제37권 제1호 Volume 37, Number 1

2014년도 마이크로파 및 전파전파 합동학술대회 논문집

일 시_ 2014년 5월 24일

장 소_ 한밭대학교

주 최_ 한국통신학회 마이크로파 및 전파 연구회
전파 엔지니어링랩

후 원_ (주) 창성, 애드모텍, 에이스테크놀로지,
담스테크, HCT, 맨앤텔

협 찬_ 알트소프트, 이너트론, 에이스웨이브텍

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Analysis of WPT System using Transient Circuit Theory

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Ⅰ. Introduction

The coupled-mode theory (CMT) is one of the models used to characterize a WPT system in steady-state by physicists at MIT [1]. However, it was shown that CMT does not give an accurate transient solution to the WPT system in low Q cases [2]. In this paper, we show transient circuit analysis can be used to define an analytic criterion of magnetic resonance coupling and inductive coupling.

Ⅱ. Transient circuit analysis

Consider KVL in the equivalent short-circuit of the two identical coupled resonators [2].

$$\frac{1}{C}\int_{0}^{t} I_1(t)dt + (R_1 + R_s)I_1(t) + L_1\frac{dI_1(t)}{dt} + M\frac{dI_2(t)}{dt} = 0$$
$$\frac{1}{C}\int_{0}^{t} I_2(t)dt + (R_2 + R_L)I_2(t) + L_2\frac{dI_2(t)}{dt} + M\frac{dI_1(t)}{dt} = 0 \quad (1)$$

characteristic equation in s-domain can be obtained using Laplace transform.

$$\left(s^2 + \left(\frac{\omega}{Q} + \frac{\omega}{Q_{ext}}\right)s + \omega^2\right)^2 = k_{12}^2 s^4 \quad (2)$$

the current of each resonator can be obtained using basis of Eq. (2) where Q_{ext} is the external Q of the resonator.

$$i_1(t) = e^{-\frac{\left(\frac{1}{Q}+\frac{1}{Q_{ext}}\right)\omega_0}{2(1-k_{12})}t}\left(\frac{I_0}{2}\cos\left(\frac{\omega_0\sqrt{4(1-k_{12})-\left(\frac{1}{Q}+\frac{1}{Q_{ext}}\right)^2}}{2(1-k_{12})}t\right) - \frac{I_0}{4Q}\sin\left(\frac{\omega_0\sqrt{4(1-k_{12})-\left(\frac{1}{Q}+\frac{1}{Q_{ext}}\right)^2}}{2(1-k_{12})}t\right)\right)$$
$$+ e^{-\frac{\left(\frac{1}{Q}+\frac{1}{Q_{ext}}\right)\omega_0}{2(1+k_{12})}t}\left(\frac{I_0}{2}\cos\left(\frac{\omega_0\sqrt{4(1+k_{12})-\left(\frac{1}{Q}+\frac{1}{Q_{ext}}\right)^2}}{2(1+k_{12})}t\right) - \frac{I_0}{4Q}\sin\left(\frac{\omega_0\sqrt{4(1+k_{12})-\left(\frac{1}{Q}+\frac{1}{Q_{ext}}\right)^2}}{2(1+k_{12})}t\right)\right) \quad (3)$$

the total energy in the resonator is the sum of electric in inductor and magnetic energy in capacitor.

$$E_1(t) = \frac{1}{2}L|i_1(t)|^2 + \frac{1}{2C}\left|\int_{0}^{t} I_1(t)dt\right|^2 \quad (4)$$

In this paper, a criterion is introduced by how much of the energy is received back after the first resonator once transmits energy. If the received energy of the first resonator after one period (1T) is greater than e^{-3} times of the initially transmitted energy (i.e., $|E_1(1T)|^2 > |E_1(0)|^2 \cdot e^{-3}$), the WPTS system is considered to be magnetic resonance coupling. The reason of e^{-3} factor is based on 5% energy rate between two resonators. However, If the received energy after one period is less than e^{-3} times of the first value, which means that the first resonator does not receive back any energy after one period has passed, the WPTS system is under the condition of inductive coupling. The energy in the first and second resonator as a function of time at each sources are shown in Fig. 1,2.

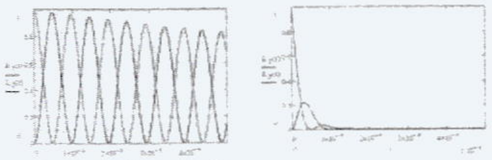

Figure 1,2. Normalized energy in each resonator as function of time when R_{ext}=0, 50 ohm.

As Fig. 1(a), (b), the results of the energy relation satisfy the condition proposed in previous section.

Ⅲ. Conclusion

An analytic criterion of magnetic resonance coupling and inductive coupling in WPTS under transient circuit analysis using power sources is proposed. Using the proposed definition, these two terms can be clarified analytically.

Acknowledgement

This research was funded by the MSIP(Ministry of Science, ICT & Future Planning), Korea in the ICT R&D Program 2014.

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