Development of Ultimate Drive System for Electric Vehicles

Wireless Power Transfer integrated In-wheel Motor

1st Osamu Shimizu
Graduate School of Frontier Science
The University of Tokyo
Kashiwa, Japan
shimizu.osamu@edu.k.u-tokyo.ac.jp

2nd Hiroshi Fujimoto
Graduate School of Frontier Science
The University of Tokyo
Kashiwa, Japan
fujimoto@k.u-tokyo.ac.jp

I. Introduction

GHG(Green House Gas) emission by internal combustion engines is one of the biggest environmental issues of vehicles. Electric vehicles (EVs) are marketed in recent years due to their high environmental performance, and the share of EVs in the market grows year by year.

The benefit of electrification is not only a change of power source but also the flexibility of the layout of the drive train due to its simple structure. This system is named "in-wheel motor". The conventional drive train of EVs is an onboard motor system like an internal combustion engine vehicle. Electric devices are easy to separate due to their simple structures. Therefore, the electric motors can be separated and set into each wheel. In-wheel motor has been proposed as an advanced propulsion system for EVs due to its high efficiency and high response [1].

The authors have developed the first-generation wireless in-wheel motor (W-IWM1) that eliminates the need for wires between the vehicle's body and the wheels by using wireless power transfer technology. W-IWM1 achieved the maximum output of 3.3 kW per wheel, 94.3 % in transmission efficiency including the power conversion circuit, and succeeded in running the actual vehicle [2]. Controlling transmitting energies by only shift phasing control is also reported [3].

On the other hand, it is a problem that EVs have a shorter cruising distance per charge than conventional internal combustion vehicles.

Dynamic wireless power transfer(DWPT) from the equipment installed under the road to vehicles is expected to ultimately solve not only the problem of the cruise distance but also drive efficiency [6]. There have been some types of DWPT systems [6]. However, the power supply while the vehicle is running on the transmitter coils, which has been studied in the past, assumes an onboard motor type EV and charges the in-vehicle battery through the coil installed on the bottom surface of the vehicle.

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Therefore, we propose a novel method of DWPT, which is suitable for the IWM [7], [5]. Instead of transferring electricity from a road coil to a body coil, power is transferred directly to the IWM from the road coil while the vehicle is on the transmitter coils. In order to verify this concept on a real vehicle, we developed the second-generation wireless in-wheel motor (W-IWM2) with DWPT for a vehicle in motion. Moreover, We proposed a novel method of DWPT, which is suitable for the IWM. That is, instead of transferring electricity from a road coil to a body coil, power is transferred directly to the IWM from the road coil while the vehicle is traveling. In order to verify this concept on a real vehicle, we developed the second-generation wireless in-wheel motor (W-IWM2) with a DWPT system. The third-generation wireless in-wheel motor (W-IWM3) shown in Fig. 1 is also proposed [8]. Improvements of W-IWM3 are WPT power, motor output, and size. This paper presents the development of W-IWM3 and the evaluation of W-IWM3.

II. Concept of W-IWM3

W-IWM3 is shown in Fig. 1. A novel DWPT method is proposed to transfer power to the IWM directly from the coils on the road as the new-type DWPT that is unique to

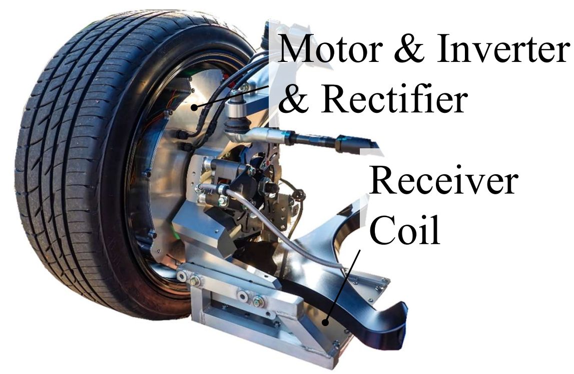

Fig. 1. structure of WIWM-3.

