EVTeC 2021
5th International Electric Vehicle Technology Conference 2021

Development of the Third-Generation Wireless In-wheel Motor

Osamu Shimizu [1] Sakahisa Nagai Toshiyuki Fujita Hiroshi Fujimoto
Daisuke Gunji [2] Yoichi Omori [3] Takukazu Otsuka[4]
1) The University of Tokyo, Graduate School of Frontier Science, Kashiwa, Chiba, Japan
E-mail: shimizu.osamu@edu.k.u-tokyo.ac.jp
2) NSK Ltd., Fujisawa, Kanagawa, Japan
E-mail: gunji-d@nsk.com
3) TOYO DENKI SEIZO K.K., Matsuyama, Ehime, Japan
E-mail: oomoriy@toyodenki.co.jp
4) ROHM Co., Ltd., Ukyo, Kyoto, Japan

ABSTRACT: The authors have developed the third-generation wireless in-wheel motor (W-IWM3) which has the capability of the Dynamic Wireless Power Transfer (DWPT) on its wheel side. The DWPT technology can drastically extend the cruising range of electric vehicles and decrease energy for driving. Developing concepts of W-IWM3 are "all components in wheel", "infinite cruising range", and "industry-academia collaboration open innovation". This paper discusses the concept "all components in wheel" and development of the W-IWM3 with the experimental results.

KEY WORDS: electric vehicle, wireless power transfer, in-wheel motor,

1. INTRODUCTION

CO_2 emission by internal combustion engines is one of the biggest environmental problem of vehicles. To solve this problem, electric vehicles (EVs) are attracting attention in recent years due to their high environmental performance. The drivetrain of EVs includes an on-board motor system and an in-wheel motor (IWM) system. The IWM places the motor inside the wheel, which has advantages such as the improved motion control performance due to its high response, and the drive efficiency though independent control of each wheel, lower weight from reduction of the number of parts in the driving system, etc [(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 the wireless power transfer (WPT) technology [(2)].

The developed 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 [(3)]. Controlling transmitting energies by only shift phasing control is also reported [(4)].

On the other hand, it is a problem that EVs have a shorter cruising distance per charge than conventional internal combustion vehicles. In order to solve this problem by vehicle speed control, optimizing the torque and speed of the motor[(5)] have been reported.

The dynamic wireless power transfer (DWPT) from the equipment installed on the road to vehicles is expected to ultimately solve not only the problem of the cruising distance [(6)] but also drive efficiency [(7)].

However, the power supply when the vehicle is running, which has been studied in the past, assumes an on-board motor type EV and charges the in-vehicle battery through the coil installed on the bottom surface of the vehicle.

Therefore, we propose a novel method of the dynamic wireless power transfer, 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 dynamic wireless power transfer (DWPT) for a vehicle in motion.

Moreover, the third-generation wireless in-wheel motor (W-IWM3) is also proposed. Improvements of W-IWM3 are WPT power, motor output, and size. In this research, development of W-IWM3 and evaluation of W-IWM3 will be mentioned.

2. Concept of W-IWM3

In this paper, 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 the IWM. The following merits are obtained as compared to the conventional dynamic WPT:

1) High efficiency can be achieved because the power is directly delivered to motors.
2) The power 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 which are necessary to charge to drive are in the wheel, that makes cabin space wider and comfortable.

The development target of the vehicle category is a middle size passenger vehicle, therefore the motor output and maximum torque are improved. Adopted wheel size is 17 inch as shown in Fig. 1. The specifications of the developed W-IWM3 are shown in Table 1.

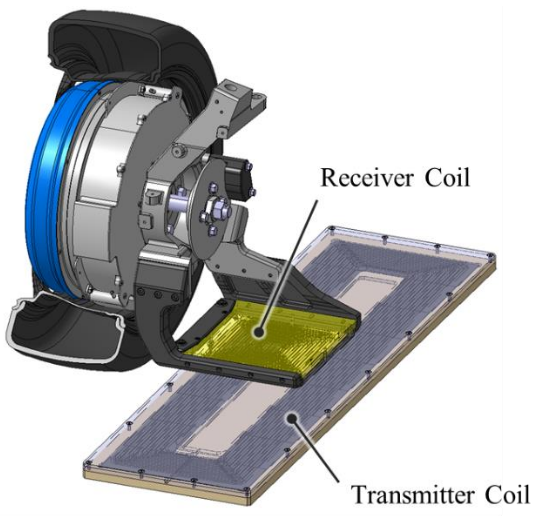


Fig. 1 Overview of W-IWM3.

