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Design of Capacitive Power Transfer System with Small Coupling Capacitance for Wireless Power Transfer

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Abstract

Wireless power transfer systems play an important role in the application of modern power supply technology. Wireless charging has been widely used in portable devices such as smartphones, laptops, and even some medical devices. Higher system efficiency can be achieved while reducing costs. This article describes the design of a capacitive power transfer (CPT) system using the Class-E amplifier method. When the capacitance of the coupling plate is small, the operation of Class-E amplifiers under Zero-Voltage-Switching (ZVS) conditions is very sensitive to their circuit parameters. By adding an additional capacitor to the Class-E amplifier, the coupling capacitance can be increased, resulting in better circuit performance. The high efficiency of the Class-E amplifier is verified by simulation and experimental results.

Keywords: Class-E amplifier; capacitive power transfer; ZVS conditions; Additional capacitor

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1. Introduction

In today's society, people's application of wireless power transmission systems is more and more extensive.[1] Mobile phones, computers, medical equipment, etc. we usually use have wireless charging applications.[2] It can achieve higher system efficiency and lower cost, and is widely used. Traditional inductive power transfer is a method of using inductive coupled coils to transfer power.[3] when delivering at a low power level with small devices, the method of inductive power transfer system seems unsuitable.[4][5] To increase the efficiency of the system, the method of generating a DC to AC voltage is most commonly used in resonant switching inverters. A class E inverter/amplifier is always a better choice for capacitive power transfer systems as it can theoretically yield high efficiencies close to 100%.[6]

The basic schematic diagram of Class-E amplifier is shown in Figure 1. Its working efficiency is higher than that of Class-B or Class-C amplifier, and it is a switching power inverter.[7] The shunt capacitor Cp is an important component that determines. The high efficiency of Class-E amplifiers, the efficiency of shunt capacitors depends on their waveform.[8][9]

The operation of a Class-E amplifier under Zero-voltage switching conditions (ZVS) and Zero-current switching conditions (ZCS) is sensitive to circuit parameters. A Class-E approach is used to propose a wireless power transfer system within the resistance range of the load network, which is sensitive to certain component tolerances, such as series capacitors and changes in inductors, when the coupling capacitance is small. [10] Therefore, additional capacitors need to be added to design a capacitive power transfer system with smaller coupling capacitance, which has better performance under ZVS conditions.[11]

This paper discusses the Zero-Voltage Switching (ZVS) condition for Class-E amplifiers. Because the load resistance, switching frequency and shunt capacitance of Class-E amplifiers will increase the tolerance of capacitive transfer system, the capacitive power transfer method of Class-E amplifiers in this paper uses capacitors with small coupling.[12] By adding an extra capacitor, the sensitivity of the circuit can be better.

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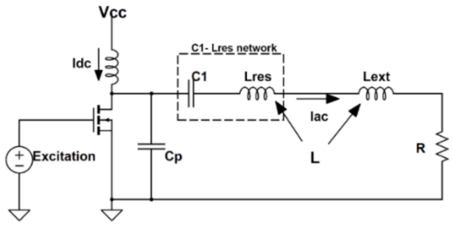


Figure 1. Basic schematic diagram of a Class-E amplifier

The main work of the second part of this paper is to explain the work of Class-E amplifiers under ZVS conditions. [13] The third part mainly introduces the traditional capacitive power transmission system. Section IV shows the circuit simulation of the proposed capacitive power transfer system in LTSPICE, and Section V discusses the experimental results. Then draw conclusions in Section VI.

2. Class-E Amplifier

From the analysis of the contents of Figure 1, the following assumptions were made in deriving the design equation.[14]

Assume that the resistance inside it is zero, so the DC voltage drop across the choke is zero.[15] When the inductance of the choke coil L is large enough, we can ignore the current ripple. The MOSFET is turned off, momentarily turned on, and has zero on-resistance.

The formula derivation for the class E amplifier design equations was previously described by Kimber. The output power is described by:

$$P_0 = \frac{BV_{cc}^2}{\pi^2 R} cos^2\phi \tag{1}$$

Equation (1).

