Feedback Effect for Wireless High-power Transmission

YUTA YAMAMOTO
Department of Materials and Informatics
Interdisciplinary Graduate School
of Agriculture and Engineering
University of Miyazaki
1-1, Gakuen-kibanadai-nishi
Miyazaki 889-2192 Japan
nc12006@student.miyazaki-u.ac.jp

KAZUYA YAMAGUCHI
Department of Materials and Informatics
Interdisciplinary Graduate School
of Agriculture and Engineering
University of Miyazaki
1-1, Gakuen-kibanadai-nishi
Miyazaki 889-2192 Japan
nc13001@student.miyazaki-u.ac.jp

TAKUYA HIRATA
Department of Materials and Informatics
Interdisciplinary Graduate School
of Agriculture and Engineering
University of Miyazaki
1-1, Gakuen-kibanadai-nishi
Miyazaki 889-2192 Japan
nc14001@student.miyazaki-u.ac.jp

ICHIJO HODAKA
Department of Environmental Robotics
School of Engineering
University of Miyazaki
1-1, Gakuen-kibanadai-nishi
Miyazaki 889-2192 Japan
hijhodaka@cc.miyazaki-u.ac.jp

Abstract: Wireless power transmission is based on electromagnetical phenomenon between two separate coils. In order to transfer power from one to the other, we have to cause a time-varying current along one coil. Many of conventional wireless power transmission systems suppose a sinusoidal current of the coil. One reason for it could be the convenience that we have a sinusoidal power source as the industry standard. If we can use a power source which generates many types of wave form, we do not necessarily use the sinusoidal wave. In this study, we propose to add a feedback signal on a sinusoidal signal, that is, we propose to utilize a non-sinusoidal input. We will evaluate the sinusoidal wave and non-sinusoidal wave from the viewpoint of transmission power and efficiency to secondary side.

Key–Words: wireless power transmission, non-sinusoidal input, feedback

1 Introduction

Wireless power transmission has attracted many researchers for demand of a new type of power transmission. In 2007, wireless power transmission was proven to have a practical value of power transmission with a longer distance than it was used before [3]. After the pioneering work, the main interest of performance of wireless power transmission has been the magnitude of average power transmitted from a primary side to a secondary side. Maximizing the transmitted power is achieved by adjusting the frequency of voltage supply at the primary side to the resonant frequency of the whole circuit, as pointed out and utilized in many literature.

Another important performance of wireless power transmission system is how efficiently one can transmit power from the primary side to the secondary side. It is revealed in [1][2] that using the resonant frequency does not lead to optimization of efficiency. Thus a problem to be solved is how to keep the total transmitted power with raising the efficiency of power transmission, if the resonance is not equivalent to the maximal efficiency. This situation, of course, depends on the circuit to be used for wireless power transmission.

This paper proposes that we use the idea of feedback [7][8] with the resonant sinusoidal supply voltage. The feedback mechanism has in nature ability of adjustment against change or variation of circuit parameters. Therefore, using feedback has a possibility to attain better efficiency without losing transmitted power. Numerical examples will show the possibility is indeed the case.

2 Problem statement

In this paper, we study how to attain wireless high-power transmission circuits. Typical configuration of wireless power transmission circuits is depicted in Figure 1.