Table 1 Specifications of W-IWM3

Item	Value
Max. motor power	25 kW
Max. motor torque	510 Nm
Reduction ratio	1(Direct Drive)
Number of motors	2 (4)
Total power	50 kW (100 kW)
Total wheel torque	1020 Nm (2040 Nm)

3. Development of W-IWM3

3.1. system configuration

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

3.2. key technology

W-WIWM3 has 3 key technologies to realize concept “all components in wheel”.

The first is direct drive motor which can improve space factor of components in the wheel as shown in Fig.3. The space to layout in-wheel motor is cylindrical and thin due to the shape of wheel. Then the shape of components should be cylindrical to improve space factor of the component layout. Direct drive motor must output torque required by vehicle driving by itself. Hence, the motor adopts outer rotor type due to high torque output.

The second is the unique circular board of the power conversion circuit displayed in Fig.4. The reason why the circular shape is the same as motor. The power conversion circuit includes the inverter, resonance capacitors, the rectifier, and their control unit. High voltage units are integrated here, then the loss of high voltage bus can be minimized.

The third is innovative small silicon-carbide (SiC) power module. Conventional SiC power module is too big to be adopted for circular board for W-IWM3. Then new SiC power module which has low thermal resistance is developed. Its thermal resistance is about 40% lower than conventional one, and it is 80% smaller than conventional one as shown in Fig.5.

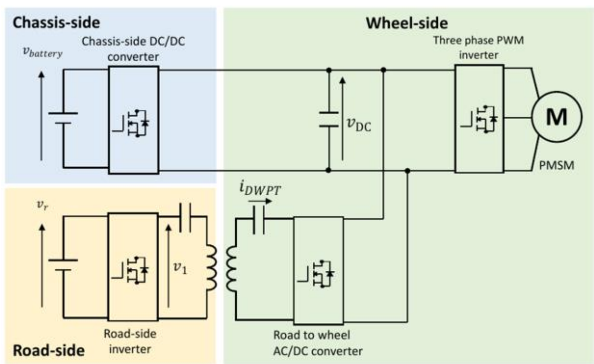


Fig. 2 System Configuration of W-IWM3.

Fig.5 Structure of Motor

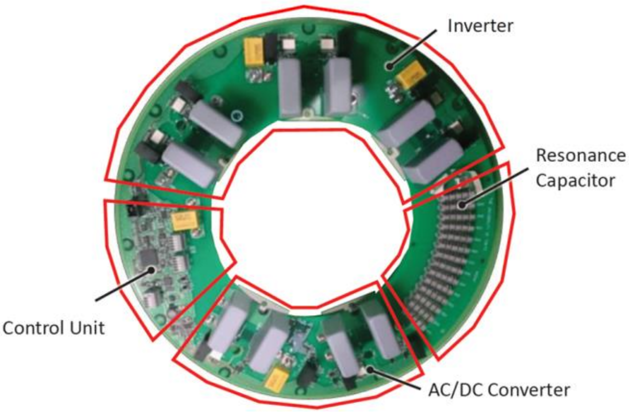


Fig.4 Circular Power Conversion Board

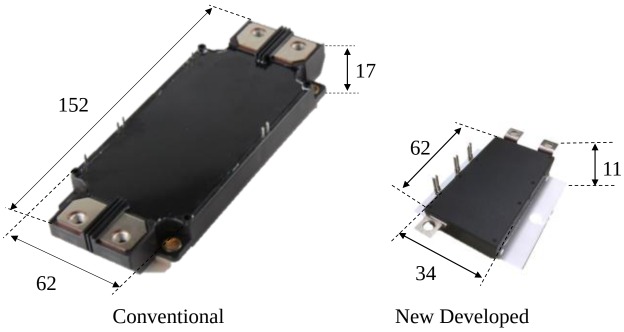


Fig.5 SiC Power Module for Inverter and Rectifier

4. Experiments of W-IWM3

4.1 experiment of WPT system

In this section, the measurement results of the efficiency tests on the bench will be described. Actual system can control DC voltage of transmitter side and receiver side separately. Then DC voltage of the receiver side are adjusted to achieve maximum DC to DC efficiency. The test bench is shown in Fig. 6. The air gap between the transmitter and the receiver coil is 50mm.

