Simulation-based Study of Capacitance Values Affected by Various Dielectric Materials and Distances for Low Power Wireless Power Transfer System

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***Abstract*—Capacitive Power Transfer (CPT) system is nowadays getting better attention by some of the researchers who are focusing on wireless power transfer field. This is because of the simplicity, small size, and better reaction towards EMI characteristics of the method. Furthermore, the efficiency of the CPT system is greatly influenced by the coupling capacitances which are varied by distances and permittivity values. Thus, this paper attempts to converge into the effect of several dielectric materials towards capacitance values and also the effect of the capacitive plates' distances towards the output power. By using Class E circuit configuration and MATLAB Simulink as the simulation software, the results are then explained graphically. From those simulations, the work achieved 90.7% as highest efficiency as compared to the theoretical values.**

***Index Terms*—Capacitive Power Transfer; Capacitance; Dielectric Materials; Wireless Power Transfer.**

I. INTRODUCTION

Wireless Power Transfer has nowadays become an important research area after being introduced by Nicola Tesla in 1897 [1], [2]. This area has shown significant contributions in complementing existing energy source since the wireless power transfer brings many benefits, especially towards the society. Some of the benefits include the ease of mobile devices charging [3], laptop charging [4], and wireless car charging [5] that have been investigated by previous researchers and are still developing. Because of this powerful enhancement, researchers are keen to look in depth into various aspects of this interesting area.

As shown in Figure 1, the circuit is made up of two main part named transmitter part and the receiver part. Furthermore, the transmission medium is this system basically divided into three; inductive, capacitive, and acoustic approach. As for this work, the capacitive approach is taken into account. This is due to the several advantages of the CPT including small-sized system [6] and reduces the electromagnetic interference by the usage of the electric field over magnetic field implemented in IPT [7].

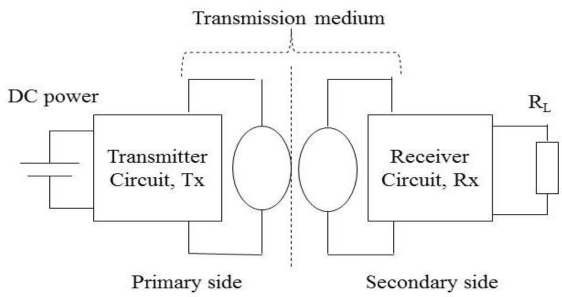

Figure 1: General circuit configuration for Wireless Power Transfer system

On the other hands, the power amplifier is the main part of a system. This part plays an important role in order to gain higher value of the output power. Thus, if a system needs to have a better configuration, the amplifier part should first be concerned of. To build up a circuit, one must first determine the suitable type of circuit to be used, and know how to measure the values of the components. In this work, researchers are focused on figuring out components values for Class E circuit configuration. Introduced by The Sokals in 1975, the Class E method is utilized because of its simplicity and the basis of the circuit operation which includes the unique principles of load network operation to achieve better efficiency [8]. Figure 2 shows the power efficiency resulting from Class E circuit configuration mentioned by Sokals.

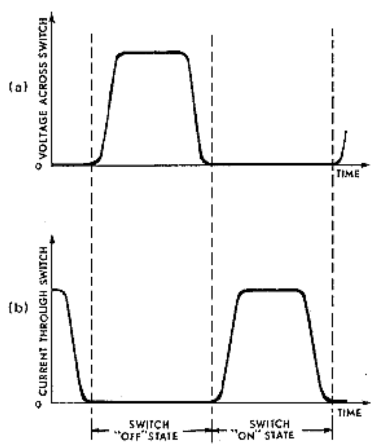

Figure 2: Optimum waveforms in Class E circuit arranged for maximum power efficiency [8]

However, the waveforms (a) and (b) in figure 1 in which the delay is increased from zero until the other waveform has completed decreasing to zero may only be formed by appropriate design of a non-resistive load network. The efficiency of the results could then be in a proper increase if the transition time of the switch is an appreciable fraction of a half-cycle of the AC waveform.

