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DEVELOPMENT OF INDUCTIVE POWER TRANSFER SYSTEM USING CLASS-D POWER AMPLIFIER

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ABSTRACT
The main aim of this study is to design efficient inductive power transfer (IPT) system which includes series L-C resonant circuit and load network. In order to achieve high efficiency, class-D amplifier, which includes two switching devices (MOSFET), was implemented and the MOSFETs are driven by 0.5 duty cycle PWM signals which are generated by IR2110 MOSFET driver. The inductive link was realized by primary and secondary coils which consists of copper wires and in the experiment, 70.58% transmission efficiency was obtained. The input and output power are 2.55 W and 1.8 W respectively. Also the switching performance of driver in class-D amplifier has been observed and analysed.

INTRODUCTION
For over centuries, the electricity has been transferred by the cables and it is a simple solution for transmitting the power. However, the cable transmission has several disadvantages such as limitation of transmitting distance, power loss, cost and etc. (Karabulut et al. 2020). Specifically, the cables cannot be properly assembled on a rotating system. Therefore, cable free methods should be solved and today, these methods are known as wireless power transmission methods. Wireless power transfer (WPT) is a method to transmit the power to desired location without wires.
The history of WPT dates back to the late nineteenth century and Nikola Tesla was a pioneer for the field of WPT. In his experiment, he has built the Wardenclyffe tower, which is also known as Tesla tower, to create electromagnetic waves and the power can be transmitted using these waves (Anthony & Navghare, 2016). Beginning with Nikola Tesla, today, WPT technology has grown in popularity for it’s compact nature.
The WPT can be categorized under two types which are radiative and non-radiative (Xie et al., 2013). In radiative techniques, microwave power transmission and laser power transmission are placed and they can used for transmitting the distance of greater than a few kilometres. These techniques has a high performance. However, they are really dangerous or living organisms (Imura & Hori, 2011). In non-radiative techniques, there are capacitive power transfer (CPT) (Liu & Hu, 2009) and inductive power transfer (IPT) (Huh et al., 2011). In CPT system, the electric field, which is generated between two copper plates, is used to transmit the power to the millimetres scale distances (Karabulut et al., 2020). Unlike CPT systems, the magnetic field is used for power transmission and magnetic flux is generated by primary coil and on secondary coil the voltage is induced based on Faraday’s law. The transmission distance can reach up to meter’s scale.

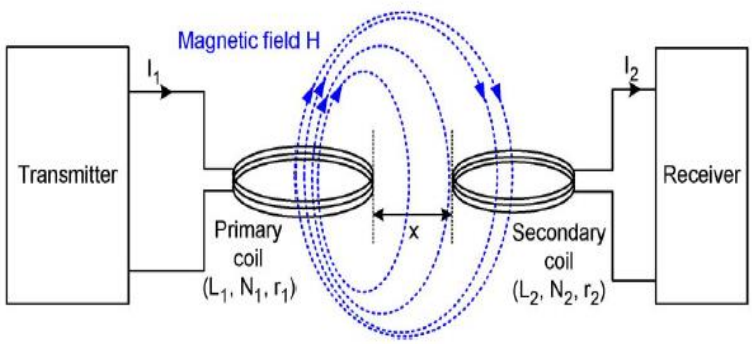

Figure 1: General scheme of IPT system (Mayordomo et al.,, 2013)

IPT system has been using in several applications such as biomedical (Clare et al., 2015), vehicle charging application (Li & Mi, 2015) and etc. In order to design high efficient IPT system, the power amplifiers are used in transmitter side and in general class-D and class-E amplifier are preferred to be used. They are more effective while comparing with the other classes of power amplifiers. They have theoretically 100% efficiency and they are controlled by switching members such as MOSFETs.

In this paper, an efficient IPT system is designed using the class-D amplifier. In the following sections, analysis of class-D amplifier were discussed and after designing the circuit, the experiment on IPT system has been realized and the results has been discussed.

