Research on the Access Capacity of Power System to Electric Vehicles Under Battery Swapping Modes

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Abstract—In view of the access capacity of the power system to electric vehicles, not only whether the power generation side can meet the load demand of electric vehicles shall be considered, but also the changes in voltage quality, capacity of lines and transformers, short-circuit current after electric vehicles accessed shall be comprehensively taken into account. Considering the electric vehicles supplement energy by swapping batteries, in a multi-objective optimization method, through the service capacity analysis of charging stations and combined with economic indicators, an improved particle swarm optimization algorithm with mutation operator was applied, and a calculation method for maximum number of electric vehicles in power system was proposed. Finally, simulation for the power system of a certain district was performed, the maximum electric vehicle capacity that can be accessed to the power system was calculated, and the corresponding site selection of centralized charging stations and charging & battery swapping stations were given.

1. Introduction

With the vigorous development of electric vehicles, China's electric vehicle industry has entered a period of rapid development. In order to meet the charging demand of electric vehicles, various provinces are actively promoting the construction of charging stations [1]. In May 2014, the State Grid issued the Working Guidance for the Electricity Supply and Installation Service for Electric Vehicle Charging and Battery Swapping Facilities. This guidance clearly supports the participation of social capital in the market of various electric vehicle charging and battery swapping facilities, and the large-scale access of electric vehicles to the power grid will be gradually realized. The large-scale access of electric vehicles will have an inestimable impact on the power system, such as the change of power system static characteristics and transient indicators, more difficulties in power grid operation optimization control and the influences on power grid planning [2]. With the large-scale access of electric vehicles, it is particularly important to study the power system access capacity to electric vehicles. The calculation of the maximum number of electric vehicles that can be accessed also has important guiding significance for the development planning of electric vehicles.

Foreign scholars have done a lot of relevant research on the existing power system's access capacity to electric vehicles. Reference [3] studied the impact of electric vehicles access on the new generation capacity of different types of units in German power system under different scenario sets. Reference [4] reported that at present, the United States had sufficient installed capacity to support 84% of automobile electrification. Reference [5] studied the impact of electric vehicle access on power generation portfolio
in Illinois, USA. The simulation results showed that the reserve capacity demand was not large. Reference [6] showed that if orderly charging was adopted, the large-scale access of electric vehicles might have little impact on the generation side of the U.S. power grid. Reference [7] studied the influence of electric vehicles on different types of new installed capacity in power grid under different charging modes. The simulation indicated that the new installed capacity was directly related to the charging mode of electric vehicles. In V2G mode, the new installed capacity was the smallest. In Reference [8], regardless of specific charging facilities, under the situation of fully meeting the natural growth demand of electric vehicles, the impact of electric vehicle charging on Vermont power load was investigated in three scenarios: optimal charging mode, night charging mode and the mode of twice charging in one day. The research showed that Vermont power grid could support 100,000 electric vehicles for charging at night, but charging at peak load would cause a great problem in power supply. Reference [9] studied, in 2020 and 2030, the potential impact of PHEV on power demand, supply, power structure, electricity price and corresponding emissions in 13 regions selected by the North American Electric Reliability Council and the Energy Information Management Organization of the United States Department of Energy.

All these above articles only analyzed the capacity of the power system for electric vehicle access from the perspective of whether the power generation side can meet the load growth caused by electric vehicles. This paper comprehensively analyzed the impact of electric vehicle access on the power system from the perspectives of power flow, voltage quality, transformer capacity, line transmission power and short-circuit current, calculated the maximum electric vehicle capacity that can be accessed to the power system using the multi-objective optimization method, and proposed the site selection scheme of centralized charging station and charging & battery swapping station in combination with the economic index. It has great guiding significance for the large-scale access of electric vehicles in the future.

2. Mathematical Model

2.1. Problem Description

The research object of this paper was a multi voltage level power system including generator nodes, alternative nodes of electric vehicle centralized charging station & charging and battery swapping station, traditional load nodes and substation nodes [10]. This paper considered the electric vehicle in the power system would take battery swapping as the electric energy supplement method. There are two ways to swap batteries of electric vehicles: one is to swap the batteries through the battery distribution station, and the other is to swap the batteries through the charging and battery swapping station. The difference between these two ways is that the batteries replaced in the distribution station will be transported to the large centralized charging station for centralized charging, and then returned to the distribution station for service after charging. Therefore, the distribution station does not have the charging function, while the charging station has. The batteries swapped in the charging station will be directly charged and put into service in the same station [11].

