Analysis on V2G Mode Charging and Discharging Circuit Based on Power Exchange Station

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Abstract. With the development of new energy industry, the number of electric vehicles is also climbing gradually, which promotes the steady development of V2G technology. Based on this status quo, this paper discusses the Vehicle-to-Grid (V2G) mode and its significance, especially the positive significance for the grid side, and details the specific working mode of the V2G mode. Based on the context of a power exchange station, this paper describes the charging and discharging circuit of V2G technology and its working principle, and uses MATLAB/Simulink to build a typical three-phase rectifier and active inverter circuit and observe and analyze its waveform. In the battery swap station, it can not only avoid the adverse impact on the power grid due to the large number of electric vehicles connected to the grid in an uncontrolled manner, but also enable vehicle owners to have a simpler and more convenient experience of changing batteries, which is a major trend for future development.

Keywords: V2G technology, three-phase active converters, converter stations.

1. Introduction

With the continuous development of society, the consumption of fossil energy is also increasing year by year, resulting in increasing environmental pollution, energy saving and environmental protection have become the main theme of development in various countries. One of the most significant developments is the development of EVs, with various electric vehicle companies emerging in the commercial market, and new energy vehicle types such as pure electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs), and hybrid electric vehicles (HEVs) coming into being.

The concept of V2G was first proposed by Amory Lovins, and was further researched and developed by Professor Kempton in 1997 [1]. V2G is a two-way interaction between EVs and the power grid, which enables electric vehicles to become energy storage units and to be connected to the grid in an idle state. This will reduce the negative impact of electric vehicles on the power grid, such as the increase in load caused by charging a large number of electric vehicles, which will increase the burden on the power grid, etc., and the V2G mode can regulate the load, "peak shaving to fill in the valley", which is also important for the construction of the smart grid [2].

Based on the current world development and China's "dual-carbon" goal, various enterprises are also actively carrying out the construction of new energy facilities, the most notable one being NIO. As of 25 June 2024, the company has already built 1,500 power stations, and by 2025 it expects to build 3,000 power stations. The purpose of the stations is to centrally store and recharge batteries, so that they can be replaced without having to go to a charging station to meet range requirements. Compared with ordinary charging piles, the advantage of the battery swap station is that it can replace batteries for electric vehicles in a short time, which greatly improves the replenishment speed. At the same time, vehicle owners do not need to worry about the problem of battery degradation, and they can replace the high-performance batteries to ensure a high range experience [3]. Its simple and convenient battery replacement method is very popular among electric car owners and has a strong momentum of development.

This paper will use MATLAB/Simulink for modelling and simulation to explore the three-phase rectifier and active inverter circuits in the V2G mode, apply them to the scenarios of battery swap stations, observe the output waveforms, and summarize the resulting waveforms so that readers can have a deeper understanding of the V2G technology and its inverter circuits in converter stations.

2. Theoretical principal of the V2G model

2.1. V2G technology and its significance

V2G refers to a two-way energy transmission technology between electric vehicles and the grid, also known as "vehicle network interaction" technology. Through the connection of charging facilities and the power grid, new energy vehicles can interact with the power grid in both directions of information and energy, V2G reduces the charging cost of new energy vehicles and is also an important part of the smart grid [4].

From the perspective of energy flow, V2G is mainly divided into three modes: Vehicle to Home (V2H), Vehicle to Building (V2B), and Vehicle to Grid (V2G). Among them, the V2H mode refers to the energy interaction between EVs and residential electric loads, the V2B mode refers to the energy interaction between EVs and commercial building electric loads. The V2G mode refers to the energy interaction between EVs and the grid directly. The core technologies of the three models are the same, mainly including bidirectional charging and discharging devices, energy management systems and communication protocols, as well as pricing and settlement mechanisms. Among them, the V2G on-board bidirectional converter is an important part of the V2G technology, which is the key core equipment and hardware foundation for realizing the energy interaction between EVs and the grid [5]. The schematic diagram of V2G mode is shown in Fig. 1 [6].

