High-Speed Permanent Magnet Electrical Machines - Applications, Key Issues and Challenges

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(Invited)

***Abstract*—In this paper, application examples of high-speed electrical machines are presented, and the machine structures are categorized. Key issues of design and control for the high-speed permanent magnet machines are reviewed, including bearings selection, rotor dynamics analysis and design, rotor stress analysis and protection, thermal analysis and design, electromagnetic losses analysis and reduction, sensorless control strategies, as well as comparison and selection of sine-wave and square-wave drive modes. Some challenges are also discussed, so that future studies could be focused.**

***Index Terms*—High-speed machine, multi-physics analysis, permanent magnet machine, power loss, sensorless control.**

I. INTRODUCTION

HIGH-SPEED electrical machines have found extensive applications in the last decades, as they have high power density (power per weight and/or power per volume) which is a critical feature for some specific applications. Furthermore, many loads such as centrifugal compressors enjoy high energy efficiency and high power density when they work at high speed. In early years when electrical motors could not run at high speed, boosting gear boxes were required to connect the motors and loads, which would cause problems of extra power loss, additional volume and weight, vibration and noise, maintenance requirement, possible lubricant leakage, and shortened service life. However, while using high-speed electrical motors, the gear boxes can be eliminated. On the other hand, some ordinary-speed electrical generators are driven by high-speed power plants (e.g., micro gas turbines), hence, reducing gear boxes have to be used. However, when using high-speed electrical generators, the gear boxes can be removed, too.

In general, by using the high-speed electrical machines, direct drive (DD) can be achieved for the motor and load, or for the power plant and generator. Such high-speed DD technique can enhance the system efficiency and reliability, reduce the system weight and volume, and make the system more environment-friendly.

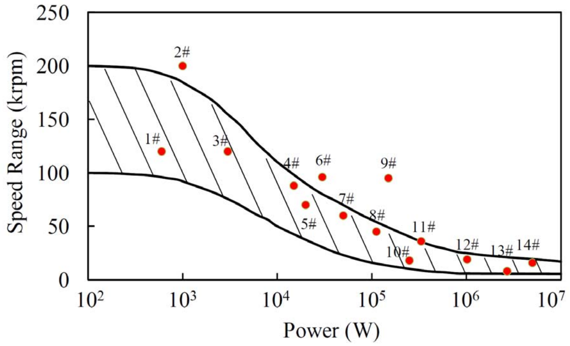

Fig. 1. Relationship between challenging high speed and power rate.

TABLE I
EXAMPLES OF HIGH-SPEED MACHINES

No.	Power (kW)	Speed (krpm)	Developed / Designed by	Application
1#	0.6	120	Shef. Univ.	Centrifuge
2#	1	200	EPFL	Air compressor
3#	3	120	ZJU	Air compressor
4#	15	88	ZJU	EAT
5#	20	70	ZJU	Air conditioner
6#	30	96	Capstone	Turbine generator
7#	50	60	Shef. Univ.	Fly wheel
8#	112	45	Xi'an Jiaotong Univ.	Turbine generator
9#	150	95	ZJU	Turbine generator
10#	250	18	Calnetix	Air compressor
11#	333	36	Kinetic	Fly wheel
12#	1,020	19	Shenyang Univ. Tech.	Compressor
13#	2,700	8	Naval Univ. Eng.	Compressor
14#	5,000	15.9	Siemens	Air compressor

However, it is difficult to make a widely-accepted definition of the high-speed electrical machines. Clearly, the higher the power is, the lower the achievable high speed. Fig. 1 shows the relationship between the said high speed and the machine power [1]. If the power is of kilowatts or less, the challenging speed can be 10 0krpm or even higher. However, if the power is

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at the level of hundreds of kilowatts, the challenging speed is just around 20krpm. Of course some exceptionally high-speed machines have been developed. For example, a 150kW 95krpm permanent magnet (PM) AC generator and a 100kW 95krpm PM AC motor were designed by the authors' team at Zhejiang University (ZJU), which were for a vessel-used gas turbine generator system. Table I shows some examples of the high-speed machines which are marked in Fig. 1.

In this paper, various PM AC machines will be reviewed, most of which were developed by the authors' team at ZJU. Certainly, technical data of some other researchers and companies will be cited, too.

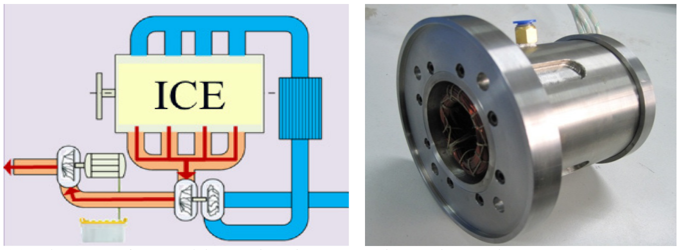
II. APPLICATIONS OF HIGH-SPEED ELECTRICAL MACHINES

In this section, some application examples of the high-speed electrical machines are presented, in the areas of such as vehicles, domestic appliances, renewable energies and high-end machining centers, which show the attractive beauties of these kinds of machines.

A. High-Speed Turbine Generators

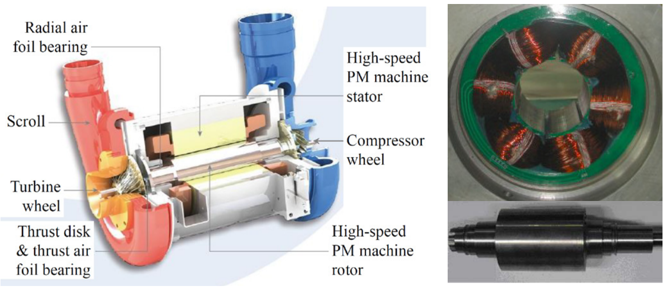
Internal combustion engine (ICE) is widely used for vehicles, vessels, etc. However, the ICE usually has a very low efficiency, as about 35% of the fuel energy is wasted in the exhaust. A common way to recycle energy from the exhaust is to use a turbo charger, which is now rather common in cars, trucks and even other special vehicles.

