Electrical Machines for High Speed Applications with a Wide Constant-Power Region Requirement

David Gerada*, David Borg-Bartolo, Abdeslam Mebarki*, Christopher Micallef*, Neil L. Brown*, and Chris Gerada*****

Abstract – This paper discusses the issues associated with the design of high speed machines for applications with a wide constant-power region requirement. Using described multi-domain design environments which put equal weight on the electromagnetic, thermal and mechanical considerations, the suitability and power density achievable using Induction Machines (IM) and Permanent Magnet Synchronous Machines (PMSM) are compared.

Keywords: High speed machines, Induction machines, Permanent magnet machines, Field weakening, Thermal modeling

1. Introduction

High speed machines are finding their way in a number of applications such as automotive, aerospace, compressors and spindles. Two currently researched automotive applications are using high speed electrical machines for engine waste-heat recovery (WHR) and electrically assisted turbocharging. In engine waste-heat recovery, the high speed machine is used as a generator to recover engine waste-heat via an Organic Rankine Cycle, with the recovered energy being fed back as electrical energy to supply the vehicle's electrical load. The benefits of using such a system can improve vehicle fuel efficiency by over 10% [1].

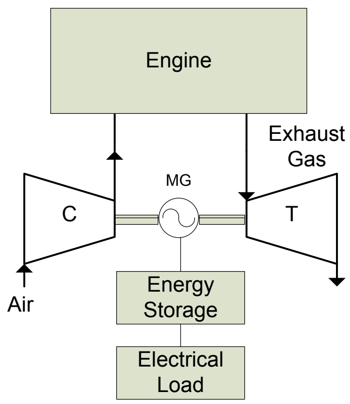

Fig. 1. Electrically assisted turbocharger system schematic

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Another automotive application is in electrically-assisted turbocharging. Turbocharged diesel engines are fitted in heavy-duty vehicles to produce the high powers and torques demanded in such applications. However, the turbocharger does not deliver the typical target boost pressure until high speeds are reached, when the centrifugal compressor can fully compress the inlet air-charge allowing full engine power to be produced. Typically the turbocharger can take up to 3seconds to run up to speed so there is a significant delay between the driver demanding full engine power and it being available. This time delay is often referred to as 'turbo-lag'. One way of reducing it, thereby improving engine performance and vehicle drive-ability, is to reduce the time it takes for the turbocharger to accelerate. This can be done by incorporating an electrical assist motor between the turbine and compressor wheel, as shown in Fig.1. At high speed and load the turbine can provide too much torque and if left to run unchecked, the turbocharger unit would over-speed. To prevent this, turbochargers use waste-gates to bypass some of the exhaust gas and so limit the over-speed. Having an electrical machine gives the possibility of using this energy to generate power and return it to the vehicle's electrical load, thereby further improving the system efficiencies.

The design of high speed machines is known to be very challenging because materials are operated closer to their mechanical limits [2],[3]. Furthermore, placing an electrical machine in a thermally aggressive environment, in-between the turbine and compressor wheel poses thermal challenges which become a critical aspect in machine type selection and design.

A lot of research work in the field of high speed machines has targeted constant speed applications. The application in hand is a water-cooled 20kW continuous machine with a base speed of 100,000 rpm and constant power region of up to 180,000rpm. The requirement translates to a continuous power density of 80MW/m3. In addition to the high power-density and thermally-aggressive environment, the field weakening requirement puts further design challenges.

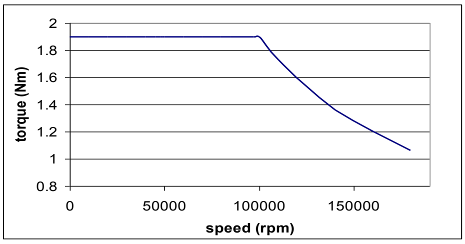

Fig. 2. Torque-speed requirement

2. Machine Types

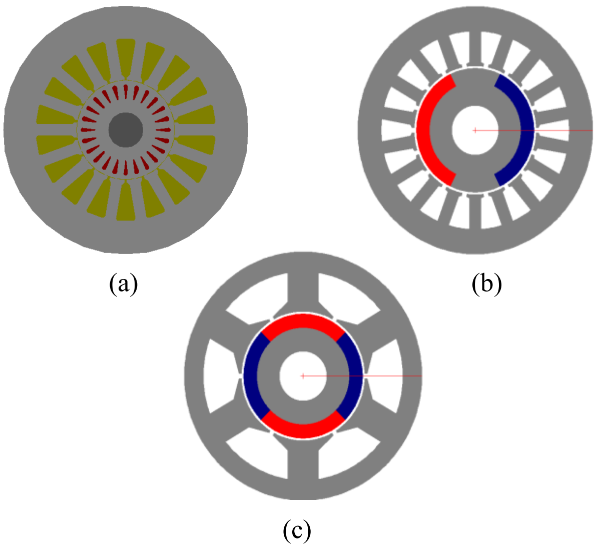

Fig.3. Compared electrical machines topologies a)Induction Machine, b)distributive-wound inset PMSM (c) concentrated-wound surface PMSM

