Open Capacity Enhancement Model of Medium Voltage Distribution Network With Mobile Energy Storage System

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ABSTRACT In order to meet the demand of prosumer for power quality and new load in distribution network, an open capacity expansion model of distribution network with mobile energy storage system (MESS) is proposed in this paper. The model gives priority to the problem of voltage violation of prosumer group on feeders. Combined with the mobile energy storage path model, the open capacity of distribution network is calculated. Firstly, the actual distribution network geographic information and traffic routes are combined to establish the distribution network model based on mesh generation. Secondly, the traffic route model of the mobile energy storage system is established on the distribution network model based on mesh generation. Then, the optimal power flow of distribution network is calculated with the optimal network loss, and the mobile energy storage system is scheduled according to the situation of voltage violation. And the specific vehicle model and its scheduling are determined, which can better deal with the problem of distributed energy consumption and make prosumer operate safely and economically. Finally, according to the proposed N-1 security check constraint of distribution network with mobile energy storage system, the maximum open capacity of distribution network is calculated after the voltage regulation is completed. The example shows the practicability and correctness of the model in this paper. This paper formulates a mobile energy storage operation strategy to improve the open capacity of distribution network. The strategy not only fully meets users’ needs, but also better guides the operation of power grid. It is conducive to releasing more potential power supply space of distribution network and improving asset utilization.

INDEX TERMS Mobile energy storage system, N-1 security check, open capacity, power supply potential, prosumer group, voltage violation.

I. INTRODUCTION
Flexible control and scheduling of controllable units in distribution network is an effective way to consume the growing distributed generators (DG). However, due to the volatility of DG itself and the voltage violation caused by the change of traditional distribution mode of distribution network, the requirements of users for power quality can’t be met [1], [2]. With the increasing cost of urban distribution network expansion, people are more concerned about the power supply potential of distribution network on the existing grid structure. The power supply potential is supposed to meet users’ growing demand for power without building new substations and feeders [3].

At present, the voltage control methods in distribution network include regulating distributed generator’s output, reactive power compensation by inverter, adjusting on-load voltage regulator’s taps [4], controlling by battery [5]–[7], etc. Nowadays, a lot of researches have been carried out on the optimal allocation of energy storage at home and abroad. The cascade utilization of energy storage in configuration is considered in reference [8], the benefits of energy storage reducing network loss and delaying power grid upgrade is also considered. The life cycle economy of different forms of energy storage battery is studied in reference [9]. In reference [10], a quantitative model of battery service life is added...
into the energy storage configuration model. The energy storage power station has a large investment, a wide area, and insufficient scheduling flexibility. Adding energy storage devices for voltage regulation will greatly reduce the economy of voltage regulation in distribution network. This paper proposes to combine energy storage and mobile emergency power vehicle to form a mobile energy storage system (MESS). Dispatching the two-way interaction with MESS and distribution network can take into account the demand of voltage regulation capacity and scheduling flexibility.

Nowadays, the theory of total power supply capability of distribution network [11], [12] has laid a certain research foundation for calculating the remaining power supply capability of distribution network. The total power supply capability model based on feeder interconnection relationship is provided in reference [13]. On this basis, a calculation method of available power supply capability of distribution network is proposed in reference [14]. The method is used to calculate the load that can be increased on the basis of the existing total load under the condition of ensuring N-1 security check. The calculation method of residual power supply capability is proposed in reference [15], [16]. In this method, the influence of existing load distribution on the power supply potential of distribution network is considered. The calculation results do not need to reduce the existing load, and can directly guide the operation of distribution network. However, the description of N-1 security check in the above articles is insufficiently comprehensive. Not all components can meet the N-1 security check. Also, no energy storage device is considered to improve the remaining power supply capability of the whole distribution network in the references.

In order to further solve the above problems, an operation strategy model of distribution network voltage regulation with MESS is put forward in this paper. The model optimizes the charging and discharging strategy and moving path of MESS, which can solve the problem of voltage violation in distribution network. On the basis of this model, the open capacity model of distribution network with MESS is proposed, the concept of open capacity is defined, and the N-1 security check constraint of distribution network is improved. Finally, the maximum open capacity of distribution network with MESS is calculated.

