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A Wireless Bidirectional Power Supply Topology Suitable for Vehicle-to-Grid Technology

Xiaoyan Jiang*[1] and Chuan He+

Abstract – *Vehicle-to-grid (V2G) technology facilitates bidirectional energy exchange between electric vehicle batteries and an electric power grid. This is an important component of smart grid technology, which not only can alleviate the problem of power grid fluctuations owing to the use of intermittent energy sources like wind and solar power, but also can benefit users of electric vehicles. In recent years, the development of wireless power transmission has provided a new route for electric vehicle charging and discharging. The absence of physical contact offers numerous advantages such as flexible mobility and safety, and is therefore more suitable for application to V2G technology. This paper proposes a bidirectional wireless energy transmission topology appropriate for V2G based on the characteristics of wireless energy transmission, and discusses the feasibility of applying wireless power transmission to V2G charging and discharging energy interactive systems. A power flow control strategy is also given according to the constant current source characteristics of this topology. Finally, the effectiveness of this topology and related control strategy is verified by simulation.*

Keywords – bidirectional converter, electric vehicle network, wireless charging.

1. INTRODUCTION

Increasingly prominent problems associated with environmental degradation and the supply of conventional energy sources has increased the urgency of environmental protection, greenhouse gas emission reduction, energy conservation, and sustainable industrial development. These issues are particularly relevant to electrical power grids, which are profoundly affected by the increasing access of a variety of new energy sources represented by solar and wind energy. The intermittent nature of these sources causes numerous problems such as high-permeability and instability. Therefore, a more advanced power grid technology is required to provide more secure, flexible, reliable, clean, economical, and user-friendly electrical energy. To facilitate the development of this future technology, many countries and organizations represented by the United States and the European Union have unanimously proposed the building of smart power grids [1]. In addition, Chinese power industry is promoting the development of smart grid technology.

Simultaneously, the transport sector, which consumes a large portion of available energy, is promoting the development of electric vehicles, which are valued for their low-carbon emissions, energy savings, and environmental friendliness, and are an inevitable trend in the auto industry. From the perspective of battery charging, electric vehicles as a charging load will have a substantial impact on electrical power grids [2],[3]. In Shanghai, for example, electric vehicle sales are expected to reach about 350,000 vehicles, according to a market penetration rate of 15%. Based on a 12 kW·h battery per vehicle configuration for an equivalent discharge rate of 0.8, the daily electricity consumption of these electric vehicles will be about 3.36 million kW·h, which represents a substantial burden on the electrical generation, transmission, and distribution of the power system, resulting in increased peak-valley electric load differences. However, from the perspective of battery discharge, electric vehicles can serve as distributed energy storage devices. for power systems, representing a large-scale active energy storage resource to guarantee and optimize the operation of power grids [4],[5]. To reduce the impact of electric vehicle charging on the power grid, and to develop simultaneously the potential of electric vehicles as large-scale distributed energy storage devices, vehicle-to-grid (V2G) technology [6]-[10] has been proposed, and has been included as a significant aspect in the development of future smart grid technology.

V2G technology embodies the two-way, real-time, controllable, and high-speed energy flow between electric vehicles and power grids. The spinning reserve realized by employing electric vehicles as mobile distributed energy storage devices provides a new approach to power grid peak regulation. In addition, V2G technology can stabilize the fluctuations in the power grid caused by intermittent energy sources such as solar and wind power.

The interaction of the charging and discharging of electric vehicles with power grids is a key aspect of V2G technology, and serves as the basis for realizing the mobile energy storage function of electric vehicles. In recent years, the development of wireless power

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transmission has provided a new means of charging and discharging electric vehicles with good prospects for development owing to the numerous advantages associated with the absence of physical contact, such as flexible mobility and safety. Considering that wireless power transmission can better meet the requirements of flexible and efficient interaction between electric vehicles and power grids via V2G technology, this paper proposes a bidirectional wireless power transmission topology to explore the feasibility of applying wireless power transmission to an interactive V2G charging and discharging system. A strategy for controlling the power flow is also provided according to the constant current source characteristics of this topology. Finally, the effectiveness of this topology and related control strategy for interactive V2G charging and discharging are verified by simulation.