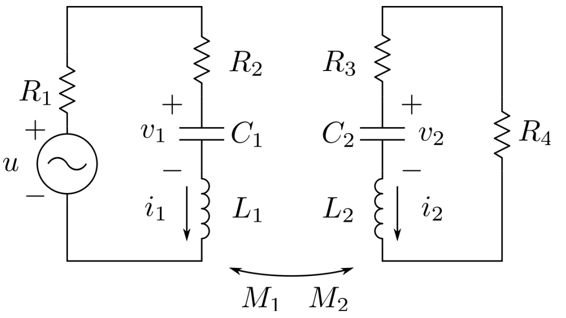

Figure 1: Wireless power transmission circuit

Any wireless power transmission has a pair of inductors (L_1 and L_2 in Figure 1) which enables power transmission with wireless connection. In practical situation, inductors are not ideal, i.e., they have unexpected characteristics besides the pure relation that the voltage across the inductor is proportional to the time-derivative of the current through the inductor. These unexpected characteristics are actually expected when we use them for the purpose of wireless power transmission – they include capacitive characteristics even if the capacitance (C_1 and C_2 in Figure 1) would be very small. Thus we recognize that a pair of coils could bring a phenomenon of resonance when using a sinusoidal input [4][5][6](u in Figure 1). This leads to maximization of average power into the receiving side, as the other literature stated. Maximization of power at the receiving side is one of desired specification on wireless power transmission, and it is accomplished by tuning the frequency of voltage supply input around the resonant frequency. This principle is valid even if we want to take resistive characteristics (represented by R_2 and R_3 in Figure 1) of coils or output resistance (R_1 in Figure 1) in the supply voltage into account. Another important specification on wireless power transmission is efficiency of the circuits. In general, efficiency of wireless power transmission system is defined as a ratio of the average power consumed at a load (R_4 in Figure 1) in a receiving side to the average power generated at a supply voltage in a transmitting side. If we decide to neglect any resistive element except for a load, we will have one hundred percent efficiency simply because we have no element with energy consumption. However, in order to aim a detailed analysis, if we decide to consider resistive elements in the coils, we will inevitably waste a small amount of power, that is, we have to suppose an efficiency less than one hundred percent in practice. The problem of our study is to investigate how to accomplish:

(1) Maximizing the average power at the load in the receiving side and

(2) Increasing the average power efficiency from the transmitting side to the receiving side.

Notice that there are cases that we cannot accomplish the both above simultaneously when we use a sinusoidal input with a pure frequency [1]. Thus we stands on the point of view that we should not necessarily use sinusoidal inputs in this paper.

3 Proposed Idea

Our problem is to obtain a method to maximize the average power at the load. Our idea is that we can use non-sinusoidal inputs of supply voltage. To be precise, we use a *feedback* plus a sinusoidal signal for a possible supply input. To explain our idea in a mathematical setting, we describe the set of equations governing the dynamics of the wireless power transmission circuit in Figure 1. Especially we prefer to describe them as a so-called *state-space equation* in the following.

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

$$A = \begin{bmatrix} 0 & 0 & \frac{1}{C_1} & 0 \\ 0 & 0 & 0 & \frac{1}{C_2} \\ \frac{-L_2}{\Delta} & \frac{M_2}{\Delta} & \frac{(-R_1-R_2)L_2}{\Delta} & \frac{(R_4+R_3)M_2}{\Delta} \\ \frac{M_1}{\Delta} & \frac{-L_1}{\Delta} & \frac{(R_1+R_2)M_1}{\Delta} & \frac{(-R_4-R_3)L_1}{\Delta} \end{bmatrix} \tag{2}$$

$$B = \frac{1}{\Delta}\begin{bmatrix} 0 \\ 0 \\ L_2 \\ -M_1 \end{bmatrix} \tag{3}$$

$$\Delta = L_1L_2 - M_1M_2 \tag{4}$$

$$x = \begin{bmatrix} v_1 & v_2 & i_1 & i_2 \end{bmatrix}^T \tag{5}$$

A common strategy is to use a sinusoidal input u with the resonant frequency. On the other hand, our idea is to use an input in the form

$$u = u_0 + Kx, u_0 = \sin\omega t \tag{6}$$

where ω is set to a frequency and K is a state feedback gain. The problem here is how to choose the feedback gain K. To solve it, we notice that the matrix A is decomposed into $A = A_0 - BK$, where

$$A_0 = \begin{bmatrix} 0 & 0 & \frac{1}{C_1} & 0 \\ 0 & 0 & 0 & \frac{1}{C_2} \\ \frac{-L_2}{\Delta} & \frac{M_2}{\Delta} & \frac{-R_1L_2}{\Delta} & \frac{(R_4+R_3)M_2}{\Delta} \\ \frac{M_1}{\Delta} & \frac{-L_1}{\Delta} & \frac{R_1M_1}{\Delta} & \frac{(-R_4-R_3)L_1}{\Delta} \end{bmatrix} \quad (7)$$

$$K = \begin{bmatrix} 0 & 0 & R_2 & 0 \end{bmatrix}. \quad (8)$$

If we apply the input (6) with K above, the state-space equation is also rewritten as

$$\dot{x} = A_0x + Bu, \quad (9)$$

whose‘ A-matrix ’A_0 is equivalent to A with $R_2 = 0$. That is, we can cancel out R_2 which is one of factors causing undesired energy consumption. Now our problem is reduced into a usual situation. That is, we concentrate on maximization of average power at the load. Therefore, we just choose ω as the resonant frequency of the system (9). Our proposed idea is described by the block-diagram in Figure 2.