The main contributions of this paper can be summarized as follows:

1) An open capacity model that makes full use of MESS to improve the distribution network is proposed in this paper. In order to meet the needs of the prosumer for power quality and new load, the remaining capacity is calculated in the distribution network and the problem of voltage over-limit is solved through the access of MESS in the distribution network in this model.

2) In the model of calculating the remaining capacity of the distribution network, the concept of open capacity is proposed, and the current load of the distribution network, the new load in the future, the charge and discharge power of MESS and the N-1 security check of the distribution network are fully considered to calculate the potential of the distribution network, which improves the accuracy of the results.

3) In this paper, the distribution network is divided into grids, a grid of structure model is established, and the operation strategy of MESS is formulated according to the requirements of prosumer, which better guides the operation of the distribution network.

The rest of this paper is organized as follows. The internal structure of MESS and the establishment of MESS structural model are introduced in Section II. The internal structure of the actual distribution network is described and the mass transportation model through the distribution network GIS system are established in Section III. The operation strategy of MESS is formulated in Section IV. The calculation model of the open capacity of the distribution network is established in Section V. Case studies are conducted in Section VI. Lastly, conclusions are drawn in Section VII.

II. PREPARATION STRUCTURAL MODEL OF MOVABLE ENERGY STORAGE SYSTEM

With the increase of distribution network load, transformers in many old urban areas supply power to the surrounding industrial and civil loads, resulting in some problems such as high line load rate and large peak valley difference. At the same time, power quality problems such as voltage fluctuation, flicker and harmonics are caused by frequency converters and other equipment in the load. Besides, distribution network has to absorb the growing distributed generators (DG). The fluctuation of DG itself will lead to voltage violation, so distribution network needs high-quality resources to ensure the reliability of power supply and power quality.

MESS joining distribution network can reduce the load rate of the substation area and improve the quality of power supply. MESS can also respond to distribution network dispatching to adjust the voltage when the distribution network voltage exceeds the limit, so as to obtain subsidies, and the rest of the time is low storage and high level arbitrage. At the same time, the mobile energy storage can be connected to distribution network to improve the open capacity of distribution network and avoid overload.

![FIGURE 1. Internal structure of MESS.](image-url)
A. INTERNAL STRUCTURE OF MESS
MESS is mainly composed of two parts: power car and container energy storage system. The container energy storage system is generally composed of energy storage battery system, monitoring system, battery management system, and battery monitoring display system, special air conditioner for container battery, energy storage converter and isolation transformer. The composition and structure of MESS is shown in Fig. 1. Compared with the fixed battery energy storage system, MESS is more flexible and convenient, easier to produce, and easy to realize accident isolation. MESS has the characteristics of modularization, rapid assembly and low installation cost, so it can be flexible according to the actual situation. By changing the time and nodes of access to the distribution network, it has strong adaptability to the changing operation of distribution network, which is essentially different from the traditional energy storage system.

B. OPERATION MODEL OF MESS
The operation model of MESS [17]–[19] considered in this paper is the same as that of the fixed energy storage system, only different at the access node. The operation model of MESS is shown in (1) - (8).

\[
0 \leq P_{ch}^m(t) \leq \alpha_{m,t}^ch P_{chmax}^m
\]

\[
0 \leq P_{dis}^m(t) \leq \alpha_{m,t}^dis P_{dismax}^m
\]

\[
\sqrt{(P_{ch}^m(t))^2 + (Q_{ch}^m(t))^2} \leq S
\]

\[
\sqrt{(P_{dis}^m(t))^2 + (Q_{dis}^m(t))^2} \leq S
\]

\[
-S \leq \eta_{m}^{dis} Q_{dis}^m(t)
\]

\[
\alpha_{m,t}^{ch} + \alpha_{m,t}^{dis} \leq 1
\]

\[
S_{m,t+1} = S_{m,t} + (\alpha_{m,t}^{ch} P_{ch}^m(t) - P_{dis}^m(t)/\eta_{m}^{dis}) \Delta t
\]

\[
S_{min} \leq S_{m,t} \leq S_{max}
\]

\[
SOC^m(t) = SOC^m(t-1) + \frac{M_{max}^m \eta_{m}^{char}}{E} M_{char}^m(t) P_{char}^m(t-1)
\]

