A Study on Efficiency of Wireless Power Transfer with Triangle and Square Coil

Muhamad Akmal bin Md Radzi
Bachelor of Electrical Engineering (Hons.)
Faculty of Electrical Engineering
Universiti Teknologi Mara
40450 Shah Alam
akmal_radzi89@yahoo.com

***Abstract*—This technical paper proposed the analysis and design the wireless power transfer by using inductive coupling concept to transmit the electric power. To transmit the power in AC, a full-bridge AC-DC resonant converter is applied to convert a DC supply to AC. The efficiency of the system is identifying by compared with 2 types of receiver which is between triangle and square shape. Beside that is orientation between the transmitter and receiver coil. When both of coils share a single axis, the transfer efficiency is maximal but otherwise the efficiency becomes lower. Lastly, the distance of the air gaps between transmitter and receiver coil affect the efficiency of the power transmitting. More closely the distance between both of the coil, the power transmitting will be more efficient.**

Keywords-Inductive coupling; Transfer efficiency; AC source; Air gap

I. INTRODUCTION

Imagine that we can charge laptop, mobile phone or other electronic gadget with the charger without wire. This dream can be realize by using wireless power transmission. The concept of wireless power transfer has been bandied about for a decade and now it is closer becoming advance. Since Nikola Tesla Carried out his experiments on wireless power transfer (WPT) before the century, many researcher studied and do research about it constantly. Recently, attention to WPT using magnetic resonant are increased dramatically. Lot of researches is going on the inductive coupling which is the basic core of WPT. Basically, concept of WPT is same like an ideal transformer but the solid magnetic core in the transformer was replaced by air core. This means that there have a high flux leakage and only a portion of the flux generate induces emf across the secondary coil.

Nowadays electronic gadget industries are increased dramatically. For example Apple and Samsung Company have produced a lot of electronic gadget such as smart phone, mp3 player, digital camera and many more. The most common way to charge this gadget is by using a conventional charger which is plugged in the charger to power supply. However this charging way has many disadvantages such as the used plug in huge quantity can cause the interconnecting wires. The interconnecting wires are inconvenient and hazardous. Beside that the common problem with the conventional charger is we cannot identify if copper inside the wire was broken.

The most challenges that the researcher have to faced during develop this technology is to maximize and maintain the efficiency of the charger. Due to the conflict between efficiency and the distance, WPT using magnetic resonant is not used very wide range.[1] If the efficiency are not maintain and at maximum level, it will affect the charging time. However there have many factors that can affect the efficiency. In this paper 3 techniques is proposed to identify the factor that will affect the efficiency during transmit the energy. First technique is orientation between transmitter and receiver coils. The factor was simulated by rotates the receiving coils at certain angle. The second technique is adjusting the distance between transmitter and receiver coils. Lastly is between triangle and square coil. All this techniques is confirmed by do testing at laboratory.

The objective if this project is to design and construct wireless power transfer using ac source. Beside that is to study about the factors that affect the efficiency of the system. In this project the type to transmit the power is by using resonant inductive coupling method. In the resonant inductive coupling method, it consist of a transmitter coil L1 and a receiver coil L2. Basic principle of the inductive coupling is when alternating current in the transmitter coil generates a magnetic field which induced a voltage at the receiver coil. Resonant inductive coupling is the combination between resonant frequency and inductive coupling. Function of the resonant frequency is to makes both coils interact strongly. So it was very important to determine the value of resonant frequency. The resonant frequency is varies with the change of the distance *d* if the inductance of the coils and the value of the capacitor remain same.[2]

$$f_r = \frac{1}{2\Pi\sqrt{LC}} \quad (1)$$

Where f_r is resonant frequency, L is inductance value and C is capacitance value.

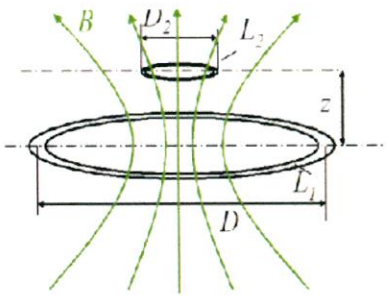

Figure 1: Typical arrangement of an inductive coupled power transfer system.

