

Proposal of Synchronous Rectification Method Using Only DC Current Values Based on Three-Phase Assumption for Reducing Leakage Magnetic Fields in Dynamic Wireless Power Transfer

Sho Igarashi

Faculty of Science and Engineering
Tokyo University of Science
Chiba, Japan
igarashi.sho25@gmail.com

Yusuke Sato

Faculty of Science and Engineering
Tokyo University of Science
Chiba, Japan

Takehiro Imura

Faculty of Science and Engineering
Tokyo University of Science
Chiba, Japan

Yoichi Hori

Faculty of Science and Engineering
Tokyo University of Science
Chiba, Japan

Abstract— One challenge in wireless power transfer during motion with multiple inputs and outputs is leakage magnetic fields. To achieve the social implementation of DWPT, control based on leakage magnetic field reduction is essential. Therefore, we propose a control method based on a three-phase DWPT system that shifts the phase difference between power transmission coils by 120-degree angle, a technique reported to reduce leakage magnetic fields. Furthermore, the synchronous rectification used in the system requires no communication between the power transmission and reception sides and can be controlled solely by the DC current at the receiving end. Simulation confirmed that the proposed method achieves a 4.5% improvement in efficiency compared to conventional systems using diode rectification and reduces the magnitude of leakage magnetic fields by 20.7 dB compared to existing systems.

Keywords— *Dynamic Wireless Power Transfer, DWPT, MIMO, Leakage Magnetic Field, Synchronous Rectifier*

I. INTRODUCTION

Currently, numerous studies are underway on electric vehicles (EVs) to achieve carbon neutrality [1]. While limited range remains a challenge for EVs, equipping them with large batteries increases vehicle weight and raises prices, hindering widespread adoption. Additionally, the lengthy charging time is a major source of stress for consumers. This has led to increased attention on Dynamic Wireless Power Transfer (DWPT) for EVs, which utilizes Wireless Power Transfer (WPT) [2]. One potential implementation site for DWPT is

highways, where its deployment on large commercial vehicles such as trucks and buses could bring significant innovation to the logistics industry. Research is being conducted on a multiple-input multiple-output (MIMO) DWPT system for transmitting and receiving high-power electricity to large commercial vehicles [3]. However, an issue arises where, as the number of transmission coils increases, the leakage magnetic field that spills out externally without coupling with the receiving coils also increases. To address this issue, it has been reported that applying a 120-degree angle phase difference between multiple transmission coils and configuring them as three phases can reduce leakage magnetic fields [4][5]. However, this pertains to Static Wireless Power Transfer (SWPT) and has not been controlled for Dynamic Wireless Power Transfer (DWPT). Furthermore, this paper employs diode rectification, which introduces conduction losses and power factor lag, leading to reduced efficiency and output power.

Synchronous rectification has been proposed as a control method unaffected by these influences. However, a challenge with DWPT, which passes over the transmission coil in a short time, is that communication between the transmission and reception systems is difficult, making phase synchronization impossible. Therefore, research [6] has been conducted on placing a signal coil decoupled from the power-exchanging coil to transmit the gate signal of the synchronous rectifier. However, this requires additional systems on both the power

transmission and reception sides. Consequently, it is necessary to construct a system capable of performing synchronous rectification under the three-phase conditions on the transmission side without adding components. Furthermore, it is important that each receiving coil requires independent control because each sending coil has a 120-degree angle phase difference.

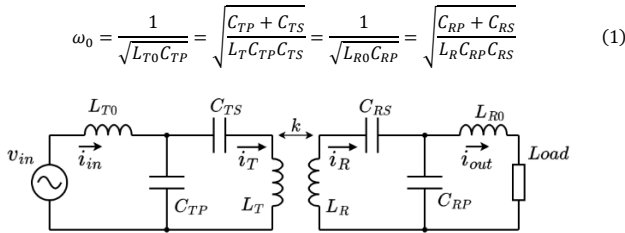
This paper proposes a controllable synchronous rectification method that can be applied even when the transmission side is three-phase. The proposed method utilizes the DC current value at the receiving end and implements phase shifting. Consequently, the proposed method achieves synchronous rectification without requiring additional components or communication systems.

