INTRODUCTION

Recently, the issue of human induced global warming, volatility in petroleum prices and security concerns associated with imported oil has received more attention. It contributes to increasing interest in electric vehicles (EVs) which are much cleaner than traditional gasoline vehicle in order to decrease greenhouse gas emissions from passenger cars and reduce reliance on fossil fuels [1]. Countries around the world greatly support the electric vehicle industry by high investment on the research and development of new power battery, accelerating construction of kit facilities, introducing subsidy policy and so on.

Charging system is the infrastructure to achieve energy supply for electric vehicles, also an important prerequisite of industrialization and commercialization of EVs. In order to shorten the time of energy supply, fast charging technology is widely adopted. By an off-board fast charger, fast charging (Level 3 charging) is able to complete recharge of a battery in less than 1 hour [2].

Previous researches have analyzed impacts of fast charging station on distribution network [3-6], which usually focus on the increasing peak demand, voltage deviations, harmonic distortion and distribution transformer losses. With the changing rate of charging power (dP/dt) coming up to 40 MW/s, the frequency of distribution network will fall to 49.8 Hz, which is not allowed in the circumstance of normal power supply. Hence, reducing the influence of dP/dt of large scale charging stations to the systematic frequency (50Hz) makes sense in industrialization and commercialization of EVs.

APPLICATION OF SUPER CAPACITOR ENERGY STORAGE IN FAST CHARGING STATION OF ELECTRIC VEHICLES

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ABSTRACT:  As the replacement of traditional gasoline vehicle, electric vehicles play an important role in the reduction of fossil energy consumption and greenhouse gas emission. With the wide spread of electric vehicles, more fast charging stations will be built. The impact of fast charging stations on distribution network should be considered. The main purpose of this paper is to investigate the application of super capacitor energy storage (SCES) in fast charging station (FCS). Firstly, the impacts of FCS on power grids are analyzed. Then a controller is designed to generate real-time power demand to SCES. Finally, the simulation model of FCS and SCES is established to analyze the effect of SCES on reducing influences of FCS. The simulation results show that power change rate of FCS can be limited by compensation of SCES based on the quick response of this energy storage system.

Keywords:  electric vehicle; super capacitor energy storage; fast charging station

1 INTRODUCTION

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To eliminate the impact of fast charging without intervention in fast chargers, compensating fast charging load by the energy storage system (ESS) such as flywheel ESS is presented in previous research [7, 8]. However application of this ESS cannot suit the response time requirements. Therefore this paper proposes a new application of super capacitor energy storage (SCES) in the fast charging station (SFC).

2 THE IMPACT OF FAST-CHARGING LOADS ON POWER GRIDS

2.1 The Impact on Voltage Static Stability

Voltage stability is one of the main aspects of power system stability. Though static voltage stability analysis simplifies the dynamic process, it is widely used to evaluate the impacts of loads on voltage static stability.

Build static load models of fast charging station based on the analysis of charger model before:

\[ P_{eq} = \frac{C_{u}}{2N} E_0 + \left( \frac{C_{u}}{2N} \right)^2 (R_{31} + R_{32}) \] (1)

In order to simplify the complex structure of power grids connected by fast charging loads, the model of two machines with three buses is taken as the example [9].

Figure 1. The model of two machines with three buses.

Where G1 represents the infinity power; G2 represents local generator sets; fast charging loads are connected to bus 3.

The reference capacity is 100 MVA. So the flow equations under steady state can be expressed below:

\[
\begin{align*}
P_u &= V_2^2 G_{11} + V_2 (G_{21} \cos \theta_2 + B_{21} \sin \theta_2) + \\
& \quad \quad \quad \quad \quad V_2 V_3 (G_{23} \cos \theta_{31} + B_{23} \sin \theta_{31}) \\
Q_u &= -V_2^2 B_{11} + V_2 (G_{21} \sin \theta_2 - B_{21} \cos \theta_2) + \\
& \quad \quad \quad \quad \quad V_2 V_3 (G_{23} \sin \theta_{31} - B_{23} \cos \theta_{31}) \\
P_2 &= V_3^2 G_{33} + V_3 (G_{31} \cos \theta_3 + B_{31} \sin \theta_3) + \\
& \quad \quad \quad \quad \quad V_3 V_4 (G_{32} \cos \theta_{32} + B_{32} \sin \theta_{32}) \\
Q_2 &= -V_3^2 B_{31} + V_3 (G_{31} \sin \theta_3 - B_{31} \cos \theta_3) + \\
& \quad \quad \quad \quad \quad V_3 V_4 (G_{32} \sin \theta_{32} - B_{32} \cos \theta_{32})
\end{align*}
\] (2)

The PV curve method being chosen as the static voltage analysis approach is introduced in [10]. Assume that G2 keeps the constant output power of 3+j0.7, the PV curve of bus 3 can be drawn in Figure 2.

