Finite Element Analysis of Contactless Power Transmission System Using Meander Antennas

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1 Introduction

In recent years, contactless power transmission techniques have been used for electric vehicles and battery charger of phone and so on. The contactless power transmission techniques are classified into four types: electromagnetic induction, electromagnetic resonance, microwave transmission and laser transmission. In the electromagnetic induction type, whose operating frequency is some kHz, coils must be located at a very short distance, which is, for example, about 10cm when using coils of 1m radius. One of the drawbacks of this type is that the energy transmission efficiency rapidly reduces when the position difference in the coil centers increases. The microwave transmission and laser transmission types can have longer transmission distance up to several kilometres as electromagnetic waves are used. The operating frequency of this type ranges from MHz and GHz. The drawbacks of this type would be that the efficiency is not high, and effects on human health have not been clarified.

On the other hand, the electromagnetic resonance type has intermediate communication distance, some meters, and the efficiency can be more than 90% when the distance of transmission is less than 1m. The electromagnetic resonance type is based on either electric coupling or magnetic coupling. In the electromagnetic coupling, the transmission power becomes the maximum at the resonant frequency of the system composed of transmission and receiver antennas. Because the operating frequency of the electromagnetic resonance type is higher than that of the induction type, the former has higher Q values and also lower power losses.

In recent studies, the contactless power transmission based on the electromagnetic resonance has been analysed using equivalent circuits which approximate the characteristics of the transmission and receiver antennas. Moreover, this system has been analyzed using the moment method [1].

In this paper, the electric coupling analysis using FEM is presented. The present method would be useful for, e.g., the analysis of bio-magnetic effects of the contactless power transmission, because complicated media can be modeled with ease. In order to realize the electric coupling, transmission and receiver antenna generically are used meander line antenna (MLA).

2 Electric coupling analysis using FEM

2.1 Meander line antenna

Let us consider the contactless power transmission system using the meander line antennas (MLA) shown by Fig. 1, which has been discussed in [2]. The transmission antenna is excited by a voltage source v, which is connected to the antenna through the transmission line with characteristic impedance Z_0, as shown in Fig.2. The receiver antenna is also connected to Z_0. The structure parameters of MLA are antenna length l (mm), antenna width w (mm) and distance of conductor wire d (mm). To know the resonant frequency, the input impedance Z of the transmission antenna is calculated by FEM. The input impedance Z is computed from

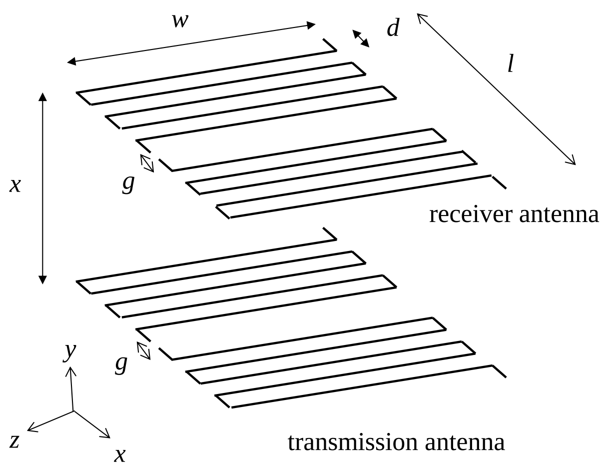

Fig.1 Geometry of contactless power transfer

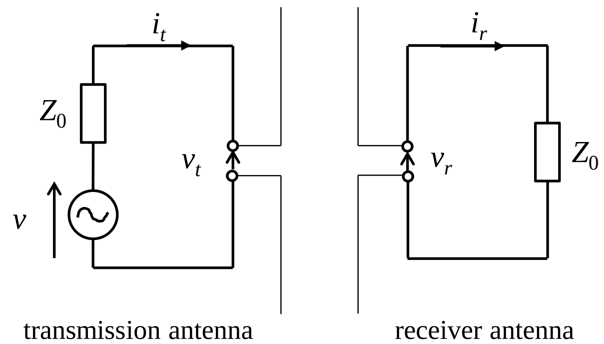

Fig. 2 Circuit of transmission and receiver antenna

$$Z = \frac{V_0}{I_0} \quad (1)$$

where V_0 and I_0 are induced voltage and current at the feeding point of MLA. At resonance, the imaginary part of input impedance is equal to zero.

2.2 Finite element analysis

The circuit equation for transmission antenna is given by

$$v_t + Z_0 i_t = v \quad (2)$$

where v_t and i_t are induced voltage and current at the feeding point of transmission antenna. Also, the circuit equation for receiver antenna part is given by

$$v_r = Z_0 i_r \tag{3}$$

where v_r and i_r are induced voltage and current at the feeding point of receiver antenna. In order to perform the electric coupling analysis using FEM, we must simultaneously solve the circuit equations (2)-(3) and the Maxwell equations

$$\nabla \times (\nu \nabla \times \boldsymbol{A}) - \omega^2 \varepsilon \boldsymbol{A} + \mathrm{j}\omega\varepsilon\nabla\varphi = \boldsymbol{J} \tag{4}$$

$$\nabla \cdot \omega^2 \varepsilon \boldsymbol{A} = 0 \tag{5}$$

where $\boldsymbol{A}$ is vector potential, φ scalar potential and $\boldsymbol{J}$ current density. To couple the Maxwell equations (4), (5) to the circuit equation (2), (3), the current density $\boldsymbol{J}$ in (4) is expressed in terms of the induced current i_t and i_r. In the FE analysis, the perfect matched layer is used on the open boundaries. The discretized equations derived from (2)-(5) are solved using the conjugate gradient method preconditioned by the incomplete Cholesky factorization (ICCG).