The power density achievable from the different types of electrical machines is compared for the design requirement. Three machine types are considered, as shown in Fig. 3. The Induction Machine (IM) is selected for its robustness and its ability to naturally field-weaken. For the case of Permanent Magnet Machines, two different topologies are considered : (I)distributive-wound inset PMSM, which has some saliency and field-weakening capability, and (II) concentrated-wound surface-mount PMSM, which gives sufficiently high inductances to field weaken at the cost of increased armature-reaction field harmonics.

3. Thermal Modeling

Given the nature of the application, having detailed system thermal models is an essential requirement in order to ensure a fair comparison between the selected machine topologies. The comparison is made taking into account the temperature limits of the constituent materials used in each topology.

Accurate thermal modelling of the electrical machine is essential in selecting the appropriate materials for use in this inherently high temperature environment. Furthermore, by understanding the operating temperature of the constituent materials in the electrical machine, mechanical analysis can be carried out at the operational temperatures so as to ensure mechanical integrity. By situating an electrical machine in between the turbine and compressor wheels of a commercial turbo-charger, the electrical machine has to operate in a steep axial thermal gradient, with the turbine wheel temperature exceeding 700°C and the compressor wheel being at around 100°C over a small axial separation distance. Thus in order to integrate an electrical machine into such a harsh thermal environment, parametric system lumped thermal models are developed for each machine topology in order to handle the multiple heat loads and quantify the temperature and heat fluxes across the electrical machine and optimize the cooling system as required.

3.1 System Level Thermal Modeling

A Gauss-Seidel iteration procedure is adopted to calculate steady-state temperatures on the electrical machines designed. This numerical method satisfies the second order Laplace partial differential equation and is the preferred method over direct matrix inversion when the number of nodal temperatures to be determined is large [4]. The nodal temperatures in the thermal network are defined as [4]:

$$T_i = \frac{q_i + \sum_j \left(T_j / R_{ij} \right)}{\sum_j \left(1 / R_{ij} \right)} \quad (1)$$

where:

q_i is the heat delivered to node i [W];

T_i is the temperature of node i [K];

T_j is the temperature of node j [K];

R_{ij} is the thermal resistance across nodes i-j [K/W].

In the thermal models developed, several axial sections of the machine are used in the rotor-stator core assembly in order to model the aforementioned axial thermal gradient. End regions are defined on the turbine and compressor side of the machine and connected to the core sections. Thus, radial and axial temperatures and heat fluxes are computed throughout the electrical machine.

The heat transfer coefficient (HTC) for the rotor-stator air-gap is determined by using the correlation developed by Becker and Kaye [5],[6] :

$$Nu = 0.409 \cdot \left(\frac{Ta}{F_g}\right)^{0.241} \quad ; \quad 10{,}000 < \left(\frac{T_a}{F_g}\right) < 10^7 \qquad (2)$$

where :
Nu is the Nusselt number;
T_a is the Taylor Number;
F_g is the geometric modification factor.

