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Designing and Analysis of an Optimal Capacitive Power System Using Class-E Power Amplifier

Abtulgalip Karabulut[#1], Oguzhan Dogan[*2], Serhan Ozdemir[#3]

[#]*Mechanical Engineering Department & İzmir Institute of Technology*
Republic of Turkey

Abstract

This study's main idea is to design a high efficient capacitive power transfer (CPT) system consisting of a load network, a series resonance L-C circuit, and MOSFET. The MOSFET was used as a switch with a 0.5 duty cycle. The system consists of two main parts: the CPT system and the E-class power amplifier circuit design. To increase the efficiency of the wireless power transfer system E-class Power amplifier was used. The power telemetry has been realized by the copper capacitive plates with a 100 cm2 surface area. The efficiency of the CPT system is 82.1%. The throughput and input power of the system are 4.99 W and 4.1 W, respectively. Also, the switching performance of the E-class power amplifier circuit has been analyzed at 1.7 MHz frequency. The circuit was operated at its resonance frequency to increase the efficiency. Finally, the capacitive power transfer system has been designed with 81.2% efficiency at 1.7 MHz frequency and high SNR.

Keywords — *Capacitive power transfer, Class-E power amplifier, Wireless data and power transfer*

I. INTRODUCTION

Electricity has been one of the main components of human life. Electricity was often tried to transmit over cables. Therefore cables were also an important member of power transmission. However, due to the current cable links, modern automation systems' power supply has been a classic difficulty [1]. Also, cable connection systems have many drawbacks, such as limitation of the transmitting distance, power loss, cost etc. The same can be said quite well for transmitting data. Particularly, cable links cannot be smoothly assembled on a rotating mechanical system. On the other hand, wireless Power Transfer (WPT) offers robustness and efficient solutions to those pitfalls that were addressed. The wireless power transfer method is an emerging field of research that extends to Maxwell [2]. James Clerk Maxwell realized the first theoretical approach to wireless communication between 1861-1862 years [3]. Nikola Tesla was the first man to conduct WPT experiments at the end of the 19th century [4]. Today, wireless power transfer (WPT) technology has grown in popularity for its user-friendliness, compact nature and respective transmission distance. While the facets of WPT are being studied, several approaches have emerged. WPT technology can be investigated under two main categories, which are radiative and non-radiative [5]. Microwave power transmission [6] (MPT), laser power transmission [7] are among those radiative methods, respectively. Radiative WPT techniques may be used for wireless power transfer systems up to air gap ranges greater than a few kilometers. High performance is also not difficult to achieve. However, it is very dangerous for the living organism [8]. Coupled magnetic resonance power transfer (CMRPT) [9], inductive power transfer (IPT) [30], and capacitive coupling [11] are among the non-radiative WPT methods. It is possible to obtain the high-efficiency with Non-radiative WPT techniques under short distance [12]. Coupled magnetic resonance transmission technique utilizes coils to transfer the power via resonance. CMRPT method provides many benefits, e.g., under long-distance power transfer. Notwithstanding, Due to a high degree of electromagnetic interference (EMI), Coupled magnetic resonance technology, could not be commercialized [13]. EMI exposure can negatively affect the performance of the electronic system, as well as human health. When the non-radiative WPT methods are debated, inductive and capacitive power transfer systems show themselves. IPT is the most famous commercial wireless systems in the literature. The IPT system wirelessly transfers electrical power from millimeters to a single meter [14]. Throughout the industry, IPT is commonly used for power transmission or wireless charging [15] [16]. IPT and CMRPT techniques utilize the magnetic flux to transmit power or data wirelessly. Generally, inductors generate the EMI while power is transferred. EMI could theoretically interfere with the stability of artificially intelligent systems. It is also impossible to transfer power and datum at the same frequency using coils [17]. Unlike CMRPT and IPT systems, electric flux is operated between two coupled foil surfaces in the CPT technology. CPT technology is utilized from parallel plates instead of coils core. These features make CPT technology attractive for wireless power and data application.

The fundamental demonstration of the CPT method is shown in Figure 1.