Figure below shows the concept of an inductive power link and it equivalent circuit. The load at receiver is modeled as a resistor R_L in the secondary resonator.*k* is the transformer coupling coefficient and L_1 and L_2 are self-inductance in the transmitter and receiver coils respectively. R_1 and R_2 is a model of the losses in the coils.C_1 and C_2 are capacitor that represent as aparasitic and external capacitance to create a resonant at the transmitter and receiver side.[3]

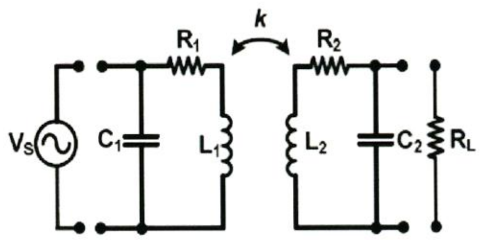

Figure 2: Equivalent circuit of WPT

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad (2)$$

Where M is Mutual inductance, L_1 is inductance of primary coil L_2 is inductance secondary coil and k is Coupling coefficient. For the mutual inductance (M), it is the current flowing in one coil and induces current an emf in the other coil. Factor that efffect the value of the mutual inductance is distance between receiver and transmitter coil. Beside that, the angle between both coils also affect the value of mutual inductance.

$$M = \frac{\mu_0 \mu_r N1N2A}{\ell} \quad (3)$$

Where μ_o is the permeability of free space $(4.\pi.10^{-7})$, μ_r is the relative permeability of the core; N is the number of coil turns, A is the cross-sectional area in m^2 and ℓ is the coils length in meters

$$M_{12} = \frac{N_2 \phi_{12}}{\ell} \quad (4)$$

Where ϕ megnetic flux, N is the number of coil turns, ℓ is the coils length in meters

$$\phi = BA \cos \theta \quad (5)$$

Where ϕ is megnetic flux, B is magnitude of the magnetic field, and A is area of the coil surface. Before transmit the energy to the receiver, the current must be convert into AC mode. Beside that, the switching frequency also must be determine because the value of switching frequency is related with resonant frequency. Therefore, resonant converter have been used in this project as a power converter that converted from DC to AC source and control it switching frequency. Type of the resonant converter that proposed in this project is full-bridge voltage-fed inverter. Basically, the full bridge topology of the switching network has four switches. The frequency, magnitude or phase of the output of a voltage-fed switching converter can be controlled with power swithes at their gate.

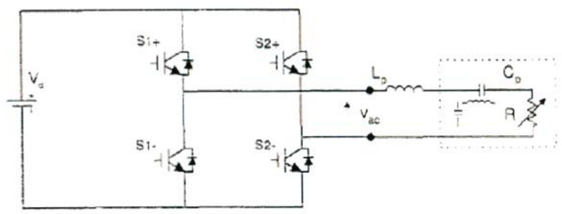

Figure 3: Full bridge voltage-fed inverter

Since this project are using AC source, it must be convert into DC first before give a supply to the resonant converter. To convert it the full bridge rectifier was applied in this project. Full bridge rectifier is rectifier that consist 4 switches that convert both the positive and negative cycle of AC voltage to DC voltage. The operational of this rectifier is during positive half cycle, the current will flow through the red diodes and during the negative half cycle, the current flow is through the blue diodes.

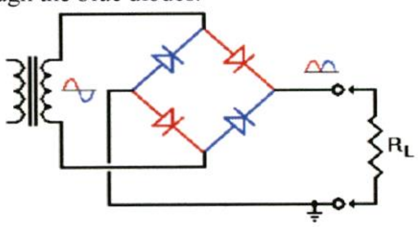

Figure 4: circuit of full bridge rectifier

II. METHODOLOGY

In general, WPT system is divided into some part. At the transmitter side, first the AC supply must be converting into DC by using full bridge rectifier before supply to the resonant converter. After that, at the inverter part, it was function to control the switching frequency and convert DC to AC. In this project the value of switching frequency was set to 100 kHz. At the receiver side, since it the energy that receives from the transmitter is in AC, it must convert first to DC before supply to the load.

