The Development of Wireless Power Transfer Technologies for Mobile Charging in Vehicles using Inductive Approach

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***Abstract*— Nowadays, the mobile charging in vehicle is a must and therefore, such technology is now available in every vehicle through wired connection approach. Using this wired connection to power up mobile device in the vehicle might be inconvenience to the user. Thus, this project aims to develop a wireless power transfer technology to power up the mobile device in a vehicle. Through this, the users will not facing difficulty of charging their device while driving. To be specific, the Inductive Power Transfer (IPT) is applied here due to its advantages where it can transfer power wirelessly with a higher efficiency in a short range. To make this work, a Class E inverter is designed to convert a direct current (DC) supply into alternating current (AC) supply at a high frequency with a higher efficiency. Furthermore, pi-2-a impedance matching circuit is also applied in this work in order to improve the efficiency of such system. To validate the efficiency of the proposed method, analysis on the gap distance between the two magnetic coils, transmitter and receiver, are performed through simulation and experimental work. At the end of this work, the designed prototype is able to yield approximately 70 % in terms of output efficiency and able to power up the mobile device wirelessly.**

***Index Terms*— Wireless Power Transfer (WPT), Inductive Power Transfer (WPT), Class E Inverter circuit, wireless mobile charger in vehicles, magnetic coils**

I. INTRODUCTION

Wireless Power Transfer Technology [1], [2] is trending itself as an actual solution for transmitting power for devices at remote distances through an air gap, without the need for current-carrying wires. The research on this framework has significantly increased over the past 10 years [3], [4]. Generally, the idea of this wireless power transfer technology is to conveniently transmit power from a power source to a load, in this case, a mobile device through an air gap or any other medium, thus eliminating the need of wires. This technology was actually developed in the late 19th and early 20th century, where electromagnetic research was deeply researched back then. These researches are the core to today's development in the transportation of electrical power [5].

The explosive growth of mobile computing has led to faster and more powerful portable devices such as mobile phones are manufactured. However, the usage of hand-held devices has its own deficiency in terms of its battery's lifespan. These days, the manufactured mobile devices are extremely powerful in a way that even its' battery storage capability is not sufficient enough to last for a single day usage. This will definitely create a huge problem especially when someone requires travelling by car for a long hour as the battery lifespan might not sufficient. Thus, currently, the usage of wired-adapters in cars for mobile charging was introduced. An adapter would be plugged into the cigarette lighter port or USB port, supplying a steady power source to charge these devices. However, the usage of this wired-charger is not safe especially when it is tangled. To untangle these wires during driving in a tight space could prove costly to the driver's safety. In addition to these wired-charging, Power Banks were also used to support one device's battery lifespan. However, in today's market, the safety protocols on these devices are often taken lightly especially those manufactured from companies that produces clone devices. Besides, in recent events, several cases of Power Banks exploded in one's pocket or even in a vehicle due to direct exposure to sunlight have questioned the integrity of these Power Banks. Thus, the idea of introducing wireless power transfer (WPT) technology would certainly bring less harm to humans especially if installed in the car. This leads us to deliver this work to power up the mobile devices in vehicle wirelessly. This consequently will resolve the previous mentioned problem.

The proposed work is based on the inductive approach and this method is commonly known as inductive Power Transfer (IPT). The main reason behind this selection is because the IPT produces the highest efficiency in comparison to its counterpart; Capacitive Power Transfer (CPT) and Acoustic Power Transfer (APT) [6]. A more detail discussion on CPT and APT system can be referred to [7] and [8]. The fact is, over the past decade, the number of researches regarding on IPT has increased tremendously. Most researches are focused on charging low powered mobile devices through inductive coupling [9], [10], [11], [12]. So, this project can be considered as extension to the existing results listed above but using Class E inverter together with impedance matching (pi-2-1). To note here that most of the existing results use Class D or Bridge inverter in their system.

