Derivation of Low-Order Harmonic Leakage Magnetic Fields in Double-LCC Circuit and its Effectiveness for their Reduction

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***Abstract*— In recent years, the technology of wireless power supply for automobiles has been attracting attention in order to reduce CO2 emissions. There are several issues to be addressed in the realization of wireless power transfer, one of which is magnetic field leakage. Magnetic leakage fields have the potential to adversely affect the surrounding human body and electronic equipment and must be reduced. Both fundamental and harmonic leakage magnetic fields need to be reduced, but there are still few examples of research on harmonics. Therefore, in this paper, as a preparatory step to reduce the harmonic leakage magnetic field, a theoretical equation for the harmonic leakage magnetic field in Double-LCC circuits is derived. The validity of the theoretical equation was confirmed by comparing calculated values using the theoretical equation with simulated values. It was also confirmed that by setting the circuit parameters appropriately, the 3rd to 11th low-order harmonic leakage magnetic fields were reduced by about 25 dB, respectively.**

Keywords—Wireless Power Transfer, Harmonic Leakage Magnetic Fields

I. Introduction

In recent years, there has been a shift from gasoline-powered to electric vehicles in order to reduce CO2 emissions. However, electric vehicles have problems such as short cruising range and time-consuming recharging. To solve these problems, wireless power transfer technology has been attracting attention. There are several challenges in realizing wireless power transfer, one of which is magnetic field leakage. There are two types of magnetic leakage fields: near magnetic leakage fields, which are mainly concerned about effects on the human body and occur at distances from the coil ranging from a few cm to 3 m, and far magnetic leakage fields, which are evaluated at 10 m from the reference location and are mainly concerned about effects on electronic equipment, and the regulation values are specified by CISPR11, Article 46 of Japan's Radio Act and other regulations [1]~[2]. Therefore, in order to realize wireless power transfer, it is necessary to reduce the leakage magnetic field to below the regulation value. Research on reducing the magnetic leakage field of the fundamental wave is in progress [3]~[5]. On the other hand, leakage field reduction methods for harmonics include shielding [6], control [7]~[9], and circuits [10].

In a previous study [6], a reactive shielded coil that does not require an additional power supply by using an induced voltage and a frequency split phenomena are used to reduce harmonic leakage magnetic fields while improving power transmission efficiency. In a previous study [7], harmonic currents are suppressed by fast switching of the inverter on the transmission side and the rectifier on the receiving side to reduce low-order harmonic leakage magnetic fields. In a previous study [8], both fundamental and harmonic currents flowing through the transmitter and receiver coils are reduced by a multi-input single-output system. In a previous study [9], harmonic currents in the currents flowing through the transmitter and receiver coils, which cause harmonic leakage magnetic fields, are reduced by installing FCCs on both the transmitter and receiver sides. In a previous study [10], by using an LCL-LCL circuit, the input impedance is increased at odd harmonics, and the odd harmonic currents and magnetic fields are reduced. This paper introduces the reduction of low-order harmonic leakage magnetic fields by Double-LCC circuit.

The purpose of this paper is to reduce the distant low-order harmonic leakage magnetic fields that occur in SWPT(Static Wireless Power Transfer). As a preparatory step to reduce the low-order harmonic leakage magnetic field, a theoretical equation for the harmonic leakage magnetic field in a Double-LCC circuit is derived, and the validity of the theoretical equation is confirmed by comparing the waveform of the current flowing in the Double-LCC circuit and the harmonic leakage magnetic field with the results of circuit simulation and electromagnetic analysis. Furthermore, by setting appropriate circuit parameters through analysis using the theoretical equation we will confirm that low-order harmonic leakage magnetic fields are reduced and verify that the Double-LCC circuit is effective in reducing the low-order harmonic leakage magnetic field.

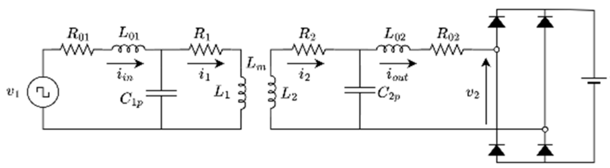


Fig. 1. LCL-LCL circuit.