In this paper, the multi-objective optimization method is adopted, and the improved particle swarm optimization algorithm with mutation operator [12] is applied to convert the calculation of the maximum number of electric vehicles into the calculation of the number of electric vehicle centralized charging station and charging & battery swapping station. Whether a construction scheme is adopted depended on the maximum number of electric vehicles can be accessed in the station construction scheme and whether various indexes of the power system meet the constraints. At the same time, due to the different investment or operation costs of charging stations with the same service capacity, combined with economic indicators, this paper finally obtained an economic station construction scheme.

2.2. Objective Function

(1) Taking the Maximum Number of Electric Vehicles as the Objective Function

\[
F_i = \max \left( F_j \times \sum_{k=1}^{n_j} x_{kj} + F_c \times \sum_{k=1}^{n_c} x_{kc} \right)
\]
where, $F_j$ and $F_c$ refer to the service capacity of the centralized charging stations and charging & battery swapping stations respectively. $n_i$ and $n_c$ are the total number of alternative station sites of the centralized charging stations and charging & battery swapping stations. $x_{kj}$ and $x_{kc}$ are the 0-1 decision variable for whether the $k$-th centralized charging station and charging & battery swapping station are put into operation.

(2) Taking the Minimum Investment and Operating Costs as the Objective Function

Considering both the maximum number of electric vehicles and the minimum sum of operation and investment costs:

$$F_2 = \min (C_{oper} + C_{inv})$$

The calculation formula of operation cost and investment cost is as follows:

$$C_{oper} = P_{loss} \times EC \times \tau \times \gamma + \sum_{k=1}^{N_k} C_{k,o} \times S_k \times x_k$$

$$C_{inv} = \sum_{k=1}^{N_k} (C_{k,f} + C_{k,v} \times S_k + l_k \times \alpha_k) x_k$$

The first item in the operating cost is the economic value converted from the active power loss under a certain station construction scheme, and $EC$ is the electricity charge, $\tau$ is the annual maximum load hours, $\gamma$ is the load coincidence factor. In the second item, $C_{k,o}$ is the average operating cost related to the unit capacity of the charging station in one year; $x_k$ is the decision variable for whether to build the $k$-th charging station; $S_k$ is the capacity of the alternative station site of the $k$-th charging station; and the active power loss $P_{loss}$ is obtained by the following formula:

$$P_{loss} = \sum_{k=1}^{N_B} G_{ij} \left( V_i^2 + V_j^2 - 2V_i V_j \cos (\theta_i - \theta_j) \right)$$

where $N_B$ is the number of system branches, $G_{ij}$ is the conductance of the $k$-th branch, $V_i, \theta_i$, and $V_j, \theta_j$ are the voltage amplitude and phase angle of node I and J, respectively.

Investment cost $C_{inv}$ is the sum of the construction costs of all centralized charging stations and charging & battery swapping stations under a certain station construction scheme. Where $C_{k,f}$ is the fixed construction cost of the $k$-th charging station, $x_k$ is the decision variable of whether to build the $k$-th charging station, $C_{k,v}$ is the average variable investment cost related to unit capacity in one year, $l_k$ is the line length for the $k$-th charging station connected to the power system, and $\alpha_k$ is the construction cost per unit length of the $k$-th line.

Since there are two objective functions, the objective functions need to be processed first to transform the multi-objective optimization problem into a single objective optimization problem. In this paper, the linear weighted sum method was used to transform the objective function [13]. Meanwhile, due to the different dimensions of the two objectives, each objective function needs to be normalized, that is:

$$F = \min (-\lambda_1 F_1/F_{1\text{max}} + \lambda_2 F_2/F_{2\text{max}} + M \times (V_{\text{limit}} + T_{\text{Climit}} + L_{\text{Climit}} + I_{\text{Dlimit}}))$$

where $\lambda_1$ and $\lambda_2$ are the weight coefficient corresponding to the objective function $F_1$ and $F_2$. And $\lambda_1 + \lambda_2 = 1$. Also, in order to transform the maximization of objective function $F_1$ into a minimization problem, the first term is taken as a negative value. $M$ is the penalty value included in the objective function when the constraint is violated.