MATERIALS AND METHODS

Class-D Amplifier

Class-D amplifier is one of the high efficient switching mode amplifiers that can be used in radio transmitter, dc-dc converters and etc (Lee et al., 1998; Hamill, n.d.). The high efficiency of class-D amplifier can be obtained by the zero current switching (ZCS) that enables the high frequency operation which is several hundred kilohertz (Husin et al., 2016; Kazimierczuk, 1991; Kazimierczuk & Szaraniec, 1992). General circuit diagram of class-D amplifier can be found below;

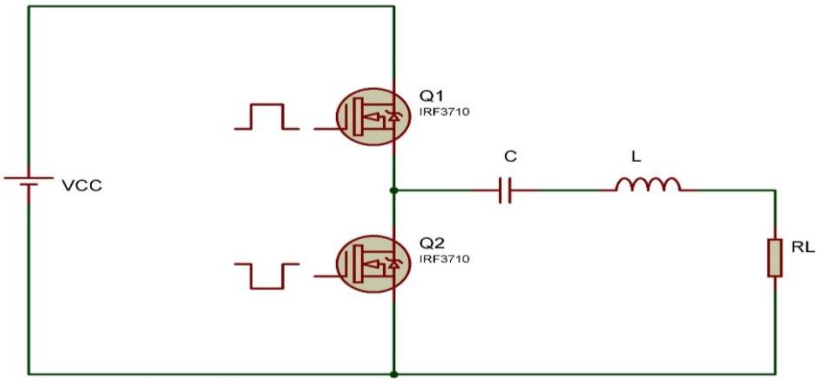

Figure 2: Basic circuit of class-D amplifier

As can be seen in figure 2, there two switching devices which are N-channel MOSFETs and L-C series resonant circuit. The MOSFETs should be properly selected according to their $R_{ds}(on)$ resistance values that should be low for less power consumption and in order to maximize the efficiency, some assumptions were confirmed. These assumptions are as follows;

- The switches are perfect (No losses)
- The duty cycle of switch is 50% (Q1 and Q2)
- Harmonic signals are ignored

In order to implement the class-D amplifier, the inductor L is used as a primary coil and R is placed on secondary side of IPT system. The implementation of class-D amplifier on IPT system can be found below;

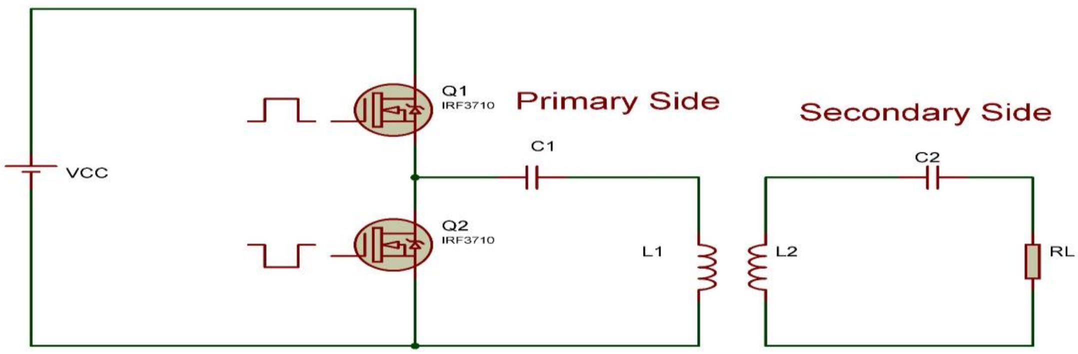

Figure 3: Implementation of class-D amplifier on IPT system

For determining the values of circuit components for IPT system, the following equations (Kazimierczuk, 1991) are used;

$$P_i = \frac{P_o}{\eta} \tag{1}$$

$$R = \frac{2V^2{}_{cc}}{\pi^2 P_i} \tag{2}$$

$$R_L = \eta * R \tag{3}$$

$$L1 = \frac{QR}{\omega} \tag{4}$$

$$\omega = \frac{1}{\sqrt{LC}} \tag{5}$$

where Q is the quality factor which is assumed to be 10 in general, and ω is the resonant frequency. This system is designed by assuming the output power equals to 3 W and the system efficiency is 90%.