However, there is still considerable energy left in the outlet gas of the turbo charger. For this reason, it is proposed to use another turbine after the turbo charger to drive a generator with the exhaust (see Fig. 2(a)), converting its energy into electricity.



(a) Diagram of ICE with a turbo charger and a turbine generator (Courtesy Tsinghua University)

(b) A 3kW 50krpm PM generator developed by ZJU



(c) Diagram of electrically assisted turbo charger (Courtesy K-Turbo)

(d) Stator and rotor of a 15kW 88krpm EAT PM machine developed by ZJU

Fig. 2. High-speed turbine generators for recycling ICE exhaust energy.

With support from the China 973 program (under the grant of 2011CB707204), Tsinghua University developed such a turbine, whilst ZJU developed a PM generator (see Fig. 2(b)) which was driven by the turbine. The generator power is 3kW and the speed is 50krpm. This extra high-speed turbine generator not only saves energy by 6%, but also helps to simplify the ICE design, because the ICE efficiency does not have to be as high as originally required, since the waste energy in the ICE exhaust can now be recycled.

Another way to recycle the ICE exhaust energy is to replace the conventional turbo charger with an electrically assisted turbo charger (EAT), which has a turbine wheel and a compressor wheel on a single shaft like a conventional turbo generator, and also has an electrical machine, of which the rotor is installed on the same shaft, refer to Fig. 2(c). Usually the turbo charger speed is around 100krpm or higher, thus, this electrical machine has to run at the same high speed.

The EAT can solve two major problems of the conventional turbo charger. First, when the ICE runs at very high speed and power, there is too much energy in the exhaust which could make the turbo charger run at over-speed, therefore, a valve must be opened to remove some exhaust before the turbo charger inlet, say, some energy of the exhaust cannot be utilized by the turbo charger. However, under such a condition, the EAT PM machine can run as a generator, so that the extra energy in the exhaust can be converted into electricity and stored in a battery. Second, when the ICE idles at low speed and suddenly more fuel is given to the ICE, ideally the turbo charger should boost up immediately to blow much more air into the ICE, however, since there is little energy in the exhaust, the turbo charger cannot response quickly. Nevertheless, the EAT PM machine can run as a motor, so as to boost up the compressor wheel very quickly, in other words, can improve the dynamic performance significantly.

It should be noted that in Fig. 2(c) air bearings are utilized. However, for most turbo charger and EAT systems, contactless oil bearings are commonly used, although precision ceramic-ball bearings are sometimes applied, too.

Fig. 2(d) shows an EAT PM machine developed by ZJU, which has a rated power of 15kW and a rated speed of 88krpm. Its rotor has 2 poles and is protected with a titanium sleeve. Its stator uses 6 concentrated coils, the current spatial harmonics of which will cause lower eddy current in the rotor than those of the 3 concentrated coils or those of the common distributed windings [2], [3]. The EAT machine shown in Fig. 2(d) is utilized for a heavy duty vehicle which requires superior dynamics as well as high energy efficiency. Under proper control, the PM machine can run at both motor mode and generator mode.

B. High-Speed Centrifugal Machines

The EAT has a rather complicated structure. Whilst, one of the basic functions of an EAT is centrifugal air compression. Therefore, to improve the ICE dynamics, it is also common to use a super charger, which consists of a high-speed motor and a centrifugal compressor wheel. In a typical super charger developed by the French company Valeo, a high-speed

(a) A 3kW 120krpm PM motor for air compressor developed by ZJU (b) A 20kW 70krpm PM motor for air conditioning compressor developed by ZJU

Fig. 3. High-speed PM motors for centrifugal compressor applications.

switched reluctance (SR) motor is applied. The SR motor has a robust rotor, which can withstand strong centrifugal force, but also suffers from severe air friction.

The super charger is actually a motor-driven centrifugal air compressor, running at very high speed. Such kind of air compressor is also widely used for fuel cells [4]. Fig. 3(a) shows a 3kW 120krpm PM AC motor developed by ZJU, in which the rotor is protected with a glass fiber sleeve. To achieve better protection, carbon fiber can be used instead of the glass fiber, but it is more expensive.

The domestic appliance vacuum cleaner is another kind of centrifugal tool. Its purpose is not to generate a high air pressure, but a very low pressure. The British company Dyson firstly developed a single phase high-speed (104krpm) PM brushless DC motor, called digital motor [5], for the vacuum cleaner in which the motor power electronics drive and the centrifugal impeller are both integrated with the motor. By using the high-speed motors, the vacuum cleaners are small and light, and work efficiently. Dyson also uses high-speed digital motors for their hair driers. “We found a better way to look after hair. It wasn't a lotion or potion - it was a motor,” said Stephen Courtney, the Dyson Concept Director [5]. Clearly, the high-speed motor plays an important role for the business of Dyson.

High-speed PM motor has also been used for air conditioning compressor [6]. For example, it was reported that GREE, one of the leading air conditioner makers in China, had developed a hundred-kilowatt high-speed centrifugal compressor. Similarly, ZJU developed a 20kW 70krpm PM motor for air conditioning compressor, as shown in Fig. 3(b). The system is designated for airplane application. The volume and weight of both the motor and the compressor are dramatically reduced due to their inherited property of high power density, e.g., the weight of the motor and compressor is 14kg only, but it was 44kg when using an ordinary-speed motor and compressor.

Nowadays, high-speed motors are also used for various centrifuges, replacing the combination of ordinary-speed motors and boosting gears. This is an obvious improvement from the points of view of both the motor and the system.

C. High-Speed Motor and Generator Dual-Mode Systems

The above-mentioned EAT PM machine is a typical dual-mode system, say, the machine need to work in both motor mode and generator mode. Such kind of dual-mode systems are actually rather common.

