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Wireless Charging System with Magnetic Field Shaping for Electric Vehicles

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Abstract

A wireless charging system with magnetic field shaping is proposed. The magnetic field of wireless power transmission is shaped by an innovated structure of resonator, which is named as Shaped Magnetic Field Resonator (SMFR). The magnetic field is shaped within the zone of active transmission and the magnetic flux density is greatly reduced outside the zone of active transmission. Therefore, the Electromagnetic Interference (EMI) to adjacent electric devices is drastically diminished. The high temperature effect of shielding material induced by eddy current on the shielding material is also improved. Besides, the transfer efficiency can be improved. The numerical analysis (Finite Element Analysis) of the proposed resonators by electromagnetic simulation software is carried out for analyzing the shaped magnetic field. Finally, the proposed system is implemented to validate the feasibility.

Keywords: Wireless Charging System, Magnetic Field Shaping, Magnetic Resonant Coupling

1 Introduction

Environmental problems are one of the biggest issues around the world in recent years. A variety of green technologies are drastically developed to improve the air quality and reduce fossil fuel consumption. As the usage of electric vehicles are expected to significantly diminish air pollution and fossil fuel consumption. Numerous studies on electric vehicles have been executed over a long time and numerous hybrid vehicles are commercially sold by several vehicles manufacturers presently.

However, there are some pending problems on electric vehicles: limitations of battery size and power, battery weight, battery life and battery recharge time, etc [1]. Such pending problems result in electric vehicles not easy to be accepted by common people. Perhaps wireless charging is one of solutions for speeding up the popularity of electric vehicles.

As researches for wireless power transfer technology around the world, there are four technologies to be categorized, i.e., magnetic resonant coupling, inductive coupling, microwave power transfer and laser power transfer [2]. The inductive coupling technology is well applied to transfer power in quite short displacement with high efficiency. However, when displacement becomes larger, efficiency is diminished a lot and not to guarantee sufficient effect of power transfer. General speaking, resonant coupling can transfer energy in 5m and its efficiency can reach 40%, which will be a new technology with wider using range [3].

Wireless power transfer of magnetic resonant coupling is realized with two coupled resonators

[4], shown in Fig. 1. The magnetic field uniformly distributes over the surroundings of the two coupled resonators. However, on the real applications, the magnetic field distribution over the zones of inactive transmission is undesired. It will cause Electromagnetic Interference (EMI) to adjacent electric devices. Usually, a shielding material, e.g., ferrite plate core, is employed to concentrate the magnetic flux, shown in Fig. 2. It not only suppresses the influence of EMI but also can improve the transfer efficiency ([4] and [5]). Besides, a metal plane is used at the receiving side to isolate adjacent electric devices suffered from EMI ([5] and [6]). However, because of high frequency time-varying magnetic field, an eddy current is induced on the shielding material and the metal plane. Therefore, the accompanied temperature rise effect is unavoidable.

Owing to the above-mentioned drawbacks, a Shaped Magnetic Field Resonator (SMFR) of wireless charging system is proposed to account for the pending problems by shaping the magnetic field.

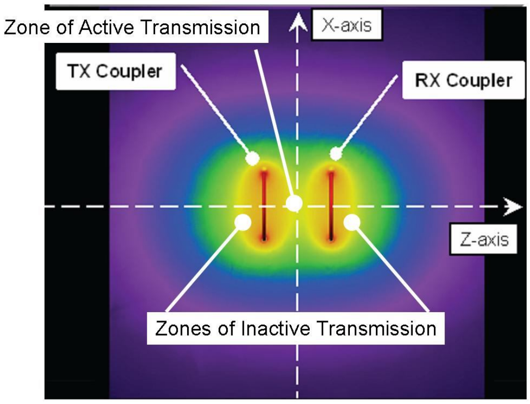

Figure 1: Magnetic Field Distribution of Conventional Wireless Power Transfer

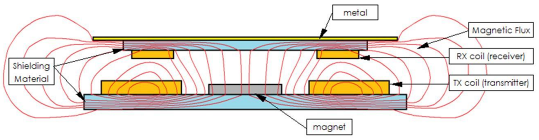

Figure 2: Schematic Diagram of Mobile Phone Wireless Charging [7]

