Wireless Power Transfer system with Flying Capacitor Converter for Current Harmonics Reduction

Rintaro Kusui
Dept. of Electrical, Electronics, and Information Engineering
Nagaoka University of Technology
Nagaoka, Japan
kusui@stn.nagaokaut.ac.jp

Keisuke Kusaka
Dept. of Electrical, Electronics, and Information Engineering
Nagaoka University of Technology
Nagaoka, Japan
kusaka@vos.nagaokaut.ac.jp

Jun-ichi Itoh
Dept. of Electrical, Electronics, and Information Engineering
Nagaoka University of Technology
Nagaoka, Japan
itoh@vos.nagaokaut.ac.jp

***Abstract*— A wireless power transmission system using a flying capacitor converter (FCC) as a primary power source has been proposed to reduce current harmonics that cause low-order harmonic radiation noise. However, the diode rectifier on the secondary side applies a square wave voltage to the secondary transmit coil. Current harmonics are not sufficiently reduced due to the harmonic content of the square wave. This paper proposes a WPT system with FCC on both the primary and secondary sides in order to reduce voltage harmonics applied to both sides of the transmission coil. The proposed system reduces the odd-order harmonics of the primary and secondary currents by more than 25 dB compared to the conventional system, as confirmed by simulations. In particular, the 3rd harmonic is reduced by 37.2 dB, and the 5th harmonic is reduced by 35.1 dB.**

Keywords—Wireless power transfer system, Flying-capacitor converter, Current harmonics, Radiation noise

I. INTRODUCTION

Electric vehicles (EVs) are becoming more widespread to achieve carbon neutrality. EVs require frequent recharging because the energy density of batteries is lower than that of gasoline for conventional vehicles. Currently, wired chargers are used to charge EVs. However, charging with a wired charger requires complicated cable operations and carries the risk of electric shock or short-circuiting due to water intrusion into the metal contacts, and so on. As a result, wireless power transfer (WPT) systems are being actively studied to enable easy and safe charging of EVs[1-3]. Although WPT systems transmit power via weak magnetic coupling, the transmission coils generate radiated emissions. Radiated emissions can cause electronic equipment malfunction and interference with wireless communications, and so on. For this reason, the WPT system must comply with the regulations established by each country based on the guidelines of the Comité International Spécial des Perturbations Radioélectriques (CISPR) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP)[4-5]. Reference levels for radiated emissions for the WPT systems are specified in CSIPR11. In particular, it is planned to reduce the reference levels by approximately 30 dB in the range from 150 kHz to 30 MHz, corresponding to the low-order harmonic component of the transmission frequency[6]. Accordingly, reduction methods for the radiated emissions are required in WPT systems, especially their lower harmonics.

The leakage magnetic field of the WPT system is emitted from the transmission coil. Many conventional WPT systems have H-bridge power converters on the primary side and diode rectifiers on the secondary side[7]. The H-bridge inverter and the diode rectifier output a square wave voltage with the amplitude of the DC voltage. The square-wave voltage has large low-order harmonics. As a result, currents with large low-order harmonics flow through the transmission coils in conventional WPT systems. These current harmonics are the main cause of the large low-order leakage field harmonics from the WPT system.

Passive, active, and resonant shielding have been proposed to reduce leakage magnetic fields using additional windings[8-10]. These techniques add winding around the main winding. In passive shielding, the current flows in the direction to counteract the leakage flux that interlinks the additional short winding[8]. In active shielding, an additional power supply is connected to the additional windings to carry current that can cancel out the leakage magnetic field more effectively[9]. In resonant shielding, a resonant capacitor is added to the short winding to improve the shielding effect by reducing the impedance at the frequency being canceled[10]. However, the main purpose of these methods is to cancel out the fundamental component. In other words, they are ineffective enough to reduce the harmonic component of radiation noise.

A WPT system with a flying capacitor converter (FCC) connected only on the primary side has been proposed to reduce current harmonics in the transmission coil[11]. The FCC outputs a stepwise sinusoidal voltage to the series circuit of the transmission coil and the resonant capacitor. The output voltage of the FCC has very few voltage harmonics compared to the square wave voltage. For this reason, the current harmonics in the coil are reduced. However, this system has a conventional diode rectifier connected on the secondary side. The diode rectifier outputs a square wave voltage with many low-order harmonics. Thus, the current harmonics caused by the square-wave voltage applied to the transmission coil on the secondary side cannot be sufficiently reduced.

