Simulation Study on Self-Frequency Tracking Control Strategy for Inductive Power Transfer System

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***Abstract*— This paper presents a closed loop Inductive Power Transfer (IPT) system. In this work, the Phased Lock Loop control system is used to control the frequency of Class E resonant converter circuit. Furthermore, self-frequency tracking control strategy with simple detection circuit is proposed as a feedback circuit to IPT system. Through this method, the frequency drifting that is due to variation in reactive components or mutual inductive coupling can be avoided successfully. The IPT system with and without frequency tracking is analyzed at different coupling coefficient. Simulation results confirm that the Class E resonant power converter circuit with frequency tracking gives a better output result with 92% efficiency at 0.8 of coupling coefficient.**

***Index Terms*— IPT system, frequency tracking and Class E circuit.**

I. INTRODUCTION

Recently, Wireless Power Transfer (WPT) system based on loosely coupled Inductive Power Transfer (IPT) system has been researched and developed widely among researchers and inventors. It is used in mobile phones [1], home appliances [2], electric vehicles [3] and medical implants [4]. This is because of its capability to transfer higher electrical power from transmitter coil to receiver coil without wired contact than its counterpart; Acoustic Energy Transfer (AET) system [5] and Capacitive Power Transfer (CPT) system [6]. The current development of IPT system is to replace the conventional method of wired charging by making them more reliable and convenient.

However, high efficiency power transfer of IPT system is hard to be achieved. This is because of the power transmission from transmitter coil to receiver coil is via an air gap. Thus, large leakage inductances occur due to the magnetic force is distributed in the air gap [7]. Since solving that problem using field shaping techniques (eg. Meta-materials and ferrite cores) at relatively low frequencies below Megahertz yields high cost [8], many researchers move on towards high frequency power transfer with particular coil size [9]. Theoretically, high frequency power transfer can be realized by soft switching the driver circuit or power converter circuit [8]. It is to drive inductive links efficiently. The inductive links refer to the coupling between the transmitting coil, L_1 and the receiving coil, L_2, see Figure 1.

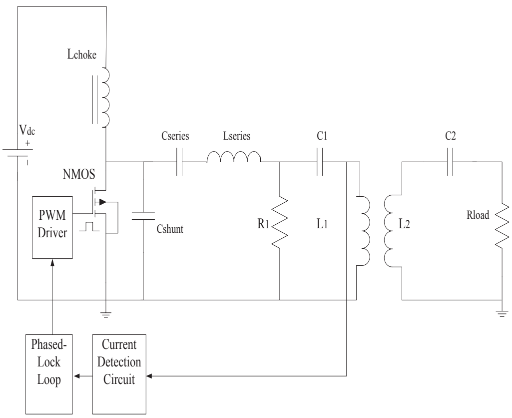


Figure 1: General block diagram of IPT system

Normally, power converter circuit is sensitive to the switching losses. This happens because of the reflected load impedance that exists in the transmitter side of the IPT system, i.e. mutual coupling and reactive components. Hence, the mismatch frequency that occurs between the drifted frequency and designed frequency will affect the efficiency of IPT system. As a result, it is hard to achieve an efficient maximum power transfer due to Zero Voltage Switching (ZVS) will not be achieved. In this work, the use of Class E resonant power converter circuit is proposed in driving the inductive links due to its low switching loss [8][10][11]. In order to ensure that the frequency is stable, control loop of Class E resonant power converter circuit is required in the IPT system, see Figure1.

Researches in duty cycle control or frequency control are among the most conducted works in investigating methods to control the driver circuit of IPT system [12][13]. In [13] and [14], duty cycle control in IPT system has been studied. However, authors in reference [15] stated that adjusting the operating frequency is the easiest method to solve the frequency variation. Thus, Phased Lock Loop (PLL) control is proposed to adjust the operating frequency. PLL will lock the phase error and produce the desired frequency. This is because PLL technologies been widely improved especially its maximum input voltage and frequency range.

Based on the previous research, PLL has been used in dual-tube resonant inverter of Class E circuit and LLC resonant circuit [16][17]. In [16], the efficiency of transmission achieved was about 80% at 3cm of air gap distance and decrease slightly when the air gap distance was increased. Meanwhile in [17], 43.5W of output power and 74.4% of efficiency had been achieved at 10mm air gap, when the IPT system worked at a frequency of 100 kHz. Since those papers proposed dual switches at driver circuit, it will lead to a dead time and switching loss. Thus, in this work, PLL will be used for frequency tracking for single switch of Class E resonant converter circuit. Class E circuit with IPT system has been discussed in detail in [18].