This paper describes the circuit configuration in Chapter 2 and the proposed method in Chapter 3. Chapter 4 presents the circuit simulation results, and Chapter 5 shows the magnetic field simulation results. Finally, Chapter 6 presents the conclusions.

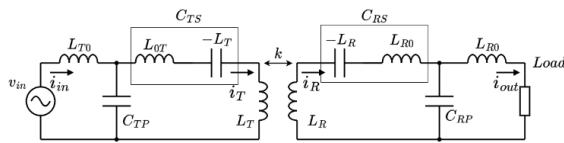
II. THEORY

A. Double-LCC Topology

WPT can significantly enhance transmission power and efficiency by utilizing magnetic resonance phenomena [7]. This paper adopts a circuit configuration known as the Double-LCC circuit [8]. The schematic diagram of the Double-LCC circuit is shown in Fig. 1(a), and the resonance condition is given by equation (1). Fig. 1(b) shows a block diagram of the Double-LCC circuit. The gyrator circuit can be formed using L_{T0} and C_{TP} , and L_{R0} and C_{RP} , and it has the property of inverting the voltage and current characteristics between the input and output terminals. This results in a constant-current characteristic on the load side, offering the advantage of being suitable for charging batteries, which are constant-voltage loads. Furthermore, the Double-LCC circuit has been reported to be effective for vehicle detection and reducing standby losses. [9][10]



(a) Circuit diagram



(b) Gyrator exploded view

Fig. 1 Double-LCC Circuit

B. Three Phase DWPT

The three-phase system, a prerequisite for this paper, aims to reduce leakage magnetic fields. Leakage magnetic fields are a concern due to their potential adverse effects on humans and electronic equipment. Therefore, as shown in Table 1, it has been reported that power transmission using a three-phase system with phases shifted by 120-degree angle on the transmission side can reduce leakage magnetic fields [4]. This paper discusses control of the receiving side based on the assumption of three-phase transmission.

Table 1 Three-phase leakage magnetic field reduction effect

	Theoretical value[nT]	Simulation values[nT]
Same phase	184	188
Three phase	58.9	58.5

III. METHOD

A. System Configuration

The system under consideration is shown in Fig. 2. This configuration consists of five transmit coils and three receive coils, forming a 5-to-3 arrangement. On the transmit side, a full-bridge inverter is connected to a DC power source. Each transmit coil is connected to a full-bridge inverter, generating a 120-degree angle phase difference between transmit coils. The resonant circuit employs a Double-LCC configuration, with a synchronous rectifier composed of MOSFETs connected to each power-receiving coil on the receiving side. After DC conversion by the synchronous rectifier, the circuit connects to the battery (constant-voltage load).

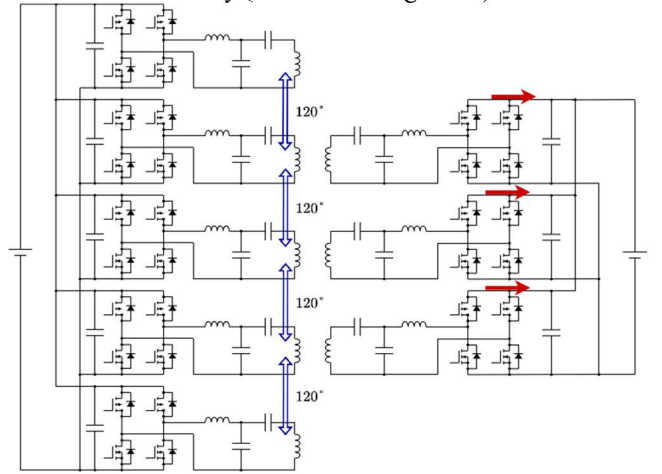


Fig. 2 System configuration

B. Proposal for Synchronous Rectification

The proposed synchronous rectification method employs a technique that utilizes only the DC current value [11]. In this implementation, this control is applied to each receiving coil, driving them independently. Consequently, this control method can accommodate phase variations between the transmission coils. The specific control method is shown in Fig. 3. The DC current value is measured at the observation point indicated by the red arrow in Fig. 2. Using the calculation within the red box in Fig. 3, the operating phase is sequentially shifted toward the point where the current value is maximum that is, the point where the received power is maximum to track the maximum power point. Ultimately, the control system ensures that each receiving coil tracks the maximum power point, achieving a 90-degree angle phase difference between transmission and reception.

