Abstract—Due to the large rotor eddy current loss and low thermal conductivity of carbon fiber sleeve, the high temperature usually occurs in high speed permanent magnet machines (HSPMMs) at the rated operation condition, resulting in irreversible demagnetization of the permanent magnet (PM). To obtain low rotor temperature, two novel rotor structures with low rotor eddy current loss are proposed in this paper. With the output torque and air gap flux density unchanged, the performance of HSPMMs with the two proposed rotor structures are analyzed based on finite element algorithm (FEA), including eddy current loss and temperature. Finally, the appropriate parameters of the proposed rotor structures are selected, and the electromagnetic (EM) performance, rotor stress and temperature are compared with those of the conventional rotor structure.

Index Terms—Eddy current loss, finite element algorithm (FEA), electromagnetic (EM) performance, high speed permanent magnet machines (HSPMMs).

I. INTRODUCTION

HIGH speed permanent magnet machines (HSPMMs) have advantages of simple structure, small size, and high energy density, which could be directly connected with the high speed load. Hence, the intermediate mechanical connection device could be eliminated. At present, HSPMMs have been widely used in high speed flywheel storage, gas turbine, air compressor, and so on [1-3].

In the design of HSPMMs, the thermal and mechanical constraints are the most significant limits [4]. As the permanent magnet (PM) exhibits low tensile strength, the high strength carbon fiber sleeve is generally used to protect the surface-mounted PMs. However, the carbon fiber sleeve will lead to a great challenge to the heat dissipation due to its low thermal conductivity [5]. Moreover, the large eddy current loss is generated in both PM and sleeve due to the time and space harmonics at high speed [6], [7]. It is obvious that the large eddy current loss can make the temperature of the sleeve and PM rise obviously [8]. And the irreversible demagnetization of PMs may occur at high temperature [9], which has bad impact on the reliability of HSPMM. Some methods, such as the application of the circumferential subsection of PMs [10] and rotor sleeve with low conductivity [11], have been proposed to reduce the rotor eddy current loss. However, the eddy current loss in HSPMMs with carbon fiber retaining rotor cannot be reduced significantly with the above approaches. Therefore, two novel rotor structures are proposed to reduce the eddy current losses in the PM and carbon fiber sleeve, and thus reducing rotor temperature rise.

This paper is organized as follows. Firstly, a conventional HSPMM is introduced and its temperature distribution is obtained by the finite element algorithm (FEA) in Section II. Then, two novel rotor structures are introduced in Section III. And the influences on rotor eddy current loss caused by the design parameters of the two proposed structures are fully analyzed by FEA in Section IV and V, respectively. Finally, these parameters are selected based on the above analysis, and the EM performance, stress and temperature are compared comprehensively with those of the conventional rotor structure.

II. CONVENTIONAL HSPMM

A. Topology

For the conventional surface mounted HSPMM, as shown in Fig.1, the sintered Nd-Fe-B PMs are glued on the rotor core and the carbon fiber sleeve is mounted on the PMs outer surface by interference fit [12]. An HSPMM with conventional rotor is designed. A 4-pole structure is adopted to reduce the end-winding length and thus increasing rotor dynamics. And a carbon fiber sleeve is adopted due to its low conductivity and high tensile strength.

For the designed HSPMM, an air and water combined cooling system is employed. The air-cooling system is placed in the stator slot and the water-cooling system is placed in the shell.
B. Characteristics of the HSPMM

The material physical properties of the HSPMM are listed in Table I. The design specifications and characteristics of HSPMM are given in Table II.

The rotor eddy current loss is great, especially in PMs and sleeve, which would cause a very high temperature rise in the rotor. The temperature of the HSPMM at rated condition is calculated by fluid-solid coupling method using computational fluid dynamics (CFD). The temperature distribution of the HSPMM is illustrated in Fig. 2. It can be observed that the highest temperature 170 °C occurs in the middle part of the rotor, which is higher than the maximum operating temperature of PM, 150 °C. It is known that PM would be easily demagnetized irreversibly at the high temperature.