It can be concluded that the inflection point of PV curve, where \( P_{LM} = 9.2 \), is the growth limit of fast charging loads. However, the corresponding bus voltage is 0.7 which is far beyond the range of normal voltage. Voltage static stability margin is usually used to evaluate the voltage static stability:

\[ K_P = \frac{P_{LM} - P_L}{P_{LM}} \times 100\% \] (3)

In fact, power loads can be divided into several kinds according to their voltage characteristics. The conventional multinomial model is shown below:

\[ P_L = P_{LM} \left( a_1 \left( \frac{V}{V_M} \right)^2 + a_2 \left( \frac{V}{V_C} \right) + a_3 \right) \] (4)

where \( a_1 \) represents the ratio of constant impedance load to total load; \( a_2 \) represents the ratio of constant current load to total load; \( a_3 \) represents the ratio of constant power load to total load.

According to the network operation data, it can be drawn that the ratio of constant impedance load is customarily more than the other two kinds of loads [11]. By only considering constant power load and constant impedance load, the conventional multinomial model can be simplified. Figure 3 shows the PV curve under different ratio of constant power loads.

Figure 2. PV curve of fast charging loads.

Figure 3. PV curves of different ratio.
It can be concluded that the static voltage margin will drop with the increasing of constant power load ratio (from 20% to 80%). So with the popularization of fast charging, constant power loads will do harm to the static voltage stability of power grids.

2.2 The Impact on Frequency Stability

The frequency of power grids is one of the main quotas which can reflect changes of active power loads. So it is important to analyze the influence on frequency stability when fast charging station is connected to the power grid.

Also take the model of two machines with three buses as the example [12]. Hydroelectric generating set, which owns strong frequency control ability, is chosen as G1; thermal power unit model is taken as G2. The frequency analysis model is shown in Figure 4.

\[ P_{\text{exchange}}(i) = P_{\text{exchange}}(i-1) + K_M \cdot \Delta t, \text{ when } K > K_M \]  
\[ P_{\text{exchange}}(i) = P_{\text{exchange}}(i-1) - K_M \cdot \Delta t, \text{ when } K < -K_M \]  
\[ P_{\text{exchange}}(i) = P_{\text{exchange}}(i), \text{ when } -K_M < K < K_M \]

\( P'_{\text{exchange}}(i-1) \) is the output result of previous computing cycle, \( \Delta t \) is sampling interval time and \( K_M = 10\text{MW/s} \) for presented simulation.

3 SCES COMPENSATION CONTROL

It is assumed that each fast charger reaches rated charging power in 0.1 second; all of the fast chargers are expected to work during the peak time. So the dP/dt of each charger will be added to reach a high value. SCES is used to compensate the changing rate of charging power. Figure 6 shows the control block diagram of SCES. P exchange is the exchange power between FCS and power grids. \( K_M \) is the specified maximum power changing rate of FCS. Constants \( K_M \) and \( -K_M \) are rising rate and falling rate parameters of rate limiter module respectively. Output signal \( P' \) exchange can be expressed below:

4 SIMULATION

4.1 Distribution network model

A low-voltage distribution network (220/380V) usually consists of industrial loads, residential loads, distribution transformers and so on. The model of distribution network in this paper is given by Figure 7.

The capacity of mentioned distribution network is 100 MW. And Table 1-3 show operational parameters of the distribution network.

4.2 Fast charging station model

Fast charging station consists of dozens of chargers. So it is essential to analysis the structure of one fast charger.
Figure 8 shows the integral structure of fast charging circuit. The basic principle of fast charger can be concluded into two points: one is AC/DC converter which is used to transform alternating current to direct current, the other is DC/DC converter which is used to transform DC to be matched with charging parameters.

Figure 9 shows details of DC/DC converter which consists of isolation transformer, power electronic device and so on [13].

The control circuit of AC/DC converter is shown in Figure 10. The given reference voltage is 500 V. The voltage control signal is changed to current signal \( i_{D1} \) through PID controller. Finally the switching signal will be calculated by multiplying \( i_{D1} \) and \( i^*_{D1} \).