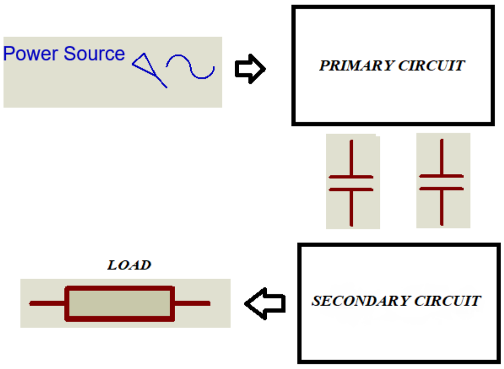

Fig 1: Capacitive power transfer system

From the past till today, capacitive coupling system has been using for artificially intelligent systems [18], biosignal processes [19], biomedical applications [20], operational amplifiers [21], battery charging systems [22], LEDs [23], vehicles [24] and synchronous systems [25]. However, efficient capacitive coupling typically limits CPT to applications where the air gap is a small distance, e.g., < 1 mm [26]. Due to the reason to design an optimal, efficient capacitive power transfer system, an E-class type power amplifier has been used. E-class power amplifiers (PA) are effective when they are compared with other power amplifiers. Theoretically, the efficiency of the E-class power amplifier is 100 %. Besides, the E-class power amplifier eliminates unwanted harmonic signals, which decreases the circuit's efficiency. The E-class power amplifier is controlled by switching members. Therefore, voltage and current could be controlled to minimize the losing energy converted to heat [27].

In this paper, a sub-kilowatt scale, an efficient CPT system, is designed to be used in a future wireless application. The wireless power transfer system includes not only a capacitive coupler also, power electronic design. The power electronic design consists of two main categories, which are theoretical calculation and experimental results, respectively. At the end of the article, obtained results and observed signal characteristics were discussed in detail. In the next section, an analysis of the capacitive coupler system and E-class power amplifier circuit design was performed.

II. ANALYSIS OF CAPACITIVE COUPLERS AND CLASS E POWER AMPLIFIER

A. Coupling Capacitors

When power electronics' frequency and performance capabilities are considered, the sub-kilowatt CPT method requires a nano farad (nF) level coupling capacitor. As is known, to obtain higher efficiency at high-frequency capacitive power transfer systems, a higher-voltage–the lower-current model should be operated. In WPT applications, the need for high power output leads the frequency to a greater value [14]. The logic behind designing an optimal capacitor is increasing the effective permittivity of dielectric material with a high voltage storage scale as much as possible for a given area. The dielectric material divided the coupling capacitor system into two parts: transmitter (primary) and receiver (secondary). The electric flux between the plates' surfaces depends on potential difference, material type, area size, etc. While those features are taken into consideration, copper plates are selected as artificial capacitors. Copper has a high conductivity number. Also, it can be found in the market easily with obtainable costs. In this study, single side copper clad plate laminate universal circuit board (PCB) has been used as a capacitor plate. Stretch film has been chosen as a dielectric material between parallel capacitor plates. According to Tsakiris et al., the conductivity of the copper plate is nearly $29 \times 10^{5} \Omega^{-1} cm^{-1}$ [28]. The pair capacitors' average capacitance is 0.17 nF at the rest position, as shown in Figure 2.

Fig 2: Capacitance value of an artificial capacitor

The capacitance values of coupling capacitors are measured by capacitance meter, as shown in Figure 2. The capacitance values of coupling capacitors are 0.18 nF and 0.16 nF. The cross-sectional area of each plate is $100 cm^2$. The permittivity of The average of these numbers is taken to use in theoretical calculations. The distance between the coupling capacitor can be calculated with equation 1.

$$C = \varepsilon_0 \times \frac{A}{d} \tag{1}$$

According to formula 1, in order to increase the farad value of the coupling capacitor, the distance between parallel plates should be minimized as much as possible. In this study, the idea has been kept in mind; therefore, stretch film has been used as the dielectric material.

B. Class E Power Amplifier

As mentioned before, the class E power amplifier has many advantages that make it attractive. For example, high efficiency, eliminated harmonic signals, lower energy loss etc. Voltage and current characteristics of switching members can be controlled in the class E PA circuit. Thus, the energy goes through heat could be minimized. This principle is known as zero voltage switching (ZVS). The basic E-class PA circuit has been demonstrated in Figure 3.

