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Future Perspective for Key Technologies of Motor Drive Systems of New Energy Vehicles

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Abstract: This study investigates key technologies and development trends for the motor drive system of new energy vehicles, including power semiconductor devices and their packaging, smart gate drivers, and the device-based system integration design, for the drive controllers; it also explores new motor technologies related to the hair-pin winding, multiphase permanent magnet motor, and permanent magnet synchronous reluctance motor. The study emphatically presents the development trends of the motor drive technologies for vehicles, and points out that permanent magnet synchronous motors will remain the main-stream drive motors in the new energy vehicle market within the next 10 years. Meanwhile, this study reveals several key issues existing in drive motor development, which could offer a reference for the technology development of new energy vehicles in China.
Keywords: new energy vehicle; motor drive system; permanent magnet synchronous motor

1 Introduction

Although China is a large country that possesses abundant resources, it still faces challenges such as a scarcity of resources per capita and a high energy consumption per unit of GDP. Therefore, the development of high-efficiency, electric-propulsion-based new-energy vehicles (NEVs) is essential for ensuring appropriate usage and conservation of energy. Meanwhile, there still exists a large gap between Chinese and western-world enterprises regarding internal-combustion engine technology, and this gap cannot be closed in the next ten years. However, as China is not very far behind the west in terms of electric drive technology, it becomes a sensible choice for China to develop NEVs based on electric propulsion, which provides a significant opportunity for Chinese vehicle manufacturers to compete with their western counterparts.

In China, batteries, motors, and drive controllers are usually regarded as essential electric technologies for NEVs. As the development of battery technology is currently at a bottleneck, research on improving the efficiency, power density, security, and reliability of motors has become the primary focus for the NEV industry, as well as for the government and enterprises, regarding policy making and future development plans.

2 Key technology and future perspective of drive controller

The drive controller of an NEV is the power conversion unit between the battery and the motor, and is also the core of the machine drive and control system. High-performance power semiconductor devices, intelligent gate drive technology, and device-level integration design will facilitate the development of high-power-density, low-loss, and high-efficiency motor controllers. Meanwhile, functionally safe and reliable designs with high-quality electromagnetic compatibility (EMC), are also needed for high-performance and reliable motor controllers.

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2.1 Power semiconductor technology

The development of motor controllers usually follows the technology roadmap of power semiconductor devices. These technologies have evolved from the conventional Si-Insulated Gate Bipolar Transistor (Si-IGBT) and single-sided cooling package, to wide bandgap (WBG) semiconductors (such as SiC and GaN), personalized modular packages, and double-sided cooling integration. Meanwhile, owing to the iterative regeneration of technology and lower cost than that of WBG semiconductors, Si-IGBT still remains as the primary choice for motor controllers for the long-term future.

Based on Si-IGBT technology, Infineon has developed a new chip technology codenamed EDT2—which aims to meet the high-power-density requirement of the NEV market—and has started the mass production of 750 V/270 A IGBT. Japanese companies such as Fuji have also developed high-power-density IGBT technology for use in automotive IGBT modules. Compared with conventional Si-based devices such as IGBT and metal–oxide–semiconductor field-effect transistors (MOSFET), the SiC device belongs to the third generation of power semiconductor materials, offering advantages such as high heat conductivity, high-temperature durability, a wider bandgap, a higher breakdown field strength, and a higher saturated electron drift rate. Furthermore, its junction temperature tolerance can exceed 225 ℃, which is substantially higher than that of existing Si-IGBT (≤175 ℃). In addition, the SiC device has a higher switching speed and can work at higher switching frequencies, thereby being more suitable for high-speed motor control. Moreover, compared with Si-IGBT, the SiC device exhibits a substantially lower switching loss and on-state loss, which helps to reduce the vehicle power loss per 100 km and simultaneously increase the overall mileage [1]. However, the current market price of SiC devices is still considerably higher than that of Si-IGBT, which forms the main obstacle for the generalization and application of SiC.