\[
- \frac{M_{max}^m \eta_{m}^{dis}}{E} M_{dis}^m(t) P_{dis}^m(t-1)
\]

where, \(m\) is the \(m\)-th MESS; \(P_{ch}^m(t)\), \(P_{dis}^m(t)\) respectively represents the charging and discharging active power of the \(m\)-th MESS at time \(t\); \(Q_{ch}^m(t)\), \(Q_{dis}^m(t)\) respectively represents the charging and discharging reactive power of the \(m\)-th MESS at time \(t\); \(\alpha_{m,t}^{ch}\), \(\alpha_{m,t}^{dis}\) respectively represents the charging and discharging states of the \(m\)-th MESS at time \(t\), where \(\alpha_{m,t}^{ch}\) indicates that if MESS is in the charging state, then \(\alpha_{m,t}^{dis} = 1\), otherwise, it is 0; \(\alpha_{m,t}^{dis}\) indicates that if MESS is in the charging state, then \(\alpha_{m,t}^{dis} = 1\), otherwise, it is 0; \(P_{chmax}^m\) and \(P_{dismax}^m\) is the maximum value of MESS High charging power and discharge power; \(S\) is the maximum apparent power of the energy storage converter of the \(m\)-th MESS; \(\eta_{m}^{ch}\) and \(\eta_{m}^{dis}\) respectively represents the charging efficiency and discharge efficiency of the \(m\)-th MESS; \(S_{min}\) and \(S_{max}\) are the minimum and maximum limits of the electric quantity of MESS. The parameter is the state of charge of the \(m\)-th MESS in time \(t\); the parameter and are charge and discharge efficiency; the parameter and are the charge and discharge power of the \(m\)-th MESS in time \(t-1\); the parameter is electric quantity.

III. PATH PLANNING OF MESS BASED ON FEEDER GRID MODEL OF DISTRIBUTION NETWORK
A. ACTUAL DISTRIBUTION NETWORK STRUCTURE
The typical connection modes of medium voltage distribution network target grid are divided into two categories: overhead line power supply mode and cable line power supply mode. Considering that MESS is generally used in urban central distribution network, and cable line power supply mode is mainly used in urban central distribution network. So this paper takes cable line connection mode as the network structure model of distribution network.

The cable power supply line is composed of medium voltage buses of two substations (or switching stations) in the same power supply area or single circuit lines fed from different medium voltage buses of one substation (switching station), which operates in an open loop. Users are connected to the main ring network through the “loop in and loop out” through the distribution room or ring network room (box). As shown in Fig. 2, feeders A and B come from different superior substations, S1~S4 are the distribution room or ring network room (box) on feeder A; S5~S8 are the distribution room or ring network room (box) on feeder B, and finally S1~S8 are equivalent to the load node on the line.

FIGURE 2. Typical wiring diagram of cable line.

Generally, according to the scale and management scope of urban medium voltage distribution network, the power supply scope of medium voltage distribution network is divided into several power supply zones according to the principles of clear target network structure, moderate scale of power grid and clear management responsibility. One power supply division contains several power supply grids, and one power
supply grid is composed of several power supply units. The hierarchical relationship between them is shown in Fig. 3.

![FIGURE 3. Schematic diagram of distribution network partition hierarchy.](image)

For the sake of understanding, the following is a simple distribution network as shown in Fig. 4 to illustrate the above definition. In the figure, there are two substations forming a power supply zone, with 4 main transformers (T₁ ∼ T₄) and 12 10kV feeders (F₁ ∼ F₁₂). Each main transformer serves as a power grid, and each 10kV Feeder line serves as a group of power supply units. There are three groups of power supply units under each power supply grid. For example, T₁ is the power supply grid 1, and there are three groups of power supply units (feeders F₁ ∼ F₃) under the power supply grid 1.

![FIGURE 4. The structure of simple distribution network.](image)

**B. PATH PLANNING OF MESS**

The visualization of geographic information and distribution network information is realized through the distribution network GIS. Combined with the actual survey results, the relevant roads that can be operated are selected and numbered. According to the actual geographical environment around the road, the distribution network structure model of grid division is established, as shown in Fig. 5. The distance between grid structures is determined in the form of grid, and the optimal path of movable energy storage system in voltage regulation is planned.

