EVTeC 2025
7th International Electric Vehicle Technology Conference 2025

Development of a 500-kW Wireless Power Transfer System with Water Cooling for Windings

Keisuke Kusaka [1)] **Kazuki Yamagata** [2)]

1) Nagaoka University of Technology, Nagaoka, Niigata, Japan

E-mail: kusaka@vos.nagaokaut.ac.jp

2) Nagaoka University of Technology, Nagaoka, Niigata, Japan

E-mail: s213184@vos.nagaokaut.ac.jp

ABSTRACT: The demand for charging power is rapidly increasing to shorten the charging time for electric vehicles (EVs) because the battery capacity of EVs on the market has grown to extend their driving range. In the standard for the EV charger CHAdeMO, the output power of the wired charger has been increased from 50 to 350–500 kW. This demand for increased capacity also applies to wireless power transfer (WPT) systems. This paper reports on the development of the 500-kW wireless power transfer system with water-cooled windings. First, a hollow copper wire for water cooling is evaluated for high-power transmission. The hollow copper wire lets the water cool from inside the transmission coils' windings. Then, the wireless power transfer system with an output power of 500 kW with a single transmission coil and a single receiving coil is designed based on the electromagnetic analysis. Finally, the 500-kW prototype is developed and demonstrated. The experimental results show that the 500-kW transmission is achieved without any heat problems. The maximum transmission efficiency is 92% at an output power of 500 kW.

KEY WORDS: wireless power transfer, electric vehicle, water cooling

1. INTRODUCTION

In recent years, there has been increasing interest in static and dynamic wireless power transfer (WPT) systems to improve the usability of EV users [(1-4)]. The WPT systems free EV users from the task of connecting cables.

Focusing on the EVs available in the market, the amount of onboard batteries has been rapidly increasing to extend their driving range. Indeed, the output power of a wired charger has been raised to 350–500 kW to meet the demand from the EV side in the CHAdeMO 3.0 standard for EV chargers [(5)]. Consequently, the output power of the WPT system should also be increased to several hundred kilowatts to reduce charging time, like the wired charger.

In the past decades, the high-power wireless power transfer system has been developed for high-power charging of electric vehicles. In (6), the 1.1-MW WPT system for electric ships has been developed. However, it is unsuitable for EVs because the transmission coils are large. In (7), the 818-W WPT system for high-speed trains has been developed. In this system, the primary feeder is placed along the rail. The feeder is suitable for high-power transmission however, it cannot be used for EV applications. For EV applications, some high-power WPT systems have multiple transmission and receiving coils to distribute the output power (8-9). The multiple coils help alleviate heat stress on the coils. However, the presence of multiple coils restricts their placement due to the cross-coupling that occurs.

For the above reasons, the high-power WPT system with single transmission and receiving coils should be developed for EV. One of the biggest challenges to increasing the output power is the heat dissipation of the windings because a current of several kiloamperes flows on the windings. Moreover, the high-frequency currents produce much ohmic loss due to the skin and proximity effect. The excessive heat on the windings may cause the degradation of the insulation of windings and the magnetic saturation of a magnetic core placed near the windings.

This paper develops and demonstrates the 500-kW WPT system with water cooling for the windings made by hollow copper pipes. The hollow copper pipes let the water cool from the wire's inside. Thus, the hollow pipes are suitable structures for the high-power WPT. The transmission coils for 500-kW transmission are designed using an electromagnetic analysis based on the FEM. Then, the 500-kW WPT system is demonstrated.

2. Transmission Coils for High-power Transmission

In this chapter, the 500-kW transmission coils are designed with a focus on thermal and electromagnetic aspects. Fig. 1 illustrates the structure of the transmission coils. The transmission coil (Tx coil) has a copper wire made of hollow pipe, ferrite place, and aluminum plate. The receiving coil (Rx coil) has the same copper wire, ferrite, aluminum plate, and iron plate. Aluminum plates are positioned at both the top and bottom of the system to reduce magnetic flux leakage. The iron plate is utilized in electromagnetic analysis to simulate the effect of a vehicle body.

2.1. Water cooling of windings

In this subsection, the cooling system for the transmission coils is evaluated. The proposed high-power WPT system utilizes a hollow pipe for the transmission coils. The 500-kW WPT system, which operates with 400-V AC, requires a current conduction of over 1000 A. This hollow pipe facilitates liquid cooling by directing the liquid through it. The coolant is injected into the pipes with a pump.

