Technical Trend of Next-generation Application Specific Electric Motors

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***Abstract-* This paper reports the latest research and development and product trend of downsizing, light weighting, high efficiency about the inverter integrated motor. Introduced applications of motors are automotive, aircraft, and industrial machinery.**

Keywords— motor, inverter, integrated motor

I. Introduction

An electromechanical integrated motor comprises a motor, drive target, and inverter. When the "machine" is the motor, the "electric" is the inverter, and when the "electric" is the motor, the "machine" is the pump, compressor, and reducer to be driven; both are provided together. For decades, special motors have been developed and manufactured as an integral component of apparatus in automotive auxiliary equipment, home appliances, and consumer products (1), where there is a high demand for ease of installation, weight reduction, and miniaturization. For example, since automobile auxiliary equipment is driven at a lower voltage than the commercial power supply, it is impossible to ignore the voltage reduction and power loss caused by wiring resistance when an inverter constitutes a separate unit. In recent years, there has been a large amount of interest in the development of integrated motors for automobile main engines and industrial pumps, where the motor output is greater than that of automobile auxiliaries, home appliances, and consumer products.

In this paper, by categorizing the integration of motor and inverter from its configuration, the latest research and development trends as well as the practical applications are described.

II. Classification of Electromechanical Integrated Motor

The integrated motor is classified into three types according to the arrangement of the motor and inverter: "adjacent arrangement," "device commonization," and "optimal layout arrangement with newly developed inverter”. (2)-(7) Table 1 shows the purposes and characteristics of each motor.

(1) Adjacent Arrangement: By using existing motor and inverter unit and placing them in proximity, wiring can be shortened; wiring space can be reduced. Leading to the decrease of the voltage drop and power loss due to wiring resistance.

Table1. Classification of the inverter integrated motor by placement of the inverter

Layout of inverter	(1) Located adjacently (2)	(2) Shared housing		(3) Exclusively designed inverter	
		Layout in radial direction (3)	Layout in axial direction (4)	Optimized layout (5)	Dispersed layout (6)(7)
Representative appearance					
Advantages	Utilize existing housing	Shared terminal box and housing		Shared terminal box and housing, Minimize inverter size,	
Purpose of integration	Shorten wining length	Shorten wiring length, Improve noise-resistance		Shorten wiring length Improve noise-resistance	
					Excite each coil

(2) Device Commonization : Along with the arrangement(1) stated above, noise resistance can be improved by sharing all three dimension of motor, inverter unit ,and connection terminals by eliminating wiring.
(3) Optimized Layout with the Newly Developed Inverter: In addition to commonization(2), the size of the inverter can be minimized by developing a new inverter according to the application and optimally arranging it in a common housing. Furthermore, when inverters are distributed, it is possible to excite each coil in the motor, which improves torque and efficiency and reduces vibration.

Furthermore, there are cases where the cooling structure is included in the study. The possible structural layouts of a water-cooled motor/inverter for the main engine of an automobile were examined in terms of compactness, wiring, and plumbing, and a configuration in which the inverter is placed on the back of the motor and a heat sink is placed around the periphery was found to be advantageous [8].

III. Recent Trends in Research and Development of Electromechanical Integrations

This chapter summarizes recent trends in research on mechanical and electrical integration.

3.1 Integrated Motors for Electric Aircraft

A motor with an integrated inverter-motor has been proposed as a main engine motor for small electric aircraft[9]. In an electric aircraft, the weight and shape of the airframe have a great influence on the performance of the aircraft, hence the onboard components must be compact and lightweight. This paper proposes an integrated mechanical and electrical system as a means of realizing compactness and weight reduction. The maximum output is reported to be 110 kW and the maximum speed is 15,000 rpm. The detail of the torque is not mentioned.

As an effect of the integrated system, the authors mentioned the reduction in size and loss by shortening the wiring path between the inverter and the motor, and the improvement in efficiency by integrating the water-cooling unit of the motor and inverter.

