Integrated Control with Energy Optimization Management of Frequency and Load Tracking for Wireless Power Transfer Systems

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Abstract
Wireless power transfer (WPT) systems are desired to provide constant output voltage with the highest possible efficiency as power supplies. In order to solve the problem of reducing the transmission efficiency caused by the dynamic change of the load condition, the coupling coefficient, the inductance coil, the compensation capacitor and the frequency offset, a method for frequency and load tracking control for WPT systems was presented in this paper. The efficiency of WPT system is analyzed through the equivalent model of transmitter and receiver circuit, the optimized value of the load impedance matching under the maximum efficiency of the system was obtained. The efficiency expression was deduced when the coil detuned by normalized inductance change, then we reveal that the inductance of transmitter coil was one of the main influencing factors of system efficiency. An efficiency evaluation method is put forward to evaluate the closed-loop control schemes. Based on integrated control strategy of average current polarity and phase-shifted pulse width modulation, the frequency and load tracking can be achieved at the same time. The MATLAB/Simulink experimental results show that the resonant frequency was tracked and output voltage was maintained constant. A very high overall efficiency was achieved over wide ranges of the inductance, coupling coefficient and load resistance.

Key words: Electromagnetic Resonance, Wireless Power Transmission, Coupling Efficiency, Frequency Tracking, Power Control.

1. INTRODUCTION

Wireless power transfer (WPT) has been preferred in many daily and industrial applications since Tesla’s principle of wireless transmission of energy (Marincic, 1982).

WPT based on magnetic resonant coupling is demonstrated to be an efficient approach to transfer power in near-field (Kurs and Karalis, 2007). Comparing with the other two popular WPT technologies - electromagnetic induction and the microwave power transfer, WPT of magnetic resonant coupling has a good balance between power transfer distance and efficiency. In recent years, more research is focused on improving the efficiency of energy transfer and output voltage accuracy. However, the output voltage and the efficiency of an open-loop WPT system depend strongly on the coils’ coupling coefficient, working frequency and the system’s load (Chen and Chu, 2010). For example, the load conditions change because during the charging of a battery and coupling coefficient is changed by the position of the receiving coils. The working frequency offset resonant frequency when the inductance and capacitance parameters are changed. Therefore, in this paper, the proposed integrated control system is intended to satisfy the requirements for both a constant output voltage and high efficiency (Lee and Zhong, 2012; Takanashi and Sato, 2012).

At present, the high frequency power of the system is mainly composed of a signal generator and a radio frequency signal power amplifier to generate a sinusoidal power signal drive system (Sample and Meyer, 2011). The power of this structure has advantages of wide band adjustment, but due to the RF signal power amplifier has larger resistance seriously affect the overall efficiency of the system. Lower output power greatly limits the application range of the magnetically coupled resonant wireless power transmission. Frequency tracking control cannot be achieved when the system is disturbed by external influences, which leads to the sharp decrease of output power and efficiency. In the reference (Zhang and Wong, 2014), a compensation scheme is proposed to achieve high transmission efficiency and good voltage range under large load variation conditions. Reference (Gao and Ginart, 2016) analyzes the main factors that affect the efficiency of WPT, and the control method of high frequency inverter operating frequency synchronous tracking the natural resonant frequency of transmission circuit is proposed, but the influence of the load change on the receiving circuit and the constant voltage output is not considered. In(Florian and Mastri, 2014; Stoecklin and Youaf, 2016; Zhong and Hui, 2015), the DC-DC converter is used in the receiver module to emulate the optimal load value, the proposed
method follows the maximum energy efficiency operating points of a wireless power transfer system by searching for the minimum input power operating point for a given output power. Experimental results are included to confirm its feasibility, but it has not considered the problem of the loss of harmonic and the coupling factor. In (Beh and Kato, 2013; Pinuela and Yates, 2013), using the impedance matching method to adjust the frequency in a certain range through the relay or a semiconductor switch to adjust the resonant capacitor, and constant output voltage regulation by changing impedance, but the impedance matching circuit is very complex, the control system to achieve more difficult. In the literature (Bertoluzzo and Buja, 2016), the frequency tracking control is realized by the direct tracking of the emitter current frequency, and the DSP and FPGA are used as the controller, which has high speed and high precision.

