

Resonant enhanced parallel-T topology for weak coupling wireless power transfer pickup applications

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Abstract: For the wireless power transfer (WPT) system, the transfer performance and the coupling coefficient are contradictory. In this paper, a novel parallel-T resonant topology consists of a traditional parallel circuit and a T-matching network for secondary side is proposed. With this method, a boosted voltage can be output to the load, since this topology has a resonant enhancement effect, and high Q value can be obtained at a low resonant frequency and low coil inductance. This feature makes it more suitable for weak coupling WPT applications. Besides, the proposed topology shows good frequency stability and adaptability to variations of load. Experimental results show that the output voltage gain improves by 757% compared with traditional series circuit, and reaches 85% total efficiency when the coupling coefficient is 0.046.

1 Introduction

Wireless power transfer (WPT) technology utilises the principle of magnetic induction to achieve contactless power transfer. In a WPT system, the primary coil and secondary coil are loosely coupled (coupling coefficient of typically 0.1–0.5). To transfer rated power in such a situation, both the primary and secondary sides are tuned with a resonant circuit. However, resonant topology studies mostly concentrated in the primary side, but less for the secondary side in the present literature. For the secondary side, series and parallel topologies are the most basic [1–3]. The parallel topology presents a boosted voltage to the load, but reflects reactive loads back onto the primary side. The series topology eliminates this problem, but the output power is relatively low because of the low open-circuit voltage [2]. As the series and parallel topology alternatives, inductor-capacitor-inductor (LCL) and inductor-capacitor-capacitor (LCC) topologies are the most widely used [2–5]. For these topologies, the reactive power at the secondary side could be compensated to form a unity power factor pickup, and an additional capacitor added in series with the pickup coil can be thought of as a current boost [2, 3]. However, both the LCL and LCC topologies are current source characteristics [4], and in practice we sometimes need a voltage-source output on the secondary side. To solve this problem, this paper presents a novel parallel-T topology for WPT pickup applications with a voltage-source output. It features unity power factor and ultra-low no-load loss. A T-matching network in parallel connection with an inductor-capacitor (LC) parallel circuit makes it work as a voltage boost, makes it possible to transfer more power under weak coupling conditions.

2 Proposed parallel-T structure

A schematic of the proposed parallel-T structure is shown in Fig. 1a. It consists of inductor (L_s), capacitor (C_s) in parallel connection and L_2 , C_2 and C_{s2} are connected in the T structure, forming a matching network. L_s and L_2 should meet $L_s < L_2$. Here, we assume that the load is purely resistive.

Reactance $X_{L_s} = -X_{C_s}$, $X_{L_2} = -X_{C_2}$ and $X_{C_{s2}} = X_{C_2} + X_{L_s}$ are the conditions for this structure. Resonant frequency of the system is

$$\omega_0 = \frac{1}{\sqrt{L_s C_s}} = \frac{1}{\sqrt{L_2 C_2}} = \sqrt{\frac{C_{s2} - C_2}{L_s C_{s2} C_2}} \quad (1)$$

Process of impedance transformation in the secondary side is shown in Fig. 1b. U_{oc} is the open-circuit voltage induced in the secondary coil, whereas r_s is the wire resistance. Here, we define λ as the transformation factor, and $\lambda = L_s/L_2 < 1$. Parameter λ is important, since it determines the transfer power and efficiency. Capacitor C_{s2} can be calculated as follows

$$C_{s2} = C_2/(1 - \lambda) \quad (2)$$

Load resistance R after transformation through matching network is named as Z'' , and further divided into real part and imaginary part

$$Z'' = (R + X_{C_2}) || X_{L_2} + X_{C_{s2}} = \frac{L_2}{RC_2} + j\omega_0 L_s \quad (3)$$

Thus, Z'' can be seen as a resistance and an inductance (L_s) in series connection and L_s , C_s constitute a new T network. Impedance after