To convert ac to dc at receiver, full wave voltage doubler has been used. It is because voltage output of the voltage doubler is 2 times to voltage input. The operating of this circuit is on the negative half cycle of the input voltage, capacitor C2 is charged through rectifier D2 to a voltage V_{in}. On the positive half cycle, capacitor C1 is also charged to a voltage of V_{in} through D1. The series voltage of capacitor C1 and C2is equal to $2V_{in}$.

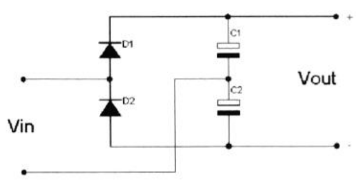

Figure 5: Full wave voltage doubler circuit

For voltage-fed DC-AC inverter, it has 2 basics topology which is full bridge and half bridge. In this project, the full bridge voltage fed inverter was proposed in the inverter part. The full bridge topology has 4 switches and for the half bridge topology, 2 of the switches are replacing with a capacitor. For the full bridge inverter, the maximum voltage output is $\pm V_d$ and for the half bridge inverter maximum voltage output is $\pm V_d/2$.

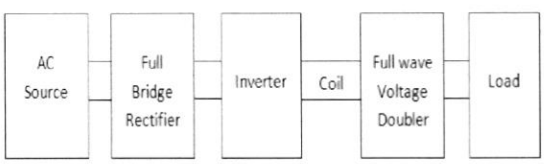

Figure 6: Block diagram of the wireless power transfer

To control the switching frequency of full bridge inverter, the IRS2153 IC driver was used. To activate this IC, it needs $15V_{dc}$ supply. This IC was used to provide the Pulse Width Modulation (PWM). PWM switching generates less low frequency harmonic component. This IC can generate the switching frequency up to 100 kHz. The switching device that used in this project is MOSFET that also need $15V_{dc}$ supply. The connection of the resonant tank for voltage fed normally it was used matches series tuned or series parallel. It is because 2 voltage sources cannot be connected in parallel due to possibility of shorting the sources. For this project, series tuned has been proposed as a resonant tank

Before construct the circuit, circuit was simulating by using PSIM software. After the simulation was success, the hardware was constructing. The hardware have been tested by using LED to identify either it function or not. In this project, to identify the factors that affect the efficiency, three techniques have been proposed. First technique is distance test between transmitter and receiver coil. Second technique is angle orientation between transmitter and receiver coil. For this technique, distance between transmitter and receiver coils is fixed which is 7cm. Then receiver coil was adjust from 0° to 90°.The last technique is test efficiency of two different shapes of coils which is between triangle and square coil. After do the experiment analyzed all the data.

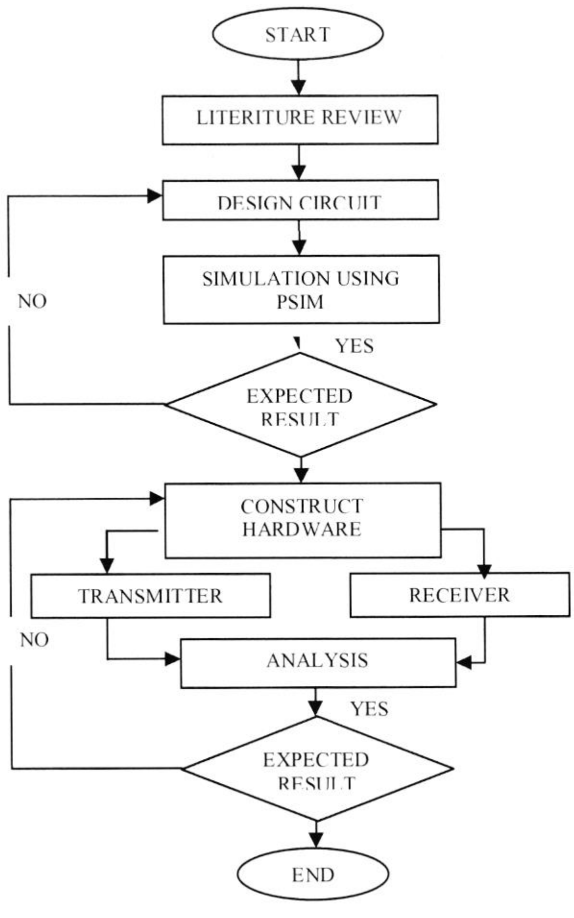

Figure 7: Project flow chart

Table 1: Hardware specification

Source	240 V_{ac} 50Hz
Switching frequency, fs	100kHz
Resonance frequency, fr	99.9kHz
Inductance, L	42.3μH
Capacitance, C	60nF
Self-inductance of transmitter square coil, L1	5.2μH
Self-inductance of receiver square coil, L2	5.1μH
Self-inductance of receiver triangle coil, L3	4.2μH
Area of square coil	18cm × 18cm
Area of triangle coil	½ × 18cm × 18cm

