Research on the Topology of Wireless V2G for Electric Vehicle

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Abstract. Based on the circuit topology for the electric vehicle wireless V2G power transmission system, the boost circuit, wireless resonance circuit and grid-connected inverter circuit of the system were studied. According to the characteristics of the boost converter, a voltage feedback closed-loop control model based on PID and PWM was established. Since the excitation and magnetic leakage of the wireless transmission coil could not be ignored, the maximum transmission power model of the wireless resonance circuit was derived. Starting from the operation mode of the three-phase grid-connected inverter circuit, the control rules of the three-phase bridge arm that sent electrical energy back to the grid in a steady state were obtained. The simulation results showed that the maximum transmission power of the electric vehicle wireless V2G power transmission system was affected by the leakage magnetic field of the wireless transmission coil, and the maximum transmission power was inversely proportional to the leakage magnetic field. In addition, the boost circuit and grid-connected inverter circuit in the system were sources of harmonics, and a large amount of harmonic energy was sent to the grid during the operation process of the electric vehicle wireless V2G circuit.

1. Introduction

At present, most electric vehicle manufacturers in China use the wired charging mode, but due to the specialty of electric vehicles and the high cost of installing charging piles, wireless charging technology has entered the public's view. Without using cables, the car can be charged in any place with a wireless charging device even while the car is running. It greatly improves the driving range and charging efficiency of electric vehicles, and at the same time does not require the user to manually operate the charging plug, which improves the safety of charging [1].

Among the wireless charging technologies for electric vehicles, electromagnetic induction WPT and electromagnetic resonance WPT are suitable for electric vehicle charging because of their relatively high efficiency. For electromagnetic resonance WPT, there have been many researches in the field of transmission coil structure, resonance network, system characteristics and power electronics [2]. Nowadays, electric vehicle wireless charger circuit topology and control technology have achieved great improvements, such as varying frequency, constant frequency PWM, phase-locked loop control, etc. [3]. In the field of the resonance network topology research, there are mainly series (Series, S) compensation, parallel (Parallel, P) compensation, series parallel (LCL) compensation, and other compensation networks derived on this basis. Many literatures have focused on different resonance modes, primary-side capacitance of the compensation network, stability conditions, input impedance and system transmission efficiency optimization methods.
Compared with wired charging, the wireless charging system is suitable for V2G (vehicle to grid). It realizes the bidirectional flow of energy between electric vehicles and the grid, and has strong advantages in power grid peak shaving and valley filling, no-load standby, peak power regulation, automatic generation control, etc. [4].

In this paper, the topology of electric vehicle wireless V2G circuit was studied, the mathematical models of BOOST circuit, wireless resonance network and grid-connected inverter circuit in the circuit topology were established. Based on the mathematical models, the electric vehicle wireless V2G circuit was analysed by computer simulation.

2. Wireless V2G topology

The circuit topology of the electric vehicle wireless V2G charging system was shown in Figure 1, where E was the voltage provided by the electric vehicle battery, and Uc was produced by the BOOST circuit in the DC/DC conversion [5].

The H-bridge circuit composed of S2, S3, S5, and S6 realized DC/AC conversion. The H-bridge adopted a phase-shift control method, which adjusted the output power of the system by adjusting the phase-shift angle of the current on the transmission coil. The output power of the system was controlled by phase shift control without adding additional hardware circuits, and when the primary side was resonant, zero voltage switching could be achieved under the condition of a phase shift angle of 180°.

In order to ensure the bidirectional controllability of the system and the symmetry of the topology, the primary and secondary sides adopted the same resonant network, and the high-frequency conversion units were all realized by the H-bridge.

On the secondary side, the H-bridge converted alternating current into direct current first and then the direct current was inverted into three-phase alternating current which met the requirements of power grid through the DC/AC circuit.

![Figure 1. Wireless V2G topology.](image)

3. System model

3.1. Boost circuit model

The voltage feedback closed-loop control boost converter based on PID and PWM was shown in Figure 2 [6].

