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Research on Frequency Control Strategy and Standardization based on Virtual Synchronous Charging and Discharging of Electric Vehicles

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Abstract: With the rapid development of renewable energy, the power system faces increasing frequency fluctuation issues, and traditional synchronous generators are gradually unable to meet the demand for frequency regulation. Electric vehicles (EVs), as an emerging flexible load resource, can participate in grid frequency regulation due to their adjustable charging and discharging characteristics. This paper establishes a model of an EV fleet participating in frequency regulation based on virtual synchronous charging and discharging technology for electric vehicles. First, the basic principles of virtual synchronous charging and discharging and their role in grid frequency regulation are analyzed. Then, a frequency control strategy for electric vehicles based on the virtual synchronous generator model is proposed, and the performance of this strategy under different grid operating conditions is studied. Finally, the paper addresses the standardization issue of virtual synchronous charging and discharging for electric vehicles and proposes corresponding technical requirements and implementation plans. Experimental results show that the virtual synchronous charging and discharging technology for electric vehicles can effectively improve grid stability and lay the foundation for the standardization of EV frequency control.

Keywords: Electric vehicles; virtual synchronous charging and discharging; frequency control; standardization; grid stability.

1. Introduction

With the ongoing global energy transition, the proportion of renewable energy sources such as wind and solar power is continuously increasing. However, the volatility and intermittency of these energy sources pose challenges to the stability of the power grid. In recent years, supported by strong national policies, electric vehicles (EVs) and charging infrastructure have seen rapid development [1-4]. With the advancement of high-power charging technologies, the large number of electric vehicles connecting to the charging network during peak electricity demand periods can result in massive amounts of energy being transferred unidirectional from the grid to the vehicles, leading to an instantaneous overload on the grid and seriously affecting the grid's safe and stable operation [5-7].

Electric vehicles (EVs), with their large-scale battery storage and flexible charging and discharging capabilities, have become a potential resource for load regulation in the power system. Virtual Synchronous Charging and Discharging (VSC) technology simulates the inertia and damping characteristics of traditional synchronous generators, enabling electric vehicles to participate in grid frequency regulation like generators. To address the issue of heavy grid load during charging peaks, many scholars have studied Vehicle-to-Grid (V2G) charging and discharging technologies, which leverage the mobile energy storage characteristics of EVs. Isolation-type V2G equipment has been designed, which charges EV batteries during off-peak periods and feeds the remaining energy back to the grid during peak periods [8-10]. If large numbers of electric vehicle users can conduct orderly charging and discharging operations within a specified time, it would help achieve "peak shaving and valley filling" [11-12], significantly reducing the peak charging load. Moreover, in order to promote the integration of clean energy and enhance the resilience of the charging network [13-15], the application of multi-energy complementary charging stations is gradually increasing [16-17]. Multi-energy complementary charging stations configure various types of energy units such as photovoltaic systems and energy storage within the station. While they can smooth out charging loads to some extent, the potential grid fluctuation issues limit their development.

To address this, Virtual Synchronous Machine (VSM) technology has become an effective solution. In [18], a load virtual synchronous machine function was realized by simulating the rotor inertia, excitation inertia, and stator electrical characteristics of a synchronous machine using a laboratory test rig, but the load could not feed energy back to the grid. In [19], a three-phase pulse-width modulation rectifier with virtual synchronous functionality was designed, which can operate in constant power or constant voltage mode, correcting the power factor and ensuring good power quality. In [20], a method for designing core parameters for virtual synchronous generator control was proposed, but the 50 kW prototype developed did not have V2G capabilities.

Currently, research on the participation of electric vehicles (EVs) in frequency regulation mainly focuses on two aspects:

1.Collaborative frequency regulation between EVs and renewable energy sources, such as the strategy proposed in [21], which applies EVs and heat pumps in a delayed environment to participate in system load frequency control; or the study in [22], which investigates methods for integrating EVs into the Danish grid with high wind energy penetration for frequency regulation.