Test result is displayed in Fig.7. W-IWM3 achieved more than 18kW output with 95.2% DC to DC efficiency.

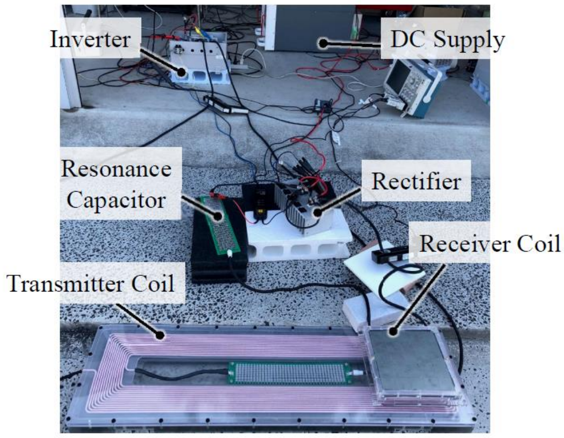


Fig.6 WPT Test Bench

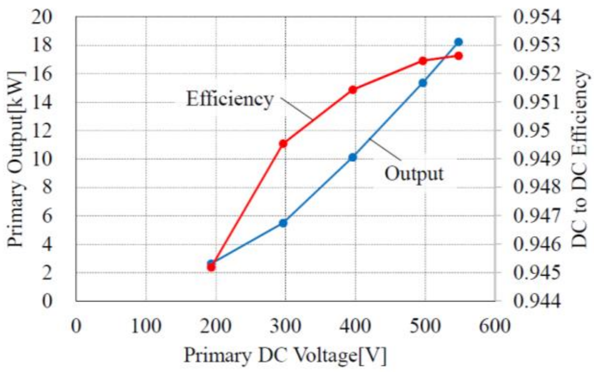


Fig.7 WPT Test Result

4.2 experiment of drive system

In this section, the measurement results of the efficiency tests on the bench will be described. Drive efficiency is evaluated on the motor bench shown in Fig.8.

The motor and the inverter are separated due to setting sensors of voltage and current. When the motor and the inverter are integrated, there are not enough space to set sensors.

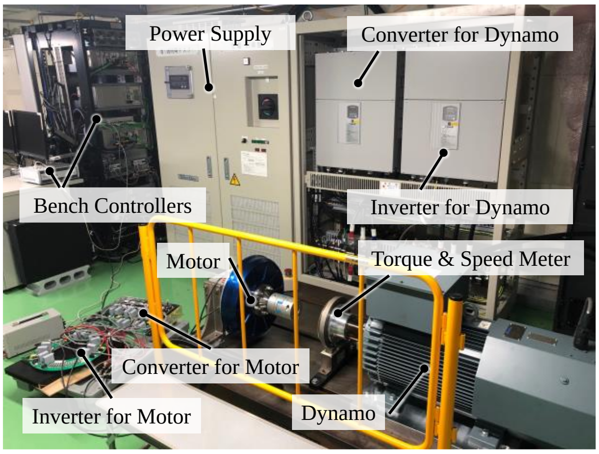
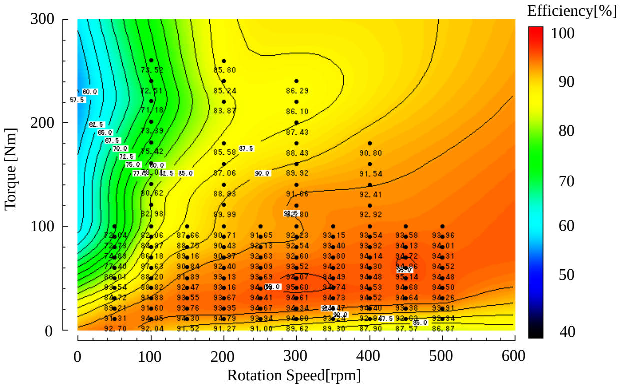


