Analysis and Design Capacitive Power Transfer (CPT) System for Low Application Using Class-E LCCL Inverter by Investigate Distance between Plates Capacitive.

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Abstract. This study presents the analysis and design of a Capacitive Power Transfer (CPT) system for low power application using a Class-E LCCL inverter based on varying the distance between capacitance plates. The Class-E LCCL inverter can produce a high-frequency alternate current and reduce the size of the capacitance plate to minimise power losses during energy transfer besides yielding low switching losses. In specific, the performance of the LCCL CPT system at 1 MHz operating frequency and 24 V DC supply voltage was analysed via simulation and experimental works. Finally, a prototype of the CPT system was successfully designed, producing 10 W output power through a capacitive plate size of 0.0327 m² and a 0.1 cm air gap at 96.68% efficiency. Based on the performance of the LCCL CPT System design, an efficiency analysis of the LCCL CPT System was performed; the capacitance plate distance was varied from 1 cm to 20 cm and produced a change in total impedance calculation from 57.69+j198.42 Ohm to −2.05j Ohm. Meanwhile, efficiency decreased from 96.68% to 1.25% but power was still transmitted in that range. These findings could be beneficial for hazardous electrical environments, portable applications, consumer electronics, and medical implants.

Keywords: Wireless Power Transfer, Capacitive Power Transfer, Class E converter

1. Introduction

Wireless Power Transfer (WPT) is a process of transferring power from one circuit to another circuit without utilization of any connected conductive elements. Several schemes for wireless power transfer are currently present such as an inductive, capacitive, laser, microwave, and etc. Among them, Inductive Power Transfer (IPT) is known as the most popular and deeply studied scheme initiated form two decades ago. However, several drawbacks have been associated with the IPT method such as relatively high common-mode source impedance to overcome the high power factor of current topologies as well as high standing power that might lead to Eddy current losses. Nevertheless, the IPT method is the most commonly utilized method to attain wireless power transfer that has been employed along with magnetic solutions for decades (i.e. wireless battery chargers, power supplies for electric vehicles). As a result of the limitations of the IPT method, this study attempts to explore new horizons of a wireless power transfer technology known as capacitive power transfer. In the capacitive interface, the field is confined between conductive plates, while alleviating the necessity for magnetic flux guiding and shielding components that increase bulk and cost to the conductive solution [1]. In contrast to the inductive-based methods, the simplicity and lower cost of capacitive interfaces make them a potential method for wireless charging stations and galvanically isolated power supplies. Currently, the conventional CPT solutions are widely utilized in applications which require large capacitors or low power, such as coupling of power and data between integrated circuits or power and data transmission to bio-signal instrumentation systems [1].

Since the establishment of the wireless power transfer, the magnetic induction method was utilized as a central principle to transfer the power through a charging pad or over the air. This method is known as IPT and has been employed to wirelessly transfer the power for material handling systems [2], battery chargers [2], and power supplies to electrical vehicles [3]. Since the establishment of the...
wireless power transfer, the magnetic induction method was utilized as a central principle to transfer the power through a charging pad or over the air. This method is known as IPT and has been employed to wirelessly transfer the power for material handling systems [4]. Moreover, in order to obtain a suitable coupling capacitance, a ferrite core is required as well as shielding in order to prevent electromagnetic inferences. Therefore, metal barriers and surroundings become less of a concern [5], [6]. However, due to the various disadvantages of the IPT method, it cannot be applied to various systems, especially in the biomedical implants since the magnetic fields can interfere with the medical electronic devices, contract with CPT which is have minimum electromagnetic interference (EMI) as the electric field is confined around the patches surfaces[7]. Hence, this study focuses on the capacitive power transfer system.

It has been reported that the efficiency of the CPT system drops with the increasing of coupling gap distances. Moreover, high efficiency could only be obtained when the coupling gap is fixed. Furthermore, the coupling plates are required to be clamped together in order to minimize the capacitance variation attributed to the flatness imperfection. The flatness imperfection is known to generate an uneven distribution of the air gap and alteration in the position or distance of the coupling plates, resulting in low coupling capacitance which leads to a significant drop in the output power. Consequently, in order to enhance the efficiency of the existing CPT system over a longer distance, analysis of distance due to changing of impedance will investigate on this journal in next section.