![Figure 2. Boost close-loop control system.](image)

In Figure 2, the PID controller calculated the control variable U from the error signal between the reference voltage Uref and the output voltage Uo to control the duty cycle of the PWM output switch signal. In this paper, a proportional integral controller was used, which was shown as below [7]:

\[
G_P(s) = K_p + \frac{K_i}{\tau_i s}
\]  \hspace{1cm} (1)
The PWM unit converted the control variable $u$ from voltage signal to duty cycle $D$, and its transfer function was as follows:

$$D = \frac{t_{on}}{T} = \frac{u}{KT}$$  \hspace{1cm} (2)

In formula (2), $K$ was the slope of the rising edge of sawtooth wave.

The main circuit topology of boost was shown in the Figure 3.

![Figure 3. Boost circuit topology.](image)

When the battery discharged, DC/DC was in a boost state, $S4$ was controlled by the signal to turn on or off, and $S1$ was always in the off state.

When $S4$ is on, the transient process of the circuit was given by formula (3):

$$E - L_1 \frac{di(t)}{dt} - R_i \cdot i(t) = 0$$ \hspace{1cm} (3)

When $S4$ is off, the transient process of the circuit was given by formula (4):

$$E + L_1 \frac{di(t)}{dt} - R_i \cdot i(t) - U_o = 0$$ \hspace{1cm} (4)

Ideally, the internal resistance of the battery was $R_1=0$ and the inductor itself did not consume energy, then the output voltage could be calculated by formula (5):

$$U_o = E \frac{t_{on}+t_{off}}{t_{off}}$$ \hspace{1cm} (5)

From formula (2), (5), the output voltage could be expressed as:

$$U_o = \frac{EK}{KT}$$ \hspace{1cm} (6)

### 3.2. Wireless resonance circuit model

The wireless resonant circuit adopted LCC resonant topology. Due to the influence of the position offset between the transmission coils of electric vehicles, the magnetic leakage of the transmission coil in the wireless resonant circuit could not be ignored. The wireless resonant circuit with the excitation and magnetic leakage of the transmission coil was shown in Figure 4.

![Figure 4. Wireless resonant circuit.](image)

In Figure 4, $Lm1$ was the excitation inductance of the transmission coil, $Ls1$ and $Ls2$ were the primary and secondary leakage inductance of the transmission coil, and $L3$ and $L4$ are the inductance
of the transmission coil. According to KVL, the steady state process of the circuit was given by formula (7):

\[
\begin{align*}
\dot{U}_o &= jwL_2 \dot{l}_2 + \frac{j}{wc_2} l_{c2} + jwL_{s1} \dot{l}_{c2} + jwL_3 \dot{l}_1 + jwMl_2 \\
\dot{U}_o &= jwL_2 \dot{l}_2 + \frac{L_2 - l_{c2}}{wc_1} \\
l_{c2} &= \frac{l_{c2}}{wc_2} + jwL_{s1} \dot{l}_{c2} + jwL_{m1}(\dot{l}_{c2} - \dot{l}_2) \\
\dot{U}_i &= jwL_6 \dot{l}_{1b} + jwL_{s2} + jwL_4 \dot{l}_2 + jwMl_4 \\
l_{1b} &= \frac{jwL_6 \dot{l}_{1b} + jwL_4 \dot{l}_2 + jwMl_4}{wc_4} \\
\end{align*}
\]

(7)

In formula (7), \(M = k\sqrt{L_3 L_4}\) was mutual inductance between primary and secondary sides of transmission coil, \(K\) is coupling coefficient.

The LCC resonance topology was derived from the LCL topology, and its resonance conditions were shown in formula (8):

\[
\begin{align*}
l_2 &= \frac{1}{wc_1} = wL_{s1} + \frac{wL_{m1}L_3}{L_{m1} + L_3} - \frac{1}{wc_2} \\
l_6 &= \frac{1}{wc_4} = wL_{s2} - \frac{1}{wc_3} + wL_4
\end{align*}
\]

(8)

Then the active transmission power of the wireless resonance circuit was shown as below:

\[
P = Re(\dot{U}_o \dot{l}_{c2}) = Re(\dot{U}_i \dot{l}_{1b}) = \frac{M wC_1 l_{m1}}{L_6 L_{m1} + L_3} |U_o||U_i|\cos(\theta_o - \theta_i - \frac{\pi}{2})
\]

(9)

