoration results, and regenerates a new network topology, which will be returned to the lower-level; finally, stable restoration schemes are obtained by iterations between the two levels.

A. Optimization Model of Upper-level

Restoring as much load as possible is the most important goal under extreme events. In the upper-level, the objective function is maximizing the restoration amounts of important loads in the whole restoration period considering the importance of the degree of loads, as shown in equation (1).

$$\max F = F_{\text{main}} + F_{\text{EB}} \tag{1}$$

$$F_{\text{main}} = \sum_{t=1}^{\text{T}} \sum_{i \in R} \lambda_i L_{i,t} y_{i,t} \tag{2}$$

$$F_{\text{EB}} = \sum_{t=1}^{\text{T}} \sum_{i \in D} \lambda_i L_{i,t} y_{i,t} \tag{3}$$

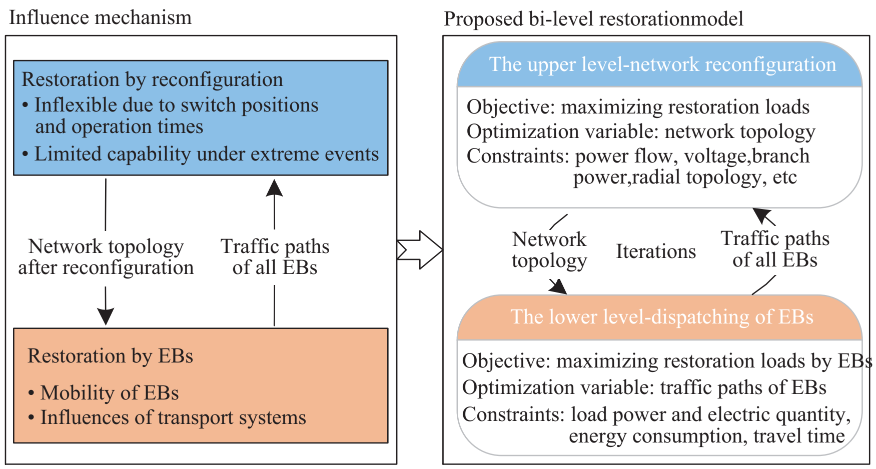

Fig. 2. The diagram of the bi-level model.

where F_{main} is the amount of the important load restored by the main grid during the restoration period; F_{EB} is the restoration amount of the important load by the EBs during the restoration period; T is the fault duration; R is a set of outage areas; D is a set of outage areas after reconfiguration; λ_i is the importance of the load on node i; $L_{i,t}$ is the load on node i at time t; $y_{i,t}$ is state parameter, $y_{i,t} = 1$ means node i at time t has been restored the power supply, $y_{i,t} = 0$ means node i at time t has not been restored.

Also, the optimization model of the upper-level is subjected to the following constraints.

$$V^{\min} \leq V_{i,t} \leq V^{\max} \tag{4}$$

$$P_{i,t} - V_{i,t} \sum_{j=1}^{n} V_{j,t}(G_{ij} \cos\theta_{ij,t} + B_{ij} \sin\theta_{ij,t}) = 0 \tag{5}$$

$$Q_{i,t} - V_{i,t} \sum_{j=1}^{n} V_{j,t}(G_{ij} \sin\theta_{ij,t} - B_{ij} \cos\theta_{ij,t}) = 0 \tag{6}$$

$$P_{j,t} \leq P_{j,\max} \tag{7}$$

$$N_{\text{re}} \in N \tag{8}$$

where $V^{\max}$ and $V^{\min}$ are allowable upper and lower voltage limits, respectively; $V_{i,t}$ is the voltage of node i at time t; $P_{i.t}$ and $Q_{i.t}$ are the injection active and reactive power of node i at time t, respectively; G_{ij} and B_{ij} are the real and imaginary parts of the node admittance matrix, respectively; θ_{ij} is the phase angle difference between node i and j at time t; n is the total number of nodes; $P_{j,t}$ is the active power of branch j at time t; $P_{j,\max}$ is the maximum allowable active power of branch j; N_{re} is the network topology after reconfiguration; N is the set of radial topologies.