**TABLE I**

| Item and Unit          | carbon fiber sleeve | PM |
|------------------------|---------------------|----|
| Density (kg/m³)        | 1800                | 7400 |
| Young’s modulus (GPa)  | 150                 | 8.8 |
| Poisson’s ratio        | 0.28                | 0.015 |
| Coefficient of thermal expansion (1/K) | -0.38x10⁻⁶ | 2.8x10⁻⁴ | 1.2x10⁻⁵ |
| Thermal conductivity (W/m·K) | 0.8 | 3 |
| Tensile strength (MPa) | 1400                | -100 |
| Conductivity (S/m)     | 2.5x10⁴             | 6.25x10⁴ |

**TABLE II**

| Item and Unit              | Value |
|----------------------------|-------|
| Rated power (kW)           | 800   |
| Rated speed (rpm)          | 25000 |
| Rated voltage (V)          | 3000  |
| Rated torque (N·m)         | 305   |
| Stator slot number         | 24    |
| Pole number                | 4     |
| Stator outer diameter (mm) | 360   |
| Rotor diameter (mm)        | 150   |
| Air gap length (mm)        | 3     |
| Sleeve thickness (mm)      | 7     |
| Air-gap flux density (T)   | 0.49  |
| carbon fiber stress (MPa)  | 541   |
| PM stress (MPa)            | 59    |
| Total rotor eddy current loss (W) | 1604 |
| PM loss (W)                | 344   |
| Carbon fiber sleeve loss (W)| 1259 |

A prototype with conventional rotor is shown in Fig. 3 (a). It is known from the above analysis, high rotor temperature occurs at the rated condition, which would cause irreversible demagnetization of PM. The demagnetized PMs and damaged carbon fiber sleeve due to high rotor temperature are shown in Fig. 3 (b). The magnetic density of the rotor surface is measured by a tesla meter as shown in Fig. 4 (a), and the test results are illustrated in Fig. 4 (b). It can be observed that the most serious demagnetization of PM occurs in the middle part of the rotor, which is consistent with what mentioned above.

III. TWO NOVEL ROTOR STRUCTURES

In order to reduce the rotor eddy current loss and obtain low rotor temperature, two novel rotor topologies (rotor A and rotor B) are proposed, as shown in Fig. 5 (a) and (b), respectively.

Rotor A: a thin layer of sintered ferrite is mounted between the PMs and carbon fiber sleeve, and the ferrites are glued on the PMs. The carbon fiber sleeve is mounted on the ferrites outer surface by an interference fit.

Rotor B: Two sleeves (inner and outer ones) are employed in this structure, and their total thickness is kept the same as that of Rotor A. Specifically, both the inner and the outer sleeves are mounted on the surfaces of PMs and ferrites by interference fit, respectively.
In order to reduce the rotor eddy current loss, ferrite is used in both novel rotors. Because ferrite has a very high electrical resistivity and the eddy current loss is very tiny at high frequencies, the ferrite eddy current loss can be neglected in this study. The physical properties of ferrite are given in Table III.

| Item and Unit                     | Value  |
|----------------------------------|--------|
| Density (kg/m³)                  | 4800   |
| Young’s modulus (GPa)            | 120    |
| Poisson’s ratio                  | 0.28   |
| Coefficient of thermal expansion (1/K) | $1.2 \times 10^5$ |
| Thermal conductivity (W/(m·K))   | 6      |
| Tensile strength (MPa)           | 35     |
| Compressive strength (MPa)       | 800    |
| Electrical resistivity (Ω·m)     | $10^5$ |

Two HSPMMs (machine A with rotor A and machine B with rotor B) with different rotor structures are introduced. In this paper, all analysis of the two HSPMMs is based on the following pre-assumptions:

1. Both machines have the same rotor diameter, core length, carbon fiber sleeve thickness and stator structure with the conventional HSPMM, which is introduced in Section II.
2. The output torque and air-gap flux density remain unchanged in the whole analysis process.

IV. HSPMM WITH ROTOR A

A. Effect of Ferrite Thickness on Rotor Eddy Current Loss

Rotor eddy current loss is the crucial reason for the temperature rise of HSPMM, so it is necessary to analyze rotor eddy current loss. The eddy current loss can be obtained by [13].

$$P_e = \int \frac{J^2}{\sigma} dV$$

(1)

where $\sigma$ is the electrical conductivity, $V$ the rotor volume, and $J$ the eddy current density in the rotor. The eddy current density can be calculated by [14].

$$J = -\frac{1}{\rho} \left( \frac{\partial A}{\partial t} + c(t) \right)$$

(2)

where $A$ is the magnetic vector potential, $\rho$ the electrical resistivity, and $c(t)$ the function of time.

