Transmission Circuit Switching Control System Combining Speed Estimation and N-Legged Converter for Dynamic Wireless Power Transfer

Akihiro OKAZAKI† Takehiro IMURA‡ and Yoichi HORI‡

†Faculty of Science and Technology, Tokyo University of Science 2641 Yamazaki, Noda-shi, Chiba, 278-8510 Japan

Abstract In recent years, research on electric vehicles has been active due to environmental issues, and among these, dynamic Wireless Power Transfer (DWPT) is attracting attention because it can contribute to battery miniaturization. However, since the vehicle passes over the transmission circuit continuously and for a short period of time, the control method is important in terms of safety and efficiency. In this paper, we propose a safe and efficient transmission system for DWPT by using an N-legged converter to optional control each circuit. The effectiveness of the proposal system is verified through simulation.

Keyword wireless power transfer , dynamic wireless power transfer, waiting loss, N-Legged converter, leakage magnetic field, speed estimation

1. Introduction

In recent years, research on electric vehicle (EV) has become active due to environmental issues. One of the technologies that has been attracting attention is the battery power supply technology using wireless power transfer. Dynamic Wireless Power Transfer (DWPT) is one of the methods to solve the problems of EVs by applying this technology. If DWPT is put into practical use, it is expected to extend cruising range, reduce vehicle weight and cost by downsizing the battery, but there are still many issues to be solved before it can be put into practical use. However, there are still many issues to be solved. Especially for DWPT, which pass over the transmission coils in a short time, it is important to control the switching of the transmission circuit that can guarantee efficiency and safety. Prior research has studied circuit characteristics considering waiting loss[1] and switching systems for each transmission section[2], but the most efficient method has not yet been proposed. Methods using detection coils[3] and wireless communication have also been considered for switching methods. However, these have the disadvantage of additional components and communication delay effects[4].A control method using speed estimation has been proposed as a method to solve these problems[5]. This method requires few additional components and does not use wireless communication, but it remains a basic study, and an optimal system needs to be investigated. In this paper, we propose a method for switching transmission circuits using speed estimation in a DWPT transmission system with a system configuration that can handle the case where multiple receiving coils exist on a single segment. The effectiveness and feasibility of the proposal system will be verified by simulation.

2. Dynamic Wireless Power Transfer

In this paper, we assume a DWPT system as shown in Fig. 1, and adopt the LCC-LCC method as shown in Fig. 2 for the circuit configuration[2]. The inductance and capacitance satisfy the resonance condition equation (1) shown below with the angular frequency ω_0 . from equation (2), the LCC-LCC circuit is considered practical because it does not draw excessive current even in the event of a system malfunction.

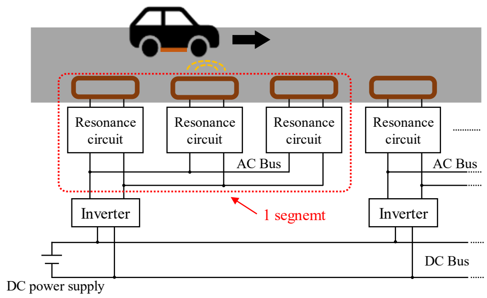

Fig.1. DWPT system.

$$\omega_0 = \frac{1}{\sqrt{L_{T0}C_{Tp}}} = \sqrt{\frac{C_{Tp}+C_{Ts}}{L_T C_{Tp} C_{Ts}}} = \frac{1}{\sqrt{L_{R0}C_{Rp}}} = \sqrt{\frac{C_{Rp}+C_{Rs}}{L_R C_{Rp} C_{Rs}}} \quad (1)$$

.

$$I_{in} = {\omega_0}^3 C_{Tp} C_{Rp} k \sqrt{L_T L_R} V_2 \quad (2)$$

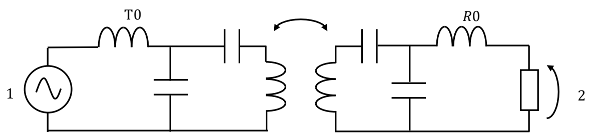

Fig.2. LCC-LCC circuit.