Constraints (4) and (7) ensure that node voltages and branch power after reconfiguration are within the allowable range. Constraints (5) and (6) are power balance constraints. Constraint (8) is used to ensure that the topology after reconfiguration is a radial one. According to references [25], [26], it is possible to ensure that the distribution network corresponds to a spanning tree connected to the main substation, regardless of the direction of the power flow, by introducing two binary variables corresponding to each line (as described in [27] by (11)–(15)).

B. Optimization Model of Lower-level

In the lower-level, EBs perform a point-to-point restoration of the rest of the loads after reconfiguration and will further affect the reconfiguration results of the main grid in turn. Although EBs have strong mobility, it will cause time and energy consumption in the process of moving. The destination nodes and traffic paths of all EBs are optimized in the lower-level considering time consumption and energy consumption during movement. The maximum restoration amounts of important loads by the EBs is taken as the objective function of lower-level optimization.

$$\max F_{\text{EB}} = \sum_{t=1}^{\mathrm{T}} \sum_{i \in D} \lambda_i L_{i,t} y_{i,t} \tag{9}$$

The constraints need to be satisfied as follows:

$$P_{i,t}^{\text{EB}} \geq L_{i,t} \tag{10}$$

$$E_i^{\text{EB}} \text{SoC}_i^{\text{initial}} - E_i^{\text{c}} \geq \sum_{t=1}^{\mathrm{T}} L_{i,t} \Delta t \tag{11}$$

where $P_{i,t}^{\text{EB}}$ is discharge power of the EB on node i at time t; $\text{SoC}_i^{\text{initial}}$ is the initial SOC of the EB; E_i^{c} is energy consumption of the EB during movement; $\sum_{t=1}^{\mathrm{T}} L_{i,t}\Delta t$ is the required electric quantity of load on node i during the restoration period.

Constraints (10) and (11) are utilized to ensure that the load power and electric quantity can be satisfied during the restoration period. Moreover, the number of EBs at each node is one at most, during the whole restoration period considering that the number of V2G piles at each node is assumed to be one at most in this paper. When the number of V2G piles at the node is greater than one, the number of EBs at the same load node can be greater than one, as long as the number of EBs is less than or equal to the number of V2G piles.

The mobility of EBs leads to a better restoration of loads, but at the same time, it also causes consumption of time and energy. On the one hand, the consumption of time will increase the power supply restoration time of loads. On the other hand, the consumption of energy worsens the insufficiency of the power supply for the load demand is much larger than available power in the restoration period.

Extreme events will cause transport system failures and increase the congestion of other traffic paths. The traffic congestion on streets results in an increment of travel time beyond the acceptance of EB drivers. In a congested transport system, the travel time of the EB on street k depends on the road length and the level of service (LOS) of street k, which can be calculated as follows [28], [29].

$$TT_{k,t}=\frac{l_k}{v_k^{\text{free}}}(1+\text{RDI}_{k,t}) \tag{12}$$

where l_k is the road length of street k; v_k^{free} represents the free-flow speed in street k; RDI_k is the relative delay index of street k at time t which quantifies the percentage increase in travel time due to traffic congestion on the street.

$\text{RDI}_{k,t}$ can be obtained according to the LOS of street k. As shown in Table I [28], the LOS is classified into six levels ranging from "A" (best service) to "F" (worst service) to determine the degree of traffic congestion at varying spaces and times.

TABLE I
RDI VALUE CALCULATION TABLE

LOS	Description	Threshold value of RDI (%)
A	Free flow; low volume; high speed	RDI < 2
B	Stable flow; speed slightly restricted	2 < RDI < 8
C	Stable flow; speed and maneuverability restricted	8 < RDI < 15
D	Approaching unstable flow; freedom to maneuverability restricted	15 < RDI < 26
E	Unstable flow; speed fluctuating; No freedom to maneuver	26 < RDI < 75
F	Forced flow; frequent stoppages and queue	RDI > 75

Therefore, the time consumption from the origin node to node i can be calculated by the sum of travel time in all streets contained in the traffic path K_i.

$$T_i^{\text{c}}=\sum_{k\in K_i} TT_{k,t} \tag{13}$$

Moreover, the energy consumption can be represented as:

$$E_i^{\text{c}}=E^{\text{per}}\sum_{k\in K_i} l_k \tag{14}$$

where E^{per} shows the energy consumption of EBs per kilometer.