2 Wireless Charging System with Resonant Coupling

The equivalent circuit of Wireless Charging System (WCS) with magnetic resonant coupling technology is shown in Fig. 3. It mainly consists of two LC resonant circuits, a high frequency transmitting power source and a receiving load. V_i is high frequency power source. R_1 and R_2 are parasitical resistances of the transmitting and receiving resonators respectively. C_1 and C_2 are series resonant capacitors. R_L is load. L_1 and L_2 are the inductances of resonators. M is mutual inductance and D is transmitting displacement.

For the WCS with magnetic resonant coupling, the resonant frequencies of the transmitting resonator and the receiving resonator are deliberately designed as identical. Once the frequency of the power source is equal to the resonant frequency of the resonators, the reactance is equal to zero in theory and the characteristic impedance of system is lowest. Therefore, the currents of the loops will be at the largest values and most energy can be delivered to receiving loop. On the other hand, the high transmitting efficiency can be obtained.

From Fig. 3, the magnetic resonant coupling model of WCS can be described as follows:

$$\begin{bmatrix} V_i \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + j(\omega L_1 - \frac{1}{\omega C_1}) & -j\omega M \\ -j\omega M & R_2 + R_L + j(\omega L_2 - \frac{1}{\omega C_2}) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{1}$$

where, ω is the operating frequency of the WCS. By Eq. (1), the currents can be obtained as follows:

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \frac{1}{Z_1 Z_2 (\omega M)^2} \begin{bmatrix} Z_2 & -j\omega M \\ -j\omega M & Z_1 \end{bmatrix} \begin{bmatrix} V_i \\ 0 \end{bmatrix} \tag{2}$$

where, Z_1 and Z_2 are the impedances of the transmitting loop and the receiving loop respectively and can be expressed as follows:

$$Z_1 = R_1 + j(\omega L_1 - \frac{1}{\omega C_1}) \tag{3a}$$

$$Z_2 = R_2 + R_L + j(\omega L_2 - \frac{1}{\omega C_2}) \tag{3b}$$

Then, the input power (P_{in}) of transmitting circuit and the output power (P_{out}) on the load can be expressed as follows:

$$P_{in} = \frac{V_i^2 Z_2}{Z_1 Z_2 + (\omega M)^2} \tag{4a}$$

$$P_{out} = \frac{V_i^2(\omega M)^2 R_L}{\left[Z_1 Z_2 + (\omega M)^2\right]^2} \tag{4b}$$

Therefore, the transmitting efficiency can be obtained as follows:

$$\eta = \frac{(\omega M)^2 R_L}{Z_2\left[Z_1 Z_2 + (\omega M)^2\right]} \times 100\% \tag{5}$$

Once the system in under resonance, $Z_1 = R_1$ and $Z_2 = R_2 + R_L$, the transmitting efficiency is functions of parasitical resistances, load, resonant frequency and mutual inductance.

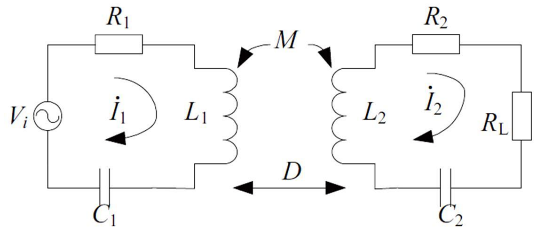

Figure 3: Equivalent Circuit of WCS

3 Proposed Shaped Magnetic Field Resonator (SMFR)

The proposed Shaped Magnetic Field Resonator (SMFR) is shown in Fig. 4. The SMFR consists of a main coil and four auxiliary coils. The main coil is located opposite to the direction of power transmission. The four auxiliary coils are arranged at the four edges of the main coil and the included angle between the faces of the main coil and that of the auxiliary coils is ninety degree. The wire of the coils can be copper wire or Litz wire. Especially, because Litz wire is designed to reduce the skin effect and proximity effect losses in conductors, it is more suitable for high frequency applications. The main coil and the four auxiliary coils are to be series connection. In other words, the SMFR has only one feeding point. The total area of the four auxiliary coils is equal to that of the main coil. The structure of the main and the auxiliary coils are not just limited to be the loop-type, but also the spiral- or the helix-type, etc. Besides, the coils can be open-end or short-end type [8].