The energy integration management control strategy is proposed in this paper includes frequency tracking control and load tracking control which can meet the requirements of constant output voltage and high efficiency. The remainder of this paper is organized into five sections. Following the Introduction, section 2 analyses the modeling and the efficiency of WPT system. In the section 3, the scheme and flow of energy integration management control are proposed. Section 4 shows how the proposed work was verified using simulation experimental results and the analysis of the effects on the frequency tracking and output power stability of WTP system. The two different methods were selected to optimize power transfer while inductance variation. Section 5 summarizes the research conclusions.

2. EFFICIENCY ANALYSIS OF WPT SYSTEM

In Figure 1, the WPT is mainly composed of the transmitting loops and the receiving loops, which can transmit wireless energy through the same frequency resonance of the transmitting coil and the receiving coil. The transmitting loops comprise a power supply, a high frequency inversion circuit, a driving circuit, a coil and a primary resonance compensation network, and the high frequency inversion circuit provides energy through the electromagnetic field to the receiving loops. The receiving loops mainly comprise a receiving coil, a secondary resonant compensation network, a high frequency rectifying voltage stabilizing circuit and a load. The receiving coil receives the electric energy and generates a DC power supply load through a high frequency rectification voltage stabilizing circuit to realize the wireless power supply.

![Figure 1. Configuration of a magnetic resonance WPT system](image)

The efficiency of WPT can be defined as the ratio of the power of the load and the power of the power supply, the power efficiency can be simplified as follows:

$$\eta = \frac{P_{out}}{P_{in}}$$  \hspace{1cm} (1)

From the Figure 1, the whole system is composed of the transmitting part, the coupling part and the receiving part, so the efficiency of the whole system can be divided into the transmitting efficiency, the coupling efficiency, the receiving efficiency, and the power efficiency is presented as follows:

$$\eta = \eta_f \cdot \eta_c \cdot \eta_j$$  \hspace{1cm} (2)

Where, $\eta_f$ is the transmitting efficiency, $\eta_c$ is the coupling efficiency, $\eta_j$ is the receiving efficiency.

The transmitting efficiency is mainly determined by the efficiency of the inverter, the coupling efficiency is mainly determined by the resonant compensation network, the coil parameters and other factors, and the receiving efficiency is mainly determined by the efficiency of the rectifier. When the high frequency inverter and the rectifier topology are determined, the $\eta_f$ and the $\eta_j$ are fix value, and the transmission efficiency of the system is determined by the coupling efficiency. Because the coupling part is a bond between the receiver and the transmitter, the coupling efficiency directly affects the structure of the receiver and the transmitter.
Figure 2. Simplified model of WPT coupling circuits

Consider a simple WPT system with its equivalent circuit shown in Figure 2, the impedances of transmitting and receiving loops are respectively expressed as

$$Z_t = R_t + j(\omega L_t - \frac{1}{\omega C_t})$$  \hspace{1cm} (3)

$$Z_r = R_t + R_r + j(\omega L_t - \frac{1}{\omega C_t})$$ \hspace{1cm} (4)

Assuming that the power losses in the ferrite plates that shield the transmitting and receiving coils are negligible, the coupled circuit equations for the system are expressed as

$$\begin{bmatrix} U_1 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_t & -j\omega M \\ -j\omega M & Z_r \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$ \hspace{1cm} (5)

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \frac{1}{Z_tZ_r + \omega^2 M^2} \begin{bmatrix} Z_r & j\omega M \\ j\omega M & Z_t \end{bmatrix} \begin{bmatrix} U_1 \\ 0 \end{bmatrix}$$ \hspace{1cm} (6)