For example, gas turbine engines [7] are getting more used to replace the traditional diesel ones, and they usually run at very high speed. When the gas turbine engine starts, it is driven by the electrical machine which runs as a motor; while the engine operates, it drives the electrical machine to generate electricity. In a typical product of micro gas turbine generator developed by the American company Capstone, the rated power and speed of the electrical machine are 30kW and 96krpm, respectively. The electrical machine uses air bearings for high-speed operation. Moreover, with support from the China 863 Program, Xi'an Jiaotong University developed a micro gas turbine generator system, in which the PM AC machine is of 112kW and 45krpm. On the other hand, as mentioned in the Introduction, in the vessel-used gas turbine generator system, a 100kW 95krpm PM AC motor is to start the gas turbine engine, whilst two 150kW 95krpm PM AC machines are to generate electricity when the engine operates, hence, neither of the machines works in dual modes.

In fly wheel systems, the electrical machines also work in dual modes of motor and generator. In 1990s, a fly wheel system was developed in the University of Sheffield, in which the PM AC machine has the peak power of 50kW, the maximum speed of 60krpm, and the stored energy of 1.3MJ [8]. The machine rotor is lifted with magnetic bearings. In early 2000s, a larger fly wheel module was developed by the British company Urenco. Each module has the peak power of 100kW, the maximum speed of 42krpm, and the stored energy of 17MJ [9]. The machine rotor is also elevated with magnetic bearings. An array of the fly wheel modules was installed on trains. When the train approached the station, the braking energy was stored in the fly wheel, while the train left the station, energy was released from the fly wheel. In this way, the impact of instantaneous power consume was reduced by 30%, being rather friendly to the power grid.

D. High-Speed Spindles for Machining Centers

High-speed electrical machines are also applied for spindles for machining centers [10], [11]. Initially the spindles use induction motors. Recently, for the Chinese spindle market, high-speed PM motors have been developed by ZJU to replace the induction motors. Therefore, for the same size, the spindle can achieve higher power, and especially, can have much better torque performance at low speed. In other words, the PM motor spindles can work at relatively low speed for, e.g., drilling and screwing, and also at high speed for, e.g., grinding. Fig. 4

Fig. 4. PM motor spindles developed by ZJU.

shows two ZJU-developed PM motor spindles for such kind of functions. Their ratings are 12kW 18krpm (upper) and 4kW 24krpm (lower), respectively. As an application example, the smaller spindle is used to process the iPhone cases. Originally, two separate machine centers equipped with induction motor spindles were needed for drilling/screwing and grinding, respectively, but now only a single machining center with the PM motor spindle is sufficient.

III. COMMON CONFIGURATIONS OF HIGH-SPEED ELECTRICAL MACHINES

High-speed single-phase AC universal motors which have brushes and commutators are available in the market, for the applications of such as pumps for washing cars. These motors are very cheap, however, basically their speed cannot be over 30krpm if the power is at the kilowatts scale, and their service life is quite short. Therefore, such a brushed configuration is not considered in this paper.

Instead, for high-speed electrical machines, brushless configuration is strongly recommended. Common brushless configurations include induction machines (IM) [12], [13], switched reluctance machines (SRM) [10], [14], PM synchronous machines (PMSM) [4], [6], [11], [15], [16], [17], and PM brushless DC (BLDC) machines [18-24].

The high-speed induction machines have been widely used for spindles and engraving machines. Usually they have copper bars on the rotors so as to improve the efficiency. Unfortunately, they are inherited with low power factor, low efficiency and controllability deficiencies. Some high-speed IMs use solid iron rotors, or solid iron rotors with copper layers, to achieve better rotor ruggedness, but their power factor and efficiency become worse than the conventional squirrel-cage IMs.

The switched reluctance machines have the simplest rotor structure, so that they are the most rugged and reliable for high-speed operation. Moreover, they are well controllable with matched drivers. However, they have vibration and acoustic problems, and their bearings are rather easily wearing-out. Furthermore, the SRMs often have rough rotor surfaces, thus, the air friction loss can be serious. Also, the rotor iron loss is severe, since the magnetic field generated by the stator armature does not rotate smoothly with synchronization to the rotor.

The PMSM and BLDC machines exhibit advantages such as high efficiency, high power factor, high power density, and superior controllability. Equipped with high energy permanent magnets, larger airgap is allowed in the PMSM and BLDC machines, thus the rotor retaining sleeve can be designed with sufficient thickness, and the motor is less sensitive to the unevenness of the airgap due to manufacturing imperfectness. However, the high-speed PMSM and BLDC machines also suffer from problems such as the rotor eddy current loss which can cause undesired temperature rise and irreversible demagnetization of the magnets. If the PMSM or BLDC machine is used for the fly-wheel system, there is another problem, say, the stator iron loss cannot be avoided during idle.

Nevertheless, among the three common brushless configurations, the PM machines are so far mostly employed for the high-speed operation. Therefore, in the following sections, only the PM machines are discussed.

IV. KEY ISSUES OF DESIGN AND CONTROL

Both design and control of high-speed PM machines are critical, since some special problems different from those of the ordinary-speed machines are encountered. More importantly, machine design and control strategy must be taken into account systematically, as the two aspects may not match each other, resulting in a deteriorated system performance or even system failure. The key issues of design and control of the high-speed PM machines include but are not limited to the following.

A. Bearings Selection and Rotor Dynamics Design

High-speed bearings have been developed dramatically in the last decade. Various bearings are now available.

Oil bearings have been used in most turbochargers, which are rather cheap and robust. The drawback is that oil leakage may occur, therefore, in general, they are not suitable for applications like the fuel cell air compressors, as the oil will pollute the compressed air and further damage the fuel cell. Obviously, the oil bearings cannot be used in the vacuum environment, either.

Air bearings have found many applications, such as the Capstone micro gas turbine generators, the K-Turbo EATs, and the centrifugal fan in the International Space Station. There are two types of air bearings, i.e., the static air bearing and the dynamic air bearing. The former is easy to implement, but consumes high-pressure air. The latter has a much simpler structure, but is difficult to design, manufacture and assemble, and cannot work at standstill or low speed. Clearly, the air bearings cannot be used in the vacuum environment.