The reactive transmission power of the wireless resonance circuit was shown as below:

\[
Q = Im(\dot{U}_i \dot{l}_{1b}) = \frac{M wC_1 l_{m1}}{L_6 L_{m1} + L_3} |U_o||U_i|\sin(\theta_o - \theta_i - \frac{\pi}{2}) + \frac{M^2 wC_4}{L_6 L_{m1} + L_3} |U_i|^2
\]

(10)

When the phase difference between \(U_o\) and \(U_i\) was 90°, the maximum active transmission power could be calculated by formula (11):

\[
|P_{max}| = \frac{M wC_1 l_{m1}}{L_6 L_{m1} + L_3} |U_o||U_i|
\]

(11)

When the phase difference between \(U_o\) and \(U_i\) was 180°, that is reversed, the maximum reactive transmission power could be calculated by formula (12):

\[
|Q_{max}| = \frac{M wC_1 l_{m1}}{L_6 L_{m1} + L_3} |U_o||U_i| + \frac{M^2 wC_4}{L_6 L_{m1} + L_3} |U_i|^2
\]

(12)

3.3. Grid-connected inverter circuit model

When the electric vehicle discharged to the grid through the wireless V2G network, it operated in a three-phase inverter state, and both the active power \(P\) and the reactive power \(Q\) were sent back to the grid [8]. The phase difference between the voltage and the current was 180°. The three-phase grid-connected inverter circuit was shown in Figure 5.

In Figure 5, \(U_a, U_b, U_c\) were the three-phase grid voltage, \(L_a, L_b,\) and \(L_c\) were the filter inductors, and \(R_a, R_b,\) and \(R_c\) were the equivalent resistance on lines a, b, and c respectively. \(I_a, I_b,\) and \(I_c\) were three-phase currents.

The unipolar logic binary function \(S_k\) was defined:

\[
S_k \begin{cases} 
0 & \text{The upper arm of kth bridge is on} \\
1 & \text{The upper arm of kth bridge is off}
\end{cases}, \text{and the lower arm is on}
\]

(13)
In formula (13), \( k = a, b, c \).

According to KVL, the transient process of the circuit was given by formula (14).

\[
\begin{align*}
L \frac{di_a}{dt} + Ri_a &= U_a - (U_c'S_a + U_{N0}) \\
L \frac{di_b}{dt} + Ri_b &= U_b - (U_c'S_b + U_{N0}) \\
L \frac{di_c}{dt} + Ri_c &= U_c - (U_c'S_c + U_{N0}) 
\end{align*}
\] (14)

In formula (14), \( U_{N0} = -\frac{U_c'}{3}(S_a + S_b + S_c) \), \( L_a = L_b = L_c = L \), \( R_a = R_b = R_c = R \). During operation process, the bridge control rules of three-phase grid-connected inverter circuit satisfied the formula (15)

\[
\begin{align*}
S_a - S_x &= \frac{u_a - L \frac{di_a}{dt} - Ri_a}{U_c'} = S_1 \\
S_b - S_x &= \frac{u_b - L \frac{di_b}{dt} - Ri_b}{U_c'} = S_2 \\
S_c - S_x &= \frac{u_c - L \frac{di_c}{dt} - Ri_c}{U_c'} = S_3 
\end{align*}
\] (15)

In formula (15), \( S_x = \frac{S_a + S_b + S_c}{3} \).

According to formula (15), the three-phase grid-connected inverter circuit could fit the curves of \( S_1 \), \( S_2 \) and \( S_3 \) by controlling the on and off of three-phase bridge, so as to send the power to the grid.

4. Simulation results

4.1. Simulation results of boost circuit

The parameters of boost circuit model were shown in Table 1.

| Table 1. Parameters of Boost circuit model |
|------------------------------------------|
| Parameter | Value |
| Kp        | 0.000005 |
| K         | 500000  |
| T         | 0.0002  |
| \( \tau_i \) | 1/4000\pi |
| Uref      | 700V    |
| L1        | 2mH     |
| E         | 350V    |
The boost circuit simulation model was shown in Figure 6.

![Simulink model of boost circuit](image)

Figure 6. Simulink model of boost circuit.

The simulation results were shown in Figure 7 and Figure 8.