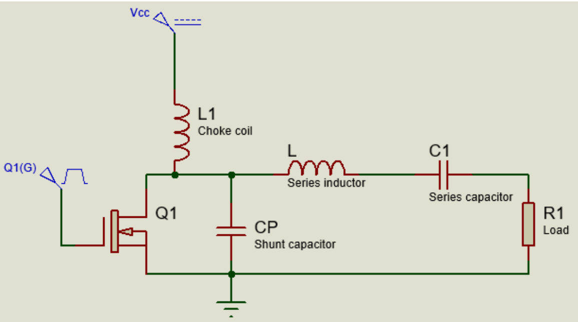

Fig 3: Typical class E power amplifier circuitry

Series inductor and series capacitor are used to create a series-resonant L-C. Therefore the series-resonant part eliminates the impedance losses in the E-class power amplifier circuit. Q1 repents the switching member, such as a transistor. The E-class PA was designed for antennas. Typically, the load on the antennas is 50 Ω. Thus, generally, the load (R1) is chosen 50 Ω. CP is the shunt capacitor that eliminates the harmonic signal. Generally, the choke inductor, L, should be chosen to high adequate to force direct current. Before the examination on the E-class PA, some assumptions were confirmed to reduce the calculations, which are;

- The switch is perfect (There are no losses)
- The choke coil on the DC supply operates as an optimally open circuit at the frequency of operation.
- The duty cycle of the switch is 50 % (Q1).
- Harmonic signals have been ignored.
- The class-E circuit is supplied while the "OFF" state of the switch at $\omega t = 2\pi n$

To provide ZVS conditions, the circuit should be operated at its resonance frequency. For this circuit, 5MHz frequency was specified as the resonance frequency of this circuit. C1 is the coupling capacitor in the circuit. The capacitance value of the C1 is 0.17 nF. Therefore, the required inductance value can be evaluated by equation 2.

$$f = \frac{1}{2\pi\sqrt{LC1}} \qquad (2)$$

L, C1 and f represent the series inductor, series capacitor, resonance frequency, respectively. From equation 2, the required inductance was specified as 5.96 µH, depending on switch conditions voltage (V(ωt)) and current (I((ωt)) across the switch are zero that are given in equation 3 and equation 4, respectively.

$$V(\omega t)\,|_{\omega t=2\pi n} = 0 \qquad (3)$$

$$\frac{d}{d(\omega t)} V(\omega t)|_{\omega t=2\pi n} = 0 \qquad (4)$$

In those circumstances, the capacitance value of the shunt capacitor is zero while the switch is opened as well as, the voltage and current across the shunt capacitor are zero. The parameters of the circuit members are represented in Figure 3. The KVL (Kirchhoff Voltage Law) and KCL (Kirchhoff Current Law) have been applied to equation (3) and (4). The full load resistance has been calculated with equation 5.

$$R_1 = \frac{8 \times V_{cc}^{\ 2}}{(\pi^2 + 4) \times P_d} \qquad (5)$$

P_d represents the total power on the load. For the shunt capacitor and series magnitudes, the conductor could be computed with equations 6 and 7.

$$L = \frac{QR1}{\omega} \qquad (6)$$

Q depends on a material characteristic, which is called a quality factor. In the literature, it was taken 10 [29].

$$CP = \frac{I_{dc}}{\omega \pi P_d} \qquad (7)$$

I_t shows the current that comes from the dc power source. The potential difference of the power source was shown with V_{cc}. The inductance value of the choke coil should be bigger than L_{min} to hold the current ripple.

$$L_{1,\min} = 2 \times (\frac{\pi^2}{4} + 1) \times \frac{R1}{f_{resonance}} \qquad (8)$$

In reality, the choke coil's inductance value is not so critical when its impedance is enough higher than the resistance of the load.

