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The Use of Mathematics and Electric Circuit Simulator Software in the Learning Process of Wireless Power Transfer for Electrical Engineering Students

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Abstract. Wireless Power Transfer (WPT) isa technique to deliver the electrical power from the source to the load without using wires or conductors.The physics of WPT is well known and basically learned as a course in high school. However, it is very recent that WPT is useful in practical situation: it should be able to transfer electric power in a significant efficiency. It means that WPT requires not much knowledge to university students but may attract students because of cutting edge technique of WPT. On the other hand, phenomena of WPT is invisible and sometimes difficult to imagine.The objective of this paper is to demonstrate the use of mathematics and an electric circuit simulator using MATHEMATICA software and LT-SPICE software in designing a WPT system application. It brings to a conclusion that the students as well the designer can take the benefit of the proposed method. By giving numerical values to circuit parameters, students acquires the power output and efficiency of WPT system. The average power output as well as the efficiency of the designed WPT which resonance frequency set on the system,leads it to produce high output power and better efficiency.

INTRODUCTION

Energy saving and energy efficiency have become the focus of many researchers recently. They have been studying many ways to improve the technology, including the wireless power transfer (WPT) system technology. Inthachot, et al. [1] developed a U-Learning model using technology to create innovations. After the learning process, they made predictions by using mathematic formulas. These formulas were implemented on the design ofnew devices. The performances ofthe new devices werefurthermore tested, before finally being ready to use. The development of wireless sensor by Loft, et al. [2] could not be separated from such those subsequent stages.

The WPT is a technology to transmit the electric power without using wires. It is working based on the principle of the inductive coupling between two coils. Faraday's law of electromagnetic induction explains how to transfer the electric power from the transmitter to the receiver. One feasible useful application of the WPT is in the battery charging process of electric devices wirelessly. It is more favorable to the. Several studies [3],[4],[5],[6]have investigated and explored the improvement and implementation of the WPT system.

The WPT system design requires the integration of some basic knowledge and skills. In order to be able to do the WPT simulation, a student needs to explore his knowledge on many things. The student should comprehend well

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mathematics, physics and electrical engineering. They must also master well the subjects on as electrical circuit, electromagnetics, computer programming. However, all those subjects are not easy to master. The use of an additional aid tool is sometimes necessary. It has long been known that a simulation tool could help improving the comprehension level of students in many subjects.This paper demonstrates how the use of computer softwarefacilitates the learning of students on the design of a WPT application system. By giving numerical values to circuit parameters, students acquires the power output and efficiency of WPT system.

Yamaguchi, et al. [7] discussed the design and development of a WPT system. The efficiency as well as the power delivered to the receiver to supply the electric load have been carefully considered to ensure that the newly developed device was safe and clean. Higher power capacity and efficiency are always required in the next WPT system development.

PURPOSE

The purpose of this paper is to show possibility to use WPT as a concrete material when students learn scientific computing and mathematics from physics and engineering. We will show a way of mathematical formulation describing phenomena in WPT. We will also have to notice our intension that we would like to transfer much power wirelessly and include the intension into the formulation. We will demonstrate how to use a commercial software of computer mathematics and circuit simulation in our situation. Students can focus on how to use them because they have already learned physics, mathematics and electric circuits that are used when they understand WPT.

EVALUATION METHODS

A WPT system is made of electrical components represented ~~as~~ ina circuit diagram of Fig. 1. It has four main parts, containing the power supply, transmitter, receiver, and load. Power supply gives the electric input power which can be measured by multiplication of its voltage and current. Thetransmitter is a coil which transforms its electric current into Electromagnetic (EM) Field. The EM field spreads along and cuts the receiver coil, so that the receiver coil transforms the EM back into the electric current. This current energizes the connected load.

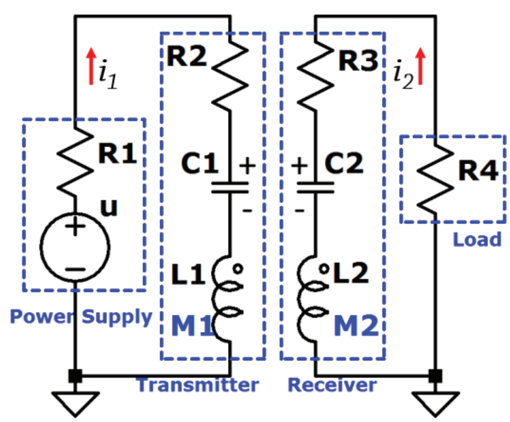

FIGURE 1. The WPT Circuit Diagram

Figure 1 shows that there are two closed loops. According to the Kirchoff Current Law (KCL) and the Kirchoff Voltage Law (KVL), each an internal resistance R_1, a parasitic resistance R_2, a parasitic capacitance C_1, self-inductance L_1, and mutual inductance M_1. In the loop 2, there are the mutual inductance M_2, self-inductance L_2, parasitic capacitance C_2, parasitic resistance R_3, and load R_4.Because of inductors and capacitors, differential equations appear in both loops. By applying KVL and KCL to both loops, the equations are:

$$u = (R_1 + R_2)i_1 + v_1 + L_1 \frac{di_1}{dt} + M_1 \frac{di_2}{dt} \tag{1}$$

$$0 = (R_3 + R_4)i_2 + v_2 + M_2 \frac{di_1}{dt} + L_2 \frac{di_2}{dt} \tag{2}$$

Where v_1 and v_2 are:

$$v_1 = \frac{1}{C_1}\int i_1 dt; \quad v_2 = \frac{1}{C_2}\int i_2 dt \tag{3}$$

The above equations contain differential equations and should be represented with a single first differential matrix equation, in a form of State Space Equation. In control theory, state space equation is applied to solve that kind of problem. The state space equation of equation 1 to 3, is:

$$\dot{x} = Ax + Bu \tag{4}$$

Where

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

$$\dot{x} = \frac{dx}{dt}; \qquad x = \begin{bmatrix} v_1 & v_2 & i_1 & i_2 \end{bmatrix}^T; \qquad \Delta = L_1L_2 - M_1M_2$$