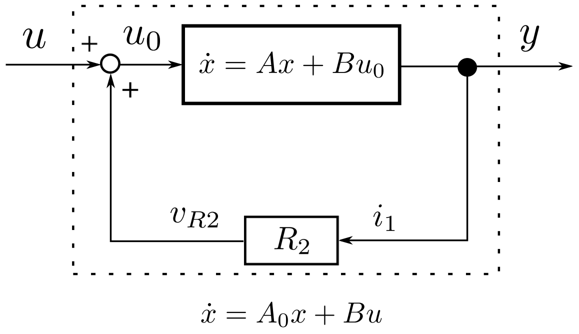

Figure 2: feedback system

To realize the input, we have to measure the current i_1 by using an appropriate sensor, and feed it back into the supply voltage. This will be done by using a microcontroller or operational amplifiers.

Then, why can we cancel a resistance with this idea? If you input a voltage in the circuit, the voltage drop is caused at a resistance. On the other hand, a circuit which is not containing resistance does not cause voltage drop of resistance. That is a matter of course and a very important thing. In short, our idea, adding the voltage of a resistance, means canceling the voltage drop at the resistance.

4 Numerical Examples

To illustrate the effect of the proposed idea in the previous section, we use numerical values of elements in the circuit as Table1 below.

We assume R_1 and R_2 are a composite resistance R_{12}, because they are connected in series.

Table 1: circuit parameters

	value
R_{12}, R_4	10 [Ω]
R_3	0.01 [Ω]
C_1, C_2	1 [nF]
L_1, L_2	10 [μH]
M_1, M_2	0.1 [μH]

We select an angular frequency ω as the resonant frequency 10^7 rad/s as in Figure 3.

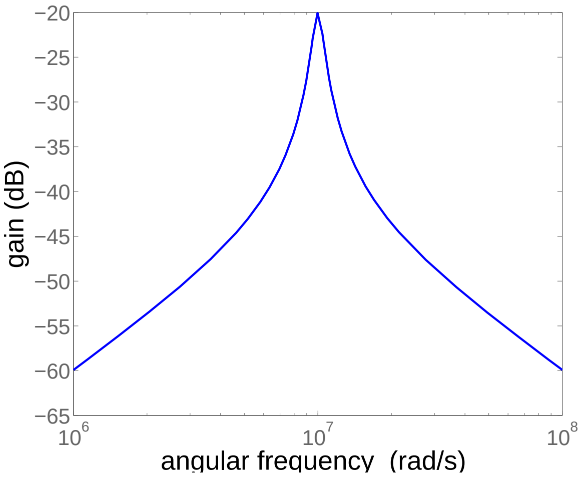

Figure 3: gain diagram

5 Comparing the power supply efficiency

We compare the power transmission efficiency of each voltage power source u_0 and u. The average power $\bar{P}_1$ at power source and $\bar{P}_4$ at R_4 are expressed in

$$\bar{P}_1 = \beta_3 - R_1(\alpha_3^2 + \beta_3^2) \quad (10)$$
$$\bar{P}_4 = R_4(\alpha_4^2 + \beta_4^2) \quad (11)$$

where

$$\begin{bmatrix} \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 \end{bmatrix}^T = -\,\omega(\omega^2 I + A^2)^{-1} B \tag{12}$$

$$\begin{bmatrix} \beta_1 & \beta_2 & \beta_3 & \beta_4 \end{bmatrix}^T = -\,A(\omega^2 I + A^2)^{-1} B. \tag{13}$$

Then, the power transmission efficiency η is

$$\eta = \frac{|\bar{P}_4|}{|\bar{P}_1|}. \tag{14}$$

We show $|\bar{P}_1|$, $|\bar{P}_4|$, η of each voltage power source u_0 and u in Table2.