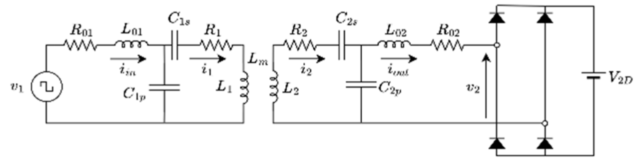


Fig. 2. Double-LCC circuit.

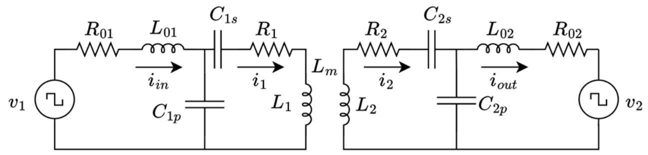


Fig. 3. Double-LCC circuit for each order.

II. THEORY

A. About Double-LCC Circuit

Fig. 1 shows the LCL-LCL circuit and Fig. 2 shows the Double-LCC circuit. in the LCL-LCL circuit, the values of the compensation inductances L_{01}, L_{02} must match the values of the transmitting and receiving coils L_1, L_2, respectively, to satisfy the resonance condition at the resonance frequency. However, by connecting capacitors in series with the transmitting and receiving coils in the LCL-LCL circuit, the resonant coils L_{01}, L_{02} can gain degrees of freedom. This circuit is the Double-LCC circuit.

B. Equations of Currents

Fig. 3 shows the circuit of Fig. 2 for each order m, where m is a positive odd number. The resonant angular frequency is ω_0, and the operating angular frequency at each order m is $\omega_{mth} = m\omega_0$. The values of the capacitors in Figs. 1~3 are expressed by (1) using the resonance condition, and the internal resistance of each inductor is expressed by (2).

$$C_{\alpha p} = 1/\omega_0^2 L_{0\alpha}\, , C_{\alpha s} = 1/\omega_0^2 (L_\alpha - L_{0\alpha}) \tag{1}$$

$$R_\beta = \omega_{mth} L_\beta / Q_\beta \tag{2}$$

However, $\alpha = 1, 2$ *and* $\beta = 01, 02, 1, 2$ respectively. Q_β is the Q value of each inductor on the circuit of Figs. 1~3.

From the circuit in Fig. 3, the input current I_{in}^m, output current I_{out}^m, transmitting coil current I_1^m, and receiving coil current I_2^m at each order m are expressed by equations (3)~(6), respectively. The parameters in (3)~(6) are shown in (7)~(11).

$$A_\alpha = \omega_0 L_{0\alpha} Q_{0\alpha} Q_\alpha + m^4 \omega_0 L_\alpha - (m^2 - 1)^2 \omega_0 L_\alpha Q_{0\alpha} Q_\alpha \tag{7}$$

$$B_\alpha = m^2 (m^2 - 1) \omega_0 L_\alpha (Q_{0\alpha} + Q_\alpha) \tag{8}$$

$$C_\alpha = m^2 (m^2 - 1) \omega_0 L_m Q_{0\alpha} Q_\alpha \tag{9}$$

$$D_\alpha = m^4 \omega_0 L_m Q_\alpha \tag{10}$$

$$E_\alpha = m Q_{0\alpha} Q_\alpha \tag{11}$$

The formula for obtaining the instantaneous value currents are expressed in (12).

$$i_\gamma = \sum_{m=1}^{11} \sqrt{2} \left\{ \begin{matrix} \mathrm{Re}(I_\gamma^m) \sin(\omega_{mth} t) \\ +\mathrm{Im}(I_\gamma^m) \sin\left(\omega_{mth} t + \frac{\pi}{2}\right) \end{matrix} \right\} \tag{12}$$

However, $\gamma = in,\ out,\ 1,\ 2$.