ϕ represents the phase angle, which is the phase angle between the load current and the shunt capacitor voltage.

V_{cc}^2 represents the input DC voltage

C_p, the shunt capacitance, the formula is as follows:

$$C_p = -\frac{2sin2\phi}{\omega R\pi^2} \tag{2}$$

where $\omega = 2\pi f$ and f refer to the switching frequency.

The following equation describes the inductance L_{ext}:

$$L_{ext} = \frac{R}{\omega}\left(cot\phi - \frac{\pi^2}{4}csc2\phi\right) \tag{3}$$

It can be known from the following equation that the series resonance component C_1:

$$C_1 = \frac{1}{\omega(QR-\omega L_{ext})} \tag{4}$$

$$L = \frac{QR}{\omega} \tag{5}$$

The qualification factor of the load is denoted by Q.

3. Capacitive Power Transfer System

3.1. Schematic diagram of CPT

Figure 2 Design of a capacitive drive system, this section describes the capacitive power transfer system shown in Figure 2. The coupled plate function is defined as series capacitors C_{11} and C_{12}, d represents the distance between the plates.[16, 19] A represents the area of the plate, and the relationship between d and A is expressed as:

$$C = \frac{\varepsilon A}{d} \tag{6}$$

ε is the dielectric constant, which refers to the dielectric constant of the dielectric material between the conductive plate and the conductive plate.[20] Due to the change in distance, the reverse and forward capacitance values change.[17-18] For convenience, C_{11} and C_{22} is usually combined into a capacitor, such as:

$$C_1 = \frac{C_{11}C_{12}}{C_{11}+C_{12}} \tag{7}$$

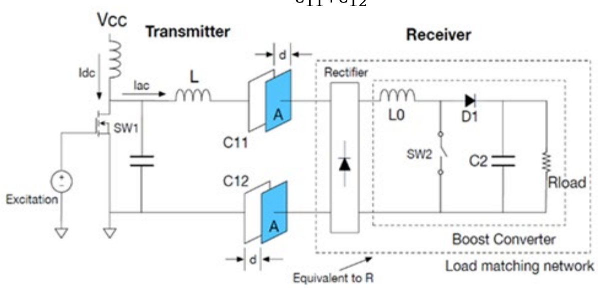


Figure 2. CPT System using Class-E access

Finally, Class-E amplifier with additional capacitor can be described by using[21] impedance matching as shown in Figure 3.

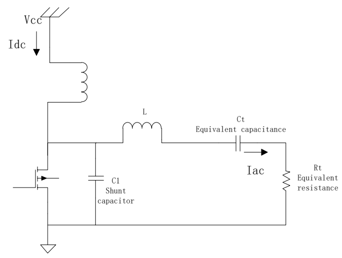


Figure 3. Class-E amplifier with equivalent capacitance and resistance

Equivalent capacitance and resistance are given by[22]:

$$R_t = \frac{C_3^2 R}{(C_2+C_3)^2+\omega^2 C_2^2 C_3^2 R^2} \tag{8}$$

$$C_t = \frac{(C_2+C_3)^2+\omega^2 C_2^2 C_3^2 R^2}{(C_2+C_3)+\omega^2 C_2 + C_3^2 R^2} \tag{9}$$

a. ii. Receiver of CPT system

A schematic diagram of the receiver of a capacitive power supply system using the Class-E amplifier method is shown in Figure 4. As shown in Figure 4, the CPT receiver receives an advanced transmitter, a rectifier and a torpedo.[23] The maximum power can be delivered through a matching network between the load and the RF energy.[24] A rectified converter converts AD to DC voltage, which can be boosted to a high level by a boost converter. Device protection is one of the reasons for using matching networks.[25]

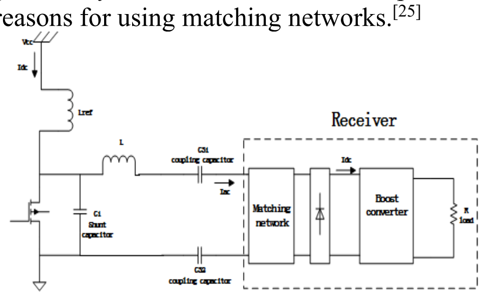


Figure 4. Schematic diagram of a receiver in a CPT system using the Class-E amplifier method