It can be observed that the eddy current loss is proportional to the eddy current density, and the eddy current density is inversely proportional to the electrical resistivity. So we can reduce the eddy current density and eddy current loss by using ferrite with high conductivity.

The rotor eddy current density at rated operation condition with different ferrite thickness is illustrated in Fig. 6. It can be observed the rotor eddy current is affected by the ferrite thickness. When the ferrite thickness is 1 mm, the maximum eddy current density of rotor is $1.17 \times 10^6$ A/m², which occurs at the Nd-Fe-B PMs. When the ferrite thickness is 3 mm, the maximum eddy current density is decreased to $5.94 \times 10^5$ A/m².

The variations of the rotor eddy current loss with the ferrite thickness are illustrated in Fig. 7. The total eddy current loss and PM eddy current loss decrease with the increase of ferrite thickness, but the eddy current loss of carbon fiber sleeve is not diminished. When the ferrite increases from 1 to 3 mm, the eddy current loss of the Nd-Fe-B PMs decreases from 344 to 48 W. However, the eddy current loss of the rotor is almost invariable when the ferrite thickness exceeds 4 mm. Therefore, it is necessary that an appropriate ferrite thickness should be chosen to reduce the rotor eddy current loss.

Two HSPMMs (machine A with rotor A and machine B with rotor B) with different rotor structures are introduced. In this paper, all analysis of the two HSPMMs is based on the following pre-assumptions:

1. Both machines have the same rotor diameter, core length, carbon fiber sleeve thickness and stator structure with the conventional HSPMM, which is introduced in Section II.
2. The output torque and air-gap flux density remain unchanged in the whole analysis process.

IV. HSPMM WITH ROTOR A

A. Effect of Ferrite Thickness on Rotor Eddy Current Loss

Rotor eddy current loss is the crucial reason for the temperature rise of HSPMM, so it is necessary to analyze rotor eddy current loss. The eddy current loss can be obtained by [13].

$$P_e = \int \frac{J^2}{\sigma} dV$$

(1)

where $\sigma$ is the electrical conductivity, $V$ the rotor volume, and $J$ the eddy current density in the rotor. The eddy current density can be calculated by [14].

$$J = -\frac{1}{\rho} \left( \frac{\partial A}{\partial t} + c(t) \right)$$

(2)

where $A$ is the magnetic vector potential, $\rho$ the electrical resistivity, and $c(t)$ the function of time.

It can be observed that the eddy current loss is proportional to the eddy current density, and the eddy current density is inversely proportional to the electrical resistivity. So we can reduce the eddy current density and eddy current loss by using ferrite with high conductivity.

The rotor eddy current density at rated operation condition with different ferrite thickness is illustrated in Fig. 6. It can be observed the rotor eddy current is affected by the ferrite thickness. When the ferrite thickness is 1 mm, the maximum eddy current density of rotor is $1.17 \times 10^6$ A/m², which occurs at the Nd-Fe-B PMs. When the ferrite thickness is 3 mm, the maximum eddy current density is decreased to $5.94 \times 10^5$ A/m².

The variations of the rotor eddy current loss with the ferrite thickness are illustrated in Fig. 7. The total eddy current loss and PM eddy current loss decrease with the increase of ferrite thickness, but the eddy current loss of carbon fiber sleeve is not diminished. When the ferrite increases from 1 to 3 mm, the eddy current loss of the Nd-Fe-B PMs decreases from 344 to 48 W. However, the eddy current loss of the rotor is almost invariable when the ferrite thickness exceeds 4 mm. Therefore, it is necessary that an appropriate ferrite thickness should be chosen to reduce the rotor eddy current loss.

The magnetic properties of ferrite are inferior to those of Nd-Fe-B. Therefore, to obtain the same air gap flux density, the amount of Nd-Fe-B would be changed when the thickness of ferrite is different. The consumption of Nd-Fe-B with different ferrite thickness is illustrated in Fig. 8, where $V_0$ and $V_c$ are the consumption of Nd-Fe-B of the conventional and proposed rotor structure, respectively. It is demonstrated that to keep the same air-gap flux density, the consumption of Nd-Fe-B should be increased with the increasing of ferrite thickness. The cost of the machine would also be increased with the increasing of ferrite thickness. Thus, the thickness of ferrite should be determined by weighing the reduction of eddy current loss and cost of whole machine.
B. Effect of Ferrite Thickness on Rotor Stress

A ferrite layer is added to the outer surface of the Nd-Fe-B PMs and the influence of ferrite thickness on rotor strength are studied by FEA. The analysis results is illustrated in Fig. 9. It can be observed that the increase of ferrite thickness, which would cause a slight increase in the Nd-Fe-B tangential stress. For the ferrite, the compressive stress in the tangential direction is presented with the increases of ferrite thickness.