C. Voltage Setting

This paper assumes that the waveform of the output voltage of the inverter on the input side is a square wave and that a diode rectifier is used as the rectifier on the output side. Therefore, it is assumed that a square wave voltage is applied to both the input and output sides in the circuit assumed in this paper. The square wave is represented by (13) using the maximum value V_D.

$$V = \sum_{m=1}^{\infty} \frac{4}{\pi} \frac{V_D}{m} \sin m(\omega_0 t + \theta) \tag{13}$$

To consider the phase difference between input and output voltages, the fundamental wave equations for input and output currents, i.e., equations (3) and (4) , are substituting $m = 1$ and are further simplified, are represented by (14) and (15).

$$I_{in} \fallingdotseq \frac{j L_m V_2}{\omega_0 L_{01} L_{02}} \tag{14}$$

$$I_{out} \fallingdotseq -\frac{j L_m V_1}{\omega_0 L_{01} L_{02}} \tag{15}$$

Since the input voltage and input current and the output voltage and output current are in phase with each other, Equations (14) and (15) show that the voltage on the output side is 90° behind the voltage on the input side in the fundamental wave.

In the resonant state, the phase of the fundamental output voltage lags behind the phase of the fundamental input voltage by 90°. Therefore, (16) and (17) are used for each order m for the voltage.

$$I_{in}^m = \frac{[\{mQ_{01}(A_1A_2 - B_1B_2 - C_1C_2 + D_1D_2) - \omega_0 L_{01} Q_{01} A_2 E_1\} + j\{mQ_{01}(A_1B_2 + A_2B_1 + C_1D_2 + C_2D_1) - \omega_0 L_{01} Q_{01} B_2 E_1\}]V_1^m - \omega_0 L_{01} Q_{01} E_2 (C_1 - jD_1) V_2^m}{\{m^2 \omega_0 L_{01} + j(m^2 - 1)\omega_0 L_{01} Q_{01}\}\{(A_1A_2 - B_1B_2 - C_1C_2 + D_1D_2) + j(A_1B_2 + A_2B_1 + C_1D_2 + C_2D_1)\}} \tag{3}$$

$$I_{out}^m = \frac{\omega_0 L_{02} Q_{02} E_1 (C_2 - jD_2) V_1^m - [\{mQ_{02}(A_1A_2 - B_1B_2 - C_1C_2 + D_1D_2) - \omega_0 L_{02} Q_{02} A_1 E_2\} + j\{mQ_{02}(A_1B_2 + A_2B_1 + C_1D_2 + C_2D_1) - \omega_0 L_{02} Q_{02} B_1 E_2\}]V_2^m}{\{m^2 \omega_0 L_{02} + j(m^2 - 1)\omega_0 L_{02} Q_{02}\}\{(A_1A_2 - B_1B_2 - C_1C_2 + D_1D_2) + j(A_1B_2 + A_2B_1 + C_1D_2 + C_2D_1)\}} \tag{4}$$

$$I_1^m = \frac{E_1(B_2 - jA_2)V_1^m - E_2(D_1 + jC_1)V_2^m}{(A_1A_2 - B_1B_2 - C_1C_2 + D_1D_2) + j(A_1B_2 + A_2B_1 + C_1D_2 + C_2D_1)} \tag{5}$$

$$I_2^m = \frac{E_1(D_2 + jC_2)V_1^m - E_2(B_1 - jA_1)V_2^m}{(A_1A_2 - B_1B_2 - C_1C_2 + D_1D_2) + j(A_1B_2 + A_2B_1 + C_1D_2 + C_2D_1)} \tag{6}$$

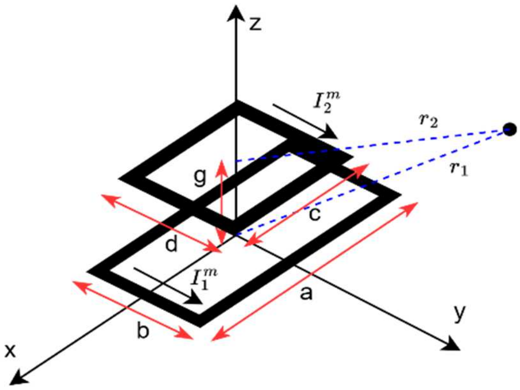


Fig. 4. Positional relationship between coil and measurement position.