2.Research on methods for EVs to autonomously participate in frequency regulation, such as the adaptive droop control model for EV participation in primary frequency regulation proposed in [23], which simulates the impact of EV participation on the grid; or the load frequency control joint optimization method in [24], which incorporates EV auxiliary frequency regulation and effectively improves the steady-state response speed of load frequency control while optimizing the system's frequency regulation performance. In [25], a charging demand distribution analysis method based on the theory of travel chains is proposed, which accounts for factors like parking duration flexibility and time-of-use electricity pricing for household EV users, but does not consider EV participation in frequency regulation auxiliary services. In [26], a VSM-based solution is presented for EV fast charging that is grid-friendly, reducing the impact on the grid while enabling rapid charging and discharging of EVs. [27] designs an auxiliary frequency regulation control algorithm based on VSM, which modifies the EV's charging and discharging power reference by calculating the "power reference correction factor," enabling EVs to participate in both primary and secondary frequency regulation in microgrids. In [28], VSM technology is applied to Vehicle-to-Grid (V2G) systems, and a fuzzy controller is designed based on the state of charge (SOC) of the battery and grid frequency fluctuations to solve the intelligent charging and discharging problem of VSM, though user charging demand is not considered. In [29], a method is proposed for reflecting user charging demand based on the average charging power (Pav) of EVs over their online duration. However, the average charging power during the remaining time after the EV connects to the grid may deviate from Pav, which could lead to discrepancies in reflecting user charging demand. Additionally, this study does not examine the discharging of EVs to the grid. Finally, [30] sets an SOC threshold for participating in frequency regulation, where EVs can engage in grid frequency regulation through V2G when the SOC reaches this threshold. However, this control method does not reflect the relationship between user demand and frequency regulation power.

This paper presents a model for an EV fleet participating in frequency regulation through virtual synchronous charging and discharging technology. It begins by analyzing the fundamental principles of virtual synchronous charging and discharging, and their role in stabilizing grid frequency. A frequency control strategy for EVs based on the virtual synchronous generator model is then proposed, and the performance of this strategy under various grid operating conditions is examined. The paper also addresses the challenges surrounding the standardization of virtual synchronous charging and discharging for EVs, offering technical requirements and implementation strategies. Experimental results demonstrate that virtual synchronous charging and discharging technology can significantly enhance grid stability, providing a solid foundation for the future standardization of EV-based frequency regulation.

2. Virtual synchronous charging and discharging technology for electric vehicles

2.1 Principles of Virtual Synchronous Charging and Discharging

Virtual synchronous charging and discharging utilizes the charging and discharging processes of electric vehicles to simulate the inertia and damping characteristics of a synchronous generator, thereby achieving stable frequency regulation of the power grid. Traditional synchronous generators provide inertia through the rotation of their rotor, which helps the grid resist short-term load fluctuations. The battery charging and discharging process of electric vehicles can be controlled to mimic this inertia effect, allowing electric vehicles to function similarly to synchronous generators when the grid frequency fluctuates.

Specifically, the virtual synchronous charging and discharging technology involves the following key points:

1.Inertia Simulation: By adjusting the charging or discharging rate of the electric vehicle, the battery's power response can be synchronized with grid frequency fluctuations, simulating the rotor inertia effect of a synchronous generator.

2.Damping Control: In addition to the inertia response, electric vehicles can adjust the rate of change in charging power based on grid frequency variations, simulating the damping characteristics of synchronous generators to accelerate frequency recovery.

3.Virtual Synchronous Machine Model: A virtual synchronous machine model is established for the electric vehicle to further optimize the charging and discharging strategy, enabling it to not only respond to frequency changes but also dynamically adjust based on the grid’s operating conditions.

2.2 Advantages of Virtual Synchronous Charging and Discharging for Electric Vehicles

Enhanced Grid Frequency Stability: By participating in frequency regulation, electric vehicles can provide inertia support similar to traditional generators, reducing frequency fluctuations and improving grid stability. Improved Renewable Energy Integration: Virtual synchronous charging and discharging helps balance frequency fluctuations, which facilitates the integration of renewable energy sources like wind and solar power. This increases the grid's ability to adapt to the variability of renewable energy. Flexibility and Scalability: As distributed energy devices, electric vehicles can flexibly adjust their charging and discharging power. This provides high adaptability and scalability for grid operations.