Generally, using Class E inverter provides a great advantage to the project because the project operates at high frequency, 1 MHz frequency. A class E inverter is known for its ability to operate at a high frequency, even when the operating frequency is varied between hundreds of kHz to tens of MHz [13]. Other than that, the topology for Class E is very simple and theoretically, the switching losses for it is almost zero as long as the zero voltage switching (ZVS) is achieved. On top of that, to further improve the performance of the project the π2a impedance matching network is introduced. This is because according to [14], the configuration of Class E inverter circuit with basic resonant circuit does not have matching capabilities. Thus, in order to transfer a specified amount of power, as in this project is 5 W, a separate circuit configuration must be designed as the values of input voltage, load output power and the load resistor, R_{load} are of dependent quantities. Thus, the introduction of a matching circuit into this class E is needed to provide an impedance transformation, hence increasing the rate of power transfer to the system.

The contribution of this paper can be summarized as follows:

i. The IPT system with Class E Inverter has been designed together with π2a impedance matching network to enhance the performance of the system in term of the output efficiency. The introduction of this type of impedance matching has able to maintain the resonant frequency of the system and the ZVS can be guaranteed to be achieved.

ii. The prototype has been developed to power up mobile device wirelessly and able to achieve nearly 70% efficiency.

This paper is organized as follows: Section II provides an overview of IPT system. Methodology of the work is given in Section III. Main results are provided in Section IV. Finally, the conclusion is drawn in Section V.

II. AN OVERVIEW ON IPT SYSTEM

The general block diagram of IPT system is shown in Figure 1. Basically, an IPT system consists of two separate circuits; a transmitter side and a receiver side. For the transmitter side, there is a primary DC/AC converter, which converts direct current (DC) energy into high frequency alternate current (AC) energy to energize the primary coil, L1 and produces magnetic field. It is also known as a driver circuit. Based on Faraday's law, the generation of magnetic field will cause an induced voltage to be transferred onto secondary coil, L2. Typically, the frequency of an IPT system is in the range of 1 kHz to 100 MHz [15].

Meanwhile, at the receiver side, it consists of an AC/DC converter circuit, which will convert the received induced voltage at a secondary coil, L2 of AC energy into DC energy that can be used for any load applications. Moreover, resonant circuit is needed to ensure resonance inductive coupling. To ensure the system yields a high efficiency output, the Zero Voltage Switching (ZVS) must be guaranteed [16].

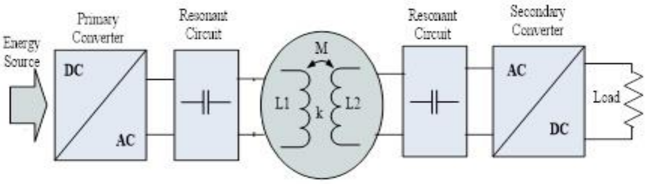


Figure 1: IPT System [16]

III. METHODOLOGY

The block diagram for this work is shown in Figure 2. From Figure 2, the Transmission Circuit consists of 12Vdc power supply, which will be supplied to the Class E inverter circuit. In order to generate a pulse width modulation (PWM) with a frequency of 1MHz and 50% duty cycle, a Peripheral Interface Controller (PIC) based circuit is used and constructed. However, the MOSFET used in the Class E inverter circuit needs a higher voltage level of the pulse produced by the PIC. Thus, a MOSFET driver is designed and the output of the driver is directed to the gate of the MOSFET. This Class E inverter circuit functions to convert the supplied 12Vdc into a higher oscillating frequency supply (alternating current). Besides that, an impedance matching network will be designed to fit into the Class E amplifier circuit which basically functions to maximize the rate of power transfer between the coil and the receiver circuits.

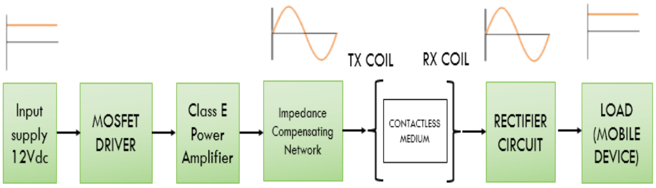


Figure 2: Block Diagram for The Work

Similarly, in the Receiver Circuit, there will be the receiver coil which is connected to a rectifier circuit and then to a load. This rectifier circuit functions to re-convert the received AC source back into DC source. As the load of this work will be a smartphone, the rectifier circuit is designed accordingly to match specifications required by the load.