Firstly, the distribution network structure is divided into grid shape, and the actual distance between each node can be represented by the distance on the graph between the two nodes shown in the grid. MESS can only run on grid lines. Assuming that the side length of the small grid in Fig. 5 is 1 km, if MESS is transferred from node 2 to node 6, then the driving distance is 5 km. The time consumed during the movement of MESS is shown in (9).

\[ t_{ij,m} = \frac{\sum \Delta L}{v_m} \quad \text{(10)} \]

where, \( t_{ij,m} \) is the time required for the m-th MESS to travel between nodes i and j; i and j represent the starting nodes of the line respectively; \( \Delta L \) is the side length passing through the small grid between nodes i and j; \( v_m \) is the average speed of the m-th MESS.

**IV. OPERATION STRATEGY OF MESS PARTICIPATING IN PROSUMER GROUP VOLTAGE REGULATION**

The operation strategy of MESS is affected by the operation status of distribution network. Network loss is an important index to assess the operation status of power grid enterprises, so the distribution network operates with the minimum network loss in the dispatching period as the goal. The specific operation strategies are as follows: when the distribution network voltage is normal, MESS is low storage and high-level arbitrage, and improves the open capacity of distribution network; when the distribution network voltage exceeds the limit, MESS is connected to the node with the most serious voltage violation; the objective function of the operation strategy of MESS can be expressed as follows:

\[ \min F = \sum_{i \in N} \sum_{j \in N} G_{ij} \left( V_i^2 + V_j^2 - 2 V_i V_j \cos \theta_{ij} \right) \Delta t \quad \text{(11)} \]

where, N is the set of distribution network nodes; \( G_{ij} \) is the conductance between nodes i and j; \( V_i \) and \( V_j \) are the voltage amplitude of nodes i and j respectively; \( \theta_{ij} \) is the voltage phase angle difference of nodes i and j; \( \Delta t \) is the simulation time step.

Besides power flow related constraints, there should be other constraints:

1) **DG OUTPUT CONSTRAINT**

\[ \begin{cases} 0 \leq P_{DG}(t) \leq P_{\text{max}}^{DG}(t) \\ 0 \leq Q_{DG}(t) \leq Q_{\text{max}}^{DG}(t) \\ P^m(t) \leq \min(P_{\text{rate}}, P_{\text{allow}}(t)) \end{cases} \quad \text{(12)} \]

where, \( P_{DG}(t) \) and \( Q_{DG}(t) \) are respectively the active and reactive power of DG in time period t; \( P_{\text{max}}^{DG}(t) \) and \( Q_{\text{max}}^{DG}(t) \) are respectively the theoretical active and reactive power maximum values of DG in time period t. The parameter \( P_{\text{allow}}(t) \) is the maximum charge and discharge power when
MESS is connected to the distribution network in time $t$ without causing a new voltage violation.

2) STATE OF CHARGE CONSTRAINTS OF MESS
The state of charge constraint and charge/discharge constraint of MESS are shown in (6)-(8) in Chapter 1.

When the distribution network operates in the optimal target mode, due to the fluctuation of the distributed generation and the mismatch between its output and the load sequence of distribution network, some load nodes in distribution network may have voltage violation. When the voltage of load nodes in distribution network exceeds the limit, the distribution network operators dispatch MESS to adjust the voltage, and it is necessary to optimize the power required for voltage regulation. The objective function is to minimize the voltage violation of each load node after the mobile energy storage is connected to distribution network. The expression is as follows:

$$\min Q = |V_{\text{most}}(t_{\text{over}}) - V_N| \quad (14)$$

Among them, $t_{\text{over}}$ refers to the period when the voltage exceeds the limit in distribution network; $V_{\text{most}}$ is the maximum value of the out of limit voltage; $V_N$ is the allowable value of the voltage; among them, the minimum value is in case of under voltage and the maximum value is in case of over-voltage.

Taking the charging and discharging power of MESS as the optimization variable, and solve the optimization problem, the minimum charging and discharging power required to adjust the voltage of the whole network to be qualified can be obtained. In order to make the value of independent variable more accurate, the following requirements should be paid attention to.