Fig. 2 illustrates the temperature rise of the coolant and coil surface due to current conduction ranging from 600 to 1000 A. The coolant flow rates are tested at 20 and 30 L/min. A thermocouple and thermal imaging are utilized to measure the temperatures of the coolant and coil surface, respectively. Each temperature is recorded three minutes after conduction begins to account for the effects of thermal heat capacity. Fig. 2 (a) indicates that the temperature increases of the coolant are approximately 8 and 5 degrees for flow rates of 20 and 30 L/min, respectively. Fig. 2 (b) shows the surface temperature of the coil. The surface temperature of the coil at flow rates of 20 and 30 L/min is approximately 27 degrees. These results indicate that a flow rate of 20 L/min is sufficient for the 500-kW transmission.

2.2. Magnetic Design of Transmission Coils

The transmission coils are designed with electromagnetic analysis based on the FEM. Figure 3 shows the section of the transmission coil with the hollow pipe coils. The coil design has multiple degrees of freedom, including the number of turns n, the radius of coils l, the span between the windings w, and transmission distance d. Thus, the structure of the transmission coils is determined based on the FEM in this paper.

Figure 4 shows the analytical results of the inductance. The different structure presents different inductance that dynamically affects the maximum transmission power and the transmission efficiency. In the WPT system with series-series compensation, the optimum inductance, which offers the maximum efficiency at the desired transmission power, is expressed as

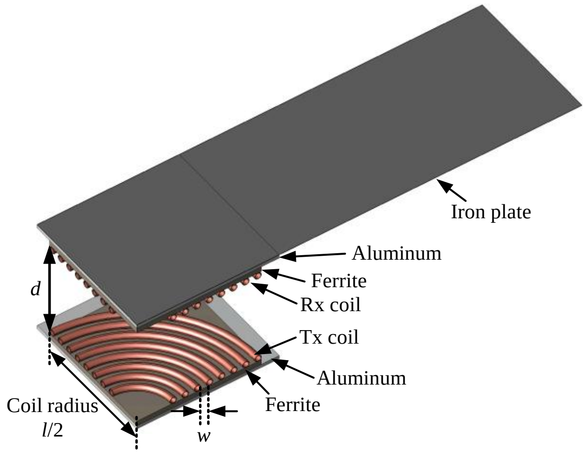
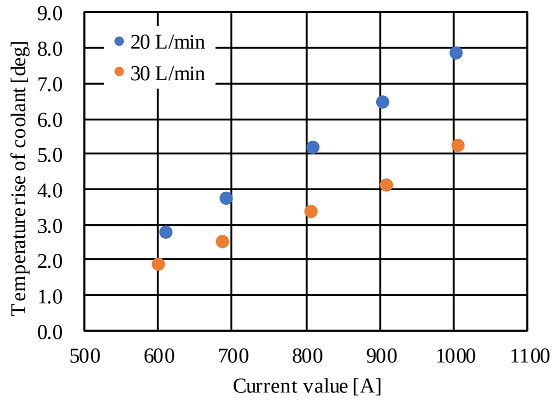
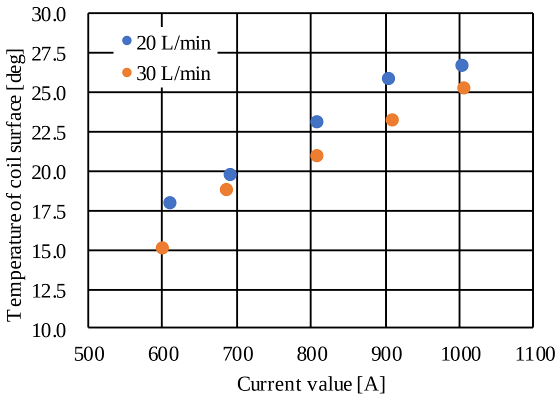


Fig. 1. Structure of transmission coils



(a) Coolant



(b) Coil surface

Fig. 2. Temperature change of the WPT system

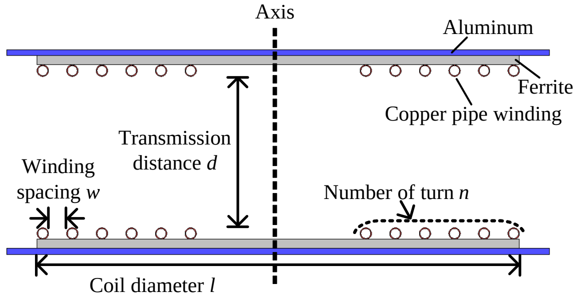


Fig. 3. Simplified two-dimensional model for electromagnetic analysis.

$$L_2 = \frac{R_{eq}}{\omega k} \quad (1),$$

where R_{eq} is the equivalent resistance of the load, ω is the angular frequency, and k is the coupling coefficient(10).

The transmission efficiency is maximized when the inductance L_2 is designed to satisfy Eq. (1). Thus, the plot near the curve, which is represented by the star, should be selected. Note that the 2D analysis, as shown in Fig. 1, has an error between the 2D model and the 3D model. Thus, the point should be selected considering the error.