A. Class E Inverter

In order to achieve a high efficiency inverter circuit, the power losses of the Class E inverter circuit has to be minimal. Therefore, a precise design of Class E inverter circuit is required.

To design and also to perform the simulation of this Class E inverter circuit, MATLAB software version R2015a is used. The parameters that are essential to be computed in order to simulate this Class E inverter circuit are the choke inductor, L_{choke}, a shunt capacitor, C_{shunt}, a series resonant circuit consisting of an inductor and capacitor, L_{series} and C_{series} and finally a load resistor, R_{load}. Figure 3 shows the configuration of this Class E inverter circuit.

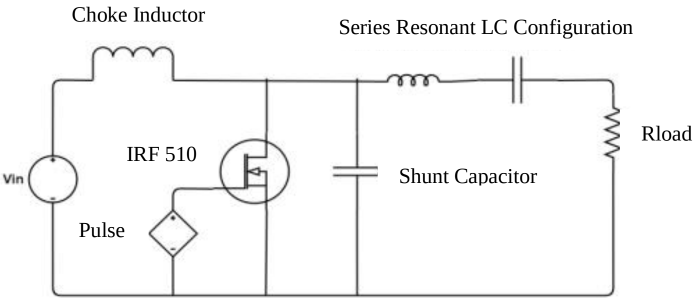


Figure 3: Configuration of Class E inverter circuit

The equations used to derive the values of these mentioned parameters are as follows: [16]

The value for R_{load} is derived from the equation

$$R_{load} = \frac{8(V_{in})^2}{(\pi^2+4)Po}. \tag{1}$$

Next, the amplitude of output voltage is computed using

$$V_{Rim} = \frac{4V_{in}}{\sqrt{\pi^2 + 4}} \tag{2}$$

The maximum voltage across the switch and shunt capacitor is given by

$$V_{SM} = 3.562V_{in}\,. \tag{3}$$

The DC input current is then given by

$$I_{in} = \frac{8V_{in}}{(\pi^2 + 4)R_{load}}\,. \tag{4}$$

Next, to compute the maximum switching current, the following equation is used

$$I_{SM} = \left(\frac{\sqrt{\pi^2 + 4}}{2} + 1\right) I_{in}. \tag{5}$$

The amplitude of current through the resonant circuit is derived from the following equation

$$I_M = \frac{I_{in}\sqrt{\pi^2 + 4}}{2}\,. \tag{6}$$

For the parameters in the Class E inverter circuit, the chosen quality factor, Q_L =10. Thus, to calculate the shunt capacitor, C_{shunt}, the following equation is used.

$$C_{shunt} = \frac{8}{\pi(\pi^2 + 4)\omega R_{load}}. \tag{7}$$

Next, for the choke inductor value, the equation used is

$$L_{choke} > 2\left(\frac{\pi^2}{4} + 1\right)\frac{R_{load}}{f}. \tag{8}$$

The resonant circuit, L_{series} and C_{series}, can be calculated as follows

$$L_{series} = \frac{Q_L R_{load}}{\omega}\,, \tag{9}$$

$$C_{series} = \frac{1}{\omega R_{load}[Q_{L-}\frac{\pi(\pi^2 - 4)}{16}]}. \tag{10}$$

Furthermore, when the MOSFET is OFF, the equivalent capacitance can be obtained as

$$C_{eq} = \frac{C_{series}C_{shunt}}{C_{series} + C_{shunt}}\,. \tag{11}$$

Then, from the obtained C_{eq}, the resonant frequency is computed by

$$f_{01} = \frac{1}{2\pi\sqrt{L_{series}C_{series}}}\,, \tag{12}$$

$$f_{02} = \frac{1}{2\pi\sqrt{L_{series}C_{eq}}}\,. \tag{13}$$

Once the values are obtained, the operating frequency of this work, which is 1MHz must be between the computed values of f_{01} and f_{02}.