$$V_1^m = 2\sqrt{2}V_D/\pi m \quad (16)$$

$$V_2^m = \begin{cases} -jV_1^m (m = 1, 5, 9) \\ jV_1^m (m = 3, 7, 11) \end{cases} \quad (17)$$

D. Harmonic Leakage Magnetic Fields

Fig. 4 shows the positional relationship between the coil and the measurement position. For the magnetic field calculation, the vector potential method described in a previous study [10] was used. Let s be the number of turns of the transmitting coil and t be the number of turns of the receiving coil. The magnetic field H_1^m generated by the transmitting coil is expressed by (18), the magnetic field H_2^m generated by the receiving coil is expressed by (19), and the magnitude of the combined magnetic field is expressed by (20).

$$H_1^m = \begin{pmatrix} H_{1,x}^m \\ H_{1,y}^m \\ H_{1,z}^m \end{pmatrix} = \begin{pmatrix} \frac{\sum_{k=1}^{s} a_k b_k}{4\pi} \frac{3xz}{r_1^5} I_1^m \\ \frac{\sum_{k=1}^{s} a_k b_k}{4\pi} \frac{3yz}{r_1^5} I_1^m \\ \frac{\sum_{k=1}^{s} a_k b_k}{4\pi} \frac{2z^2 - x^2 - y^2}{r_1^5} I_1^m \end{pmatrix} \quad (18)$$

$$H_2^m = \begin{pmatrix} H_{2,x}^m \\ H_{2,y}^m \\ H_{2,z}^m \end{pmatrix} = \begin{pmatrix} \frac{\sum_{k=1}^{t} c_k d_k}{4\pi} \frac{3x(z-g)}{r_2^5} I_2^m \\ \frac{\sum_{k=1}^{t} c_k d_k}{4\pi} \frac{3y(z-g)}{r_2^5} I_2^m \\ \frac{\sum_{k=1}^{t} c_k d_k}{4\pi} \frac{2(z-g)^2 - x^2 - y^2}{r_2^5} I_2^m \end{pmatrix} \quad (19)$$

$$H^m = \sqrt{\left|H_{1,x}^m - H_{2,x}^m\right|^2 + \left|H_{1,y}^m - H_{2,y}^m\right|^2 + \left|H_{1,z}^m - H_{2,z}^m\right|^2} \quad (20)$$

The regulation values for low-order harmonic leakage magnetic fields shall be more stringent for each order among the values specified in CISPR11 and Article 46 of the Radio Act.

III. For the Values of Compensation Inductances L_{01} and L_{02}

A. Setting Conditions

Set the values of compensation inductances L_{01} and L_{02} based on the current and low-order harmonic leakage magnetic fields calculated by theoretical calculation. The conditions for setting the values of compensation inductances L_{01} and L_{02} were that the third-order harmonic leakage magnetic field should be below the regulation value and that each current flowing through the circuit should be below 96 A, which is the allowable current for the Litz wire assumed for use.

The resonant frequency of the coil was set to 85 kHz as was the operating frequency. The output power was fixed at 3.3 kW to account for low-order harmonic leakage magnetic fields in SWPT. The magnetic field was measured at $x = 0$ m, $y = 11.9$ m, and $z = 1$ m in the coordinate system with the center of the transmitting coil as shown in Fig. 4 as the origin. The 11.9 m distance was chosen because the SAE standard defines a radius of 1.9 m from the center of the receiving coil as the WPT Measurement Boundary which power supplies and other equipment are installed, and the analysis point was set 10 m, which is considered far field in leak age magnetic field, away from there. The values of compensation inductances L_{01} and L_{02} were varied by 0.5 μH from 0.5 μH to 45.5 μH, respectively.

