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Harmonic Current Control Method for Selective EMI Reduction in Electric Vehicle Wireless Power Transfer System

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ABSTRACT: This paper proposes a method to selectively reduce electromagnetic interference (EMI) in an electric vehicle (EV) wireless power transfer (WPT) system. As power levels increase, it becomes more difficult to meet EMI limits, and specific harmonics that exceed these limits can cause problems in certain devices. In addition, additional shielding materials that increase the system's weight, volume, and cost should be used a lot to meet EMI limits. The proposed method presents an appropriate selection method of resonant circuit elements to adjust the harmonic currents, enabling the reduction of specific problematic harmonic without additional shielding materials. The proposed method was validated through simulation. Through the proposed method, it was confirmed that the 3rd, 5th, and 7th harmonics, which significantly exceed the EMI limits, can be reduced by 29.56 dB (3rd), 14.25 dB (5th), and 36.08 dB (7th), respectively.

KEY WORDS: Electric vehicle (EV), Electromagnetic interference (EMI), Leakage magnetic field, Wireless Power Transfer (WPT)

1. INTRODUCTION

As global interest in the environment increases, the transition from conventional internal combustion engine vehicles to electric vehicles (EVs) accelerates. There are various methods of charging EVs, but wireless charging is an attractive charging solution considering convenience and safety [1]. Recently, to create clear and consistent standards and commercialize EV wireless power transfer (WPT) technology, the American Automotive Association (SAE) established SAE J2954 standards [2].

WPT is a technology that wirelessly transmits power without physical contact by inducing a voltage to the receiving coil (RX) by the time-varying magnetic field of the transmitting coil (TX) and acting as a power source for the RX. During the WPT, a magnetic field coupled from the TX to the RX and a magnetic field leaking to the periphery exist. This magnetic field creates electromagnetic field (EMF) and electromagnetic interference (EMI) problems and may affect the human body or other devices.

The inverter and rectifier of the WPT system produce a square wave. This square wave contains odd harmonic components in addition to the fundamental frequency, and these odd harmonics are emitted, creating an EMI problem. Fig. 1 shows the EMI spectrum of the EVs WPT system. The target frequency for EMI reduction should vary depending on the target device or environment. Therefore, it is important to selectively reduce EMI depending on the target frequency.

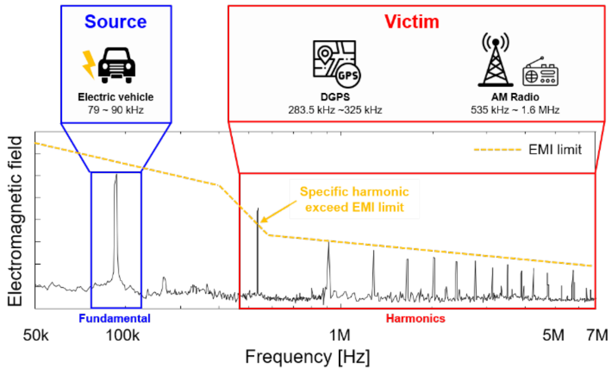


Fig. 1. EMI spectrum of the WPT system.

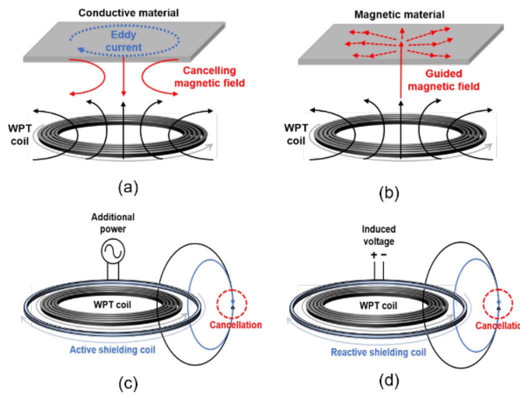


Fig. 2. Various shielding methods: (a) Conductive shielding. (b) Magnetic shielding. (c) Active shielding. (d) Reactive shielding.