From formula (6), the $I_1$ and $I_2$ are the current vectors of the transmitting and receiving loops respectively, which can be expressed as:

$$I_1 = \frac{Z_tU_1}{Z_tZ_r + \omega^2 M^2} = \frac{U_1}{Z_t + \frac{\omega^2 M^2}{Z_t}}$$ \hspace{1cm} (7)

$$I_2 = \frac{j\omega M U_1}{Z_tZ_r + \omega^2 M^2} = \frac{j\omega M I_1}{Z_r}$$ \hspace{1cm} (8)

Assuming the core losses in the magnetic ferrite plates and the power inverter losses are negligible, the energy efficiency of a WPT system can then be expressed as:

$$\eta = \frac{\frac{U_1}{Z_tZ_r + \omega^2 M^2}}{\frac{I_1}{U_1}} = \frac{(\frac{j\omega M U_1}{Z_tZ_r + \omega^2 M^2})^2 R_r}{Z_tU_1^2} = \frac{\omega^2 M^2 R_r}{(Z_tZ_r + \omega^2 M^2)Z_r}$$ \hspace{1cm} (9)

When the receiving loops and the transmitting loops of the system are in the resonant state

$$\omega L_t - \frac{1}{\omega C_t} = 0 \hspace{0.5cm} \omega L_r - \frac{1}{\omega C_r} = 0$$ \hspace{1cm} (10)

Transmission efficiency can be expressed as:

$$\eta =\frac{\omega^2 M^2 R_r}{(R_2 + R_r + \omega^2 M^2)(R_2 + R_r)}$$ \hspace{1cm} (11)

From the above, when resonance, the equivalent impedance is the smallest and the current is the largest of the transmitter and the receiver, so the transmission efficiency is the highest. The transmission efficiency of the system is determined by the load and the frequency when the transmission distance and the position are given. In order to ensure the maximum energy transfer efficiency of the WPT system, the resonant frequency and load variation must be tracked during the whole process.
The resonant frequency is mainly related to the inductance of the coil and the compensation capacitance, and the parameters change will lead to the frequency detuning, and the transmission efficiency will be reduced. At resonance, the compensating capacitor at the transmitter and the receiving end can be expressed as:

\[
\begin{align*}
C_1 &= \frac{1}{\omega R_1 Q_1} = \frac{1}{\omega^2 L_1} \\
C_2 &= \frac{1}{\omega R_2 Q_2} = \frac{1}{\omega^2 L_2}
\end{align*}
\]

To simplify the analysis, changes the inductance and capacitance values are normalized to the equivalent that the capacitance value is constant and the inductance value is changed.

In the same conditions of normalization, the impedances of transmitting and receiving loops at resonance are respectively expressed as

\[
\Delta Z_t = R_1 + j(\omega(L_1 + \Delta L_1) - \frac{1}{\omega C_1}) = R_1 + j\omega\Delta L_1
\]

\[
\Delta Z_r = R_2 + R_3 + j(\omega(L_2 + \Delta L_2) - \frac{1}{\omega C_2}) = R_2 + R_3 + j\omega\Delta L_2
\]

Where, \(\Delta L_1\) and \(\Delta L_2\) are change of the inductance, respectively.

At this time the system efficiency can be expressed as:

\[
\eta = \frac{\omega^2 M^2 R_1}{(\Delta Z_t \Delta Z_r + \omega^2 M^2)\Delta Z_r}
= \frac{\omega^2 M^2 R_1}{(R_1 + j\omega\Delta L_1)(R_2 + R_3 + j\omega\Delta L_2) + \omega^2 M^2}(R_2 + R_3 + j\omega\Delta L_2)
\]

The natural frequencies of the transmitter and the receiver are respectively expressed as

\[
\omega_1 = \frac{1}{\sqrt{(L_1 + \Delta L_1)C_1}}
\]

\[
\omega_2 = \frac{1}{\sqrt{(L_2 + \Delta L_2)C_2}}
\]

\[
\omega_1 \neq \omega_2 \neq \omega
\]