Fig.1 shows an overview of an integrated motor for electric aircraft. The inverter is placed directly above the motor windings, and a circular substrate with a hole drilled in the center to pass the shaft. Although the motor is a five-phase motor, there are no synergistic effects or design constraints due to the integration of the machine and electronics. Silicon Carbide (SiC) is used as the power device. Due to the layout constraint that the inverter board must be the same size as the motor outline, it is considered difficult to make a large IGBT power module with an integrated electromechanical configuration.

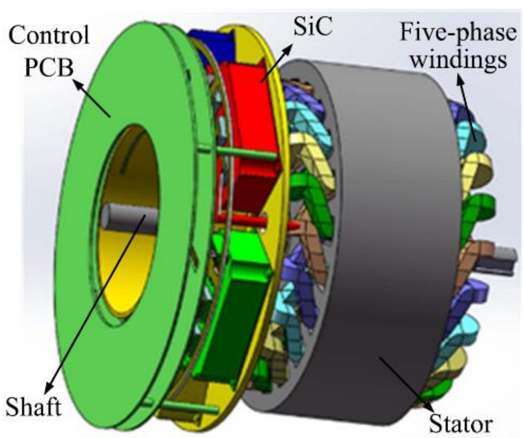
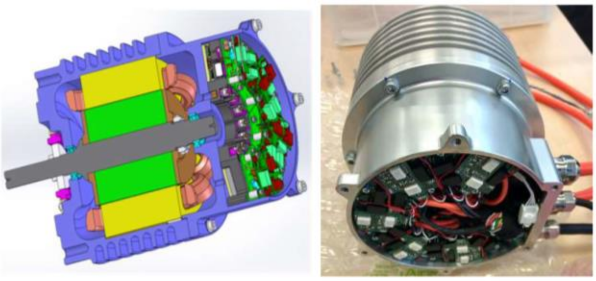


Fig.1 Electromechanical integrated motor for electric aircrafts[9]

3.2 Integrated motor for automobile driving

An integrated motor that combines an in-wheel motor and an inverter has been proposed for use in the main engine of automobiles. An in-wheel motor is a drive system in which the motor is located inside the wheels. By placing the motor inside the wheel, it expands the cabin space and realize highly responsive independent wheel drive control which delivers torque directly and independently to the wheels. In-wheel motors are required to be smaller and lighter by virtue of the restriction of fitting the parts inside the wheel. Therefore, by integrating the mechanical and electrical components, the aim is to efficiently fit each component inside the wheel.

Fig.2 shows an overview of the integrated motor, which combines an in-wheel motor[6] and an inverter, and the inverter module. The maximum output power is 40 kW. To achieve high efficiency by switching the windings and high output by improving the winding coefficient, the motor is a five-phase motor equivalent to the mechanical-electrical-integrated motors for aircraft, but this technology is not indispensable for mechanical-electrical integration. The circular inverter is made up of fan-shaped inverter modules that fit efficiently into the outer shape of the motor. The power device used in the inverter is SiC.


(a) Overview

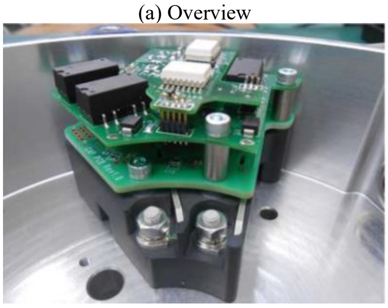
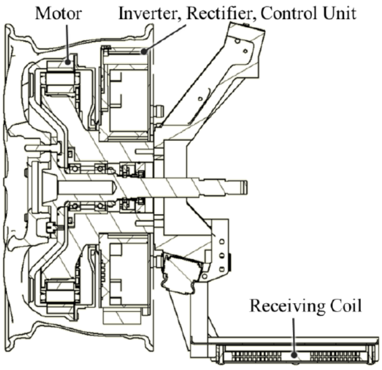

(b) inverter module

Fig.2 Inverter integrated in-wheel motor[6]



(c) Component Layout

Fig. 3.   nverter and converter integrated in-wheel motor[10]

Fig. 4.   Appearance of e-Axle by NIDEC[12]

Fig. 5.   Appearance of e-Axle with electric oil pump by MEIDENSHA[5]

Since the motor is designed to be used with a reduction gear, its torque type is small with high rotation. The maximum torque as indicated in the source table is 72Nm and the maximum speed is 20,000min^{-1}.