This paper proposes a WPT system that has FCCs not only on the primary side but also on the secondary side. The FCC on the secondary side also outputs a multi-level voltage with fewer low-order voltage harmonics than the square-wave voltage. The new contribution of this paper is to propose the WPT system with very few low-order harmonics of transmission coils. The current harm onics on the primary and secondary sides are significantly reduced by applying the multi-level voltage to the transmission coils. In other words, the proposed system can reduce the radiated emission harmonics than the conventional system. First, a current analysis using an equivalent circuit shows the cause of current harmonics in the WPT system. Then, the configuration of the proposed system and the switching pattern to keep the flying capacitor voltage balance are shown. Finally, the operation of the proposed system is demonstrated by simulation. In addition, the harmonic analysis shows that the proposed method reduces the current harmonics that cause radiated emission harmonics.

II. Configuration of Proposed WPT System

A. Current harmonics in the WPT system

Figure 1 shows the configuration of a conventional WPT system. Most conventional WPT systems have a two-level full-bridge inverter on the primary side and a diode rectifier on the secondary side, as shown in Fig. 1(a). As a result, a square-wave voltage is applied to the compensation circuit and the transmission coil on the primary and secondary sides, respectively. For this reason, a current with many low-order harmonics flows in the transmission coils on both the primary and secondary sides according to the resonance characteristics of the transmission coils and the compensation circuit.

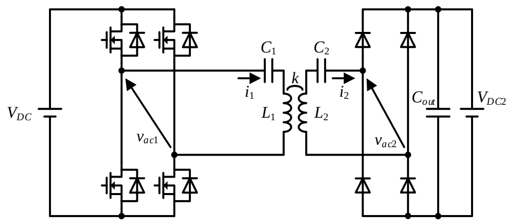
Ref.[11] has proposed a WPT system with an FCC and an unfolder on the primary side instead of a full-bridge inverter as the primary side power supply, as shown in Fig. 1(b). In this system, the FCC outputs a stepwise full-wave rectified voltage. The unfolder switches the polarity of the FCC output voltage to apply a multi-level sinusoidal voltage with few harmonics to the transmission coil and compensation circuit. As a result, this system reduces primary-side current harmonics but has limited effect in reducing secondary-side current harmonics. The cause of this problem is discussed in the current analysis using an equivalent circuit.

Figure 2 shows the equivalent circuit of a series-series (S-S) compensation WPT system with resonant capacitors connected in series with the primary and secondary coils, respectively; $\boldsymbol{V}_1$ and $\boldsymbol{V}_2$ are the output voltages of the inverter or rectifier, and $\boldsymbol{I}_1$ and $\boldsymbol{I}_2$ are the primary and secondary transmission coil currents. From Fig. 2, the circuit equation is expressed as (1) from Kirchhoff's voltage law.

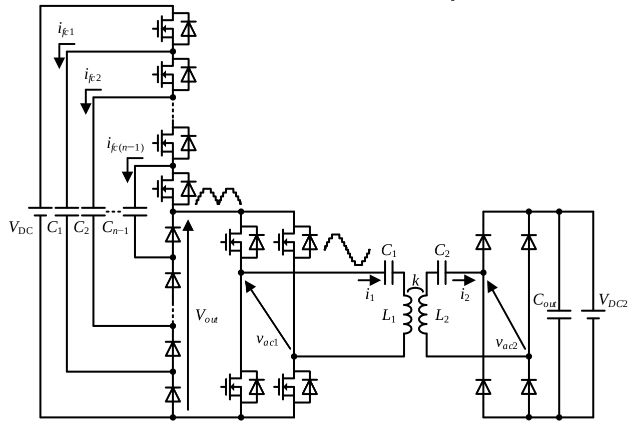
$$\begin{pmatrix}\mathbf{V}_1\\ \mathbf{V}_2\end{pmatrix}=\begin{pmatrix} j\omega L_1+\dfrac{1}{j\omega C_1} & j\omega M\\ j\omega M & j\omega L_2+\dfrac{1}{j\omega C_2}\end{pmatrix}\begin{pmatrix}\mathbf{I}_1\\ \mathbf{I}_2\end{pmatrix} \quad (1),$$

where L_1 and L_2 are the self-inductance of the primary and secondary transmission coils, C_1 and C_2 are the primary and secondary resonant capacitors, and M is the mutual inductance. The transmission coil currents $\boldsymbol{I}_1$ and $\boldsymbol{I}_2$ are derived from (1) and expressed as

$$\mathbf{I}_1=\frac{j\omega L_2+\dfrac{1}{j\omega C_2}}{\Delta}\mathbf{V}_1-\frac{j\omega M}{\Delta}\mathbf{V}_2 \quad (2),$$



(a) WPT system with inverter on the primary side and diode-rectifier on the secondary side.