In this case the operating frequency of the power is inconsistent with the inherent resonance frequency of the coil. When a certain distance and location of the transmitting and receiving coils, the efficiency of the system is affected caused by transmitting and receiving coils detuned as shown in Figure 3.

\[\text{Figure 3. Efficiency versus transmitting and receiving coils detuned}\]

From Figure 3, when the transmit coil inductance value offset ± 1μH, namely ± 4% of the theoretical value, the system efficiency is decreased by about 10%. But, when the same offset receiver coil inductance occurs, the system efficiency is essentially unchanged.

For a parameter established system, if the transmission distance and the resonant frequency of a certain, then the corresponding system transmission efficiency will be determined. Therefore, the offset of the inductance value of the transmitting coil is one of the main factors of the efficiency decrease in the working process of the system. When the system is in the resonance state, derivation for \(R_1\) in formula (15).
\[ \frac{\partial \eta}{\partial R_L} = 0 \]  
(19)  

Figure 4. Efficiency versus load change

When the maximum efficiency is obtained. The optimal value of the equivalent load impedance can be expressed as:

\[ R_L = R_{L_{op}} = \sqrt{\frac{1 + (\omega M)^2}{R_1 R_2}} R_2 \]  
(20)

Therefore, the maximum efficiency of WPT system is expressed as

\[ \eta_{\text{max}} = 1 - \frac{2}{\sqrt{1 + \frac{(\omega M)^2}{R_1 R_2} + 1}} \]  
(21)

When a distance and position between the transmitter and the receiver is fixed, the effect of the load change on the system efficiency is shown in Figure 4.

3. ENERGY INTEGRATION MANAGEMENT CONTROL STRATEGY

Energy integration management control strategy is composed of two parts, frequency tracking control and load tracking control, which make the system track the resonant frequency and keep the constant output power when the circuit parameters, the coupling coefficient and the load change. The energy optimization management of frequency and load tracking based on different combinations of two control variables, until the point of maximum efficiency is achieved and locked for the required power level. Frequency and load tracking control block diagram shown in Figure 5.

Figure 5. Frequency and load tracking control block diagram
From Figure 5, the full-bridge inverter consists of the four MOSFETs. The control variables are the DC bus current polarity average $u$ and the shifting-phase angle $\phi$ of the driving pulse of MOSFETs. The $\phi$ is equal to the phase difference between the relative-leg driving signals.

3.1. Frequency Tracking Control

Frequency tracking is designed to control the inverter output frequency is the same as the resonant frequency of the coil, and when the change of parameters can track the resonant frequency, which can make the power switch loss to zero, so the energy transfer efficiency of WPT reached the maximum.

$$\omega_1 = \omega_2 = \omega$$ (22)

The detuning caused by the change of coil inductance leads to the change of the equivalent load impedance angle at the receiver end, which causes the DC bus current polarity to change. The time that the current is less than zero and greater than zero is obtained by zero comparator after the bus current is detected from the transmitting loops, and then convert them into polarity signals, output the high level $U$ and the low level 0 after that we can get the polarity average $u$. Frequency tracking control block diagram shown in Figure 6.

3.2. Load Tracking Control

Load tracking control using phase-shifted pulse width modulation (PS-PWM). When the system works in the resonant frequency, the variation of the load will cause the change of circuit quality factor, which leads to a decrease in transmission efficiency. The purpose of power control is to provide a constant power to the load and the maximum transmission efficiency.