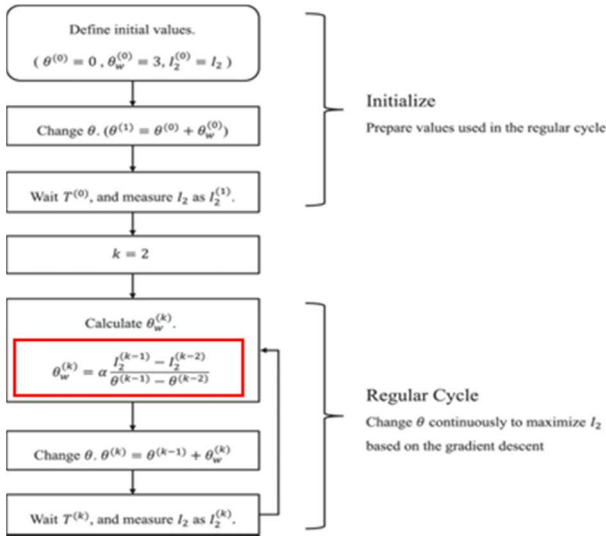


Fig. 3 Synchronous Rectification Process [11]

IV. SIMULATION OF CIRCUIT

A. Circuit Simulation Conditions

To verify the feasibility of the proposed synchronous rectification method, simulations were performed using MATLAB/Simulink. In the simulation, a system comprising five transmission coils and three reception coils, as shown in Fig. 4, was configured and verified. The Cross-Coupling (CC) between reception coils was set to $k_{RR} = -0.01$, targeting regions where the influence of cross-coupling between reception coils is not dominant. The circuit parameters used in this simulation are shown in Table 2. Fig. 5 shows the 5-to-3 coupling coefficient data used in this simulation.

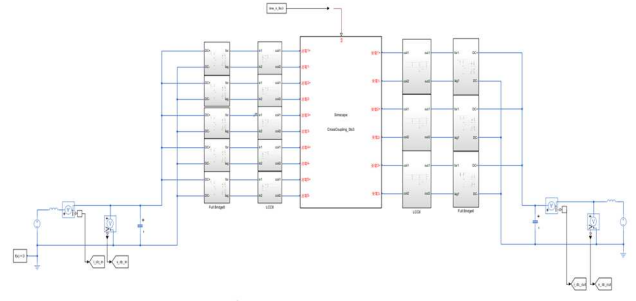


Fig. 4 Circuit Simulation Configuration

Table 2 Simulation parameters.

Vehicle velocity	v	20 km/h
Primary voltage	V_{DC}	200 V
Operation frequency	f	85 kHz
Primary compensated inductance	L_{T0}	49.3 μ H
Primary compensated capacitor	C_{TP}	71.1 nF
Primary resonant capacitor	C_{TS}	22.4 nF
Primary transmitter inductance	L_T	205.8 μ H
Secondary compensated inductance	L_{R0}	26.4 μ H
Secondary compensated capacitor	C_{RP}	132.6 nF
Secondary resonant capacitor	C_{RS}	139.8 nF
Secondary receiver inductance	L_R	51.5 μ H