EXPERIMENT AND RESULTS

In the experiment, the IPT system shown in figure 3 has been designed and the circuit components has been calculated and selected. At first the primary and secondary coils were designed as shown in figure 4 and as a switching device IRF3710 MOSFET was selected. It has low drain-source resistance value which is 0.023 ohm. In order to drive the MOSFETs, dual MOSFET driver IR2110 IC was used to pump the sufficient current to activate MOSFETs. As a MOSFET driver signal, 10Vp-p square wave voltage has been applied to the gate of MOSFETs. Other design parameters are specified as follows; DC power supply V_{cc}=15V, operating frequency f=200 kHz and according to equation 1 and 2 the load resistor and capacitor values are calculated.

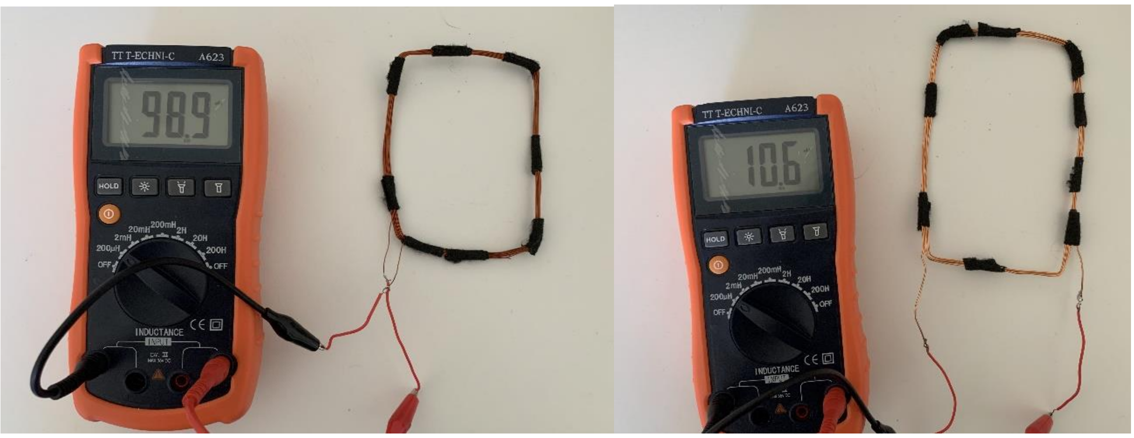

Figure 4: Inductance values of primary and secondary coils

Table 1. Operated and calculated values of circuit components

Circuit Component	Calculated Value	Operated Value
L1 (primary coil)	97.8uH	98.9uH
L2 (secondary coil)	10.8uH	10.6uH
C1	6.47 nF	6 nF
C2	58.63 nF	57 nF
R (load resistor)	12.31 Ω	10 Ω

The IPT system has been demonstrated using the values that are mentioned above and after demonstration 15V DC supply was applied to the circuit and the current I_{cc}=0.17A was drawn from DC supply. As a result, the output voltage on the load resistor was obtained as shown in figure 5.

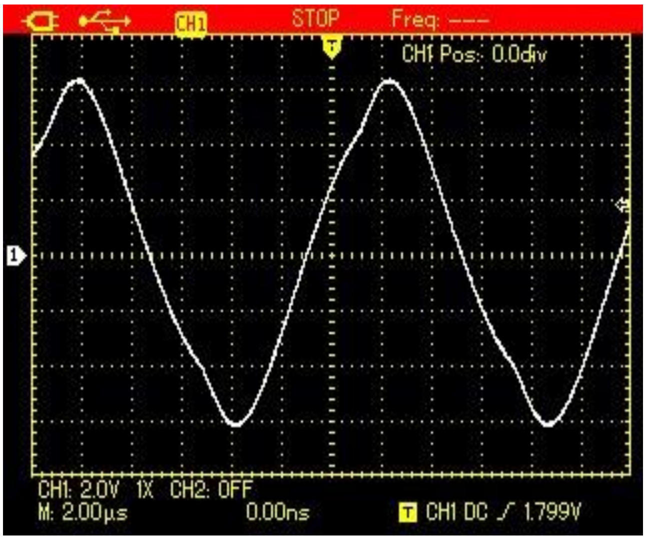

Figure 5: Voltage waveform on load resistor

As can be seen in in figure 5, 12Vp-p output voltage signal was obtained and in order to calculate efficient output power on the load resistor, the following equations are applied according to the voltage characteristics of the output signal.