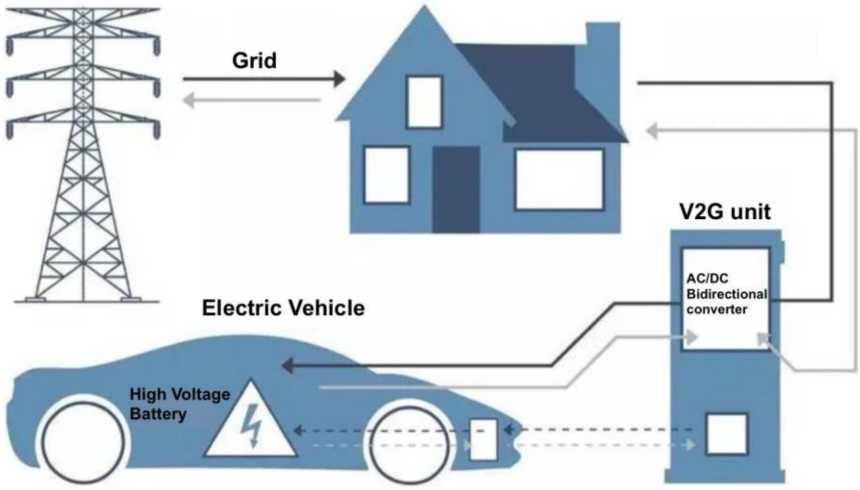

Figure 1. Schematic Diagram of V2G Mode [6]

The realization of V2G technology is of great significance for both users and the grid: 1) EVs interact with the grid through decentralized access and centralized control, i.e. charging the car during low power consumption and enabling the battery to release energy to the grid during peak power consumption. To regulate the peak frequency and reduce the pressure on the grid. 2) Be able to be used as an emergency power source. When sudden natural disasters cause large-scale power outages, V2G access to the power grid can ensure the normal operation of the power system with high reliability and rapid response. 3) Access for distributed power supply to smooth out disturbances. Studies have shown that electric vehicles are parked more than 90% of the time, so they can be regarded as energy storage devices that feed excess energy into the grid. In this way, V2G technology can effectively help the power system to achieve efficient and economical operation [7].

2.2. V2G operating mode of the exchange station

According to the power supply methods, there are four ways to implement the V2G mode.

2.2.1 Centralized V2G

Centralized V2G is a central control system that manages the charging and discharging process of multiple electric vehicles. This method centralizes EVs in a certain area and connects them to a central control system using Telematics for real-time vehicle information monitoring and control. This centralized V2G approach can significantly improve grid stability and reliability, reduce reliance on conventional power plants and promote the use of renewable energy. It requires significant capital investment and technical support. In addition, the overall complexity of implementation is high due to the need to manage a large fleet of electric vehicles.

2.2.2 Autonomous V2G

Autonomous V2G systems are suitable for situations where new energy vehicles are distributed in different locations and cannot be centrally controlled. This mode requires smart charging stations for detecting and managing vehicle status; communication technologies including wired and wireless communication for transmitting vehicle data and managing the interaction between vehicle batteries and the network; and intelligent control algorithms for planning and controlling the charging and discharging of EV batteries by predicting network loads, optimizing charging and discharging strategies, and evaluating battery capacity. This approach has the characteristics of easy charging and use, and is not restricted by space and location, but its charging and discharging behaviors are highly stochastic. Therefore, further research and technical support is needed to determine whether global optimization can be achieved. In addition, although the introduction of on-board chargers increases the cost of electric vehicles, it also improves their practicality and flexibility.

2.2.3 Microgrid-based V2G

A microgrid is a system consisting of loads and micro power sources, including wind power, solar power and other power generation devices, and is connected to the main power grid. Microgrid-based V2G implementations directly target microgrids rather than large grids, and are designed to support distributed energy sources within the microgrid and power their associated loads [1]. This approach is suitable for both domestic and commercial users. The microgrid-based V2G mode of operation realizes bidirectional power exchange between EVs and the microgrid through smart charging piles, communication technologies and control algorithms, which enhances the microgrid's peaking and energy storage capabilities, improves the efficiency and stability of energy utilization, promotes the utilization of renewable energy sources, reduces the dependence on the main power grid and carbon emissions. This model requires well-established communication and control infrastructure, as well as standardized interfaces and protocols.

2.2.4 V2G based on battery pack replacement

V2G technology based on replacing battery packs achieves bidirectional flow of electrical energy by replacing the batteries of electric vehicles. This method relies on the support of smart charging piles, communication technology and intelligent control algorithms, and also requires reliable battery pack replacement technology that enables battery replacement to be completed in a short time. This technology also requires consideration of battery pack safety, ease of use and cost.

