

A Review of Vehicle - to - Grid (V2G) Technology with Low Power - grid Impact

Xiaojie Sun^{1, a}

¹Overseas Education College, Chengdu University, Chengdu, 610106, China

^a202311716103@cdu.edu.cn

Abstract: Vehicle - to - grid (V2G) technology, as the key to achieving bidirectional energy flow between electric vehicles and the power grid, has enormous potential in improving energy utilization efficiency and promoting the development of smart grids. However, its large-scale application faces many challenges, especially the impact on the power grid. This article comprehensively reviews the voltage fluctuations, frequency deviations, harmonic pollution, and load forecasting challenges caused by V2G technology in the power grid, and explores in depth the corresponding low power grid impact technology strategies. This article elaborates on the methods of reducing power grid impact through intelligent algorithm control (fuzzy control, model predictive control, neural network control). Research has shown that these strategies have their own advantages and disadvantages in addressing the impact of V2G technology on the power grid. In the future, V2G technology needs to further improve its standard system, enhance market acceptance, and continuously optimize low grid impact technologies to achieve efficient and coordinated development with the power grid.

Keywords: Vehicle to Network Interaction (V2G) technology; Power grid impact; Low power grid impact technology; Intelligent algorithm control.

1. Introduction

In the era of global energy transition and sustainable development, the electric vehicle industry is flourishing, and vehicle to grid interaction (V2G) technology, as a key technology for the coordinated development of electric vehicles and the power grid, has received widespread attention [1]. V2G technology allows for bidirectional energy flow between electric vehicles and the power grid, transforming electric vehicles from simple electricity consumers to flexible distributed energy storage units. It has great potential in improving energy utilization efficiency, promoting the consumption of renewable energy, and enhancing grid stability.

However, V2G technology faces many challenges in its large-scale application, among which the impact on the power grid is particularly prominent. The disorderly charging and discharging behavior of a large number of electric vehicles can cause voltage fluctuations, frequency deviations, harmonic pollution, and other problems, seriously affecting the power quality and safe and stable operation of the power grid. For example, when a large number of electric vehicles are charged simultaneously, it may cause a sudden drop in local grid voltage, affecting the normal operation of other electrical equipment; However, large-scale discharge may cause unstable grid frequency and threaten the reliability of the power system. In addition, the differences in user travel habits and changes in electricity pricing policies have led to a high degree of uncertainty in the demand for electric vehicle charging, further increasing the difficulty of power grid load forecasting. Therefore, researching V2G technology with low grid impact is crucial for promoting the widespread application of V2G technology and ensuring stable operation of the power grid.

In view of this, it is of great theoretical and practical

significance to deeply analyze the impact mechanism of V2G technology on the power grid and explore effective low power grid impact technology strategies. This not only helps to enrich the theory of power system operation and promote interdisciplinary integration, but also effectively improves the stability and reliability of the power grid, promotes the development of the new energy vehicle industry, and assists in the transformation of the energy structure towards a clean and low-carbon direction. This article will provide a comprehensive overview of V2G technology for low grid impact, review the current research status, analyze grid impact issues, and explore corresponding technical strategies, in order to provide reference for further research and application in this field.

2. V2G Technology

V2G technology enables bidirectional energy flow between electric vehicles and the power grid [2]. In this process, electric vehicles are no longer just consumers of electricity, but can also serve as small "power plants" when needed by the grid. The system mainly consists of electric vehicles, bidirectional charging and discharging units, and the power grid. The bidirectional charging and discharging unit is like an "energy transfer station", responsible for coordinating the transmission of electrical energy between electric vehicles and the power grid. When electric vehicles are charged, electrical energy flows from the power grid into the vehicle battery through bidirectional charging and discharging units; During peak load periods in the power grid, electric vehicles can transmit electricity to the grid through bidirectional charging and discharging units. The implementation of this bidirectional energy flow relies on the collaborative operation of power electronics technology, communication technology, and control technology to ensure the safety, efficiency, and accuracy of energy transmission and information exchange.