B. Allowable Current

The conditions are found for compensation inductances L_{01} and L_{02} such that each current flowing through the circuit in Figure 3 is less than the allowable current of 96A. The fundamental wave equations for input and output currents, i.e., equations (5) and (6) , are substituting $m = 1$ and are further simplified, are represented by (21) and (22).

$$I_1 \fallingdotseq -j\frac{V_1}{\omega_0 L_{01}} \quad (21)$$

$$I_2 \fallingdotseq j\frac{V_2}{\omega_0 L_{02}} \quad (22)$$

From equations (14) and (15), the larger the compensation inductances L_{01} and L_{02}, the smaller the input and output currents. Also, from (21), the larger L_{01} is, the smaller the transmitting coil current is, and from (22), the larger L_{02} is, the smaller the receiving coil current is. Therefore, it's considered the larger the compensating inductances L_{01} and L_{02} should be under the condition of allowable current.

Fig. 5 shows the conditions for each current flowing in the circuit. The blue and orange areas satisfy the conditions for an allowable current of 96 A or less, indicating that the compensation inductances L_{01} and L_{02} should be larger. From Fig. 5(c), (d), it can be seen that the values of L_{01} and L_{02} should be close together, because the difference in current values of the transmitting and receiving coils becomes larger when the values of L_{01} and L_{02} are far apart.

C. Allowable Leakage Magnetic Field

The conditions are found for the compensation inductances L_{01} and L_{02} such that the low-order harmonic leakage magnetic field generated by the transmitting/receiving

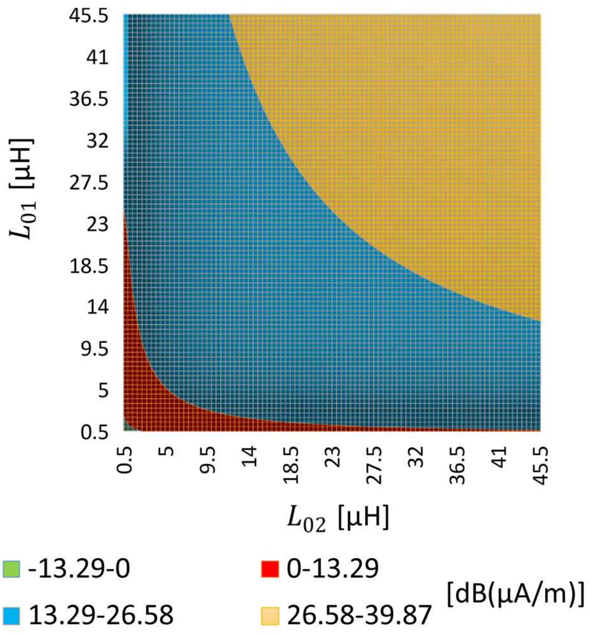


Fig. 6. 3rd harmonic leakage magnetic field condition.

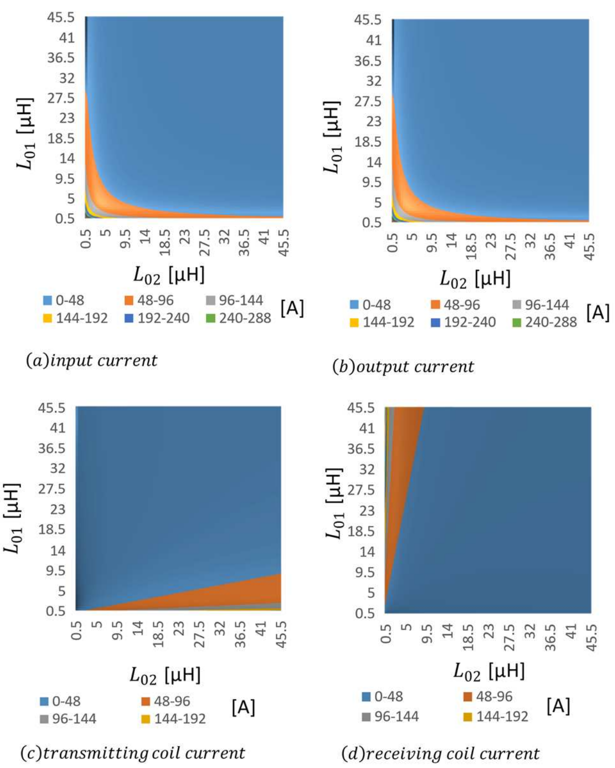


Fig. 5. Currents conditions.

coil in the circuit shown in Fig. 3 is less than the regulation value.