2.3 Electric Vehicle Frequency Regulation Control Strategy

Frequency regulation mainly involves adjusting the output power of power sources in the grid to maintain the stability of the grid frequency. Electric vehicles can participate in frequency regulation in two ways: (1) Charging Mode (Power Absorption): When the grid frequency is too high, EVs absorb power and charge, helping to consume the excess power. (2) Discharging Mode (Power Release): When the grid frequency is too low, EVs discharge to the grid, providing additional power support.

When EVs participate in frequency regulation, they typically use a Droop Control strategy. The core idea of this strategy is to adjust the power output of the EVs based on the frequency deviation in the grid.

In response to frequency deviation, the power output of the EV can be represented by the following Droop control equation:

$$P_{\mathrm{EV}} = -K \cdot \Delta f \quad (1)$$

where P_{EV} is power provided by the EV during frequency regulation (positive value indicates discharging, negative value indicates charging). K is the droop constant, determining the sensitivity of the EV's response to frequency deviation. $\Delta f = f_{nominal} - f_{current}$ is the frequency deviation, i.e., the difference between the current grid frequency and its nominal frequency. For example, if the grid frequency decreases (i.e., Δf is negative), the EV will discharge to the grid to provide additional power and help increase the frequency. When the grid frequency decreases ($\Delta f < 0$), the EV will discharge, increasing the grid's power output. When the grid frequency increases (($\Delta f > 0$), the EV will absorb power, reducing the grid's power output.

The charging or discharging power of an EV can be described by the following equation:

$$P_{\mathrm{EV}}(t) = P_{\max} \cdot \left(1 - \frac{|f(t) - f_{\mathrm{nominal}}|}{\Delta f_{\mathrm{threshold}}}\right) \tag{2}$$

where $P_{\mathrm{EV}}(t)$ is the charging or discharging power of the EV at time t. $P_{\max}$ is the maximum power output or charging power of the EV. $f(t)$ is the current grid frequency at time t. f_{nominal} is the nominal grid frequency (typically 50 Hz or 60 Hz). $\Delta f_{\mathrm{threshold}}$ is the frequency deviation threshold. The EV will only start adjusting its power when the frequency deviation exceeds this threshold. This equation indicates that the power output of the EV is adjusted based on the deviation between the current frequency and the nominal frequency. When the frequency deviation is small, the power adjustment is small; when the frequency deviation is large, the power adjustment increases.

When participating in frequency regulation, EVs need to sense changes in the grid frequency and dynamically adjust their frequency regulation strategy based on their battery state (SOC, State of Charge) and charging power limits. The frequency regulation control strategy for EVs typically considers the following factors: SOC and maximum power limits. The remaining charge in the EV's battery affects its ability to charge or discharge. If the SOC is too low, the EV may not be able to discharge further; if the SOC is too high, the charging demand of the EV may be limited. EVs have a maximum charging/discharging power, which, if exceeded, could damage the battery or cause system instability.

Therefore, in practical applications, the power adjustment equation for EVs may need to include constraints on SOC and power limits.

$$P_{\mathrm{EV}}(t) = \min\left(P_{\max}, f_{\mathrm{droop}}\left(f(t), SOC(t)\right)\right) \tag{3}$$

where $f_{\mathrm{droop}}\left(f(t), SOC(t)\right)$ is the frequency regulation response function of the EV based on the frequency and SOC. It is usually adjusted based on the battery charge state and the frequency deviation.

2.4 Model for an EV Group Participating in Frequency Regulation

All electric vehicles in the group will provide or absorb power based on their individual battery statuses and frequency deviations. Assuming the electric vehicles in the group adjust their power output according to the above model, the total power of the group $P_{\mathrm{total}}(t)$ is the sum of the powers of each electric vehicle.

$$P_{\mathrm{total}}(\mathrm{t}) = \sum_{i=1}^{N} P_{\mathrm{EV}_i}(t) \tag{4}$$

where $P_{\mathrm{EV}_i}(t)$ is the frequency modulation power of the i-th electric vehicle, which is calculated based on the vehicle's maximum power and battery status.