Charging and Discharging Process under V2G Technology

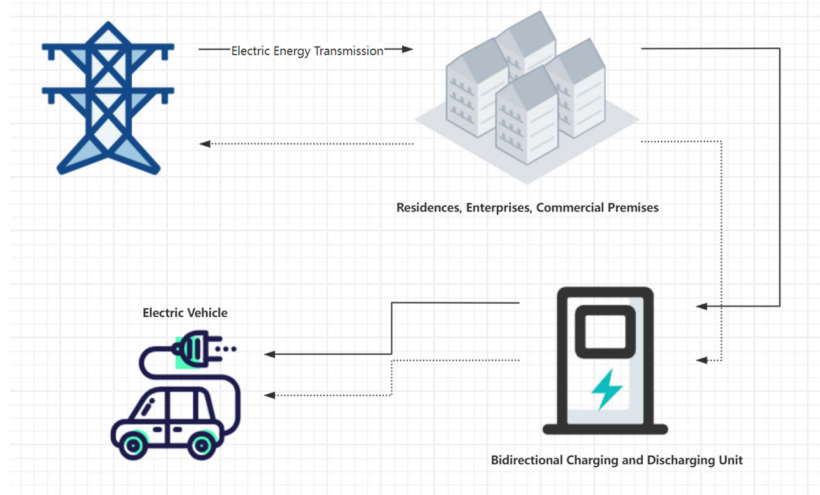


Figure 1. V2G conceptual diagram

3. Power Grid Impact Analysis

3.1. Voltage fluctuations and flicker

Simultaneous charging or discharging of a large number of electric vehicles can cause rapid changes in line current, resulting in significant voltage drops in line resistance and causing voltage fluctuations in the power grid [3]. The high-power characteristics and power fluctuations of fast charging stations can exacerbate the risk of voltage fluctuations and cause voltage flicker. In the concentrated area of urban fast charging stations, when multiple electric vehicles are rapidly charging at the same time, the voltage of the nearby distribution network will fluctuate significantly, and in severe cases, the voltage flicker value may exceed the allowable range.

This may lead to overcharging or abnormal increase in charging current during the battery charging process. This will generate excessive heat inside the battery, and when the heat cannot be dissipated in time, the battery temperature will rapidly rise, leading to thermal runaway of the battery. In a state of thermal runaway, the chemical reactions inside the battery will accelerate rapidly, producing a large amount of gas and heat, which may cause the battery to bulge, smoke, or even catch fire. This not only renders the battery useless, but also poses a serious threat to the surrounding environment and personnel. Moreover, voltage fluctuations pose a significant threat to capacitors [4]. When the voltage is higher than the rated value, the operating current of the capacitor increases, and the electric field strength borne by the internal medium increases, which may cause partial discharge and accelerate insulation aging.

3.2. Voltage imbalance

In practical V2G applications, the distribution of electric vehicles connected to the three-phase power grid is often uneven, with differences in the number and charging/discharging status of electric vehicles connected to different phases, resulting in power imbalance among the three-phase loads and voltage imbalance [5]. Some electric vehicle chargers have design flaws, such as uneven power absorption or injection in the three-phase power grid, resulting in uneven distribution of harmonic currents in the three phases, further exacerbating the three-phase power

imbalance and ultimately leading to voltage imbalance problems.

The three-phase current imbalance caused by voltage imbalance will cause uneven heating of the motor winding, accelerate the aging of insulation materials, reduce insulation performance, generate additional vibration and noise, intensify the wear of internal mechanical components of the motor, significantly shorten the service life of the motor, and increase equipment replacement and maintenance costs.

3.3. Frequency deviation

When a large number of electric vehicles are simultaneously connected to the power grid for charging, a huge demand for active power will be generated instantly. According to the study in reference, in a certain regional power grid, if there are numerous electric vehicles charging at a certain power in a short period of time, such as each electric vehicle charging power P_1 and the number of charging vehicles n , the additional charging load $P_2 = n \times P_1$ [6]. This additional load will rapidly increase the active power demand of the power grid, and the generation side of the power grid cannot immediately increase the corresponding active power output due to limitations such as unit response speed. At this point, the active power balance of the power grid is disrupted, resulting in an active power deficit ΔP .