In the process of frequency tracking, power control is an open loop. After the operation frequency is equal to the resonant frequency, the control of the output voltage RMS is realized by adjusting the phase shift angle of the two bridge arms of the high frequency inverter, so as to control the output power. The load tracking control block diagram is shown in Figure 8.
The fundamental voltage amplitude is

\[ U_{\text{lm}} = \frac{4U_d}{\pi} \cos \frac{\varphi}{2} \]  

(23)

The RMS values of fundamental harmonic of inverter output voltage is expressed as

\[ U_i = \frac{2\sqrt{2}U_d}{\pi} \cos \frac{\varphi}{2} \]  

(24)

The RMS values of fundamental harmonic of inverter output current is expressed as

\[ I_i = \frac{2\sqrt{2}U_d}{\pi(R + \frac{(\omega M)^2}{R_i})} \cos \frac{\varphi}{2} \]  

(25)

Assuming that the output power factor is 1, the relationship between the output power and the phase shift angle in the PS-PWM control mode can be expressed as

\[ P = U_i I_i = \frac{8U_d^2}{\pi^2(R + \frac{(\omega M)^2}{R_i})} \cos^2 \frac{\varphi}{2} \]  

(26)

From formula (26), the output power will be changed with \( \varphi \) in the PS-PWM, the change trend of the per-unit value of output power and \( \varphi \) as shown in Figure 9. The whole change trend is monotone decreasing, which proves the feasibility of PS-PWM modulation.

Because the switching frequency of the high frequency inverter is typically in the order of tens of hundreds of kilo-Hertz, so the control action of the converter can be much faster than that of the load impedance. The load resistance can be assumed to be constant in the iterative search process of the maximum transmission efficiency point. The phase shift angle of the drive pulse of the bridge arm will maintain a constant voltage output which means the output power is constant. When the WPT system is operating at the resonant frequency, the power supply voltage is regulated until the input power of the transmitter circuit reaches a minimum value. Therefore, when a minimum input power point is found, it is also a maximum efficiency point.

The control flows of frequency and load tracking are described as follows.

1. If \( f = f_0 \), control of frequency tracking is not required. When \( f > f_0 \), the Polarity mean value \( u \) is detected, and if the \( u \) is close to the high level \( U \), only small steps are required to approximate the resonant frequency. If the \( u \) is far away from the \( U \), the resonant frequency is approximated by a long stride length. When the \( f < f_0 \), tracking method is the same.

2. When the system is in resonant state, the initial voltage of the power supply is set to \( V_{\text{in0}} \) according to the given load power \( P_{\text{out}} \). The initial value of shifting-phase angle is \( \varphi_0 \).

3. Adjust the power supply voltage to \( V_{\text{in}} \), so that the output voltage of the receiving loop \( V_{\text{out}} \) is equal to the rated voltage of the load, and the phase shift angle of the bridge arm of the high frequency inverter is \( \varphi_i \).
4. To measure and record the input power of the transmitter \( P_{in0} \). The input AC voltage \( V_{in} \) is then increased or decreased slightly (e.g, \( \Delta V_{in} = \pm 5\% V_{in0} \)) to a new value \( V_{in1} = V_{in0} \pm \Delta V_{in} \). Changing the input AC voltage to the transmitter coil on the primary side will change the input DC voltage of the receiver side.

5. Once again, the inverter will be forced to regulate its shifting-phase angle in order to regulate the output voltage. Now the shifting-phase angle is denoted as \( \phi_2 \).

6. The input power \( P_{in1} \) to the Transmitter coil is measured and recorded.

7. Compare \( P_{in1} \) and \( P_{in0} \). If \( P_{in1} \) is smaller than \( P_{in0} \) (which means the energy efficiency of the system rises), then repeat step 4 and 5 until the input power stops decreasing. Then a minimum input power point or a maximum efficiency point is found. Otherwise, if \( P_{in1} \) is larger than \( P_{in0} \) (which means the energy efficiency of the system decreases), then the searching direction is reversed (i.e. apply \( V_{in1} = V_{in0} - \Delta V_{in} \)). Similarly, repeat step 4 and 5 until the input power stops decreasing and a maximum efficiency point is found.

8. The optimum operation point will be kept for a designated time interval, say \( T \).

9. After this time interval \( T \), a new searching process will start from this selected operating point in case that the load and the coupling have varied.