The value of the state parameter $y_{i,t}$ is related to time consumption T_i^{c}.

$$y_{i,t}=\begin{cases}1 & \text{if } T_i^{\text{c}}\le t\\ 0 & \text{if } T_i^{\text{c}}> t\end{cases} \tag{15}$$

EBs need to travel before reaching the destination for important load supply restoration. If the traveling time of EB T_i^{c} is greater than t, which means that EB has not reached the target node i at time t, $y_{i,t}$ will be 0. If the traveling time of EB T_i^{c} is less than or equal to t, which means that EB has reached the target node i at time t and starts discharging, $y_{i,t}$ will be 1.

IV. OPTIMIZATION ALGORITHM OF BI-LEVEL MODEL

In the upper-level, the PSO [30] is used to formulate the power grid restoration scheme and the corresponding outage area. In the lower-level, the EBs are taken as power supplies, and an improved genetic algorithm (GA) [31] is used to optimize the traffic paths. After repeated iterations, the optimal coordinated network topology of the main grid and the traffic paths of EBs are completed, which will achieve the minimum outage load of the whole network.

The calculation flowchart of the proposed bi-level optimization model is shown in Fig. 3, and the process is as follows.

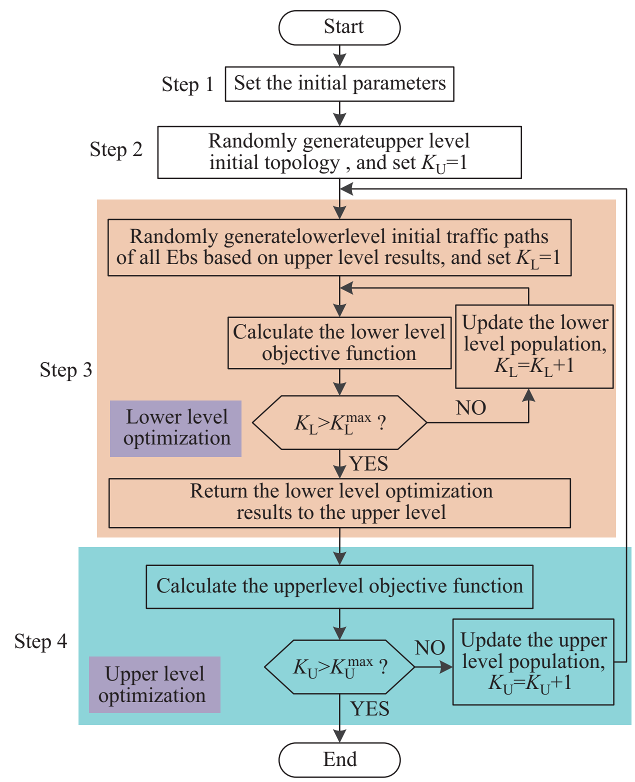

Fig. 3. Flowchart of the algorithm.

Step 1: Set the initial parameters, including distribution system parameters, typical daily load and EB parameters.

Step 2: Randomly generate upper-level initial network topology that satisfy the constraints (4)–(8). At the same time, the number of upper-level iterations K_{U} is set to 1.

Step 3: First, for each topology in the upper-level, the lower-level generates initial traffic paths of all EBs which satisfy the constraints (10)–(15) and the number of lower-level iterations K_{L} is set to 1; then, the optimal individual in the lower-level is obtained through the GA; next, optimization results are returned to the upper-level.

Step 4: The upper-level objective function shown in (1) is calculated. After that, determine whether K_{U} reached the maximum allowable number of iterations $K_{\text{U}}^{\max}$ or not. If it is reached, the calculation is finished, otherwise, the population of the upper-level is updated and go to Step 3.

V. Case Study

A. Simulation Background

A distribution system with 5 feeders shown in Fig. 1 is used to verify the effectiveness of the proposed method. The rated voltage is 10 kV and the maximum daily load of the system is 10619.85 kW + 7266.99 kVar. The loads are divided into primary loads with red dots, secondary loads with blue dots and tertiary loads with black dots by prioritizing them according to importance degrees, and parameter λ_i is set to 100, 10 and 5 in this paper. There is at least one V2G charging pile for the primary and secondary loads. In corresponding transport systems, there are three EB depots located in node 62, node 44 and node 106.

