Optimal Scheduling of Mobile Energy Storage in Emergency Support of Power Systems

Yuan Shen¹, Chen Zhou², Yuwei Wang¹, Yibin Tao², Tao Wen¹, Kaichao Xiao³ and Weiqiang Qiu³,*

¹State Grid Jiangsu Electric Power Co., Ltd. ZhenJiang Power Supply Branch, ZhenJiang, China
²China Electric Power Research Institute Co., Ltd, Nanjing 210003, China
³College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China

*Corresponding author. Email: 11910037@zju.edu.cn

Abstract. Mobile energy storage has been employed in many fields, including the disaster prevention and emergency support of a power system, with the developed technology and the reduced cost. This paper proposed an optimal scheduling scheme of mobile energy storage in emergency, in order to recover the power supply of important loads and reduce the outage losses. In the proposed scheme, an optimal scheduling model, which takes into account the load classification and travel time of mobile energy storage, is proposed to minimize the total outage losses and ensure the continuous power supply of the first level load. To solve the model, a genetic algorithm is applied. Finally, case study shows that the proposed scheme can achieve the reasonable scheduling of mobile energy storage and then avoid the major outage losses.

Keywords: Mobile energy storage, Emergency power supply, Optimal scheduling model.

1. Introduction

In past few years, there have been many blackouts in the globe such as the August 14th blackout in the US and Canada, and the China blackout caused by ice disaster in 2008 [1, 2]. Therefore, it is very necessary to establish a sound and effective emergency power supply system, giving priority to ensure the power supply of important customers.

In the existing emergency power supply system, mobile emergency power source (the diesel generator installed on the truck usually) is an important part, and is responsible for recovering power supply to loads in the shortest possible time [3-5]. In [5], a multi-objective optimal scheduling model of mobile emergency power source in consideration of the customer demand and distance is proposed to minimize outage losses and surplus capacity.

With the development of energy storage material, technology and corresponding auxiliary circuit, energy storage system (ESS) has been widely applied in power systems [6, 7]. In different kinds of ESSs, mobile energy storage system (MESS) starts to gradually replace the traditional mobile emergency power source in emergency power supply system due to its flexibility and multifunction [8, 9]. Therefore, the energy constraint of MESS, which is a key factor, should be considered in the optimal scheduling model compared with the other scheduling methods of emergency resources [10, 11].
This paper proposes an optimal scheduling scheme of MESS in emergency, which take the minimization of the total outage losses of important customers as its optimization objective, and the load classification and travel time of mobile energy storage are considered in the proposed model.

2. Optimal scheduling model of mobile energy storage in emergency

2.1. Mobile energy storage system
In recent years, MESS has been a novel kind of electrical device due to its flexibility, controllability and reasonable cost. Compared with the traditional ESSs, it is different for MESS that energy storage units and auxiliary circuits have been modularized and integrated into the standard containers which are transported by a truck [12]. In other hands, the energy storage units in MESS are usually batteries because of modular characteristic, mature technology and wide capacity range [13]. A typical structure of MESS is shown in Fig. 1.

Figure 1. A typical structure of MESS.

Considering that MESS can change the access point flexibly, and therefore the requirements of customers in different locations are satisfied. Moreover, MESS is more environmental-friendly and noiseless compared to traditional mobile emergency power source. Furthermore, except for emergency power supply function, MESS can be applied in many fields such as power quality improvement, rural power grid promotion, renewable energy accommodation and so on, reducing the comprehensive investment and operation cost significantly [14].

2.2. Optimal scheduling model considering travel time and load classification
After extreme weather events such as typhoon, ice disaster and earthquake, a large-scale blackout may occur in urban power system as a result of transmission line damage and power equipment outage. Among all affected customers, some customers including hospital, train station, government organ and school are more important than other resident customers. Therefore, power emergency department should ensure and restore power supply of such customers (i.e., important loads) as soon as possible. According to the requirement of power supply reliability and the degree of political and economic losses caused by power outage, power loads are classified into three types, i.e., the first level loads, the second level loads and the third level loads [15]. As for important loads, it is composed of a certain proportion classified loads, which can be expressed as:

\[ \mu_1 + \mu_2 + \mu_3 = 1 \] (1)

where \( \mu_1, \mu_2 \) and \( \mu_3 \) denotes the proportion of the first, second and third level loads respectively. As for the first level loads, its interruption of power supply will cause casualties or major losses in political and economic levels. It is a basic demand for power emergency department to ensure the continuous power supply of the first level loads. Even though important customers need to prepare the
self-contained power supply for the first level loads, MESS will extend the use time of self-contained power supply and improve the reliability of power supply when the outage time is quite long.