B. Transmitter and Receiver Coil Design

This part is very important to ensure the power can be transmitted from transmitter to receiver. 2 coils will be designed which is the first one is for transmitter and the second is for receiver. According to [3], the value of inductance between the two coils should be the same. As a result, two similar coils are designed based on a rectangular shape with a length and width of 5.5cm respectively. Figure 4 shows the design of the mentioned transmitter and receiver coils.

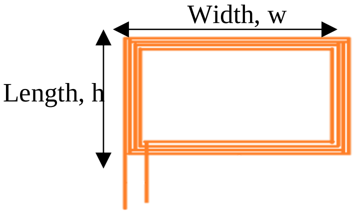


Figure 4: Coil Design

To determine the inductance value of the coil, the following equations is used

$$L_{rec} = \frac{\mu_o\mu_r}{\pi}\left[-2(w + h) + 2\sqrt{h^2 + w^2} + temp\right] \tag{14}$$

where,

$$temp = -h\,In\left(\frac{h + \sqrt{h^2 + w^2}}{w}\right) - w\,In\left(\frac{w + \sqrt{h^2 + w^2}}{h}\right) + h\,In\left(\frac{2h}{r}\right) + w\,In\left(\frac{2w}{r}\right) \tag{15}$$

μ_o = Permeability of free space (1.257×10^{-6})
w = width of proposed coil
h = length of proposed coil
r = radius of the wire

C. Rectifier Circuit

The load that is used in this work is a smartphone. To be specific, the standard voltage and current required to charge mobile phones are approximately at 5V and 800mA, respectively. Hence, to regulate the output voltage to be at 5 V, a 7805 voltage regulator is used. Furthermore, since the operating frequency of this project is 1 MHz, the diodes used to rectify the input must be able to operate in that stated frequency. Thus, ultra-fast diodes model of UF4004 are chosen to form a bridge circuit. Capacitors are added to reduce ripple effects based on the circuit requirements. Figure 5 shows the designed rectifier circuit.

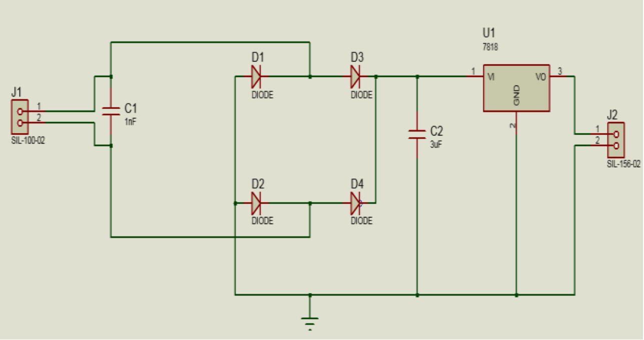


Figure 5: Rectifier Circuit

IV. MAIN RESULTS

A. *Class E Inverter*

For Class E inverter circuit, the parameter values such as the L_{choke}, C_{shunt}, L_{series}, C_{series} and R_{load} can be calculated from the equations stated in (1) to (13). In this work, output power, P_o, is set at 5W, V_{in} and Q_L, are 12V and 10 V, respectively. The mentioned parameters' are given in Table 1.

Table 1
Class E Parameters

Parameter	Calculated value	Actual value
Choke Inductor, L_{choke}	> 115.20µH	330µH
Shunt Capacitor, C_{shunt}	1759pF	1800pF
Series Inductor, L_{series}	26.44µH	27µH
Series Capacitor, C_{series}	1083pF	1000pF
Load Resistor, R_{load}	16.61Ω	22Ω

Based on the computed values of the parameters, see Table 1, the Class E inverter circuit is designed as shown in Figure 1. The L_{choke} value is considered to be at the minimum value, so that it ensures that the peak-to-peak current ripple is less than 10% of the DC current flowing in the circuit.

The simulation result for the calculated Class E Inverter is shown in Figure 6. Meanwhile, the result for the actual component value that is used in this work is given in Figure 7.