III. RESULT AND DISCUSSION

A. Simulation result

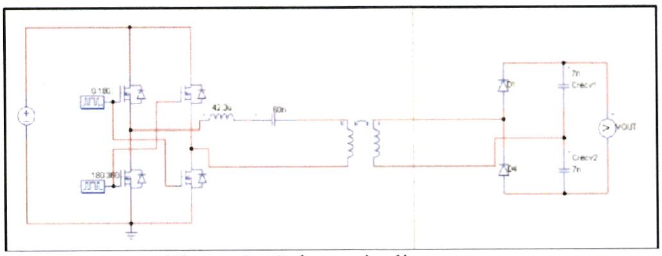

Figure 8 : Schematic diagram

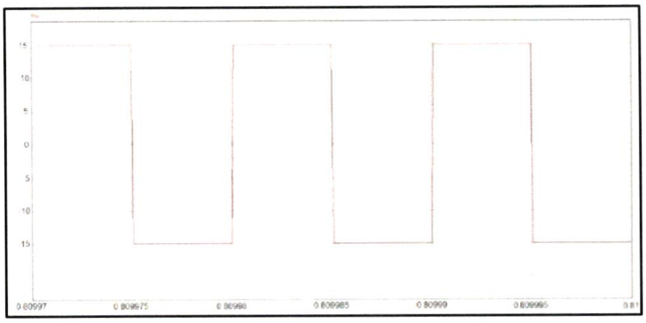

Figure 9: Output voltage at transmitter

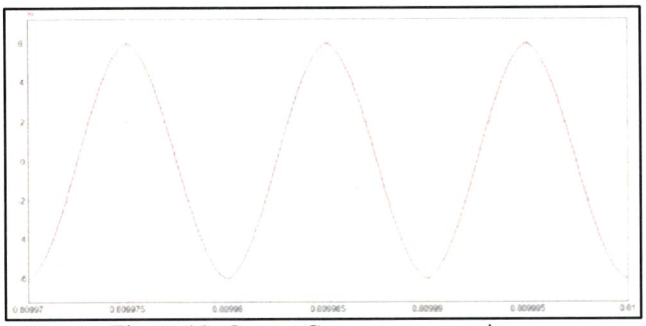

Figure 10: Output Current at transmitter

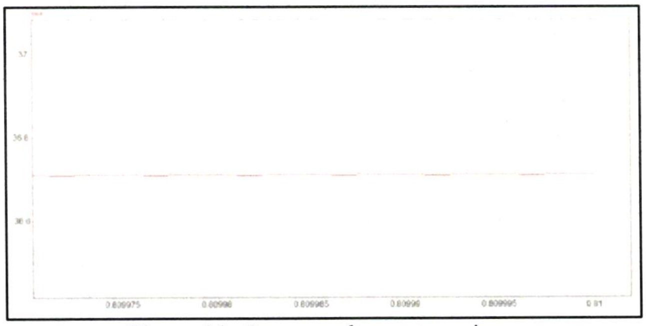

Figure 11: Output voltage at receiver

B. Experiment result

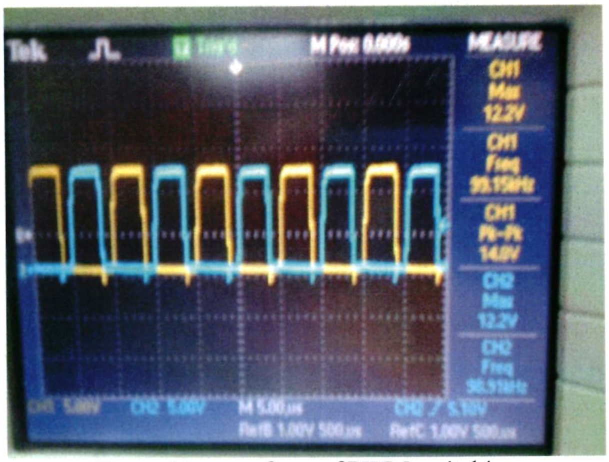

Figure 12: waveform of PWM switching

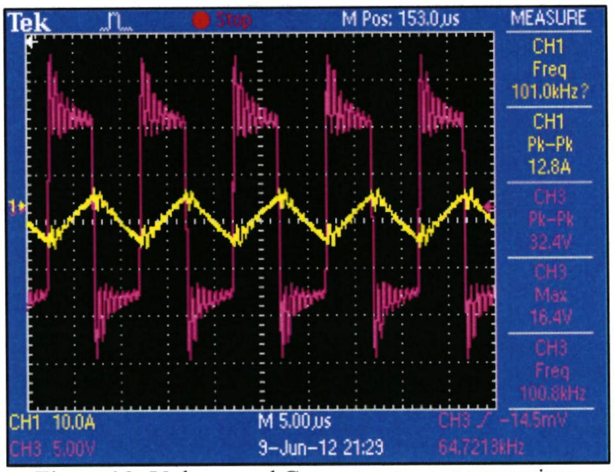

Figure 13: Voltage and Current output at transmitter

Figure 14: Dead time of switching

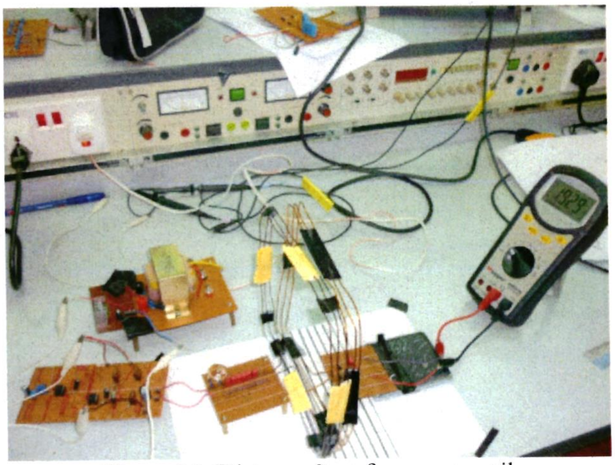

Figure 16: Distance 0cm for square coil