Another factor that should be considered in optimal scheduling model is the travel time of MESS. In an urban power system, some MESSs are assigned to several district power supply stations and power emergency department will issue scheduling command to the stations according to the scheduling model, dispatching MESSs to power for the important customers. Therefore, the travel time between power supply stations and important customers should be considered in the model.

Based on aforementioned analysis, an optimal scheduling model aiming at minimizing the total outage losses can be established. The objective function $f$ can be represented as:

$$f = \sum_{l=1}^{3} \sum_{j \in J} S_{jl}P_{jl}^{\text{load}}T_{\text{blackout}} - \sum_{h=1}^{H} \sum_{l=1}^{3} S_{jl}P_{jl}^{\text{level}} \Delta T_{jh}$$

(2)

$$\Delta T_{jh} = \begin{cases} T_{\text{arr}} - T_{\text{arr}}^* & h, s = 1,2,..., H - 1 \\ T_{\text{blackout}} - T_0 - T_{\text{arr}}^* & h, s = H \end{cases} \quad \forall j \in J$$

(3)

where $j$ is the index of important customers, and $J$ is the set of important customers. $l$ is the index for load classification. $S_{jl}$ denotes the value coefficient of the $l$-th level load. $P_{jl}^{\text{load}}$ is the load of the $j$-th important customer; $T_{\text{blackout}}$ is total blackout time, which can be obtained from power company. The first term of objective function stands for the total outage losses of important customers if power supply is not recovered from the blackout; and the second one stands for the profits obtained by dispatching MESSs to recover the power supply. For an important load, there will be MESSs from different power supply stations arriving at different time, causing several time periods where the total output power of MESS is changeable. $h$ is the index of time periods. $H$ is the total number of time periods, which is equal to the number of power supply stations; $\Delta T_{jh}$ stands for the $h$-th time period of the $j$-th important customer, and its equation can be expressed as equation (3). $s$ is the index of arrival sequence of MESS, and $T_{\text{arr}}^*$ is the travel time where the $s$-th batch of MESS arriving at the $j$-th important customer. $T_0$ is the response and communication time between power emergency department and power supply stations; $P_{jl}^{\text{level}}$ is the power provided by MESS, supplying the $l$-th level load of the $j$-th important customer in the $h$-th time period, which may vary for every time period. In order to solve the variable conveniently, the available energy of MESS is represented as:

$$E_{j}^{ \text{ava}} = \sum_{l=1}^{3} \sum_{i \in I} \sum_{k \in K} n_{ijk} \min\{E_{k}^{\text{ava}}, P_{k}^{\text{rated}}(T_{\text{blackout}} - T_{\text{travel}} - T_{0})\}; \quad \forall j \in J$$

(4)

where $E_{j}^{\text{ava}}$ is the available energy of MESS in the $j$-th important customer in this blackout. $i$ and $I$ are the index and the set of power supply station, respectively. $k$ and $K$ are respectively the index and the set of MESS types; $n_{ijk}$ denotes the number of the $k$-th type MESS dispatched to the $j$-th important customer by the $i$-th power supply station. Supposing that the battery state of the same type of MESS is equal. $E_{k}^{\text{ava}}$ and $P_{k}^{\text{rated}}$ are the available energy and rated power of the $k$-th type of MESS. $T_{ij}^{\text{travel}}$ is travel time between the $i$-th power supply station and the $j$-th important customer. According to (4), the MESS output power $P_{jh}^{\text{MESS}}$ of the $j$-th important customer in the $h$-th time period is represented as:
where \( t \) is also the index of time periods. \( S \) is the set of arrival sequence of MESS. \( n_{jk}^a \) is the number of the \( k \)-th type MESS arrived to the \( j \)-th important customer by the \( s \)-th order, which is depending on \( n_{ik} \) and \( T_{ij}^{travel} \). Finally, \( P_{jhl}^{level} \) can be obtained as:

\[
P_{jhl}^{level} = m_{jhl} (P_j^{MESS} - \sum_{c=0}^{I} P_j^{load}) + (1 - m_{jhl}) \mu_l P_j^{load}; \quad \forall j \in J, h = 1, 2, ..., H, \forall l \in \{1, 2, 3\}
\]  

(6)

\[
m_{jhl} = \begin{cases} 1 & P_j^{MESS} > \sum_{c=0}^{I} P_j^{load} \\ 0 & P_j^{MESS} \leq \sum_{c=0}^{I} P_j^{load} \end{cases}; \quad \forall j \in J, h = 1, 2, ..., H, \forall l \in \{1, 2, 3\}
\]  

(7)

where \( m_{jhl} \) is a binary variable, and its expression is shown in (7). Based on (2)-(7), an objective function with the decision variable \( n_{ij} \) can be obtained.