The main objective of this paper is to analyze the IPT system with frequency tracking and without frequency tracking using LTspice simulator. In relation to this, the paper is structured as follows: Section II presents the research design for PLL and the current detection circuit in IPT system. The proposed 1MHz frequency tracking control strategy via PLL has been validated through the simulation work. Thus, the main results and a brief discussion on IPT system with frequency tracking and without frequency tracking performances when varying the inductive coupling coefficient are described in Section III. Lastly, section IV provides the conclusion of this work.

II. Research Design

Figure 2 shows the general block diagram of PLL, which generates PWM with a stable frequency for gate MOSFET. It consists of phase detector, filter and Voltage Control Oscillator (VCO). The voltage error signal, V is produced by the phase comparator after comparing the output voltage of current sensing, V_{det} and output VCO and VCO_{out}. If the phase error (error signal) is not zero, the phase detector develops a non-zero output signal. The error signal needs to be filtered by external loop filter circuit. The output signal of loop filter would cause the VCO to change its operating frequency in such a way that the phase error finally eliminates [20].

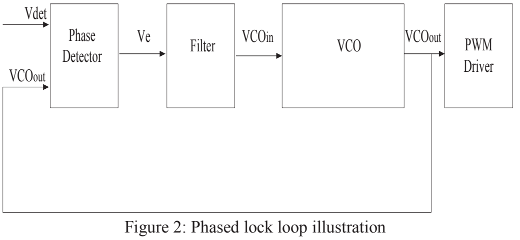


Figure 2: Phased lock loop illustration

A. Class E Resonant Power Converter Circuit

Class E resonant power converter circuit as shown in Figure 3 is designed to generate high frequency alternate current (AC) signal. The magnetic field will be generated at the transmitter coil to produce induced voltage. So, the induced voltage at the transmitter coil will be transferred into the receiver coil. This circuit is proposed due to the high efficiency power transfer [21]. The parameters used for Class E resonant power converter circuit are given in Table 1.

Table 1
Circuit Parameters of Class E Resonant Power Converter Circuit

Circuit Parameters	Values
Power MOSFET, NMOS	IRF510
Operating Frequency, f_o	1MHz
Input DC supply, V_{dc}	9.0V
Rated Power, P_o	3.0W
Choke Inductor, L_{choke}	5.0mH
Shunt Capacitor, C_{shunt}	2.2nF
Series Capacitor, C_{series}	1.0nF
Series Inductance, L_{series}	30.0µH
Primary and Secondary Coil, L_1 and L_2	24µH
Primary and Secondary Capacitor Compensation, C_1 and C_2	1.0nF
Load Resistance, R_L	100Ω

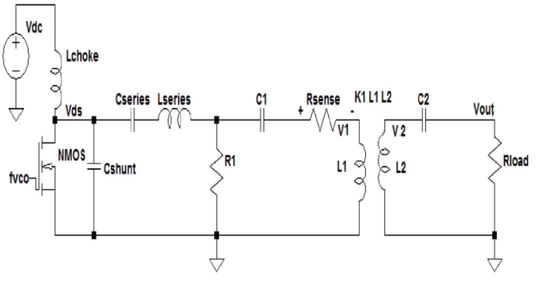


Figure 3: Class E resonant power converter circuit with inductive links

B. Current Detection Circuit

In real time frequency tracking control, the first step required is the current detection circuit design. Its purpose is to detect the frequency variation at resonant tank of IPT system. If there is no detection circuit for real time implementation work, frequency tracking cannot be achieved. Figure 4 shows a single op amp of difference amplifier (TL062CN) and four external resistors.