In the power system, frequency is closely related to active power. According to the frequency characteristics of the power system, a shortage of active power can lead to a decrease in system frequency. Simply put, the power grid is like a massive rotating system, with generators acting as power sources to drive rotation, and loads acting as resistance that consumes power. When the "resistance" caused by electric vehicle charging suddenly increases and the "power source" cannot be strengthened in time, the "rotational speed" (i.e. frequency) of the entire system will decrease.

When a synchronous generator operates at its rated frequency, its internal mechanical components are in a relatively stable stress state. When there is a deviation in the system frequency, such as a decrease in frequency, the speed of the generator will correspondingly decrease. In order to maintain output power, the prime mover of the generator (such as water turbine, steam turbine, etc.) needs to increase power input, which will cause greater mechanical stress on

the rotor, shaft system and other components of the generator. Long term exposure to such overstress can accelerate component wear, reduce its service life, and even lead to fatigue damage of components, such as serious accidents like shaft fracture.

3.4. Harmonic Pollution

3.4.1. Nonlinear characteristics of power electronic devices

In V2G systems, the charging and discharging equipment of electric vehicles needs to be connected to the power grid through power electronic converters, such as DC/AC inverters [7]. These power electronic devices convert DC electrical energy into AC electrical energy or vice versa during operation. The internal switching devices (such as IGBTs) have nonlinear changes in voltage and current during conduction and turn off, which can cause distortion of the current waveform and generate harmonics.

3.4.2. The impact of control strategies and modulation methods

In order to achieve efficient and stable operation of V2G systems, various control strategies and modulation methods are usually adopted, such as pulse width modulation (PWM) [8]. Different control strategies and modulation methods can affect the voltage and current waveforms output by power electronic devices. When the modulation ratio, switching frequency, and other parameters are not selected properly, it will cause the output waveform to deviate from the ideal sine wave and increase the harmonic content.

When harmonic current flows through a transformer, it will generate additional losses in the transformer winding. According to the study in reference, harmonic currents can increase copper and iron losses in transformers [9]. Due to the high frequency of harmonic currents, the skin effect is more pronounced, resulting in an increase in winding resistance and copper loss. Meanwhile, harmonics can cause an increase in hysteresis and eddy current losses in the transformer core, resulting in a corresponding increase in iron loss. These additional losses will increase the temperature of the transformer, accelerate the aging of insulation materials, and reduce the service life and operating efficiency of the transformer.

3.5. Load forecasting

The differences in user travel habits result in a high degree of randomness in the charging demand for new energy vehicles. The travel purposes, travel times, and travel distances of different users vary, resulting in significant uncertainty in the timing and charging capacity of new energy vehicles connected to the power grid. Commuting users' charging time may be concentrated after work or before work, while users engaged in commercial activities or leisure travel have unpredictable charging time and location.

Electricity pricing policy is one of the important factors affecting the charging behavior of new energy vehicles. Under the time of use electricity pricing policy, users tend to charge during periods of lower electricity prices in order to reduce charging costs, which may significantly increase the load during the low valley period and even create new load peaks [10]. When the peak valley electricity price difference is large, users will be more proactive in adjusting their charging time, which increases the uncertainty of charging load. If the electricity price policy is frequently adjusted, the charging behavior of users will also change frequently, further

increasing the unpredictability of charging behavior.

4. Strategy Analysis

4.1. Fuzzy Control

Fuzzy control is a control method based on fuzzy logic, which can transform human experience into specific control rules [11]. Traditional control methods often rely on precise mathematical models, and in many complex systems, precise modeling is extremely difficult. Fuzzy control takes a different approach, based on fuzzy set theory, knowledge representation in fuzzy language form, and fuzzy logical reasoning. Its core lies in imitating the vague concepts of human judgment and achieving control through a series of steps.