3. N-Legged converter system

In DWPT, the circuit parameters and number of coils on the receiving side may vary from vehicle to vehicle. Therefore, it is desirable to have highly flexible controllability in each transmission circuit. A low-cost and accurate control system using speed estimation [5] has been proposed, but this has the drawback that the same voltage is applied to each transmission circuit, as shown in Fig. 3. One system that can solve this drawback is the N-Legged converter (NLC) [6]. This converter consists of multiple legs, as shown in Fig. 4. The voltage V_n applied to the nth circuit is shown in Equation (3) using the DC Bus voltage V_{dc}, so the voltage of each circuit can be adjusted simply by manipulating the phase angle α between the legs.

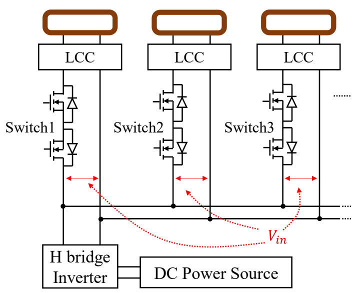

Fig.3. Conventional system.

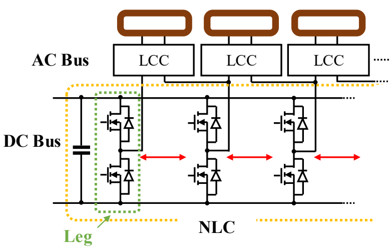

Fig.4. N-Legged converter.

$$V_n = \frac{2\sqrt{2}}{\pi} V_{dc} \sin\left(\frac{\alpha_n}{2}\right) \quad (3)$$

4. Switching system using speed estimation

4.1. Speed estimation with NLC

A transmission circuit switching control using speed estimation has been proposed in a system with an H-bridge inverter additional switches, which can also be applied to NLC. This control method uses the variation of the input current I_{in} to the circuit due to the approach of the receiving coil. Therefore, speed estimation using NLC can be achieved by installing current sensors in each circuit as shown in Fig. 5.

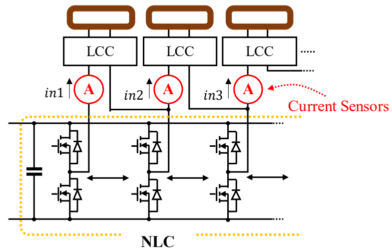

Fig.5. Proposal NLC system configuration.

4.2. Switching control

Switching control using NLC requires controlling the phase angle between each leg, as shown in equation (3). However, a large transient current is generated in I_{in} when the circuit voltage is instantaneously increased[5]. To deal with this, the phase angle between legs is gradually changed to control the circuit input voltage so that it does not rise instantaneously, thereby suppressing the transient current. A flowchart of this control is shown in Fig. 6. To suppress transient currents, it is necessary to determine $\Delta\alpha$, the phase angle for each control step, based on the passing time of the vehicle and the performance of the DSP and other devices. For switching control, I_{th_sw} is established as the current threshold for switching, and the switching operation is based on the estimated speed. The flowchart of this switching control is shown in Fig. 7. Since vehicle detection is based on current value fluctuations, the phase angle α_1 of the first transmission circuit always standby at 180° to monitor current values. Passive switching is performed based on I_{th_sw} until the second circuit, when the speed estimation is completed. After that, switching control is performed based on the estimated speed. Specifically, the time t_{wait} is calculated to wait at phase 0° until the vehicle arrives, and at the same time, the time t_{off} is measured to keep the phase at 0°. If t_{off} exceeds t_{wait}, control the phase angle of the next circuit to 180°. At that time, if the phase angle is not 0°, the phase angle is reset to 0° and then controlled to 180° again. This control is continued until n exceeds the last transmission coil Tx_{max}.

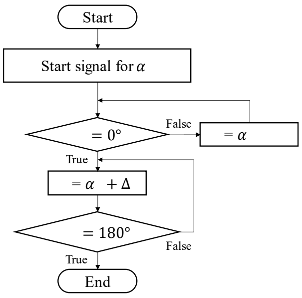

Fig.6. Flowchart of transient current suppression control.