At present, there are already technologies that can quickly change battery packs, such as automatic change stations and change boxes. These technologies combine the benefits of fast and traditional charging to solve the problem of insufficient range of some electric vehicles. However, to achieve this approach, uniform standards for batteries and charging interfaces are needed to ensure that different brands and models of electric vehicles are compatible [7]. In the future, the promotion and implementation of V2G technology based on battery pack replacement will require a lot of capital and technical support. In particular, further research and development is needed to build a comprehensive infrastructure, ensure security and enhance the user experience.

This paper mainly discusses the V2G technology of battery swap stations, the technology of sending the electricity generated by electric vehicle batteries back to the power grid in the context of battery swap stations. This mode can not only provide backup power for the grid, but also help balance the load of the grid. Electric vehicles go to the battery swap stations to have their batteries replaced. The intelligent control system of the battery swap station monitors the status of the vehicle batteries and decides whether they need to be recharged. When the electric vehicle is fully charged or has sufficient power, the control system of the battery swap station records and monitors the charging status of these batteries. The battery swap station can communicate with the grid and monitor the grid demand. If the power grid needs more power (such as during peak load) or needs to reduce power (such as during low power consumption), the battery swap station will receive the corresponding signal. According to the demand for electricity, the battery swap station decides to feedback part of the energy stored in the car battery to the power grid. At the same time, the battery swap station will adjust the amount and duration of the feedback process based on the real-time demand of the grid and the remaining power of the electric vehicle. The system of the battery swap station can analyze the data of the grid and the batteries of electric vehicles to improve the overall efficiency and stability.

Compared with common charging piles and charging stations, the most significant advantages of battery swap stations lie in their significant impact on the grid: (1) Battery swap stations can balance the load. Battery swap stations can charge batteries when the power grid load is low and provide fully charged batteries to vehicles during peak hours, which is the so-called "peak shaving and valley filling", thereby helping to balance the power grid load. (2) Battery swap stations can keep the power grid stable. By controlling the charging time and speed of battery swap stations, the power grid can better manage power demand, avoid power grid congestion through centralized charging, and improve power grid stability. (3) Battery swap stations can collect and centrally manage data. Battery swap stations can collect a large amount of data on electric vehicle usage and charging needs, providing important information for network optimization and management. (4) Battery swap stations can promote the use of renewable energy. Battery swap stations can increase the use of renewable energy by charging large amounts of electricity during peak renewable energy generation periods (such as solar energy during the day) and supplying power at other times. (5) Battery swap stations can reduce the pressure on power distribution. The centralized charging and battery swapping model at battery swap stations reduces the demand for high loads on the power grid by households or businesses, alleviates the pressure on the distribution system, and reduces the investment and maintenance costs of the distribution system. In summary, it can be concluded that the investment in V2G in battery swap stations is beneficial to the power grid, making this technology of great significance to the future development of power grids and electric vehicles.

3. V2G Working Principle

3.1. Analyisi of V2G Charge and Discharge Modelling

In general, the charging and discharging model in V2G mode generally consists of a filter, a bidirectional AC/AC converter, and a bidirectional AC/DC converter, and the two-stage V2G structure is shown in Fig. 2 [8].

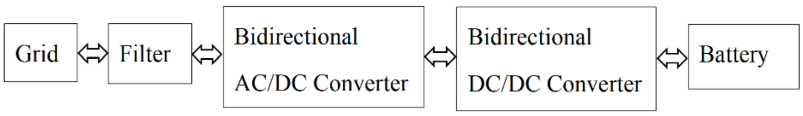

Figure 2. Two-stage V2G structure (Photo/Picture credit: Original)

The main function of AC/DC converters used in V2G technology is to provide bidirectional energy exchange [9]. From the perspective of charging from the power grid to the electric vehicle, the main function of the AC/DC converter is to achieve rectification, DC side output voltage control and power factor correction; in the discharge direction, the AC/DC converter can achieve DC inverter function, output current control and grid connection. [10].

The system has two operating modes. During system operation, the bidirectional AC/DC converter operates in rectification mode to charge the electric vehicle battery. The alternating current passes through a filter to remove unwanted frequency components and is forwarded to a bidirectional

AC/DC converter, which converts it into direct current. Since the output voltage of the bidirectional AC/DC converter is not necessarily consistent with the DC side voltage, a bidirectional DC/DC converter must be used to ensure the correct charging voltage [1]. In the other mode, the bidirectional AC/DC converter operates as an inverter and the battery serves as a constant voltage power source for the grid. During the discharge process, the battery transfers electrical energy to the DC side energy storage device to keep the DC side voltage stable, and the bidirectional DC/DC converter increases the voltage of the grid, which is in boost mode [11, 12].