Magnetic bearings were successfully applied about 20 years ago in the Urenco fly wheel systems for practical train traction [9]. Magnetic bearings are versatile for different environments. But they are complicated, consume energy, and sometimes are unsuitable for heavy load and very high-speed operation due to the limited dynamic performance.

The above three are contactless bearings, hence, theoretically they can have long service life. On the other hand, the dynamic air bearings bring little friction loss on the machine rotor, the oil bearings perform slightly worse in the aspect of friction loss, whilst the static air bearings and magnetic bearings consume energy for their own operation.

Study on the contactless bearings, especially the dynamic air bearings and magnetic bearings, has been greatly supported by Chinese foundations, and significant progress has been made in the last decades. This is very helpful for the development of high-speed electrical machines.

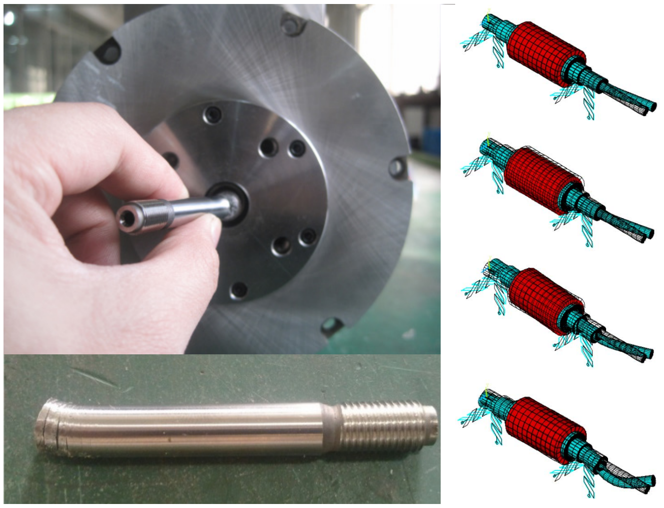
Precision ceramic ball bearings look similar to the traditional ball bearings, but can work at very high speed provided that they are properly lubricated and cooled. However, the lubrication and cooling systems are usually complicated, and assembly of the bearings, shaft and bearing housings must be very precise with specific tools. Of course, the ball bearings are unsuitable for the vacuum system nor the applications where oil leakage is prohibited.

Bearings should be chosen according to rotary speed, the radial and axial loads on them, as well as the environment requirement. More importantly, different types of bearings have their own features which will influence the rotor dynamics. For example, the ceramic ball bearings are of “hard support”, which have a small clearance between the stationary and rotary parts and have a very strong stiffness. However, all the contactless bearings have larger clearance and much lower stiffness (of course these bearings have different characteristics, too), hence, are of “soft support”. They can largely influence the rotor dynamics of the electrical machines, in aspects of vibration modes and resonant frequencies. Therefore, for electrical machine designers, it is nowadays easy to select and purchase high-speed bearings, but it is still critical to analyze and design the rotor dynamics according to the characteristics of the selected bearings, whilst most bearing manufacturers cannot provide the bearing characteristics, either.

B. *Rotor Dynamics Analysis*

Rotor resonance is a serious problem in the high-speed machines, which must be carefully considered and avoided [17], [25], [26]. Rotor resonance will occur if the frequency of the force ripple engaged on the rotor is close to the rotor resonant frequency with the same vibration mode. The resonance may cause damage to the rotor. Therefore, when designing the high-speed machines, finite element analysis (FEA) is needed to predict the rotor vibration modes and resonant frequencies, as well as the torque and force ripples engaged on the rotor. Clearly, the bearing characteristics should be considered in the FEA. It is essential to make the lowest resonant frequency exceed the motor operation speed, in other words, the maximum operating speed should be lower than the resonant speed. However, in many cases this is not achievable. Therefore, when accelerating or decelerating the rotor, it is essential to skip the resonant speeds quickly, so as to avoid operating at the resonant speeds for long time. Therefore, it is needed to predict in advance the rotor resonant frequencies with FEA.

Usually, to avoid rotor resonance, it is essential to design a thick shaft, shorten the distance between the pair of bearings, and avoid long shaft end [26], [27]. Moreover, all the load conditions should be taken into account. By way of example, Fig. 5(a) shows a high-speed air compressor motor made by ZJU, the ratings of which are 15kW and 88krpm. On the shaft end a compressor impeller should be mounted. FEA was made, showing that no resonance would occur from standstill to the rated speed. However, when testing the prototype, the impeller was not installed, and, at the speed of ~50krpm, the shaft end broke suddenly. A further FEA showed that, without the impeller, resonance did happen at this speed, as shown in Fig. 5(b). Therefore, a complete FEA considering all load conditions is critically needed.



(a) Damaged high-speed motor prototype

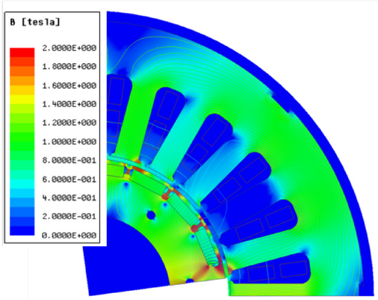
(b) FEA of rotor dynamics with different vibration modes

Fig. 5. Rotor dynamics of a ZJU-made 15kW 88krpm motor.