Firstly, define variables, determine the system conditions to be observed, and consider the control actions to be taken. In V2G charge and discharge control, input variables may include real-time grid status (such as voltage deviation, frequency deviation) and electric vehicle battery status (such as state of charge (SOC), battery health status (SOH)), while output variables are the adjustment of charge and discharge power. These variables are called fuzzy variables. Next, fuzzification is performed by converting the input values into numerical values in the domain of discourse in appropriate proportions. The process of measuring physical quantities is described using colloquial variables, and the relative membership degree of the values is calculated to form a fuzzy subset. For example, correspond the language values of "large", "medium", "small" voltage deviation to the actual voltage deviation range and determine their membership degree.

The knowledge base is an important component of fuzzy control, including databases and rule bases. The database provides relevant definitions for handling fuzzy data, such as the domain scope and membership functions of each fuzzy variable. The rule library describes control objectives and strategies through a series of language control rules, which are usually summarized based on expert experience or actual operational data and presented in the form of "if... then...". Afterwards, through logical judgment, fuzzy logic and fuzzy inference methods are used for inference to obtain fuzzy control signals. Finally, defuzzification converts the inferred fuzzy values into explicit control signals as input values for the system, thereby achieving control over the controlled object.

In the V2G charging and discharging control scenario, fuzzy control can formulate effective charging and discharging rules based on fuzzy variables such as real-time grid status and electric vehicle battery status, in order to smooth out power fluctuations and reduce grid shocks [12]. When there is a deviation in the voltage of the power grid, if the voltage is lower than the set value and the deviation is "large" (according to the fuzzy definition), and the SOC of the electric vehicle battery is at a "high" level, according to the predetermined fuzzy rules, it can be inferred that the discharge power of the electric vehicle should be appropriately increased to supplement electrical energy to the power grid and improve the voltage of the power grid. If the voltage deviation is "small" and the battery SOC is "medium", the current charging and discharging state can be maintained or the power can be fine tuned to avoid unnecessary impact on the battery and grid caused by excessive adjustment.

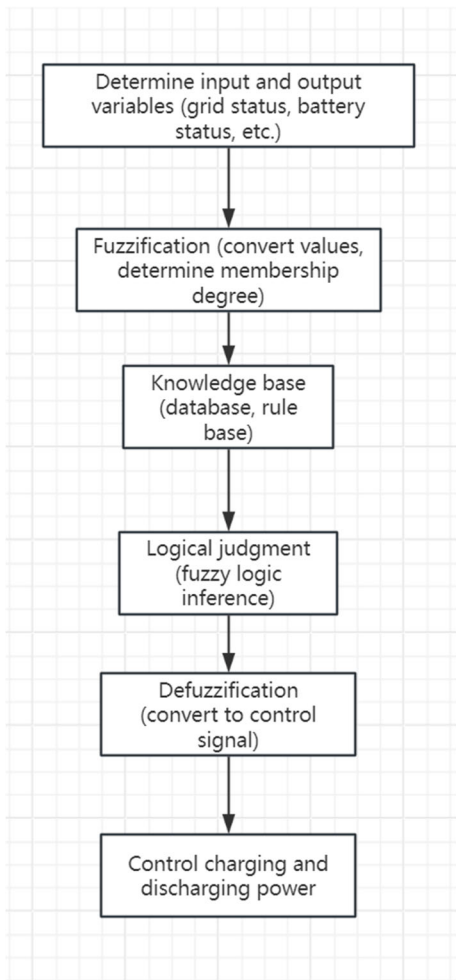


Figure 2 Fuzzy Control

4.2. Model Predictive Control

Model predictive control describes the future behavior of a system by establishing a predictive model and selecting appropriate model types based on system characteristics, such as linear models, nonlinear models, neural network models, etc [13]. At each sampling moment, rolling optimization is performed based on the current system state and prediction model to solve the optimization problem and obtain control inputs that optimize the set performance indicators. Considering the uncertainty of the actual system, the deviation between the predicted model output and the actual system output is adjusted through feedback correction, and the control input is implemented in a rolling manner. In V2G systems, this control method can reasonably arrange the charging and discharging power of electric vehicles. During peak load periods, electric vehicles with sufficient battery capacity can be arranged in advance to discharge and alleviate power supply pressure; During low load periods, electric vehicles are arranged to charge and store excess electricity, thereby smoothing out power fluctuations in the grid, maintaining voltage and frequency stability, and effectively solving frequency deviation problems. By optimizing the charging and discharging plan, model predictive control can reduce the peak valley difference of power grid, lower the losses of power grid equipment, and improve the reliability and operational efficiency of the power grid.