Additionally, some advanced novel package technologies such as copper-wire bonding, flip chip, silver sintering, and transient liquid phase bonding, will further increase the current density and service lifetime of IGBT modules; therefore, these are currently the most popular research topics. Thus far, companies such as Denso, Delphi and CRRC Times Electric have developed double-sided cooling-based IGBT modules and motor controllers, the batch application of which has been partially achieved in automotive products. Si-IGBT-based machine-controller design will still remain the main long-term focus for market, while Si-IGBT chip and power module package technologies will continue to be innovated and upgraded.

2.2 Intelligent gate drive (IGD)

For a motor controller, the gate drive technology is the band between the high-voltage power semiconductor device and the low-voltage control circuit, and is also the key factor for the drive control of the power semiconductor device. In addition to its fundamental functions such as isolation, drive, and protection, it is necessary to accurately control the process of switching on and off of IGBT bridge arms according to the IGBT characteristics; this can help to achieve an optimal trade-off between the loss and the electromagnetic interference (EMI) [2].

Active gate-drive control and the functions of monitoring and diagnosis are two main features of IGD. Active gate-drive control is a method of actively refining and optimizing the switching control of IGBT according to the operation environment and conditions. It is now a primary research focus regarding IGBT application. The basic concept is to divide the switching-on and -off process into different stages. For a specific case, the method only needs to focus on the gate tuning corresponding to the relevant stage, which has a relatively small or negligible influence on other system parameters [3].

Based on the aforementioned analysis, the application of IGD will facilitate peak-performance operation of power semiconductor devices, for example, through a reduction in loss, an improvement to the voltage utilization, and online health-condition monitoring of the device. Moreover, IGD can also satisfy the design requirements of safety and reliability of motor controllers.

2.3 Integrated design of power module

To meet the requirements of high power density, long service life, and high reliability in NEVs, almost all power semiconductor device package of typical motor controller products available in the international market offer customized designs [4]. The distinction between power semiconductor devices and other electronic devices is gradually being erased, and device-based integrated design is becoming the new trend regarding NEV motor controllers.

Device-level integrated design can be classified into physical integration design and requirement integration design. According to investigations on the physical structure of various components of motors, physical integration design can balance the optimization of parasitic parameters, heat cooling, and mechanical strength. It can also optimize mechanical, electrical, thermal, and magnetic designs, and help to achieve the final design objective, that is, a high-power-density and reliable motor controller. Requirement integration design is an extension of the requirements of the vehicle and electrical drive system to the fields of IGBT chip design and power module packages. It follows the requirements of vehicle performance design and has

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led to a vehicle-design-oriented optimization method that includes all elements, from the system to the core components. The resulting advantages include both increased mileage and decreased battery size.

2.4 Other key technologies

In addition to the three aforementioned technologies, there are still several noteworthy technologies for the NEV industry:

(1) EMC and reliability design are key technologies for the industrialization of NEV electrical motor controllers, and are also key indices for the evaluation of power electronic products. A more efficient EMC has always been the objective, and the finite-element-analysis-based method will gradually become the mainstream technology roadmap. This method can build the EMC high-frequency “component–part–controller” simulation model for the study of failure mechanisms, and can achieve direct design of EMC, with the aid of experimental evaluation.

(2) The functional safety design of vehicles is an effective solution for alleviating the various safety risks due to functional abnormalities in electronic and electrical systems. Currently, the demand for functionally safe motor controllers is at the ASIL C level. In the future, it will elevate to the ASIL D level, which will require a more complex, redundant, and reliable design of drive controllers [5].

(3) The reliability design of electrical motor controller is essential for NEVs. The motor controller is the core drive part of a NEV, and its reliability has a direct impact on the user experience and market reputation. German and American companies have jointly proposed the robustness validation (RV) approach [6]. This approach has been adopted by Infineon and Bosch for the reliability design and analysis of discrete-semiconductor devices. However, its generalization and effectiveness in complex systems, such as motor controllers, still need further investigation.

3 Key technology and future perspective of drive motors

The electric motors, which is used as the power take-off component of NEVs, has been employed as a replacement for the traditional internal combustion engine (ICE). Owing to the increasing demand for motors with a wider range of speed tuning, higher power density, and higher efficiency, the NEV industry has started using the rare-earth permanent magnet (PM) synchronous machine (PMSM) as the mainstream drive machine, and is gradually replacing traditional DC and induction machines. However, with the demand for even higher power densities and efficiencies, PMSM designs based on conventional structures and produced using conventional manufacturing processes are gradually becoming inferior to the market competition. Hence, both established vehicle manufacturers and new entrants to the NEV industry, are currently trying to develop new solutions and alternatives.