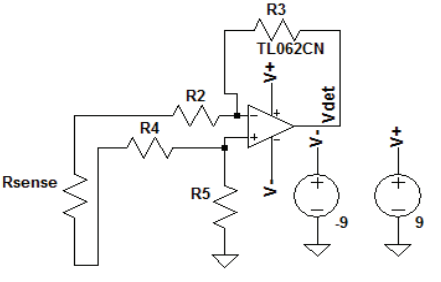


Figure 4: Current sensing circuit

In this work, the high side current detection circuit is chosen due to its ability to eliminate ground disturbances and detect high load current [19]. The detected resistor, R_{sense} is chosen to be small enough, which is 10Ω. Differential amplifier is used to amplify the small voltage drop across the detected resistor, which is known as the detected voltage signal. It is amplified by the ratio of R3/R2, where R3=R5 and R2=R4. In this research, R2 and R3 values are 2.2kΩ and 22k Ω, respectively. Hence the gain of the amplifier is 10.

C. Phased Lock Loop

CD4046 of PLL is used in IPT system as a feedback circuit for tracking the frequency as shown in Figure 5. Meanwhile, self-starting loop which consists of voltage divider (R8 and R9), parallel capacitor, C3 and diode, D1 is designed for VCO input of PLL for 1MHz operating frequency. Its purpose is to ensure the gate pulse starts to be self-oscillated to trigger NMOS in Class E resonant converter circuit. D1 acts a protection circuit when C3 becomes short circuit when the PLL is powered on.

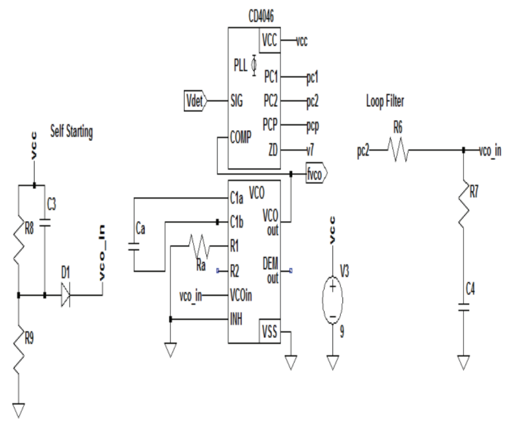


Figure 5: Phased lock loop and its external circuit

In order to ensure VCO is activated, external resistor, R_a and capacitor, C_a need to be connected for determining the frequency range of the VCO. While R2 pin is the optional resistor that enables VCO to have a frequency off-set. To achieve 1MHz starting frequency, the value of those components have been referred to the datasheet, which are Ra=10kΩ and Ca=55pF, respectively. Meanwhile, the use of passive lead lag low pass filter circuit is proposed due to its capability to filter the noise efficiently. Transfer function, F(s) of that filter can be determined as:

$$F(s) = \frac{1 + t_2 s}{1 + s(t_1 + t_2)}. \qquad (1)$$

The pole is at $1/(\tau_1+\tau_2)$ and the zero at $1/\tau_2$, where $t_1 = R_6C_4$ and $t_2 = R_7C_4$. Since the pole is smaller than the zero, the filter is lead-lag. Passive filters should have no amplitude nonlinearity. Thus, in order to determine the value of R_6=3.3kΩ and R_7=330Ω, the value of capacitor, C_3 is assumed as 3nF and its cut-off frequency is 1 MHz.

III. Simulation Results

Figure 6 shows the result of Class E resonant converter circuit without frequency tracking. There is no feedback detection circuit connected to the input signal of PLL. So, the detection circuit voltage (pin SIG) and the reference voltage (pin fvco) have not been compared. At this time, the inherent frequency is about 1.1MHz, which is greater than the 1MHz of operating frequency of Class E resonant converter circuit. Consequently, this produced a non-optimized of ZVS operation. It produced 24 V_{peak} of drain-to-source voltage, V (vds) and 15 V_{peak} of output voltage across transmitter coil, V(vout).