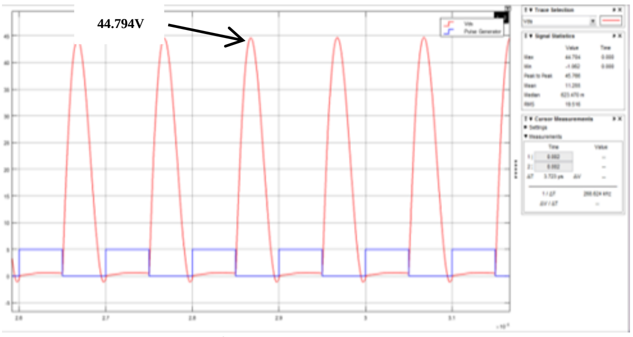


Figure 6: Simulated ZVS of designed Class E using calculated component value

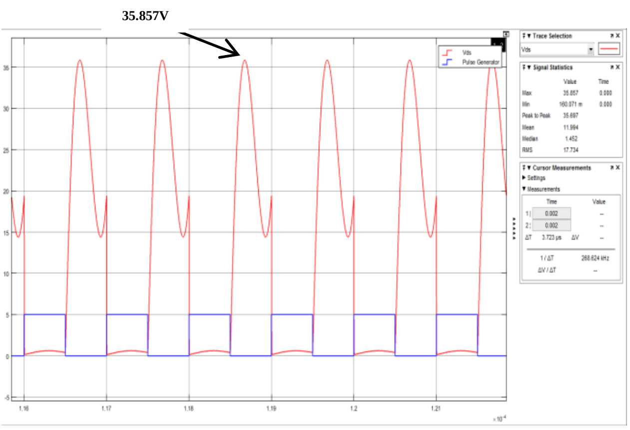


Figure 7: Simulated ZVS of designed Class E using actual component value

Referring to Figure 6 and 7, it can be noticed that the changes in the values of the components used caused an unsmooth zero voltage switching condition (ZVS) as shown in Figure 7. This is because the values of the components used do not match the circuit's requirements to operate at its optimum level. Thus, components tuning was conducted to smoothen the ZVS obtained using component values that are obtainable in the market. A range of approximately ±25% difference between the calculated values and the actual components is set as its condition. This is because the circuit is designed specifically to produce a desired output of 5 W with a frequency of 1MHz. Thus, huge differences between the computed values and selected component values will affect the Class E inverted circuit from operating at optimum condition.

In order to increase the efficiency of the power transfer, an impedance matching network is configured for the inverter circuit. For this inverter circuit, a π2a impedance matching network is calculated accordingly. Figure 8 and Figure 9 shows the design of the Class E inverter with impedance matching network circuit and the simulated ZVS results of the circuit.

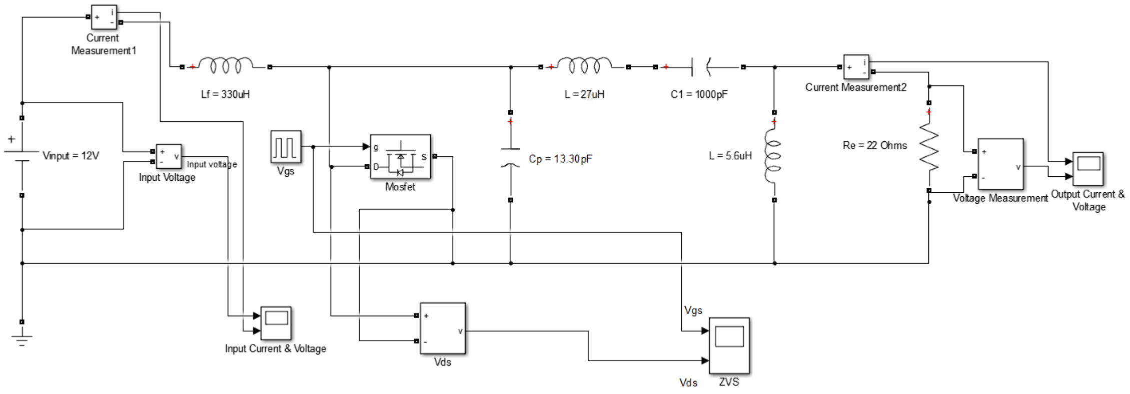


Figure 8: Design of Class E inverter circuit with impedance matching circuit.