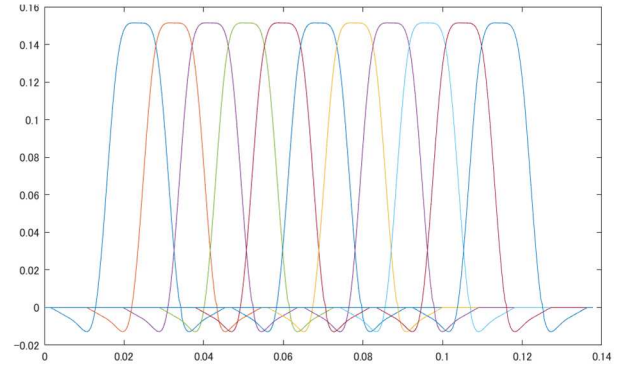


Fig. 5 5-to-3 coupling coefficient data

B. Circuit simulation results

The waveforms shown in Fig. 6 represent the input power and output power waveforms during synchronous rectification in the proposed method. Next, Fig. 7 shows the output current waveform for each receiving coil. Fig. 8 shows the phase change pattern when focusing on the first receiving coil. The areas enclosed by red frames indicate where control is being applied, and it can be observed that the phase difference from each transmission coil, offset by 120-degree angle, is tracking the target value of 90-degree angle advance. Finally, Fig. 9 shows the output power waveforms for the conventional diode rectification method. Furthermore, Table 3 shows the comparison results for efficiency and average output power. Table 3 confirms that the proposed method improves system efficiency by approximately 4.5 % and increases average

power by approximately 100 W compared to conventional diode rectification. The improved efficiency and average output power can be attributed to the elimination of conduction losses caused by the forward voltage drop of diodes through synchronous rectification. Additionally, phase control on the receiving side improved the power factor, reducing reactive power.