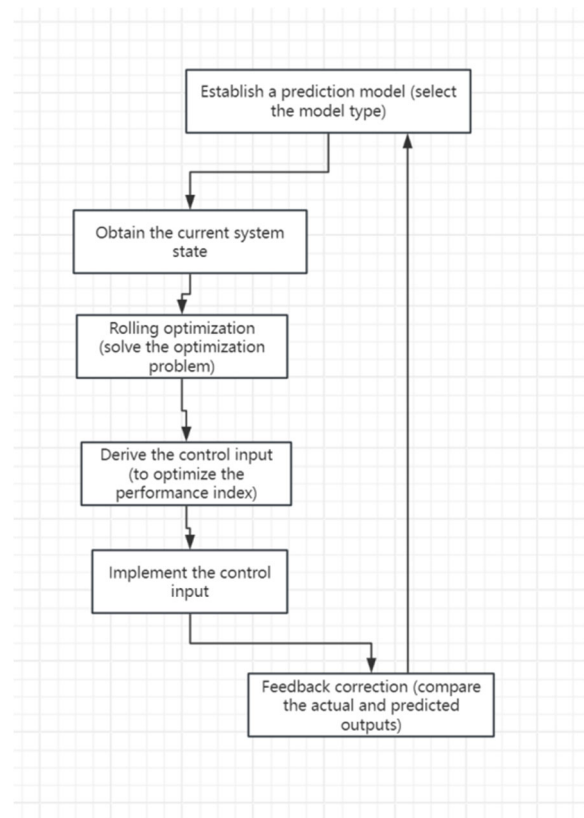


Figure 3. Model Predictive Control

4.3. Neural Network Control

Neural network control is a method of using artificial neural network technology to control a system [14]. Artificial neural network is a mathematical model constructed by mimicking the way neurons in the biological brain are interconnected and process information. It consists of a large number of interconnected neural nodes that complete various complex tasks by receiving, processing, and transmitting information. In the field of control, neural network control is to enable this "artificial brain" to learn and understand the operating rules of the system, and then generate appropriate control signals based on the current state and expected goals of the system to achieve effective control of the system.

Working principle: Firstly, it is necessary to collect a large amount of data related to the controlled system, including input variables of the system (such as control signals, external disturbances, etc.) and corresponding output variables (such as the actual state of the system, performance indicators, etc.). Then, these data are input into the neural network, and the weights of the network are continuously adjusted through learning algorithms to make the output of the network as close as possible to the output of the actual system. This process is like a person accumulating experience through continuous learning and practice, gradually mastering how to better complete a task. This stage is called the training phase. The trained neural network can be used to control the system. In actual operation, neural networks obtain real-time information about the current state of the system as input, calculate appropriate control signal outputs based on learned knowledge and rules, and adjust the system's operation to achieve the desired goals. For example, in the motion control of a robot, a neural network can output signals to control the motor based on the robot's current position, speed, and other information, allowing the robot to accurately complete various actions.

In the load forecasting of V2G systems, neural network

control can be trained by collecting a large amount of data related to charging behavior, learning the complex relationship between user travel habits, electricity pricing policies, and charging demand. After training, it can

accurately predict the charging load of new energy vehicles based on real-time system status information, providing strong support for power grid scheduling and solving the problem of load forecasting.