Assuming that an extreme event appears at 10:00 a.m., the restoration period lasts 6 hours. The scheduling time interval of the proposed restoration strategy is 1 hour. After an extreme event, some transport lines and power lines have been destroyed as shown in Fig. 1. According to the schedule of buses, the initial SOC and location of spare EBs are determined as shown in Table II. The maximum charging/discharging power, battery's capacity, speed and energy consumption per kilometer of these type EBs are 100 kW, 200 kWh, 60 km/h and 0.2 kWh, respectively. Learning factor, population number and maximum iteration times of PSO are 2, 20 and 50, respectively. Population number, crossover rate, mutation rate and maximum iteration times of GA are 50, 0.9, 0.1 and 100, respectively.

TABLE II
Initial Status of Spare EBs at Depots

NO.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
SOC	1.0	0.5	0.8	1.0	0.5	0.8	1.0	1.0	0.5	1.0
Node	62	62	44	44	44	44	106	106	106	106

B. Superiority of the Proposed Method Considering the Coordination of Reconfiguration and EBs

To verify the superiority of the coordination of reconfiguration and EBs, three different restoration strategies are adopted as follows.

Strategy 1: Power supply restoration only by network reconfiguration.

Strategy 2: Restoration by network reconfiguration first, and then by EBs.

Strategy 3: Coordinated restoration of reconfiguration and EBs proposed in this paper.

The optimization results of topology and EBs under different strategies are shown in Table III and Fig. 5. And Table IV illustrates electricity quantity restored by the three strategies.

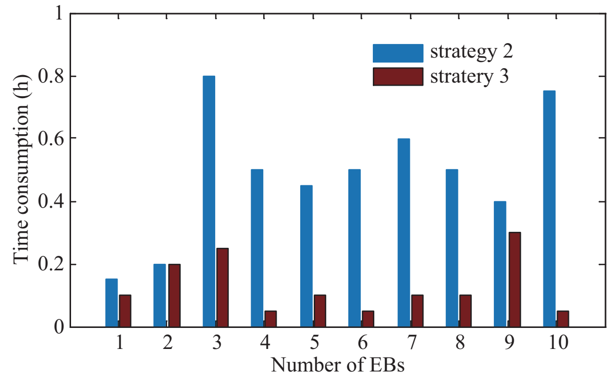

Fig. 4. Time consumption of EBs to reach destination node.

After extreme events, the head branch of the three feeders has been destroyed, and the capacity of the two normal feeders is limited. Strategy 1 realizes the restoration only by changing network topology through reconfiguration. It can be seen from Table IV that the recovery electricity quantity of the primary load, secondary load and tertiary load are 1247.4 kWh, 1212.0 kWh and 10908.0 kWh, respectively. After the reconfiguration, the open switches are 16, 17, 18, 8, which is showing that the percentage of recovery electricity quantity of the primary loads is 77% but the percentage of the total recovery electricity quantity is only 38.0%. Strategy 2 adds EBs on the basis of recovery results of strategy 1, and EBs perform a point-to-point restoration on the remaining loads after reconfiguration. Optimization results of switches and EBs under strategy 2 is shown in Fig. 5(a). As seen from Table IV, the recovery electricity quantity of three types of loads increases to 1571.6 kWh, 2869.4 kWh and 12313.9 kWh, respectively. The percentage of the total recovery electricity quantity increases to 47.7%.

TABLE III
Results of Topology and EBs of Different Strategies

Strategy	Open switches	Destination nodes of the EBs									
		1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
1	16, 17, 18, 8	/	/	/	/	/	/	/	/	/	/
2	16, 17, 18, 8	58	59	3	9	24	25	10	13	16	8
3	2, 18, 19, 20	60	75	66	71	69	59	104	108	112	106