If the optimal access points of two adjacent time step mobile energy storage are inconsistent, MESS needs to be converted between the two points, and cannot be conducted during the period. Therefore, frequent transfer of access points will affect the economy of MESS scheduling. Therefore, it is necessary to reduce the access nodes as much as possible. This paper stipulates that the operation strategy of the MESS will switch access nodes according to the following principles: ① if the switching time between the access nodes of MESS is less than the interval time between the two voltage regulation periods, the charging and discharging nodes will be converted, otherwise the charging and discharging nodes remain unchanged. ② when the state of charge of MESS is about to exceed the limit, it will be charged and discharged through the conversion node.

V. OPEN CAPACITY MODEL OF DISTRIBUTION NETWORK WITH MESS
A. THE CONCEPT OF OPEN CAPACITY
In this paper, a concept of open capacity of distribution network is proposed, which means that under the premise of no reduction of node load, in order to cope with the new load in the future distribution network, and make each element in distribution network still meet the N-1 security check [20]–[22]. The remaining power supply capability of distribution network under the current load level is calculated without reconfiguration, so as to facilitate the planning of new load in the period of line restructuring, that is, the available residual capacity of distribution network under the current load level. As shown in Fig. 6, there are two cases of node load increase: one is that the existing load continues to increase; the other is to add new load nodes. In the figure, $T_i$ is the main transformer; $F_i$ is the power supply line; the black node is the existing load node; the red node is the new load node; the red line is the new load.

In order to cope with the increasing load, the increasingly complex network structure and the user’s test of power supply reliability, and to ensure the sustainable and healthy operation and long-term development of distribution network, the power supply department needs to accurately evaluate the open capacity of distribution network, so as to provide an important basis for the subsequent business expansion. The open capacity evaluation of distribution network is the planning of load access point under the premise of network security. Its core is to consider the thermal stability limit optimization of N-1 equipment.

The traditional open capacity evaluation of distribution network is to increase the load based on the specified topology until the equipment quota is reached. The technical means adopted are mainly manual judgment and empirical formula. However, most of the current methods fail to fully consider the N-1 and the switching operation after N-1, which leads to the optimistic evaluation result of the open capacity, and finally endangers the system operation safety. In order to solve the above problems, this paper first establishes an open capacity model of distribution network considering sufficient N-1 security.

B. DISTRIBUTION NETWORK N-1 VERIFICATION
N-1 security check is an important technical criterion of distribution network. It means that when a component (such
as main transformer, feeder, etc.) in distribution network fails, there will be no unreasonable user power outage in the power grid. Distribution network N-1 verification mainly includes feeder N-1 and main transformer N-1.

1) FEEDER N-1 SECURITY CHECK

Feeder N-1 security check is to check whether the fault can be isolated and the load to be recovered can be transferred to other connected feeders in case of fault at any position of feeder. Feeder outlet fault is the most serious situation. Due to the large scale of distribution network, N-1 verification of the whole network is often only aimed at feeder outlet fault in planning.

The access of MESS has an important impact on the security and reliability of distribution network. For the distribution network, MESS can be used as an isolated island after the fault of the standby power supply, or it can be used as a non standby power supply. When N-1 verification is carried out for a certain feeder, the load of each feeder after transfer should be less than its own feeder capacity [23]. Take Fig. 7 as an example to illustrate.

![FIGURE 7. Illustration of N-1 test for feeder.](image)

There are three feeders in Fig. 7, in which feeder A is divided into two sections by section switch, and the two sections are connected with feeder B and feeder C respectively through tie switch. According to the wiring mode in the figure, when all the three feeders meet the feeder N-1 verification, the following constraints shall be met:

\[
\begin{align*}
P_{S1} + P_{S2} + P_{S3} & \leq R_{FA} \\
R_{FA} & \leq R_{FB} \\
P_{S2} + P_{S3} & \leq R_{FB} \\
P_{S1} + P_{S4} & \leq R_{FC}
\end{align*}
\]

(15)

where, \( P_{Si} \) is the load power of the i-th node and \( R_{Fi} \) is the capacity of the i-th feeder.