The purpose of this paper is to design a crystal unit with a certain capacitance value that can be used as a parallel resonant oscillator circuit. A parallel crystal circuit using a single inverter is shown in Figure 5 with two capacitors in this feedback loop.[26] In order to ensure that it works in the linear region, the R_1 inverter can be biased, and the crystal unit can be biased through the R_2. C_{L_1} and C_{L_2} are called the load capacitance and determine the frequency at which the oscillator works with the crystal unit. The crystal unit is denoted by X_1.

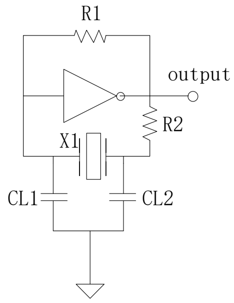


Figure 5. Parallel resonant oscillator circuit

C_L represents the specified value of the load capacitance, and the formula for calculating the capacitance value under the condition of the parallel resonant oscillator circuit is as follows:

$$C_L = \frac{C_{L_1} \times C_{L_2}}{C_{L_1} + C_{L_2}} + C_s \tag{10}$$

Where,

C_s is typically 3 to 5 pF and represents circuit stray capacitance.

C_{L_1} and C_{L_2} refer to the load capacitance, and the frequency of the load causes the oscillator to oscillate at different frequencies.

The following formula represents the sum of the load capacitance C_L and the parallel capacitance C_0 of the crystal oscillator:

$$C_t = C_0 + C_L \tag{11}$$

f_s refers to the crystal unit of the series resonant frequency, which is expressed by the following formula:

$$f_s = \frac{1}{2\pi\sqrt{L_1 C_1}} \tag{12}$$

Where,

L_1 represents the inductance of the motion.

C_1 represents a capacitor with quartz elastic motion.

The load resonant frequency of the circuit, f_L is expressed as:

$$f_L = \frac{1}{2\pi\sqrt{\frac{C_t C_1}{C_t + C_1} L_1}} \tag{13}$$

3.3. Design of load matching network

It is assumed that ideal components are used here, and the L-shaped matching network is implemented with capacitors and inductors, as shown in Figure 6 is a basic L-shaped matching network.

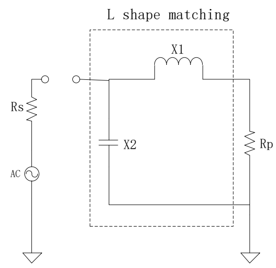


Figure 6. Basic L shape matching network

R_p is matched with a capacitor in series and parallel with the inductor, resulting in a load R_s as shown in Figure 6.

The formulas for calculating the inductance and capacitance are as follows:

$$X1 = \sqrt{(R_s R_p) - R_p^2} \tag{14}$$

$$X2 = R_s \frac{R_p}{X1} \tag{15}$$

Where $R_s > R_p$ is assumed.

4. Simulation

4.1. Complete CPT System Calculations

The purpose of this document is to design a capacitive power transmission system to be implemented using a Class-E amplifier in LTSPICE, as shown in Figure 7. Has the following specifications:

From (7), the coupling capacitor $C_{31} = C_{32} = 25pF$ in series can be known.

The DC power supply of the circuit is $V_{CC} = 15V$, the operating frequency of $C_{33} = \frac{C_{31}C_{32}}{C_{31}+C_{32}} = 12.5pF$ in the system is $f = 4MHZ$, the load resistance is $R = 15000\Omega$, and the expected output power of the system is $P_0 = 4.2W$. In the matching network, $R_s = 15000\Omega$ and$R_p = 22\Omega$. the load capacitance of the system, $R = 15000\Omega$.