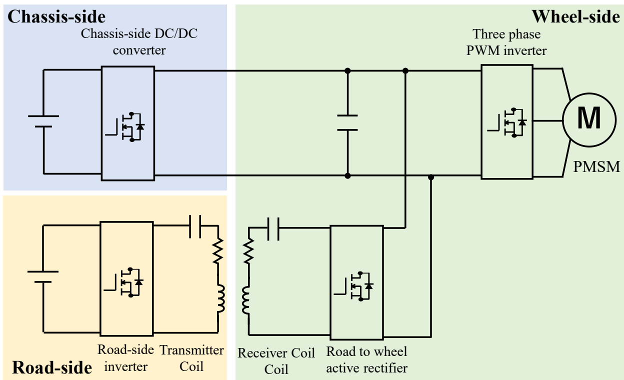

Fig. 2. system configurations.

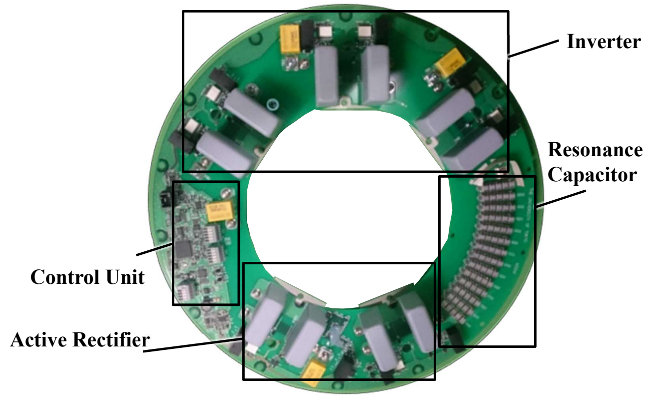

Fig. 3. power conversion board.

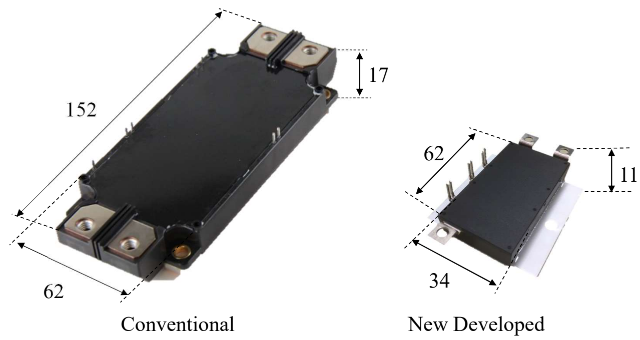

Fig. 4. improvement of SiC module.

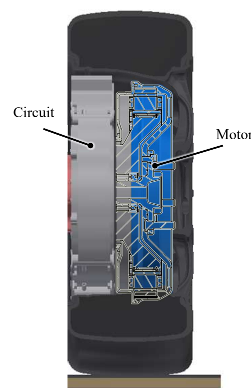

Fig. 5. components layout of in-wheel motor.

the IWM. The following merits are obtained as compared to the conventional dynamic WPT:

1) High efficiency can be achieved due to the direct power supply from the receiver coil to the motor.

2) The receiver coil is arranged in the IWM, the air gap with the road surface coil is kept constant even when the suspension is displaced, and the air gap can be minimized.

3) Since power is supplied to each wheel, the output per road coil can be reduced.

4) All components that need to charge to drive are in the wheel, which makes cabin space wider and more comfortable.

W-IWM3 has the motor, inverter for motor driving, AC/DC converter(active rectifier), control unit, and their cooing unit inside of the wheel. The system configuration of W-IWM3 is shown in Fig. 2. The electric power is transmitted from the road-embedded coil to the wheel-side receiver coil. The electric power can be used for a motor drive directly or charging a battery. DC/DC converter is set onboard. Therefore, the voltage of the receiver side can be controlled to optimize WPT efficiency.

III. Structure of W-IWM3

A. *Key technologies*

W-IWM3 has 3 key technologies. The first technology is a direct drive motor which can improve the space factor of components in the wheel. The space for the layout of the components is cylindrical and thin due to the shape of a wheel. Then the shape of the components should be cylindrical to improve the space factor of the component layout. The direct drive motor must output torque by itself. Hence, the motor is an outer rotor type due to high torque output. The second technology is the circular board of the power conversion circuit displayed in Fig. 3. The power conversion circuit includes the inverter, resonance capacitors, active rectifier, and control unit. High voltage units are integrated here, then the loss of high voltage bus can be minimized. The control unit controls the power of the inverter and active rectifier. It also communicates with other control units onboard. The third technology is an innovative small silicon-carbide (SiC) power module. The conventional SiC power module is too big to be adopted for this circular board. Therefore, this SiC power module which has low thermal resistance is developed. Its thermal resistance is about 40% lower than a conventional one, and it is 80% smaller than a conventional one as shown in Fig. 4.