II. CAPACITIVE POWER TRANSFER

Capacitive power transfer which has been introduced to overcome the limitations of inductive power transfer is a mean for electric field charging method by using electrodes of capacitive plates. Based on a series of experiments by [9], there was a part whereby the effective capacitance between transmitter and receiver is $\frac{C}{2}$ since the two capacitors are in series. An H-bridge driver converts V_S into an AC voltage to make the current able to flow through the capacitors. Besides, inductors L are also placed in series with the coupling capacitance in order to reduce the impedance between the transmitter and receiver at resonance and to enable soft-switching. Then, there was a diode rectifier which converts the AC voltage back to DC. A voltage source models the load, which is equivalent to a resistive load in parallel with a sufficiently large hold-up capacitor.

Moreover, [6] has proposed a topology regarding the effective capacitive power transfer. In the project, the author calculated some parameters before proposing a system which overcomes the limitations such as limited output power and/ or efficiency by achieving higher values of cosine and reducing the current flowing through the interface with respect to the load current. The system proposed consisted of a half-bridge (or alternatively full-bridge) inverter, three resonant inductors, two resonant capacitors, the capacitive interface and a current-fed rectifier. As the result, several times higher output power is achieved without the need to increase the frequency of operation, and the algorithm of the design ensures minimization of the system size and compliance with the voltage ratings of the interface.

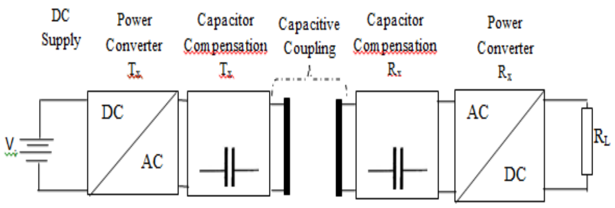

Figure 3: Basic design of capacitive power transfer system including the capacitive coupling as transmission medium

A. Class E Circuit Configuration

Class E circuit is classified as a simple topology for a power amplifier of a wireless power transfer system as detailed in Figure 2 [10]. The circuit can be called as a switched-mode circuit in which it is able to amplify a phase-modulated constant-envelope RF carrier [11]. Class E has also been selected because the circuitry is easy to be understood and can withstand higher frequencies up to Mega-Hertz.

From Figure 2, this paper is focusing on the class-E resonant power amplifier which is located at the transmitter part of the system. The basic circuit of the Class-E circuit is as shown in figure 2. Taking into account about the Class E circuit operation [12], the switch swapped periodically by the input signal V_{in} with approximately 50% duty cycle. Therefore current is built up and linearly increase through the inductor when the switch is on. When the switch is off, wise, capacitor steered the current and cause rising of the voltage across the switch.

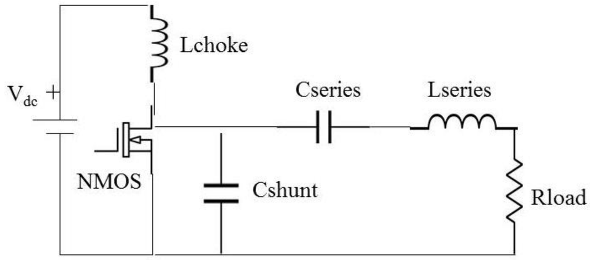

Figure 4: Basic Class-E circuit configuration [10]

B. Zero-Voltage-Switching of Class E CPT System

Zero voltage switching is the condition whereby the change in drain-to-source (V_{DS}) voltage is equal to zero, and the gate-to-source voltage V_{GS} increases much faster than in the power amplifier itself, with hard-switching. This situation can also be known by the condition whereby the slope of the transistor voltage is large as the transistor turns on [13].