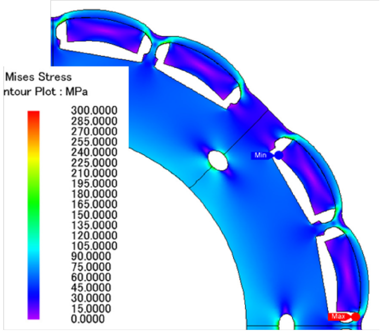
C. *Rotor Stress Analysis and Protection*

Since centrifugal force is proportional to the square of rotating speed, the rotor suffers from an enormous centrifugal force, which may damage the rotor [17], [25]. FEA is the most direct and effective way to investigate the stress distribution in a high-speed machine rotor. However, it must be noted that the material property may degrade even if a very small deformation has occurred, therefore, the rotor may deform further and further. Such gradual deformation, which is ignored by most machine designers, may finally cause the rotor failure. To predict such gradual deformation, iteration of the FEA is needed, by substituting the degraded material property into each step of calculation. Moreover, when calculating the rotor stress, the centrifugal force is not the only factor. Instead, it is essential to present the electromagnetic force on the rotor, which will take function together with the centrifugal force. Fig. 6(a) shows the electromagnetic field in a high-speed motor, from which the electromagnetic force can be obtained. Fig. 6(b) shows the stress distribution of the rotor, in which the electromagnetic force, the centrifugal force and the material property degrading have all been considered. However, the electromagnetic force is usually lower than the centrifugal force, therefore, in most cases it can be neglected.

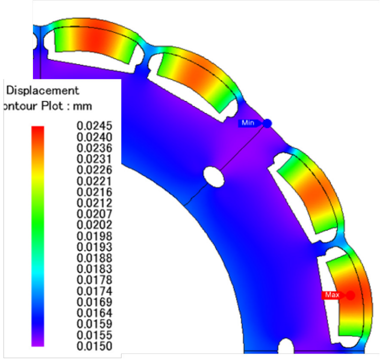
The simplest way to protect the rotor against the centrifugal force is to use a retaining sleeve, the material of which can be carbon fiber (CF) (see Fig. 7), glass fiber (GF) (refer to Fig. 3(a)), titanium (see Fig. 3(b)), inconel or non-magnetic stainless steel. It is easy to analyze the strength of the retaining



(a) Electromagnetic field distribution



(b) Stress distribution



(c) Displacement

Fig. 6. FEA of rotor stress and deformation in a high-speed machine.

sleeve with FEA.

However, additional problems may appear when the retaining sleeve is employed. First, since the retaining sleeve is made of nonmagnetic material, the electromagnetic airgap of the machine becomes much larger, resulting in lower flux density and power density. Second, if the retaining sleeve is of metal, significant eddy current will occur in the sleeve. Although the eddy current loss is usually low and has little influence on the motor efficiency, it can cause remarkable temperature rise due to the difficulty of heat dissipation from the rotor, and consequently irreversible demagnetization of the permanent magnets. On the other hand, if the retaining sleeve is made of nonmetallic material, it usually has very low thermal conductivity, preventing heat in the rotor from dissipating outwards. Similarly, this will also cause remarkable temperature rise in the rotor.

Moreover, when the rotor heats up, the characteristics of the retaining sleeve will change, and thermal expansion of different parts of the rotor will occur, too. Thus, the sleeve strength must be further investigated.

Fig. 7. Carbon fiber retaining sleeve for high-speed rotor.

Fig. 8. Cut-away view of high-speed motor stator with impregnation, developed by ZJU.

Therefore, design of the rotor retaining sleeve is a multi-physics processing. The rotor mechanical stress, the machine electromagnetic performance and losses, the thermal behavior must be analyzed and designed systematically. So far it is difficult to realize fully-coupled multi-physics processing simultaneously, therefore, iteration of each single-physics processing is a workable solution.

D. Thermal Analysis and Design

When the high-speed electric machines enjoy the merit of high power density, they meanwhile really suffer from the high loss density [28-31], which will much more likely, compared with the case of the ordinary-speed machine, cause high temperature rise and even local over-temperature. Therefore, thermal analysis and design must be carried out very carefully with FEA to improve the thermal condition. Also, special process can be used, too. For example, Fig. 8 shows a stator encapsulated with epoxy resin. The epoxy resin has higher thermal conductivity than the commonly used winding varnish. Especially, wires in the stator core slots must be fully impregnated.

It should be mentioned that the temperature rise will increase the winding resistance and cause extra copper loss. It will also degrade the permanent magnet property (although it is usually reversible) and the iron core permeability, and consequently deteriorate the machine electromagnetic performance and then cause more energy losses and higher temperature rise. Therefore, as mentioned in the preceding subsection, multi-physics (thermal and electromagnetic) analysis and design should be iterated.

E. Prediction and Reduction of Electromagnetic Losses

Electromagnetic losses are analyzed and reduced not only to improve the power efficiency, but also to improve the thermal condition. Some losses are negligible in the low-speed and moderate-speed machines, but they can be extremely dominant in the high-speed machines [1]. Therefore, special attentions must be paid to some of the electromagnetic losses, such as the extra copper loss due to the winding AC resistance, the stator iron loss due to high operation frequency, and the rotor eddy current loss.

Rotor air friction loss can be as large as 40% of the total losses [15]. And, the bearing loss also plays an important role if ball bearings are used [27]. However, these mechanical losses are not detailed in this paper.

1) *Winding AC resistance and extra copper loss*

When a machine runs at very high speed and high frequency, AC resistance of the windings, instead of the ordinary DC resistance, should be considered. The AC resistance is higher than the DC resistance due to the skin effect and proximity effect, which accounts for an extra copper loss in the high-speed machines [1]. To take adequate use of the armature wires, a common way is to use litz wires or a bundle of thin wires in parallel [32] instead of a single thick wire. Moreover, the winding AC resistance and the extra copper loss can be reduced with the wire twisting and winding transposition techniques. Fig. 9 illustrates a part of a 5-turn transpositional coil, in which each turn is wound with a bundle of twisted thin wires (see the shadowed wires).

The drawback of using litz wires is that the slot filling factor becomes lower. To keep sufficient cross-section area of the wires, it is essential to slightly increase the slot areas. This needs to refine the electromagnetic design, or to slightly enlarge the machine size. Another problem due to the lower slot filling factor is the higher thermal resistance of the windings. Therefore, the windings must be impregnated or varnished with special process, otherwise, over temperature could happen in the litz wire windings.