3.2. Working principle of rectifier charging circuit

The topology of a three-phase bridge rectifier circuit is shown in Fig. 3.

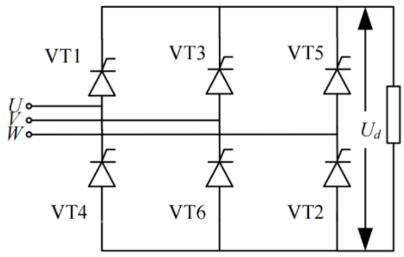

Figure 3. Three-phase bridge rectifier circuit topology diagram [13]

The circuit mainly includes six switching devices, which are connected into a bridge structure. The three thyristors VT1, VT3, and VT5 at the cathode are connected together, which is called a common cathode group, and the three thyristors VT4, VT6, and VT2 at the anode are connected together, which is called a common anode group. This configuration allows current to flow through the load in a precise sequence, thus producing an even and smooth DC current at the output. The sequence and timing of the thyristors is controlled by an external trigger signal to obtain the desired voltage waveform and current waveform. The thyristor conduction sequence for a three-phase bridge rectifier circuit is VT1-VT2-VT3-VT4-VT5-VT6. Thyristor conductivity conditions indicate that for a cathode group with a phase potential higher than that of the other two phases, the thyristor is conducting in that phase; and vice versa for a common anode. In order to form a loop in the rectifier circuit, it is necessary to ensure that both the common cathode and anode group each have a conducting thyristor at the same time [14].

3.3. Principle of operation of inverter discharge circuit

The difference between inverter and rectifier is mainly the difference in control angle. When the angle of the control angle is at 0°~90°, the circuit works in the rectifier state; at 90°~180°, the circuit works in the inverter state [15]. The topology diagram of the three-phase active inverter circuit is shown in Fig. 4.

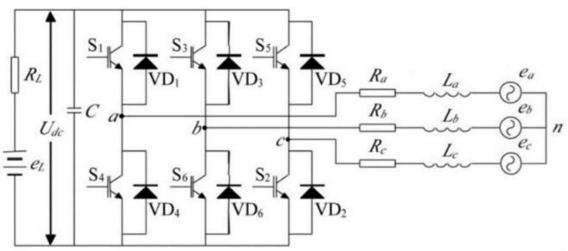

Figure 4. Three-phase active inverter circuit topology diagram [16]

A voltage type three-phase inverter circuit, which is composed of three half-bridge circuits. Its main function is to convert DC to AC by controlling the opening and closing of the switching tubes. Switching devices can be used full-control devices, VD1 ~ VD6 for the renewal diode. Three-phase inverter circuit conductive mode for 180° conductive, that is, each bridge arm of the conductive angle of 180°, the same phase of the upper and lower two bridge arms alternately conduct current, each phase begins to conduct the electrical angle difference of 120°.

Two main conditions are required to realize an active inverter. Firstly, the external condition is that the DC side of the inverter must be connected to a DC power supply whose voltage polarity is consistent with the forward conduction direction of the thyristor, and the voltage value of the power supply must be higher than the average voltage of the DC side of the inverter. This condition ensures that the inverter circuit receives sufficient power to convert DC to AC. Secondly, the internal condition is that the inverter must operate in a specific region, i.e., the control angle needs to be greater than π/2. By the combined action of these two conditions, the active inverter converts DC to AC and returns the power to the grid.

4. Simulation and Results

4.1. Introduction to MATLAB/Simulink

MATLAB is widely used in power system modeling and analysis. Its openness enables it to provide powerful development tools, thus always staying at the forefront of science and engineering. The Simulink environment is the graphical modeling function of MATLAB. It has vivid and practical modeling and simulation functions and is very popular among users [17].

MATLAB/Simulink provides a toolkit for the modelling and simulation of power electronic systems, highlighting the characteristics of the power electronics discipline, and is an ideal tool for research, development and application of power electronics technology. MATLAB/Simulink enables us to directly create circuit simulation models and arbitrarily modify the simulation parameters to obtain simulation results immediately. Through Simulink's modelling simulation, the signals and waveforms presented by the rectifier circuit can be visualized under different simulation models and parameters. Therefore, this paper uses MATLAB/Simulink simulation software for simulation.

