전기자동차용 고효율 무선 온보드 충전기의 설계

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Design of the High Efficiency Wireless On–Board Charger for Electric Vehicles

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ABSTRACT

In this paper a high efficiency wireless on-board charger for Electric Vehicle (EV) is proposed and the theoretical analysis based on the two–port network model to come up with suitable design for the battery charge application is presented. The proposed Wireless Power Transfer (WPT) method has adopted four-coil system with air core and its superior performance is proved by comparing it to the conventional two-coil system by the mathematical analysis. In addition, since the proposed WPT converter is able to operate at an almost constant frequency regardless of the load, CC/CV charge of the battery can be simply implemented. A 6.6kW prototype is implemented with 20cm air gap to prove the validity of the proposed method. The experimental results show that the dc to dc conversion efficiency of the proposed system achieves 97.08% at 3.7 kW.

Index Terms – Four-coil Wireless Power Transfer (WPT) system, High efficiency, (WPT), Electric Vehicles (EVs)

1. Introduction

Wireless Power Transfer (WPT) topology has got more attention during the last few years since it is able to transfer the electrical energy with no wire connection and also allows to recharge their devices more safely and conveniently. However, the energy transfer efficiency is declined rapidly if the distance between the transmitter and receiver is extended as a result of weak magnetic coupling. Recently, some studies proposed methods to use high permeability material such as ferrite to enhance its magnetic coupling, however it contributes to the increase in volume, weight and cost which makes it unsuitable for electric vehicle applications [1]. Another approach is to take the advantages of the intermediate coils to improve the coupling factor and three-coil system has been proposed [2]. In this paper four–coil WPT system is introduced to further improve the energy transfer efficiency without using ferrite core. In addition the system is designed to operate almost at a constant frequency during the CC and CV charge mode, respectively, thereby making it easier to implement the CC/CV charge. Detailed analysis based on the two-port network is provided to show the necessary condition for the self-resonant frequency ratio of the resonators to achieve high efficiency.

2. Analysis of the four-coil WPT system

2.1. AC equivalent circuit of the four-coil system

The proposed series-series four resonators WPT topology is shown in Fig.1. Its ac equivalent circuit and simplified two–port network model is shown in Fig.2. and Fig.3. The relationship between the input and output impedance can be expressed as (1).

$$Z_{pri} = Z_{lkp} + Z_{mag}, Z_{se} = Z_{lks} + Z_{mag} \qquad (1)$$

Where, Z_{mag} is the magnetizing impedance between the transmitter and receiver. The real part of Z_{mag} is assumed to be small and can be neglected. Z_{lkp} and Z_{lks} are leakage impedances of the transmitter and receiver of which values are assumed to be same. By applying the Kirchhoff's voltage law to the circuit, the following equations can be derived.

$$U_1 = I_1 Z_{pri} + I_2 + Z_{mag}, I_1 Z_{mag} + I_2\left(Z_{se} + R_{L,eq}\right) = 0 \qquad (2)$$