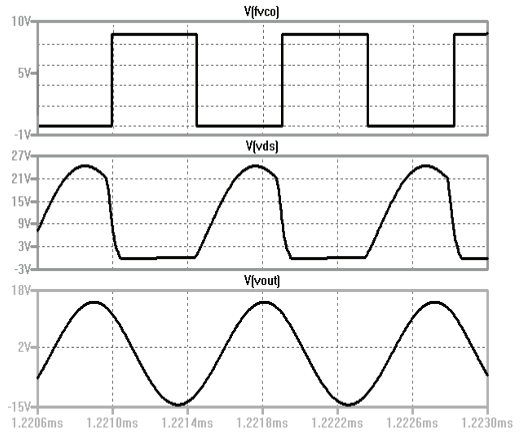


Figure 6: Output waveform of IPT system without frequency tracking

Meanwhile, Figure 7 illustrates the result of Class E resonant converter circuit with frequency tracking. It shows that an optimum of ZVS operation has been achieved. This is because the feedback detection circuit, $V_{(vdet)}$ has been implemented, producing about 1.04 MHz of inherent frequency, which is closer to the 1MHz of operating frequency of Class E resonant converter circuit. It produced 26.8 Vpeak of drain-source-to-voltage, $V_{(vds)}$ and 26 V_{peak} of output voltage, $V_{(vout)}$. Thus, it shows that the output voltage across transmitter coil with frequency tracking is better than the previous result, which is only 15 V_{peak}. With the higher output voltage obtained, it is guaranteed that the output power transfer will also be higher.

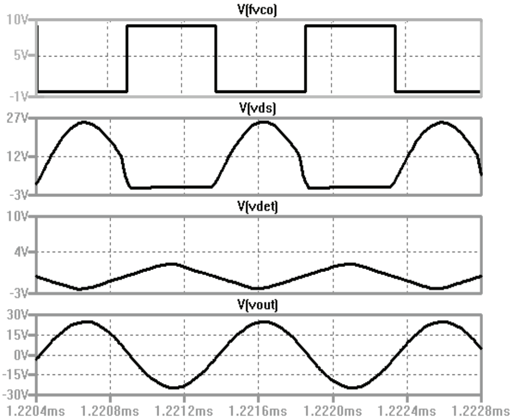
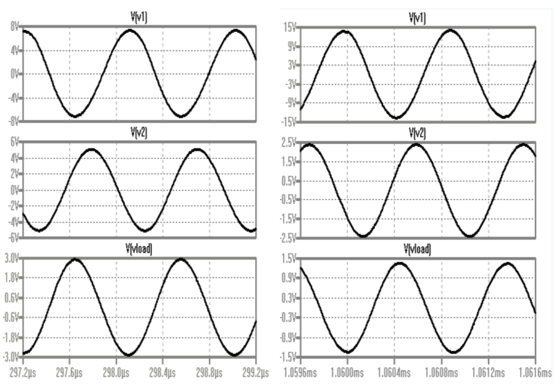


Figure 7: Output waveform of IPT system with frequency tracking

In order to analyze the performance of inductive links between the use and the non-use of frequency tracking approach, mutual coupling coefficient, *k* was first identified by doing a measurement test. *k* has been measured at 5 mm and 30 mm of air gap distance at identical load. Thus, it was selected at high and low possible value, which are 0.8 and 0.1, respectively. Those values have been determined through the ratio of measured secondary peak voltage of receiver coil, V_2 to the measured primary peak voltage of transmitter coil, V_1, as follows [21]:

$$k = \frac{V_2}{V_1}. \tag{2}$$

Figure 8 shows the simulated result of the output waveform of inductive links without frequency tracking. At this time, there is no connection of feedback circuit to track the frequency at different coupling coefficient value.



a) k=0.8 b) k=0.1

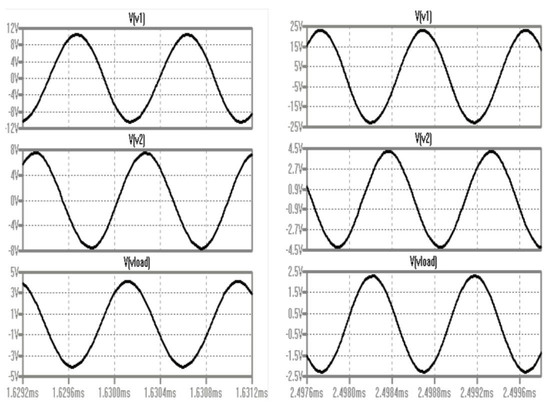
Figure 8: Inductive links without frequency tracking

For 0.8 of coupling coefficient, the peak of primary voltage, V_1 has produced 7V and its secondary peak voltage, V_2 is 5V, as shown in Figure 8(a). So, the simulated *k* is 0.7 based on Equation (2). Meanwhile, Figure 8(b) shows the result of output waveform of inductive links for *k*=0.1 without feedback circuit. Thus, V_1 produced 15 V of primary peak voltage and the secondary peak voltage, V_2 is 2.5V.Then, the simulated k is equal to 0.16 based on Equation (2). So, the simulated mutual inductance can be determined as [21]:

$$M = k\sqrt{L_1 L_2}; \tag{3}$$

Moreover, based on Figure 8, the output voltage across 100Ω load resistance for k=0.8 is higher than k=0.1without frequency tracking. As a result, higher coupling coefficient gives a higher output power, which is 45.0mW has been produced at 0.8 coupling coefficient. This happened because of less leakage inductance.