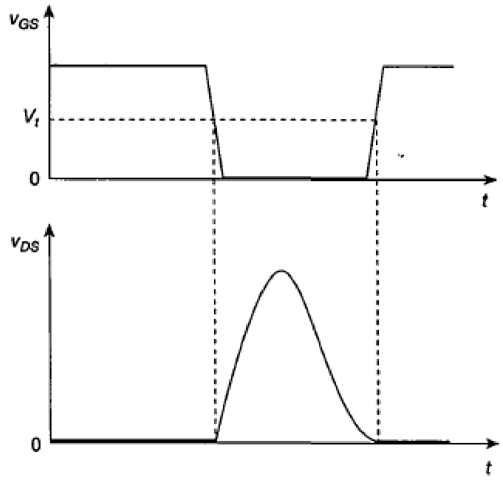

Figure 5: Waveforms of gate-to-source voltage (V_{GS}) and drain-to-source voltage (V_{DS}) in Class E qero-voltage-switching power amplifier

III. DESIGN AND SIMULATION WORKS

Part 1: The Effect of Capacitance of Different Dielectric Materials for Different Distances

The first part of this simulation works including four different types of materials as shown in Table 1 [14].

Table 1
Permittivity for Some Insulating Materials

Material	Relative Permittivity, ε_r
Paper	2.5
Rubber	3.0
Porcelain	6.5
Glass	7.0

Formula of C = $\frac{A\varepsilon_o\varepsilon_r}{d}$ [15] is used, whereby d is the distance between the transmitter and the receiver plate, and A is the area of the capacitive plate which is fixed at $0.05m^2$.

Besides, ε_o is a constant (8.85×10^{-12}), and ε_r is the relative permittivity of the material, as shown in Table 1.

When $\varepsilon_r = 2.5$ and *d* is 0.3mm,

$$C = 3689.24\text{pF}, \tag{1}$$

Then, if $\varepsilon_r = 7.0$ and *d* is 3mm,

$$C = 1032.99\text{pF} \tag{2}$$

The calculations were done for all distances and different permittivity values. Then after getting the values of capacitance for each distance and material, a graph is plotted to show the graphical result of the simulation work. The graph is explained in the results section.

Part 2: The Effect of Output Power of the System for Increasing Distances

As for Part 2, the work is going depth as authors picked a specific dielectric material to be utilized. In this paper, authors used paper with a relative permittivity of 2.5 as the dielectric material. The reason for selecting paper is because of its functionality and safety. Besides, for this simulation, the authors also decided to use a piece of a thick paper as the dielectric material because of the easy-to-be-found criteria.

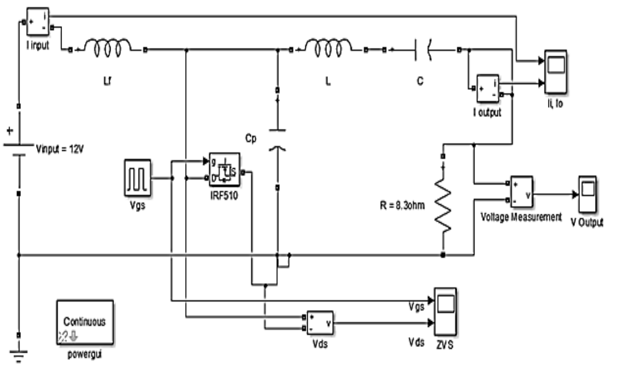

Figure 6: Design of Class E power amplifier used for the simulation work

Figure 5 shows MATLAB representation of the Class E simulation for this experiment. All the components values were plugged into the simulation by calculations prior to it. In order to be certain of the components values, a series of formula by Marian K. Kazimierczuk [13] have been utilized. The calculations are as follows:

Table 2
Pre-determined specifications of Class E Power Amplifier

Specification	Value
Output power, P_o	10W
Input voltage, V_i	12V
Duty cycle, D	0.5
Frequency, f	1MHz
Quality factor, Q	10