2.3. Constraint Condition

(1) Power Balance Constraint

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n_i} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) = 0$$

$$Q_{Gi} - Q_{Di} + \sum_{j=1}^{n_i} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) = 0$$

where, $P_{Gi}$ and $Q_{Gi}$ are the injected active and reactive power at node I, respectively; $P_{Di}$ and $Q_{Di}$ are the active and reactive power of the load at node I, respectively; $V_i, V_j$ are the node voltages of node I and node J, respectively; $\theta_{ij}$ is the phase angle difference between node I and node J; $G_{ij}$ is the conductivity value of branch IJ. Formula (7) and (8) define the power flow constraint of the system.

(2) Node Voltage Limit

$$V_{\text{min}} \leq V_i \leq V_{\text{max}}$$

3
Each node voltage must meet the upper and lower limit constraints of voltage amplitude. The $V_{limit}$ is introduced to the objective function to characterize the node voltage out of limit:

$$V_{limit} = \sum_{i=1}^{N} \max \{ V_i - V_{imax}, V_{imin} - V_i, 0 \}$$

(10)

(3) Transformer Capacity Limit

$$S_{Ti} \leq 0.8 S_{Timax}$$

(11)

The apparent power of transformers in substations at all levels of the power system shall not exceed the upper limit of their capacity. The $TC_{limit}$ is introduced to the objective function to characterize the transformer capacity out of limit:

$$TC_{limit} = \sum_{i=1}^{N_T} \max \{ S_{Ti} - 0.8 \times S_{Timax}, 0 \}$$

(12)

(4) Line Transmission Power Limit

$$P_{Li} \leq P_{Limax}$$

(13)

The transmission power of each line in the power system shall not exceed the upper limit of the transmission power of the line. The $LC_{limit}$ is introduced to the objective function to characterize the line transmission power out of limit:

$$LC_{limit} = \sum_{i=1}^{N_L} \max \{ P_{Li} - P_{Limax}, 0 \}$$

(14)

3. Service Capacity of Charging Station

3.1. Average Daily Battery Swapping Times of Electric Vehicles

The maximum mileage of fully charged electric vehicle is $S_{max}$, the average travel distance of each electric vehicle is $S$, then the average daily battery swapping times of an electric vehicle is:

$$t = \frac{S}{S_{max}}$$

(15)

3.2. Service Capacity of Centralized Charging Station

As the distribution unit, the standard battery box is uniformly distributed from the centralized charging station to the distribution station. The standard battery box contains $a$ sets of batteries.

The maximum battery size of a centralized charging station is $G$ sets, which can provide the distribution for $h=G/a$ standard battery boxes. The centralized charging station needs to centrally charge the battery and carry out round-trip distribution to the distribution station it serves. It is considered that the cycle times of charging + distribution in one day of a centralized charging station is $n_p$, then it can provide distribution for $n_p \times h$ standard battery boxes at most in one day.

Similarly, the number of standard battery boxes in the distribution station is $m_p$, one electric vehicle is considered as $b$ sets of batteries. Then the service capacity of the distribution station is as follows:

$$F_p = n_p \times m_p \times a \times \frac{1}{b} \times \frac{1}{t}$$

(16)

Because the number of distribution stations that a centralized charging station can serve is:

$$F_{jp} = \frac{h}{m_p}$$

(17)

The service capacity of a centralized charging station is:

$$F_j = F_{jp} \times F_p = G \times n_p \times \frac{1}{b} \times \frac{1}{t}$$

(18)

3.3. Service Capacity of Charging and Battery Swapping Station

The charging and battery swapping station also takes the charging and battery swapping of standard battery modules as the core, and the number of charging cycles per day of the charging and battery swapping station is $n_c$ times, including $m_c$ standard battery boxes. One standard battery box contains $a$ sets of batteries, and one electric vehicle is considered as $b$ sets of batteries. The service capacity of the charging and battery swapping station is as follows:

$$F_c = n_c \times m_c \times a \times \frac{1}{b} \times \frac{1}{t}$$

(19)
4. Calculation of Maximum Number of Electric Vehicles

4.1. Particle Swarm Optimization Algorithm with Mutation Operator

According to the standard deviation of population fitness of particle swarm $\sigma$ and the theoretical or empirical optimal value $f_{best}$, the basis of convergence judgment was given and mutation operation was carried out. The calculation of $\sigma$ is as follows:

$$\sigma = \frac{1}{n^2} \sum_{i=1}^{n} (f_i - f_{ave})^2$$ (20)

where $n$ is the population size of particle swarm, $f_i$ is the fitness of the $i$-th particle, $f_{ave}$ is the current average fitness of particle swarm, and the calculation formula is as follows:

$$f_{ave} = \frac{1}{n} \sum_{i=1}^{n} f_i$$ (21)