(b) WPT system with flying-capacitor converter on primary side and diode-rectifier on secondary side.

Fig. 1. Conventional configuration of WPT system.

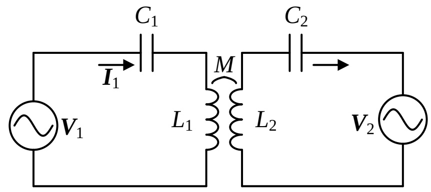


Fig. 2. Equivalent circuit of S-S compensated WPT system.

$$\mathbf{I}_2=-\frac{j\omega M}{\Delta}\mathbf{V}_1+\frac{j\omega L_1+\dfrac{1}{j\omega C_1}}{\Delta}\mathbf{V}_2 \quad (3),$$

where Δ is the determinant of the impedance matrix of the equivalent circuit and is expressed as

$$\Delta=\left(j\omega L_1+\frac{1}{j\omega C_1}\right)\left(j\omega L_2+\frac{1}{j\omega C_2}\right)+\omega^2 M^2 \quad (4).$$

The primary side voltage harmonics are reduced in the conventional configuration, but the secondary side voltage harmonics are not. From (2) and (3), it is seen that each current harmonic remains on the primary and secondary sides by leaving the voltage harmonics on the secondary side. Thus, it is necessary to reduce the voltage harmonics not only on the primary side but also on the secondary side in order to reduce both current harmonics sufficiently.

B. Proposed WPT system configuration

Figure 3 shows the configuration of the proposed WPT system. The proposed system has an FCC and an unfolder on the primary side and an FCC and a diode rectifier on the secondary side. In this paper, S-S compensation is used as the compensation circuit of the WPT system. The primary-side FCC outputs a stepwise full-wave rectified voltage as in conventional WPT systems with a single FCC. The unfolder outputs a multi-level sinusoidal voltage by switching the polarity of the FCC output voltage. The diode rectifier on the secondary side supplies full-wave rectified current to the FCC by switching the polarity depending on the polarity of the secondary coil current. The secondary-side FCC outputs a stepped full-wave rectified voltage that agrees with the phase angle of the secondary coil current. As a result, a multi-level sinusoidal voltage is applied to both the primary and secondary sides of the transmission coil. In other words, the proposed system reduces the harmonics of the voltage applied to the primary and secondary sides of the transmission coil, respectively. Therefore, the proposed system sufficiently reduces current harmonics that cause harmonics in radiated emissions.

III. SIMULATION RESULT

Table 1 shows the simulation conditions. Simulations are performed for a conventional system with only an inverter and a diode rectifier, a conventional system with only the primary side FCC, and a proposed system with FCCs on both the primary and secondary sides. The FCC has a lower voltage utilization ratio than the full-bridge converter due to the stepped sinusoidal voltage output. For this reason, the DC voltage is modified so that the fundamental amplitude of the output voltage is the same for all systems. The inductance of the transmission coils and the capacitance of the resonant capacitors are the same for all systems. In addition, the FCC has nine output voltage levels.

A. Operation of the conventional system

Figure 4 shows the simulation results of a conventional WPT system with a full-bridge inverter on the primary side and a diode rectifier on the secondary side. The waveforms show the primary unfolder output voltage, the primary transmission coil current, the secondary diode rectifier output voltage, and the secondary coil current. The simulation result shows that the power factor of the primary power supply is approximately unity. From this, it is seen that the conventional system operates under the resonance condition and the rated condition. In addition, it is seen that both the primary and secondary coil currents are distorted. In this system, a full-bridge inverter and a diode rectifier output a square-wave voltage to a series circuit of a transmission coil and a resonance capacitor on both the primary and secondary sides, respectively. As a result, the harmonic current that causes current distortion flows through the transmission coil on the primary and secondary sides according to the resonance characteristics of the transmission coil and the compensation circuit.