Let $u = \sin(\omega t)$ and $T = 2\pi/\omega$. The solution of Eq. (4) which provides the steady state equations is:

$$x_s(t) = -\big(\omega I cos(\omega t) + A sin(\omega t)\big)(\omega^2 I + A^2)^{-1}B \tag{5}$$

Where I is four by four identity matrix. The average power is the integral of the power over one period. From the steady state matrix X_S, Input and output power can be calculated. Then, efficiency which is the ratio between output and input power can be obtained. The input power P_1, output power P_4, and the efficiency η are:

$$P_1 = \frac{1}{T}\int_0^T i_{s1}(t)\big(u(t) - R_1 i_{s1}(t)\big)dt \tag{6}$$

$$P_4 = \frac{1}{T}\int_0^T R_4 {i_{s2}}^2(t)dt \tag{7}$$

$$\eta = \frac{P_4}{P_1} \tag{8}$$

Some equations are long enough to be done by a person. It is better to do mathematics calculation and circuit simulation by a computer. To deal with long calculation, a software called Wolfram MATHEMATICA is used. This software can compute long equations faster whether in numeric or in symbolic. This software can also solve differential equation and plot the result. This software is very useful for engineering field.After all the calculation is finished, the designed WPT is being simulated by a software which evaluates thecircuit. This software is called LT-SPICE from Linear Technology. It can simulate the customized circuit by showing the waveforms and measuring that. Many electrical components can be used on it.

RESULTS AND DISCUSSION

TABLE 1. Numerical value of the components in the circuit

Component	Value	Component	Value
R_1	50 Ω	L_1=L_2	10 mH
R_2	0.1 Ω	M_1=M_2	1 mH
R_3	0.1 Ω	C_1	1 μF
R_4	50 Ω	C_2	1 μF

To get clearer picture about the output power and the efficiency of the WPT, the numerical examples are given in the table 1. These values are computed by MATHEMATICA by applying Eq. 5-9. They are also simulated by LT-SPICE. Then, output power P_4 and efficiency η are plotted in the angular frequency ω by Excel. Fig 2 and Fig 3 are the calculation results of MATHEMATICA and LT-SPICE.

From the Fig 2, it is known that The highest output power P_4 and efficiency η are in the same angular frequency $\omega=10^4$ rad/s. This frequency is the resonance frequency. It leads WPT to produce high power and efficiency. There are some difference between MATHEMATICA and LT-SPICE curves. In the Fig 2, the highest P_4 and η are 0.37 mW and 95.04%, whilein the Fig 3, the highest P_4 and η are 0.35 mW and 92.48%.

Too much or too less angular frequency are not recommended because the P_4 and η are decreasing. The efficiency curve b) are more decreasing than a). So, the resonance frequency isvery important for the WPT performance.

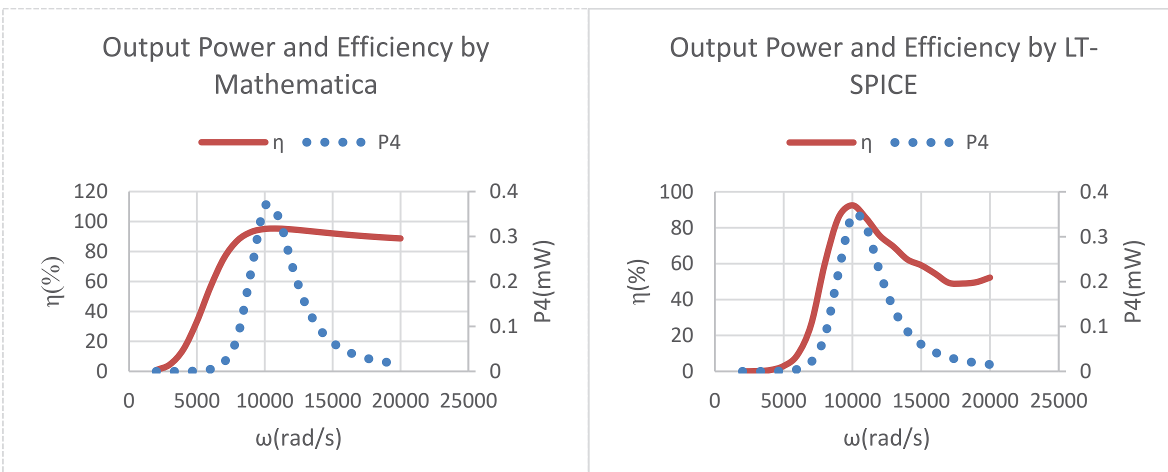

FIGURE 2. The calculation results obtained using a) MATHEMATICA and b) LT-SPICE

CONCLUSION

The A WPT system can be represented using a simple circuit diagram. Based on this diagram, the corresponding mathematical equations can be derived. Solving the equations can be done by using the state-space equation. By using MATHEMATICA and LT-SPICE, the estimation of the WPT's output power and efficiency can be carried out more easily and faster. It is also demonstrated how the aid tools can help indicating the most appropriate frequency to apply on the WPT system to get the best performance. The WPT system should be set at resonance frequency, otherwise the power and efficiency are decreasing.

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