B. *Structure of Motor*

The motor is set on the wheel rim side in the wheel shown as Fig. 5. Half of the space in the wheel is for the motor and the other half is for the power conversion circuit.

The motor has an outer rotor shown in Fig. 6. Though IPM (Interior Permanent-magnet Motor) is popular in the

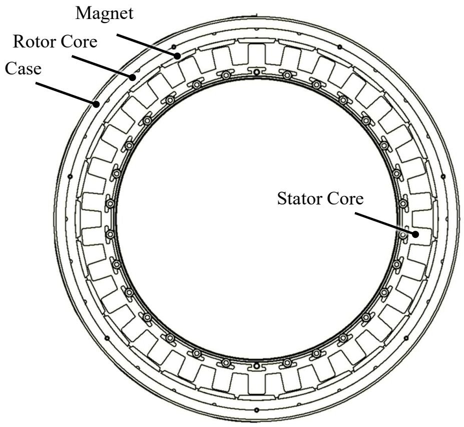

Fig. 6. structure of motor.

propulsion system of EVs, this motor adopts SPM(Surface Permanent-magnet Motor). Torque output has a relation to the radius of the air gap. To get a bigger air gap, the inner rotor has a back yoke bigger. One of the benefits of IPM is the reluctance torque that occurs by the rotor core between magnets and the air gap.

C. structure of power circuit case.

The power conversion circuit is set in the vehicle side of the wheel. There are two types of power conversion circuits. One is to drive the in-wheel motor, the other is to receive the transmitting power from the road. There is a liquid cooling system around the case, that consists water pump, two radiators, and a reserve tank. The cooling system cools both the motor and power conversion circuit. The motor case and the case of the power conversion circuit have water channels running through them. Radiators are set around the cylindrical case, therefore the radiators are bent along the case.

D. structure of road-side equipment.

This subsection gives an outline of the road facility of the D-WPT. In previous studies of the DWPT, various circuit configurations were proposed for the road-side equipment [10]. Roughly, they are divided into the following two groups:
1) Install more than ten-meter-long road coils in the direction of travel and drive with large-capacity inverters
2) Many road coils that are shorter than the vehicle's length are installed and each coil is driven by a small-capacity inverter

As a feature of configuration 1), although the number of necessary inverters is small, there is a need for a large capacity inverter due to the possibility that multiple EVs being present in one coil section. In addition, since the wire through which the high-frequency AC flows is longer, there is a higher loss from the wiring and the coil.

Road-embedded equipment is only coils and capacitors. The resonance voltage is expressed below,

$$V_{res} = V_{ac} Q_1 \tag{1}$$

$$Q_1 = \frac{\omega_0 L_1}{R_1} \tag{2}$$

TABLE I
TARGET SPECIFICATION OF COILS OF WIWM-3.

Symbol	Parameter	Value
P_{tar}	Maximum Output of Transmitter	18 kW
$\eta_{\max}$	Theoretical Maximum AC Efficiency	99%
V_{1dc}	DC Voltage of Transmitter	450 V
$V_{2dc\min}$	Minimum DC Voltage of Receiver	V_{bat}
$V_{2dc\max}$	Maximum DC Voltage of Transmitter	730 V
V_{bat}	Voltage of Battery	280-360V
$I_{1\max}$	Maximum Current of Transmitter	70 A
$I_{2\max}$	Maximum Current of Receiver	50 A
$V_{c1\max}$	Maximum Voltage of Resonance Capacitor	7000 V
$V_{c2\max}$	Maximum Voltage of Resonance Capacitor	2000 V
ω_0	Resonance Frequency	85 kHz

where V_{res} is resonance voltage, V_{ac} is output voltage of inverters, Q_1 is quality factor of the transmitter coils, ω_0 is resonance frequency, L_1 is inductance of transmitter coils, R_1 is resistance of transmitter coils. The quality factor of transmitter coils is more than one hundred, therefore the distance between coils and resonance capacitors should be minimized for isolation. Hence, the resonance capacitors are set in the resin case of the transmitter coil and connected in the case. Specifications of coils are shown in Table. I