TABLE IV
Comparison of Recovered Electricity Quantity of Different Strategies

Strategy	Electricity quantity restored by main grid (kWh)			Electricity quantity restored by EBs (kWh)			Electricity quantity restored by whole network (kWh)			Percentage of recovery electricity quantity (%)				EB energy consumption (kWh)
	I	II	III	I	II	III	I	II	III	I	II	III	sum	
1	1247.4	1212.0	10908.0	0.0	0.0	0.0	1247.4	1212.0	10908.0	77.0	36.7	36.1	38.0	0
2	1247.4	1212.0	10908.0	324.2	1657.4	1405.9	1571.6	2869.4	12313.9	97.0	87.0	40.7	47.7	38.8
3	363.6	2142.2	13965.0	1238.7	651.9	1702.4	1602.3	2794.1	15667.3	98.9	84.7	51.8	57.1	10.4

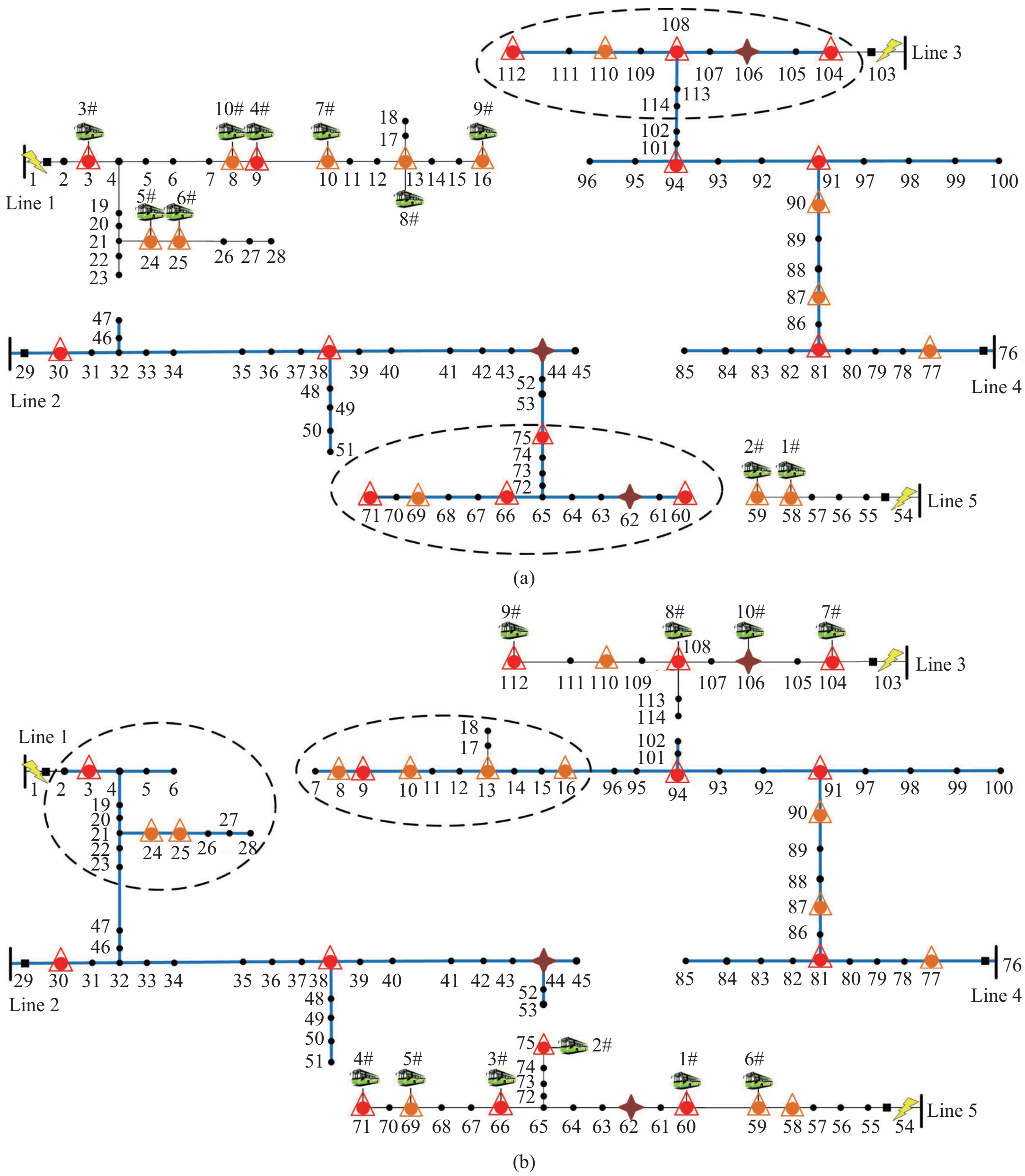

Fig. 5. Optimization results of switches and EBs. (a) Strategy 2. (b) Strategy 3.