III. DESIGNING OF AN EFFICIENT CAPACITIVE POWER TRANSFER SYSTEM

The efficient capacitive power transfer system's circuit members are MOSFET, a choke inductor, shunt capacitor, MOSFET driver, and series resonance L-C part. A standard MOSFET might not be triggered easily at the high-frequency operation. There is a small capacitor at the gate pin of MOSFET. The sufficient quantity charge or current should be pumped to activate the MOSFET. MOSFET drivers operate as a charge pump in the circuit. In this study the design parameters are specified as follows; dc power supply voltage, V_{cc} =

12V, dc power supply current, I_{cc} = 0.40A, operating frequency f =5MHz, function generator, voltage of PWM signal V_{pp} = 6V, current of PWM signal I_{PP}= 0.01A, dc power supply voltage of MOSFET driver, V_{driver} = 8V, current draw by MOSFET driver, I_{driver} = 0.02A. The duty cycle of PWM is 50%. These values have taken from the experiment as tabulated. The circuit component values have been calculated by previously equations. However, the exact values not available such as 5.96 µH. Therefore closest values were operated. To obtain the resonance frequency of the circuit, the frequency scanning process has been applied. The maximum efficiency value was recorded at 1.739 MHz without any destruction on the waveform characteristic.

TABLE I
The Voltage, Current and Frequency Values of CPT system

V_{cc} (V)	I_{cc} (A)	V_{pp} (V)	I_{PP} (I)	V driver (V)	I driver (I)	Frequency (MHZ)
12	0.4	6	0.01	8	0.02	1.739

IRF 510 MOSFET has been used as a switching device in the circuit. It is an n-channel enhancement type MOSFET. It is very useful for high-speed applications. TC 4405 was selected as MOSFET driver. The used values and calculated values of circuit components have been shown in Table 2. The MOSFET driver was supplied with 8V, and 0.02 A. 6V peak-to-peak and 0.01A have driven the switching member (MOSFET). After the frequency scanning process, the resonance value of the circuit has been obtained.

TABLE II
Operated and theoretically calculated values of circuit elements

Circuit Members	Calculated value	Operated Value
CP (nF)	0.844	0.362
L (µH)	5.96	13.6
R (Ω)	17.30	21.90
f (MHz)	5	1.739

The CPT system demonstrated in Figure 4, and shamanic was given in Figure 5. In this Figure, C1, C3 represents pair capacitors. In this study, the two-channel capacitive coupling system was realized.

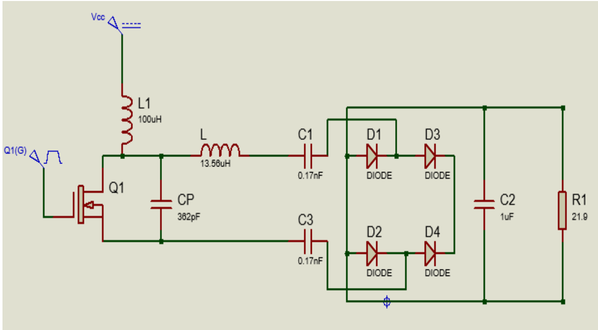

Fig 4: Sub-kilowatt scale, efficient CPT circuit

As shown in Figure 4, the obtained throughput of the E-class power amplifier circuit is direct current. In this case, the circuit is ready for use in different wireless application areas. The full-bridge rectifier circuit has been used to convert ac to dc. 1n4007 diodes were used.