Table 2: Output for square coils distance test

Distance (cm)	V_o (no load)	V_o (with R = 10Ω)	I_o(A)	η(%)
0	19.29	3.00	0.30	19.66
2	11.40	2.00	0.20	8.74
4	7.37	1.40	0.14	4.28
6	5.06	1.00	0.10	2.18
8	3.31	0.60	0.06	0.79
10	1.97	0.00	0.00	0.00
12	1.45	0.00	0.00	0.00
14	0.83	0.00	0.00	0.00

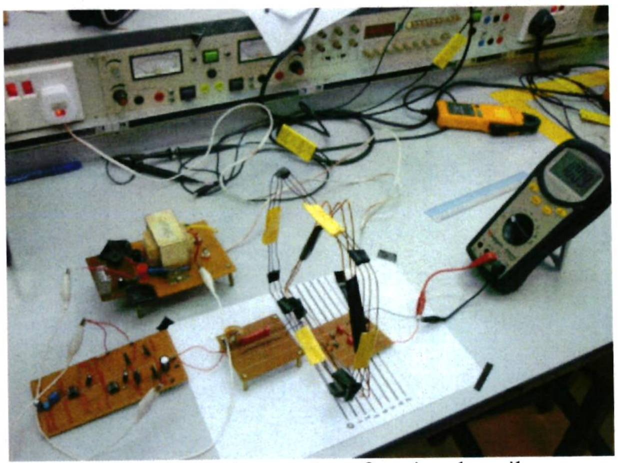

Figure 17: Distance 0cm for triangle coil

Table 3: Output for triangle coils distance test

Distance (cm)	V_o (No load)	V_o (with R = 10Ω)	I_o(A)	η(%)
0	10.09	2.00	0.20	8.74
2	6.42	1.20	0.12	3.15
4	4.35	0.60	0.06	0.79
6	2.94	0.40	0.04	0.35
8	1.83	0.00	0.00	0.00
10	1.16	0.00	0.00	0.00
12	0.73	0.00	0.00	0.00
14	0.42	0.00	0.00	0.00