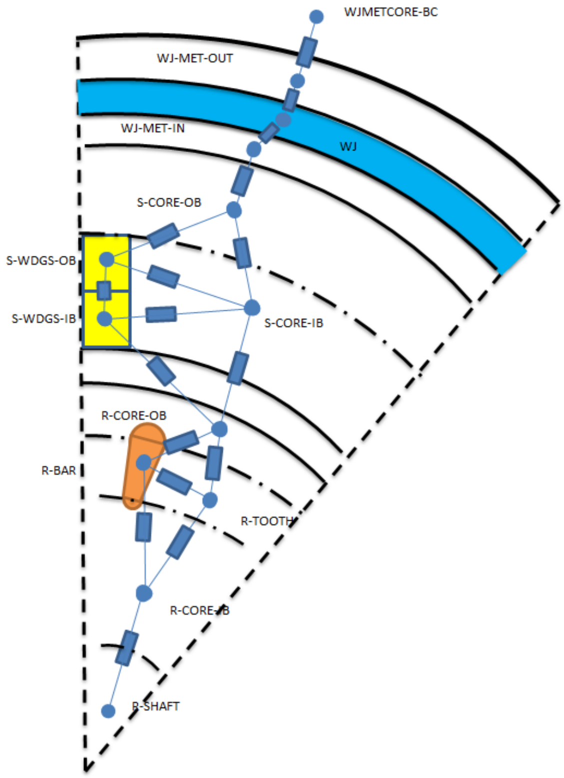

Fig. 4. Axial section for the developed Induction Machine thermal model

Saari [7] conducted thermal modelling of high speed machines and reported equation (2) to give accurate, yet conservative results when compared to measured experimental temperatures. The HTC for the water jacket has been calculated according to the Dittus-Boelter equation for fully developed turbulent flow in pipes [4]:

$$Nu_d = 0.023 \cdot \mathrm{Re}_d^{0.8} \cdot \mathrm{Pr}^{0.3} \qquad (3)$$

where :
Nu_d is the Nusselt number evaluated at the water jacket's hydraulic diameter;
Re_d is the Reynolds number evaluated at the water jacket's hydraulic diameter.

Hay et al. [8] carried out an extensive literature review and presented a correlation brought forward by Oslejsek [9] for the heat transfer in the end regions for a totally enclosed electrical machine. The flow regime in an end winding is similar to that of a stirred vessel [8], and the aforesaid correlation is used to determine the HTC of the air in the end regions to the adjacent end winding, housing and bearing walls.

$$Nu = K_1 \mathrm{Re}^{0.8} \qquad (4)$$

where : K_1 is a constant varying from 0.031 to 0.04 for different end winding configurations, Re is the Reynolds number for the flow in the end winding region.

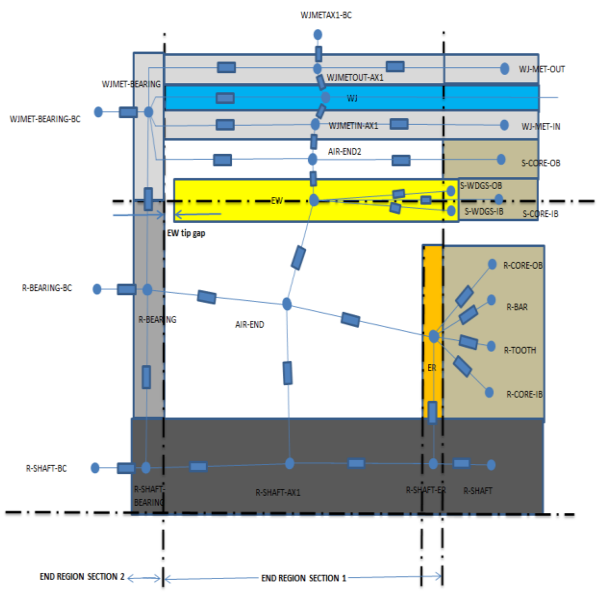

Fig. 5. Induction Machine end-winding region lumped-thermal model

4. Induction Machines

High speed Induction Machines can be of a solid rotor construction or a laminated rotor construction. The machines with the highest rotor peripheral speeds (>200m/s) usually have the more-robust solid rotor construction due to the higher centrifugal stresses at higher speeds, however if a laminated rotor topology is mechanically possible, it is preferred as it results in significantly higher efficiencies due to the reduced rotor eddy current losses. In [10] different types of solid rotor constructions are compared to a laminated rotor topology, and it is reported that the laminated rotor topology has 2-3% higher efficiencies than the different solid rotor constructions as well as a higher power factor. Similar results comparing solid rotors to laminated rotors are reported in [11].

4.1 Materials for High Speed Induction Machines

For the stator and rotor laminations, initially different 0.35mm Silicon Iron and Cobalt Iron alloys are considered. Cobalt Iron ensures highest saturation magnetization, going above 2 Tesla, thus enabling highest power densities to be achieved, however its high cost makes it difficult to use in an automotive application. For this reason, in this paper the Induction Machine designs make use of Silicon Iron.

The choice of Silicon Iron grade is an important decision. For the stator, low iron losses are required due to the high fundamental frequencies, while for the rotor high yield strength and good ductility are required due to the high centrifugal stresses generated at elevated speeds. These two critical electrical steel requirements are in opposition, as shown in Table 1, which compares the iron-losses and yield-strength for grades of conventional (M235-35A), and high yield strength (35HST780Y) 0.35mm SiFe electrical steel sheets.