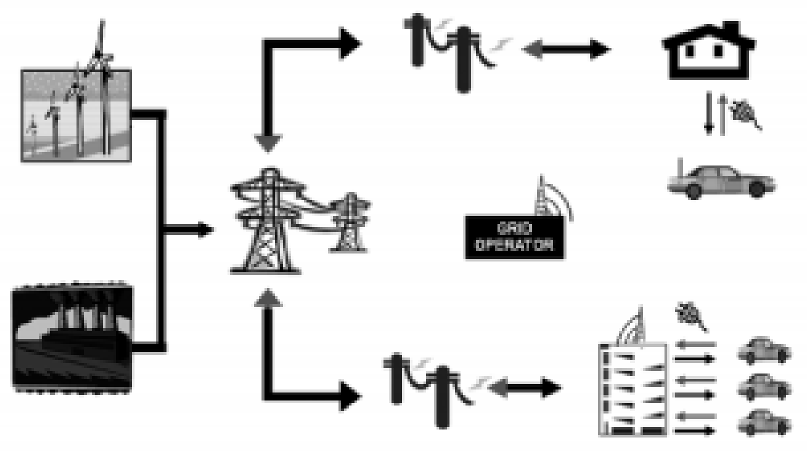


Fig. 1. Schematic diagram of V2G technology.

2. MATERIALS AND METHODS

2.1 Wireless Transmission Technology for Electric Vehicles

Presently, wireless charging technology for electric vehicles has gained considerable attention. Wireless charging mainly employs processes based on electromagnetic induction and magnetic resonance [11]. A wireless charging facility is illustrated in Figure 2, and is divided into two parts: the first involves a transmitter circuit installed in the roadbed, and the second involves a receiver circuit installed in the chassis of an electric vehicle. The transmitter circuit modulates the commercial frequency alternating current (AC) obtained from a power grid into a high-frequency electromagnetic field, and the receiver circuit couples to the alternating electromagnetic field energy around the transmitter circuit by means of resonance at the same frequency as the transmitter. The coupled energy is routed to the onboard battery charger in the form of an alternating voltage for conversion into a DC voltage for charging the battery.

Compared to conventional charging platforms, wireless charging eliminates the use of conductive cabling while charging, which provides for the following advantages.

1) Greater flexibility and convenience. Wireless charging devices can be installed any place where a vehicle can be parked, including the workplace, home, shopping malls, parking lots, garages, and even the road side. For battery charging, a user need only park their vehicle at a charging site. With the additional development of wireless charging technology, it will be possible in the future for electric vehicles to connect to the grid while moving.
2) Greater safety and no requirement for interface standardization. The elimination of conductive cabling solves the problems associated with inconsistent charging cable interfaces. In addition, wireless charging produces no sparks, so it can be used in a humid environment with minimal concern.
3) Reduced construction investment. Urban land is becoming increasingly scarce, which makes the allocation of land resources increasingly difficult and expensive. The installation of wireless charging facility transmitters under the road paving can eliminate the need for the construction of large-scale charging facility sites, which would greatly reduce the required level of investment. Moreover, the development of one-to-many wireless charging technology would further reduce the area required for charging facilities.

A mature wireless charging technology would capitalize on the above advantages of wireless power transmission, and facilitate the use of wireless bi-directional converters to meet the requirements of future V2G technology for the flexible interaction between power grids and electric vehicles. Therefore, it is necessary to study the bidirectional wireless transmission topology applicable to V2G. Madawala *et al.* [12] proposed a converter topology for a high-frequency isolated DC/DC two-stage structure with a single-phase pulse-width modulated (PWM) rectifier in the front and an inductive power transfer (IPT) at the back. This topology employs LCL series-parallel resonance to realize the zero-voltage switching (ZVS) turn-on of 8 switch tubes in the DC/DC structure. In addition, the direction and volume of energy flow can be controlled by adjusting the phase difference between the voltages of a single receiver coil and the transmitter coil. Thus, simultaneous V2G interaction between multiple electric vehicles and the power grid can be achieved. This solution can effectively reduce site requirements. The previous design of Madawala *et al.* required the inductance of the primary/secondary compensation inductor to be equivalent to that of the power coil. This paper further extends this topology to reduce this symmetry requirement and make the selection of compensation network parameters more flexible.