As the frequency is 1MHz and quality factor, Q = 10, the value of the components can be computed as:

Load resistor, R_L:

$$R_L = \frac{8}{\pi^2 + 4}\left[\frac{Vi^2}{PRi}\right] \tag{3}$$

Series inductor, L

$$L = \frac{Q_L R_i}{\omega} \tag{4}$$

Shunt capacitor, Cp

$$C_p = \frac{8}{\pi(\pi^2 + 4)\omega Ri} \tag{5}$$

The series capacitor, C

$$C = \frac{1}{\omega Ri\left[Q_L - \frac{\pi(\pi^2 - 4)}{16}\right]} \tag{6}$$

The choke inductor value:

$$L_f = 2\left[\frac{\pi^2}{4} + 1\right]\frac{Ri}{f} \tag{7}$$

Table 3
Calculated Values of Components for Class E Design Specification

Specification	Value
Load resistance, R_L	8.31Ω
Series inductor, L	13.23μH
Shunt capacitor, Cs	3.52nF
Series capacitor, C	2.16nF
Choke inductor, L_f	1MHz

After all of the desired values have been calculated as in Table 3, a graph of output power and the efficiency of the system over distance are plotted separately to show in details about the decreasing outcome.

According to [13], the output power can be determined by the formula:

$$P_{Ri} = \frac{V^2{}_{Rim}}{2_{Ri}} \tag{8}$$

whereby $V^2{}_{Rim}$ is the squared value of the output voltage, and 2_{Ri} is the fixed value of the load resistor which is 8.31Ω. The tabulated results are as shown in the Results section.

IV. Results and Analysis

A. Part 1

In this section, the explanation will be focused on the values of capacitance towards a different type of materials (which leads to different values of permittivity). Four types of material have been used in order to prove the effect of capacitance for each material. The permittivity constant for each dielectric material is as shown in Table 1.

Table 4
Values of Capacitance for Different Materials for Various Distances

Distance (mm)	Capacitance values for Different Dielectric Materials (pF)			
	Paper	Rubber	Porcelain	Glass
0.3	3689.24	4427.09	9592.04	10329.89
0.6	1844.62	2213.55	4796.02	5164.94
0.9	1229.75	1475.70	3197.35	3443.30
1.2	922.31	1106.77	2398.01	2582.47
1.5	737.85	885.42	1918.41	2065.98
1.8	614.87	737.85	1598.67	1721.65
2.1	527.03	632.44	1370.29	1475.70
2.4	461.16	553.39	1199.00	1291.24
2.7	409.92	491.90	1065.78	1147.77
3.0	368.92	442.71	959.20	1032.99

The values stated in Table 4 are the capacitance in pF. As we can see, the pattern of the results linearly decreases with increasing distance and is increasing with the increment of value of permittivity.

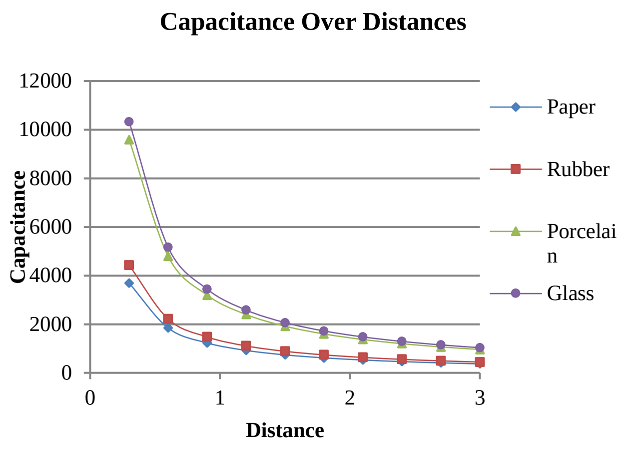

Figure 7: Graph of capacitance over distances for different materials

From the graph, it is shown that as the relative permittivity of a material is increased, the value of the capacitance is also increased. As represented by the equation of capacitance in Equation (3); capacitance, C = $\frac{A\varepsilon_o\varepsilon_r}{d}$, it is clearly shown that the values of capacitance will be increased with the increase of permittivity of materials (ε_r) but is decreased as the distance, *d* is increase. This is with condition that the other values (A, and ε_o) are fixed.