Table 1. Iron losses and yield strength for conventional and high-strength electrical steels

lamination grade	loss (W/kg), 1T/50Hz	yield strength (MPa)
M235-35A	0.92	460
35HST780Y	4.75	780

The rotor bar and end-ring material also requires careful selection. High yield strength is required at high temperatures as the bars serve a mechanical function besides the electromagnetic function. The bars also add to the stiffness of the rotor assembly and thus help increase the critical speed of the machine. Pure copper cannot be used because it softens rapidly above 200ºC, as shown in Fig.6, which compares the ultimate tensile strength as a function of temperature for copper and some of its alloys. Several different types of high strength copper alloys have been utilized for high speed Induction Machines such as Copper Zirconium, Copper Beryllium and Copper Aluminum Oxide (Glidcop) [2], [12] which retains high mechanical strength at very high temperatures.

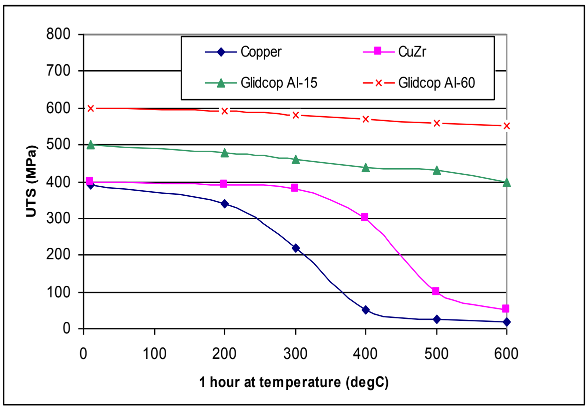

Fig. 6. Mechanical properties of copper and copper alloys at elevated temperatures

4.2 Induction Machine Designs

Given the very high power density requirement demanded in the application, a drop shaped-bar is used, as this permits the rotor current density (and hence rotor copper losses) to be minimized, albeit an increase in lamination stress with respect to the conventionally-used circular bar [2]. For the rotor cage a high-temperature CuAl2O3 alloy is used.

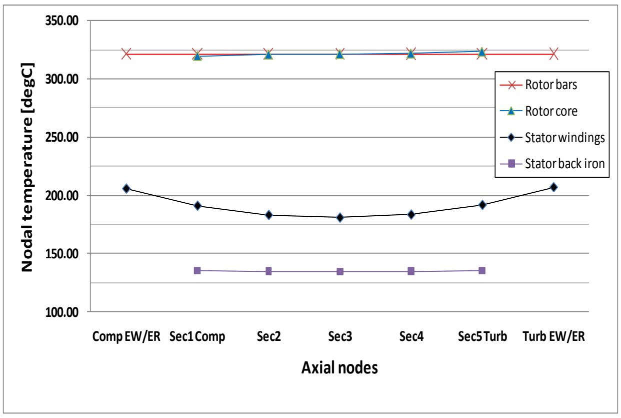

Fig. 7. Induction Machine axial temperature map for a 0.475 rotor split ratio

Fig. 7 plots the axial temperature variation for the rotor bars, rotor core, stator winding and stator iron for a 0.475 rotor split ratio. In general, for high speed machines it is preferred to minimize the rotor OD, in order to reduce the rotor peripheral speed and hence the peak centrifugal stresses. However, in the case of the Induction Machine, reducing the rotor OD has the effect of reducing the available rotor copper area, hence increasing the copper losses and peak rotor temperature, as shown in Fig. 8. Thus, in order to avoid a thermal runaway situation in the rotor, and obtain highest-possible power densities, the use of an increased rotor split ratio together with high yield-strength lamination steel in the rotor is required.

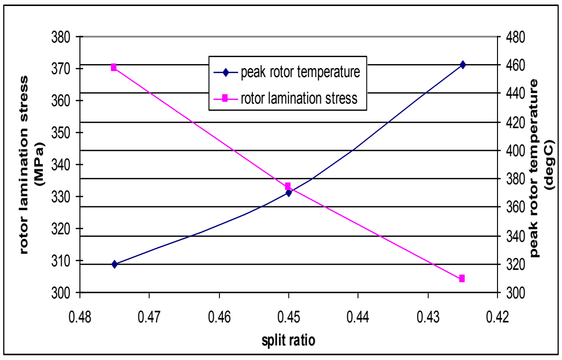

Fig. 8. Peak rotor temperature and lamination stress for different split ratios

5. Distributed Wound Inset PMSM

This topology consists of a solid steel shaft with two inset magnet segments placed in between iron-pockets as shown in Fig. 3b. A 2 pole, 18slot design is considered, with high temperature Sm_2Co_{17} magnets. The magnets are physically retained by a high yield strength metallic alloy, such as Inconel. The sleeve is sized in such a way as to maintain the magnets in compression by having suitable interference, taking into account the deformation of the magnets and the sleeve at the high speeds [13].