The IPT is currently the predominant method of implementing WPT systems. However, in cases of powering small devices at low power level, especially in compact physical places, IPT systems are not practical. This is due to the fact that IPT systems are more efficient at lower frequencies, which require large circuit components [8]. As the value of frequency increases, the CPT method may compete with IPT, as the former is capable of offering equally good galvanic isolation at lower cost and does not require a costly and high-frequency magnetic core. It has been reported that CPT can be applied on vehicle applications, while upgrading the coupling capacity between every two to six plates can significantly reduce the electric field emissions [9]. In another study, output power of 9.5W was generated through a combined interface (PCB plate) capacitance of 2.82nF at an operating frequency of 1MHz, with 95.44% efficiency. The experimental work utilized impedance matching in order to select the precise frequency operating of CPT and to reduce the error of zero voltage switching (ZVS) [10][11].

The CPT system works based on the capacitive coupling which comprises of two metal plates separated by an air gap, as illustrated in Figure 1. Furthermore, a primary converter circuit is located at the transmitter side that transforms the direct current (DC) source into alternate current (AC) source. Since the power transmission from transmitter side into the receiver side is executed via an air gap, it requires a high-frequency current in order to drive both capacitor plates [13]. Hence, the class E resonant converter circuit has been proposed in this study due to its low switching losses [14]–[16].

2. Class E LCCL Mosfet Inverter for CPT System

The Class E MOSFET converter design emphasises on switching performance. Figure 2 displays the basic schematic for a Class E amplifier with an inductive choke. It can be observed that the transistor is utilised in such a way that it is either in a completely off state or a completely on state.
In other words, there is a slight overlap in the switch voltage and current waveforms, which could lead to power loss. Power losses are always present due to parasitic resistance in inductors and capacitors. However, these losses have been neglected in the analysis of this study. The class-E amplifier has two significant features, namely the existence of a shunt capacitor across the switch and a net series load inductance that provides the essential phase shift for the fundamental wave, which allows the circuit to perform as a harmonic open circuit.

![Figure 2: Basic schematic of Class-E amplifier with inductive choke.](image)

The voltage across the switch is signified by $V(\omega t)$, while the current through the switch is represented by $I(\omega t)$ at any instant of normalised time ($\omega t$). In order to improve the output power, LCCL Class E proposed in this circuit [17]. Class E LCCL is a combination of two circuits; one is a Class E LC topology circuit while the other is an LC match circuit. The proposed circuit is able to convert impedance to the desired impedance to match with the power requirement. Class E-LCLC is illustrated in Figure 3.

![Figure 3: Class E Schematic LCLC Capacitive system](image)

Since the choke inductor is assumed to be ideal (no resistance), the value of supply voltage ($V_{cc}$) must be equal to the average voltage across the switch/shunt capacitor over a full on-off cycle. This produces the first formula for the design relationship, given by Equation (1)

$$V_{cc} = \frac{1}{2\pi} \int_{\pi}^{2\pi} V(\omega t)d(\omega t) = \frac{I_0}{\pi \omega C}$$  \hspace{1cm} (1)

Since the switch is assumed to be perfect and all class-E conditions are assumed to be satisfied, the DC power provided by the bias DC source must be equivalent to the power dissipated in the load resistor. Hence, the power delivered to the load could be defined as Equation (2) until (9) by refer in [17]

$$P_{load} = \frac{BV_{cc}^2}{(\pi^2+4)R_L}$$  \hspace{1cm} (2)
The reactance of Capacitor value:

\[ C_1 = \frac{1}{\omega R_1 \left( \frac{\pi^2}{4} + 1 \right)^{\frac{1}{2}}} \]  

(3)

The reactance of Inductance value:

\[ L_2 = \frac{QR}{\omega} \]  

(4)

The minimum of resonance inductor value:

\[ L_1 = 2 \left( \frac{\pi^2}{4} - 1 \right) \frac{R}{f} \]  

(5)

The coupling capacitor value:

\[ X_{cp} = \frac{R_3 \left[ (Q-1.1525)^2 + 1 \right]}{Q-1.1525 - \sqrt{\frac{R_3 \left[ (Q-1.1525)^2 + 1 \right]}{R_L} - 1}} \]

\[ C_p = \frac{1}{2\pi f X_{cp}} \]  

(6)

Transmit resonant capacitor value:

\[ X_{c2} = R_L \sqrt{\frac{R_3 \left[ (Q-1.1525)^2 + 1 \right]}{R_L} - 1} \]

\[ C_3 = \frac{1}{2\pi f X_{c2}} \]  