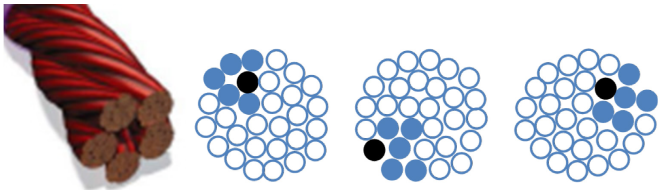


Fig. 9. Diagram of wire twisting and winding transposition.

2) *Stator iron loss*

The well-known Bertotti model shows an obvious positive correlation between the stator iron loss and the operating frequency, whilst the frequency is determined by the machine speed and the number of pole-pairs, and hence is difficult to reduce. To restrain the stator iron loss, a low flux density in the core is preferred when designing the high-speed machines. Of course this will enlarge the machine volume, however, generally the high-speed machines have a higher power density than the ordinary-speed machines, hence, it is not necessary to be to too critical to reduce the machine volume. On the other hand, from the point of view of heat dissipation, it is not necessary to extremely size down the machine, either.

To further reduce the stator iron loss, special core materials can be applied, such as the thinner silicon-steel laminations, amorphous alloys, nanocrystalline materials, and soft magnetic composite (SMC). However, the electromagnetic design must be refined according to the used materials, and more importantly, the manufacturing process must be re-designed.

3) *Rotor eddy current loss*

Although the PM machines are synchronous machines, eddy current exists in the rotor magnets, yoke, shaft and retaining sleeve (if metal) during the high-speed operation. The rotor eddy current loss is mainly caused by three factors: time harmonics in the armature currents, spatial harmonics of the stator magnetic motive force (MMF), and variation of airgap permeance due to the stator slots [3], [15], [26], [33], [34]. In actual fact, the rotor eddy current loss has little influence on the machine energy efficiency, as it is usually much smaller than the other losses [15]. However, it is not negligible in consideration of the poor heat dissipation condition of the rotor, since even a very small rotor eddy current loss can cause a serious over-temperature problem.

Detailed measures to reduce the rotor eddy current loss were reviewed in [27]. By way of example, the rotor eddy current loss can be restrained with proper design of the machine stator. Fig. 10 shows three different stator structures for a 2-pole machine, among which the 6-tooth 6-concentrated-coil structure (the right one in the figure) presents lower stator MMF spatial harmonics than the other two [35], hence, causes lower rotor eddy current, too. Also, properly reducing the stator slot opening width and enlarging the airgap length are beneficial, too [35], [36], [37]. Nevertheless, the narrow slot openings will make the winding assembly more difficult, and the large airgap will decrease the machine output power.

The rotor eddy current loss can be restrained with some specific rotor configurations. By way of example, segmenting is a common technique to reduce the eddy current in the permanent magnets. However, axial segmenting (see Fig. 11 (left)) is much more effective than circumferential segmenting (Fig. 11 (right)), whilst the latter may even increase the eddy current loss when the number of segments is not adequate [38]. This is because the eddy current mainly flows in the axial

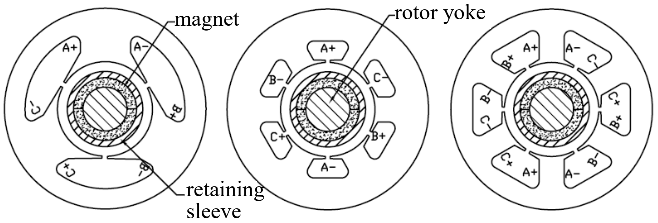


Fig. 10. Three 2-pole stator structures with different MMF harmonics. From left to right: 3-tooth concentrated windings, 6-tooth overlapping windings, and 6-tooth concentrated windings.

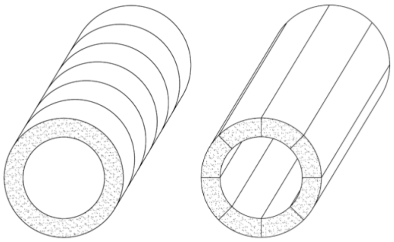


Fig. 11. Magnet segmenting in axial (left) and circumferential (right) ways for rotor eddy current reduction.

Fig. 12. Smooth and circumferentially grooved rotors of a 10kW, 70krpm PM BLDC machine developed by ZJU.

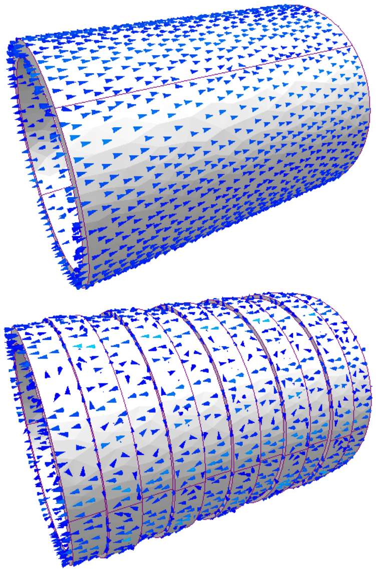


Fig. 13. Eddy current distribution in smooth and circumferentially grooved rotor retaining sleeves.

direction but less in the circumferential direction, thus, the axial segmenting can effectively cut the eddy current path and reduce the eddy current, but the circumferential segmenting cannot. Moreover, the circumferential segmenting will change the eddy current path and even increase the eddy current density and then the related loss [38]. Therefore, the circumferential segmenting technique must be carefully investigated with FEA. Similarly, the metal retaining sleeve can be axially segmented, too. As an example, the titanium sleeve is grooved [39], as shown in (see Fig. 12). Although the sleeve is not segmented thoroughly, as the grooves are shallow, the path of the eddy current is largely obstructed by the grooves, as shown in Fig. 13. Thus, the rotor eddy current loss in the studied 10kW 70krpm PM BLDC motor was cut by 29%, and the rotor temperature was reduced by ~40°C. Besides, the grooves hardly increase the rotor air friction loss or deteriorate the retaining sleeve strength, but help to improve the heat dissipation condition [39].