2) MAIN TRANSFORMER N-1 SAFETY CHECK

For a main transformer in the distribution network, it can be connected with the main transformer in the station through the bus tie switch in the station, or with the feeder outside the station (main transformer) through the feeder tie switch. When N-1 fault occurs in the main transformer of the substation, the load can be transferred through the connections inside or outside the station. When the load transfer is completed, the load of each feeder and main transformer shall not exceed its corresponding capacity. At the same time, when the main transformer N-1 fails, the load transfer shall comply with the following rules [24]–[28].

a. Priority should be given to the transfer of main transformer in the station. For the substation with more than two main transformers, priority should be given to the main transformer with large load margin. The transfer of tie switch outside the station shall be considered after the failure of transfer in station.

b. Feeder N-1 security check is adopted for out of station transfer rules.

c. For the load directly connected to the bus, the load is transferred only through the interconnection switch in the station.

Take the main transformer 1 in Fig. 4 as an example to illustrate the principle of main transformer N-1 verification. In order to make main transformer 1 meet the N-1 verification principle of main transformer, the following constraints shall be met:

\[
\begin{align*}
P_{F1} + P_{F7} & \leq R_{F7} \\
P_{F1} + P_{F3} & \leq R_{T3} \\
P_{F2} + P_{F11} & \leq R_{F11} \\
P_{F2} + P_{F4} & \leq R_{T4} \\
P_{F3} + P_{T2} & \leq R_{T2}
\end{align*}
\]

(16)

Among them, \( P_{Fi} \) is the load of feeder i; \( P_{Ti} \) is the load of main transformer i; \( R_{Ti} \) is the rated capacity of main transformer i.

C. OPEN CAPACITY MODEL OF THE DISTRIBUTION NETWORK WITH MESS

According to Section 5.2, the open capacity of feeder can be calculated after meeting the N-1 security check boundary of distribution network, and the expression is as follows:

\[
\begin{align*}
\Delta P_i' & \leq \min \left[ R_{Fmi} + P_{dis_{mi}}(t) - \left( P_{mi} + P_{ch_{mi}}(t) + \Delta P_{mi} \right) \right] \\
\Delta P_i' & \leq \sum_{j=1}^{Tmi} \left( P_{ji} + \Delta P_{ji} + P_{ch_{ji}}(t) \right) - P_{mi}'
\end{align*}
\]

(17)

The left side of the inequality is the N-1 security check constraint. \( Pt_{mi} \) is the outlet load of feeder mi which is connected with feeder section i at time t; \( R_{Fmi} \) is the rated capacity of feeder with feeder section i; \( P_{ch_{mi}}(t) \) and \( P_{dis_{mi}}(t) \) are the charging and discharging power of the m-th MESS on feeder section i at time t. When feeder i outlet fault or main transformer fault leads to feeder power loss and line N-1 fault occurs, it will be transferred to feeder mi, and feeder mi shall not have line overload, that is, the new load on feeder i must be less than or equal to (16).

\[
R_{Fmi} + P_{dis_{mi}}(t) - \left( P_{mi} + P_{ch_{mi}}(t) + \Delta P_{mi} \right) - P_{mi}'
\]

(18)

The right side of the inequality is the main variable N-1 security check constraint. \( R_{Ti} \) is the rated capacity of
main transformer of feeder connected with feeder section i; $P_{ji}$ is the load of other feeders or feeder sections connected with $P_{Ti}$ in the same main transformer at time $t$; 
$$
\sum_{j \in T_{ml}, S_j \notin S_i} (P_{ji}^t + \Delta P_{ji}^{ch}(t)) - \sum_{j \in T_{ml}} (P_{ki}^t + \Delta P_{ki}^{ch}(t)) - P_{ji}^{ch}
$$

The failure mode in this paper is considered the most serious export fault, but it is also a common fault mode in N-1 verification of distribution network, which is suitable for the security research of distribution network. If the probability of fault occurrence is considered according to the actual operation of the power grid, the results closer to the actual situation can be obtained.

It should be pointed out that the model simplified in this paper deals with network loss and voltage constraints, because the length of urban distribution lines is short, the voltage drop is small, and the voltage can be regulated through reactive power equipment and transformer tap. N-1 verification generally meets the voltage constraint, which has little effect on the results and can be ignored or approximately considered.