For the conventional antennas, the magnetic flux goes outside one face of the antenna and returns to the other face, while it is energized. Therefore, the magnetic field is distributed around the antenna, as illustrated in Fig. 1. Regarding the SMFR, the mail coil and the four auxiliary coils are deliberate series connection so that the induced polarity of that coils pointing inside the SMFR is identical. For example, the north pole of all coils is within the inside face of SMFR, i.e., the magnetic flux goes out from the internal faces and enters the external faces of SMFR. Therefore, the return magnetic flux almost does not go to the back of the mail coil but is guided into the front of the mail coil, so that the magnetic field is shaped within the zone of active transmission and the magnetic flux density is greatly reduced outside the active transmission.

The magnetic field distribution of the SMFR is shown in Fig. 5. It obviously shows that the magnetic field is shaped into the direction of power transmission and the magnetic field distribution is weak on the other side of the SMFR. The magnetic field distribution of Wireless Charing System (WCS) with SMFR is shown in Fig. 6. It evidently shows that magnetic field is strongly distributed between the transmitting antenna and the receiving antenna and is weakly distributed outside the range of between the transmitting and receiving antennas. In the words, the magnetic flux is concentrated on the zone of active transmission but on the zones of the inactive transmission. Hence, the magnetic flux is hardly distributed over shielding material and metal plane such that the eddy currents induced on shielding material and metal plane are quite small. Further, the temperature rise of the shielding material and metal plane caused by eddy current is drastically improved. Besides, the Electromagnetic Interference (EMI) to adjacent electric devices can be greatly diminished. Owing to the magnetic field concentrated on the zone of active transmission, the transfer efficiency can evidently be enhanced.

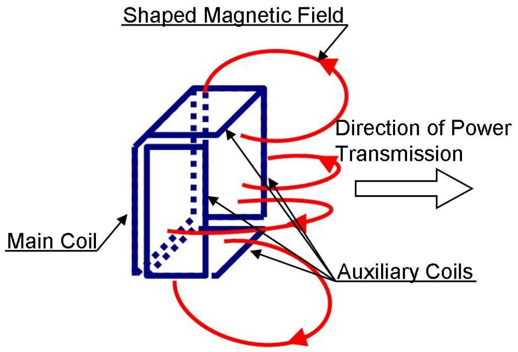

Figure 4: Proposed Shaped Magnetic Field Resonator (SMFR)