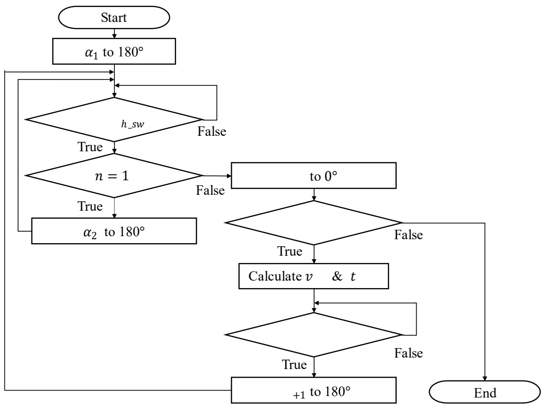

Fig.7. Flowchart of switching control with NLC.

5. SIMULATION

The proposal system is verified by simulation using MATLAB/Simulink for the case of one and two receiving coils (Case1 and 2). The configuration is shown in Fig. 9. The size of the transmitting and receiving coils are long on either side in the direction of travel, 800×550 mm and 1600×750 mm, there are three transmitting coils (Tx1, Tx2, and Tx3) in both cases. For the Case2, the maximum number of receiving coils in a segment is two. Also, the passing speed of the receiving coils is assumed to be constant at 60 km/h. The parameters of the simulation are shown in Table 1. The speed estimation results are shown in Table 2, and the simulation results are shown in Fig. 10(a), (b) and (c). Fig. 10 (a) and (b) shows the input current results I_{in1},I_{in2}, and I_{in3} for each of the transmission circuits in Fig. 9. Fig. 10 (a) shows that Tx1 is always standby mode and Tx2 is activated immediately after Rx passes through Tx1. After passing through Tx2, the speed estimation is completed and Tx3 is activated after a certain time interval. These results indicate that the switching control of the proposal system is controlled properly based on the estimated speed. Furthermore, since no transient current is generated during the switching operation, it shows that the suppression control is functioning. Also, Fig.10 (6) shows that the switching control can be achieved with appropriate control of each circuit and transient current suppression, even if there are multiple receiving circuits in a single segment. Furthermore, the output of the first circuit is stopped while the two receiving circuits are on the segment so that the maximum number of receiving coils is not exceeded.

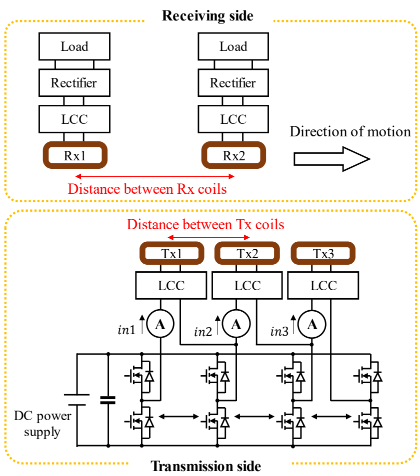

Fig.9. Simulation configuration.

Table1. Simulation parameters.

		Tx side	Rx side
Input DC Voltage [V]	V_{dc}	300	-
Operation frequency [kHz]	f	85	-
Air gap [mm]		250	-
Distance between coils [mm]		2400	2000
Compensated inductance [μH]	L_{T0}, L_{R0}	18	18
Compensated resistance [Ω]	r_{T0}, r_{R0}	0.031	0.031
Compensated capacitance [nF]	C_{Tp}, C_{Rp}	195	195
Resonant capacitance [nF]	C_{Ts}, C_{Rs}	32.6	25.1
Tx / Rx inductance [μH]	L_T, L_R	125.45	157.25
Tx / Rx resistance [Ω]	r_T, r_R	0.1	0.1
Load resistance [Ω]	R_L		8.33

Table2. Speed estimation results

	Movement speed [km/h]	Estimation speed [km/h]	Estimation error [%]
Case1	60	59.9750	0.042
Case2 (Rx1)	60	59.9958	0.007
Case2 (Rx2)	60	60.0042	0.007