What is more, an integrated power supply motor has been proposed that it incorporates not only an inverter for driving the motor but also a power receiving circuit for non-contact power supply. The ov erview of the unit, the power circuit board and its layout are shown in Fig. 3. The power circuit board also has components arranged in a circular pattern. Placed at the top of the board is the power device for the inverter and on the bottom is the power device for the rectifier circuit. The power devices for the inverter and rectifier are SiC.

On the right side of the board is a capacitor for the resonance of the magnetic field resonance coupling type non-contact power supply coil, and on the left side are the circuits for control and communication. The left side of the board contains the control and communication circuits.

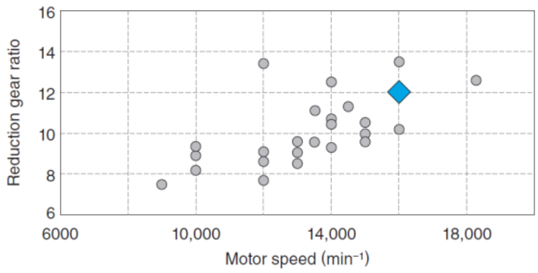


Fig.6 Speed and reduction ratio of e-Axle[5]
vertical axis is gear ratio, horizontal axis is motor speed

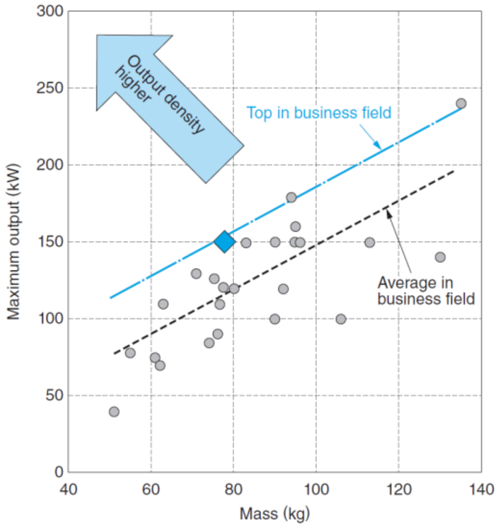


Fig.7 Maximum power and unit weight of e-Axle[5]
vertical axis is maximum power, horizontal axis is mass

The motor is a direct drive type without a reduction gear, so it has a high torque and low rotation speed. The maximum output, maximum torque, and maximum speed are 25 kW, 510 Nm, and 1500 min-1, respectively.

3.3 Summary of Research Trends

This chapter summarized three of the current research trends. Although the structure of the motors is different, two things in common are that the inverter substrate is circular, and that the power device is SiC. It can be concluded that the use of SiC is fundamental to achieve high output and miniaturization of the power device for the sake of the integrated motor requiring higher requirements for miniaturization and thermal management owning to the concentration of functions.

IV. Trends in Practical Application of Electromechanical Integration

4.1 Automotive Main Driving Motors

The trend of electromechanical integration is accelerating in motors for automobile main engines, and last couple of years, vast number of component suppliers have begun to develop and commercialize such motors. This paper introduces the trends in the practical application of these technologies.

Fig.8. Appearance of e-Axle with electric oil pump by AICHI STEEL[13]

Fig. 9. High power density e-Axle by YAMAHA[14]

The “e-Axle” is a vehicle drive unit that integrates three components: motor, inverter, and reduction gear. e-Axle has the potential to contribute to the simplification of electric vehicle development and production processes for automakers because of its ease of installation in vehicles. Since e-Axle has the potential to help automakers simplify their electric vehicle development and production processes due to its ease of vehicle installation, many suppliers are developing e-Axle, and the release information of e-Axle development has expanded from around 2019. Figure 4 shows the basic appearance of the e-Axle(12).