4.2. Simulation content

In this paper, the use of MATLAB/Simulink to establish a bidirectional three-phase bridge rectifier and active inverter circuit model, which includes a DC power supply, three-phase AC power supply, resistors, capacitors, switching devices and other electrical components, as well as a pulse generator, voltage measurements and current measurements, oscilloscopes used to observe the input and output waveforms. Due to the rectifier technology has been more mature in the international arena, so this part of the content will not be repeated, the main part of the discussion for the inverter part of the V2G technology. Bidirectional three-phase bridge rectifier and active inverter circuit diagram shown in Fig. 5.

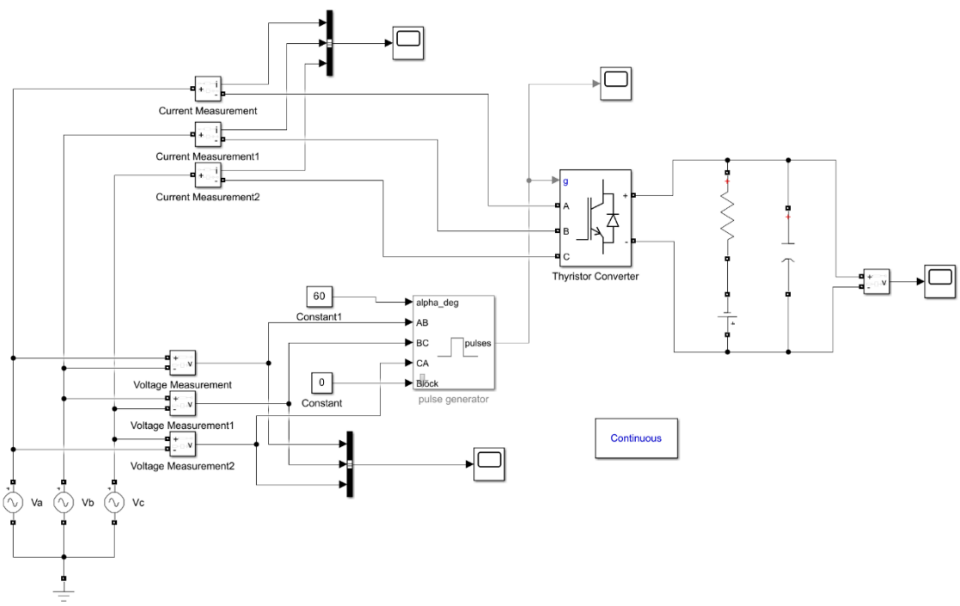

Figure 5. Simulation Circuit Diagram (Photo/Picture credit: Original)

In the simulation diagram, the DC side is set as a battery to simulate the actual electric vehicle battery; the AC side is set as a three-phase power supply to simulate the operation of the grid. In the simulation circuit, the voltage peaks of Va, Vb, and Vc are all set to 220V, the angles are set to 0, 120, and 240 degrees respectively, and the frequency is set to 50Hz. Among them, Thyristor Converter is set to three bridge arms, the switching device is set to IGBT/Diodes, and the cache resistor is set to 50Ω. The DC side battery voltage is set to 100V, the series resistor is set to 5Ω, and the capacitor is set to 5F.

Setting the frequency of the synchronous six-pulse generator to 50 Hz and the pulse width to 10. The output waveform of the synchronous six-pulse generator is shown in the Fig. 6., there are six pulse triggers in each cycle, and the blue, green, purple, yellow, red, and black lines represent the six pulses in a cycle.

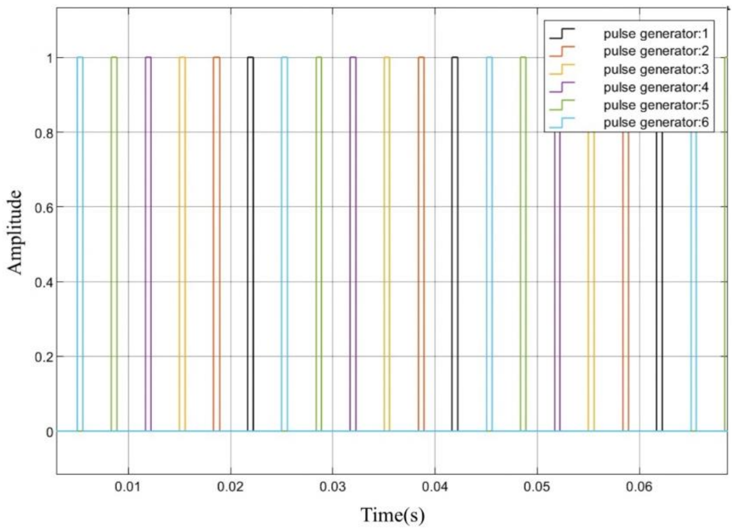

Figure 6. Synchronous six-pulse generator waveform (Photo/Picture credit: Original)

The DC-side output voltage waveform and AC-side output voltage waveform are shown in Fig. 7 and Fig. 8, where the DC-side voltage is stabilized at 380V and the AC-side voltage is shown as a sinusoidal waveform. From the output waveforms, it can be seen that the waveforms of the three-phase active inverter circuit in V2G mode are also applicable based on the scenario of the battery swap station.