Due to the "aggregation" phenomenon of particles in particle swarm optimization algorithm regardless of global convergence or premature convergence, the smaller the standard deviation calculated by formula (20) is, the more the particle tends to converge. When its value is 0, the algorithm reaches global or local convergence. Then, according to the comparison between the global optimal value $g_{fit}$ obtained at this time and the theoretical or empirical optimal value $f_{best}$, we could judge whether $g_{fit}$ is a global extreme value or a local extreme value.

When it is judged that the algorithm tends to converge locally, the global optimal vector $g_{best}$ at this time will mutate according to a certain probability $p_m$ and the calculation formula of $p_m$ is as follows:

$$p_m = \begin{cases} 0.4, & S < 0.2 \text{ and } g_{fit} > f_{best} \\ 0, & \text{others} \end{cases}$$ (22)

The specific meaning of formula (22) is: for the global optimal vector $g_{best}$, the first $\text{Int}(p_m \times \text{DIM})$ bit shall flip by the 0-1 decision variable, where $\text{DIM}$ is the dimension of the particle.

4.2. Calculation Process of Maximum Number of Electric Vehicles

To sum up, the flow of the calculation is described as follows:

Step 1: initialize the particle swarm, determine the population size $n$, the maximum number of iterations $Iter$, and the weight coefficients of the objective functions $\lambda_1$ and $\lambda_2$, randomly generate the position and velocity of each particle;

Step 2: calculate the fitness of each particle, and save the individual optimal fitness value, optimal vector, global optimal value and global optimal vector;

Step 3: calculate the standard deviation of population fitness according to formula (20) and (21), calculate the mutate probability $p_m$ according to formula (22) and conduct mutation operation;

Step 4: update the speed and position of particles;

Step 5: calculate the fitness of each particle, and update the individual optimal fitness value, optimal vector, global optimal value and global optimal vector;

Step 6: check the termination conditions and judge whether the algorithm reaches the maximum number of iterations $Iter$. If so, conduct Step 7; otherwise, jump back to Step 3;

Step 7: output the global optimal value and position vector, and the calculation ends.

5. Example Analysis

5.1. Overview of Power System

A certain regional power system with 9 generators, 6 220kV substations, 56 110kV substations, 13 35kV substations, and 1433.166MW original total load was analyzed hereby.

The electric vehicle central charging station is connected through the 35kV bus, with a maximum load of 17.6 MW. The electric vehicle charging and battery swapping station is connected through the 10kV bus, with a maximum load of 1MW. There are 50 35kV buses that can be connected to the central charging station and 72 10kV buses that can be connected to the charging & battery swapping station.
5.2. Power System Operation Constraints
Referring to the classic design of 2011 General Design of Transmission and Transformation Project of State Grid Corporation of China, the relevant power system operation constraints are set as follows:

1. **Node Voltage Limit**
   0.95p.u.—1.15p.u.

2. **Capacity Limit of Main Transformer in Substation**
   The maximum capacity of two main transformers in 220kV substation is 180MW. The maximum capacity of two main transformers in 110kV substation is 50MW. The maximum capacity of main transformer in 35kV substation is 50MW.

3. **Line Transmission Power Limit**
   The upper limit of total transmission power is 100MW for double-circuit outgoing lines of 110kV bus. 60MW for four-circuit outgoing lines of 35kV bus. 48MW for eight-circuit outgoing lines of 10kV bus.

5.3. Calculation of Service Capacity of Centralized Charging Station and Charging & Battery Swapping Station

1. **Average Battery Swapping Times of Electric Vehicles**
   The maximum fully charged mileage $S_{\text{max}}$ of the electric vehicle is taken as 200, and the daily average journey $S$ is taken as 60 according to the operating experience parameters, then the average battery swapping times required for an electric vehicle per day can be determined as $t=0.3$ according to formula (17).