Fig.8 Motor Bench

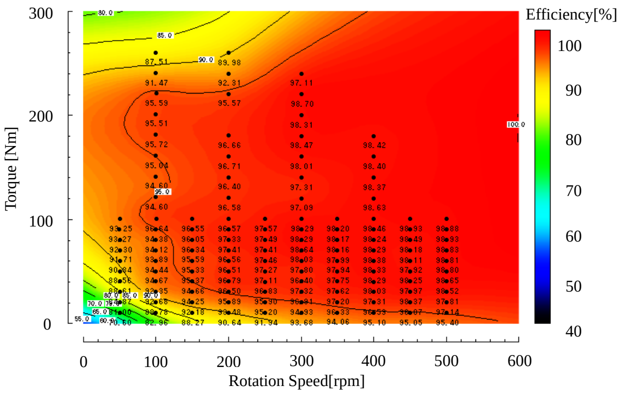
The measurement result is displayed in Fig.9. Motor efficiency includes friction loss of bearing. DC Voltage input of the inverter is 300V. Inverter achieved 98.9% of efficiency due to its low loss of SiC power module.

5. Conclusion

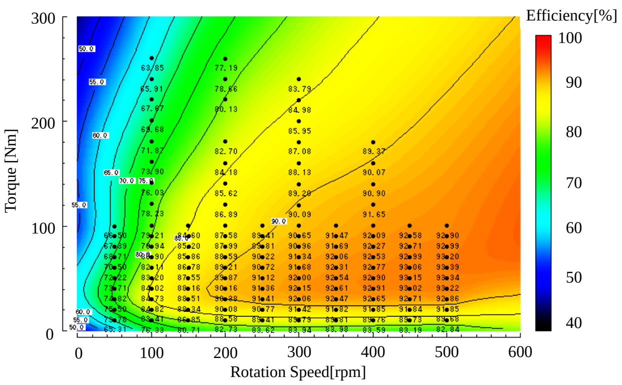
In this paper, the third-generation wireless in-wheel motor were introduced. This paper presents the novel DWPT for a vehicle and its unique application to the IWM. The experimental vehicle equipped W-IWM3 revealed DWPT system can realize enough performance for passenger vehicles.



(a) motor



(b) inverter



(c) Total efficiency

Fig.9 Drive Efficiency of W-IWM3

In the future, we will advance research toward the development of practical applications such the generation method of SoC of energy storage and further improve the transmission efficiency by implementing the operating point optimization.

ACKNOWLEDGMENT

This work was partly supported by JST-Mirai Program (JPMJMI17EM) and JSPS KAKENHI (18H03768), Japan.

REFERENCES

(1) S. Murata: "Innovation by in-wheel-motor drive unit, Vehicle System Dynamics", *International journal of Vehicle Mechanics and Mobility*, 50:6, pp. 807-830, 2012.

(2) M. Sato, G. Yamamoto, D. Gunji, T. Imura, and H. Fujimoto: "Development of Wireless In-Wheel Motor using Magnetic Resonance Coupling", *IEEE Transactions on Power Electronics*, vol.31, no.7, pp.5270-5278, 2016

(3) Giorgio Lovison, Takehiro Imura, Hiroshi Fujimoto, and Yoichi Hori: "Secondary-side-only Phase-shifting Voltage Stabilization Control with a Single Converter for WPT Systems with Constant Power Load", *IEEJ J. Industry Applications*, vol.8, no.1, pp.66-74, 2019

(4) Van-Duc Doan, Hiroshi Fujimoto, Takafumi Koseki, Tomio Yasuda, Hiroyuki Kishi, and Toshiyuki Fujit: "Iterative Dynamic Programming for Optimal Control Problem with Isoperimetric Constraint and Its Application to Optimal Eco-driving Control of Electric Vehicle", *IEEJ J.Industry Applications*, vol.7, no.1, pp.80-92, 2018

(5) M. Sato, G. Guidi, T. Imura, and H. Fujimoto: "Model for Loss Calculation of Wireless In-Wheel Motor Concept Based on Magnetic Resonant Coupling", *IEEE Workshop on Control and Modeling for Power Electronics*, (2016)

(6) G. A. Covic and J. T. Boys: "Modern Trends in Inductive Power Transfer for Transportation Application", *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no.1, pp.28-41, Mar.2013.

(7) O. Shimizu, S. Nagai, T. Fujita, H. Fujimoto: "Potential for CO2 Reduction by Dynamic Wireless Power Transfer for Passenger Vehicles in Japan" , *Energies 2020*, 13, 3342, Jun. 2020