C. Effect of Ferrite Thickness on Temperature

From the previous analysis, it is known that the ferrite thickness has huge influence on the rotor eddy current loss, and the temperature of rotor is mainly caused by the rotor eddy current loss. It is that the rotor eddy current loss is diminished by adding to ferrite, and the temperature will also have same trend. The variations of the temperature of machine A with ferrite thickness are illustrated in Fig. 10. It can be observed that when the ferrite thickness is increased from 1 to 3 mm, the temperature of rotor is decreased from 170 to 156 °C, due to the large reduction of rotor eddy current loss. When the ferrite thickness exceeds 3 mm, the temperature of rotor is basically unchanged as before. The variations trend of the rotor temperature and the rotor eddy current loss are consistent. Therefore, an appropriate ferrite thickness should be chosen through comprehensive consideration.

D. Effect of Sleeve Thickness on Temperature

The carbon fibre sleeve thickness also has huge influence on the rotor temperature rise. In order to analysis the variations of the machine temperature with thickness of carbon fibre sleeve, a 3 mm ferrite is chosen. Keeping the same condition of output torque, rotor diameter, core length, the variations of the temperature of machine A with thickness of carbon fibre sleeve are illustrated in Fig. 11. It can be observed that the rotor temperature decreases with the increases of thickness of carbon fibre sleeve. And when the thickness of carbon fibre sleeve exceeds 7mm, the change of rotor temperature is very tiny.

V. HSPMM WITH ROTOR B

The novel rotor A only reduces the eddy current loss of PM, but the eddy current loss of carbon fiber sleeve, which is the main loss in the rotor, is not diminished. According to the previous analysis, when the thickness of ferrite is increased to a certain extent, the rotor eddy current loss and temperature are almost invariable change. So the novel rotor B combining the ferrite and two carbon fiber sleeves (inner and outer ones) is proposed to further reduce the eddy current loss of carbon fiber sleeve and the rotor temperature. The total thickness of inner and outer sleeve is kept in same step with that of Rotor A. The outer sleeve decreases with the increases of thickness of inner sleeve. Therefore, the inner sleeve is selected as an example in the following analysis.

A. Effect of Inner Sleeve Thickness on Rotor Eddy Current Loss

Fig. 12 displays the rotor eddy current density distribution under different thicknesses of inner sleeve. It can be observed that the eddy current density of inner sleeve is tiny, and the eddy current loss is mainly concentrated in the outer carbon fiber sleeve. The eddy current loss would be reduced by the reducing of outer sleeve thickness, as shown in Fig. 13. It is apparent that the eddy current loss of outer sleeve would be...
reduced with the increase of inner sleeve thickness. Meanwhile, because the total thickness of ferrite and sleeve has not changed, the eddy current loss of PM remains unchanged.

Fig. 12. The distributions of rotor eddy current density. (a) Inner sleeve 1 mm. (b) Inner sleeve 4 mm.

Fig. 13. Eddy current loss under different thicknesses of inner sleeve.

B. Effect of Inner Sleeve Thickness on Rotor Stress

Two sleeves (inner and outer ones) are employed in machine B, and the total thickness of the sleeves kept the same as rotor A. Meanwhile, the ferrite thickness of this rotor structure is set to 3 mm. The influence of the inner carbon fiber sleeve thickness on rotor stress is analyzed. Fig. 14 shows the variations of rotor stress with inner carbon fiber sleeve thickness. It can be observed that all the stress on ferrite, sleeve and Nd-Fe-B increase with the increase of inner carbon fiber sleeve thickness. When the inner sleeve thickness exceeds 4 mm, the stress of the ferrite beyond the safety range of material and the ferrite will be destroyed. So the mechanical constraints must be fulfilled at the process of selecting sleeve.

Fig. 14. Rotor stress under different thicknesses of inner sleeve.