Figure 5 shows the simulation results for a conventional system with a 9-level FCC on the primary side and a diode rectifier on the secondary side. Fig. 5(a) shows the output voltages of the power converter and the transmission coil currents on the primary and secondary sides, respectively. The results show that the power factor is unity even when the FCC is connected on the primary side. Accordingly, it is confirmed that this system also operates under resonance and rated conditions. The primary converter outputs a 17-level sinusoidal wave voltage, unfolding the nine-level full-wave rectified voltage output by the FCC. The primary current harmonics are suppressed by the significant reduction of voltage harmonics due to the multi-level voltage output. As a result, the primary current distortion on the primary side is improved. However, voltage harmonics remain because the

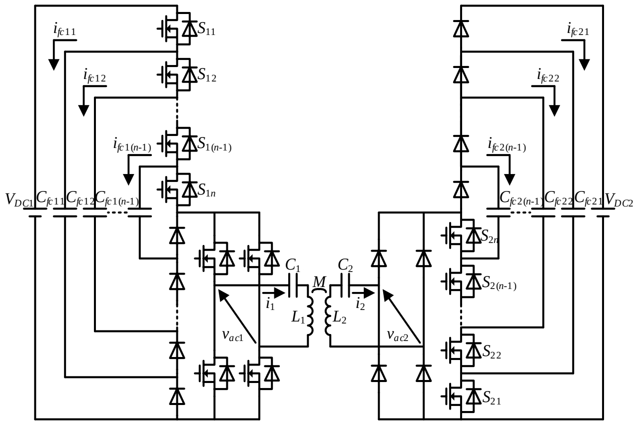


Fig. 3. Proposed WPT system configuration with flying capacitor converter on both the primary and secondary sides.

Table 1. Simulation and experimental conditions.

Prameters	Symbol	Value	
Input/Output DC voltage	V_{DC}	Inv. (D. Rec.): 300	V
	V_{DC2}	FCC: 380	V
Rated output power	P_{out}	1	kW
Transmission frequency	f	85.0	kHz
Self-inductance	L_1,L_2	451	μH
Resonant capacitors	C_1,C_2	7.78	nF
Flying capacitors	C_{fc}	65.0	μF
Coupling coefficient	k	0.275	-
Number of level for FCC	n	9	-

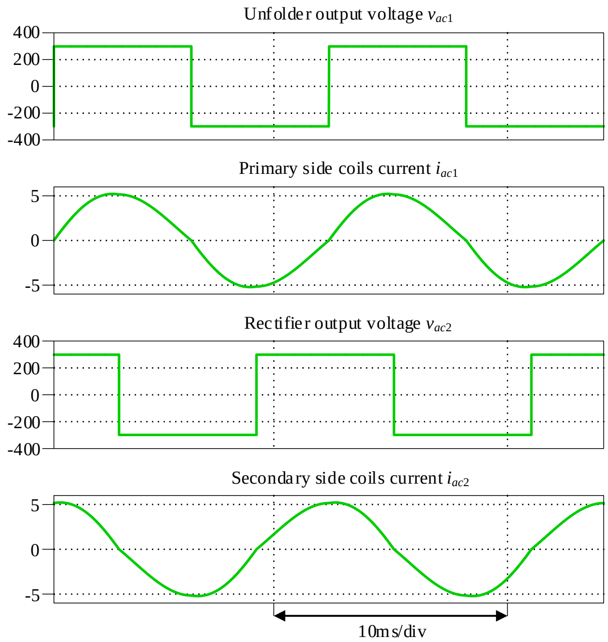
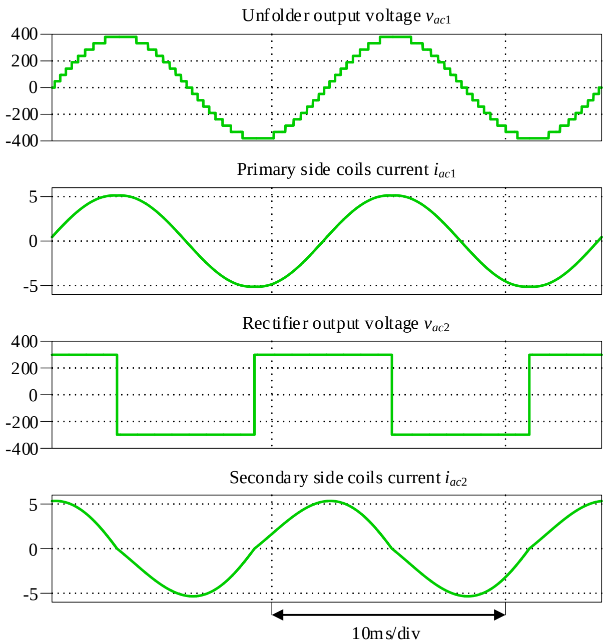
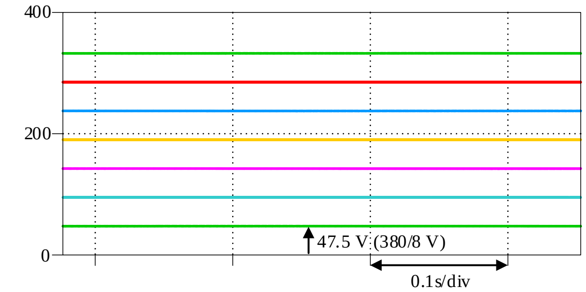