Compared with strategy 2, the restoration of strategy 3 is achieved by coordination of reconfiguration and EBs. Because strategy 3 takes into account travel time on the road and energy consumption of EBs in the optimization model, the reconfiguration stage will tend to restore the hard-to-reach loads for EBs shown in Fig. 5(b) (such as node 3 and node 9). Fig. 4 shows time consumption of EBs during movement under strategy 2 and strategy 3. The time for every EB to reach the destination node of strategy 3 is less than or equal to that of strategy 2. The total time consumption of strategy 3 is 1.3 h, which is 73% less than the that of strategy 2 (4.85 h). At the same time, the energy consumption of EBs on the road under strategy 3 is also reduced 28.4 kWh compared with strategy 2, because the length of the traffic path is reduced.

After implementing the reconfiguration scheme of strategy 2, the two normal feeders still have remaining capacity. However, the primary load is restored as much as possible considering that the objective function is to maximize the weighted load. Compared with the reconfiguration results of strategy 2, although the primary load restored by reconfiguration of strategy 3 is reduced, the total restoration of the three types of loads is increased. This is because of the coordination of reconfiguration and EBs in strategy 3. The main network can restore the secondary load and tertiary load as much as possible within the capacity range, under the premise that the EBs can recover the remaining primary load, so as to realize the full utilization of the main network resources. It is precisely because of this coordination, that the percentage of the total recovery electricity quantity increases to 57.1%.

C. Analysis of Continuous Power Supply for Important Loads

The previous subsection analyzed the recovery capability of the proposed coordinated restoration strategy of EBs and network reconfiguration. For post-disaster restoration under extreme events, it is not only necessary to restore important loads as much as possible, but also to consider the continuous power supply for important loads. In order to compare the continuous power supply for the important loads under different restoration strategies, a recovery strategy denoted as strategy 4 is added. Strategy 4 is also a coordinated restoration strategy of reconfiguration and EBs, but it does not consider the time and energy consumption of EBs during the movement.

The open switches of strategy 4 are 3, 18, 19, 15, and destination nodes of the EBs are 71, 69, 108, 75, 66, 60, 112, 104, 110, 59, respectively. Under strategy 3, except for the traveling time of EBs at the beginning shown in Fig. 4, each EB can realize continuous power supply to the destination load until the end of the restoration period, which is 6 h. Taking load 108 as an example, Fig. 6 shows the load restoration of load 108 during restoration period under strategy 3 and strategy 4. In strategy 3, the EB takes 0.3 h to reach node 108 (from node 106), and then continues to supply power to the load during the entire restoration period. In strategy 4, the EB takes 0.8 h to reach node108 (from node 44), because the traffic path is longer than that in strategy 3. In addition, the EB cannot be discharged due to insufficient power at 5.5 h, because the energy consumption on the road is relatively high compared with strategy 3, which are 14 kWh in strategy 4 and 2.4 kWh in strategy 3. The continuous power supply time under strategy 4 is only 4.7 h.

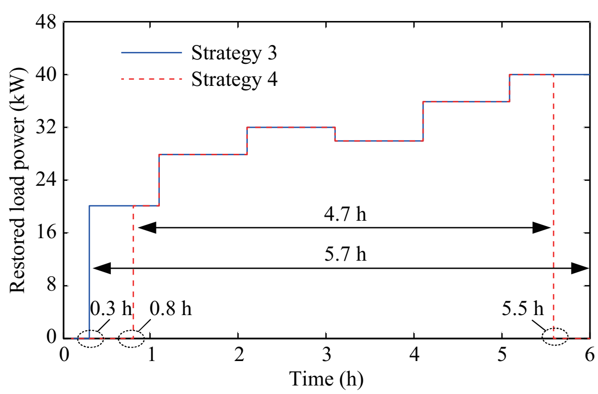

Fig. 6. Continuous power supply for load 108.