(7)

The receiver impedance inductor value:

\[ L_3 = \frac{\sqrt{1316 R_L - 1}}{2\pi f} \]  

(8)

The receiver impedance capacitor value:

\[ X_{c3} = \frac{1316 R_L}{2\pi f L_3} \]

\[ C_3 = \frac{1}{2f \omega X_{c3}} \]  

(9)

3. Analysis and Comparison Simulation and Experimental work

Based on calculation theoretical, the result efficiency of system absolutely in 100%, by validate in simulation result and hardware result, the matlab Software have been selected to measure zero voltage switching (ZVS), power input and Power Output, then lastly the result will conclude to investigate distance 1cm to 10cm of coupling distance. For the reference, a table 1 of variables relevant to the analysis is provided below:

**Table 1**: Table of pertinent variables
Figure 4: Schematic Circuit simulation for CPT LCCL system by Matlab

Figure 5: Experiment Setup for CPT LCCL system

Figure 4 and Figure 5 show the simulation circuit and experimental setup of the LCCL CPT system, respectively. For the experimental setup, the components used are close to or exactly match the simulation circuit to ensure precise results, especially in measuring the ZVS, the input power, the output power, and the efficiency of the CPT LCCL system. The simulation result and experiment result are then discussed in detail with a distance of 1 mm being set between the coupling plates, Cp. Zero voltage switching is an important variable in this system, as it ensures the power losses during switching in MOSFET remain minimal. [18]

Figure 6: Result Simulation of ZVS CPT LCCL system
By referring to the ZVS simulation result in Figure 6, it can be observed that the system showed smooth, efficient switching, with a Vds = 87.77 V. In the experimental result in Figure 7, the ZVS result was still acceptable with a Vds = 98 V. The simulation result and the experimental result recorded a Vds value 3–4 times more than the value of Vcc, indicating good Vds values for switching value based on the theoretical concept. In the analysis of the CPT LCCL system efficiency, the result of input power and output power from the simulation and experimental results were recorded and presented in Figure 8 to Figure 11 below:

**Figure 7: Result Experimental of ZVS CPT LCCL system**

**Figure 8: Result Simulation for Voltage input and Current input**

**Figure 9: Result Simulation for Voltage output and Current Output**

**Figure 10: Result Experimental for Voltage Input and Current input**
The results of input power and output power in Figure 8 to Figure 10 could be used to determine the efficiency of the system by inputting them in Equation (10)

$$\% n = \frac{V_o(rms) \times I_o(rms)}{V_{in}(dc) \times I_{in}(dc)}$$ (10)

### Table 2: Result Efficiency of System

| System variable          | Unit | Result Simulation | Result Experimental |
|--------------------------|------|-------------------|---------------------|
| Input Voltage(dc)        | Vin(dc) | 24.00V            | 24.10V              |
| Input Current(dc)        | Iin(dc) | 0.41A             | 0.40A               |
| Output Voltage(rms)      | Vo(rms) | 21.86V            | 20.71V              |
| Output Current(rms)      | Io(rms) | 0.44A             | 0.45A               |
| Efficiency               | %n    | 97.77%            | 96.68%              |

Table 2 shows the simulation and experimental results of the LCCL CPT system with efficiencies of 97.96% and 97.21%, respectively. These results have high efficiency in transferring power to load, which is 10 W at a 50-Ohm load. This result is based on a 1 mm distance between the capacitance plate couplings. To investigate the effect of varying plate distance on the system efficiency, the plate distance was varied from 1 cm to 10 cm, and input voltage, input current, output voltage, and output current were recorded to analyse the efficiency of the LCCL CPT system. Table 3 shows the variance in plate distance from 1 cm to 10 cm. The table below show variance of distance plate 1cm to 10cm in practically.

| System variable          | Distance between 2 plates of capacitive, C, cm |
|--------------------------|-----------------------------------------------|
|                         | 2cm   | 4cm   | 6cm   | 8cm   | 10cm  |
| Input Voltage(dc)        | 24.10V| 24.20V| 24.10V| 24.10V| 24.10V|
| Input Current(dc)        | 0.58A | 0.70A | 0.73A | 0.82V | 0.83V |
| Power Input              | 13.98W| 16.94W| 17.59W| 19.76W| 20.00W|
| Output Voltage(rms)      | 14.21V| 9.26V | 5.23V | 4.38V | 3.61V |
By referring result in Table 3, shows the result of power output reduced when capacitance plates change distance 1cm to 10cm. The result power input and power output can shows graph in Figure 12, its can assume emission field energy will decreasing due to change distance capacitance plates and effected by total impedance. The total impedance of circuit will decreasing when varying capacitance plates 1cm to 10 cm by analysis the calculation of total impedance in Figure 13 to Figure 14.