B. Part 2

This section is concerning on the effect of output power as the distance is increased, by using a specific dielectric material; a piece of paper.

By referring to Table 5 and the Figure 9, the graph clearly showed us that the output power of the circuit is becoming lesser which leads to the low quality of capacitive power transfer system. From this, we can say that the basic circuit of capacitive power transfer cannot maintain the capacitance if the distance is increased, and therefore the output power would be reduced greatly.

Table 5
Output Value for Different Distance Measured for Paper as The Dielectric Material

Distance (mm)	Output Power (P)	Efficiency (%)
0.3	9.07	90.7
0.6	0.98	9.8
0.9	0.88	8.8
1.2	0.75	7.5
1.5	0.48	4.8
1.8	0.46	4.6
2.1	0.34	3.4
2.4	0.30	3.0
2.7	0.17	1.7
3.0	0.10	1

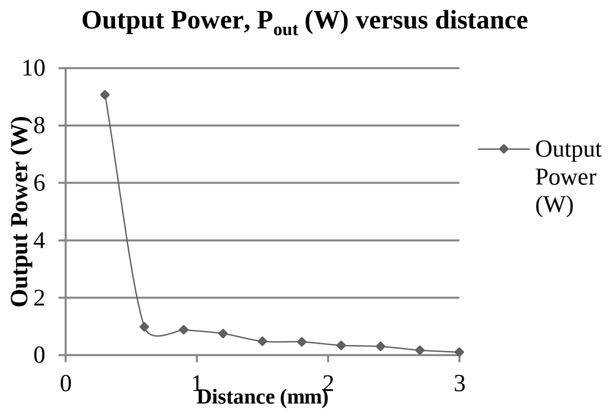

Figure 9: Graph of output power for increasing distance

C. Efficiency of the system

Table 5 shows the values of output power which are resulted from the simulation and the efficiency which is calculated as follows:

$$\eta = \frac{P_o}{P_i} x\ 100\%$$

For example, for 0.3mm gap of the system, the efficiency is:

$$\eta = \frac{P_o}{P_i} x\ 100\% = 90.7\%$$

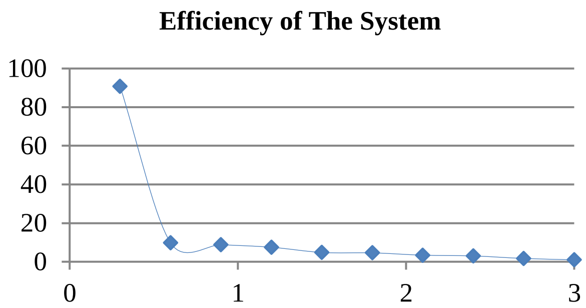

Figure 10: Efficiency of the system

V. CONCLUSION AND FUTURE WORKS

The permittivity of a material affects the capacitance values as proved in this simulation work. As the relative permittivity is increased, the value of capacitance will also increase. However, in this case of capacitive power transfer, one has to choose any suitable dielectric materials to be used according to his applications as the results would not be as desired if the material is chosen wrongly. In terms of the output power of the system, basic common Class E CPT system will decrease critically, as a theoretical explanation. As explained in the last part of the paper, the efficiency initially is 90.7% but as distance increases, the efficiency decreased vastly to less than 10%. However, these results would be improved by introducing impedance matching circuit into the earlier circuit. Thus, for future works, an impedance matching circuit should be a great improvement towards the enhanced system, especially in hardware implementation.

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