After the above analysis, the open capacity model of distribution network with MESS is expressed as follows:

$$
OCC' = \max \sum \Delta P_i^t
$$

The model calculates the maximum open capacity of a power supply zone by the sum of the maximum load added on each feeder, so as to guide how to plan the new load in the period of line reconfiguration. The model has two major constraints: MESS constraint, (1)-(8), the distribution network N-1 security check constraint, (17). Among them, (3)-(4) are non-linear constraints. After the method of inscribed polygon in circle is used to linearize the current-carrying capacity constraint, the model in this paper is a mixed integer linear programming problem, so it can be solved directly by Gurobi or CPLEX.

To sum up, the main work flow of this paper is as follows:

**VI. EXAMPLE ANALYSIS**

**A. BASIC INFORMATION OF THE EXAMPLE**

In this paper, a power supply partition in a city is selected as an example. The grid structure of the example grid is shown in Fig. 9. In the example, there are two substations, four main transformers, 22 feeders or feeder sections, which are recorded as $F_1 \sim F_{22}$, including 12 single tie feeders and 10 multi-sectioned and multi-linked feeders. JKLYJ-240 is selected as the feeder specification, assuming that the feeder length is the same and there is no heavy load area. The total transformer capacitance is 160MVA, and the capacity of all feeders is 11.2 MVA. Among them, feeder $F_4$ and $F_9$ are connected with distributed PV with capacity of 1.63MW and 1.35MW respectively. The initial SOC of MESS is set as 0.5, and the upper and lower limits of the SOC are taken as 0.9 and 0.2. Under the initial condition, the access number of MESS is set as 3, and the rated capacity of each MESS is 2MW. The rated power is 2MW. Record the three MESS as E1, E2 and E3 respectively.

**B. ANALYSIS OF VOLTAGE REGULATION RESULTS CONSIDERING PROSUMER GROUP**

The upper level model takes the minimum loss as the goal. Firstly, the optimal power flow is calculated for distribution
network without MESS, and the daily minimum network loss and the corresponding operation parameters of distribution network are obtained. The results show that the daily minimum loss of distribution network is 1.0143MW, and the feeder and time of voltage violation are shown in Table 1. Due to the mismatch between photovoltaic output and load peak in feeder F4 and F9, there is a certain degree of undervoltage in both feeders from 17:00 to 18:00, among which the under voltage at F4 terminal is the most serious, which can guide the load area corresponding to the F4 end of feeder to make corresponding adjustment to meet the voltage safety standard; while feeder F1 and F19 have a certain range due to uneven load distribution. In this way, the unbalanced load of some stations under the feeders F1 and F19 can be analyzed, which makes a basic research for the transfer and reorganization of low-voltage loads. According to the operation strategy model in this paper, the corresponding power required for MESS voltage regulation is obtained, as shown in Table 1.

| Time slot       | feeder | Voltage (pu) | MESS | Discharge power/MW |
|-----------------|--------|--------------|------|--------------------|
| 09:00–10:00     | F19    | 0.9226       | E3   | 0.847              |
| 13:00–14:00     | F1     | 0.9167       | E2   | 0.949              |
| 17:00–18:00     | F4     | 0.9027       | E1   | 1.347              |
| 17:00–18:00     | F9     | 0.9138       | E3   | 1.027              |
| 20:00–21:00     | F4     | 0.9203       | E1, E2 | 0.873             |

It can be seen from Table 2 that the photovoltaic output of feeder F4 drops sharply while the load is at the peak, which leads to the voltage exceeding the limit again when the peak value of load increases from 20:00 to 21:00. The voltage exceeds the limit on the same feeder, and only one MESS can adjust the voltage to normal. Due to the insufficient capacity of E1, E2 moves to feeder F4 for discharge, which ensures the voltage quality of users and meets the charging demand of electric vehicles at night and increase the number of electric vehicles that can be accommodated in residential areas.

C. OPEN CAPACITY ANALYSIS

On the basis of the upper model, the lower model calculates the maximum open capacity of distribution network containing MESS after satisfying the security check of (17) N-1, and obtains the access feeder positions of three MESS in distribution network, as shown in Table 2, and Fig. 10 shows the power consumption diagram of each MESS. Fig. 11 shows the open capacity of distribution network at 24 hours.