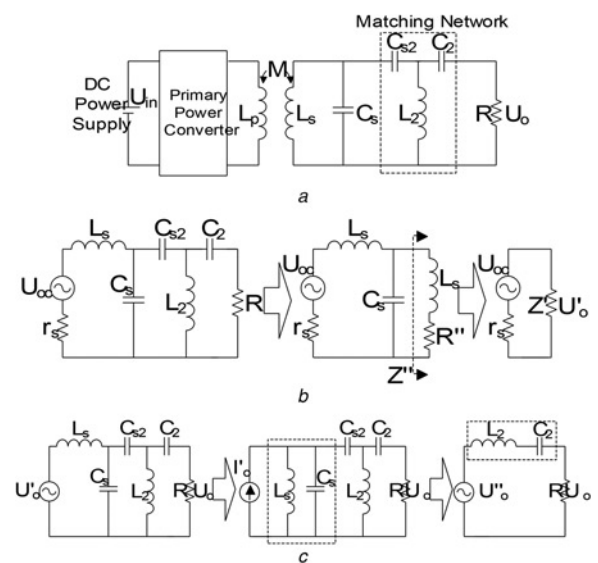


Fig. 1 Analysis of the proposed parallel-T structure
a Schematic of the proposed WPT system
b Analyse from impedance transformation view
c Analyse from circuit transformation view

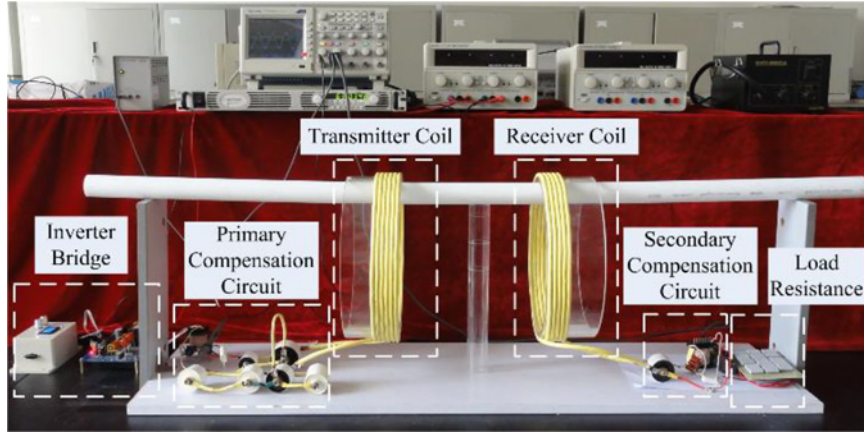


Fig. 2 Experimental setup

this T network is named Z'

$$Z' = \lambda^2 R \quad (4)$$

When the load is purely resistive, Z' only has the real part. The quality factor of the secondary side circuit then becomes

$$Q_s = \omega_0 L_s / (\lambda^2 R + r_s) \quad (5)$$

Compared with the traditional series structure of the secondary side, the proposed structure increases the Q value, and enhances the resonance at the receiving end. In fact, there are four kinds of topologies in the secondary side that can realise this transformation. In this paper, the proposed structure is chosen so that the number of inductors can be minimised and the secondary circuit will be smaller.

Process of circuit transformation is shown in Fig. 1c. With a Norton equivalent circuit transformation from a voltage-source U'_o to a current source I'_o , L_s and C_s cancelling each other at resonant frequency, and we have: $I'_o = U'_o / (\omega_0 L_s)$.

Applying Thevenin's theorem for further transformation, current source I'_o is converted to voltage-source U''_o , and L_2 , C_2 cancelling each other, the expression of output voltage is obtained

$$U_o = U''_o = \frac{L_2}{L_s} U'_o = \frac{1}{\lambda} U'_o \quad (6)$$

Since the wire resistance is small, the output voltage is about $1/\lambda$ times to the induced voltage. If the coupling coefficient remains constant, the output voltage can be adjusted by setting parameter λ .

According to the analysis above, the no-load loss of the proposed structure is

$$P_{\text{no_load}} = \left| \frac{U_{\text{oc}}}{(X_{L_s} || X_{C_s}) + X_{L_s} + r_s} \right|^2 r_s \quad (7)$$

Since $X_{L_s} || X_{C_s}$ equivalent to a large reactance, the no-load loss is very low. This character is similar to the series structure.

Table 1 Parameters for the experimental setup

Name	L_p , μH	L_s , μH	L_2 , μH	C_s , nF	C_2 , nF	C_{s2} , nF	f_0 , kHz
value	20.58	14.29	130	492.4	54.12	60.8	60

However, for structures such as parallel or LCL, no load is not allowed when a given current is applied to the primary coil.