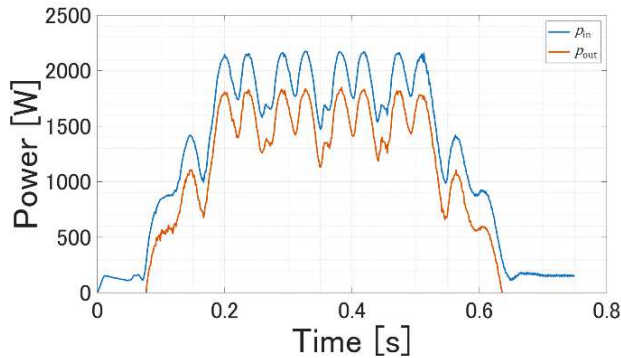


Fig. 6 Power waveform

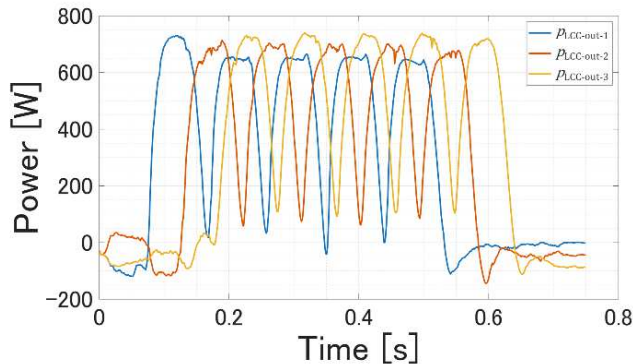


Fig. 7 Rx power waveform

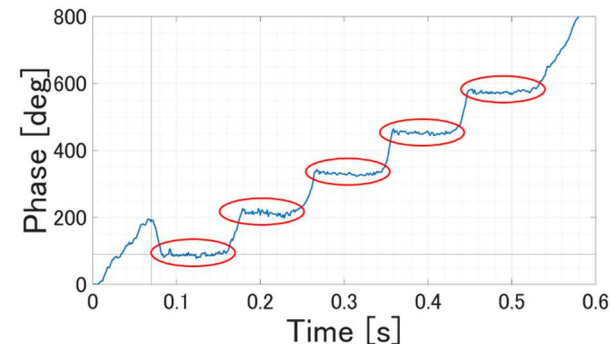


Fig. 8 Phase tracking performance

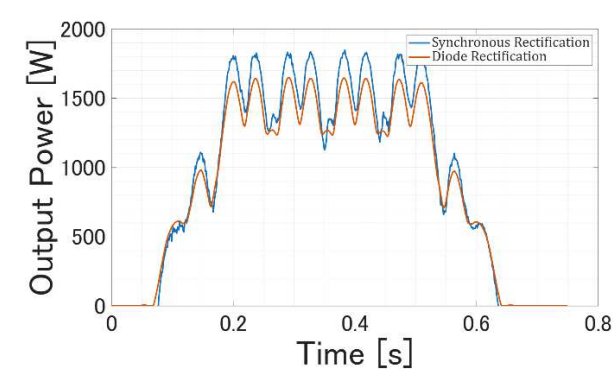


Fig. 9 Power waveform comparison

Table 3 Output Power and Efficiency Comparison		
Rectification method	η [%]	$P_{out\ Av}$ [kW]
Diode Rectification	74.65	1.156
Synchronous Rectification	79.15	1.259

V. SIMULATION OF LEAKAGE MAGNETIC FIELDS

A. Magnetic Field Simulation Conditions

Simulations were performed using FEKO, an electromagnetic field analysis software based on the method of moments. The simulation model consisted of three transmission coils and three reception coils, as shown in Fig. 10. This configuration assumes that only three of the transmission coils laid on the road surface contribute to power transmission and reception. Comparisons were made between a three-phase configuration with a 120-degree angle phase difference between transmission coils, similar to circuit simulation, and a phase-free, in-phase state. Measurements were taken at a height of $z=1$ m, along a circular path with a radius of 11.9 m, covering the range from 0-degree angle to 360-degree angle, as shown in Fig. 11. This distance of 11.9 m is based on the evaluation criteria set forth in SAE J2954.

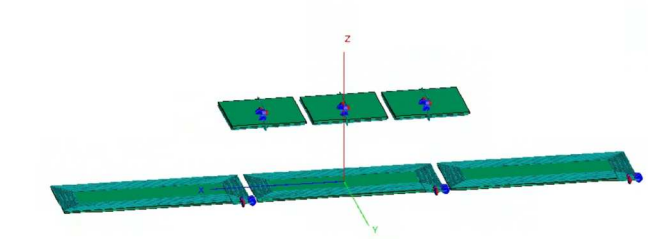


Fig.10 Magnetic Field Analysis Model

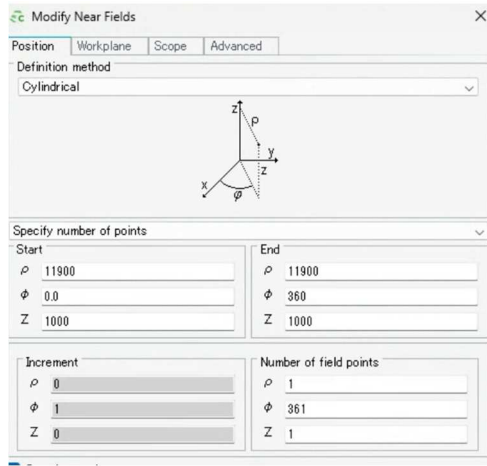


Fig.11 Measurement position for magnetic field analysis

B. Results of magnetic field simulation

The results of the magnetic field simulation are shown in Fig. 12. From Fig. 12, it can be visually confirmed that the leakage magnetic field is reduced when performing synchronous rectification with three-phase compared to the conventional method using the same phase. The respective average values in Fig. 12 are 72.3 dBuA/m for single-phase and 51.6 dBuA/m for three-phase, confirming a reduction of 20.7 dB. This reduction effect stems from the property that the magnetic fields generated by the three-phase currents from each coil cancel each other out.