It can be seen from Fig. 10 that each MESS has different charging and discharging strategies in one day, but several charge and discharge cycles have been completed, and E1, E2 and E3 are in the same charge and discharge state or floating charge in each period. There is no one charge and one discharge situation. In the morning and noon load trough, MESS starts to charge, and in the morning and evening load peak, MESS is opened to power. Table 2 shows the charging and discharging time and path of MESS, and the overall charging and discharging time is corresponding to Fig. 10, which verifies the accuracy of the model in this paper. At the same time, it shows that the model can give full play to the peak shaving and valley filling function of MESS and improve the open capacity of the system.

TABLE 1. Voltage and corresponding required discharge power.

| Time slot       | feeder | Voltage (pu) | MESS | Discharge power/MW |
|-----------------|--------|--------------|------|--------------------|
| 09:00–10:00     | F19    | 0.9226       | E3   | 0.847              |
| 13:00–14:00     | F1     | 0.9167       | E2   | 0.949              |
| 17:00–18:00     | F4     | 0.9027       | E1   | 1.347              |
| 17:00–18:00     | F9     | 0.9138       | E3   | 1.027              |
| 20:00–21:00     | F4     | 0.9203       | E1, E2 | 0.873             |

TABLE 2. Access time of MESS.

| Time    | Feeder | Time    | Feeder | Time    | Feeder |
|---------|--------|---------|--------|---------|--------|
| 00:00–06:00 | E1     | 06:00–12:00 | E2     | 12:00–18:00 | E3     |
| 09:00–15:00 | E1     | 15:00–21:00 | E2     | 21:00–00:00 | E3     |
D. COMPARATIVE ANALYSIS OF RESULTS

In order to verify whether MESS can improve the open capacity of distribution network, this paper compares the open capacity of distribution network with that without MESS. As shown in Fig. 11, the red line in the figure is the open capacity of distribution network without MESS at 24 hours; the blue line is the open capacity of distribution network with MESS at 24 hours.

![Figure 12. Result of OCC of F_d.](image)

It can be seen from Fig. 11 that the open capacity of distribution network with MESS is lower than that of distribution network without MESS from 00:00 to 06:00, because MESS is charged during this period, and the load at this time is at a low ebb. Whether to increase the open capacity is of little significance to the whole distribution network. From 16:00 to 20:00, the open capacity of distribution network with MESS is higher than that of distribution network without MESS. The new load in the future is likely to be in this period. For distribution network with MESS, it is not necessary to build new lines to supply power to the new load, so as to reduce the investment cost. Fig. 12 shows the open capacity of a heavy haul line F_d in distribution network, which can better illustrate the conclusion.

VII. CONCLUSION

In this paper, an open capacity expansion model of distribution network with MESS is proposed. The model gives priority to the problem of voltage violation of prosumer group on feeders. Combined with the mobile energy storage path model, the open capacity of distribution network is calculated, which lays a foundation for tapping the remaining capacity of medium voltage feeders and studying the reconfiguration and transfer of low-voltage loads. The upper model plans the charging and discharging strategy of MESS with the minimum voltage violation as the goal, and plans the moving path of MESS. On the basis of the upper model, the lower level model further formulates the operation strategy of MESS with the goal of maximizing the open capacity of distribution network. The following conclusions are obtained:

1) Through the operation strategy model proposed in this paper, the voltage violation problem of distribution network can be solved, and the power quality requirements of users can be met. At the same time, in the distribution network, MESS can participate in multiple services and achieve win-win situation of multiple stakeholders.

2) The charging and discharging strategies of the configured MESS are different, but there will be no one charging and discharging. The reasonable scheduling will be carried out during the voltage violation period to complete the voltage regulation together.

3) The open capacity model proposed in this paper can be applied to the complex distribution network structure with multiple connections. The open capacity of distribution network with MESS can be further improved, and the heavy load lines can meet the demand of users’ load growth without new feeders.

4) This paper conducts modeling for the actual distribution network, which is of great significance for the short-term planning of the transformation of the existing power network and small load growth, and makes full use of the existing power network to alleviate the problems caused by the new load access in the distribution network.

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