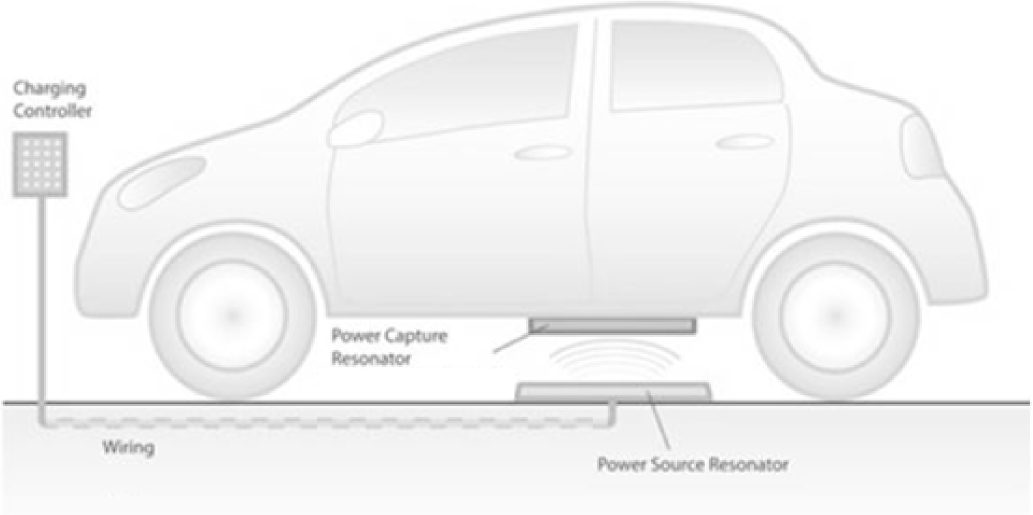


Fig. 2. Wireless charging of electrical vehicle batteries.

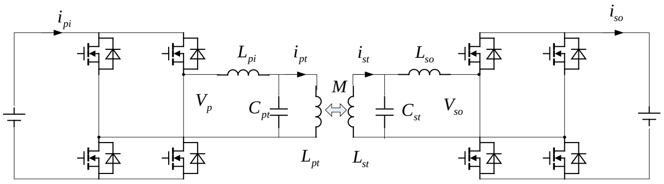


Fig. 3. LCL bidirectional wireless power transmission topology.

2.2 Topological Modeling of a Bidirectional Wireless Converter

The following LCL bidirectional converter circuit was established according to the previously proposed bi-directional converter topology [9].

The primary and secondary sides are the LCL inverter bridge topology with the primary side connecting to the DC power grid and the secondary side connecting to the electric vehicle charging load. The primary inverter bridge is controlled by feedback, so that the AC current I_{pt} flowing through the primary coil L_{pt} maintains a constant amplitude and resonant frequency. Secondary-side inverter phase-locked control allows the output voltage V_{so} to track the primary inverter frequency and phase. By adjusting the phase difference of the output AC voltages from the inverters on two sides, the power flow direction can be controlled. Thus, the bi-directional power flow between the power grid and electric vehicles can be achieved. Here, L_{pt} and the compensation inductance L_{pi}, and the secondary coil L_{st} and the compensation inductance L_{so}, are not required to employ equivalent parameters.

In the steady state, the voltage induced by L_{st} is $V_{si} = j\omega MI_{pt}$, where $j = \sqrt{1}$, is the resonant frequency, and M is Mutual inductance between the primary and secondary coils. The alternating magnetic field generated by L_{st} ensures that the voltage induced by L_{pt} is $V_r = -j\omega MI_{st}$, where I_{st} is the current flowing through L_{st}. The bidirectional converter circuit can be expressed as given in Figure 4.

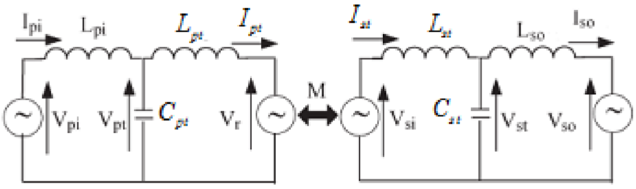


Fig. 4. Simplified T-type equivalent circuit.