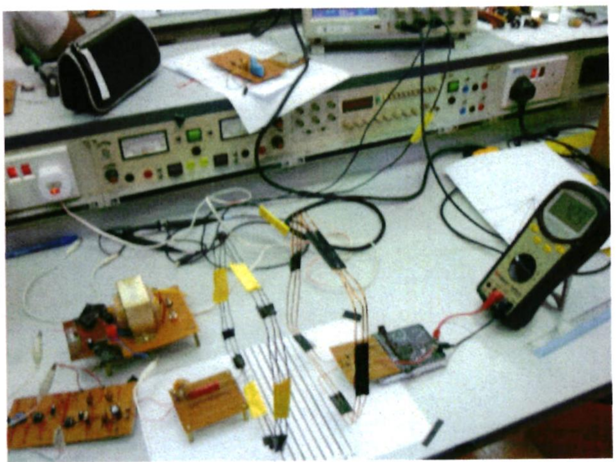

Figure 18: Distance 7cm for square coil

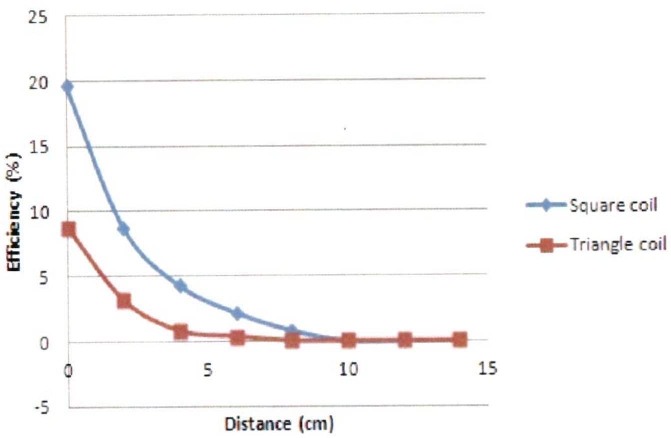

Figure 15: Graph Efficiency vs Distance

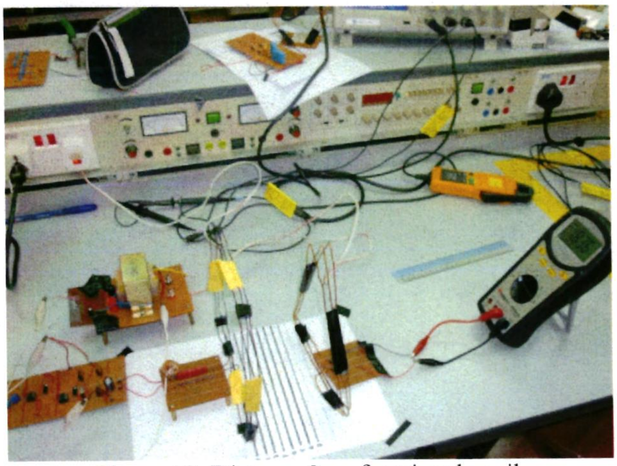

Figure 19: Distance 8cm for triangle coil

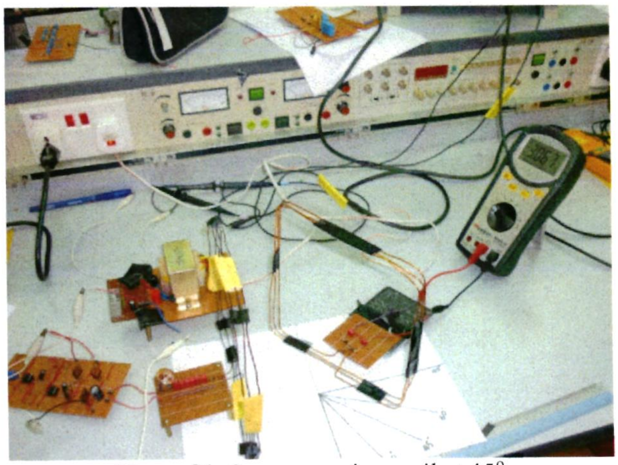

Figure 21: Square receiver coil at 45°

Table 4: Output for square coils angle test

Angle	V_o (No load)	V_o (with $R = 10\Omega$)	I_o(A)	η(%)
0°	4.23	0.80	0.08	1.40
30°	3.75	0.70	0.07	1.07
45°	3.06	0.60	0.06	0.79
60°	2.67	0.00	0.00	0.00
90°	0.00	0.00	0.00	0.00