3.1 Flat-wire winding

Fig. 1 shows a flat-wire winding, which is also known as a hair-pin winding. The application of hair-pin windings can increase the slot fill factor and consequently increase the power density of the motor. Moreover, the hair-pin winding has a relatively short winding end, which results in a lower copper loss and better heat-cooling performance. However, manufacturing technologies, equipment, and patents for this type of motors are primarily from traditional vehicle-manufacturing superpowers such as Japanese, Italian, and German automotive firms. In 2018, some Chinese electric vehicle parts suppliers, such as INOVANCE and SANTROLL, entered this field, offering their own hair-pin motor products.

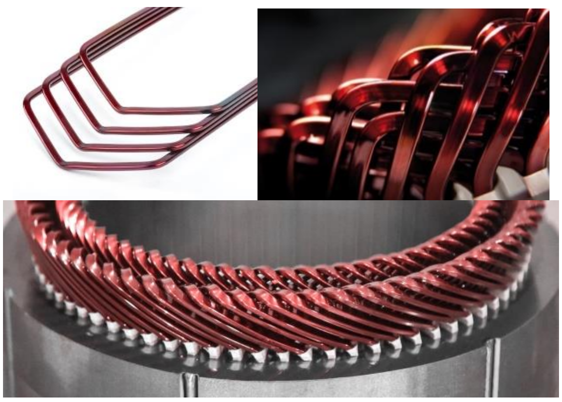

Fig. 1. Hair-pin winding (or flat-wire winding).

Nevertheless, compared with conventional winding that uses round copper wire, hair-pin winding has a more pronounced high-frequency skin effect. Thus, the current-circulation loss due to hair-pin windings is more significant in large-power drive motors [7,8]. In addition, the manufacturing process for hair-pin windings is usually complex, and the insulation layer is usually easily damaged upon bending. Thus, the reduction of the skin effect and eddy-current loss due hair-pin windings is being actively researched. Meanwhile, improved material-manufacturing accuracy and enhancements to the relevant technologies of hair-pin windings will also facilitate its localization in China.

3.2 Multiphase permanent motor

Even with a lower DC bus voltage, a multiphase motor still can produce the same output power as a conventional three-phase machine, and it also exhibits relatively lower torque ripple and better fault tolerance properties [9]. Thus, multiphase motors have been preferred in the electric drive system of NEVs, which has strict requirements in terms of noise, vibration, and harshness (NVH) [10]. Taking the dual-three phase PMSM as an example, its two sets of phase windings have a 30° displacement in between their electrical angles, which can eliminate the 5th and 7th harmonics of the magnetic potential, as well as significantly reduce the torque ripple [11,12]. Meanwhile, its two sets of windings have isolated neutral points, which can reduce the system order compared with four-phase and five-phase machines. Furthermore, a multiphase motor also can facilitate algorithm analysis and drive control, and its fault tolerance control does not require a substantial change to the system configuration when there is a malfunction in the motor or/and drive controller. Thus, its applications in electric drive systems of NEVs have been actively studied by both academia and the industry.

3.3 PM-assisted synchronous reluctance motor

The PM-assisted synchronous reluctance machine is a hybrid of the PMSM and the reluctance machine. Compared with the conventional PMSM, it simultaneously involves a lower usage of rare-earth PMs and a high reluctance torque, and is thus regarded as a less- or non-rare-earth scheme.

In addition, the PM-assisted synchronous reluctance motor not only has a quite high torque–current ratio, high power density, and low magnetic saturation, but also has a considerably wider high-efficiency speed range. Therefore, this technology has been employed in the BMW i3 and i8, as shown in Fig. 2.