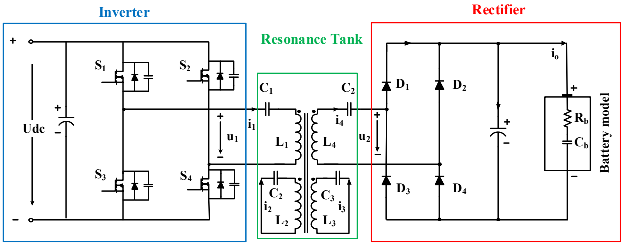


Fig. 1. Proposed four–coil WPT system

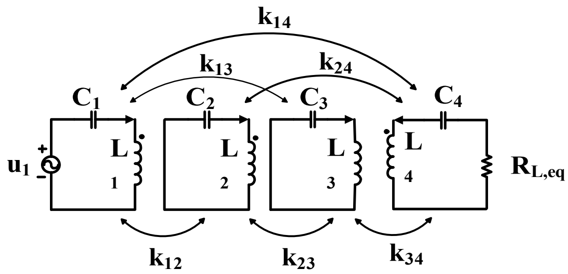


Fig. 2. AC equivalent circuit of the proposed four-coil system

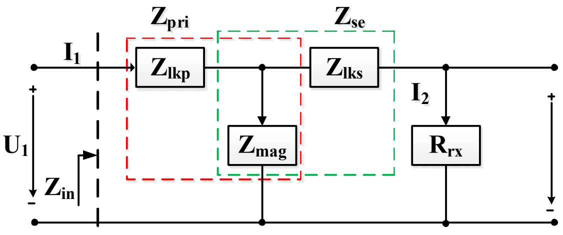


Fig. 3. Two–port impedance network of the series–series WPT system

$$\eta = \frac{\mathrm{Im}^2\left\{Z_{mag}\right\}R_{L,eq}}{\mathrm{Re}\left\{Z_{pri}\right\}\left(\left(\mathrm{Re}\left\{Z_{pri}\right\}+R_{L,eq}\right)^2+\mathrm{Im}^2\left\{Z_{pri}\right\}\right) + \mathrm{Im}^2\left\{Z_{mag}\right\}\left(\mathrm{Re}\left\{Z_{pri}\right\}+R_{L,eq}\right)} \qquad (3)$$

The above equation indicates that the efficiency can be improved by increasing the magnetizing impedance Z_{mag}. In this research energy transfer efficiency of the system is improved by increasing the magnetizing impedance with two intermediate coils and by selecting the suitable self-resonant frequency ratio.

2.2. Operating frequency for maximum efficiency

As mentioned above the magnetizing impedance plays an important role in the WPT system. In addition to the magnetic coupling factor between transmitter and receiver resonators k_{14}, other magnetic coupling factors such as k_{12}, k_{13}, k_{23}, k_{24}, and k_{34} also contribute to the energy transfer. Fig. 4 shows the variation of the magnetizing impedance of four-coil resonators with respect to the operating frequency in comparison with the conventional two-coil resonators. It can be found from the Fig. 3 that Z_{mag} becomes very large at two poles as shown in (4).

$$f_{p1} = \frac{f_2}{\sqrt{1+\kappa_{23}}} \text{ or } f_{p2} = \frac{f_2}{\sqrt{1-\kappa_{23}}} \tag{4}$$

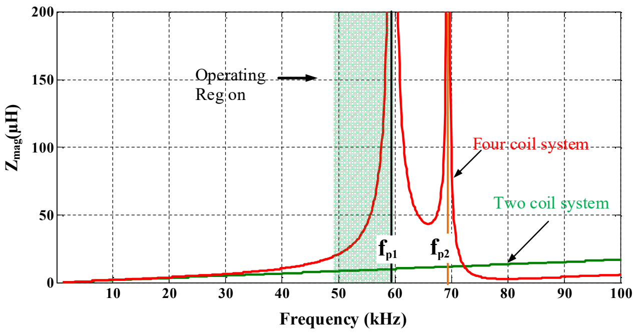


Fig.4. Comparison of the magnetizing impedance in four-coil and two-coil system

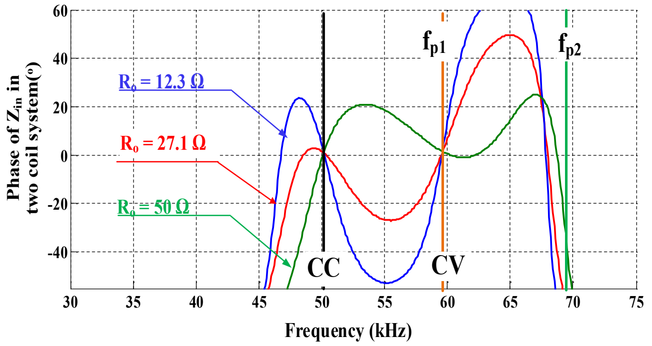


Fig. 5. Phase plot of input impedance at two-poles in proposed four-coil system

2.3. Zero Phase Angle (ZPA) condition in CV mode for high efficiency

In the CV mode, the input impedance can be calculated as (5).

$$Re\{Z_{in}\} = \frac{\left(R_{L,eq}+Re\{Z_{pri}\}\right)Im^2\{Z_{mag}\}+Im^2\{Z_{pri}\}Re\{Z_{pri}\}}{\left(R_{L,eq}+Re\{Z_{pri}\}\right)^2+Im^2\{Z_{pri}\}} \tag{5}$$

$$Im\{Z_{in}\} = \frac{j\left(R_{L,eq}+Re\{Z_{pri}\}\right)^2 Im\{Z_{pri}\}}{\left(R_{L,eq}+Re\{Z_{pri}\}\right)^2+Im^2\{Z_{pri}\}} \tag{6}$$