4. EXPERIMENTAL RESULTS AND ANALYSIS

As shown in Figure 10, the simulation model of the whole magnetically coupled resonant WPT system was created in MATLAB/Simulink software, and then it simulated under the condition of the device parameters and simulation parameters were set. This method was testified correctly and flexibly by analyzing the simulate result. Simulations are performed for the component values of Table I.

<table>
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<th>Type / Value</th>
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</tr>
<tr>
<td>M</td>
<td>1.78μH</td>
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<tr>
<td>C1, C2</td>
<td>11.2nF</td>
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<tr>
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<td>f0</td>
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</tr>
</tbody>
</table>

Table 1. Simulation component values

Figure 10. The simulation model of the whole magnetically coupled resonant WPT system

The \( i/f \) module is shown in Figure 11, and the \( u/f \) module is shown in Figure 12.

Figure 11. The module of current-to-frequency
Without frequency tracking of the voltage and current waveforms are shown in Figure 13(a) and (b).

When the inductance value of the transmitting coil is changed, the output voltage of the power supply and the loop current of the transmitting coil have a large phase difference, so that the load voltage and current in the receiving coil are reduced and the output power and system efficiency are decreased.

When the frequency tracking mode based on the average value of the current polarity is used, the power supply is close to the actual high frequency inverter, and the simulation results are shown in Figure 14.
When the transmitter coil inductance value changing, the output voltage of the inverter and the transmitting coil loop current remains the same phase, then makes the receiving coil circuit in the load voltage and current remains unchanged, to ensure the constant output power and efficiency.

The simulation of frequency tracking is shown in Figure 15 (blue for the working frequency, pink for the resonant frequency). After 5μs, the frequency of operation is coincident with the resonance frequency, that is, frequency tracking is realized.

The phase shift pulse generator module is shown in Figure 16. Among them, Out2, Out1 is the leading bridge arm, and Out3, Out4 is the lag bridge arm. Four bridge arms have a certain time of dead time. The phase shift angle between Out1, Out2 and Out3, Out4 can be adjusted. The simulation waveform of phase shift pulse is shown in Figure 16.
By formula (24) - (26) the power control model can be obtained as shown in Figure 18. The simulation results of power control are shown in Figure 19, in the whole process, the output power is maintained at 1kW.

Figure 18. The model of power control

The system reaches the optimum point after 0.05ms as shown in Figure 20. The simulated of phase shift angle curve of the two bridge arms of the high frequency inverter is displayed in Figure 20. It can be seen that phase shift angle is 0 before 7μs, where the system tracks the resonant frequency. For 7 to 50μs, the phase shift angle is adjusted to search for maximum energy transfer efficiency. After 50μs, the phase shift angle is kept at 54 degrees, and the output power is stable at 1 kW. The simulated efficiency curve of the system is displayed in Figure 23. It can be seen that an energy transfer efficiency of 48% can be achieved under magnetic coupling.

Figure 19. The simulation of power control

5. CONCLUSIONS

In this study, a new method for optimizing the energy transfer efficiency of WPT with energy integration management control strategy was presented. The new methods include frequency tracking control and load tracking control, which used the average value of the current polarity and phase-shifted pulse width modulation. The main conclusions are drawn as follows:
(1) Based on the equivalent model of transmitter and receiver circuit, the transmission efficiency of the system is derived, and the transmission efficiency of the system is determined by the load and the resonant frequency.

(2) A maximum energy efficiency tracking control strategy is proposed, which consists of frequency tracking control and load tracking control. Compared with the existing control methods, it can improve the transmission efficiency and reduce the transmission efficiency caused by the dynamic change of the load condition, the coupling coefficient and the frequency offset.

(3) The strategy is implemented and tested in Matlab/Simulink, and the results prove that the strategy can make the WPT system complete frequency tracking after 5 s and achieve constant power output in 5ms, can track the permitted maximum efficiency point.

REFERENCES


