Different Frequencies between Power and Efficiency in Wireless Power Transfer

Muhammad Afnan HABIBI[a], Ichijo HODAKA[b]

Abstract

Wireless Power Transfer (WPT) has been recognized as a common power transfer method because it transfers electric power without any cable from source to the load. One of the physical principle of WPT is the law of electromagnetic induction, and the WPT system is driven by alternative current power source under specific frequency. The frequency that provides maximum gain between voltages or currents is called resonance frequency. On the other hand, some studies about WPT said that resonance frequency is able to produce high power and high efficiency on the WPT system. There are cases that make WPT system has two different frequencies. One leads maximum power and another leads maximum efficiency. If WPT system works under the resonance frequency, WPT produces maximum power with lower efficiency on it. As the solution of that, the intersection frequency able to balance both power and efficiency.

Keywords: Wireless Power Transfer, Frequency, Resonance, Power, Efficiency

1. INTRODUCTION

Electric power, generated by power supply, needs transmission system to be delivered to electric load. Generally, wires should be suitable for transmitting electric power because they are cheap and dependable. Many electric loads supplied by wires which are represented as electronic devices. The number of devices increases as the human population increases. The number of used wires also increases. It would be difficult to arrange the wires. In order to decrease wires, people do research about wireless power transmission.

Wireless Power Transfer (WPT) is an electronic device which capable to transfer electric power through the electric load without conductor. There are four parts in this device: power supply, transmitter, receiver, and load. A power supply generates electric power which is equal to the multiplication of the voltage and the current in this circuit. This power supply connected to transmitter. A transmitter transforms the electric energy in several turns of conductor into magnetic field. This magnetic field spread along the transmitter and intersect the another coil. This coil is receiver. Magnetic field is induced in receiver and transformed into electric energy. Then the electric load, series connected with receiver, could be energized.

WPT system should decide about how much the frequency applied in the system. It also consider the produced power and the efficiency as well.

Some people may build their own WPT systems. But, WPT should be improved even though it has many benefits.

There are several studies about improving WPT. André Kurs, et al.[1] who successfully made WPT over two meters distance with 40% efficiency. Teck Chuan Beh, et al. [2] improved WPT by using the impedance matching circuit to adjust the resonance frequency to 13.56 MHz at different certain distances. Vladimir Kindl, et al.[3] explained the measured and predicted WPT efficiencies for small devices. Yusuke Moriwaki, et al. [4] has reduced reflected power by using DC/DC converters.

WPT which operates in a resonance frequency able to produce higher power than other frequencies. But, it does not mean that high power WPT always has high efficiency on the system. It means that WPT has different frequencies which is producing high power or producing high efficiency. This paper explains about the relation between produced power and efficiency of the WPT. The produced power and the efficiency of the WPT are plotted in the angular frequency axis. These graphs shows what kind of the WPT is considered.

2. EVALUATION METHOD

WPT can be represented as electric circuit called equivalent circuit. This equivalent circuit provides the behavior of the currents and voltages in the WPT system. The product of the voltage and the current is the power. Then, the output power is the multiplication of the output voltage and output current. So do the

a) Master Student, Department of Environmental Robotics
b) Professor, Department of Environmental Robotics

input power. The ratio between the output power and the input power is the efficiency.

Let the WPT circuit is shown at Figure 1. u is a sinusoidal power supply with internal resistance R_1. The transmitter coil L_1 which has parasitic components. They are parasitic capasitor C_1 and resistor R_1. So do the receiver coil L_2 with both C_2 and R_2. This receiver is series connected with the load R_4.

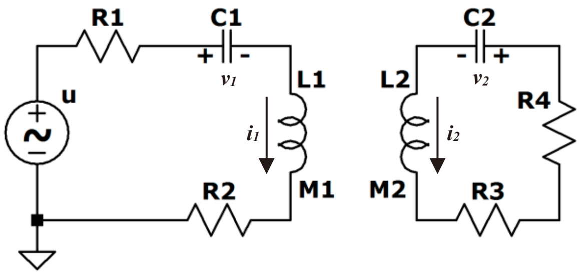

Fig 1. The Equivalent Circuit of the WPT

To get the equations of the circuit, Kirchoff's Current Law (KCL) and Kirchoff's Voltage Law (KVL) are used. The equations contains integral and/or differential because of L-C components. When there are n^{th}-order differential equations, state-space equations can be obtained. The state-space equation from the circuit is

$$\dot{x} = Ax + Bu \tag{1}$$

Where

$$\dot{x} = \frac{dx}{dt}$$

$$x = \begin{bmatrix} v_1 & v_2 & i_1 & i_2 \end{bmatrix}^T$$

$$\Delta = L_1 L_2 - M_1 M_2$$

$$A = \frac{1}{\Delta}\begin{bmatrix} 0 & 0 & \dfrac{\Delta}{C_1} & 0 \\ 0 & 0 & 0 & \dfrac{\Delta}{C_2} \\ -L_2 & M_2 & -(R_1+R_2)L_2 & (R_3+R_4)M_2 \\ M_1 & -L_1 & (R_1+R_2)M_1 & -(R_3+R_4)L_1 \end{bmatrix}$$