There are various shielding methods to reduce leakage magnetic field, as shown in Fig. 2. The first method is conductive shielding

[3]. The eddy current generates a canceling magnetic field, but it generates heat. The second method is magnetic shielding [4]. Magnetic material has low reluctance, so the magnetic field is guided. However, it increases the weight and cost of the system. The third method is active shielding [5]. The additional power source can generate the canceling magnetic field. However, this method requires additional power sources, making the system complex. The last method is reactive shielding [6]. The leakage magnetic field can generate the canceling magnetic field. However, there is a limit to canceling the magnetic field since the leakage magnetic field is used as a source. The above shielding methods require additional materials that increase the system's weight, volume, and cost.

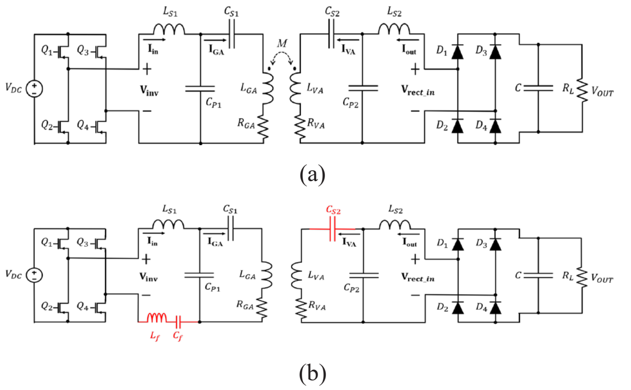
In this paper, we propose a space-efficient selective EMI reduction method through the appropriate selection of resonant circuit elements. This method is achieved by adjusting the magnitude and phase of harmonic current, taking into account the magnetic field contribution by the shape of ground assembly (GA) and vehicle assembly (VA) coils.

2. METHOD FOR REDUCING EMI SELECTIVELY

In the EV WPT system, as shown in Fig. 3(a), the magnetic field caused by specific harmonic currents is determined by the sum of the magnetic fields generated by GA and VA coils. Each magnetic field is affected not only by the magnitude and phase of the harmonic currents passing through the coils but also by the physical shape of the coils as expressed in (1), where α and β represent the contribution of the magnetic field by the physical shape of GA and VA coils respectively.

$$\vec{B}_{total,n\omega_o} = \vec{B}_{GA,n\omega_o} + \vec{B}_{VA,n\omega_o} = \alpha\left|\vec{I}_{GA,n\omega_o}\right|\angle\left(\vec{I}_{GA,n\omega_o}\right) + \beta\left|\vec{I}_{VA,n\omega_o}\right|\angle\left(\vec{I}_{VA,n\omega_o}\right) \tag{1}$$

Due to the different physical shapes of the GA and VA coils, each affects the measured magnetic field differently. α and β can be determined from the induced voltage measured by the loop antenna when the same current is passed through the GA and VA coils, respectively. In the EV WPT system, α is greater than β. Once these coils are made, the magnetic field determined by their shapes becomes fixed. Therefore, the only variables that can be adjusted to minimize the magnetic field are the magnitude and phase of the harmonic current. By adjusting the harmonic current considering each coil's fixed geometric contributions, the overall magnetic field can be effectively reduced.



(a)

(b)

Fig. 3. Double-sided LCC topology for the EV WPT systems. (a) Conventional equivalent circuit, (b) Modified equivalent circuit.

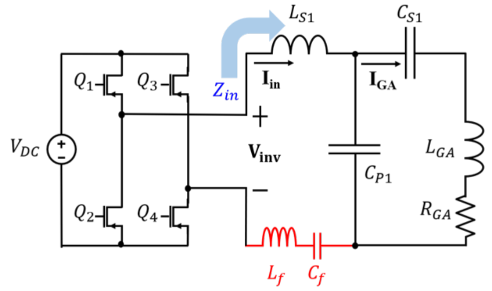


Fig. 4. Resonant circuit of GA side with LC filter.