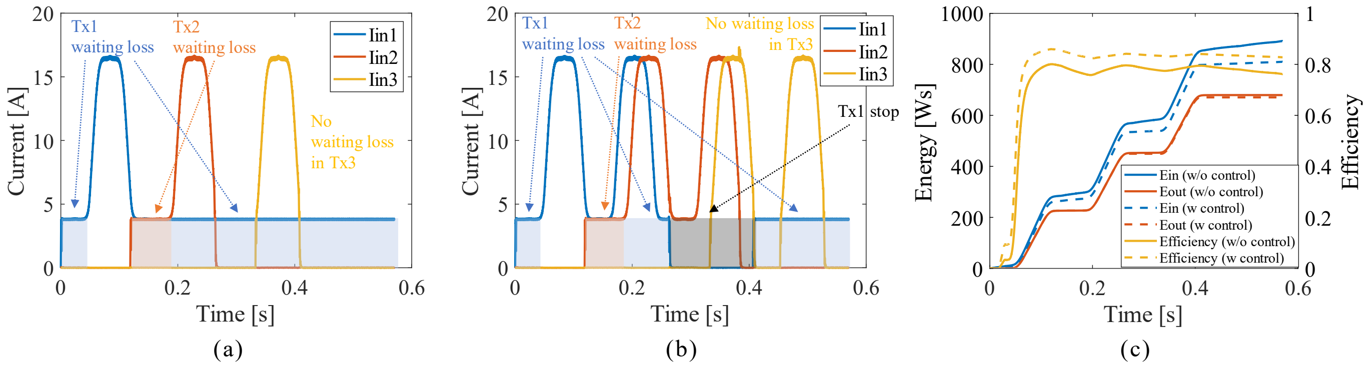

Fig.10. Simulation results. (a) One receiving coil. (b) Two receiving coils. (c) Effects of switching control on efficiency and energy

Regarding speed estimation, high accuracy estimation within an error of 0.05% is achieved in both cases. The proposal system drives only the minimum number of circuits, which leads to a reduction in waiting loss. To confirm this effect, Fig. 10 (c) compares the efficiency and energy of the proposal system with that of the standby system, in which all circuits are always energized (standby system). Note that there is only one receiving circuit. The efficiency of the standby system was about 76.2% due to the waiting loss in the section without power transmission. The efficiency of the proposal system is about 82.8% due to the reduction of waiting loss, which is about 6.6% higher than the standby system. The amount of receiving energy decreased by about 1.33 % from 679.56 Ws to 670.54 Ws, but the amount of receiving energy is expected to improve by adjusting I_{th_sw}.

6. Conclusion

This paper proposes a new system configuration for a transmission circuit switching system using speed estimation, and verifies it by simulation. The proposal system not only reduces the number of MOSFETs, but also makes it possible to apply arbitrary voltages to individual circuits, thus achieving transient current suppression control and control corresponding to multiple receiving circuits. The effectiveness and feasibility of the proposal system have been confirmed by the achievement of switching control of the transmission circuits through speed estimation within an estimation error of 0.05 %, and the efficiency of the system has been increased by 6.6 % through the reduction of waiting loss while keeping the reduction in the amount of receiving energy to approximately 1.33 %.In the future, we will study the reduction of waiting loss in the first circuit and the control method for vehicles entering from the middle of the segment, and verify them through experiments.

7. References

[1]T. Kodai and K. Takafumi, “Design of Output Power Characteristic and Maximization of Transmission Efficiency Considering Waiting Loss for Multi-Paralleled Dynamic Wireless Power Transfer”, *IEICE technical report*, vol.117, No.85, pp. 23-28, 2017.

[2]K. Sasaki and T. Imura, “Combination of Sensorless Energized Section Switching System and Double-LCC for DWPT,” *IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW)*, pp. 62-67, 2020.

[3]D. Patil, J. M. Miller, B. Fahimi, P. T. Balsara and V. Galigekere, “A Coil Detection System for Dynamic Wireless Charging of Electric Vehicle,” *IEEE Transactions on Transportation Electrification*, vol. 5, no. 4, pp. 988-1003, 2019

[4] A. C. Bagchi, A. Kamineni, R. Zane and R. B. Carlson, “Comparative Analysis of DWPT Topologies and Regulation Schemes for Improved Controllability,” *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2020, pp. 5199-5206

[5]A. Okazaki, T. Imura and Y. Hori, “Transmission Circuit Switching Control System Using Speed Estimation for Dynamic Wireless Power Transfer,” *IEEJ Industry Applications Society Conference*, 2022, pp. 261-264

[6] F. Farajizadeh, D. M. Vilathgamuwa, D. Jovanovic, P. Jayathurathnage, G. Ledwich and U. Madawala, “Expandable N-Legged Converter to Drive Closely Spaced Multitransmitter Wireless Power Transfer Systems for Dynamic Charging,” *IEEE Transactions on Power Electronics*, vol. 35, no. 4, pp. 3794-3806, April 2020,