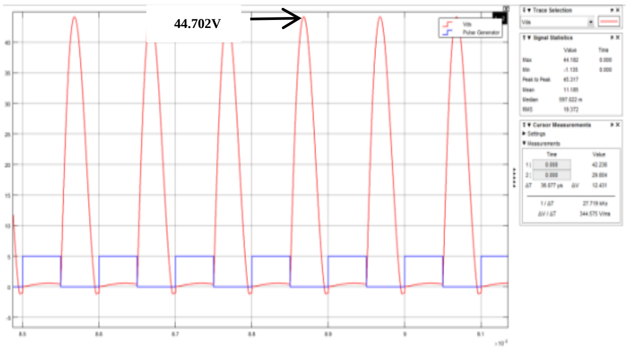


Figure 9: Simulated ZVS of Class E with impedance matching circuit.

From Figure 9, we can see that the ZVS is well established and therefore the switching loss can be very minimum. The reason of this is because the impedance matching circuit has locked the resonant frequency to resonant at the same frequency of the operating frequency. This is actually the advantage of introducing the pi-2-a impedance matching circuit to the system. Hence, the new parameter used here is tabulated in Table 2.

Table 2
New Class E Parameters

Parameter	Calculated value	Actual value
Choke Inductor, L_{choke}	> 115.20 µH	350 µH
Shunt Capacitor, C_{shunt}	1759 pF	1800 pF
Series Inductor, L_{series}	23.79 µH	27 µH
Series Capacitor, C_{series}	1083 pF	1000 pF
Π2a configuration	5.29 µH	5.6 µH
Load Resistor, R_{load}	33.22 Ω	22 Ω

As shown in Figure 8, there is a new inductor placed parallel to the load resistor, R_{load}. This is the newly computed configuration of the π2a impedance matching network circuit. Figure 9 shows the result of MOSFET drain voltage via simulation in which the higher peak represents the waveform of voltage drain and the lower peak line represents the gate pulse. It can be noticed that the MOSFET drain voltage for this newly designed circuit is approximately around 44.704 V. This newly obtained MOSFET drain voltage value is approximately 3.73 times higher than the DC voltage, V_{DD}. Besides that, both MOSFET voltage and current have zero crossover value during switching transition. As a result, the concept of ZVS is well achieved through this circuit.

Next, we show the experimental result of the Class E inverter. To note here that the experimental set up for this circuit is based on the circuit shown in Figure 8 that is with π2a impedance matching network. The result is given in Figure 10.

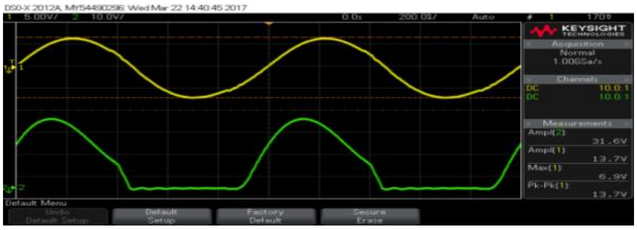


Figure 10: Experimental results of Class E inverter with impedance matching network

The MOSFET drain voltage is 31.6 V, as shown in Figure 10. This is because, during simulation process, the components used are to be said in ideal condition, thus having an efficiency of 100%. However, in experimental cases, each components used will have their own internal resistance and their parasitic elements, which affects the components performance. However, based on Figure 10, ZVS is still successfully achieved. Hence, the circuit can be used in this work.

B. *Coil Design*

Based from the equations (14) and (15), the coils are manually turned by hand. A square coil with the length and width of 5.5 cm is turned respectively. The number of turns of both the coils is approximately 5 turns. Both the coils must have the same inductance value, thus having the same number of turns and size. Figure 11 shows the designed coils. Both coils are to have an inductance value of 3.5 µH, with the transmitter coil later replacing the, R_{load}, in the Class E inverter circuit. The details of inductance value of transmitter and receiver coil is shown in Table 3.

