Wireless power transfer system based on frequency and impedance matching hybrid adjustment against system detuning

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Abstract. System detuning caused by a variation in the distance between the transmitting and receiving terminals can greatly reduce the transmission power and efficiency of a magnetic resonance-coupled wireless power transmission (WPT) system, which limits the WPT application scope. This paper proposes a magnetic resonance coupling wireless power transmission system, which is based on jointly and continuously adjustable frequency compensation (CAFC) and two-transistor-controlled variable capacitor circuits (TCVCs). Therefore, this system can reach the resonant state by using CAFC and two-TCVCs when the transmission distance is changed. The proposed system can adaptively adjust combinations of the operating frequency and equivalent compensation capacitor’s capacitance to achieve impedance matching avoiding the phase difference caused by the imaginary part of the impedance, thus maintaining stable transmission efficiency under the condition of transmission distance variation. Compared to the traditional magnetic coupled resonant circuit based on impedance matching or variable resonant frequency, the proposed system achieves higher efficiency and stability and dynamic distance adaptation.

1. Introduction

Wireless power transmission (WPT) is an emerging technology that has a broad application prospect in the fields of daily consumer electronic products, biomedical implants, electric vehicle charging, and other consumer electronic products [1]. Magnetic coupling resonance is an important technique in WPT. The basic principle of magnetic coupling resonance is that exchanging the energy at resonance is more efficient than at non-resonance [2]. Due to the usage of strong coupling resonance technology, the magnetic coupling resonance wireless power transmission (MCR-WPT) can achieve high power and efficiency [3]. However, the application of the MCR-WPT has been limited by its poor stability due to its sensitivity to the changes in the external conditions, such as distance and receiver load [4]. Particularly, the change in the operational distance between the transmitter and receiver can result in impedance mismatch, thus decreasing the transmission efficiency [5].

Generally, there are two common methods for transmission efficiency improvement under different distances or detuning conditions. The first method is based on impedance matching, which includes using DC-DC converters for tuning the load impedance and passive circuits for impedance matching. Since the power converter can be flexibly controlled by altering the equivalent impedance of the load, the DC-DC converters for tuning load impedance have been widely discussed [6-8]. Since the optimal
energy efficiency conditions change with the coupling coefficient k, the greatest challenge is how to
feedback control to locate the maximum energy transmission efficiency conditions. Besides DC-DC
converters for altering the load impedance method, another common approach is using the passive
circuits for impedance matching. According to the maximum power transfer theorem, this method
requires impedance matching with the power source. However, this approach is suitable only for very
low power applications (below 1 W) because it has a relatively high power loss in the power source
resistance. The second method is to use variable resonant frequency methods, which include the
operating frequency changing and using reconfigurable resonant circuits and coils. The former can
achieve higher efficiency than the latter by adjusting the resonant frequency with the load resistance
[9]. However, only when the load resistance is much larger than the optimum load resistance, the
transmission efficiency can be obviously improved [6, 10]. Moreover, even when the frequency is
adjusted to a suitable value, the equivalent input impedance of capacitance and inductance parameters
can also change due to the distance change. Thus, by adjusting only the frequency, the circuit cannot
fully restore the resonance state. The latter usually involves a switchable capacitor array [11],
reconfigurable coils [10, 12], or their combinations [13, 14] for adjusting the resonant frequency in
order to achieve the optimal energy transmission efficiency conditions when the load changes.
Although using a large number of switchable capacitors or inductors can provide wide discrete
changes in the resonant frequency, the complexity and size of a circuit are greatly increased since
numerous switches and the corresponding driving circuits and control are required. Moreover, the
impedance can be adjusted only in a few coil points, which makes the circuit adjustment has a certain
certainty and fail to achieve the optimal transmission efficiency.