2.3. Prototype

Figure 5 shows the configuration of the 500-kW WPT system, and Table 1 shows the parameters of the coils. The series-series compensation is used for power factor correction. The resonance capacitors are designed to oscillate with the self-inductance of each coil. The resistive load is directly connected to the secondary coil through the resonance capacitor on the secondary side.

Figure 6 shows the experimental setup for 500-kW transmission. The coils made from a hollow pipe are placed on the ferrite plates. The white tube is for water cooling of the transmission coils. The cooling liquid is injected into the hollow pipes.

3. EXPERIMENTS

3.1. Operation waveforms

Figure 7 shows the experimental waveforms with an output power of 500 kW. In Fig. 7 (a), the waveforms are the output voltage of the inverter, primary current, and secondary current from the top to the bottom. Also, the waveforms are the output voltage on the load, and current on the load in Fig. 7 (b). This shows that a power of 500 kW is wirelessly transmitted to the secondary side. Here, the output voltage and current on the primary side are in phase. It means that the S/S compensation is employed as designed.

3.2. Efficiency characteristics

Figure 8 shows the efficiency characteristics. The input power of the high-frequency inverter, the output power of the inverter, and the output power of the WPT system are measured by a power meter. The efficiency between the output of the inverter and the output power of the WPT system is over 92% in the entire load conditions. The efficiency from the input of the WPT system including power loss of the high-frequency inverter is 89%.

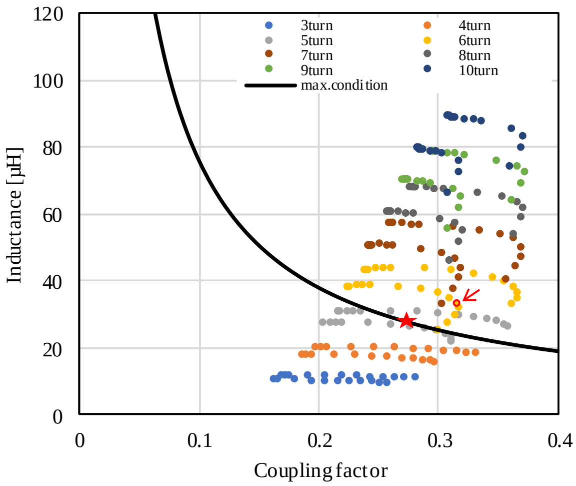


Fig. 4. Analytical results for coil design.

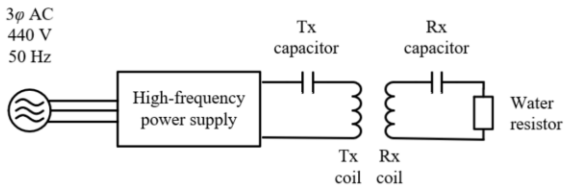


Fig. 5. System configuration for 150-kW test.

Table 1. Parameters of 500-kW transmission coils.

(a) Dimensions of coils

	Value
Number of turn	6
Coil diameter [mm]	800
Winding spacing [mm]	30
Transmission distance [mm]	250

(b) Electric specifications

	Value
Tx coil inductance (sim) [μH]	28.3
Rx coil inductance (sim) [μH]	28.4
Tx coil inductance [μH]	31.4
Rx coil inductance [μH]	31.8
Coupling factor	0.25

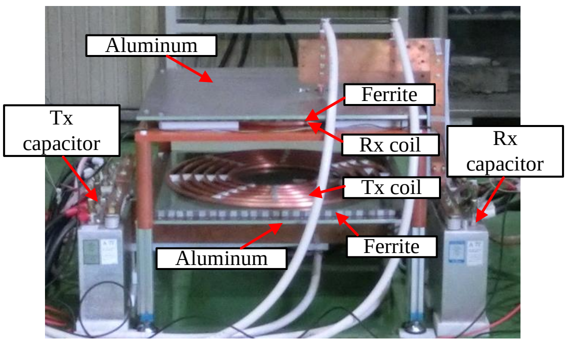
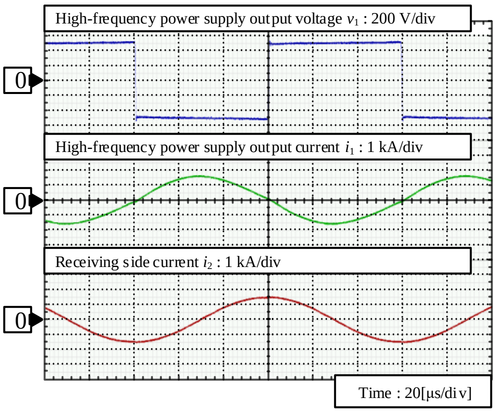
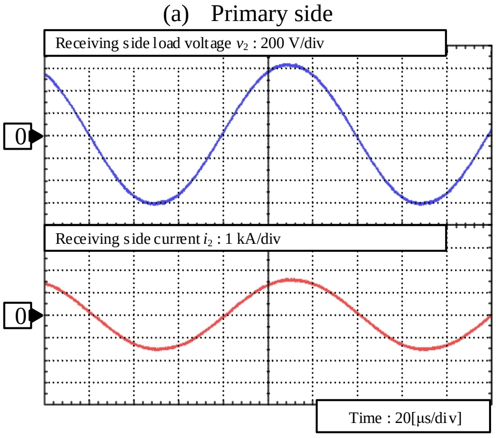


Fig. 6. Prototype of the 500-kW WPT system.