IV. EXPERIMENT OF WPT SYSTEM

In this section, the measurement results of the efficiency tests on the bench will be described. Coil parameters are shown in Table. II Theoretical efficiency which is expressed below

$$\eta_{\max} = \frac{(R_2 + R_L)\left\{R_1 R_L + R_1 R_2 + (\omega_0 L_m)^2\right\}}{(\omega_0 L_m)^2 R_L} \tag{3}$$

is over 99%. Here, $\eta_{\max}$ is theoretical efficiency, R_2 is resistance of receiver coil, R_L is equivalent load, L_m is mutual inductance.

WPT bench is shown in Fig. 7 The actual system can control DC voltage of the transmitter side and receiver side separately. Then DC voltage of the receiver side is adjusted to achieve maximum DC-to-DC efficiency. The air gap between the transmitter and the receiver coil is 50mm. The test result is displayed in Fig. 8

The actual system

W-IWM3 achieved more than 18kW output with 95.2 % DC to DC efficiency as the test result.

TABLE II
EVALUATION RESULT OF THE COILS

Symbol	Parameter	Calculated	Measured
L_1	Self Inductance of Transmitter	247.9μH	238.5 μH
R_1	Resistance of Transmitter	98.5mΩ	78.6 mΩ
L_2	Self Inductance of Receiver	101.3 μH	93.8μH
R_2	Resistance of Receiver	27.8 mΩ	29.9 mΩ
L_m	Mutual Inductance	23.5μH	25.6 μH
η_{max}	Theoretical Maximum Efficiency	0.992	0.993

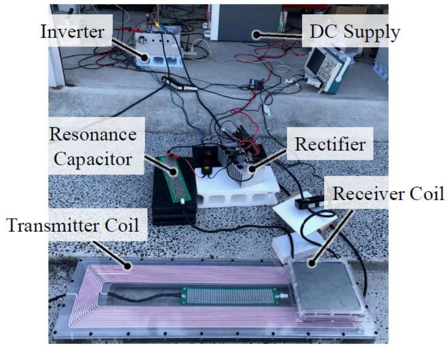

Fig. 7. equipment of WPT bench.

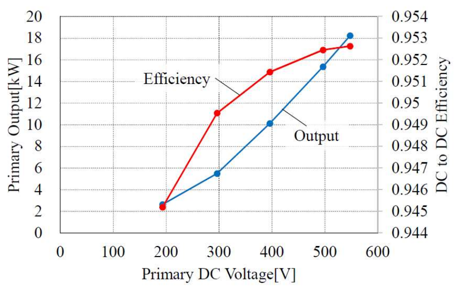

Fig. 8. test result of WPT.

V. Experiment of Drive system

Drive efficiency is evaluated on the motor bench. The motor and the inverter are separated due to setting sensors of voltage and current. When the motor and the inverter are integrated, there is not enough space to set sensors. DC Voltage input of the inverter is 300V. Inverter achieved 98.9 % of efficiency due to its low loss of SiC power module.

VI. Future Prospective

The facilities of research are prepared to realize environmentally friendly and human-friendly mobility. It is important to share the facilities for efficient development. The test course for the vehicles which have the DWPT system and the autonomous drive system is constructed in Kashiwa city shown in Fig.10. The test course is for open innovation, therefore anyone can use and investigate their own technologies with this equipment. Integration of both the DWPT system and the autonomous drive system, which can realize a completely automated charging-to-driving system, is planned. The road map of the combined technology is shown in Fig.10.

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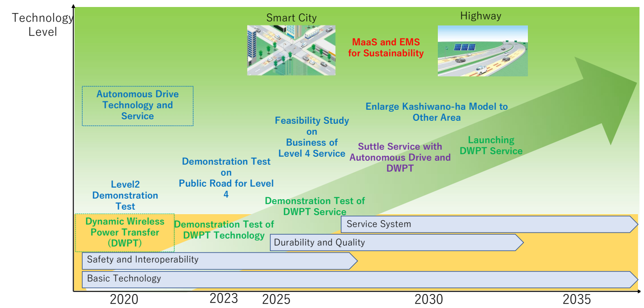

Fig. 9. road map of DWPT and autonomous vehicles.

Fig. 10. test field for DWPT and autonomous vehicles.

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