As another development trend, an e-Axle equipped with an electric oil pump, oil cooler, and even a parking lock mechanism, as shown in Fig. 5, has also been developed[5]. The motor of this e-Axle is oil-cooled and has a self-contained cooling system in which oil is circulated by the oil pump and oil cooler for cooling. The inverter is water-cooled, and the cooling water supplied from the vehicle is used to cool the inverter and to exchange heat with the motor oil. The motor torque is reduced by increasing the motor rotation speed to reduce the size and weight, and the axle torque is maintained by using gears with a high reduction ratio. Fig. 6 shows the relationship between the motor speed and reduction ratio of each company's e-Axle, and Fig. 7 shows the relationship between the maximum output and unit weight of each company's e-Axle. Fig. 7 shows the relationship between the maximum output and the unit weight of the e-Axle. These characteristics show that the e-Axle is one of the best in the industry in terms of power density, which is the relationship between the maximum output and the unit weight. In addition, the motor, inverter, and reduction gear are arranged in an axial direction to reduce the height of the unit, and the design allows for sufficient interior space even when mounted under the rear floor of the vehicle.

More recently, the focus of development has been on improving performance, especially in terms of system efficiency and miniaturization, and features such as ultra-high speed and high output have been developed, as shown in Figs. 8 and 9. In the electric axle shown in Fig. 8, the motor rotates at a maximum speed of 34,000 min-1 and the speed is reduced to the practical range by a reduction gear. The high-speed rotation of the motor and the reduction gear is expected to reduce the size of the axle by about 40% compared to conventional electric axles. The electric motor unit shown in Fig.9 is characterized by its high output density of up to 350 kW, and multiple units are expected to be installed in a vehicle[14].

As described above, the development of e-Axle motors for automobile main engines is accelerating, combining the strengths and characteristic technologies of each component supplier. e-Axle motors equipped with further technologies are expected to appear in the future.

Fig.10 Structure of controller integrated motor with pump[3].

4.2 Auxiliary Motors for Automobiles

Motors that drive auxiliary equipment in automobiles require an Electronic Control Unit (ECU) to control them. Due to space constraints, motors and ECUs are often developed as a single unit(1). According to Reference 15, the ECU is placed on the back of the motor, and the mass is reduced by 10% by eliminating the motor case, integrating the motor bracket (frame end) and heat sink, and simplifying the structure by reducing the number of through bolts. In this case, the neodymium magnet was replaced with a ferrite magnet to reduce the risk of rare earth (REE) supply. According to Reference 16, by moving the ECU from the front to the rear, eliminating the fastening part of the motor and ECU housing that protrudes in the radial direction, and press-fitting it into a uniform cylindrical frame, the maximum radial dimension can be shortened while the diameter of the motor electromagnetic part is enlarged to expand the motor output. In addition, the power module and capacitor, which had been placed on one side of the heat sink, were divided and placed on both sides to shorten the overall length.

4.3 Industrial Motors

In industrial applications, there are many examples of development for fan, pump, and compressor applications [3][4]. In this case, the valve control by a constant speed induction motor is made more energy efficient by variable speed operation with an inverter drive (Fig. 11). In order to maintain size compatibility, the induction motor is replaced by a PM motor and the inverter is integrated into the space secured by the downsizing. According to Reference 3, the main components of the inverter such as the main circuit board and capacitor are placed on the side of the motor, and according to Reference 4, they are integrated into the back of the motor.

V. Summary

To sum up, this paper classified integrated motors according to the arrangement and configuration of the inverter, discussed the research trends and how to apply practically. In the past decades, motors and devices were developed as a single unit for automotive auxiliary equipment, home appliances, and consumer products. Nowadays, the use of integrated motors and devices has become the mainstream for automotive main engines, and the number of products for industrial pumps and fans has been increasing drastically. It is expected that motors and inverters will be more flexible and integrated into a form that suits the application for the years to come.

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