The PM-assisted synchronous reluctance motor has now been widely accepted in industry and is regarded as an effective roadmap. However, it still faces challenges such as a complex rotor structure, complex manufacturing process, expensive manufacturing equipment, and large variations in the optimal current angle; thus, addressing these issues has become the current focus of research. However, these issues remain a challenge for companies that depend on cheap rare-earth PMs and have inadequate research and manufacturing capabilities.

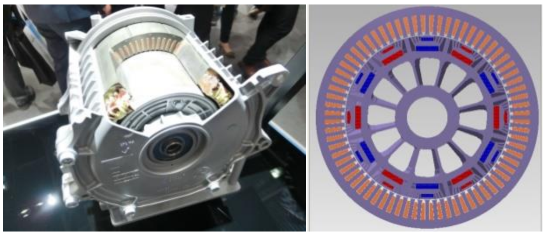

Fig. 2. PM-assisted synchronous reluctance motor for BMW i3.

3.4 In-wheel motor

There are various types of in-wheel motors, and the most widely investigated type is the outer-rotor in-wheel motor [13−16]. In-wheel motors offer clear advantages. For example, they eliminate the need for mechanical drive components such as transmissions, shafts, and differentials. They can also provide four-wheel-drive capability and clear more chassis space for the battery package. However, in-wheel motors still face several challenges, such as a significant increase in the unsprung weight and in the moment of inertia of the wheels, waterproofing and dustproofing issues, heat dissipation, and complex drive-control algorithms [16]. Companies such as Protean and Elaphe have proposed various prototype in-wheel motors (Fig. 3), and they have cooperative localizations with Chinese companies such as APG and VIE. In addition, Chinese companies such as TeT Drive Technology (now owned by the Evergrande Group) have also developed prototype schemes for special and large commercial vehicles.

3.5 Heat dissipation of PMs

Stable performance of the PM is essential for efficient output performance of the vehicle drive motor. A temperature rise in a PM results in demagnetization, which consequently reduces the output torque of the motor. An exceedingly high temperature will also shrink the size of high efficiency areas of the motor, as well as decrease the power factor [17]. To address

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this issue, temperature monitoring of rotor PMs has been studied by both academia and the industry [18]. However, in real-world applications, the use of low-cost thermal sensors remains the only accepted solution in the PMSM used in NEVs.

Research on the heat dissipation of motors is currently focused on the analysis of stator windings and winding-ends. This will be of great significance for the improvement of the power stability of NEVs if the heat-dissipating structures and methods of rotor design could be thoroughly investigated. In addition, the development of temperature-resistant PMs for high-power-density motors can provide a radical solution to the issue of degradation of magnetic properties under high-load and/or high-temperature conditions.

Fig. 3. Elaphe 110 kW liquid-cooled in-wheel motor.

3.6 Other technologies

The NEV industry involves the following noteworthy research fields: 1) Ultra-conductive copper–carbon nanotube wire; 2) Motor with switched stator winding; 3) High-voltage insulation material; 4) Partial demagnetization technology.

Considering that China is the world's largest market for NEVs, certain technologies used in China are not as developed as those used in the west. Examples include high-speed bearings, brushless electrical excited synchronous motor, and deeply integrated motors and drives. The Chinese NEV industry needs to overcome these difficulties through research and industrial distribution. The inexpensive and abundantly available rare-earth PMs in China will eventually be exhausted, and the NEV industry will face challenges from both environmental and technological perspectives.

4 Conclusions

Over the next five to ten years, the NEV industry will enter its golden age of development. China, being as the world's largest vehicle market, will witness extensive changes and developments in its NEV industry. According to the current status and progress regarding the key NEV drive controller technologies mentioned earlier, it can be concluded that Si-IGBT will remain the dominant choice in the machine controller market for the foreseeable future. Meanwhile, with the decreasing costs associated with SiC device manufacturing, the highly reliable 800V SiC drive controller will be the focus of development for the next-generation electrical drive system for passenger vehicles. In addition, this study highlights that China needs to be alert regarding its dependence on the abundant and inexpensive rare-earth PMs, and needs to focus on the emerging electrical motor technologies, for example, new motor design technologies, new materials, advanced manufacturing technologies, and high-accuracy equipment. This will be of great significance in overcoming potential technological barriers and staying competitive with motor companies from the western countries.

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