In order to address the above-mentioned problems, this paper proposes a continuously frequency-
and-impedance matching hybrid adjustment WPT system (CFIMHA-WPT) based on jointly and
continuously adjustable frequency compensation and multiple transistor-controlled variable capacitors
(TCVCs) to obtain the maximum transmission efficiency under detuning caused by variations in
transmission distances. The proposed architecture is inspired by one of the previous works [15], where
the equivalent capacitance of the TCVC was simply controlled with a DC voltage similar to varactors
so that the zero voltage switching frequency of the system could be adjusted smoothly. Furthermore,
in order to overcome the problem of limited adjustment accuracy and the conflict between a large
adjustable range and a long diode conduction period of a single TCVC, there are two main
improvements in the proposed system: (1) the accuracy of the impedance matching adjustment can be
effectively improved by connecting one large TCVC and one small TCVC in series, thus obtaining the
maximum transmission efficiency under different distance conditions; (2) in addition to the effect of
frequency adjustment, jointly and continuously adjustable frequency compensation and two TCVCs
are used together to adjust the circuit to a new resonance state. Compared to the traditional tuning
circuits, the proposed system with simple circuits can achieve higher adjustment accuracy and easily
extend the adjustment range and dynamic distance adaptation because the capacitance circuits are
continuously adjustable.

2. Proposed continuously frequency-impedance matching hybrid adjustment WPT system
Based on the previous analysis[12,16], when \( \omega = 1/\sqrt{LC_T} = 1/\sqrt{LR_CR_R} \), where \( C_T \) and \( C_R \) denote the
equivalent capacitances, and \( L \) and \( L_R \) are the equivalent inductances of the transmitter and receiver,
respectively, the condition of resonance can be satisfied. According to the two-port network theory
[17], the input and output impedance of a system can be respectively expressed as:

\[
Z_{in} = R_T + \frac{\omega M^2 (R_T + R_R)}{(R_T + R_R) + (\omega L - 1/\omega C_T)},
\]

\[
Z_{out} = -R_T + \frac{\omega M^2 (R_T - R_R)}{(R_T - R_R) + (\omega L - 1/\omega C_R)}.
\]

where \( R_T \) and \( R_R \) are equivalent resistances, and \( L \) and \( L_R \) are equivalent inductances of the transmitter
$C_R$ is the equivalent capacitance of receiver; $M$ is mutual inductance; $C_w$ is equivalent compensation capacitance. Therefore, when the transmission distance changes, the imaginary parts of the input and output impedances can be set to zero by adjusting the frequency $\omega$ or $C_w$ or combinations of $\omega$ and $C_w$, which means that the system can obtain the resonant state again.

The basic idea, according to (1) and (2), is to tune operating frequency or the equivalent compensation capacitor or inductance or their combinations to achieve impedance matching avoiding the phase difference caused by the imaginary part of impedance. If the inductance is used as phase compensation, circuit complexity will increase, which may cause stability problems. In addition, increasing the compensation inductance can also produce a certain energy loss [18]. Therefore, besides frequency adjustment, the capacitance is adjusted by using TCVC as a circuit whose capacitance value can be adjusted by controlling the transistor via feedback voltage [15]. When the control voltage changes, the on and off states of the capacitor are controlled by the diode turning on or off, respectively, and the equivalent capacitance can be calculated using the on-time $t_{on}$ [15]. In order to resolve conflict between a large adjustable range and a longer diode conduction period, two or more TCVCs connections is proposed in this manuscript. Take two TCVCs connections as an example, the structural diagram of the CFIMHA-WPT is presented in Figure 1 ($C_{u1}$ and $C_{u2}$ represent capacitances of the first and second TCVCs, and $C_{u1} > C_{u2}$). The two-TCVCs circuit structure is shown in Figure 2. The basic working principle of the CFIMHA-WPT based on two-TCVCs is as follows. When a longitudinal distance between the transmitter and receiver coils changes, the current and voltage phases are collected by the current and voltage detection modules and then transmitted to the phase discriminator to determine the phase difference. Then, the phase difference signal is transmitted in the form of voltage to the controller, and the output frequency of the inverter circuit and the value of the TCVC are adjusted by the controller based on the received signal. Considering that the adjustment accuracy of a TCVC is inversely proportional to its adjustable range, the adjustable range of the TCVC is defined by the voltage-controlled large-variable-capacitance circuit ($C_{u1}$), and the adjustable precision of the TCVC is defined by the voltage-controlled small-variable-capacitance circuit ($C_{u2}$). The system can reach a more accurate resonance state by adjusting $C_{u1}$ and $C_{u2}$ simultaneously. Therefore, the accuracy of the TCVC adjustment can be effectively improved by connecting one $C_{u1}$ and one $C_{u2}$ in series. Coupled with the effect of frequency adjustment, the two methods are used together to adjust the circuit to a new resonance state better.