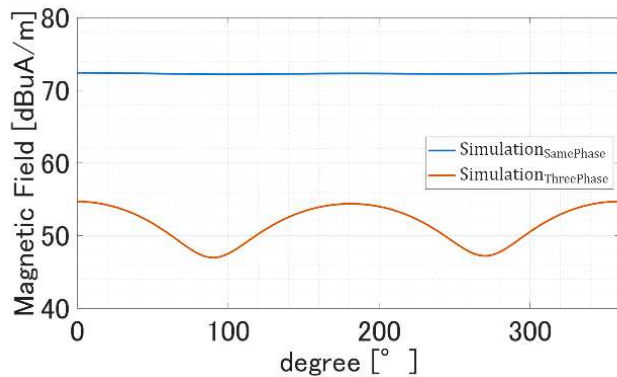


Fig.12 Results of magnetic field analysis

VI. CONCLUSION

This paper proposes a synchronous rectification method based on three-phase transmission coils with a 120-degree angle phase difference on the transmission side, which can reduce leakage magnetic fields. Simulation results demonstrate

that the proposed method improves efficiency by approximately 4.5 % compared to conventional methods and reduces leakage magnetic fields by 20.7 dB. Future work will focus on control in regions with strong cross-coupling and verification through actual equipment experiments.

REFERENCES

- [1] A. Emadi, Y. J. Lee and K. Rajashekara, "Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles," in *IEEE Transactions on Industrial Electronics*, vol. 55, no. 6, pp. 2237-2245, June 2008,
- [2] C. C. Mi, G. Buja, S. Y. Choi and C. T. Rim, "Modern Advances in Wireless Power Transfer Systems for Roadway Powered Electric Vehicles," in *IEEE Transactions on Industrial Electronics*, vol. 63, no. 10, pp. 6533-6545, Oct. 2016
- [3] B. J. Varghese *et al.*, "Multi-Pad Receivers for High Power Dynamic Wireless Power Transfer," *2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, USA, 2020, pp. 5162-5168
- [4] A. U. Ibrahim, W. Zhong and M. D. Xu, "A 50-kW Three-Channel Wireless Power Transfer System With Low Stray Magnetic Field," in *IEEE Transactions on Power Electronics*, vol. 36, no. 9, pp. 9941-9954, Sept. 2021
- [5] S. Huh, S. Woo, H. Lee and S. Ahn, "Selective Activation of Transmitter Coils to Reduce Leakage Magnetic Fields in Wireless Power Transfer Systems with Multiple Transmitters," *2024 IEEE Wireless Power Technology Conference and Expo (WPTCE)*, Kyoto, Japan, 2024, pp. 50-54
- [6] Y. Zhang, X. Li, S. Chen and Y. Tang, "Soft Switching for Strongly Coupled Wireless Power Transfer System With 90° Dual-Side Phase Shift," in *IEEE Transactions on Industrial Electronics*, vol. 69, no. 1, pp. 282-292, Jan. 2022
- [7] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless Power Transfer via Strongly Coupled Magnetic Resonances," *Science* (1979), vol. 317, no. 5834, pp. 83–86, Nov. 2007, doi: 10.1016/j.aop.2007.04.017.
- [8] S. Li, W. Li, J. Deng, T. D. Nguyen and C. C. Mi, "A Double-Sided LCC Compensation Network and Its Tuning Method for Wireless Power Transfer," in *IEEE Transactions on Vehicular Technology*, vol. 64, no. 6, pp. 2261-2273, June 2015
- [9] S. A. Al Mahmud, P. Jayathurathnage, Y. Liu, J. Kyyrä and S. Tretyakov, "A New Receiver Detection and Fast System Activation Method for Wireless Power Transfer," *2023 IEEE Wireless Power Technology Conference and Expo (WPTCE)*, San Diego, CA, USA, 2023, pp. 1-5
- [10] Yusuke Sato *et al.* Reduction of Standby Losses in Wireless Power Transfer During Vehicle Operation Using Series Voltage Division in the Power Transmission Coil and a Vehicle Detection Method *Transactions of the Institute of Electrical Engineers of Japan. D, Industrial Applications Section = IEEJ Transactions on Industry Applications*. 145(6):2025.6, pp. 409-417.
- [11] D. Shirasaki, T. Fujita and H. Fujimoto, "Novel Synchronous Rectification and Receiving Power Compensation Method for WPT Only by DC Current Sensor," in *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 3, no. 4, pp. 1159-1167, Oct. 2022,