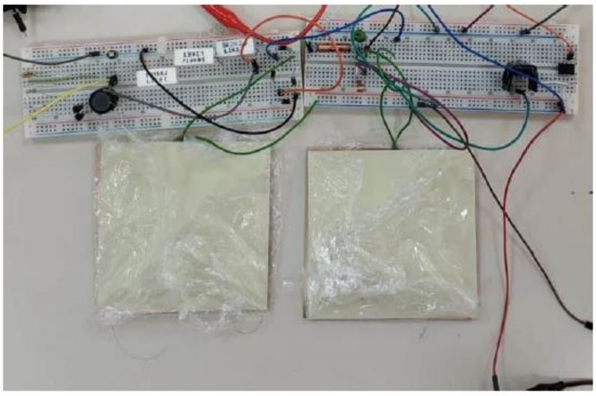

Fig 5: Demonstration of CPT system with class E PA

IV. EXPERIMENTAL RESULTS

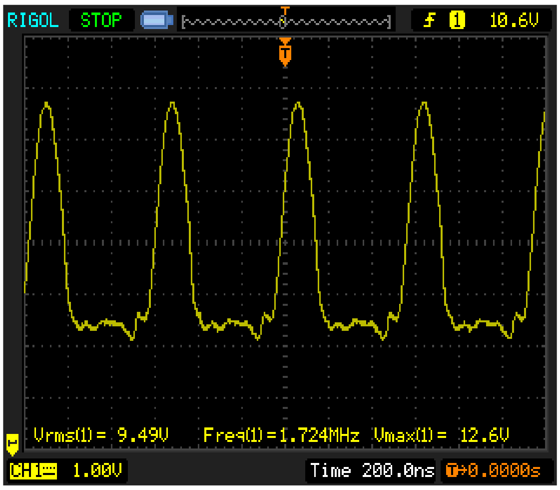

Fig 6: Output of class E PA

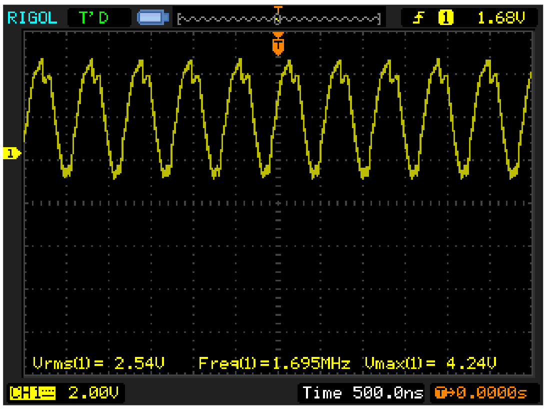

Fig 7: Gate-source voltage signal of MOSFET

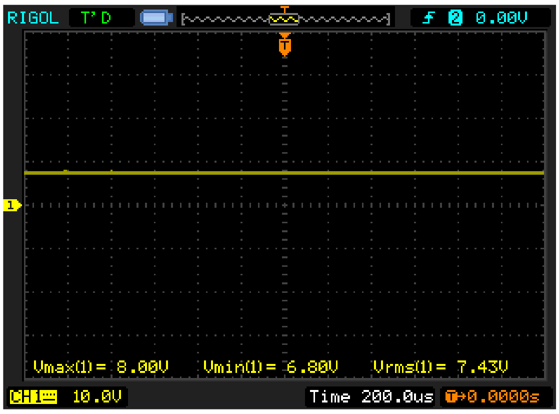

Fig 8: Rectified signal on the load

The following equations could do efficiency measurement according to the characteristics of the obtained signals from the figures mentioned above.

$$P_{dc,in} = 0.40A \times 12v = 4.8W \quad (9)$$

$$P_{driver} = 8V \times 0.02A = 0.16W \quad (10)$$

$$P_{driver,pulse} = V_p \times I_{driver,pulse} = 3\text{V} \times 0.01A = 0.03W \quad (11)$$

$$P_{total,in} = P_{dc,in} + P_{driver} + P_{driver,pulse} = 4.99W \quad (12)$$

$$P_{out} = \frac{(9.48V)^2}{21.9\Omega} = 4.1W \quad (13)$$

$$\eta = \frac{P_{out}}{P_{total,in}} \quad (14)$$

$$\eta = \frac{4.1W}{4.99W} = 82.1\% \quad (15)$$

The efficiency value was computed from the RMS of alternating current, and the diodes losses are ignored. As can be seen in Figure 6, there are harmonic losses. The PWM signal is not so smooth. Therefore, it will cause losses of inefficiency. The total input power was computed as 4.99 W. The throughput power was calculated as 4.1 W. The efficiency of the capacitive power transfer system was specified as about 82.1 %. The higher efficiency was obtained at the resonance frequency because the circuit's total impedance value goes through zero.

V. CONCLUSION

An overview of the function of the Class-E power amplifier was provided here. IRF510 MOSFET has been used as a switching circuit element. To trigger the MOSFET, the MOSFET driver was operated. The results show that the ZVS condition could be succeeded. In the experiment, the MOSFET was controlled 0.5 duty cycle. The 82.1 % efficiency has been obtained at the resonance frequency. There are no so smooth PWM signals to supply MOSFET perfect. Besides, due to harmonic signals, the efficiency of the circuit decreased. However, as can be understood from the figures, the high SNR was achieved. 4.1 W throughput power was obtained at the 1.7 MHz frequency. Thus, the potentials of sub-kilowatt, efficient capacitive power transfer systems have been investigated. This methodology might well be deployed in defense, medical, automotive, aerospace etc. The author believes that this technique promises new opportunities in the coming years.

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