Magnetic Field-forming for Wireless Power Transfer

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Abstract

Magnetic field-forming technique for wireless power transfer systems, realized as a system of two coils (Helmholtz coils), is proposed and analyzed. Analytical result shows that magnetic field-forming, though dependent on the distance between the transmitter and receiver, increases power transfer efficiency significantly.

Keywords : Magnetic field-forming, wireless power transfer, Helmholtz coil.

1. Introduction

Beamforming technique provides a significant improvement in traditional communication systems over conventional single antenna transmitter/receiver where a signal processing technique of using array of sensors to provide spatial filtering [1] is utilized. Spatial filtering enables directional signal transmission and/or reception in the presence of noise and interfering signals [2]. Spatial filtering is achieved by processing and combining the signals induced on the different elements of an array [3]. The improvement of using beamforming over a conventional omnidirectional signal transmission/reception is measured by directivity.

In the context of magnetic field-forming, spatial filtering entails the creation of a region in which the magnetic field is strong while zeroing or minimizing the magnetic field on other regions. An example of a magnetic field-forming is a Halbach array. In Halbach array, permanent magnets are specially arranged to create a strong field on one side of the array while cancelling the field near to zero on the other side.

Magnetic field-forming enables wireless power transfer (WPT) system with reduced or no interference. For WPT system, magnetic field-forming is much more significant in the transmitting mode than in receiving mode. During wireless power transfer, the generated strong magnetic field can interfere with the proper functioning of nearby electrical and electronic devices. It can also cause temperature increase in these devices and nearby metallic objects due to power dissipation of generated eddy currents. Magnetic field-forming at the transmitter side can alleviate these problems by forming a directive beam only in the region in which the receiver device is likely to be found and null in other regions. Although magnetic field-forming can be performed at the receiver side, its application is limited. An example can be two different WPT systems operating at different resonant frequency.

In the following sections, we present the proposed magnetic field-forming using Helmholtz coils and analyze the directivity of magnetic field-forming systems.

2. Magnetic field-forming Using HELMHOLTZ Coils

In this section, we present Helmholtz coils as a magnetic field-forming system in its basic sense. Due to its special physical arrangement (as is the case with Halbach array), a Helmholtz coil creates a region in which the magnetic field is uniform. The spatial filtering in the case of Helmholtz coils is the creation of this special relatively strong and uniform magnetic field region. There is, however, no special processing performed to cancel out the magnetic field in the other regions.

The schematic diagram of a Helmholtz coil WPT system is shown in Fig. 1. A coil having a radius r_r and N_r number of turns is used as a receiver. The transmitter consists of two coils with each coil having radius R and N_t turns which are separated by a distance $d=R$. I_h is the current flowing in the transmitter coils

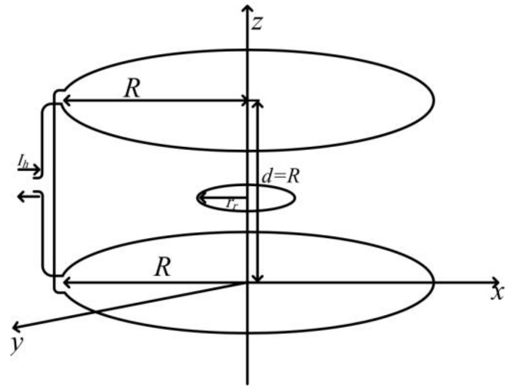

Figure 1. Schematic diagram of a Helmholtz coil WPT system.

3. Directivity

3.1 **Definition**

In beamforming, the array directivity, D is formulated as

$$D = \max\left(\frac{\text{Radiated power density}(\theta,\phi)}{\text{Total radiated power}/4\pi}\right). \tag{1}$$

WPT systems use the non-radiative near field region and hence it is meaningless to talk about radiated power. Instead, the directivity for magnetic field-forming can be defined as the amount of power that can be transferred using magnetic field-forming compared with the amount of power that can be transferred using a conventional circular coil that forms no beams (isotropic). The directivity can hence be easily determined by calculating the ratio of the efficiency of a magnetic field-forming WPT system and a conventional (single transmitter coil) WPT system. Thus, the directivity, D

$$D\big|_{dB} = \left(\frac{\eta_{\rm b}}{\eta}\right), \tag{2}$$

where $\eta_{\rm b}$ and η represent the efficiency of a magnetic field-forming and a conventional WPT system, respectively.

3.2 **Directivity of Helmholtz coils**

Conventional WPT system has the same geometry and settings as in the Helmholtz coils (Fig. 1) but with only one transmitter coil instead of two. The current flowing in the conventional transmitter coil is designated by I.