And we change the feedback gain K which means we try varying values of canceling resistance. So, Canceling resistance is zero means using sinusoidal input u and the other is using non-sinusoidal input u_0. According to Table2, we obtained big power when we use u_0 for voltage power source, especially when we cancel a bigger resistance.

Then, Figure 4, Figure 5 and Figure 6 are comparing the wave form of u and varying u_0. We see from them, canceling bigger resistance requires bigger voltage amplitude.

Table 2: circuit parameter

Cancelled resistance [Ω]	$\lvert\bar{P}_1\rvert$[W]	$\lvert\bar{P}_4\rvert$[W]	η[%]
0.0	9.515×10^{-4}	9.505×10^{-4}	99.9
1.0	1.178×10^{-3}	1.176×10^{-3}	99.9
2.0	1.518×10^{-3}	1.517×10^{-3}	99.9
3.0	1.981×10^{-3}	1.979×10^{-3}	99.9
4.0	2.684×10^{-3}	2.682×10^{-3}	99.9
5.0	3.841×10^{-3}	3.837×10^{-3}	99.9
6.0	5.943×10^{-3}	5.937×10^{-3}	99.9
7.0	1.040×10^{-2}	1.039×10^{-2}	99.9
8.0	2.265×10^{-2}	2.263×10^{-2}	99.9
9.0	8.258×10^{-2}	8.249×10^{-2}	99.9

6 Conclusion

In this paper, we proposed a method to improve the power transmssion efficiency of the wireless power transmission system. We shown numerical examples of canceling the parasitic resistance by adding v_{R_2} to voltage power source. We compared power transmission efficiency of sinusoidal input u and our proposed input u_0. Finally, we demonstrated our proposed input

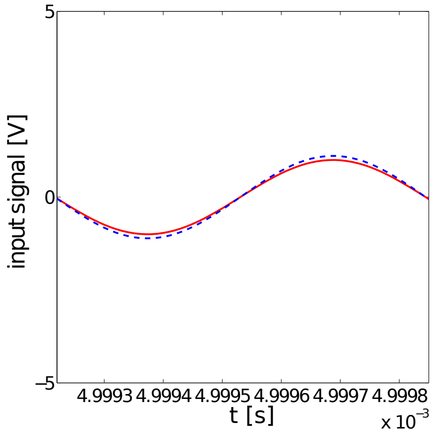

Figure 4: Canceling 1.0 Ω

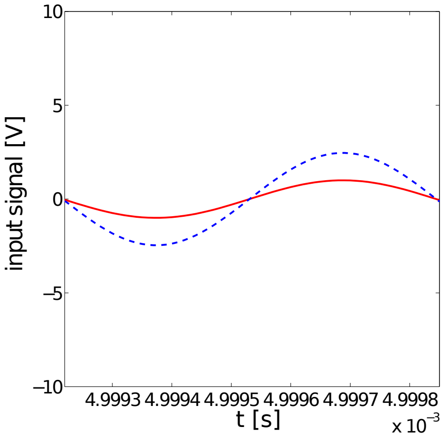

Figure 5: Canceling 6.0 Ω

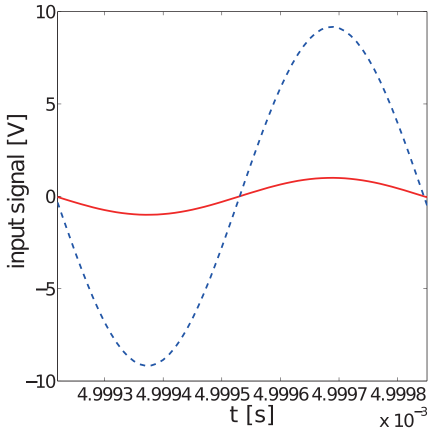

Figure 6: Canceling 9.0 Ω

is better than sinusoidal input as an input for wireless power transmission.

From the result, we have known canceling big resistance requires big voltage amplitude. So, we should consider the voltage amplitude when we evaluate the wireless power transmission system.

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