Table 5: Output for triangle coils angle test

Angle	V_o (No load)	V_o (with $R = 10\Omega$)	I_o(A)	η(%)
0°	2.63	0.40	0.04	0.35
30°	2.36	0.30	0.03	0.20
45°	2.01	0.00	0.00	0.00
60°	1.17	0.00	0.00	0.00
90°	0.00	0.00	0.00	0.00

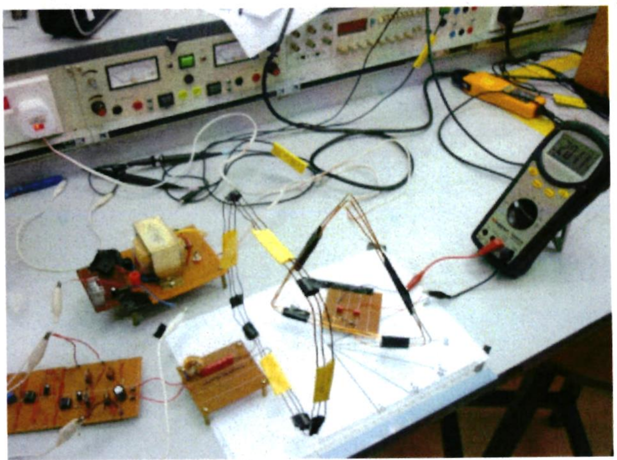

Figure 22: Triangle receiver coil at 45°

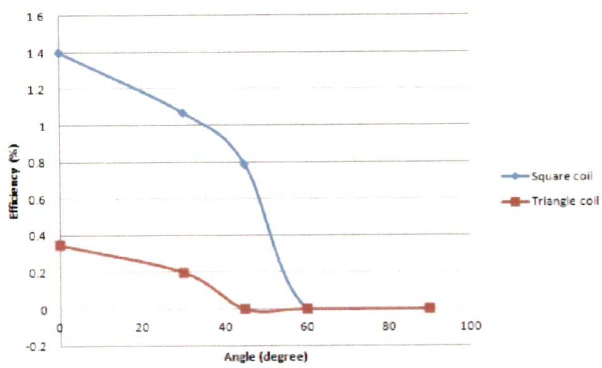

Figure 20: Graph Efficiency vs Angle

C. Discussion

From the figure 15, the result show that relationship between distance and the efficiency is prove that distance between transmitter coil and receiver coil is affect the efficiency of the system. In the inductive coupling, the magnetic field was creates when electric currents flowing through a transmitter coil. With the magnetic field, it will produce a voltage at receiver. Coupling must be tight in order to get the maximum efficiency. The mutual inductance varies inversely proportional to distance. That means when the distance is increased, mutual inductance will decrease. So, the output voltage also will decrease.

Second factor that have been test in this project is identify either angle of the receiver are affected the efficiency of the WPT system. In this case, the coils spacing is kept fixed while the angle is varied from 0° to 90°. From the figure 20, result show that when receiver coil at 0° which receiver coil at the same axis with transmitter coil the efficiency are maximum. After that, the angles of the receiver are increased to 30°, 45°, 60° and 90°. The results show that the efficiency of the system was decreased. It is observe that when the angle is increased, output voltage will drop because the reduction in mutual inductance which is inversely proportional to the angle. When the receiver coil angle is 90°, there is no mutual inductance between coils. That why the output voltage is zero.

Lastly In this experiment, the different shapes of the receiver coils also take into account to test the efficiency. Both coils have the same width and length. From the figure 15 and figure 20 show that the efficiency of the square coil is higher than triangle coil. It is because the efficiency is directly proportional to area of the coil. Since the area of the square coil is bigger than triangle coil, that why the efficiency of the square coils is higher than triangle coil.