For a large-scale group of electric vehicles, simple independent frequency regulation may bring the following problems: (1) Excessive power fluctuations: When multiple electric vehicles respond to frequency changes simultaneously, it may cause severe power fluctuations in the system, affecting the stability of the power grid. (2) Energy waste: Electric vehicles may still overcharge or discharge when the frequency deviation is small, wasting battery energy and shortening battery life. (3) Unbalanced load: Different vehicles have varying response sensitivities, which may result in some vehicles taking on excessive frequency modulation tasks.

To address these issues, the following cooperative control strategies are typically employed:

(1) Distributed Control

Each electric vehicle independently makes decisions based on its own state and frequency deviation, but they share information through some protocol (such as a communication network) to collaboratively adjust their frequency modulation strategies. The primary goal of distributed control is to allow each vehicle to adjust its frequency modulation response according to global objectives, such as minimizing power fluctuations or maximizing regulation accuracy. For example, a distributed control strategy based on optimization algorithms can be used, where each electric vehicle dynamically adjusts its power output based on its own battery status, frequency deviation, and network information. Common optimization algorithms include: Gradient Descent: Dynamically adjusting the electric vehicle's response power based on changes in the grid frequency deviation. Game Theory: Using game theory models to achieve a Nash equilibrium in the power response of the electric vehicle group, thereby enabling coordinated regulation.

(2) Centralized Optimal Scheduling

In centralized optimal scheduling, a central controller (such as a grid dispatch center) schedules the power output of each electric vehicle based on the grid's frequency deviation and the battery status, maximum power, and other parameters of each vehicle. The advantage of this approach is that it allows for global optimization, but it may face challenges related to information transmission delays and system scalability.

A common centralized optimization model is the optimization scheduling problem, which aims to minimize the total power fluctuation of the system and maximize the frequency regulation effect. The specific model is as follows:

$$\min \sum_{i=1}^{N} \left(P_{\mathrm{EV}_i}^2(t) \right) \text{ subject to } P_{\mathrm{EV}_i}(t) \le P_{\max,i},\ SOC_i(t) \ge SOC_{\min,i} \tag{5}$$

The objective is to minimize the sum of the squared power responses of all electric vehicles in order to reduce system fluctuations. At the same time, the maximum power and minimum battery charge constraints of each electric vehicle must be considered.

The hybrid control strategy combines the advantages of both distributed and centralized control. In this framework, a portion of the electric vehicles in the group decide their frequency modulation strategy through centralized coordination, while other vehicles perform local optimization and execution based on this strategy. This approach ensures global optimization while improving the robustness and response speed of the system.

2.5 Application Scenarios of the Electric Vehicle Group Frequency Modulation Model

Taking a typical single-area power system frequency regulation model as an example, this paper analyzes the impact of electric vehicles (EVs) integrated into the grid using an intelligent charging and discharging control strategy on the system frequency. The results are shown in Fig. 1.

When there is a sudden increase in grid load, the grid frequency typically experiences significant deviations, especially in cases of sharp increases in system load or large fluctuations in renewable energy generation. An increase in frequency deviation not only affects the stability of the grid but may also negatively impact the operational safety of equipment. To address this issue, the frequency regulation strategy proposed in this paper shows clear advantages. Specifically, when the system frequency deviation is less than 0 (i.e., the grid frequency is lower than the normal value), according to the proposed strategy, electric vehicles (EVs) will discharge to the grid, thus providing the necessary load support to the grid.

The core advantage of this regulation mechanism is that even when the electric vehicles are supposed to be in the charging state, the strategy can still control the charging and discharging behavior of the EVs, enabling them to discharge to the grid when needed, effectively acting as additional load. This flexible charging and discharging behavior can quickly respond to frequency fluctuations in the grid, thereby effectively reducing frequency deviation. This effect is particularly noticeable when there is a sudden increase in load.