Equation (23) is a simplified version of equation (5) for the transmitting coil current. From (23), it can be seen that there is no correlation between the compensation inductances and the transmitting coil current. Simplifying (6) for the receiving coil current also shows no correlation with the compensation inductances, as in (23). Since the transmitting and receiving coils are fixed this time, the harmonic leakage

magnetic field depends on the magnitude of the input/output voltage. Therefore, with the receiving power fixed, the value

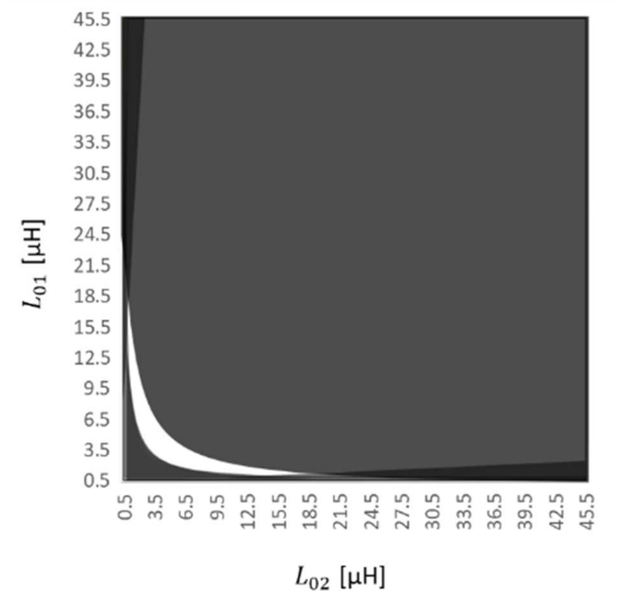


Fig. 7. Compensation inductances condition.

of output current should be increased to reduce the voltage value. In other words, under the condition of low-order harmonic leakage magnetic field, it's considered the compensation inductances should be small.

$$I_1^m \fallingdotseq j\frac{m(m^2-1)L_2V_1^m - m^3L_mV_2^m}{(m^2-1)\omega_0\{(m^2-1)^2L_1L_2 - m^4L_m^2\}} \qquad (23)$$

Fig. 6 shows the values of the third harmonic leakage magnetic field, where the red and green areas in Fig. 6 are below the regulation value (13.29 dB (μA/m)).

D. Compensation Inductances Setting

The combined conditions shown in Figs. 5 and 6 are shown in Fig. 7, where white area satisfies all conditions. From Fig. 7, the compensation inductances L_{01} and L_{02} were set to the same value because the magnitude of the transmitting /receiving coil currents is not biased and the low-order harmonic leakage magnetic field is easily reduced. In that case the values of compensation inductances L_{01} and L_{02} that satisfy the setting conditions are 3.5~5 μH. In this case, the value of compensation inductances L_{01} and L_{02} was set to 5 μH.

IV. Currents in Double-LCC Circuit

A. Comparison of Theoretical Calculation and Circuit Simulation

Circuit simulation was performed using LTspice. Table 1 shows the parameters used for theoretical calculations and circuit simulations, electromagnetic field analysis. The maximum value of the square wave, V_D, is set so that the power received is 3.3 kW. The capacitors in the circuit model were calculated from (1). For resistance, the fundamental wave value obtained from (2) was used.

Figs. 8 and 9 show a comparison of current waveforms in Double-LCC circuit obtained from theoretical calculations and circuit simulations. The current waveform obtained by

TABLE I. PARAMETERS

Parameter	value
Operating frequency	85 kHz
V_D （Double-LCC）	62.41 V
V_D （LCL-LCL）	1011 V
L_1	96.8 μH
L_{01}	5.00 μH
L_2	67.9 μH
L_{02}	5.00 μH
L_m	14.1 μH
Quality factor	500
order m	1, 3, 5, 7, 9, 11