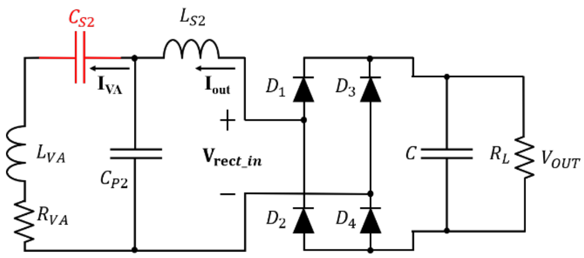


Fig. 5. Resonant circuit of VA side.

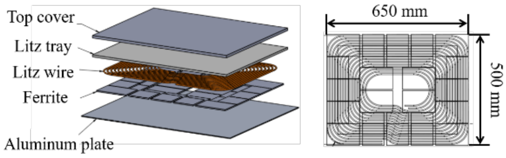
Fig. 4 shows the resonant circuit of the GA side with an LC filter. Adding an LC filter to the first loop can increase the harmonic impedance seen by the inverter overall, thereby reducing harmonics. Therefore, the magnitude of the GA side's harmonic current can be adjusted by adding an LC filter. The resonant frequency of the LC filter is set to be the same as the WPT system's operating frequency so that the system's operation is not affected by adding an LC filter.

Fig. 5 shows the resonant circuit of the VA side. The current phase difference between GA and VA currents is 90 degrees in the resonance condition. However, when C_{S2} is changed, it is no longer in the resonance condition, and the current phase difference between GA and VA currents may be less than or greater than 90 degrees [7]. Therefore, the phase of the harmonic current of the VA side can be adjusted by the value of C_{S2}.

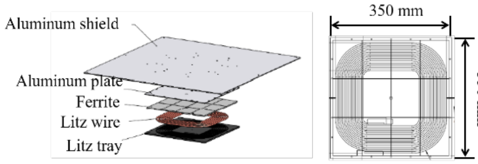
Fig. 3(b) shows the modified double-sided LCC topology of the EV WPT system designed for selective EMI reduction. To find

$$\begin{bmatrix} \frac{j(n-1)(n+1)\omega_o L_{S1}}{n}+\frac{j(n-1)(n+1)\omega_o L_{f1}}{n} & \frac{-\omega_o L_{S1}}{jn} & 0 & 0 \\ \frac{-\omega_o L_{S1}}{jn} & \frac{j(n-1)(n+1)\omega_o L_{GA}}{n} & jn\omega_o M & 0 \\ 0 & jn\omega_o M & \frac{\omega_o L_{S2}}{jn}+\frac{1}{jn\omega_o C_{S2}}+jn\omega_o L_{VA} & \frac{-\omega_o L_{S2}}{jn} \\ 0 & 0 & \frac{-\omega_o L_{S2}}{jn} & \frac{j(n-1)(n+1)\omega_o L_{S2}}{n} \end{bmatrix} \begin{bmatrix} \mathbf{I_{in}} \\ \mathbf{I_{GA}} \\ \mathbf{I_{VA}} \\ \mathbf{I_{out}} \end{bmatrix} = \begin{bmatrix} \mathbf{V_{inv,n\omega_o}} \\ 0 \\ 0 \\ \mathbf{V_{rect\_n\omega_o}} \end{bmatrix} = \begin{bmatrix} \frac{4V_{DC}}{n\pi} \\ 0 \\ 0 \\ \frac{4V_{OUT}}{n\pi}\mathbf{e^{jn\theta}} \end{bmatrix} \quad (2)$$

$$\text{where } \theta = -\left(\frac{\pi}{2}+tan^{-1}\frac{D}{C}\right), \quad where\ C = \frac{1}{{\omega_o}^2{C_{p2}}^2 R_{L,in}}, D = \omega_o L_{VA} - \omega_o L_{S2} - \frac{1}{\omega_o C_{S2}}$$



(a)



(b)

Fig. 6. SAE J2954 EV WPT coil: (a) GA coil. (b) VA coil.

values of LC filter and C_{S2} such that $\vec{B}_{GA,n\omega_o}$ and $\vec{B}_{VA,n\omega_o}$ have almost the same magnitude and GA and VA harmonic currents are close to phase of 180 degrees, nth harmonic Kirchhoff's voltage law (KVL) is applied as (2). Through this, the EMI caused by a specific harmonic current can be minimized from the measurement point.