Figure 9(a) shows the result of output waveform of inductive coupling when the circuit is set up at k=0.8 with frequency tracking contol strategy. The primary peak voltage, V_1 produced 10 V and the secondary peak voltage, V_2 is 8.0V. As a result, *k* of simulation work is equal to 0.8 based on Equation (2). Therefore, the output voltage across 100Ω of load resistance with frequency tracking has increased by 0.5 at 0.8 of coupling coefficient.



a) k=0.8 b) k=0.1

Figure 9: Inductive links with frequency tracking

Meanwhile, Figure 9(b) shows the result of output waveform of inductive coupling when the circuit is set up at k=0.1 with feedback circuit. Thus, V_1 produced 23 V of peak voltage and the secondary peak voltage, V_2 is 4.5V. Then, the simulated k of inductive coupling with frequency tracking is equal to 0.2. The output voltage across 100Ω load resistance for k=0.8 is higher than k=0.1. As a result, higher coupling coefficient gives a higher output power, which is 80.0mW that has been produced at 0.8 coupling coefficient. Thus, the results of mutal inductance, *M* and its output power across 100Ω load resistance with and without frequency tracking can be summarized in Table 2.

Table 2: Summarized result of output power across 100Ω load resistance

Inductive Coupling	k=0.8		k=0.1	
	M (uH)	P_{load} (mW)	M (uH)	P_{load} (mW)
Without Frequency Tracking	16.8	45.0	3.8	7.2
With Frequency Tracking	19.2	80.0	4.8	20.0

Based on Table 2, the output power across 100Ω load resistance with frequency tracking has produced a better output result compared to the inductive links without frequency tracking. This is because the frequency has been tracked at 1MHz to match the designed frequency. However, the output power is decreased when the coupling coefficient became small due to the leakage inductance occured. On the other hand, the efficiency of inductive links, n_{links} depends on the mutual inductance coupling value as follows [22]:

$$\eta_{links} = \frac{\omega^2 M^2 R_{Load}}{R_1\left(\left(R_2 + R_{Load}\right)^2 + \left(\omega L_2 - \frac{1}{\omega C_2}\right)^2\right) + \omega^2 M^2 \left(R_2 + R_{Load}\right)}. \quad (4)$$

Therefore, the efficiency of inductive coupling with and without frequency tracking has been plotted versus the coupling coefficient as shown in Figure 10. The inductive links efficiency, n_{links} has increased linearly proportional with the coupling coefficient. The best efficieny of IPT system with frequency tracking that can be obtained is 92% at k=0.8.

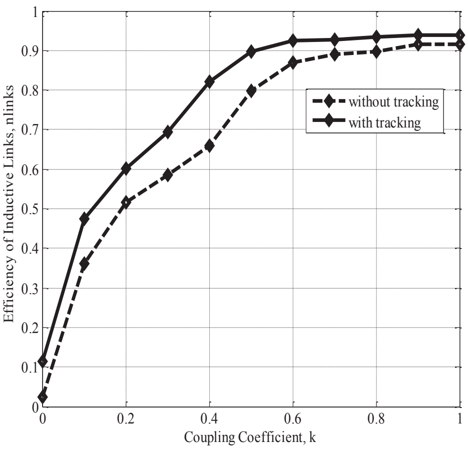


Figure 10: Efficiency of inductive links versus coupling coefficient

IV. CONCLUSION

Class E resonant converter circuit with frequency tracking and without frequency tracking has been analyzed through the simulation works using LTspice. The results from both analysis showed that Class E resonant converter circuit with frequency tracking produced a better output result. For the frequency tracking control strategy, PLL and detection circuit has been used as a feedback circuit to lock the desired frequency. Therefore, the best output power across 100Ω load resistance of IPT system with frequency tracking is 80mW with 92% efficiency at 0.8 coupling coefficient. This result is better than the result of IPT system without frequency tracking. For future work, experimental works will be done to verify the simulated results. The geometrical coil design and air gap distance will be also considered.

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