In order to calculate the efficiency of both systems, we first need to calculate the mutual inductance between the transmitter and receiver coils. Since the magnetic field created by Helmholtz coils is uniform, it is enough to consider only the axial magnetic field to determine directivity. The mutual inductance is thus calculated by determining the magnetic field along the z-axis and reasonably assuming, given the relative size of the transmitter and receiver, that the magnetic field remains constant throughout the surface of the receiver.

The axial magnetic field for the conventional WPT system is given by

$$B(z) = \frac{\mu_0 N_{\rm t} I R^2}{2}\left(R^2 + z^2\right)^{-\frac{3}{2}} \tag{3}$$

The magnetic flux, $\Phi_{\rm m} = B(z)A$ where A is the area of the receiver coil. The mutual inductance can be calculated from the magnetic flux as

$$\begin{aligned} M &= \frac{\Phi_{\rm m}}{I} \\ &= \frac{\mu_0 N_{\rm t} I R^2}{2I}\left(R^2 + z^2\right)^{-\frac{3}{2}} \pi N_{\rm r} r_{\rm r}^2 \\ &= \frac{\mu_0 \pi N_{\rm t} N_{\rm r} R^2 r_{\rm r}^2}{2}\left(R^2 + z^2\right)^{-\frac{3}{2}} \end{aligned} \tag{4}$$

The axial magnetic field of the Helmholtz coil is given as

$$B_{\mathrm{h}}(z)=\frac{\mu_0 N_{\mathrm{t}} I_{\mathrm{h}} R^2}{2}\left[\left(R^2+z^2\right)^{-\frac{3}{2}}+\left(R^2+(z-R)^2\right)^{-\frac{3}{2}}\right] \tag{5}$$

The mutual inductance for the Helmholtz Coil based WPT system can be calculated from the magnetic flux of the Helmholtz coil $\Phi_{\mathrm{m\text{-}h}}=B_{\mathrm{h}}(z)A$ as

$$\begin{aligned} M_{\mathrm{h}} &= \frac{\Phi_{\mathrm{m\text{-}h}}}{I_{\mathrm{h}}} \\ &= \frac{\mu_0 N_{\mathrm{t}} I_{\mathrm{h}} R^2}{2I_{\mathrm{h}}}\left[\left(R^2+z^2\right)^{-\frac{3}{2}}+\left(R^2+(z-R)^2\right)^{-\frac{3}{2}}\right]\pi N_{\mathrm{r}} r_{\mathrm{r}}^2 \\ &= \frac{\mu_0 \pi N_{\mathrm{t}} N_{\mathrm{r}} R^2 r_{\mathrm{r}}^2}{2}\left[\left(R^2+z^2\right)^{-\frac{3}{2}}+\left(R^2+(z-R)^2\right)^{-\frac{3}{2}}\right] \end{aligned} \tag{6}$$

The ratio of the mutual inductance of the Helmholtz coil based WPT system and conventional WPT system can be calculated as

$$\begin{aligned} \frac{M_{\mathrm{h}}}{M} &= \frac{\frac{\mu_0 \pi N_{\mathrm{t}} N_{\mathrm{r}} R^2 r_{\mathrm{r}}^2}{2}\left[\left(R^2+z^2\right)^{-\frac{3}{2}}+\left(R^2+(z-R)^2\right)^{-\frac{3}{2}}\right]}{\frac{\mu_0 \pi N_{\mathrm{t}} N_{\mathrm{r}} R^2 r_{\mathrm{r}}^2}{2}\left(R^2+z^2\right)^{-\frac{3}{2}}} \\ &= 1+\left(\frac{R^2+(z-R)^2}{R^2+z^2}\right)^{-\frac{3}{2}} \end{aligned} \tag{7}$$

The efficiency of a WPT system is determined by the figure-of-merit coupling-to-loss ratio, κ/Γ. For WPT systems, the higher the coupling-to-loss ratio, the higher is the efficiency [4]. The coupling-to-loss ratio of the Helmholtz coil is given by

$$\frac{k_{\mathrm{h}}}{\Gamma_{\mathrm{h}}}=\frac{\omega M_{\mathrm{h}}}{\sqrt{R_{\mathrm{t\text{-}h}} R_{\mathrm{r\text{-}h}}}} \tag{8}$$

where ω is resonance frequency of the coils, and $R_{\mathrm{t\text{-}h}}$ and $R_{\mathrm{r\text{-}h}}$ are the resistance (ohmic and radiation) of the transmitter and receiver coil, respectively. $R_{\mathrm{t\text{-}h}}=2R_{\mathrm{t}}$ whereas $R_{\mathrm{r\text{-}h}}=R_{\mathrm{r}}$. R_{t} and R_{r} are the resistance (ohmic and radiation) of the conventional transmitter and receiver coil respectively. Thus, using the above and (7)

$$\begin{aligned} \frac{k_{\mathrm{h}}}{\Gamma_{\mathrm{h}}} &= \omega M\left(1+\left(\frac{R^2+(z-R)^2}{R^2+z^2}\right)^{-\frac{3}{2}}\right)\Big/\sqrt{2R_{\mathrm{t}}R_{\mathrm{r}}} \\ &= \frac{\kappa}{\Gamma}\frac{1}{\sqrt{2}}\left(1+\left(\frac{R^2+(z-R)^2}{R^2+z^2}\right)^{-\frac{3}{2}}\right) \end{aligned} \tag{9}$$