**Figure 12:** Result of Power input and Power Output for variance of distance from 1cm to 10 cm

| Output Current (rms) | 0.30A | 0.20A | 0.11A | 0.09A | 0.07A |
|---------------------|-------|-------|-------|-------|-------|
| Power Output        | 4.26W | 1.85W | 0.58W | 0.39W | 0.25W |
| Efficiency, %       | 30.50%| 10.93%| 3.30% | 1.98% | 1.25% |

**Figure 13:** Schematic circuit LCCL CPT System impedance view for movement plate direction.

Based on result, the total impedance in $Z_T$ can be analysed based on the results above. Fig. 13 shows the analysis of the schematic circuit for the LCCL CPT System; when the receiver circuit moves a bit further—1 cm to 10 cm away from the transmitter circuit—total impedance changed in calculation from 57.69+j198.42 Ohm to $-2.05j$ Ohm with no contact with the transmitter circuit. Due to decreasing total impedance, total input current increased and input power increased. In turn, the efficiency of the system decreased.
The simplified equivalent circuit after simplifying $Z_T$ is shown in Figure 14. The equation for total impedance can be derived based on 2 situations; contact in detecting transfer current and no contact (far away) with the transmitter circuit where Equation (11) until (13) can be used and the value of capacitance plate impedance, $X_{CP}$, is replaced with $-j1316.42$ Ohm.

The first condition for the 1 mm plate distance is given by Equation (11) to (12):

$$Z_A = \frac{R X_{C2} + X_{L2} X_{C2} + X_{P} X_{C2} + X_{CP} R + X_{CP} X_{L2}}{X_{C2} + R + X_{L2}}$$  (11)

$$Z_T = \frac{X_{C1} X_{L2} + X_{C2} X_A}{X_{L2} + X_{C1} + X_A}$$  (12)

The second condition for the receiver circuit to be far away from the transmitter circuit is given by Equation (13).

$$Z_T = \frac{X_{C1} X_{L2} + X_{C1} X_{C2}}{X_{L2} + X_{C1} + X_{C2}}$$  (13)

4. Conclusion

This study analysed an LCCL CPT system at 1 MHz operating at 96.68% efficiency via simulation and experimental works. The efficiency of the overall CPT system has been found affected by power losses in the transmitter unit, capacitive coupling distance, and rectifier. This study focused on power losses in the transmitter unit with the aim of enhancing the efficiency of the CPT system. Future work could focus on increasing the efficiency of the system by finding the optimal plate distance for all applications such as biomedical implants, medical applications, and charging space-confined systems such as robots, or mobile devices. This research is capable of further advancing the technology of wireless charging, especially in medical applications. These are aligned with the Malaysian Government Policy, namely the Eleventh Malaysia Plan (RMK-11), which include strategic developments in advanced fields. Moreover, this study also fulfils the National Key Economic Area (NKEA), which aims to enhance the Education Sector and become a developed country by the year 2020.

ACKNOWLEDGEMENTS

This research was funded by the Malaysia Ministry of Education [600-RMI/FRGS 5/3 (083/2019)] grant. Sincerely to express the appreciation to Universiti Teknologi MARA (UiTM) and Universiti Teknikal Malaysia Melaka (UTeM) for professional support.

5. References
[1] M. Kline, I. Izyumin, B. Boser, and S. Sanders, “Capacitive power transfer for contactless charging,” in Conference Proceedings - IEEE Applied Power Electronics Conference and
[2] J. T. Boys, G. A. Covic, and A. W. Green, “Stability and control of inductively coupled power transfer systems,” *IEEE Proc. - Electr. Power Appl.*, vol. 147, no. 1, p. 37, 2000.

[3] B. Choi, J. Nho, H. Cha, T. Ahn, and S. Choi, “Design and Implementation of Low-Profile Contactless Battery Charger Using Planar Printed Circuit Board Windings as Energy Transfer Device,” *IEEE Trans. Ind. Electron.*, vol. 51, no. 1, pp. 140–147, 2004.