In the circuit, the primary and secondary inverters are equivalent to controllable AC voltage sources V_{pi} and V_{so} , respectively. The operating frequency is equivalent to ω . The following relationships are established:

$$\omega^2 = \frac{1}{L_{pi}C_{pt}} = \frac{1}{L_{so}C_{st}} \tag{1}$$

Under the condition of Equation (1), the primary and secondary LCL compensation networks have the characteristics of constant current sources. Then, the primary current can be represented by V_{pi} and V_r , as follows.

$$\begin{aligned} I_{pi} &= I_{pi} + I_{C_{pt}} = \frac{V_{pi}}{j\omega L_{pi}}\left[1+\left(j\omega L_{pt}\right)\left(j\omega C_{pt}\right)\right]+V_r\left(j\omega C_{pt}\right) \\ I_{pt} &= \frac{V_{pi}}{j\omega L_{pi}} \end{aligned} \tag{2}$$

Similarly, the secondary current is given as follows.

$$\begin{aligned} I_{so} &= I_{st} + I_{C_{st}} = -\frac{V_{so}}{j\omega L_{so}} + \left[-\frac{V_{so}}{j\omega L_{so}} j\omega L_{st} - V_{si}\right]\left(j\omega C_{st}\right) \\ &= -\frac{V_{so}}{j\omega L_{so}}\left[1+\left(j\omega L_{st}\right)\left(j\omega C_{pt}\right)\right] - V_{si}\left(j\omega C_{st}\right) \\ I_{st} &= -\frac{V_{so}}{j\omega L_{s0}} \end{aligned} \tag{3}$$

Assuming that the parasitic losses of the primary and secondary compensation networks are neglected, the transmission power depends on the transmitting/receiving power of the primary/secondary transmitting/receiving coils. With reference to the secondary receiving power, the transmission power is given as follows.

$$\begin{aligned} P_{tran} &= V_{si} I_{st}{}^{*} = \left(j\omega M I_{pt}\right)\left(-\frac{V_{so}}{j\omega L_{s0}}\right)^{*} \\ &= \frac{M}{\omega L_{s0} L_{pi}} V_{pi} V_{so}{}^{*} \end{aligned} \tag{4}$$

As can be seen from the above equation, controlling the relative phases between V_{so} from the controllable secondary inverter and V_{pi} from the primary inverter can control the energy flow direction. Assuming the relative phase lag between V_{so} and V_{pi} is θ, the active power obtained from the secondary side is:

$$P_{tran} = \frac{M}{L_{st}} \frac{V_{pi}}{\omega L_{pt}} \left|V_{so}\right| \sin(\theta) \tag{5}$$

3. RESULTS

3.1 Simulation Model

The following simulation model was established according to the bi-directional converter topology shown in Figure 5.

3.2 Parameter Settings

The primary DC voltage was 400 V, the secondary DC voltage was 200 V, $C_{pt} = C_{st} = 13.6\mu F$, $L_{pi} = L_{so} = 20\mu H$, $L_{pt} = L_{st} = 30\mu H$, , the operating frequency was 20 kHz, and the coupling coefficient between the primary and secondary coil $k = 0.27$. The primary side inverter employed a current closed-loop control switch duty cycle to provide a 150 A AC current with constant amplitude flow in the primary coil. The voltage phase difference reference was obtained according to the transmission power instruction.

