Dynamic Load Optimization System of Wireless Charging Pile for Smart Grid

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Abstract. Against the backdrop of a sharp increase in the number of electric vehicles, the demand for wireless charging piles has also grown. Therefore, it is particularly important to regulate the dynamic load fluctuations and instability of grid connection to reduce the impact on the power grid. Through employing technical interventions, the issue of instability and fluctuations in the power grid can be effectively resolved. This study focuses on the coupled application of wireless charging piles in various scenarios within DC microgrids. In response to this issue, this study adopted NiZn ferrite core with low inductance loss. Under the collaborative optimization strategy NSGA-II algorithm, AI and digital twin technology were integrated to use LSTM model to predict charging peaks and valleys, and electricity prices were determined based on load. The voltage fluctuations of grid nodes tended to stabilize, reducing operating costs and improving operational efficiency and revenue. A power system with balanced supply and demand is the development direction. The peak and off-peak periods of power generation and consumption in the power system are unstable. The coupling mode of the photovoltaic storage DC microgrid and charging piles is introduced. Through the dynamic electricity price response mechanism, the discharge electricity price of electric vehicles is increased during the high-load period of the power grid to promote the reverse power supply of electric vehicles to the power grid. Reducing the charging electricity price during the off-peak load period can increase the underutilized electricity consumption and promote the stability of the power system load.

Keywords: Power system load, wireless charging, dynamic load, dynamic electricity price, ferrite core.

1. Introduction

At present, the smart grid and electric vehicles are growing together, and the wireless charging pile has contradictions in the dynamic load scenario. The smart grid is facing the challenge of random, high proportions, and fluctuating load caused by the explosive growth of electric vehicles. Wireless charging is an important technology that can greatly improve the convenience of users and reduce the impact on the power grid through reasonable control.

The large-scale access of wireless charging piles to the power system will bring about the dynamic load optimization problem, and the wireless charging technology still objectively has the core contradiction between efficiency, distance, convenience and power grid stability and economy. At the system level, since the current power system prioritizes ensuring the stability of the power grid, it may sacrifice economy, it is necessary to coordinate the scheduling strategy V2G to achieve a balance between the overall economy and efficiency of the system, otherwise the contradiction will be further transformed into a sharp increase in the cost of electricity customers [1].

Among them, due to the NSGA-II algorithm optimizing multiple objective functions, including user costs, operator revenue, and grid voltage quality, it can achieve a 33.43% increase in electricity revenue and a 68.89% decrease in voltage deviation. The MOPSO algorithm reduces user costs by 21.51%, resulting in a 17.06% decrease in revenue for charging stations, which directly drives subsequent investment in charging infrastructure. According to the spatiotemporal distribution of charging demand, due to the pursuit of excessive grid optimization, the energy consumption costs of users have decreased by 18.86% and 21.51% respectively, while the costs of NSGA-II and MOPSO have increased by 54.14% respectively [1].

Consumers tend to prefer cheaper charging methods, while charging station operators need to increase electricity prices to obtain more profits. How to balance the contradictions between the above macro and specific cases and solve the problem of overall planning of efficiency and economy after the scale of wireless charging is a research breakthrough in this field.

This paper discusses the theoretical basis and key technologies, emphasizes the integration of the system through the collaborative optimization of smart grid and wireless charging piles, studies the objective conditions of challenges and benefits after the scale of wireless charging, and provides solutions to the smooth operation of power systems under dynamic load changes.

2. Theoretical Foundation

2.1. The Basic Role of Inductance and Magnetic Coupling Theory

According to the basic theory of inductance, magnetic coupling is a physical phenomenon in which the energized coils are connected to each other through the magnetic field. Inductance can be regarded as a process in which two current-carrying coils have different currents, and then the magnetic fields they generate interact with each other, eventually reaching a dynamic equilibrium.

In the aspect of inductance design, the Q value of the hollow inductor is relatively high and the volume is large. At 300 A current, the magnetic ring is saturated, and the EMI filter fails. Therefore, the frequency is shortened, the capacitance lead is reduced, the parasitic inductance is reduced, and the high-frequency insertion loss is improved [2]; Magnetic core inductors are small in size but have high high-frequency losses, enhancing the magnetic field and are suitable for high-power scenarios in electric vehicles. Mutual inductance is the direct carrier of energy transmission [3].NiZn ferrite can also be selected as a new material to make a magnetic core inductor. The loss reaches a low point in the MHz frequency band, 40 air gaps reduce the edge loss, and improve the reluctance application. The parallel interleaved foil double winding AC resistance can be reduced by 65 %. This process can reduce the loss [4].

2.2. Magnetic Induction and Magnetic Resonance

Based on Faraday's law of electromagnetic induction, the transmitting coil is excited by an alternating current of 85 kHz with low frequency, low EMI and low device cost to generate an alternating magnetic field. The receiving coil can couple the induced current to complete the energy transmission within 10 cm. If it is greater than 10cm, the coupling coefficient K will decrease rapidly, resulting in a significant decrease in efficiency. In order to solve this problem, the coil can be designed as a square and a ferrite core is added to the back, which can effectively improve the coupling coefficient, and the whole energy exchange process is only non-radiative magnetic field coupling, without the risk of additional electromagnetic radiation [5].