2. **Service Capacity of Centralized Charging Station**
   The largest battery scale $G$ of a centralized charging station is set as 6000. At present, the centralized charging generally takes 3 hours, and the round-trip distribution time of 1 hour is considered additionally. Therefore, the charging + distribution cycle of all distributable batteries in a centralized charging station can be considered as 4 hours. Meanwhile, the charging needs to avoid the peak power consumption duration. Take $n_p$ as 5, the number of battery packs of an electric vehicle as $b=4$; and $a=20$. According to formula (20), the service capacity $F_j$ of the centralized charging station is 25000.

3. **Service Capacity of Charging & Battery Swapping Station**
   The average charging time of the charging & battery swapping station is 3 hours. Considering that charge twice at night and 4 times in daytime within one day, that is, $n_c = 6$. The scale of a charging & battery swapping station is 10 standard battery boxes, and $a=20$. According to formula (21), the service capacity $F_c$ of the charging & battery swapping station is 1000.

5.4. Economic Index Parameters
Relevant economic indicators can refer to [15] [16] and engineering experience would be considered as well. The investment costs of centralized charging station and charging & battery swapping station are set in different types according to different land prices and location conditions.

(1) **Investment Cost Parameters**

|                          | $C_{k_f}$ (CNY) | $C_{k_f}$ (CNY/MW) | $a_k$ (CNY/KM) |
|--------------------------|-----------------|--------------------|----------------|
| Centralized Charging Station 1 | 2,000,000       | 60,000             | 550,000        |
| Centralized Charging Station 2 | 2,500,000       | 80,000             | 550,000        |
| Charging & Battery Swapping Station 1 | 500,000         | 60,000             | 160,000        |
| Charging & Battery Swapping Station 2 | 600,000         | 80,000             | 160,000        |
| Charging & Battery Swapping Station 3 | 700,000         | 100,000            | 160,000        |
(2) Operating Cost Parameters
The annual maximum load time is 6570 hours, and the load coincidence factor $\gamma = 0.83$, the electricity charge $EC = 0.5$ yuan / kWh, and the variable operating cost $C_{k.o} = 60000$ yuan/MW.

5.5. Result Analysis
Since the primary goal of the algorithm is to obtain the maximum number of electric vehicles that the power system can access, the weight coefficients of the objective functions $\lambda_1 = 0.9$ and $\lambda_2 = 1$. After simulation analysis, the number of various types of centralized charging stations and charging & battery swapping stations is shown in Table 2. The maximum number of electric vehicles that can be accessed in this area is 420,000.

| Centralized Charging Station | Quantity | Charging & Battery Swapping Station | Quantity |
|-----------------------------|----------|-------------------------------------|----------|
| Centralized Charging Station 1 | 7        | Charging & Battery Swapping Station 1 | 22       |
| Centralized Charging Station 2 | 8        | Charging & Battery Swapping Station 2 | 15       |
|                              |          | Charging & Battery Swapping Station 3 | 8        |

Through in-depth analysis of the simulation results, it is found that the reason why more centralized charging stations cannot be built is that the transmission power of 110kV line is close to the upper limit and unavailable for more centralized charging stations. Meanwhile, since the voltage amplitudes of four 35kV buses have reached the lower limit, they are unavailable for more charging & battery swapping stations as well.

Due to the large load of the centralized charging station, its access has a great impact on the power system, so the simulation results do not reflect its economic expectation, even though the centralized charging stations have lower investment costs. The load of a single charging & battery swapping station is small, and its access has little impact on various indicators of the power system, so the number of different levels of charging & battery swapping stations shows better economic expectation. Thus, the effectiveness of this method is verified.

6. Conclusion
From the perspective of power system, this paper establishes a method for calculating the maximum number of electric vehicles that can be accessed in the power system. This paper converts the calculation of the maximum number of electric vehicles into the calculation of the number of electric vehicle centralized charging stations and charging & battery swapping stations. It comprehensively considers the power flow, voltage quality, transformer capacity, line transmission power, short-circuit current and so on. Not only the maximum number of electric vehicles, but also the economic indexes are taken into consideration. Adopt the multi-objective optimization method, and apply the improved particle swarm optimization algorithm with mutation operator to obtain the station construction scheme under the maximum electric vehicle access capacity, which has a great guiding significance for the large-scale access of electric vehicles in the future.

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