3. VALIDATION OF THE PROPOSED METHOD

The validation is performed through simulation for the following 4 cases:

1) A system without any applied modification (Reference)
2) When 3rd harmonic significantly over EMI limits (n=3)
3) When 5th harmonic significantly over EMI limits (n=5)
4) When 7th harmonic significantly over EMI limits (n=7)

3.1. Simulation Setup

The magnetic field contribution, depending on the shape of the GA coil, is 2.8 times larger than that of the VA coil, as expressed in (3). Therefore, by adding an LC filter on the GA side, the GA coil harmonic current must be adjusted to be 2.8 times smaller than the VA coil harmonic current.

$$\frac{\alpha}{\beta} = \frac{Induced\ voltage\ at\ I_{GA} = 1\ A,\ \ I_{VA} = 0\ A}{Induced\ voltage\ at\ I_{VA} = 1\ A,\ \ I_{GA} = 0\ A} = \frac{9.49\ \mu V}{3.39\ \mu V} = 2.8 \quad (3)$$

Table 1. Parameters of circuit simulation.

	Values			
	Reference	**n=3**	**n=5**	**n=7**
f_o [kHz]	85			
P_{out} [kW]	10			
V_{out} [V]	400			
L_{GA} [μH] $R_{L_{GA}}$ [mΩ]	38.65 34.65			
L_{VA} [μH] $R_{L_{VA}}$ [mΩ]	42.23 60.95			
M	6.78			
L_{S1} [μH] $R_{L_{S1}}$ [mΩ]	11.17 27.80			
C_{P1} [nF] $R_{C_{P1}}$ [mΩ]	314.00 3.27			
C_{S1} [nF] $R_{C_{S1}}$ [mΩ]	125.00 5.81			
L_{S2} [μH] $R_{L_{S2}}$ [mΩ]	14.02 36.33			
C_{P2} [nF] $R_{C_{P2}}$ [mΩ]	250.00 4.12			
L_f [μH] R_{L_f} [mΩ]	-	62.53 122.46	60.00 114.85	56.17 108.66
C_f [nF] R_{C_f} [mΩ]	-	56.07 4.70	58.43 4.82	62.42 5.16
C_{S2} [nF] $R_{C_{S2}}$ [mΩ]	124.00 7.70	119.26 8.11	110.00 2.17	130.06 3.55

SAE J2954 offers various coil models to optimize power transmission across different environments and needs. As shown in Fig. 6(a), a universal GA coil is used. Additionally, the WPT3Z2 VA coil, designed for a 10 kW output and a ground clearance of 140 to 210 mm, is used, as shown in Fig. 6(b). Table 1 shows the parameter values for the entire circuit.

3.2. Simulation Results

Fig. 7 shows the total harmonic magnetic field vector diagram, illustrating the magnitude and phase of magnetic fields. The magnitude of each magnetic field vector is determined by the product of the coil shape's contribution and the magnitude of the harmonic current. In addition, there is a constant phase difference between the two vectors.