Another special rotor design is to employ a copper shield between the permanent magnets and the retaining sleeve [38], [40]. Most of the rotor eddy current loss shifts from the magnets to the copper shield, thus there is extra eddy current loss in the shield. However, due to the high conductivity of the copper shield, this extra loss is not significant, whilst the reduction of the eddy current loss in magnets is dominant. Fig. 14 shows the original and shielded rotors of a 3kW 150krpm PM BLDC motor which was developed at ZJU [38]. By utilizing the copper shield, the overall rotor eddy current loss is reduced from 18.5W to 7.9W, dramatically leading to a ~50°C decrease of the rotor temperature.

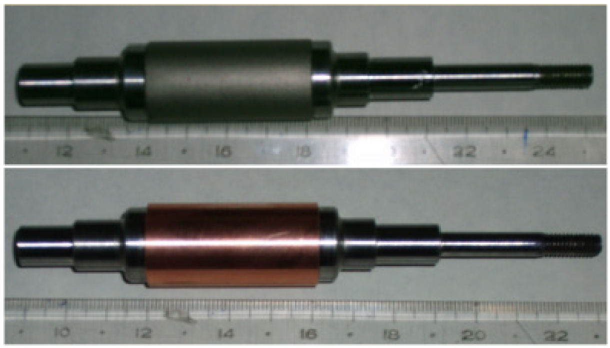
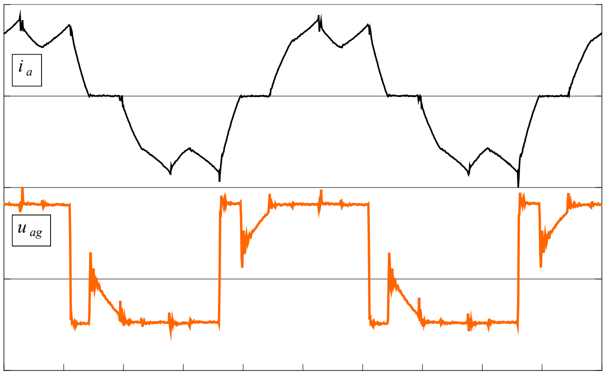


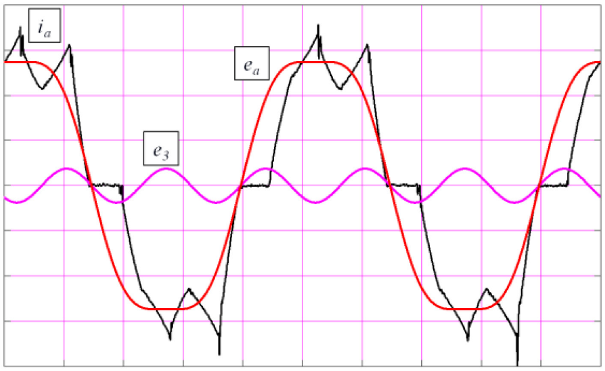
Fig. 14. High-speed PM machine rotor without (left) and with (right) copper shield.

F. *Rotor Position Sensorless Control Methods*

For the high-speed machines, it is uneasy to install rotor position sensors, thus, sensorless control is usually needed. The most common method is to detect the six zero-crossings of the 3-phase back-EMFs (e.g., e_a in Fig. 15) for the PM BLDC drive, whilst the phase back-EMFs are obtained from the motor terminal voltages (e.g., u_{ag}). However, when the motor runs at very high speed, the current freewheeling in the switched-off phase is very long (refer to i_a in Fig. 15), which could obscure the phase back-EMF zero-crossings, hence, the sensorless control method will not work. Therefore, it was proposed to replace the 3-phase back-EMFs with the 3rd harmonic back-EMF (i.e., e_3 in Fig. 15) which has six zero-crossings

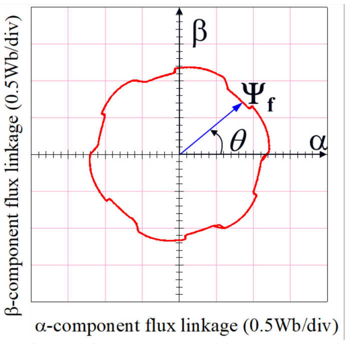


(a) Phase current and terminal voltage

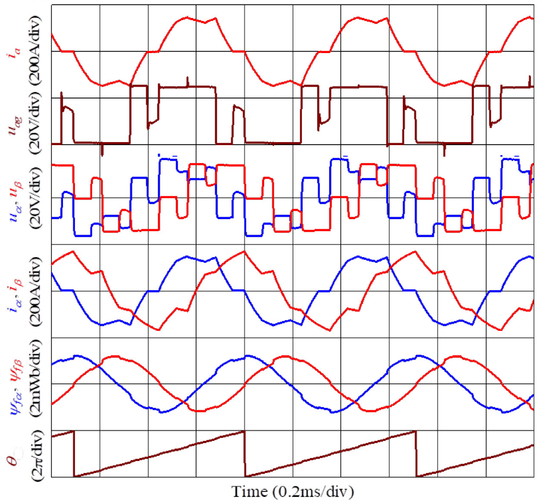


(b) Phase back-EMF and 3rd harmonic back-EMF

Fig. 15. 3rd harmonic back-EMF-based sensorless control for high-speed BLDC drive.



(a) Locus of rotor flux vector within one operation cycle



(b) Waveforms of current, voltage and rotor flux vectors

Fig. 16. Rotor flux observer-based sensorless control for high-speed BLDC drive.

overlapping those of the phase back-EMFs and will not be distorted by the current freewheeling [23], [24], [41]. The 3rd harmonic back-EMF can be easily reconstructed with very simple hardware such as resistors and capacitors. This control method worked well for a 120krpm PM BLDC motor as reported in [24].