3 Experiments and results

To validate the proposed structure, the experimental setup has been built as shown in Fig. 2. LCL structure is adopted in the primary side since it has the constant current in primary coil. Both the transmitter and receiver are 30 cm diameter helical coils wound with litz wire to reduce the skin effect. Load resistance changes from 12

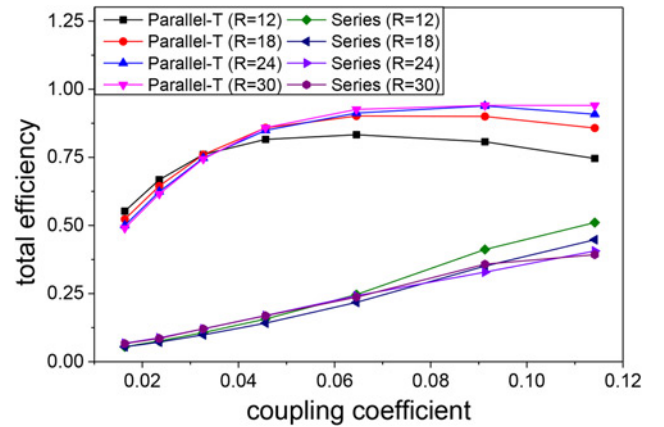


Fig. 3 Total efficiency under different coupling coefficients

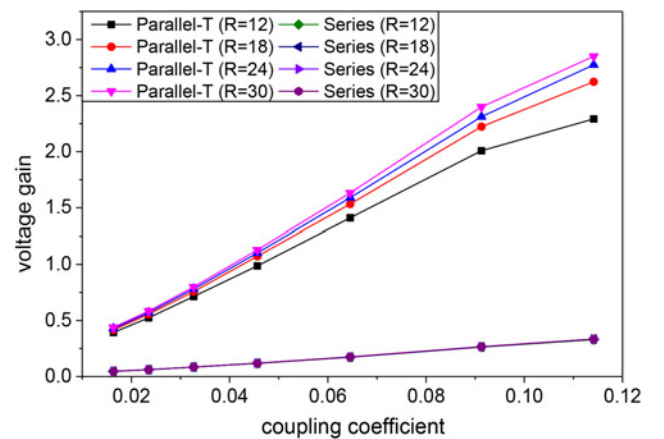


Fig. 4 Output voltage gain under different coupling coefficients

to 30 Ω . Specific parameters are shown in Table 1. Metal–oxide semiconductor field effect transistor for the inverter bridge is IPW60R041C6.

Both the parallel-T and series structure which is composed of L_s and C_s , are adopted in the secondary side. The transfer distance varies from 40 to 12.5 cm, whereas the coupling coefficient changes from 0.0164 to 0.114. The total efficiency (i.e. the efficiency of DC source output to the load) and the voltage gain (i.e. the ratio of U_o and DC input voltage) are measured as shown in Figs. 3 and 4.

Experimental results show that parallel-T structure has a much higher efficiency and voltage gain. In this system, the resonant frequency and the coil inductance are relatively low. This led to the low induced voltage under weak coupling condition. Owing to the voltage boost effect, parallel-T structure increases about 757% voltage gain than series structure in average, and reaches 85% efficiency when the coupling coefficient is 0.046. When the coupling coefficient increased, the efficiency of the parallel-T shows a downward trend, which is caused by the LCL circuit in the primary side, as part of the power consumption in the inverter bridge.

4 Conclusion

In this paper, we propose a simple and effective parallel-T compensation topology for WPT pickup applications. With a T-matching network added in the LC parallel resonant circuit, the pickup

turns into a voltage–source, and the output voltage become $1/\lambda$ times to the induced voltage. Besides, the proposed topology features low no-load loss and unity power factor when the load is purely resistive. A 60 kHz WPT system with 20.58 μH transmitter coil and 14.29 μH receiver coil has been built. The results show that, compared with traditional series circuit, the parallel-T structure can achieve much higher power and efficiency under weak coupling conditions. This confirms that the proposed topology can be applied to large air gap or misalignment applications.

5 References

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