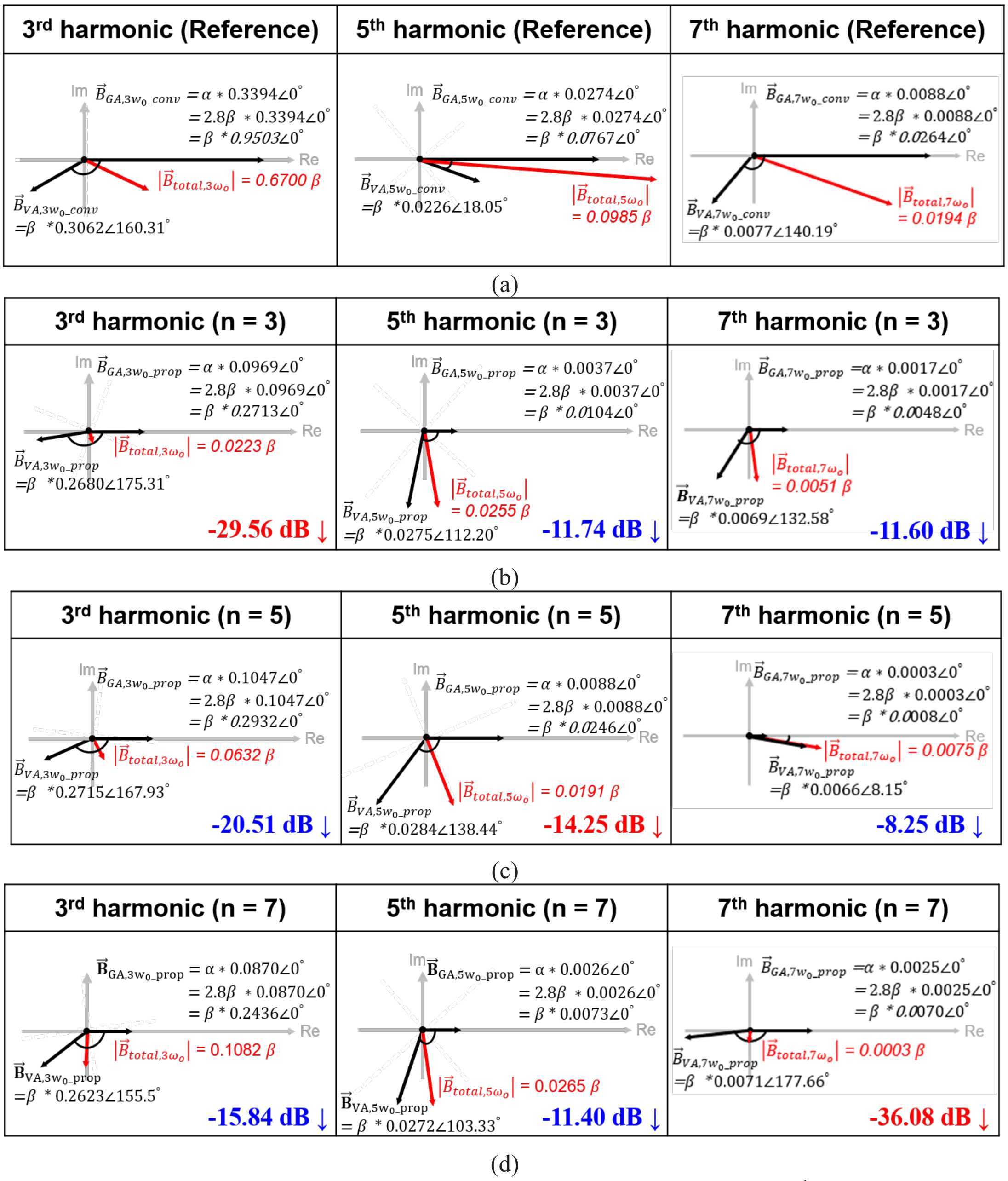


Fig. 7. Simulation results. (a) A system without any applied modification (Reference), (b) When 3rd harmonic significantly over EMI limits (n=3), (c) When 5th harmonic significantly over EMI limits (n=5), (d) When 7th harmonic significantly over EMI limits (n=7).

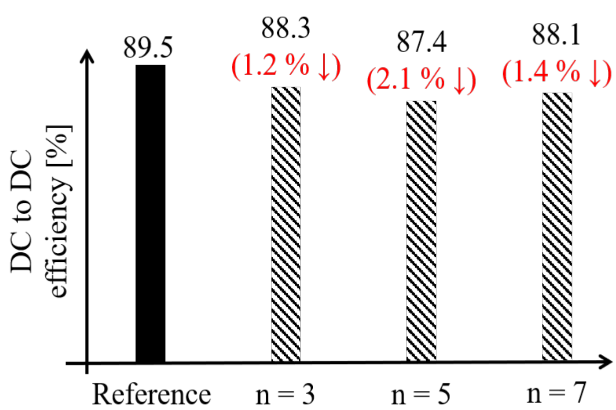


Fig. 8. Simulation results comparing the power transfer efficiency of Reference and n=3, n=5, and n=7.