The rapid popularization of electric vehicles has highlighted the drawbacks of traditional plug-in charging. In this context, wireless power transfer (WPT) with intelligence, safety, and convenience has three modes: static, dynamic, and quasi-dynamic. As of 2020, the global number of electric vehicles has exceeded 10 million. With the development of wireless charging technology, the wireless charging market is predicted to expand at a compound annual growth rate of 46.8%. Technically, WPT can be divided into near-field coupling represented by inductive IPT and capacitive CPT, and far-field radiation represented by microwave MPT and laser. In other aspects, standardization, data security, cost control, operational safety, material selection, V2G and grid friendliness also play important roles in the specific application of WPT [6].

2.3. The Key to the System from Theory to Practice

When designing a wireless charging coil, the first step is to clarify the required power transmission level, then select the appropriate wire diameter. The optimal coupling coefficient K=0.1-0.35 should avoid overly thick wires; if the transmitted power is low, such as for phone charging, thinner wires can be used to save costs and space. However, for electric vehicle charging, a wire diameter of 5mm is typically used, which reduces heat generation while ensuring high current flow. In the electric vehicle wireless charging system, the maximum allowable current through a 5mm Litz wire can exceed 50A, meeting the power transmission requirements of existing electric vehicles. When selecting the magnetic core, after meeting the power transmission standards, it is necessary to try to minimize the overall size and weight of the coil as well as the amount of magnetic core used. Power, as an important measurement indicator, is a constant throughout and also determines the choice of magnetic core material and shape. In practical applications, it's necessary to ensure efficiency while also focusing on controlling size and weight [7].

3. Collaborative Optimization of Smart Grid and Wireless Charging Pile

3.1. Coupling Mode of Photovoltaic-storage DC Microgrid and Charging Pile

From 2009 to 2023, the number of electric vehicles charging stations in China has increased dramatically. It can be observed that the construction of charging piles is almost synchronized with the growth in sales of new energy vehicles, albeit with a slight lag [8]. The integrated photovoltaic storage and charging DC microgrid unifies the three important nodes of photovoltaic power generation, battery energy storage and electric vehicle charging, that is, DC distribution, and manages energy transmission through the DC microgrid. The cost of generating electricity by charging with wind or solar energy is very low but unstable, while batteries can be charged when electricity prices are low and discharged when they are high. The bidirectional power transmission (WPT) technology is at the core of this system, enabling electric vehicles to be regarded as mobile batteries that can store excess power generated from uncontrollable renewable energy and help balance the load on the power grid. Therefore, researchers need to consider how to reduce the cost and improve the efficiency in the operation and production of the entire microgrid. Considering that there is no physical contact between the transmitting and receiving ends of wireless charging, the maintenance cost will be lower than that of wired charging. The cost of the wireless charging system comes from the battery. To reduce the power of the on-board battery, a potential economic benefit analysis based on dynamic wireless charging DWPT is conducted. The construction of wireless charging stations may significantly reduce the energy storage capacity of vehicles and their prices, so there needs to be a sufficient number of charging stations [9].

To avoid the introduction of constant power DC loads causing oscillations in the DC voltage, a new multi-mode virtual inertia control system utilizing energy storage batteries enhances the inertia of the DC microgrid. This system dynamically compares the rate of change of the DC voltage and selects either a linear or an exponential method to allocate power for smoothing, thereby suppressing voltage fluctuations [10]. Secondly, in order to reduce the battery size of electric vehicles, the application of dynamic wireless charging (DWCS) technology in the process of use, because the electric vehicle is charged during driving, because short-term, pulse and other factors will have an impact on the grid load, pulse-type high power output and grid imbalance, DC voltage will also produce second harmonics. The speed of the running vehicle conforms to the normal distribution. Combined with the coil mutual inductance and the vehicle position model, according to the 24-hour power demand, the energy storage is introduced to stabilize the load and maintain the voltage stability [11].

In rural areas, to promote the use of new energy vehicles (NEVs), China is vigorously implementing the "New Energy Vehicles Going to the Countryside" policy. The total number of NEVs in China's rural areas is expected to exceed 70 million by 2030. Remote villages are far from load centers, so there is currently a need to adapt to low-power weak grids, with existing household charging equipment being the most ideal popularization solution. To tackle the resonance challenges associated with weak grids, a model of an integrated solar-storage charging pile can be constructed, employing the incremental conductance (IC) maximum power point tracking (MPPT) control strategy to achieve dynamic, precise power tracking. Additionally, a quasi-proportional-resonant (quasi-PR) controller can be used for zero-static-error tracking of single-phase sine voltage commands, forming a phase-locked loop (PLL) based on a second-order generalized integrator (SOGI), which not only ensures synchronization with the grid voltage but also mitigates the resonance effects caused by the operation of weak grids [12].