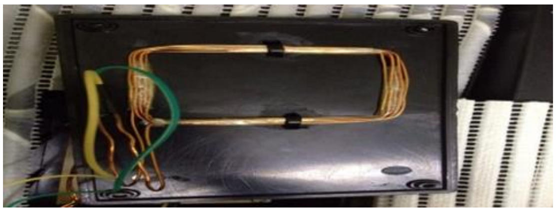


Figure 11: Designed Transmitter Coil

Table 3
Inductance Value of Transmitter and Receiver Coil

Parameter	Value	Unit
Permeability of Free Space, μ_0	$1.257\ x\ 10^{\wedge} - 6$	Wb
Number of Turns, N	5	-
Width of Coil, y	5.5	cm
Length of Coil, x	5.5	cm
Radius of Coil Wire, r	1	mm
Inductance of Transmitter Coil	3.5	µH
Inductance of Receiver Coil,	3.5	µH

C. Prototype

Figure 12 shows the PCB design circuit for Class E inverter circuit together with MOSFET Driver circuit. In this PCB design, it can be seen that the Class E inverter circuit is combined together with the MOSFET Driver circuit.

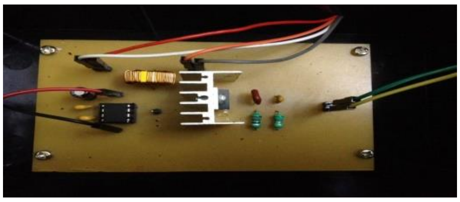
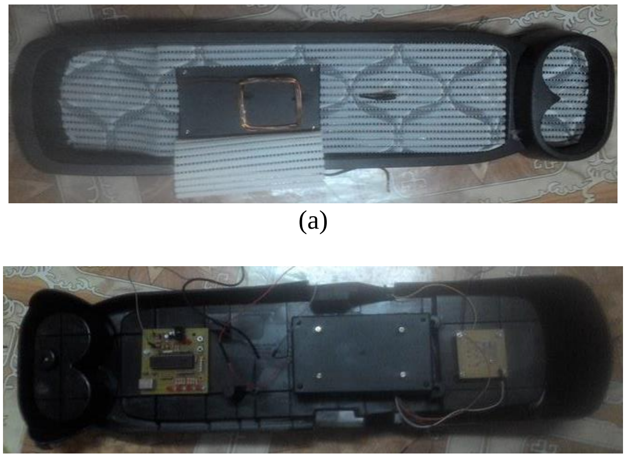


Figure 12: PCB Board for Class E inverter with MOSFET Driver

The complete prototype of the system is shown in Figure 13. As shown in Figure 13(a), only the receiver coil is placed on the surface of the console board. The rectifier and PWM circuit is placed accordingly based on its best position on the console box. The concept of wireless charging is shown as there is no direction connection between the rectifier coil and transmitter coil. So, anytime the driver would like to charge his phone, what he needs to do is just to place it on the console at the specified region. To note here that, in real application the receiver coil is located at the phone itself.



(a)

(b)

Figure 13: Prototype design; (a) Front view of the prototype; (b) Back view of the prototype.

D. Analysis of Gap Distance Between Transmitter and Receiver Coil

Table 3 describes details of the analysis in term output voltage, output current, charging status and the output efficiency. The output efficiency is calculated using following:

$$Efficiency, \eta \frac{Output\ Power}{Input\ Power}\ x\ 100\% \qquad (16)$$

As for this work, the output power is calculated from the receiver coil by using the following formula

$$Output\ Power = Voltage\ x\ Current \qquad (17)$$

Once the output power is obtained, the main analysis which is the gap distance between the transmitter coil and receiver coil will be conducted. A starting gap of 0 cm up to 5 cm, with a constant step size increment of 0.5 cm will be executed. Figure 14 illustrates on the method of analysis that is conducted.