C. Effect of Inner Sleeve Thickness on Temperature

The variations of the maximum temperature of machine B with the inner carbon fiber sleeve thickness are illustrated in Fig. 15. It can be observed that the temperature of rotor decreases with the increase of the inner carbon fiber sleeve thickness, which is mainly caused by the reduction of rotor eddy current loss. But, the temperatures of winding and stator core are almost kept unchanged. The variations trend of the rotor temperature and the rotor eddy current loss are consistent.

Fig. 15. Temperature under different thicknesses of inner sleeve.

D. Effect of Ferrite Thickness on Temperature with Two Sleeves

For the rotor B, the ferrite thickness also has large influence on the rotor temperature. The effect of the ferrite thickness on the temperature with 4 mm inner sleeve is illustrated in Fig. 16. It can be observed that when the ferrite thickness is increased from 1 to 3 mm, the temperature of rotor is decreased from 154 to 144 °C. Compared with the conventional rotor structure, the rotor temperatures are reduced by 9.4% and 15.3%, respectively. When the ferrite thickness exceeds 3 mm, the rotor temperature has little change as before. Therefore, the novel rotor B is helpful to reduce the rotor temperature.

Fig. 16. Temperature under different thicknesses of ferrite with 4 mm inner sleeve.

VI. PERFORMANCE COMPARISON

A. EM Performance and Rotor Stress

Three HSPMMs with different rotor structures are compared under the same condition of sleeve thickness, rotor diameter, core length, and stator parameters. The structural parameters, EM performance, and rotor stress of the three HSPMMs are shown in Table III. Based on the above analysis, a 3 mm ferrite is chosen for Rotor A and Rotor B, and the inner sleeve thickness and the outer sleeve thickness are determined to be 4 and 3 mm, respectively. Besides, the air gap flux density and
the output torque of three machines at the rated load condition are illustrated in Figs. 17 and 18. It is seen, for the rotor A and rotor B, a thicker Nd-Fe-B PM is necessary to keep the same air gap flux density and the output torque compared with the conventional one, which would cause higher Nd-Fe-B PM stress, but they are all within the safe range of the material.

| Item                        | Conventional rotor | Rotor A | Rotor B |
|-----------------------------|--------------------|---------|---------|
| Rotor diameter (mm)         | 150                | 150     | 150     |
| Core length (mm)            | 410                | 410     | 410     |
| Air gap length(mm)          | 3                  | 3       | 3       |
| Nd-Fe-B thickness (mm)      | 12                 | 16.2    | 16.2    |
| Ferrite thickness (mm)      | 0                  | 3       | 3       |
| Air gap flux density (T)    | 0.49               | 0.49    | 0.49    |
| Output torque (N·m)         | 305                | 305     | 305     |
| Inner sleeve thickness (mm)| 0                  | 0       | 4       |
| Outer sleeve thickness (mm)| 7                  | 7       | 3       |
| Nd-Fe-B stress (MPa)        | 59                 | 62      | 69      |
| Inner sleeve stress (MPa)   | 0                  | 0       | 291     |
| Outer sleeve stress (MPa)   | 541                | 536     | 587     |
| Ferrite stress (MPa)        | 0                  | -30     | 33      |

| TABLE IV                        |                     |         |         |
|---------------------------------|----------------------|---------|---------|
| Item                            | Conventional rotor   | Rotor A | Rotor B |
| Rotor diameter (mm)             | 150                  | 150     | 150     |
| Core length (mm)                | 410                  | 410     | 410     |
| Air gap length(mm)              | 3                    | 3       | 3       |
| Nd-Fe-B thickness (mm)          | 12                   | 16.2    | 16.2    |
| Ferrite thickness (mm)          | 0                    | 3       | 3       |
| Air gap flux density (T)        | 0.49                 | 0.49    | 0.49    |
| Output torque (N·m)             | 305                  | 305     | 305     |
| Inner sleeve thickness (mm)     | 0                    | 0       | 4       |
| Outer sleeve thickness (mm)     | 7                    | 7       | 3       |
| Nd-Fe-B stress (MPa)            | 59                   | 62      | 69      |
| Inner sleeve stress (MPa)       | 0                    | 0       | 291     |
| Outer sleeve stress (MPa)       | 541                  | 536     | 587     |
| Ferrite stress (MPa)            | 0                    | -30     | 33      |

B. Rotor Eddy Current Loss

The rotor eddy current density and the eddy current loss distributions of three HSPMMs at rated operation condition are illustrated in Figs. 19 and 20. It can be observed that the eddy current densities of rotor A and rotor B are much less than the conventional rotor, so the eddy current losses of the two novel structures are much lower than that of the conventional rotor. The eddy current losses of the conventional rotor, rotor A and rotor B are 1604, 1298, and 1162 W, respectively. The eddy current loss of conventional rotor and rotor A in carbon fiber sleeve are the same, but the eddy current loss of rotor A in Nd-Fe-B PMs is reduced by 295 W. The total eddy current loss and the eddy current loss of the carbon fiber sleeve of rotor B are the smallest in three rotor structure. Therefore, it is obvious that the proposed two rotor structures can significantly reduce rotor eddy current losses.