For this model, the following constraints should be respected.

\[
\sum_{j=0}^{H} n_{ij}^a \leq n_{ik}^{hold}; \quad \forall i \in I, \forall k \in K
\]  

(8)

\[
E_j^{ava} \geq P_j^{load} \sum_{a=1}^{H} \Delta T_{ja}; \quad \forall j \in J
\]  

(9)

\[
E_k^{ava} \leq E_k^{rated} (SOC_k^{max} - SOC_k^{min}); \quad \forall k \in K
\]  

(10)

Constraint (8) represents that the total number of the \( k \)-th type of MESS of the \( i \)-th power supply station should be no more than the MESS ownership \( n_{ik}^{hold} \). Constraint (8) indicates that the available energy of MESS in the \( j \)-th important customer should be no less than the required energy of the first level load in the power supply period. Equation (9) defines the constraints of available energy of the \( k \)-th type of MESS associated with its state of charge (SOC) and rated energy \( E_k^{rated} \).

In summary, the optimal scheduling model of MESS in emergency is represented as:

\[
\begin{align*}
\min J \\
\text{s.t.} \quad \sum_{j=0}^{H} n_{ij}^a \leq n_{ik}^{hold}; \quad \forall i \in I, \forall k \in K \\
E_j^{ava} \geq P_j^{load} \sum_{a=1}^{H} \Delta T_{ja}; \quad \forall j \in J \\
E_k^{ava} \leq E_k^{rated} (SOC_k^{max} - SOC_k^{min}); \quad \forall k \in K
\end{align*}
\]  

(11)

Considering that the optimal scheduling model is a mixed integer linear programming problem, a genetic algorithm is utilized to solve the proposed model in this paper. Genetic algorithm is a common heuristic algorithm, simulating the process of biological evolution. The basic principle is that initial population is selected randomly, and then the individuals having higher fitness are obtained by using
fitness function. The selected individuals generate next population through crossover and mutation. Finally, the optimal individual will be obtained after a certain generation.

3. Case study

Table 1. Types and number of MESS in the district power supply stations.

| Number order | Types and number of MESS       |
|--------------|--------------------------------|
|              | (I) 50kW/125kWh | (II) 100kW/250kWh | (III) 200kW/300kWh |
| 1            | 3                     | 2                   | 1                   |
| 2            | 4                     | 3                   | 2                   |
| 3            | 2                     | 2                   | 1                   |
| Total number | 9                     | 7                   | 4                   |

There are 3 district power supply stations in an urban area, and the configuration of MESS is shown in Table 1. Supposing that these MESSs are brand new and fully charged, and therefore the available energy is 80% of the rated value. The district power supply stations are responsible for providing emergency power supply for 10 important customers. The important customers have deployed the self-contained power supply for the first level load. In a blackout, the self-contained power supply powering the first level load until MESSs arrive. The outage loads of the important customers, and the travel time between important customers and power supply stations are summarized in Table 2. In this case, supposing that the blackout time is 100 min, and the reaction time is 2 min. Otherwise, the value coefficients are respectively 10, 0.1 and 0.05 for different levels loads.

Table 2. Outage loads of the important customers, and the travel time between important customers and power supply stations.

| Number order | Outage loads of the important customers | Travel time/min |
|--------------|-----------------------------------------|-----------------|
|              | µ₁ | µ₂ | µ₃ | Total load/kW | Station 1 | Station 2 | Station 3 |
| 1            | 0.2 | 0.35 | 0.45 | 405          | 7.5       | 14.5      | 19        |
| 2            | 0.15 | 0.3 | 0.55 | 250          | 3.5       | 10.5      | 15        |
| 3            | 0.2 | 0.25 | 0.55 | 180          | 5         | 8         | 12.5      |
| 4            | 0.1 | 0.3 | 0.6 | 200          | 2         | 5         | 9.5       |
| 5            | 0.15 | 0.35 | 0.5 | 400          | 7         | 6         | 10.5      |
| 6            | 0.2 | 0.35 | 0.45 | 210          | 6         | 1         | 5.5       |
| 7            | 0.1 | 0.25 | 0.65 | 380          | 6.5       | 8.5       | 13        |
| 8            | 0.15 | 0.25 | 0.6 | 215          | 9         | 6         | 8.5       |
| 9            | 0.2 | 0.35 | 0.45 | 195          | 8.5       | 1.5       | 3         |
| 10           | 0.2 | 0.35 | 0.45 | 465          | 14        | 7         | 4.5       |

After receiving the information of this case, the genetic algorithm is used to obtain the optimal solution as shown in Table 3. It can be seen from the results that the first level load will be powered by MESS until the blackout ends. The continuous power supply of the first level load can be ensured, and part of the second and third level loads is also recovered to reduce the outage losses. Therefore, the total outage losses of important customers decrease to ¥ 30,211 from ¥ 495,431 without the service of MESS.
Table 3. Optimal scheduling results of MESS in emergency.