Figure 11 is a typical power curve of a real 50 kW charger which consist constant current mode and constant voltage mode in a charging period [15]. Assume the fast charging station owns 20 chargers. And the

<table>
<thead>
<tr>
<th>Item</th>
<th>Frequency (Hz)</th>
<th>Active power (kW)</th>
<th>Reactive power (kVar)</th>
</tr>
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<tbody>
<tr>
<td>Residential load 1</td>
<td>50</td>
<td>120</td>
<td>8</td>
</tr>
<tr>
<td>Residential load 2</td>
<td>50</td>
<td>140</td>
<td>10</td>
</tr>
<tr>
<td>Residential load 3</td>
<td>50</td>
<td>200</td>
<td>15</td>
</tr>
<tr>
<td>Residential load 4</td>
<td>50</td>
<td>120</td>
<td>8</td>
</tr>
<tr>
<td>Residential load 5</td>
<td>50</td>
<td>160</td>
<td>12</td>
</tr>
<tr>
<td>Industrial load 1</td>
<td>50</td>
<td>30000</td>
<td>100</td>
</tr>
<tr>
<td>Industrial load 2</td>
<td>50</td>
<td>10000</td>
<td>60</td>
</tr>
<tr>
<td>Fast charging station</td>
<td>50</td>
<td>5000</td>
<td>40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>( r ) (Ohms/km)</th>
<th>( l ) (mH/km)</th>
<th>( c ) (F/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission line</td>
<td>0.01273</td>
<td>0.9337</td>
<td>12.74e-9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>Winding 1/2 connection</th>
<th>Voltage ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer 1</td>
<td>( Yg/\Delta )</td>
<td>66kV/10.5kV</td>
</tr>
<tr>
<td>Transformer 2</td>
<td>( \Delta/Yg )</td>
<td>10.5kV/380V</td>
</tr>
</tbody>
</table>

Lithium battery circuit topology is shown in Figure 11. \( R_{bi} \) represents the internal resistance of lithium battery; \( E_B \) represents the battery voltage which is constantly changed by state of charge (SOC); \( C_B \) and \( R_{a2} \) are used to simulate the dynamic characteristics of lithium battery [14]. And the equations of mentioned circuit can be expressed below:

\[
\begin{align*}
U_B &= E_B \\
Z_B &= \frac{C_B R_{Bi} R_{Bi2} s + R_{Bi} + R_{Bi2}}{C_B R_{Bi2} s + 1}
\end{align*}
\]

Figure 12 is a typical power curve of a real 50 kW charger which consist constant current mode and constant voltage mode in a charging period [15]. Assume the fast charging station owns 20 chargers. And the
fast charging station model is shown in Figure 13.

Figure 12. Power curve of 50 kW charger.

Figure 13. Fast charging station model.

4.3 Simulation results

In order to start the simulation, it is assumed that a charging power level of 250 KW is available at the fast charging station for each vehicle; each fast charger reaches rated charging power in 0.1 second; all of the fast chargers are expected to work during the peak time. So the dP/dt of each charger will be added to reach a high value. When the dp/dt of FCS exceeds KM, SCES will release power to compensate the power vacancy in order to reduce the influence on frequency of power grids. The capacity determination of SCES is not only a technical but also an economical issue. Hence in this simulation, half-compensation is chosen. For example, the changing rate of SCES is 20MW/s while dp/dt of FCS is 40MW/s.

Figure 14 is a typical power curve of emulational charging station and SCES during the peak time.

Figure 14. Fast charging station model.

Figure 15 shows the frequency curve of FCS with and without SCES. When the fast charging station works on the peak operation, the changing rate of charging power (dP/dt) will be superimposed, even up to dozens MW/s. It will certainly lead to frequency drop of the distribution network. The lowest frequency of distribution network is about 49.8 Hz without SCES. However, when using SCES to compensate the high power impulse of fast charging load, the lowest frequency will be improved to 49.9 Hz.

Figure 15. Fast charging station model.

5 CONCLUSION

To enable and encourage widespread consumer adoption and use of EVs, a system with enough public recharging stations (including fast charging stations), to allow drivers to recharge on a regular basis during the day, will be necessary [16]. In this paper, the fast charging station is modelled and impacts of changing rate of charging power (dP/dt) on the frequency of distribution network are investigated. The results show that when the dp/dt comes up to dozens MW/s, the frequency of power grids will drop below 59.8 Hz which is not allowed in normal operation. In addition, this paper proposes a new application of SCES in the FCS in order to solve the mentioned problem. The simulation results illustrates that the dp/dt of FCS becomes controllable by power output of SCES. Future research is the capacity allocation in order to improve the economic performance.

REFERENCES