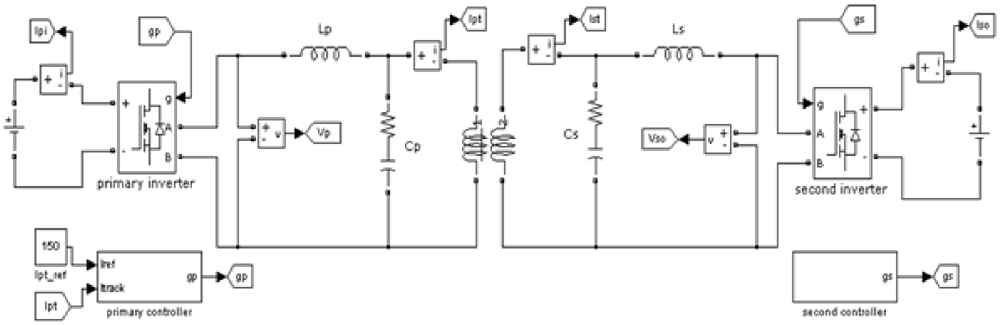
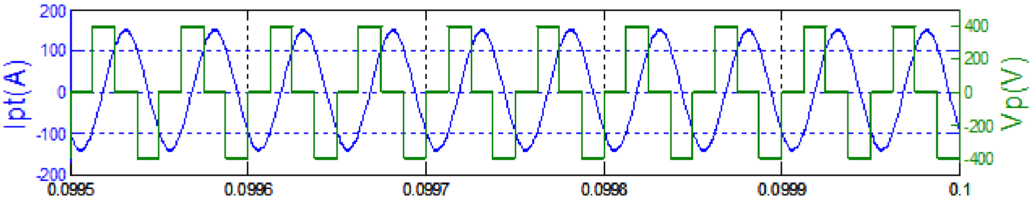


Fig. 5. Simulation module of the bidirectional converter.

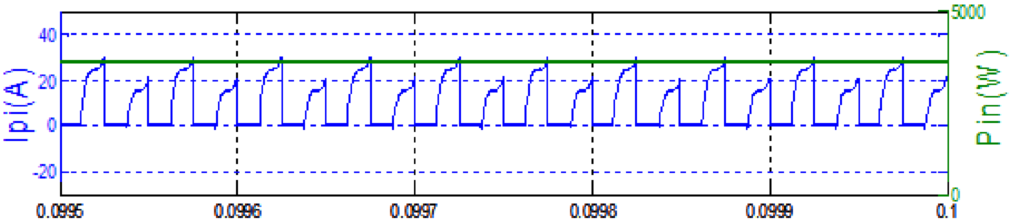
4. DISCUSSIONS

By controlling the secondary inverter switch trigger time, the output voltage of the secondary inverter maintained a given phase difference with respect to the primary inverter output voltage. The following two cases were simulated.

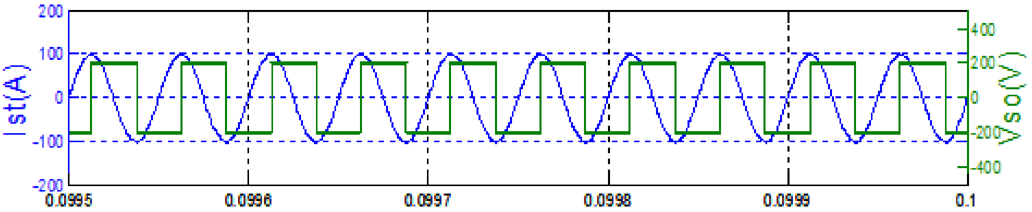
(1) A charging load receiving power of 3 *k*W.



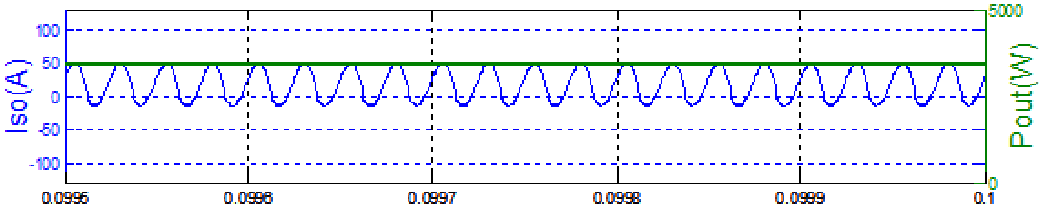
(a) Primary inverter output voltage Vpi and primary coil current Ipt (with an amplitude set at 150 A).



(b) Current and input power on the primary DC side.