$$V_o(rms) = \frac{V_m}{\sqrt{2}} = \frac{6}{\sqrt{2}} = 4.242\ V \tag{6}$$

$$P_o = \frac{{V_o}^2}{R_L} = 1.8\ W \tag{7}$$

$$P_i = V_{cc} * I_{cc} = 2.55\ W \tag{8}$$

$$\eta = \frac{P_o}{P_i} = 70.58\% \tag{9}$$

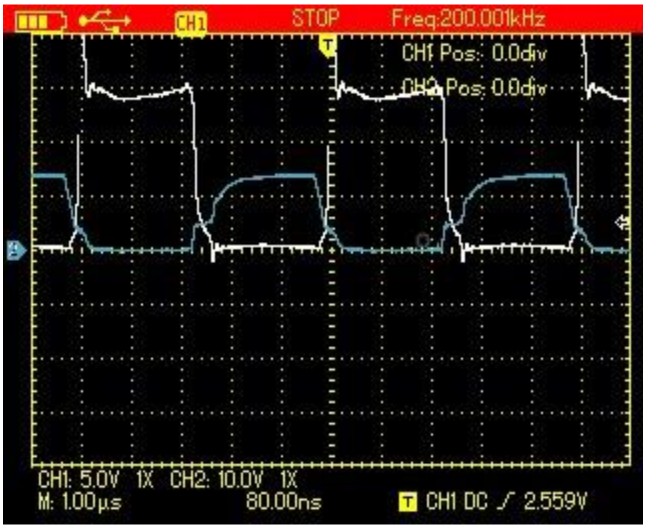

Figure 6: Gate-source (blue) and drain-source (white) voltage of MOSFET

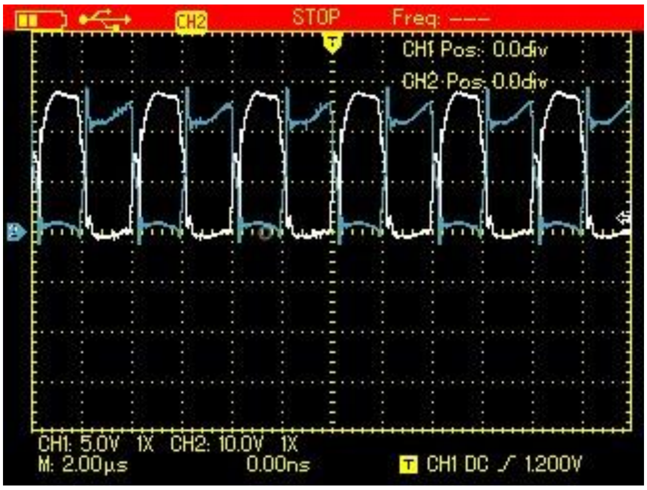

Figure 7: Gate signal of MOSFETs (blue for Q1 and white for Q2)

As it can be understood from figure 6, there is an intersection between gate-source and drain-source voltage of MOSFET which causes the more power losses and in figure 7, the PWM signals are not smooth. Due to these reasons, 70.58% efficiency was achieved.

CONCLUSION

An implementation of class-D amplifier on IPT system has been investigated in this paper. As a switching device IRF3710 MOSFET has been used and in order to drive the MOSFETs, the MOSFET driver IR2110 has been used. In the experiment section, the MOSFETs were controlled 0.5 duty cycle PWM signals and 15 V DC voltage was supplied to the drain of high side MOSFET. As a result 70.58% efficiency has been achieved at the resonance frequency. The transfer distance between the coils is in centimetre scale. The PWM signals in figure 7 are not smooth and there is an intersection between gate-source and drain-source voltages of MOSFETs. Due to these reasons, the efficiency of the system was decreased. However, at the output 1.8 W power was achieved and it can operate several ICs wirelessly. Thus, IPT system has a potential as a future technology and it can be deployed in many application areas such as medical, automotive and etc.

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