C. Temperature

With the same cooling system as conventional HSPMM, the temperature distributions of the two proposed HSPMMs are obtained by FEA. The temperature distributions and comparison with conventional HSPMM are illustrated in Figs. 21 and 22. The maximum temperatures of the conventional rotor, rotor A and rotor B are 170, 156 and 144 °C, respectively. It is obvious that the temperature of rotor B in Nd-Fe-B PMs is the lowest, owing to that the eddy current loss of rotor B is smallest. Especially, the temperature of the PM is reduced for rotor B, and the risk of irreversible demagnetization of PM is greatly lowered.

VII. CONCLUSION

In this paper, two novel rotor structures are proposed and analyzed. The EM performance, stress and temperature are
eddy current loss and temperature of rotor are greatly reduced by 27.5% and 15.3%, respectively. Therefore, the results show the eddy current loss and temperature of rotor A can be reduced by 19% and 8.2%, respectively. With conventional rotor, the eddy current loss and temperature calculated at the rated operation condition by FEA. Compared to the conventional rotor, the temperature distribution of two HSPMMs with the proposed rotor structures. (a) Rotor A. (b) Rotor B. calculated at the rated operation condition by FEA. Compared with conventional rotor, the eddy current loss and temperature of the proposed rotor A can be reduced by 19% and 8.2%, respectively. For the proposed rotor B, they are reduced by 27.5% and 15.3%, respectively. Therefore, the results show the eddy current loss and temperature of rotor are greatly reduced by adopting the two novel rotor structures.

REFERENCES

[1] J. N. Dong, Y. K. Huang, L. Jin, H. Y. Lin, and H. Yang, “Thermal optimization of a high-speed permanent magnet motor,” IEEE Trans. Magn., Vol. 50, No. 2, pp. 749-752, Feb. 2014.

[2] S. M. Barrans, M. J. Al-Ani, and J. Carter, “Mechanical design of rotors for permanent magnet high-speed electric motors for turbocharger applications,” IET Elect. Syst. Trans., Vol 7, No. 4, pp. 278-286, Dec. 2013.

[3] W. Xu, M. J. He, and C. Y. Ye, “Novel synchronous machine with permanent magnet in stator yoke,” IEEE Trans. Appl. Super., vol.26, no.7, Article #: 0607205, Oct. 2016.

[4] Z. Kolondzovski, A. Arkko, J. Larjola, and P. Sallinen, “Power limits of high-speed permanent-magnet electrical machines for compressor applications,” IEEE Trans. Energy Convers., Vol. 26, No. 1, pp. 73-82, Jan. 2011.

[5] F.G Zhang, G. H. Du, T. Y. Wang, G. W. Liu, and W. P. Cao, “Rotor retaining sleeve design for a 1.12-MW high-speed PM machine,” IEEE Trans. Ind. Appl., Vol. 51, no. 5, pp. 3675-3685, Sept./Oct. 2015.

[6] Z. Y. Huang, J. C. Fang, X. Q. Liu, and B. C. Han, “Loss calculation and thermal analysis of rotors supported by active magnetic bearings for high speed permanent magnet electrical machines,” IEEE Trans. Ind. Elec., Vol. 63, No. 4, pp. 2027-2035, Apr. 2016.

[7] H. B. Qiu, R. Yi, W. L. Li, and N. Jin, “Influence of rectifiers on high-speed permanent magnet generator electromagnetic and temperature fields in distributed power generation systems,” IEEE Trans. Energy Convers., vol. 30, No. 2, pp. 655-662, Jun. 2015.

[8] H.Y. Fang, R.H. Qu, J. Li, P. Zheng, and X. G. Fan, “Rotor design for high-speed high-power permanent magnet synchronous machines,” IEEE Trans. Indus. Appl., Vol. 53, No. 4, pp. 3411-3419, July/Aug. 2017.