[4] C. Liu, A. P. Hu, and M. Budhia, “A generalized coupling model for Capacitive Power Transfer systems,” in *IECON Proceedings (Industrial Electronics Conference)*, 2010, pp. 274–279.

[5] A. P. Hu, C. Liu, and H. L. Li, “A novel contactless battery charging system for soccer playing robot,” in *15th International Conference on Mechatronics and Machine Vision in Practice, M2VIP ’08*, 2008, pp. 646–650.

[6] A. G. Andreou, “Capacitive Inter-Chip Data and Power Transfer for 3-D VLSI,” *IEEE Trans. Circuits Syst. II Express Briefs*, vol. 53, no. 12, pp. 1348–1352, 2006.

[7] R. Erfani, F. Marefat, A. M. Sodagar, and P. Mohseni, “Transcutaneous capacitive wireless power transfer (C-WPT) for biomedical implants,” in *Proceedings - IEEE International Symposium on Circuits and Systems*, 2017.

[8] K. Lu and S. K. Nguang, “Design of auto-tuning capacitive power transfer system for wireless power transfer,” *Int. J. Electron.*, vol. 103, no. 9, pp. 1430–1445, 2016.

[9] H. Zhang, F. Lu, H. Hofmann, W. Liu, and C. C. Mi, “Six-Plate Capacitive Coupler to Reduce Electric Field Emission in Large Air-Gap Capacitive Power Transfer,” *IEEE Trans. Power Electron.*, vol. 33, no. 1, pp. 665–675, 2018.

[10] Y. Yusop, Z. Ghani, S. Saat, H. Husin, and S. K. Nguang, “Capacitive power transfer with impedance matching network,” in *Proceeding - 2016 IEEE 12th International Colloquium on Signal Processing and its Applications, CSAP 2016*, 2016, pp. 124–129.

[11] Y. Yusop, S. Saat, S. K. Nguang, H. Husin, and Z. Ghani, “Design of Capacitive Power Transfer Using a Class-E Resonant Inverter,” *J. Power Electron.*, vol. 16, no. 5, pp. 1678–1688, Sep. 2016.

[12] K. K. Hasan, S. Saat, Y. Yusof, M. A. H, Z. M. Yusoff, N. M. M. Shaari, and M. Z. Mustapa, “Design of Capacitive Power Transfer ( CPT ) for Low Power Application using Power Converter Class E triggered by Arduino Uno Switching Pulse Width Modulation ( PWM ),” *Int. J. Eng. Technol.*, vol. 7, pp. 77–81, 2018.

[13] C. Liu and A. P. Hu, “Steady state analysis of a capacitively coupled contactless power transfer system,” in *2009 IEEE Energy Conversion Congress and Exposition, ECCE 2009*, 2009, pp. 3233–3238.

[14] K. Kh, Shakir Saat, Y. Yusmarnita, and N. Jamal, “Analysis and Design of Wireless Power Transfer : A Capacitive Based Method for Low Power Applications,” *WSEAS Trans. Circuits Syst.*, vol. 14, pp. 221–229, 2015.

[15] Y. Yusmarnita, S. Saat, A. H. Hamidon, H. Husin, N. Jamal, K. Kh, and I. Hindustan, “Design and Analysis of 1MHz Class-E Power Amplifier 2 Circuit Description,” *WSEAS Trans. Circuits Syst.*, vol. 14, pp. 373–379, 2015.

[16] K. Kamarudin, S. Saat, and Y. Yusmarnita, “Analysis and design of wireless power transfer: A capacitive based method,” in *2014 IEEE Symposium on Industrial Electronics & Applications (ISIEA)*, 2014, vol. 14, pp. 136–141.

[17] Y. Yusop, H. Husin, S. Saat, S. K. Nguang, and Z. Ghani, “Class-E LCCL for capacitive power transfer system,” *PECCON 2016 - 2016 IEEE 6th Int. Conf. Power Energy, Conf. Proceeding*, pp. 428–433, 2017.

[18] M. K. Uddin, S. Mekhilef, and G. Ramasamy, “Compact wireless IPT system using a modified voltage-fed multi-resonant class EF<sup>inf</sup>-2<sup>inf</sup>-inverter,” *J. Power Electron.*, vol. 18, no. 1, pp. 277–288, 2018.