For a given value of κ/Γ, $\kappa_{\mathrm{h}}/\Gamma_{\mathrm{h}} < \kappa/\Gamma$ only for distances $z \ll R$. This case is negligible compared with the working range and hence $\kappa_{\mathrm{h}}/\Gamma_{\mathrm{h}} > \kappa/\Gamma$ for almost all distances. The improvement is more pronounced as the receiver moves further away from the transmitter. From [4], the efficiency of a WPT system given κ/Γ is

$$\eta=\left(1+\frac{\Gamma_{\mathrm{r}}}{\Gamma_{\mathrm{work}}}\left[1+\frac{1}{\mathrm{fom}^2}\left(1+\frac{\Gamma_{\mathrm{work}}}{\Gamma_{\mathrm{r}}}\right)^2\right]\right)^{-1} \tag{10}$$

where $\mathrm{fom}=k\big/\sqrt{\Gamma_{\mathrm{t}}\Gamma_{\mathrm{r}}}$ and $\Gamma_{\mathrm{work}}/\Gamma_{\mathrm{d}}=\sqrt{\mathrm{fom}^2+1}$ .Thus, for a given WPT system design, the directivity can be calculated by substituting (9) in (2). The directivity depends on the design parameters of the WPT system and on the distance between the transmitter and receiver.

As an example, a WPT system using a 20 cm radius Helmholtz coil and a receiver having 3.5 cm with its conventional counterpart is considered. For a κ/Γ =1.95 at a distance of 20 cm, the change in efficiency and the directivity of the Helmholtz coil field-former as a function of distance is shown in Fig. 2.

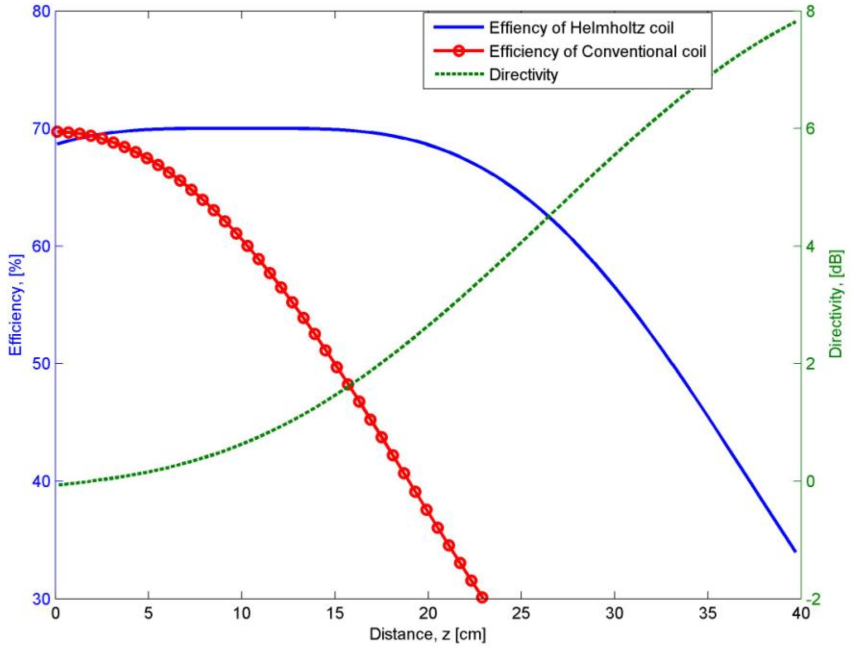

Fig. 2. Efficiency of a Helmholtz and conventional WPT system.

The efficiency of Helmholtz coils is constant within the uniform magnetic field region. The directivity starts negative and then increases with increasing distance between the transmitter and receiver.

4. Conclusion

In this letter, we have shown that it is possible using magnetic field-forming to design more efficient WPT system. It is also possible to design WPT systems with strong magnetic field in the required operating region while conforming to the electromagnetic compatibility (EMC) directive in other regions.

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Acknowledgments

This work was supported by the IT R&D program of MKE/KEIT. [10035255 , Development of a Dual-Band Multi-Mode Interactive Wireless Charging System for Portable Device].