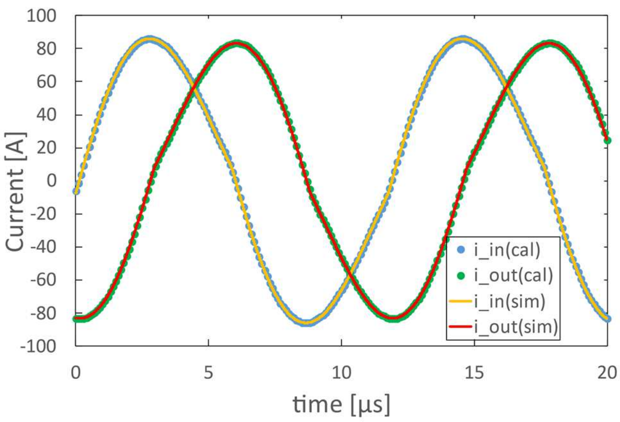


Fig. 8. Input/output current waveform.

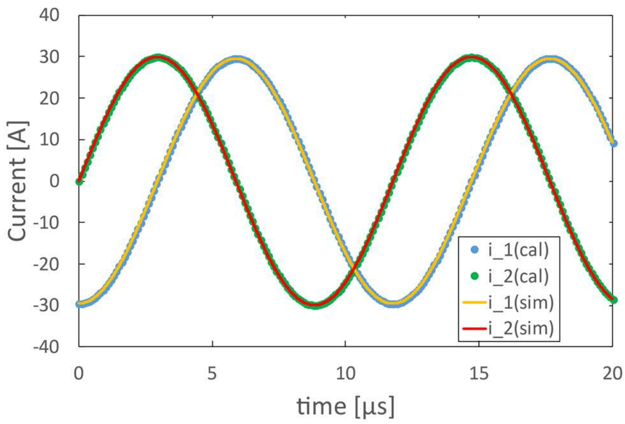


Fig. 9. Transmitting and Receiving coil current waveform.

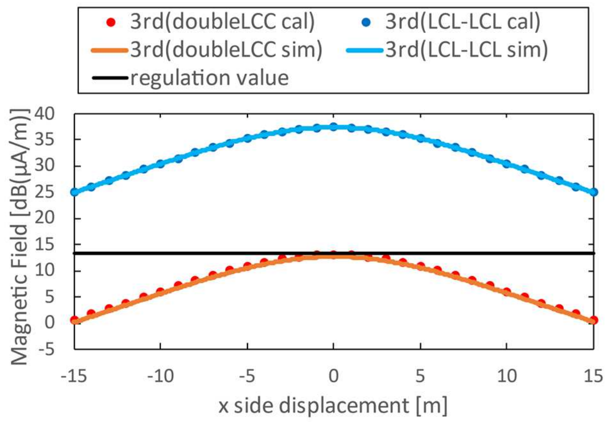
theoretical calculation is a composite waveform from the fundamental to the 11th order.

Figs. 8 and 9 show that the current waveforms obtained by calculation and by circuit simulation are almost identical.

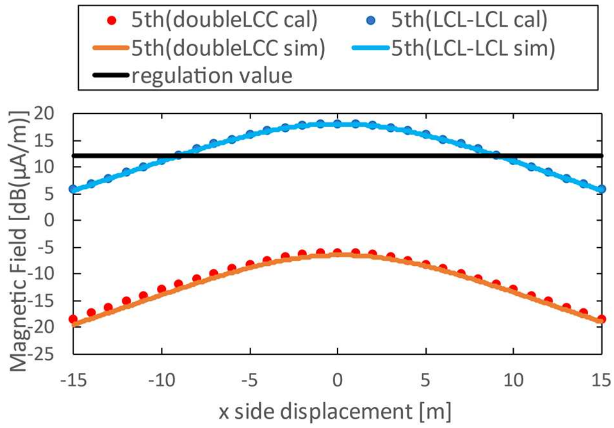
V. ABOUT LOW-ORDER HARMONIC LEAKAGE MAGNETIC FIELDS