From (14) and (15),

$$X1 = \sqrt{(R_s R_p) - R_p^2} = \sqrt{(15000 \times 22) - 22^2}$$
$$= j574.88\Omega$$
$$\mathrm{X2} = \mathrm{R_s}\frac{\mathrm{R_p}}{\mathrm{X1}} = 15000 \times \frac{22}{\mathrm{j}574.88} = -574.03\Omega$$

Therefore, the capacitor in the matching network in this design is $C_m = \frac{1}{2\pi f X_2} = 6.2pf$, and the inductance of the matching network is $L_m = \frac{X_1}{2\pi f} = 22.84\mu H$.

Then multiply by V_{CC} and rearrange on both sides of (1),

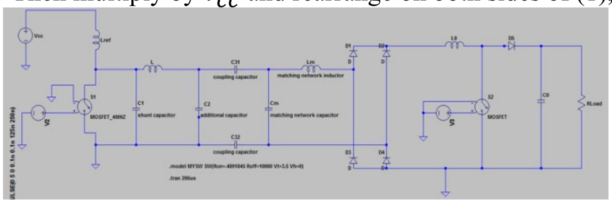


Figure 7. Schematic diagram of the system circuit

$$\cos\phi = \frac{\pi}{V_{cc}}\sqrt{\frac{P_O R}{8}} = \frac{\pi}{15}\sqrt{\frac{4.2 \times 39.44}{8}} = 0.9531 \qquad (16)$$

Hence, $\phi = -17.63°$.

$$C_1 = -\frac{2\sin 2\phi}{w\pi^2 R_t} = 118pF$$

From (2), the shunt capacitor

Form (3),

$$\omega L_{ext} = R_t\left(\cot\phi - \frac{\pi^2}{4}\csc 2\phi\right) = 44.47 \qquad (17)$$

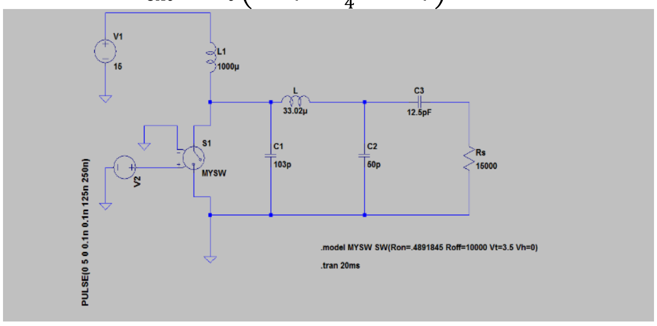


Figure 8. Circuit of Class-E amplifier with additional capacitor

By using (4) gives,

$$Q = \frac{1+\omega^2 C_1 L_{ext}}{\omega C_1 R_t} = 21 \qquad (18)$$

Employing (5) renders,

$$L = \frac{R_t Q}{\omega} = 33.02\mu H$$

Q represents the quality factor, and its value is less than 20 for better performance. In the above case the parameters of the circuit should be based on additional capacitors.

4.2. Simulation of Class-E amplifier with additional capacitor

Simulation circuit of Class-E amplifier with additional capacitor can be seen in Figure 8.

Table 1. The additional capacitance, C_2, additional capacitances to complete the ZVS condition, C_1.

C_1	$6.25pF$	$12.5pF$	$25pF$
Additional capacitance	$45pF$	$50pF$	$60pF$

When the coupling capacitance is small, the additional capacitance method described in this design can still work normally under ZVS conditions, and its working state has nothing to do with the non-constant current of the system.

The reliability of the system is tested by changing the value of the series inductance L to determine whether the ZVS condition can be met.

Figure 10 shows a particular case when the series inductance L is reduced from 33.02 μH to 31.02 μH. The additional capacitance used was $C_2 = 100pF$. When the switch is turned off, the drain voltage is larger at this time, exceeding 60V. However, Z can be achieved by adjusting the series inductance, as shown in Figure 9 and Figure 10.