For the nth harmonic that significantly exceeds EMI limits, the proposed LC filter and C_{S2} values are applied to adjust the magnitudes of the GA and VA magnetic field vectors to be similar to the reference case, and the phase difference between the two vectors has been brought closer to 180 degrees. Using this method, the 3rd harmonic was reduced by 29.56 dB for n=3, the 5th harmonic by 14.25 dB for n=5, and the 7th harmonic by 36.08 dB for n=7.

The added LC filter not only reduced the problematic nth harmonic but also decreased the magnitude of the GA coil's harmonic currents, thereby lowering the total magnetic field vector sum. This resulted in an overall reduction of other harmonics.

When the proposed method was applied, the parasitic resistance of the LC filter and the changes in resonance conditions due to C_{S2} resulted in efficiency reductions of 1.63 % (n=3), 1.99 % (n=5), and 1.28 % (n=7) compared to the reference, as shown in Fig. 8.

4. CONCLUSIONS

This paper proposes a method for suppressing the EMI selectively by controlling the magnitude and phase of harmonic currents. The proposed selective EMI reduction method can be achieved by selecting the appropriate resonant circuit elements without additional shielding materials. The magnetic field generated in the EV WPT system was analyzed, and based on this, a method for adjusting the magnitude and phase of the harmonic currents was introduced. The proposed method was validated through simulation. The results confirmed that the 3rd, 5th, and 7th harmonics could be reduced by 29.56 dB (3rd), 14.25 dB (5th), and 36.08 dB (7th), respectively, when significantly exceeding the EMI limits. Furthermore, an overall reduction was also achieved for harmonics other than the specific problematic ones.

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REFERENCES

[1] S. Li and C. C. Mi, "Wireless Power Transfer for Electric Vehicle Applications," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 1, pp. 4-17, March 2015

[2] Wireless Power Transfer for Light-Duty Plug-In/Electric Vehicles and Alignment Methodology, International Standard SAE J2954, 2019. [Online] Available: https://www.sae.org/standards/contents/j2954_201904/

[3] H. Kim, J. Cho, S. Ahn, J. Kim and J. Kim, "Suppression of leakage magnetic field from a wireless power transfer system using ferrimagnetic material and metallic shielding," *2012 IEEE International Symposium on Electromagnetic Compatibility*, Pittsburgh, PA, USA, 2012

[4] J. Rhee, S. Woo, C. Lee, and S. Ahn, "Selection of Ferrite Depending on Permeability and Weight to Enhance Power Transfer Efficiency in Low-Power Wireless Power Transfer Systems," *Energies*, 2024

[5] S. Cruciani, T. Campi, F. Maradei and M. Feliziani, "Active Shielding Design for Wireless Power Transfer Systems," in *IEEE Transactions on Electromagnetic Compatibility*, vol. 61, no. 6, pp. 1953-1960, Dec. 2019

[6] C. Lee, S. Woo, Y. Shin, J. Rhee, J. Moon and S. Ahn, "EMI Reduction Method for Wireless Power Transfer Systems with High Power Transfer Efficiency Using Frequency Split Phenomena," in *IEEE Transactions on Electromagnetic Compatibility*, vol. 64, no. 5, pp. 1683-1693, Oct. 2022

[7] S. Woo, Y. Shin, C. Lee, J. Rhee, J. Ahn, J. Moon, S. Son, S. Lee, H. Kim and S. Ahn, "Minimizing Leakage Magnetic Field of Wireless Power Transfer Systems Using Phase Difference Control, " *Energies*, 2022