Compared to traditional grid frequency regulation methods, using electric vehicle virtual synchronous charging and discharging technology allows for more efficient utilization of existing EV resources, creating a "flexible load" that helps balance the grid. This not only reduces the grid's reliance on traditional reserve power sources but also minimizes the risk of grid equipment damage caused by frequency fluctuations. Through this approach, electric vehicles not only meet their own charging needs but also help maintain the stability of the grid to some extent.

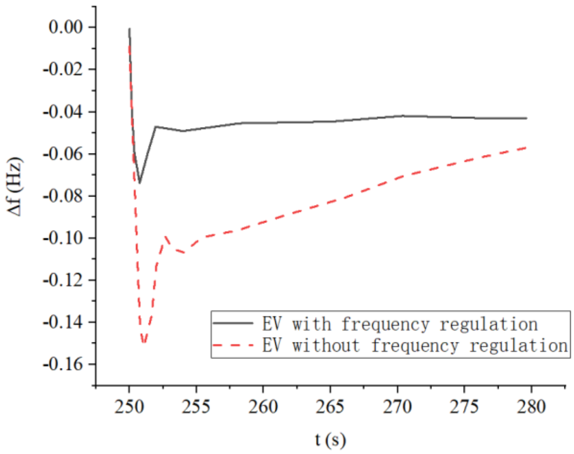

Fig.1 Frequency regulation effect of multiple EVs.

3. Standardization Research on Virtual Synchronous Charging and Discharging of Electric Vehicles

3.1 Necessity of Standardization

With the widespread adoption of electric vehicles (EVs) in power grids, ensuring that electric vehicle devices from different manufacturers can be compatible and efficiently participate in grid frequency regulation has become an urgent issue. Standardization not only enhances the interoperability of electric vehicles but also ensures their safety and stability in grid frequency regulation.

3.2 Key Standardization Requirements

Communication Protocol Standards: The frequency regulation system of the electric grid and electric vehicles should use a unified communication protocol to ensure real-time frequency data transmission and control commands.

Power Regulation Standards: A standard for electric vehicle charging and discharging power regulation needs to be developed, specifying parameters such as power regulation rates and response times during inertial response and frequency recovery processes.

Safety and Reliability: When participating in grid regulation, electric vehicles must ensure the safety of their batteries to prevent damage or degradation of battery life caused by overcharging or discharging.

Certification and Testing: Standards for the certification and testing of electric vehicle virtual synchronous charging and discharging functionality should be established to ensure that devices meet grid frequency regulation requirements.

3.3 Implementation Plan

To achieve the standardization of virtual synchronous charging and discharging of electric vehicles, this paper proposes the following implementation plan:

Multi-party Collaboration: Power companies, automobile manufacturers, and standardization organizations should collaborate to promote the standardization of electric vehicle virtual synchronous charging and discharging technology.

Experimental Validation: During the standard-setting process, experiments and simulations should be carried out to verify the feasibility and effectiveness of the standards, ensuring their reliability in practical applications.

Gradual Promotion: Start with small-scale experimental zones, gradually promoting the virtual synchronous charging and discharging technology for electric vehicles, accumulating practical experience, and optimizing the standard content.

4. Conclusion

Electric vehicles, as an emerging flexible load resource, can participate in grid frequency regulation due to their adjustable charging and discharging characteristics. This is especially significant in grids with a high proportion of renewable energy. This paper establishes a model of an EV fleet participating in frequency regulation based on virtual synchronous charging and discharging technology. First, the basic principles of virtual synchronous charging and discharging and their role in grid frequency regulation are analyzed. Then, a frequency control strategy for electric vehicles based on the virtual synchronous generator model is proposed. Finally, the paper discusses the standardization of virtual synchronous charging and discharging technology for electric vehicles, proposing corresponding technical requirements and implementation plans. Experimental results show that virtual synchronous charging and discharging technology for electric vehicles can effectively improve grid frequency regulation capabilities, enhance grid stability, and lay the foundation for the standardization of EV frequency control.

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