![Output of boost circuit](image)

Figure 7. Output of boost circuit.
4.2. Simulation results of wireless resonance circuit

The parameters of the wireless resonance circuit model were shown in Table 2.

| Parameters | Value          |
|------------|----------------|
| C1         | 5000μF         |
| C2         | 50μF           |
| C3         | 50μF           |
| C4         | 5000μF         |
| Lm1        | 50μH           |
| |Un|   | 600V          |
| |Ut|   | 600V          |
| k          | 0.4            |
| Ls1        | 10nH-100nH     |

When the leakage inductance $L_s1$ changed in the range of 10nH-100nH, the simulation results of $|P_{\text{max}}|$ and $|Q_{\text{max}}|$ were shown in Figure 9 and Figure 10.
Figure 10. The relationship between maximum reactive power and leakage inductance.

4.3. Simulation results of grid-connected inverter circuit
Grid-connected inverter circuit model parameters were shown in Table 3.

| Parameters | Value |
|------------|-------|
| L          | 2mH   |
| R          | 0.2Ω  |
| Ua         | $220\sqrt{2}\cos(2\pi f kT)$ |
| Ub         | $220\sqrt{2}\cos(2\pi f kT - \frac{2}{3}\pi)$ |
| Uc         | $220\sqrt{2}\cos(2\pi f kT + \frac{2}{3}\pi)$ |
| f          | 50Hz  |
| T          | 0.0002 |
| Uc’        | 400V  |
| I          | 10A   |
| ia         | $I\cos(2\pi f kT + \pi)$ |
| ib         | $I\cos(2\pi f kT + \frac{\pi}{3})$ |
| ic         | $I\cos(2\pi f kT + \frac{5\pi}{3})$ |

The control rules Sa, Sb, Sc of the three-phase bridge were shown in Figure 11.
According to formula (15) and the control rules of Sa, Sb, and Sc, the fitting curves of S1, S2, and S3 were shown in Figure 12.

5. Summary
According to the circuit topology of the electric vehicle wireless V2G power transmission system, the models of the boost circuit, the wireless resonance circuit and the grid-connected inverter circuit were established. Based on the models, the output characteristics of the boost circuit, the relationship between the maximum transmission power and the leakage magnetic inductance, and the control rules of the grid-connected inverter circuit under steady state were analysed by computer simulation.

The simulation results showed that:
(1) During the operation process of the voltage feedback closed-loop control boost circuit based on PID and PWM, the harmonic energy output was inevitable.
(2) The maximum transmission power of the wireless resonance circuit was affected by the leakage magnetic field of the wireless transmission coil, and the maximum transmission power was inversely proportional to the leakage magnetic field.

(3) The control rules of the three-phase bridge of the grid-connected inverter circuit achieved a fitting method of producing the grid-connected current and voltage waveforms, but the harmonic energy generated during the control process was simultaneously sent to the grid.

For future research, we will focus on the design of low leakage magnetic inductance transmission coil, improving wireless transmission power, reducing harmonic power and decreasing the impact on the power grid.

References
[1] Lu, Y. Xu, S. (2018) Wireless charging technology and its application in electric vehicles. Manufacturing research, 12:110-111.
[2] Zhao, Z., Liu, F., Chen, K. (2016) New Progress of Wireless Charging Technology for Electric Vehicles. Transactions of China Electrotechnical Society, 31(20):30-40.
[3] Cai, L., Chen, Q., Ren, X. Ruan, X. (2012) Review of the Efficient Wireless Power Transmission Technique for Electric Vehicles. Transactions of China Electrotechnical Society, 27(8):2-13.
[4] Cai, L., Gao, L., Xu, Q., Zhang, W. (2020) Research and application progress in V2G key technology of electric vehicle. Battery Bimonthly, 50(1): 87-89.
[5] Chen, Y., Liang, X., Zhou, J. (2017) Overview of topology of Bidirectional DC-DC converter. Electrical Automation, 39(6): 1-6.
[6] Zhu, W. (2012) Design and Simulation of boost circuit feedback controller. Silicon Valley, 1:71-72.
[7] Chen, K., Zhao, Z. Liu, F. Yuan, L. (2017) Resonant topology analysis of bidirectional wireless charging system for electric vehicles. 41(2): 66-71.
[8] Deng, W., Liu, Y., Guo, Y., Shen, C. (2019) Three-Port Converter Based on 3-1MC and Its Application in V2G. Transactions of China Electrotechnical Society, 34(2): 618-628.