3. Experimental prototype analysis

According to the previous theoretical and simulation analyses, the experimental circuit was built. The hardware consisted of a power module, an inverter module, a transmission module, and two-TCVCs, as shown in Figure 3. When the system was under the resonance conditions (i.e., the distance between the two coils was 10 mm), the phase difference between the voltage and current was equal to zero, as shown in Fig.4a. When the transmission distance between the two coils was longer than 10 mm, a large phase difference between the voltage and current occurs, which means that the system was in the detuned state [7, 19]. In this case, the phase difference between the voltage and current was very smaller by using the two-TCVCs than that using one TCVC, as shown in Figure 4(b) and (c). It can be speculated that a further increase in the number of TCVCs could improve the system’s transmission efficiency, but it will also increase the complexity and reduce the stability of the system. Therefore,
using two-TCVCs is considered to be the optimal solution from the aspect of the overall system performance. Especially, the voltage and current of a transmitter can reach the same phase when the frequency adjustment and two-TCVCs are used simultaneously, which can make the system work at the resonance state, as shown in Figure 4(d). The experimental results are in agreement with the above-mentioned theoretical results.

![Figure 3. The photo of the CFIMHA-WPT based on the TCVCs.](image)

![Figure 4. The adjusted waveforms of the CFIMHA-WPT: (a) resonance conditions; (b) one TCVC; (c) two-TCVCs; (d) both frequency adjustment and the two-TCVCs.](image)

The measured transmission efficiency and the corresponding distance change curves under the joint effect of two-TCVCs and frequency adjustment are shown in Figure 5. The results show that the adjustment effect of two-TCVCs is better than that of single TCVC. Furthermore, the best transmission efficiency of the system is achieved by jointly using frequency adjustment and two-TCVCs; also, the transmission efficiency achieved in this way decreases much more slowly than that of the other adjustment methods at a long distance between the two coils. The transmission distance
was limited to 50 mm in the experiments due to the low-power source and low-frequency source in our laboratory. It should be noted that for the tested distances, the experimental results were in agreement with the theoretical results; thus, all the drawn conclusions are reliable.

4. Conclusion

In this paper, a method for mitigating the detuning in a dynamic wireless power transfer system based on the joint effect of two-TCVCs and frequency adjustment is proposed. The proposed CFIMHA-WPT can realize a continuous, adjustable capacitance to achieve the best impedance matching easily, and it is simpler and has a smaller volume than that used the capacitor matrix structure. Both simulation and experimental results show that the proposed CFIMHA-WPT with joint usage of the frequency adjustment and two-TCVCs has better transmission efficiency at variable transmission distance than the system with single TCVC adjustment type. The analysis results also speculate that when a larger number of TCVCs are used in the system, higher transmission efficiency can be achieved under the conditions of variable long transmission distance. Consequently, the proposed system can significantly improve the transmission efficiency of a system for different transmission distances. The proposed method can be used in low-power against system detuning applications design, such as consumer electronics, as well as in higher-power applications design.

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