Another way to realize the sensorless control is to use a rotor flux observer, which can present continuous high-resolution rotor position information, so that phase-advancing control can be implemented for the PM BLDC motor, or sinusoidal drive can be realized for the PMSM. The rotor flux vector can be calculated as

$$\boldsymbol{\Psi}_\mathbf{f} = \int(\mathbf{U} - R\mathbf{I})\mathrm{d}t - L\mathbf{I} \qquad (1)$$

where the voltage vector **U** and current vector **I** can be obtained from the measured voltages and currents with coordination transformation. There are two components in the rotor flux vector $\boldsymbol{\Psi}_\mathbf{f}$, the α-component $\Psi_{f\alpha}$ and the β-component $\Psi_{f\beta}$. Its locus during steady-state operation should be a circle, but can be slightly distorted due to the commutations in the PM BLDC motor, as shown in Fig. 16(a) [20]. Thus, the rotor position can be calculated as (2), whilst the locus distortion brings very small, hence negligible, rotor position error.

$$\theta = \arctan(\Psi_{f\beta} / \Psi_{f\alpha}) \qquad (2)$$

For the ordinary-speed PM machines, the above calculations can be implemented within each PWM cycle, and the obtained rotor position information has sufficient resolution. However, for the high-speed machines, the rotor position changes a lot during each PWM cycle, hence, the calculation seems too slow. To solve this problem, hardware is used again to instantly accomplish the calculations of coordination transformation and flux vector observation, as can be seen from the waveforms of phase current, terminal voltage, and the two components of the current, voltage and rotor flux vectors, respectively (refer to Fig. 16(b)) [20]. The hardware is simple, consisting of resistors, capacitors and op-amps only. The control method worked well for a 25V 1.8kW 85krpm PM BLDC motor. It should also be noted that the current freewheeling lasts so long (see Fig. 16(b)) that the traditional back-EMF-based sensorless control would be unworkable, nevertheless, the hardware-based flux observer method is well functional.

G. *Selection of Sine-Wave and Square-Wave Drives*

Theoretically, the PMSM with sine-wave drive has lower stator iron loss and rotor eddy current loss than the PM BLDC motor with square-wave drive, due to the lower time harmonics in the stator currents. However, this is not the case for the high-speed machines. The fundamental frequency can be at the level of kHz, whilst the PWM frequency is just several times the fundamental frequency, therefore, the PWM switching is insufficient during each fundamental cycle, and the armature current becomes far away from the ideal sinusoidal waveform, containing very rich time harmonics. However, if the PM machine is driven with the square-wave mode (i.e., the BLDC mode), the armature current will be of the typical waveform with some switching-frequency ripples, containing even lower time harmonics. Fig. 17 shows the measured rotor temperature of a 3kW 120krpm PM machine which was driven in the sine-wave and square-wave modes, respectively [1]. The rotor temperature is related to the rotor eddy current loss, and further to the armature current time harmonics. It is seen that, during high-speed operation, the square-wave drive performs better.

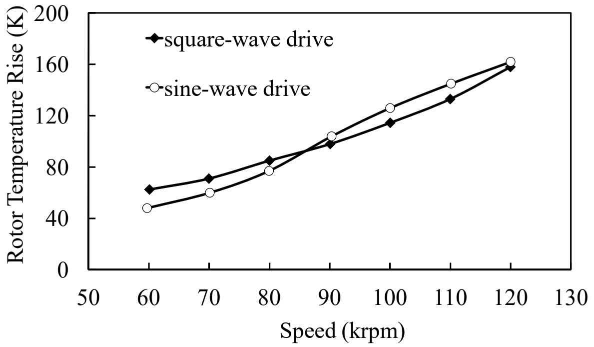


Fig. 17. Rotor temperature rise with different drive modes for a 3kW 120krpm PM machine.

V. CHALLENGES

Though high-speed PM machines have found extensive applications, challenges still exist, which are attracting more and more study interests.

1) It is essential to further extend the power range and maximum speed. Obviously, the multi-physics

(electromagnetic, thermal, mechanical, fluid, etc.) designs will be more difficult. It is quite common that when a measure is beneficial to improve the performance of one physics, it harms the performance of other physics. For example, the rotor retaining sleeve should be designed thicker to achieve sufficient strength, but this would reduce the machine electromagnetic torque, and increase the rotor temperature due to larger rotor eddy current loss or higher thermal resistance.

2) It is essential to enhance the heat dissipation, especially to remove heat from the rotor. In high-speed machines, the rotor air friction loss is significant. It can be up to 40% of the total loss [15]. Therefore, it is often recommended to place the high-speed machine in vacuum to eliminate the air friction loss. A critical problem has then to be dealt, as the heat in the rotor can hardly be removed through thermal conduction or convection, whilst the thermal radiation is not effective at all.
3) It is essential to realize sufficient PWM switching within each fundamental cycle of the high-speed machine. The switching frequency of the common power electronic devices ranges from 10kHz to 20kHz, and can be even lower if the inverters is of high power, while the fundamental frequency of the high-speed machines can be 1kHz or even higher, therefore, the PWM switching is inadequate, thus, the armature currents cannot be modulated to proper waveforms. To solve this problem, the SiC devices can be tried, but currently they are expensive. Other methods such as using ordinary MOSFET or IGBT devices but special inverter and machine topologies are under study [42].

Besides these, many other aspects of the high-speed PM machines should be further studied, not only for the theoretical analysis, but also for the design and control, as well as for the practical manufacturing and applications.

VI. CONCLUSIONS

High-speed machines, especially the PM machines, have found extensive applications due to their unique features. Some power losses which are negligible in the ordinary-speed machines can become significant due to high-speed operation, hence special attentions should be paid to these extra losses. Special materials and processing techniques are often needed to reduce the power losses. Over temperature is a key issue due to the high loss density. Therefore, the most critical concern is not to reduce the losses as much as possible, but to distribute the losses properly so that local over-temperature can be avoided. Moreover, multi-physics design and advanced control should be considered systematically.

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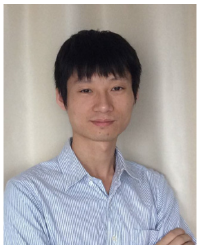

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