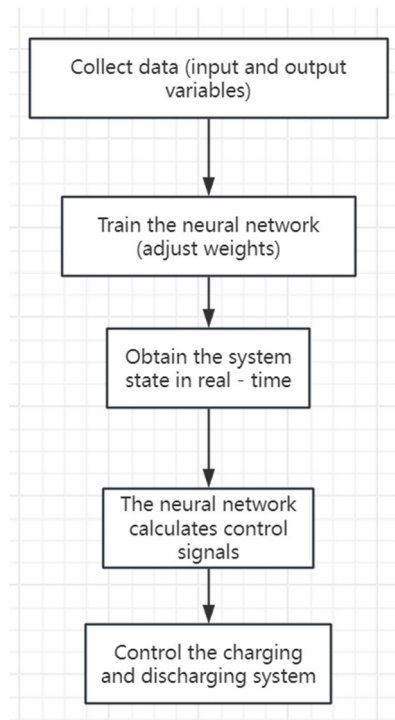


Figure 4: Neural Network Control

Table 1. Advantages and Disadvantages of Each Control Strategy

Control Strategy	Advantage	Disadvantage
Fuzzy control	<ol style="list-style-type: none"> 1. It has excellent robustness, does not require an exact mathematical model, can well cope with the uncertainties of the V2G system, and ensures the stability of the control effect. 2. It has high flexibility and can formulate rules based on experience and expert knowledge to handle multi - input variable tasks. 3. The algorithm is simple, has a small amount of calculation, has low requirements for hardware, and is easy to implement. 	<ol style="list-style-type: none"> 1. Rules are formulated based on fuzzy logic and experience, and it is difficult to guarantee the control accuracy. 2. It is difficult to adjust and optimize in real - time after the rules are determined, and the control performance will decline when the system changes. 3. Errors or oscillations are likely to occur when the system is in a steady - state, affecting the stability of the power grid and the power quality.
Model Predictive Control	<ol style="list-style-type: none"> 1. By establishing a model to predict system behavior and optimizing the control strategy, the control accuracy is high. 2. It can simultaneously take into account multiple objectives such as power grid power balance, voltage stability, and battery life. 3. It can update the strategy according to real - time status and prediction information, and has strong adaptability and dynamic adjustment capabilities. 	<ol style="list-style-type: none"> 1. The control effect highly depends on the accuracy of the model. The V2G system is complex, and the difficulty of modeling is high. Model errors will affect the control performance. 2. A large amount of online calculation and optimization - solving are required, which has high requirements for the performance of computing devices. In a large - scale system, it may not be able to meet the real - time control requirements. 3. It relies on accurate and real - time system states and prediction information. Difficult data acquisition or poor data quality will affect the control effect.
Neural network control	<ol style="list-style-type: none"> 1. It can learn the system rules through a large amount of data and adaptively adjust the control strategy. 2. It is good at handling the complex non - linear relationships between the charging and discharging of electric vehicles and the power grid, with precise control to reduce impacts. 3. It has good fault - tolerance and robustness and can still maintain good performance when some data is abnormal. 	<ol style="list-style-type: none"> 1. The training process is complex and time - consuming, requiring a large amount of high - quality data and powerful computing resources, and data collection and annotation are cumbersome. 2. The decision - making process and basis are difficult to understand, which is not conducive to operators' mastery and trust, and increases the difficulty of system management and maintenance. 3. To achieve real - time computing and response, high - performance hardware devices are required, increasing the system construction and operation costs and limiting the application scope.

5. Conclusion

Vehicle to grid interaction (V2G) technology has enormous potential for improving energy efficiency and developing smart grids. However, large-scale applications face challenges such as power grid shocks, including voltage fluctuations, frequency deviations, harmonic pollution, and load forecasting difficulties. In response to these issues, low grid impact technology strategies have been explored from one aspect: intelligent algorithm control. In intelligent algorithm control, fuzzy control relies on experience to formulate rules, with strong robustness but limited accuracy; Model predictive control has high accuracy and can be optimized for multiple objectives, but it relies on models and has a high computational burden; Neural network control can adaptively learn and handle nonlinear relationships, with complex training and poor interpretability. In the future, V2G technology needs to improve its standard system, enhance market acceptance, and continuously optimize low grid impact technologies to achieve efficient and coordinated development with the power grid.

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