(a) Primary side



(b) Secondary side

Fig. 7. Experimental results with an output power of 150-kW test.

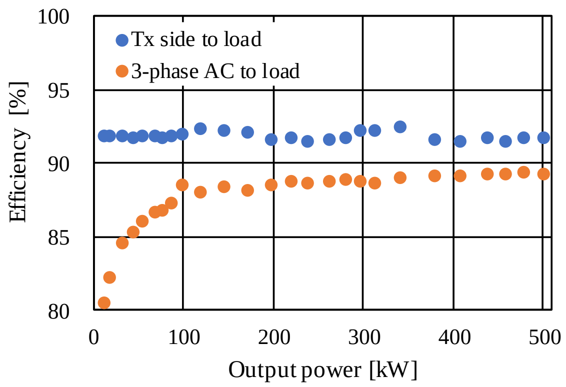


Fig. 8. Efficiency characteristics.

4. CONCLUSION

This paper proposes a high-power wireless power transfer system with water cooling for the windings. In the high-power wireless power transfer system, the heat of the windings is one of the challenges because the windings have high equivalent resistance due to the proximity and the skin effect. The proposed coils are hollow copper wire, and the cooling water goes through the inner of the windings for cooling. The transmission coils are designed and developed with an output power of 150 kW. In the final paper, the cooling performance of the WPT system will be unveiled.

ACKNOWLEDGMENT

This study was partially conducted with substantial technical support from Neturen Co., Ltd. In particular, we received valuable cooperation in the construction of experimental equipment. We would like to express our sincere gratitude. Additionally, this paper is based on results obtained from a project, 24000773-0, subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

REFERENCES

(1) H. Hu, S. Duan, T. Cai, P. Zheng, “A Current-Sharing Compensation Method for High-Power-Medium-Frequency Coils Composed of Multiple Branches Connected in Parallel,” in IEEE Transactions on Industrial Electronics, vol. 69, no. 5, pp. 4637-4651, May 2021

(2) H. Zhou, J. Chen, Q. Deng, F. Chen, A. Zhu, W. Hu, X. Gao, “Input-Series Output-Equivalent-Parallel Multi-Inverter System for High-Voltage and High-Power Wireless Power Transfer,” in IEEE Transactions on Power Electronics, vol. 36, No. 1, pp. 228-238 Jan. 2021

(3) J. Shin, S. Shin, Y. Kim, S. Ahn, S. Lee, G. Jung, S.-J. Jeon, and D.-H. Cho, “Design and Implementation of Shaped Magnetic-Resonance-Based Wireless Power Transfer System for Roadway-Powered Moving Electric Vehicles,” IEEE Transactions on Industrial Electronics, vol. 61, no. 3, pp. 1179-1192, March 2014

(4) H. Hao, G. A. Covic, and J. T. Boys, “A Parallel Topology for Inductive Power Transfer Power Supplies,” IEEE Transactions on Power Electronics, vol. 29, no. 3, pp. 1140–1151, March 2014

(5) CHAdeMO Association, “CHAdeMO protocol 3.0)

(6) G. Guidi et al.: "Wireless Charging for Ships: High-power inductive charging for battery electric and plug-in hybrid vessels", IEEE Electrification Magazine, Vol.5, No.3, pp.22-32 (2017)

(7) Jae Hee Kim et al.: "Development of 1-MW Inductive Power Transfer System for a High-Speed Train", IEEE Trans. Ind. Electron., Vol.62, No.10, pp.6242–6250 (2015)

(8) Conductix-Wampfler: "12-meter Electric Bus in Regular Service with Inductive Opportunity Charging"

(9) J. Shin et al.: “Design and Implementation of Shaped Magnetic-Resonance-Based Wireless Power Transfer System for Roadway-Powered Moving Electric Vehicles”,

IEEE Trans. Ind. Electron., Vol.61, No.3, pp.1179–1192 (2014)

(10) R. Bosshard, J. W. Kolar, J. Mühlethaler, I. Stevanović, B. Wunsch, F. Canales, "Modeling and η-α-Pareto Optimization of Inductive Power Transfer Coils for Electric Vehicles," vol. 3, no. 1, pp. 50-64, 2015