Fig. 4. Operation waveform of conventional system with full-bridge inverter on the primary side and diode rectifier on the secondary side.

diode rectifier outputs a square-wave voltage on the secondary side. Thus, the secondary current harmonics cannot be reduced, i.e., the secondary current distortion remains. Note that voltage and current harmonics are analyzed in detail in Section C, respectively. In order for the FCC to keep operating, the flying capacitor voltages must be balanced. Fig. 5(b) shows the simulation result of the flying capacitor voltage



(a) Operation waveform



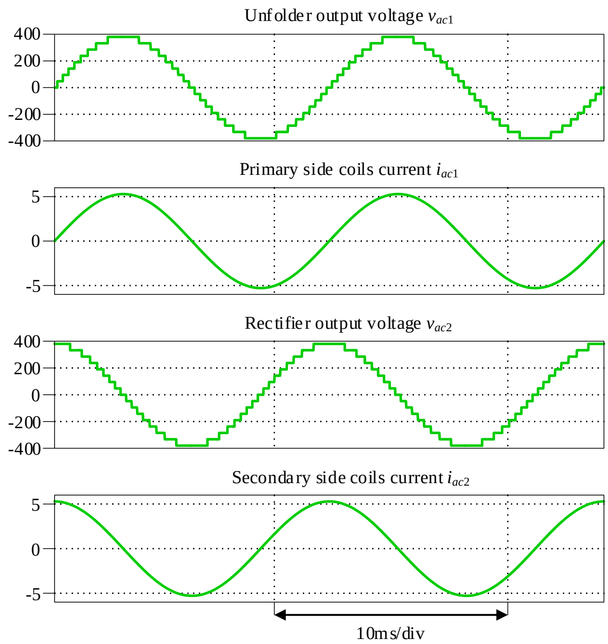
(b) Flying capacitor voltage

Fig. 5. Operation waveform of conventional system with flying capacitor converter on the primary side and diode rectifier on the secondary side.

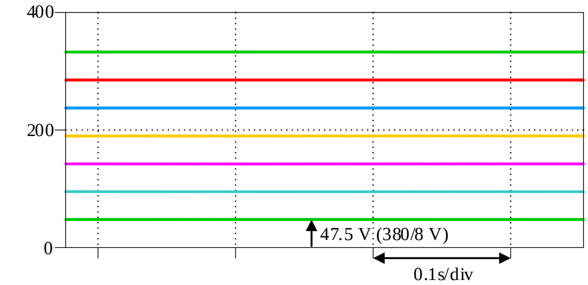
over a long period. A nine-level FCC has seven flying capacitors. Each voltage ideally has a value that is an integer multiple of $V_{DC}/8$. The simulation results confirmed that the voltages of the seven flying capacitors maintain their nominal values.

B. Operation of the proposed system

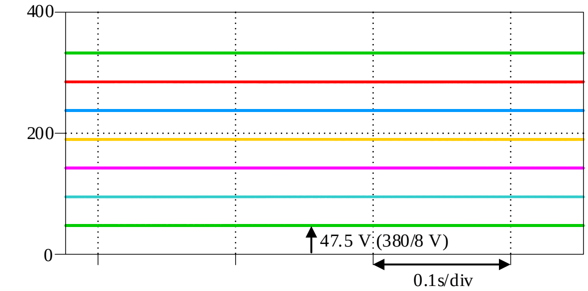
Figure 6 shows the simulation results of the proposed WPT system with 9-level FCC on both the primary and secondary sides. Fig. 6(a) shows the power supply output voltages and the transmission coil currents on the primary and secondary sides, respectively. The waveforms show that a 17-level multi-level voltage is applied to the series circuit of the transmission coil and the resonance capacitor on the primary and secondary sides. In addition, the power factor of the primary power supply in the proposed system is also unity. In other words, it is confirmed that the proposed system transmits the power under resonance conditions. The received power and transmission efficiency decrease as the load power factor decreases when the secondary side FCC output voltage phase is different from the secondary side current phase. The simulation results confirmed that the load power factor on the secondary side is also unity. The proposed system meets the design specifications for these results without reducing the transmission power. The primary and secondary sides converter outputs a multi-level voltage with less low-order harmonics. From Fig. 6(a), it is confirmed that the current