| Number | Outage load power (the First level one)/kW | Station 1 | Station 2 | Station 3 |
|--------|------------------------------------------|-----------|-----------|-----------|
|        |                                          | I         | II        | III       | I         | II        | III       |
| 1      | 405(81)                                  | 1         | 1         | 1         |           |           |           |
| 2      | 250(37.5)                                | 1         |           |           | 1         |           | 2         |
| 3      | 180(36)                                  | 1         |           |           |           | 1         |           |
| 4      | 200(20)                                  | 1         |           |           |           | 1         |           |
| 5      | 400(60)                                  | 1         | 1         | 1         |           |           |           |
| 6      | 210(42)                                  | 1         |           |           | 1         |           |           |
| 7      | 380(38)                                  | 1         |           |           | 1         |           |           |
| 8      | 215(32.25)                               | 1         | 2         |           |           |           |           |
| 9      | 195(39)                                  |           |           |           |           | 1         |           |
| 10     | 465(93)                                  |           |           |           |           |           | 1         |
| Total number | 2900(478.75)                         | 3         | 2         | 1         | 4         | 3         | 2         |

4. Conclusion
In order to speed up the construction of the emergency platform of urban power system and promote the use of MESS in power emergency, this paper proposes an optimal scheduling scheme for MESS in emergency support of power systems. The objective of the proposed optimal model is to minimize the total outage losses of important customers considering the load classification and travel time of MESS. Moreover, the genetic algorithm is applied in solving this model. Finally, the effectiveness of the proposed method is verified by the case study. The results show that the continue power supply of the first level load can be ensured and the total outage losses decline significantly.

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References
[1] Zhou L, Fan M, Zhang Z. Study on the optimal allocation of emergency power supplies for urban important customers[C]//2009 International Conference on Sustainable Power Generation and Supply. 2009: 1-5.
[2] Minkel J R. The 2003 Northeast Blackout—Five Years Later[J]. Scientific American, 2008, 13.
[3] Lei S, Wang J, Chen C, et al. Mobile emergency generator pre-positioning and real-time allocation for resilient response to natural disasters[J]. IEEE Transactions on Smart Grid, 2016, 9(3): 2030-2041.
[4] Lei S, Wang J, Chen C, et al. Mobile emergency generator pre-positioning and real-time allocation for resilient response to natural disasters[J]. IEEE Transactions on Smart Grid, 2016, 9(3): 2030-2041.
[5] Wang H, Lin Z, Wen F, et al. Optimal scheduling of urban mobile emergency power sources[J]. Automation of Electric Power Systems, 2014, 38(3): 123-129.
[6] Drinčić F, Mujović S. Energy storage systems: An overview of existing technologies and analysis of their applications within the power system of Montenegro[C]/2018 23rd International Scientific-Professional Conference on Information Technology (IT). 2018: 1-4.
[7] Faisal M, Hanman M A, Ker P J, et al. Review of energy storage system technologies in microgrid applications: Issues and challenges[J]. Ieee Access, 2018, 6: 35143-35164.
[8] Lei S, Chen C, Zhou H, et al. Routing and scheduling of mobile power sources for distribution system resilience enhancement[J]. IEEE Transactions on Smart Grid, 2018, 10(5): 5650-5662.
[9] Kim J, Dvorkin Y. Enhancing distribution system resilience with mobile energy storage and microgrids[J]. IEEE Transactions on Smart Grid, 2018, 10(5): 4996-5006.
[10] Yao S, Wang P, Liu X, et al. Rolling Optimization of Mobile Energy Storage Fleets for Resilient Service Restoration[J]. IEEE Transactions on Smart Grid, 2019.
[11] Song Y, Liu Y, Wang R, et al. Multi-Objective Configuration Optimization for Isolated Microgrid With Shiftable Loads and Mobile Energy Storage[J]. IEEE Access, 2019, 7: 95248-95263.
[12] Abdeltawab H H, Mohamed Y A R I. Mobile energy storage scheduling and operation in active distribution systems[J]. IEEE Transactions on Industrial Electronics, 2017, 64(9): 6828-6840.
[13] Boicea V A. Energy storage technologies: The past and the present[J]. Proceedings of the IEEE, 2014, 102(11): 1777-1794.
[14] Abdeltawab H, Mohamed Y A R I. Mobile Energy Storage Sizing and Allocation for Multi-Services in Power Distribution Systems[J]. IEEE Access, 2019, 7: 176613-176623.
[15] Yang H, Zhang J, Qiu J, et al. A practical pricing approach to smart grid demand response based on load classification[J]. IEEE Transactions on Smart Grid, 2016, 9(1): 179-190.