A. Low-Order Harmonic Leakage Magnetic Fields

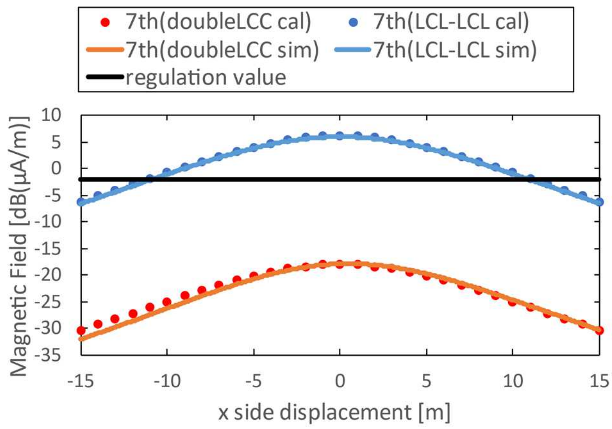
A comparison of theoretical calculations and simulations of low-order harmonic leakage magnetic fields was performed. Simulations were performed by the method of moments using FEKO, an electromagnetic field analysis software. The magnitudes of the magnetic fields in the Double-LCC and LCL-LCL circuits are compared to confirm the reduction of



(a) Leakage Magnetic Field (3rd wave).



(b) Leakage Magnetic Field (5th wave).



(c) Leakage Magnetic Field (7th wave).

Fig. 10. Low-Order Harmonic Leakage Magnetic Field.

the low-order harmonic leakage magnetic field by setting the values of the compensation inductances L_{01} and L_{02}. Also, a comparison with the regulation values will be performed.

The parameters in Table 1 were used for theoretical calculations and electromagnetic field analysis. Values obtained from FEKO were used for the Quality factor of the transmitting and receiving coils. The measurement points of magnetic field was set at $x = -15 \sim 15$ m, $y = 11.9$ m, $z = 1$ m in the coordinate system with the center of the transmitting coil as shown in Fig. 4 as the origin.

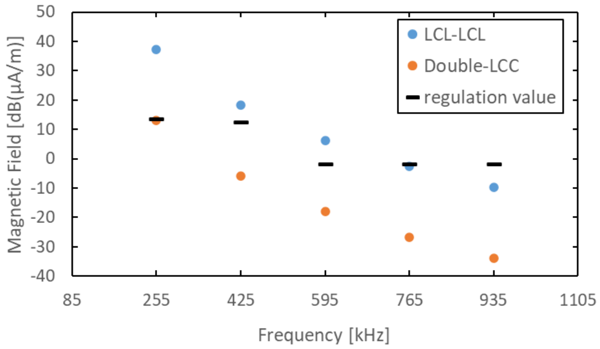


Fig. 11. Leakage Magnetic Field (3rd~11th wave).

B. *Comparison of Theoretical Calculation and Electromagnetic Field Analysis*

Fig. 10 shows a comparison between theoretical calculation and electromagnetic field analysis of the magnitude of low-order harmonic leakage magnetic fields at 3rd, 5th, and 7th orders, respectively. Fig. 11 compares theoretical calculation and regulation values for the magnitude of the 3rd~11th harmonic leakage magnetic field at $x = 0$ m.

Fig. 10 shows that the magnitudes of the far-field low-order harmonic leakage magnetic fields obtained by theoretical calculation and electromagnetic field analysis are almost identical. From Fig. 11 it can be seen that by properly setting the element parameters of the Double-LCC circuit, the leakage magnetic field was reduced by about 25 dB(μA/m) at each order compared to the LCL-LCL circuit. Due to this reduction it was lower than the regulation value.

VI. Conclusion

In this paper, the effectiveness of Double-LCC circuit in case of reducing the far-field low-order harmonic leakage magnetic fields generated in SWPT was verified through theoretical calculations and simulations. The validity of the theoretical equation is demonstrated by comparing the waveform of the current flowing in the circuit and the magnitude of the magnetic field between theoretical calculations and simulated values. In addition, the 3rd to 11th harmonic leakage magnetic fields were reduced by about 25 dB(μA/m) each by appropriately setting the values of compensation inductances L_{01} and L_{02} to satisfy the conditions with the output power kept constant based on the theoretical equation.

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