(a) Operation waveform



(b) Flying capacitor voltage on the primary side



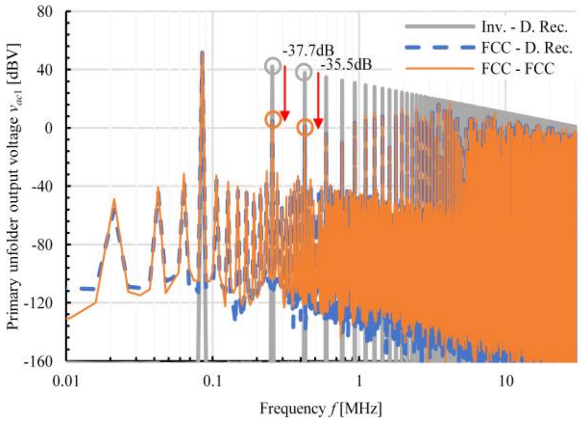
(c) Flying capacitor voltage on the secondary side

Fig. 6. Operation waveform of the proposed system with flying capacitor converter on both the primary and secondary sides.

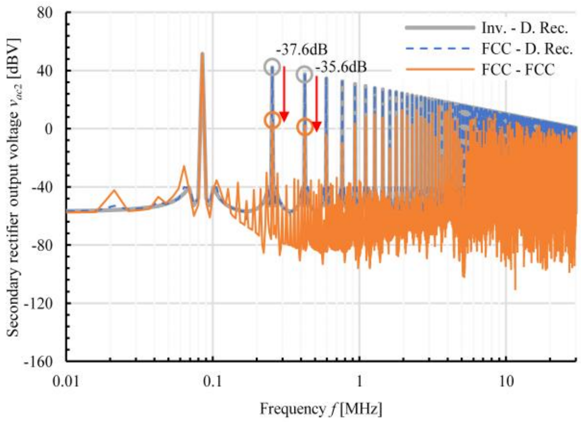
distortion on both the primary and secondary sides can be significantly improved by sufficiently suppressing the current harmonics on both sides. In addition, the flying capacitor voltage simulation results on the primary and secondary sides are shown in Fig. 6(b) and (c). Similar to the conventional system, the proposed system must also keep the balance of the flying capacitor voltage. The simulation waveforms show that the flying capacitor voltage is an integer multiple of 1/8 of the DC voltage on both the primary and secondary sides; it can be confirmed that the proposed system also maintains the flying capacitor voltage balance.

C. Current harmonics analysis

Figure 7(a) shows the harmonic analysis results of the primary converter output voltage and Figure 7(b) shows the harmonic analysis results of the rectifier output voltage. In

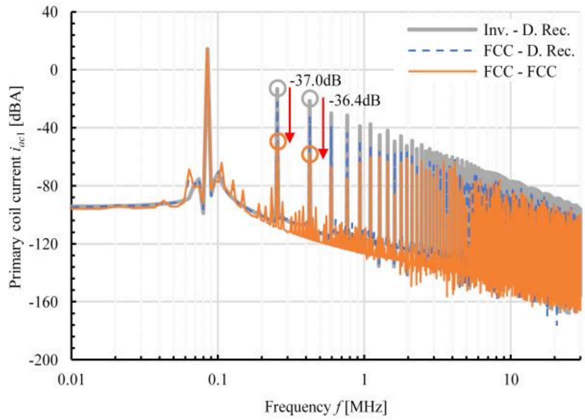


(a) Primary side

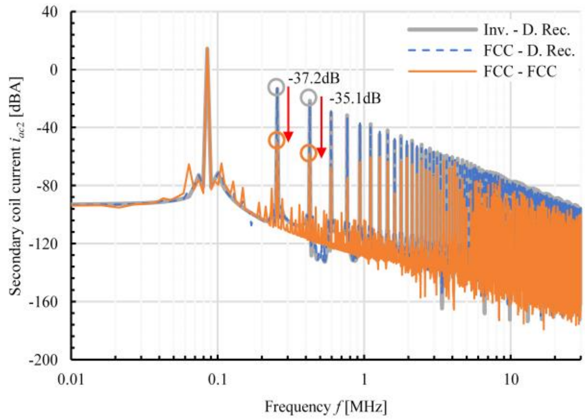


(b) Secondary side

Fig. 7. Harmonics analysis of power supply output voltage on the primary or secondary side.