$$B = \frac{1}{\Delta}\begin{bmatrix} 0 \\ 0 \\ L_2 \\ -M_1 \end{bmatrix}$$

The solution of state-space equation give the equation of state variables x(t) in time function. While matrix A from Eq. (1) is in stable condition, x(t) should be in steady-state condition which[5)] had been derived as $x_s(t)$. By applying sinusoidal input u=sin(ωt), the steady-state of state variables $x_s(t)$ is:

$$x_s(t) = -\big(\omega I\cos(\omega t) + A\sin(\omega t)\big)(\omega^2 I + A^2)^{-1}B \tag{2}$$

Where I is the identity matrix which has four in both columns and rows.

The average power is the integral of the power over one period. The power input P_1 and output P_4 in steady-state condition are:

$$P_1 = \frac{1}{T}\int_0^T i_{s1}(t)\big(u(t) - R_1 i_{s1}(t)\big)dt \tag{3}$$

$$P_4 = \frac{1}{T}\int_0^T R_4 {i_{s2}}^2(t)dt \tag{4}$$

Where period $T = \frac{2\pi}{\omega}$

Then, the efficiency, the ratio between output and input power is:

$$\eta = \frac{P_4}{P_1} \tag{5}$$

3. ANALYSIS AND RESULT

Numerical values of the circuit components is convenient to be applied. It gives more simple analysis of power output P_4 and the efficiency η in respect with angular frequency ω. The numerical values are given in three different conditions. Every condition has different resonance frequency.

Condition 1

To give more details explanation, the circuit components is set as in Table 1.

Table 1. Components Value for Condition 1

Circuit Components Value			
Components	Value	Components	Value
R_1	50Ω	R_3	0.1Ω
R_2	0.1Ω	R_4	50Ω
L_1	10μH	L_2	10μH
M_1	0.5μH	M_2	0.5μH
C_1	1nF	C_2	1nF

All values in the in the Table 1 is subtitued in Eq. (1) to (5). The power output P_4 (μW) and efficiency η

(%) is plotted with respect with angular frequency ω (rad/s). Then, the plot result can be obtained.

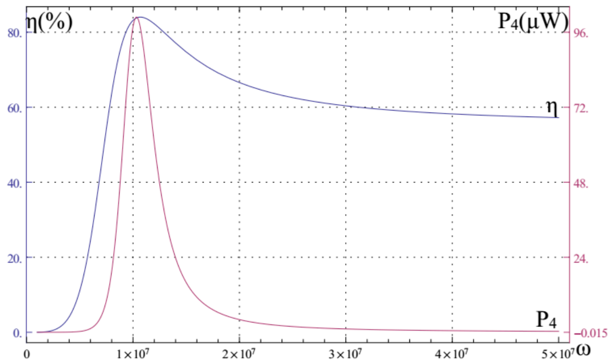

Fig. 2. Plot for Condition 1

WPT should have high power in the finite frequency applied on the system. While WPT is not operating in the finite frequency, the efficiency of the system is decreasing. The frequency which produces maximum power is called resonance frequency. In Figure 2, resonance frequency is maximizing both power and efficiency. The resonance frequency, which has maximum efficiency 84%, is:

$$\omega_{res} = \omega_{\eta} = 1.06 \times 10^{7}\ rad/s$$

All components values are the same but there is small changes. For condition 2, Only the value of L_2 is changed and shown in Table 2. For condition 3, Only the value of C_2 is changed and shown in Table 3.

Table 2. Components Value for Condition 2

Circuit Components Value			
Components	Value	Components	Value
R_1	50Ω	R_3	0.1Ω
R_2	0.1Ω	R_4	50Ω
L_1	10μH	L_2	20μH
M_1	0.5μH	M_2	0.5μH
C_1	1nF	C_2	1nF

Table 3. Components Value for Condition 3

Circuit Components Value			
Components	Value	Components	Value
R_1	50Ω	R_3	0.1Ω
R_2	0.1Ω	R_4	50Ω
L_1	10μH	L_2	10μH
M_1	0.5μH	M_2	0.5μH
C_1	1nF	C_2	0.5nF

The way to plot is the same way as in condition 1. The plot result for condition 2 is shown in Figure 3.

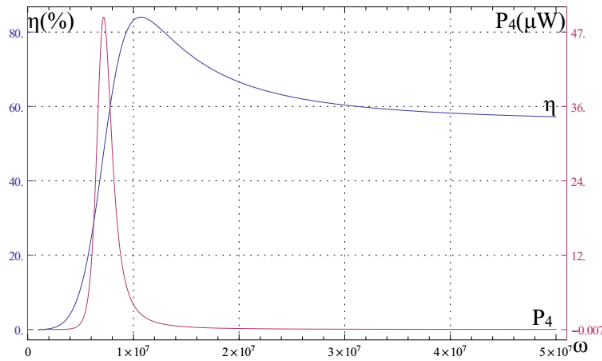

Fig. 3. Plot for Condition 2

There are two different frequencies. The first resonance frequency ω_{res} allows WPT to maximize the power. While another frequency is maximizing the efficiency which is the same as resonance frequency ω_{η} in the condition 1.