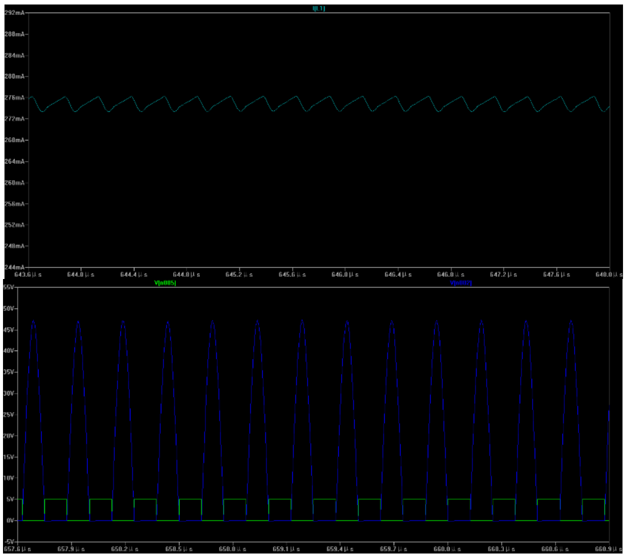


Figure 9. Waveforms of drain voltage, switch voltage and DC supply current

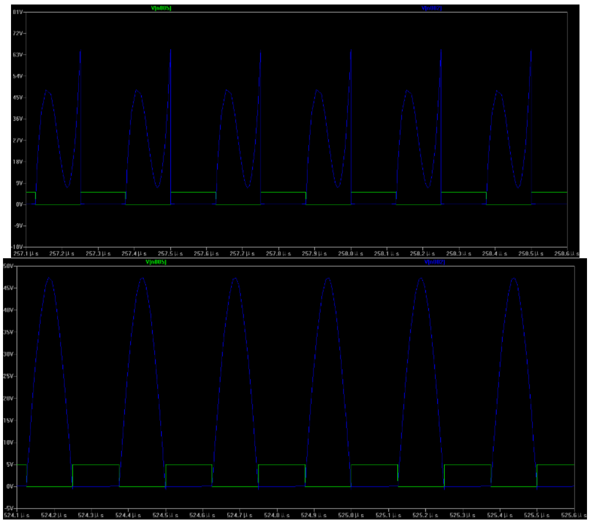


Figure 10. Waveforms of drain voltage and switch voltage with $C_2 = 100pF$

5. Experimental Results

As shown in Figure 11, a capacitive power supply system and a Class E amplifier with additional capacitors were used to test the effectiveness of the overall system's simulation circuitry.

C_{31} and C_{32} are the forward and return capacitances consisting of two sets of parallel copper plates, as shown in Figure 11. The capacitance from the two couplers is expressed by

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} \tag{19}$$

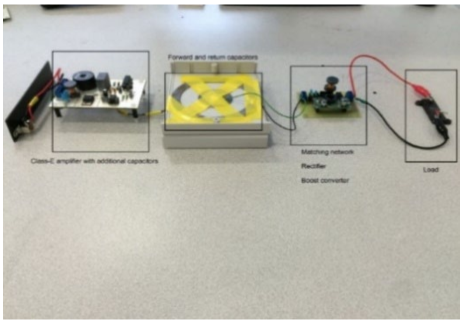


Figure 11. Implementation of CPT system

Where,

A refers to the area where the two boards overlap, d refers to the gap between the board and the board.

ε_0 is the permittivity of free space ($\varepsilon_0 \approx 8.854 \times 10^{-12} Fm^{-1}$).

ε_r refers to the relative permittivity, the relative permittivity of the plate to the material before the plate.

In this experiment, the copper plate sizes used are $11.94 cm^2$ and $28.27 cm^2$, since the shape of the forward capacitor plate is circular, the return capacitor is annular. In this experiment, the forward capacitance is $9.5pF$, the return capacitance is $9.8pF$, and the thickness of the plastic film in this design is 1mm. The series capacitances C_{31} and C_{32} can be known from equation (7)

$$C_3 = \frac{C_{31}C_{32}}{C_{31}+C_{32}} = 6.4\text{pF}$$

The measured value of C_3 for this design is roughly $6.25pF$.

The calculated component values of the system and the experimentally measured values are compared in Table 1 above. Under the premise of adopting the same specifications, the experiment put two plastic films between the polar plate and the polar plate to obtain the parallel capacitive wave as shown in Figure 12.