3.2. Optimization

A Dynamic Wireless Charging System (DWCS) can charge electric vehicles while they are in motion, reducing the onboard battery capacity while significantly extending the range of the vehicle. However, the pulsed, high-power, and short-duration charging characteristics of DWCS can easily impact the operation of the power grid, threatening the voltage and power balance of the distribution network. By increasing energy storage systems (ES) or supercapacitors to smooth power fluctuations, the impact on the grid can be reduced. Additionally, through Integrated Energy Systems (IES), photovoltaic (PV) or other renewable energy sources can be allocated to achieve localized energy self-sufficiency, thereby decreasing or even eliminating reliance on critical power networks [11].

Unlike traditional power systems, DC systems have about 7-10% higher energy efficiency than AC systems, and both line losses and converter losses are lower. With the development of integrated solar storage charging, it will be applied more widely [13]. However, the integration of optical storage and a DC microgrid is faced with the problem of efficiency decline. The fixed droop control strategy has the problems of large DC bus voltage deviation and slow SOC equalization speed. In order to obtain the real-time state of the power grid, the dynamic adjustment droop coefficient is studied. The process of the ampere-hour integration method is more complicated and needs to be combined with other methods. The internal resistance compensation method needs to introduce new compensation for the problem that the internal resistance of the battery heats up with use, which may lead to new errors. Therefore, the real-time SOC state of the battery is dynamically adjusted. If it is high, the discharge is mainly used to reduce the charge, and if it is low, the charge is mainly used to reduce the discharge. The first-order SOC term is used to further optimize the reasonable power distribution and increase the SOC equalization speed equalization speed by 2.2 %, and the maximum deviation of the DC bus voltage is reduced by 10.77 %. Get a faster response and have a stronger and stable system. Using SOC to adjust the state requires a certain amount of economic investment, but for the enterprise in the long run, it can significantly improve production efficiency, prolong battery life, reduce equipment maintenance time and cost. In the future, the technology will be further iteratively updated in combination with AI, digital twin and other technologies, which plays an important role in the development of DC microgrid [14].

4. Challenge and Development

4.1. Challenge

In terms of technical direction, wireless charging technology has the problem of low energy transmission efficiency. The coupling coefficient decreases as the distance increases. Currently, the common effective transmission distance is only about 15 cm. High-frequency electromagnetic fields interfere with the operation of electronic devices and also generate radiation that is harmful to the human body. Therefore, appropriate shielding measures need to be considered.

Under the framework of the new energy system, the large-scale use of wind, solar and energy storage has led to an imbalance in energy supply in terms of time and space. Introducing DC microgrids for energy transmission management to supply environmentally friendly and low-cost energy such as wind and solar power, and how to charge dynamically, intelligently, efficiently and economically when electricity prices are low and discharge when they are high is an important direction for current technological research breakthroughs. Among them, WPT is the key. Electric vehicles have become mobile energy storage devices that can store unstable excess power generation from new energy sources and balance the load on the power grid for peak shaving and valley filling. From this, it can be seen that to control the cost of microgrids, it is necessary to consider wireless charging that is cheaper, more material-saving, or even has no physical contact. In this way, the main focus can be on the control of battery costs. The technical challenges to solve these problems include reducing the power of on-board batteries and the energy storage capacity of vehicles, how to efficiently utilize a sufficient number of charging stations after construction, and how to build and popularize wireless charging stations in the future.

4.2. Anlysis of Economics

In terms of economic impacts, the rapid expansion of electric vehicle charging stations and future reverse charging applications as energy storage batteries will cause a sharp increase in grid load, thereby raising operational costs for power system management. The uneven power quality requires unified standards while addressing issues like harmonics and flicker, which complicate grid operations. Additionally, high-power wireless charging remains prohibitively expensive, necessitating policy incentives to encourage more innovative solutions [15].

5. Conclusion

In this paper, the charging pile with a dynamic wireless charging mode is taken as the research object, and a system configuration optimization and evaluation method are proposed to achieve the optimal economic benefit of the system under the premise of normal operation of the power system. In order to cope with the transformation of new power systems with new energy as the main body, energy storage is an important control method for the large-scale application of relatively unstable wind and solar power generation. Therefore, electric vehicles as large-scale popular micro-battery, can be used as potential energy storage components. Wireless charging technology is an important part of solving the low efficiency of charging and discharging. Building upon the large-scale integration of photovoltaic-storage-charging systems, this study provides a comprehensive analysis of wireless charging's fundamental theories, application feasibility, development potential, challenges, and technical innovations. The research covers advanced materials for NiZn ferrite-core inductors, NSGA-II algorithm for real-time dynamic prediction, and coupling mechanisms between photovoltaic-storage DC microgrids and charging stations. It explores cost reduction, efficiency enhancement, and stable operation of power systems. This work identifies critical research gaps in managing dynamic loads from wireless charging, offering new perspectives for future studies in this field.

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