Having a metallic sleeve induces eddy-current losses therein due the space and time-harmonics. These eddy current losses can be estimated either by a full 3D FEA time-stepping simulation or, alternatively, using a developed rigorous 2-D analytical model which takes into account the eddy-current reaction and skin effect together with suitable end-effect correction factors [14]. These losses are mainly concentrated in the sleeve as shown in Fig.9.

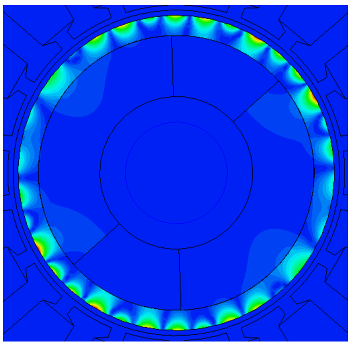

Fig. 9. Current density plot in 18-slot 2-pole machine rotor, showing the induced eddy currents in the magnets and in the sleeve

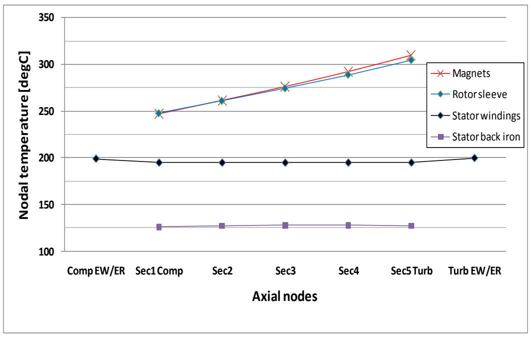

Fig. 10. 18-slot, 2-pole distributed wound Inset PMSM nodal axial temperature distribution for magnets, rotor sleeve, stator windings and stator back iron

Fig.10 shows the axial temperature map for the designed machine. Rotor-stator core sections are denoted ‘Sec 1-5’, end windings are denoted ‘EW’, and ‘Turb’ and ‘Comp’ denote turbine and compressor wheel end regions. The magnet losses, are relatively low in comparison to the other machine losses and peak magnet temperature is 300ºC at the turbine-side of the rotor, which is within the temperature limits of the material. Also, with respect to the Induction Machine, the PM machine can be designed with a lower rotor OD (i.e. lower split ratio), hence reducing the centrifugal stresses and ensuring a higher mechanical factor of safety on the constituent rotor components.

However the field weakening capability of the inset PM machine is not sufficient for the application, due to low inductance values of such a design, since the magnets behave as large air-gaps in the machine’s magnetic circuit. The limited constant power capability above base speed of this topology is shown in Fig.11, which plots the torque and power capability as a function of speed. A possibility in order to achieve a wider constant power region is to design the machine for a higher knee-point voltage, however this is undesired as it over-sizes the converter rating and hence the cost of the power electronics.

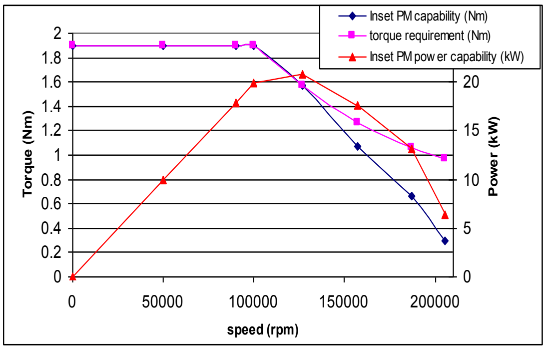

Fig. 11. Torque and power capability of distributed wound inset PMSM

6. Concentrated Wound PMSM

The concentrated-wound surface-mount PMSM is another potential option. The concentrated winding leads to an inherently high inductance and hence the ability to field-weaken over a wide speed-range. The capability and design of concentrated wound machines for optimal flux weakening has been dealt rigorously in [15]. It has also been investigated for a lower-power node high speed (2kW,220 krpm) turbocharger application with a wide field weakening requirement [16].