(a) Primary side



(b) Secondary side

Fig. 8. Harmonics analysis of transmission coil currents on the primary or secondary side.

Table 2. Harmonics analysis results of the each converter outoput voltage at low-order harmonic components.

	Configuration	Number of order					
		1st	3rd	5th	7th	9th	11th
Primary side [dBV]	Inv. − D. Rec.	51.6	42.1	37.6	34.7	32.5	30.8
	FCC − D. Rec.	51.6	4.37	2.07	-4.18	-9.65	3.47
	FCC − FCC	51.6	4.37	2.07	-4.18	-9.64	3.48
Secondary side [dBV]	Inv. − D. Rec.	51.6	42.1	37.6	34.7	32.5	30.8
	FCC − D. Rec.	51.6	42.1	37.6	34.7	32.5	30.8
	FCC − FCC	51.6	4.46	2.05	-4.19	-9.64	3.47

Table 3. Harmonics analysis results of the each coil current at low-order harmonic components.

	Configuration	Number of order					
		1st	3rd	5th	7th	9th	11th
Primary side [dBA]	Inv. − D. Rec.	14.4	-13.3	-21.5	-30.0	-31.5	-38.9
	FCC − D. Rec.	14.4	-22.4	-32.6	-38.9	-43.8	-48.2
	FCC − FCC	14.5	-50.3	-57.8	-67.3	-74.8	-63.8
Secondary side [dBA]	Inv. − D. Rec.	14.4	-13.3	-21.5	-30.0	-31.5	-38.9
	FCC − D. Rec.	14.5	-13.0	-22.7	-28.8	-33.3	-36.9
	FCC − FCC	14.5	-50.2	-57.8	-67.3	-74.8	-63.8

addition, Table 2 shows the values of the 11th and lower voltage harmonics in the odd-order harmonics of the transmission frequency. Similar to the simulation, the harmonics are analyzed for a conventional configuration with an inverter on the primary side and a diode rectifier on the secondary side, a conventional configuration with an FCC on the primary side and a diode rectifier on the secondary side, and a proposed system with an FCC on both the primary and secondary sides. Each configuration is analyzed and compared. The analysis results show that the fundamental wave amplitudes are almost the same in each configuration on both the primary and secondary sides. In addition, from Fig. 7(a), an FCC on the primary side reduces the low-order harmonics of the voltage by 25 dB or more compared to a configuration without an FCC. In particular, the third harmonic is reduced by 37.7 dB, and the fifth harmonic is reduced by 35.5 dB. On the other hand, Fig. 7(b) shows that the voltage harmonics do not change with or without an FCC on the secondary side. This is because each converter is controlled and operated independently. Similarly, the voltage harmonics on the secondary side are reduced when the FCC is connected to the secondary side. The secondary FCC also reduces the lower harmonics on the secondary side by approximately 25 dB. Specifically, the third harmonic is reduced by 37.7 dB, and the fifth harmonic is reduced by 35.5 dB.

Figures 8(a) and (b) show the harmonic analysis results of the primary and secondary coil currents, respectively. In addition, Table 3 shows the values of the current harmonics of the odd-order components of the transmission frequency. The current harmonics are also analyzed and compared with three configurations in the same way as the voltage. From the analysis results, it is confirmed that the fundamental wave component does not change in any configuration. These results show that the proposed system does not change the transmission power. From Fig. 8, the current low-order harmonics are reduced by about 5 to 10 dB when FCC is applied to the primary side only. In particular, the third harmonic is reduced by 9.12 dB, and the fifth harmonic is reduced by 11.2 dB. Also, the current harmonics on the secondary side have significantly changed. It is seen that the conventional configuration with FCC on the only primary side reduces the secondary current harmonics, which are mainly caused by the secondary voltage harmonics. By contrast, the proposed configuration with FCC on the secondary side reduces the low-order current harmonics on the primary side by more than 25 dB compared to the conventional configuration with an inverter on the primary side. In particular, the third harmonic is reduced by 37.2 dB, and the fifth harmonic is reduced by 35.1 dB. In addition, the secondary side current harmonics are reduced by 25 dB or more as in the case of the primary side, especially the 3rd harmonic is reduced by 37.2 dB, and the 5th harmonic is reduced by 35.1 dB.