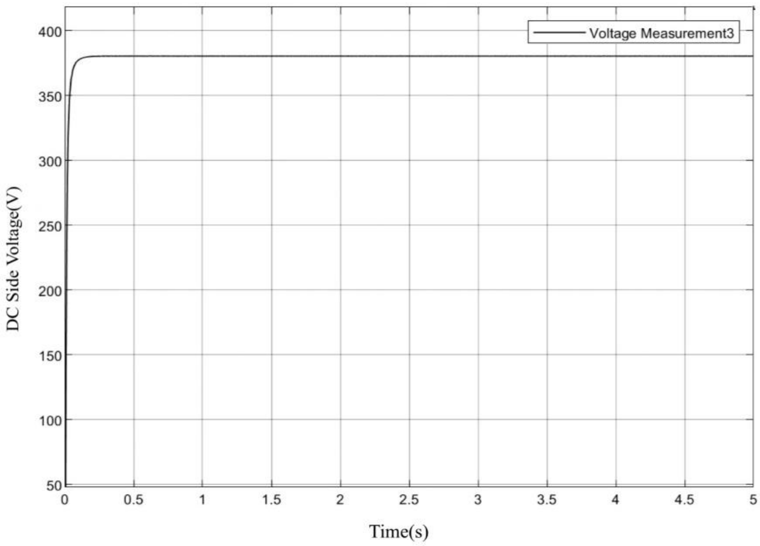

Figure 7. DC Side Voltage Waveform (Photo/Picture credit: Original)

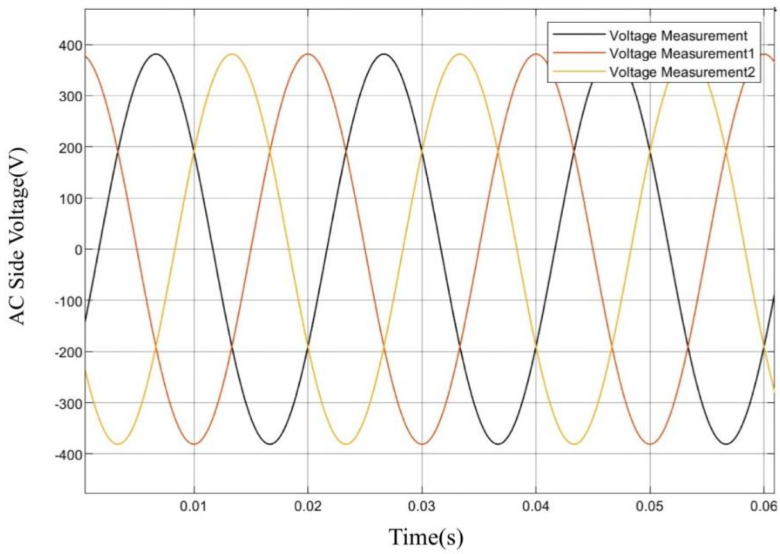

Figure 8. AC side three-phase voltage waveform (Photo/Picture credit: Original)

5. Conclusion

Nowadays, the development of industry has brought increasingly serious environmental problems to the world, the energy crisis has also become a threat, and the proportion of new energy vehicles is also increasing. Focusing on the development of V2G technology for new energy vehicles can not only alleviate current environmental problems, but also bring benefits to users and power grids. Car owners can meet their driving needs, benefit from V2G services; power grid companies can reduce load fluctuations through V2G to ensure its safe and stable operation. The V2G model based on the scenario of battery swapping stations will also become an emerging development trend in the future.

Based on the working principle of V2G mode, this paper builds a three-phase rectifier and active inverter circuit model using MATLAB/Simulink, then simulates and analyses it. It can be shown that the V2G technology can obtain a stable and desired output voltage waveform using typical three-phase rectifier and active inverter circuits under the switching station mode. There is no doubt that V2G mode has become a major development trend, and it also of great significance for the development of V2G technology and the construction of smart grids in the future in the context of battery swap stations.

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