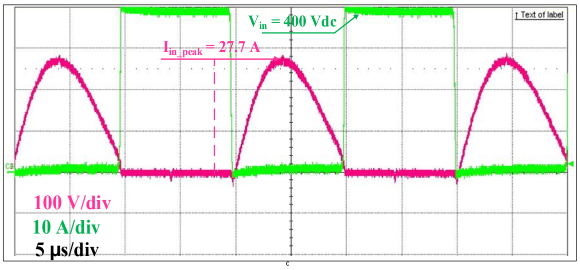
It can be noticed from the equations (5) and (6) that ZPA condition for the converter can be achieved by making the value of Re/Im small. Since the Re/Im is calculated as $\left(R_{L,eq}+Re\{Z_{pri}\}\right)/Im\{Z_{mag}\}$, the system can achieve ZPA condition if $Im\{Z_{mag}\}$ is large. Thus it is desirable to operate the system at f_{p1} or f_{p2} where the $Im\{Z_{mag}\}$ is maximum as shown in Fig. 5.

3. Experimental results

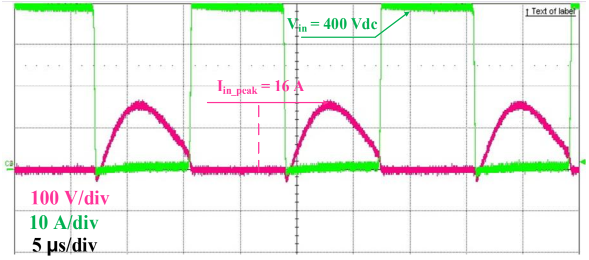
In order to prove the validity of the proposed WPT system a 6.6 kW system was implemented. The distance between the primary coil and the secondary coil was 20cm. Fig.6 shows the voltage and current waveforms of the MOSFETs in both CC and CV charge mode, respectively. As shown in the Fig. 6 the ZVS tur-on and ZCS turn-off of the switch is achieved. Fig. 7 shows the overall efficiency plots of the dc-dc converters with proposed four-coil system and peak efficiency of 97.08 % was obtained at 3.7 kW in CV charge mode.

TABLE 1
SPECIFICATION OF TOPOLOGY

Power rating (P_o)	6.6 kW
Input voltage (V_{in})	400 V
Rated output voltage (V_o)	420 V
Rated output load current (I_o)	15.7 A
Switching frequency (f_s)	> 50 kHz



(a) Input current and voltage waveforms at 6.6 kW in CC mode



(b) Input current and voltage waveforms at 3.7 kW in CV mode

Fig.6. Input waveforms on MOSFETs in CC and CV mode charging.

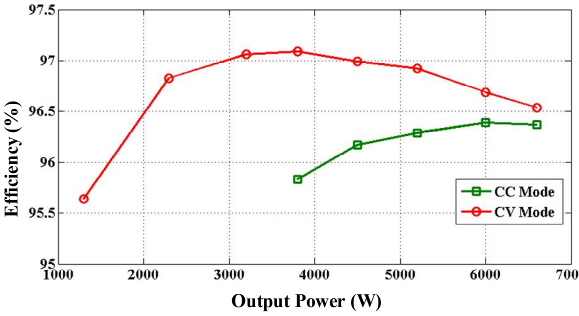


Fig. 7. Efficiency of the four–coil system

4. Conclusion

In this paper, a novel WPT charger with four-coil system and the analysis based on two-port network was presented. It has been proved that the WPT system with four-coil can provide the better efficiency than that with two coil. It has been found that the soft switching was possible over the wide range of charge operation by achieving ZPA condition. Since the proposed system is able to achieve the high efficiency with no ferrite, it is suitable for the on-board charger of electric vehicle.

References

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[2] Sang Cheol Moon; Gun-Woo Moon, "Wireless power transfer system with an asymmetric 4-coil resonator for electric vehicle battery chargers," in *Applied Power Electronics Conference and Exposition (APEC), 2015 IEEE* , vol., no , pp.1650-1657, 15-19 March 2015