There are two factors that affect the continuous power supply of EBs. One is the travel time of the EBs to the destination node, and the other is the energy consumption of the EBs on the road. Strategy 4 does not consider the travel time and energy consumption of EBs when optimizing the destination nodes and traffic paths. Therefore, the EBs in strategy 4 take a longer time to reach the destination node, so the power outage time of the load increases. At the same time, EBs may not be sufficient to continuously supply the load power due to energy consumption during driving.

D. Impact of Traffic Congestion on Restoration

In this subsection, strategy 5 is designed as follows in order to further reflect the impact of traffic congestion on restoration results.

Strategy 5: Based on the reconfiguration results of strategy 3, the rest loads are restored by EBs without considering the traffic congestion of the transport system.

Compared with strategy 5 and strategy 3, because the topology of the main network is the same, the load restored by the main network is also the same. So, the next part only compares the recovery results by EBs. Fig. 7 shows the actual travel time and distance of EBs under strategy 3 and strategy 5. Because strategy 5 only uses the length of streets to calculate the travel time, without considering the traffic congestion when optimizing the paths, the length of paths selected by strategy 5 is shorter than that of strategy 3 as well as the energy consumption of EBs. However, during the recovery period, due to the failure of some lines in the transportation network, the congestion of other lines has also increased. Therefore, when EBs move along the paths optimized by strategy 5, the travel time will increase sharply. The total time of strategy 5 is 3.82 h which is longer than that of strategy 3.

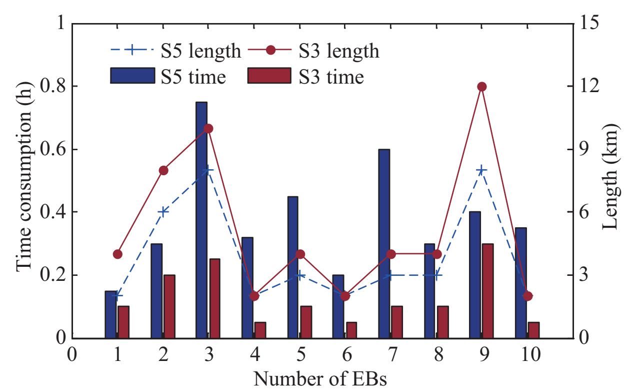

Fig. 7. Time consumption and path length of EBs.

As shown in Table IV, the electricity quantity of the three types of loads recovered by strategy 3 through EBs is 1238.7 kWh, 651.9 kWh and 1702.4 kWh, respectively, while that of strategy 5 is 1176 kWh, 560.0 kWh, 1344.0 kWh. Compared with strategy 3, the restoration of the three types of loads is reduced by 5.06%, 14.09 %, and 21.05 %, respectively, and the total recovered electricity quantity is reduced by 14.28%. This is because the increase in the traveling time of EBs leads to a reduction in the continuous power supply time of the loads, so the recovered electricity quantity is also reduced. Therefore, it is necessary to consider the failure of the transportation network or the traffic congestion when the EBs participate in the restoration.

VI. Conclusion

In this paper, a coordinated restoration method for reconfiguration and EBs is proposed considering the influences of transport systems, which are aimed at enhancing the resilience of the distribution system.

The coordination of the reconfiguration and EBs can realize the full utilization of the existing resources. On the one hand, the recovery strategy of EBs is directly affected by the network topology after reconfiguration. Consider the time consumption and energy consumption of the EB, which in reconfiguration can make the main grid tend to restore hard-to-reach locations for EBs. On the other hand, under the premise that the EB can recover some important loads, the main network can recover as many other loads as possible within the range of capabilities, so as to fully utilize the resources of the main network. The simulation results show that the load recovery of the coordination of reconfiguration and EBs is increased by 19% compared with restoration only by reconfiguration, and increased by 10% compared with restoration by reconfiguration first and then by EBs.

In the restoration model of EBs, if the congestion of the transport system is not considered, the traveling time of EBs during actual recovery will increase. The increase in the traveling time of EBs leads to a reduction in the continuous power supply time of the loads, so the recovered electricity quantity is also reduced. In this paper, the actual restored electricity without considering traffic congestion is reduced by 14%.

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