Condition 2

In condition 2, In order to satisfy the high power urgency, resonance frequency ω_{res} should be applied to the WPT system. But the efficiency of the system get lower. The resonance frequency which the efficiency is 56.2%, is:

$$\omega_{res} = 7.07 \times 10^{6}\ rad/s$$

When the WPT system urgency is having higher efficiency, ω_{η} is more convenient. As an alternative choice, the WPT system urgency is both of power and efficiency. The intersection frequency ω_{int}, which the efficiency is 60%, should be adjusted at:

$$\omega_{int} = 8 \times 10^{6}\ rad/s$$

Condition 3

On the right side of ω_{η}, the efficiency curve is slighter than left side. Figure 4 means that small increase of the frequency, the efficiency decrease smaller than on the left side. In condition 3, both ω_{res} and ω_{int} change into other frequencies.

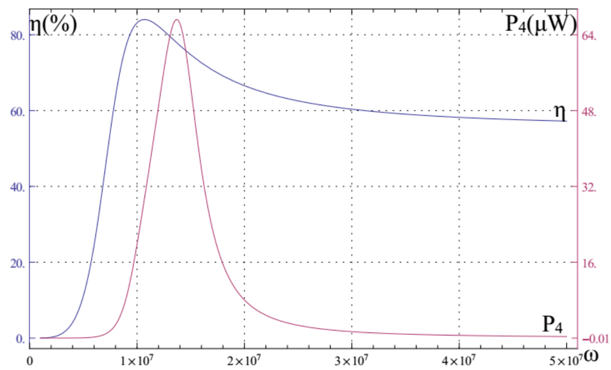

Fig. 4. Plot for Condition 3

The value of both ω_{res} and ω_{int} in condition 3 are:

$$\omega_{res} = 1.37 \times 10^7\ rad/s$$

$$\omega_{int} = 1.31 \times 10^7\ rad/s$$

When the frequency of WPT is set on ω_{res}, the efficiency is 76.3%. When the frequency is set on ω_{int}, the efficiency is 80%.

It is easier to see the correlation of those three conditions at the same table as shown in Table 4. WPT should apply ω_{int} rather than ω_{res} to get more better efficiency.

Table 4. Correlation of Three Conditions

		ω (rad/s)	η (%)
Condition 1	ω_{res}	1.06×10^7	84
Condition 2	ω_{res}	7.07×10^6	56.2
	ω_{int}	7.95×10^6	60
Condition 3	ω_{res}	1.37×10^7	76.3
	ω_{int}	1.31×10^7	80

4. CONCLUSION

In order to get better efficiency, WPT should take care about how much the frequency is. There are two different frequencies. One is maximizing efficiency ω_η and another is maximizing power ω_{res}. Those three conditions can be inferred as:

1) The frequency in range $\omega_\eta \le \omega \le \omega_{int}$ gives higher efficiency.
2) The frequency in range $\omega_{res} \le \omega \le \omega_{int}$ gives higher power.
3) The intersection frequency ω_{int} gives the balance both power and efficiency.
4) Other frequency out of that range is not suggested, because the efficiency is getting more lower.

REFERENCES

1) André Kurs, Aristeidis Karalis, Robert Moffatt, J. D. Joannopoulos, Peter Fisher, Marin Soljačić, Wireless Power Transfer via Strongly Coupled Magnetic Resonances, Science 317, pp. 83-86, 2007
2) Teck Chuan Beh, Takehiro Imura, Masaki Kato, Yoichi Hori, Basic Study of Improving Efficiency of Wireless Power Transfer via Magnetic Resonance Coupling Based on Impedance Matching, 2010 IEEE International Symposium on Industrial Electronics, Bari, pp. 2011-2016, 2010
3) Vladimir Kindl, Tomas Kavalir, Roman Pechanek, Karel Hruska, Basic Operating Characteristics of Wireless Power Transfer System for Small Portable Devices, 40th Annual Conference of The IEEE Industrial Electronics Society, Dallas, TX, pp. 3819-3823, 2014
4) Yusuke Moriwaki, Takehiro Imura, Yoichi Hori, Basic Study on Reduction of Reflected Power using DC/DC Converters in Wireless Power Transfer System via Magnetic Resonant Coupling, IEEE 33rd International Telecomunications Energy Conference (INTELEC), Amsterdam, pp. 1-5, 2011
5) Kazuya Yamaguchi, Takuya Hirata, Yuta Yamamoto, Ichijo Hodaka, Resonance and Efficiency in Wireless Power Transfer System, WSEAS Transactions on Circuit and Systems, Vol 13, pp. 218-223, 2014