IV. Conclusion

A WPT system was proposed with FCC on the primary and secondary sides to reduce the current low-order harmonics in the transmission coil. The proposed system connects the FCC and the unfolder or diode rectifier as primary or secondary power sources. FCC significantly reduces coil current harmonics by applying a stepwise sinusoidal voltage to the transmission coil and compensation circuit. The proposed system operation and current harmonic reduction effect were verified by simulation. The proposed system performed the same power transfer as the conventional system under resonance conditions. Harmonic analysis results show that FCC reduces voltage harmonics by more than 25 dB. In particular, the third harmonic was reduced by 37.2dB and the fifth harmonic by 35.1 dB. The proposed system also reduced low-order current harmonics by more than 25 dB. In particular, the third harmonic was reduced by 37.2dB and the fifth harmonic by 35.1 dB.

In future work, the reduction effects of the current harmonics and the radiated emission harmonics will be verified by the prototypes with the proposed system.

References

[1] K. Kusaka, R. Kusui, J. Itoh, D. Sato, T. Shijo, S. Obayashi, M. Ishida: “A 22kW Three-phase Wireless Power Transfer System in Compliance with CISPR 11 and ICNIRP 2010,” IEEJ Journal of Industry Applications, vol. 11, no. 4, pp. 594-602 (2022)

[2] R. Okada, R. Ota, N. Hoshi: "Novel Soft-Switching Active-Bridge Converter for Bi-directional Inductive Power Transfer System," IEEJ Journal of Industry Applications, vol. 11, no. 1, pp. 97-107 (2020)

[3] H. Sumiya, E. Takahashi, N. Yamaguchi, K. Tani, S. Nagai, T. Fujita, H. Fujimoto: "Coil Scaling Law of Wireless Power Transfer Systems for Electromagnetic Field Leakage Evaluation for Electric Vehicles," IEEJ Journal of Industry Applications, Vol. 10, No. 5, pp. 589-597 (2021)

[4] Ministry of Internal Affairs and Communications, Japan, “Inquiry of technical requirements for wireless power transfer system for EVs in technical requirements for wireless power transfer system in standards of International Special Committee on Radio Interference (CISPR)”, (2015)

[5] International Commission on Non-Ionizing Radiation Protection (ICNIRP): “Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz)”, Health Phys., vol. 118, no. 5, pp. 483-524 (2020)

[6] N. Misawa：" Situation of EMC Limit Level of WPT for EV in CISPR, " 2019 JSAE Annual Congress (Spring) Latest Trend of EV Charging System, No. 20194438, pp.15-20 (2019)

[7] K. Kusaka, J. Itoh: “Development Trends of Inductive Power Transfer Systems Utilizing Electromagnetic Induction with Focus on Transmission Frequency and Transmission Power,” IEEJ Journal of Industry Applications, vol. 6, no. 5, pp. 328-339 (2017)

[8] A. Tejeda, S. Kim, F. Y. Lin, G. A. Covic and J. T. Boys, "A Hybrid Solenoid Coupler for Wireless Charging Applications," in IEEE Trans. on Power Electronics, vol. 34, no. 6, pp. 5632-5645 (2019)

[9] K. Furukawa, K. Kusaka, J. Itoh: "General Analytical Model of Inductance Variation by EMF-canceling Coil for Inductive Power Transfer System", IEEJ Journal of Industry Applications, vol. 8, no. 4, pp. 660-668 (2019)

[10] S. Kim, H. -H. Park, J. Kim, J. Kim, S. Ahn, "Design and Analysis of a Resonant Reactive Shield for a Wireless Power Electric Vehicle," IEEE Trans. on Microwave Theory and Techniques, vol. 62, no. 4, pp. 1057-1066 (2014)

[11] R. Kusui, K. Kusaka, J. Itoh: “Wireless Power Transfer System with Multi-level Inverter for Reduction of Current Harmonics”, 2022 IEE-Japan Industry Applications Society Conference, vol. 1, no. 24, pp. 127-130 (2022)