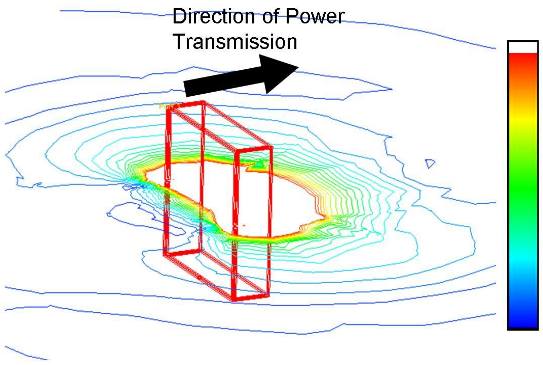

Figure 5: Magnetic Flux Distribution of SMFR

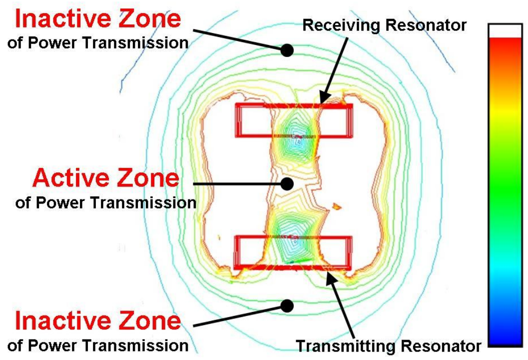

Figure 6: Magnetic Flux Distribution of WCS with SMFR

4 Experiment and Measurement Results

The picture of the SMFR is shown in Fig. 7. The mail coil and the auxiliary coils are helix and short-end type. The mail coil and all auxiliary coils are to be series connection so that only one feeding point is needed, as shown in Fig. 7. A rectangle acrylic is used to position the mail and the auxiliary coils. The parameters of SMFR are listed in Table 1. The coils are made of copper and the diameter of wire is 0.6mm. The resistance of SMFR is 0.277Ω. The inductance and capacitance of SMFR are 2.54μH and 22nF respectively. The resonant frequency of SMFR is 658kHz. Therefore, the operating frequency of the amplifier is deliberately designed identical to the resonant frequency of SMFR, i.e., 658kHz.

The test rig of WCS with SMFR is shown in Fig. 8. The test rig mainly consists of an amplifier, a transmitting loop (with the SMFR) and a receiving loop. For amplifier circuit, two MOS chips are employed to generated sinusoidal output power with 658kHz operating frequency. The transmitting antenna is the SMFR, but the receiving antenna is helix type. The reason is that another test rig is setup (not shown in this paper) for comparison with the proposed WCS with SMFR. Its transmitting and receiving antennas are helix type, which is the conventional structure in present designed. The receiving antennas of that and the proposed test rig are identical such that the baseline is the same for experimental measurements. A fuse lamp is employed as a load in the receiving loop for easy examining the functionality of WCS, as shown in Fig. 8.

The induced voltages on loads of the proposed and the conventional test rigs are listed in Table 2. It is obviously shown that the induced voltages of the proposed system are 46% (average value) greater than that of conventional one with the same transmitting displacements. On the other hand, the transmitting efficiency is enhanced by the proposed WCS with SMFR.

Figure 7: Picture of SMFR

Table1: Parameters of SMFR

Parameters	Values
Inductance	2.54μH
Capacitance	22nF
Resistance	0.277Ω
Diameter of Wire	0.6mm

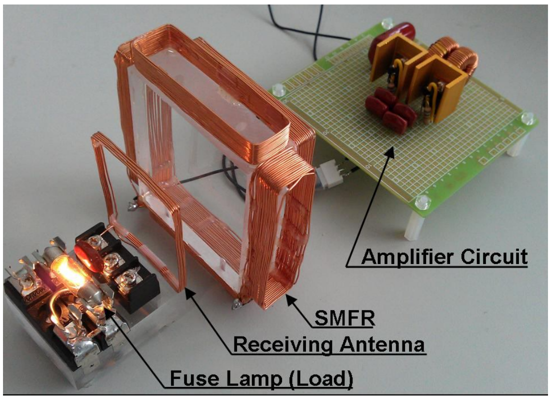

Figure 8: Test Rig of WCS with SMFR

Table2: Induced Voltages on Loads of Proposed and Conventional Test Rigs

Resonator Type D	SMFR	Convent.	Increased Ratio
	Induced Voltage (V)		
1cm	21.98	13.19	40%
2cm	19.74	9.352	53%
3cm	14.22	7.309	48%
4cm	8.539	4.82	43%

5 Conclusions

A wireless charging system with magnetic field shaping is proposed. The magnetic field of wireless power transmission is shaped by an innovated structure of resonator, which is named as Shaped Magnetic Field Resonator (SMFR). The SMFR consists of a mail coil and four auxiliary coils. The auxiliary coils are employed to guide the magnetic flux of the mail coil such that the magnetic field of SMFR is shaped within the zone of active transmission and the magnetic flux density is greatly reduced outside the zone of active transmission. Therefore, the transmitting efficiency can be evidently enhanced. The numerical analysis (Finite Element Analysis) of SMFR is undertaken to examine the magnetic field contribution. Finally, the proposed system is implemented to verify the efficacy. From the experimental results, the transmitting efficiency is drastically improved.

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