(c) Secondary inverter output voltage Vso and the secondary coil current Ist



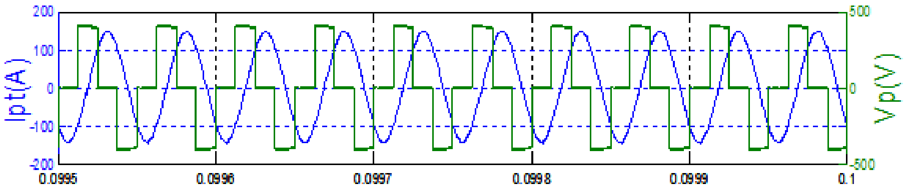
(d) Current and output power on the secondary DC side.

Fig. 6. The secondary side receives 3 kW of power.

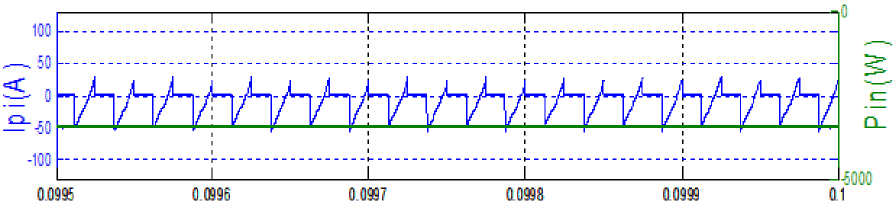
From the simulation results, it can be seen that the output of the primary inverter is positive active power, and the output of the secondary inverter is negative active power, indicating that the power is transferred from the primary side to the secondary side. The power closed-loop adjustment produces a phase lag of about π/2 between V_{so} and V_{pi}.

(2) A charging load output power of 3 *k*W

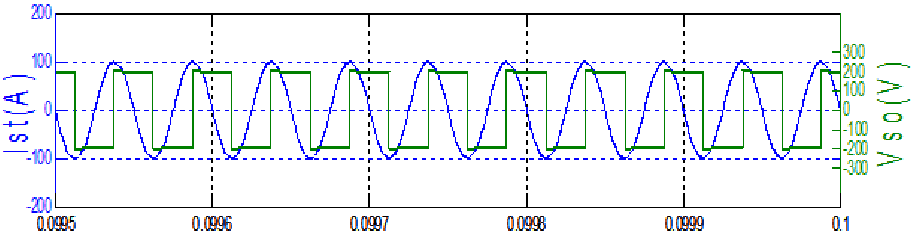
From the simulation results it can be seen that the primary inverter outputs negative active power, while the secondary inverter outputs positive active power, indicating that the power is transferred from the secondary side to the primary side. The power closed-loop adjustment produces a phase lead of about π/2 between V_{so} and V_{pi}.



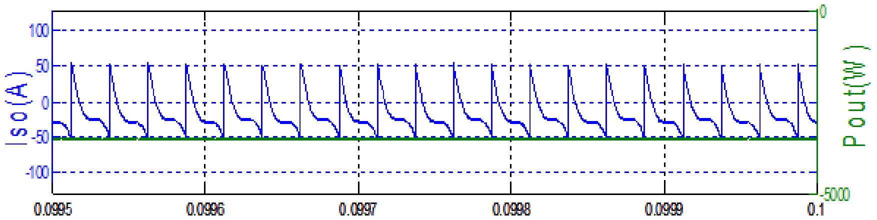
(a) Primary inverter output voltage Vpi and primary coil current Ipt (with the amplitude set at 150 A).



(b) Current and input power on the primary DC side.



(c) Secondary inverter output voltage Vso and the secondary coil current Ist.



(d) Current and output power on the secondary DC side.

Fig. 7. The secondary side outputs 3 kW of power.

5. CONCLUSION

This paper has summarized the basic concepts of V2G and wireless electrical power technology. Based on the characteristics of wireless energy transmission, a new V2G bi-directional wireless energy transmission topology was proposed, and the feasibility of applying wireless power transmission to a V2G charging and discharging energy interaction system was discussed. Theoretical and simulation analyses were conducted for an LCL bi-directional converter suitable for the bidirectional transmission of wireless power. The simulation results showed that, when the system parameters were selected as a constant current source network, the inductance parameters were not required to be symmetrical, and the bidirectional control of energy flow could be realized well when operating at the resonant frequency. Therefore, the LCL bi-directional converter topology presented in this paper provided a favorable foundation for the application of wireless power transmission technology to the V2G system.

ACKNOWLEDGEMENTS

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