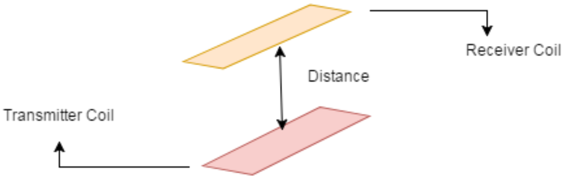


Figure 14: Method of selected analysis

Table 4
Inductance Value of Transmitter and Receiver Coil

Distance (cm)	Voltage (V)	Current (mA)	Output Power (W)	Charging Status	Efficiency (%)
0.00	15.70	543	4.26	YES	68.27
0.25	15.23	516	3.93	YES	62.98
0.50	15.11	501	3.79	YES	60.74
0.75	14.98	493	3.69	YES	59.13
1.00	14.87	471	3.50	YES	56.09
1.25	14.67	447	3.28	YES	52.56
1.50	14.48	429	3.11	YES	49.84
1.75	13.98	403	2.82	YES	45.19
2.00	13.57	378	2.56	NO	41.03

Based on Table 4, the highest efficiency recorded is approximately at 68.27%. However, once the gap distance between transmitter coil and receiver coil exceeds 1.75 cm, the mobile device does not charge anymore. This is because the power generated in the receiver coil is not sufficient enough to charge the mobile device. This can be related to the fact that as the distance between the transmitter coil and receiver coil increases, the strength of the magnetic field induced decreases. Figure 15 shows the output from the transmitter coil whereas Figure 16 shows the output from the receiver coil, at when the gap distance is at 0 cm. The current flowing through the transmitter coil before being transferred is 565 mA. Thus, by using (17), the power generated at the transmitter coil is approximately 6.24 W.

As shown in Figure 15, the transmitter coil is able to transfer up to 6.24 W. This amount is higher than the desired one which is 5 W. This difference is due to the transmitter coil which is used to replace the R_{load} from the circuit. The value of the resistor that is replaced is 22 **Ω**. Thus, by using the equation (18), the computed inductance value of the resistor is approximately 3.5 µH.

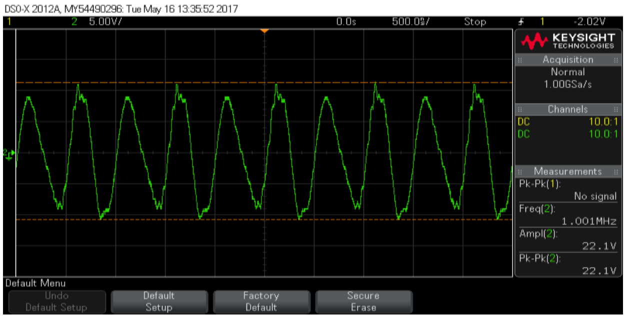


Figure 15: Output voltage from Transmitter Coil.

$$L = \frac{R_{load}}{j\omega} \tag{18}$$

where

$$\omega = 2\pi f$$

However, the manually hand turn coils have an inductance value of approximately 3.85 µH, which differs slightly from the calculated value, thus affecting the output of the Class E inverter circuit.

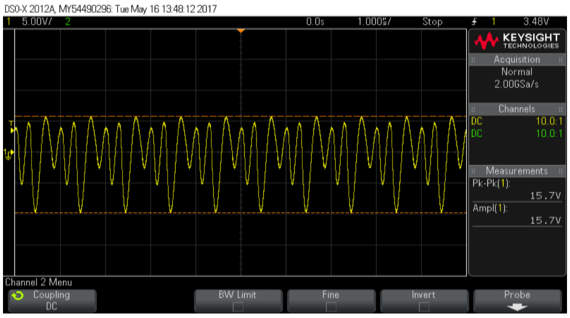


Figure 16: Induced voltage from Receiver Coil

Then, based on Figure 16, induced voltage measured from the receiver coil is 15.7 V. From here, approximately 6.4 V is lost during the transfer. This is due to the air gap between the coil turns, thus affecting the coil's efficiency.

V. CONCLUSION

A prototype for powering up mobile devices in vehicle has been established in this work. The prototype succeed to power up mobile phone wirelessly with 70% efficiency. A Class E converter with π2a impedance matching has been proposed here to establish a more efficient system. The future work lies in the framework of improving the efficiency of the circuit and ensuring the system follows the standard set by the wireless power transfer body, i.e Qi Consortium.

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