A 20kW 6-slot, 4-pole concentrated wound PMSM is investigated in this study. The rotor eddy-current losses with such a slot-pole combination are high in comparison to the other machine losses and managing the aforesaid losses becomes the primary concern of the design [18]. The air-gap dimension is an important optimisation parameter, as increasing the air-gap has the effect of reducing the losses, albeit reducing air-gap heat transfer [17], [18]. The eddy-current losses can also be reduced by circumferential and/or axial segmentation. Fig. 12 compares the losses for 1mm and 2mm air-gap dimensions, for a number of cases of sleeve/magnet axial segmentations.

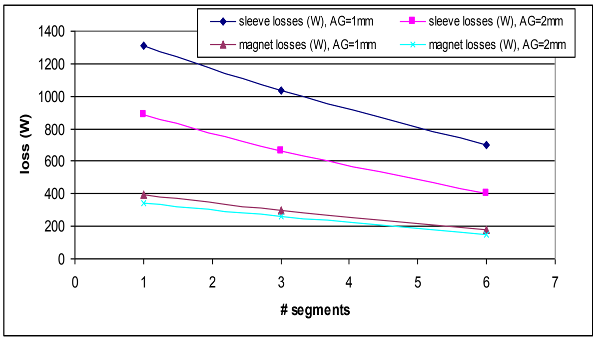

Fig. 12. Rotor losses for 6-slot 4-pole machine designs with different air-gap lengths and segmentations

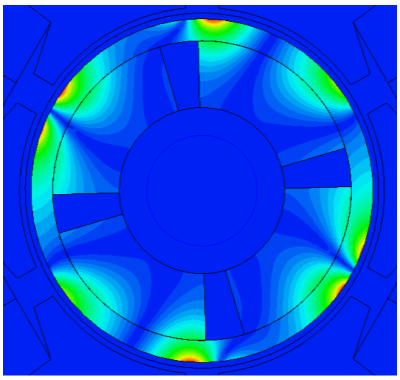

Fig. 13. Current density plot in 6-slot 4-pole machine rotor, showing the induced eddy currents in the magnets and in the sleeve

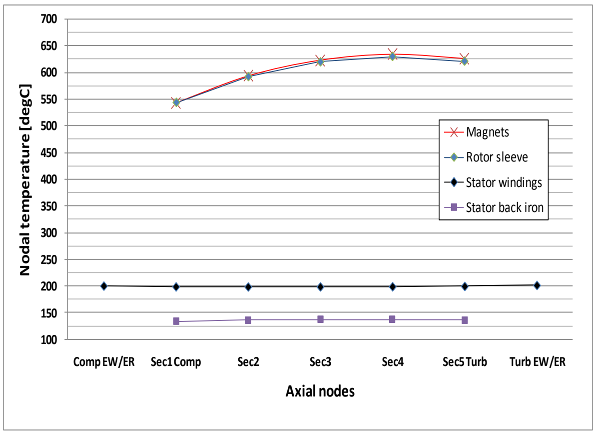

Fig.14.6-slot,4-pole concentrated wound SPMSM nodal axial temperature distribution for magnets, rotor sleeve, stator windings and stator back iron

Fig. 14 presents the thermal results for a 2mm air-gap machine with 6 axial sleeve and magnet segments. The eddy-current losses generated are primarily in the sleeve, as shown in Fig.13, and are very high due to the harmonic-rich armature reaction field. The losses lead to excessive rotor temperatures, even after increasing the air-gap and segmenting the sleeve and magnets. The magnets cannot withstand such high operational temperatures. A possible way to mitigate the sleeve losses is to use a carbon fibre retention mechanism, however the high temperature application environment precludes the aforesaid.

7. Conclusion

This multi-disciplinary machine topology selection study has highlighted the importance of using a multi-domain design approach for the design of very high speed electrical machines in a challenging design environment. The field weakening requirement is major consideration in the design selection study. The commonly used distributive-wound inset PMSM cannot achieve the required field-weakening capability without significant PE converter over-sizing, while the concentrated wound 6-slot 4-pole PMSM has excessive rotor losses at the frequencies considered resulting in elevated rotor temperatures which are well above the magnet withstand capabilities.

The Induction Machine, despite the rotor copper losses, can be designed to withstand very high temperatures and by suitable steel-grade selection a high degree of robustness can be achieved on the rotor. Moreover it naturally field-weakens, thus making it the most suitable electrical-machine topology for the design requirement.

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