For the dead time of the switching frequency, the IRS2153 IC driver was control the switching frequency with dead about 1.1 µs. Dead time determined by the on and off delays of the switching devices. A dead time between the turn on and turn off of the switches is to avoid the shorting of the voltage source that wills failure the switching devices.

IV. CONCLUSION

A wireless power transfer system using inductive coupling was proposed. After finish this project, the conclusion is the distance between transmitter coil and receiver coil affect the efficiency of the system was confirm by the measurement. From the result we can see that when the distances between receiver and transmitter coils are minimum, the efficiency of the system is maximum. Beside that another factor that proposed is orientation the angle of the receiver coil. When two coils share a single axis, the transfer efficiency is maximal but otherwise the efficiency becomes lower. In this project, the different shape of the coils also been tested to determine the efficiency. The efficiency is directly proportional to the area of the coil. Since the area of the square coil larger than triangle coils, so the efficiency of the square coil is higher than triangle coil. For the future to get the result more accurate, maybe the receiver and transmitter coil can be construct in printed circuit board (PCB). Beside that the different material of the coil also can be test in order to know which material have high efficiency.

ACKNOWLEDGMENT

The special thanks to my supervisor, Dr Mohammad Nawawi B Seroji. The criticism and guidance that he gave truly help the progression and smoothness of my final year project. The co-operation is much indeed appreciated. My grateful thanks also go to my family. Their encouragement really lifts my spirit to complete this project successfully. Not forget, great appreciation go to Mohd Safwan B Mohd Subri that help me from time to time during this project. Last but not least I would like to thank to all my friends and those who help me directly or indirectly during do this project.. The kindness, cooperation from all of the above mentioned people would always be remembered.

REFERENCES

[1] Jin-Ju Jang; Won-Yong Chae; Ho-Sung Kim; Dong-Gil Lee; Hee-Je Kim; , "A Study on Optimization of the Wireless Power Transfer Using the Half-Bridge Flyback Converter," Computer Research and Development, 2010 Second International Conference on , vol., no., pp.717-719, 7-10 May 2010 doi: 10.1109/ICCRD.2010.164

[2] Miyamoto, T.; Komiyama, S.; Mita, H.; Fujimaki, K., "Wireless power transfer system with a simple receiver coil," Microwave Workshop Series on Innovative Wireless vol., no., pp.131-134, 12-13 May 2011doi: 10.1109/IMWS.2011.5877107

[3] Sangwook Han; Wentzloff, D.D.; , "Wireless power transfer using resonant inductive coupling for 3D integrated ICs," 3D Systems Integration Conference (3DIC), 2010 IEEE International , vol., no., pp.1-5, 16-18 Nov. 2010 doi: 0.1109/3DIC.2010.5751455

[4] Sunkyu Kong; Myunghoi Kim; Kyoungchoul Koo;Seungyoung Ahn; Bumhee Bae; Joungho Kim; , "Analytical expressions for maximum transferred power in wireless power transfer systems," Electromagnetic Compatibility (EMC), 2011 IEEE International Symposium on , vol., no., pp.379-383, 14-19 Aug. 2011doi: 10.1109/ISEMC.2011.6038340

[5] Youndo Tak; Jongmin Park; Sangwook Nam; , "The Optimum Operating Frequency for Near-Field Coupled Small Antennas," Antennas and Propagation, IEEE Transactions on , vol.59, no.3, pp.1027-1031, March 2011 doi: 10.1109/TAP.2010.2103034

[6] Yanping Yao; Hongyan Zhang; Zheng Geng; , "Wireless harger prototype based on strong coupled magnetic resonance," Electronic and Mechanical Engineering and Information technology (EMEIT), 2011 International Conference on , vol.5, no.,pp.2252-2254, 12-14 Aug. 2011doi: 10.1109/EMEIT.2011.6023559

[7] Garnica, J.; Casanova, J.; Jenshan Lin; , "High efficiency midrange wireless power transfer system," Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications (IMWS), 2011 IEEE MTT-S International , vol., no., pp.73-76, 12-13 May 2011 doi: 10.1109/IMWS.2011.5877094