3 Numerical Results

3.1 Input impedance

In the analysis, the structure parameters of MLA are set as follows: l=840mm, w=840mm, g=20mm and d=40mm and the driving frequency ranges from15MHz to 35MHz. The resultant input impedance of MLA is shown in Fig. 3, from which we can see that the resonant frequency is about 26MHz.

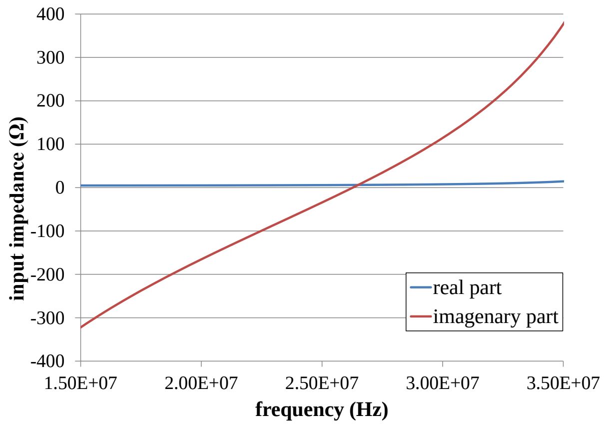

Fig.3 Input impedance characteristic of MLA

3.2 Power transmission rate

We analyze the power transmission rate between the MLAs shown in Figs.1 and 2, which is defined by

$$\eta = \left| \frac{v_r^* i_r}{v_t^* i_t} \right|^2 \times 100(\%). \tag{6}$$

The distance x between transmission and receiver antennas is set to 400 and 500 mm. The results are shown in Fig.4, from which we can see that the peaks in η are at 26MHz and their maximum values are about 60 and 40 %, respectively. The profiles in Fig.4 are slightly unsymmetric. This would come from the discretization errors. It is observed that this non-symmetry becomes more remarkable when x decreases. Hence the number of finite elements must be increased to obtain sufficiently accurate results especially when x is small. The electric field distribution around MLA is shown in Fig. 5. We can see in Fig.5 that there are concentrations of the electric field near the gaps of MLA.

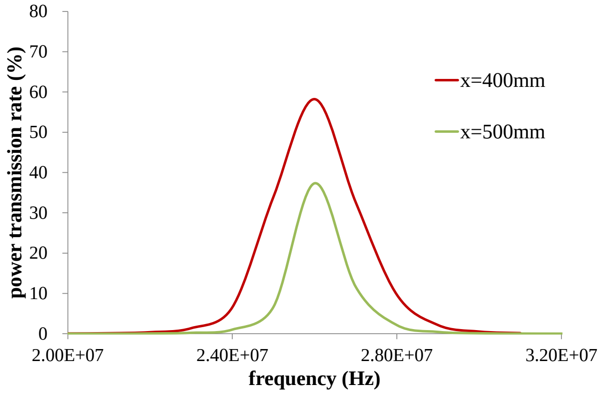

Fig. 4 Power transmission rate

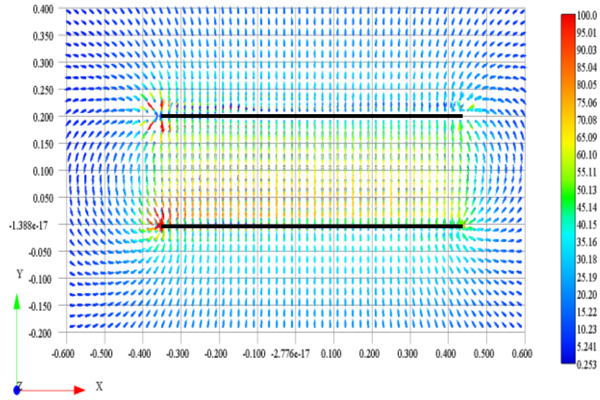

Fig.5 Electric field around MLA

4 Conclusion

In this paper, we have presented FE analysis of a contactless power transmission system using MLAs. The power transmission rate η can be about 60% when x/l is about 0.5. The dependence of η on the number of fold in MLA will be discussed, and optimization of the shape of MLA will be presented in the final paper.

References

[1] T. Imura, H. Okabe, T. Uchida, and Y. Hori, "Study of Magnetic and Electric Coupling for Contactless Power Transfer Using Equivalent Circuits," (in Japanese) *IEEJ Trans. IA*, vol. 130, no.1 pp,84-92, 2010.

[2] T. Imura, H. Okabe, T. Uchida, and Y. Hori, "Wireless Power Transfer during Displacement Using Electromagnetic Coupling in Resonance," (in Japanese) *IEEJ Trans. IA*, vol. 130, no.1 pp,76-83, 2010.