[9] G. Du, W. Xu, J. Zhu, and N. Huang, “Power loss and thermal analysis for high power high speed permanent magnet machines,” IEEE Trans. Ind. Elec., 2019, in press.

[10] K. Atallah, D. Howe, P. H. Mellor, and D. A. stone, “Rotor loss in permanent-magnet brushless AC machines,” IEEE Trans. Ind. Appl., vol. 36, no. 6, pp: 1612-1618, Nov/Dec. 2000

[11] J. H. Ahn, C. Han, C. W. Kim, and J. Y. Choi, “Rotor Design of High-Speed Permanent Magnet Synchronous Motors Considering Rotor Magnet and Sleeve Materials,” IEEE Trans. Appl. Super., vol. 28, No. 3, Article#17460346, Dec. 2018.

[12] F. G. Zhang, G. H. Du, T. Y. Wang, F. X. Wang, W. P. Cao, and J. L. Kirtley, “Electromagnetic design and Loss Calculations of a 1.12MW high-speed permanent-magnet machine for compressor applications,” IEEE Trans. Energy Convers., vol. 31, No. 1, pp. 132-140, Mar. 2016.

[13] Y. Zhang, S. McLoone, W. P. Cao, F. Y. Qiu, and C. Gerada, “Power loss and thermal analysis of a MW high-speed permanent magnet synchronous machine,” IEEE Trans. Energy Convers, Vol. 32, No. 4, pp. 1468-1478, Dec. 2017.

[14] L. Papini, T. Raminosoa, D. Gerada, and C. Gerada, “A high speed permanent magnet machine for fault tolerant drivesine,” IEEE Trans. Ind. Elec, Vol. 61, No. 6, pp. 3071-3080, Jun. 2014.

Xin Cheng received the B.S. degree from electrical engineering from Luoyang Institute of Science and Technology, Luoyang, China, in 2015. He is currently working toward the M.S. degree in the School of Electrical and Electronic Engineering, Shanghai University of Engineering Science, Shanghai, China. His research interests include design methods for high speed machine.

Wei Xu (M’09-SM’13) received the double B.E. and M.E. degrees from Tianjin University, Tianjin, China, in 2002 and 2005, and the Ph.D. from the Institute of Electrical Engineering, Chinese Academy of Sciences, in 2008, respectively, all in electrical engineering. From 2008 to 2012, he held several academic positions in both Australian and Japanese universities and companies. Since 2013, he has been full professor with the State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, China. His research topics mainly cover design and control of linear/rotary machines. He is Fellow of the Institute of Engineering and Technology (IET). He has served as Associate Editor for several Journals, such as IEEE Transactions on Industrial Electronics, IEEE Journal of Emerging and Selected Topics in Power Electronics, IEEE Transactions on Vehicular Technology, etc.

Guanghui Du received the B.E. degree from Qingdao Agricultural University in 2010, and the Ph.D. from Shenyang University of Technology in 2015. He joined in CRRC Yongji Electric Co. Ltd, China, from 2015 to 2017. Since 2018, He has worked as one postdoctoral fellow with with the State Key Laboratory of...
Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, China. His current research interests include design and analysis of a high speed electrical machine.

**Guohui Zeng** received the B.E. degree in electrical engineering from Nanchang University, Jiangxi, China, in 1995, the M.E. degree and Ph.D. from the Shanghai Jiao Tong University, Shanghai, China, in 2003 and 2007. Now he is Associate Professor and Associate Head with the School of Electrical and Electronic Engineering, Shanghai University of Engineering Science, Shanghai, China. His research interests include power electronics, motor drive and control, etc.

**Jianguo Zhu** (S’93–M’96–SM’03) received the B.E. degree in 1982 from Jiangsu Institute of Technology, Jiangsu, China, the M.E. degree in 1987 from Shanghai University of Technology, Shanghai, China, and the Ph.D. degree in 1995 from the University of Technology Sydney (UTS), Sydney, Australia, all in electrical engineering. He was appointed a lecturer at UTS in 1994 and promoted to full professor in 2004 and Distinguished Professor of Electrical Engineering in 2017. In 2018, he joined the University of Sydney, Australia, as a full professor and Head for School of Electrical and Information Engineering. His research interests include measurement, computational electromagnetics and modelling of magnetic properties of materials, electrical machines and drives, power electronics, renewable energy systems and smart micro grids.