As it can be seen in Table 2, The operating frequency is 4MHZ, the series coupling capacitance was small. By adding an additional capacitor C_2 from (9), we can get an equivalent capacitance, C_t ,which increases the series coupling capacitance.

In the case of the same copper plate and additional capacitor $C_2 = 25pF$, as shown in Figure 13, the voltage waveform of the parallel capacitor is shown, which shows the difference before and after the tuning series inductance is adjusted.

With the same copper plates and the additional capacitance $C_2 = 100\text{pF}$, the waveforms of the shunt capacitor voltage before and after being adjusted by the series tuning inductor are shown in Figure 14.

Table 2. Comparison of theoretical, computed and experimental values for CPT system with additional capacitance

	C_1	C_2	C_3	L	*Efficiency*	C_1
Theoretical	$6.4pF$	$50pF$	$190pF$	$32.5\mu H$	100%	$4.2W$
Experimental measured	$6.25pF$	$50pF$	$125pF$	$33.02\mu h$	78%	$4W$

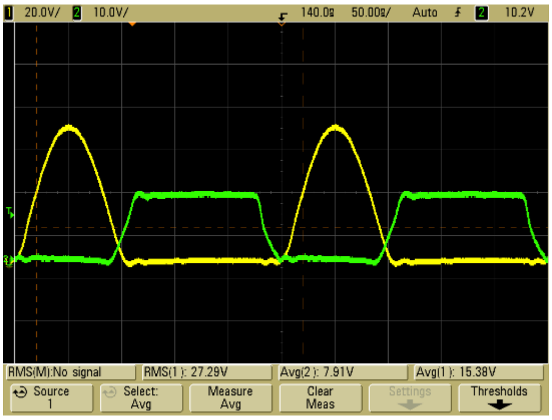
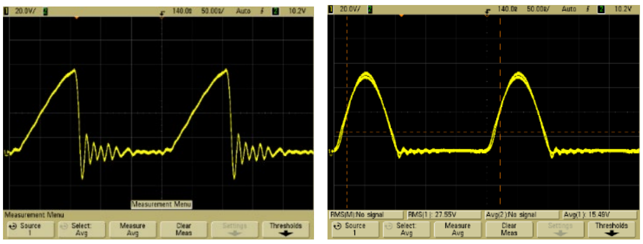
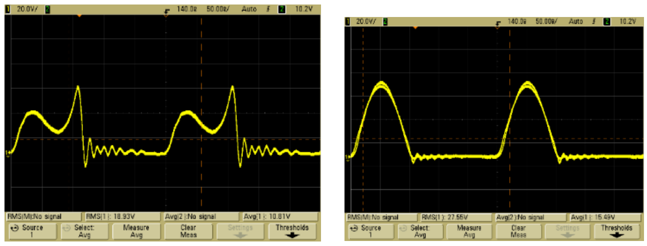


Figure 12. Waveforms of shunt capacitor and switch voltage



(a). Before adjustment (b). After adjustment

Figure 13. Waveforms of shunt capacitor when $C_2 = 25pF$



(a). Before adjustment (b). After adjustment

Figure 14. Waveforms of shunt capacitor when $C_2 = 100pF$

6. Conclusions

In this paper, a capacitive power delivery system is introduced, which uses the method of a Class-E amplifier. In the case of small series coupling capacitor, adding an additional capacitor can increase series the coupling capacitance which makes the load quality factor Q around 15 - 20. Thus, the circuit is not sensitive when the ZVS condition active. This means that the capacitive power transmission system used in this paper can transmit power more efficiently. Through simulation and experiment, the rationality of the proposed procedure is verified

The existing system analysis is mainly based on the static model of the system, and the basis of the closed-loop regulation of the system is the dynamic model of the system, and the establishment of the dynamic model of the system is the basis for the subsequent expansion of the application scenarios of the wireless transmission system. With the deepening of the research of wireless transmission technology and the development of wireless transmission industry, the application scenarios of wireless transmission technology will be richer.

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