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Some Problems with the Design of a Permanent Magnet Synchronous Machine of 50KW and 50Krpm

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Abstract

A number of significant advancements have increased the appeal of very high-speed electrical machines (either motor or generator). The key drivers in a transition to higher speed include rising power electronics switching speed, high energy magnets, and high strength retaining materials, stronger high speed bearings, and advancements in design analysis. The mechanical design, both in terms of strength and resonant modes, and the electromagnetic design, notably in terms of iron losses and ac losses in various conducting elements, including the rotor, present design issues. This paper details the design work on a permanent magnet (PM) synchronous machine with a speed of 50,000 rpm and a power of 50kW. It describes studies on rotor eddy current losses utilising a number of methodologies, including both 2D and 3D finite element analysis.

Keywords: *High speed, PM motor, rotor and stator losses, finite- element analysis*

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INTRODUCTION

High-Speed Electrical Machines Have Recently Been The Focus Of A Lot Of Research. For high–speed applications, squirrel cage induction motors, permanent magnet synchronous machines, and switching reluctance machines can all be used. Many of these alternatives, such as induction, permanent magnet, axial gap synchronous, and switched reluctance machines, are reviewed in [1] from the perspective of high rotational speed, their characteristics, and the benefits and drawbacks of each machine type, and the paper concludes that PM machines are a good choice for high speed applications. High-power density permanent magnet materials are becoming more affordable, prompting high-speed machine designers to use magnets to energise the rotor. Higher speed translates to smaller size, which can save money and improve the whole application.

Fuel pumps, energy storage flywheels, grinding and milling spindles for machine tools, compressor drives, high-speed generators that can link to gas turbines directly without a gearbox, and many other applications employ high-speed electrical machines (motor/generator) [3]. When designing a high-speed PM machine, a variety of aspects must be considered, including the PM material, rotor diameter and length, pole number, rotor strength and rigidity, bearing design, and so on. Mechanical, electromagnetic, and thermal behaviour are the most difficult aspects of high-speed PM machines to master. (1), (4), (5), and (6).

During typical operation of a 50,000 rpm, 50KW permanent magnet synchronous machine, this study gives a completeexamination of electromagnetic, rotor, and stator loss.

GENERAL DESIGN CONSIDERATI--ONS

When permanent magnets are used to energise the rotor, the high fields available result in a reduction in rotor volume of [7], which can lead to low cost even with their high cost. It's worth noting that shrinking the size of a high-speed machine makes it more difficult to distribute heat, and the increased loss associated with high-speed tends to reduce the machine's efficiency. PM materials ranging from high energy magnets (sintered NdFeB or SmCo) to low energy magnets (sintered NdFeB or SmCo) can be used (ferrite or bonded NdFeB). Good magnet characteristics, a high operating temperature, and a low cost are all factors to consider when choosing a PM material. In this design, sintered NdFeB was chosen.

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Another important consideration is the motor's pole number; the lower the motor's pole number for a particular speed, the lower the fundamental frequency. The stator and rotor core back thickness, on the other hand, increases as the number of poles increases. For high-speed applications, two or four poles are the most popular; two pole was chosen for the high-speed PM in [5] [8], while four pole was chosen in [6, 9]. In this design, a 4 pole was used to provide a reduced core back depth, resulting in a reduction in the machines outside size when compared to a two pole machine design.

In high-speed machines, magnets are frequently held in place by a sleeve, which can be metallic or composite. In this design, a high-strength nonmagnetic stainless steel (Inconel) was employed since it has about the same yield strength as carbon-fibre but is significantly less expensive. Because the nonmagnetic sleeve lengthens the effective air gap from a magnetic standpoint, the enclosure (sleeve) should be as thin as possible. In several designs, a carbon-fibre or glass-fibre sleeve has been employed. A thin carbon-fiber sleeve can help reduce the air gap, which improves power density. The carbon-fiber, on the other hand, acts as a heat insulator. As a result, additional attention should be paid to the rotor's cooling [11].

DESIGN OF THE MACHINE

The motor electromagnetic and mechanical quantities were determined using an analytical approach as well as 2D and 3D finite element analysis approaches. In order to find a solution, one pole of the two pole field of three phases PM synchronous machine must be meshed with proper boundary conditions. The boundary conditions that can be applied to the machine are shown in Figure 1.

A = 0 is put on the machine's outer surface, both up and down. Natural boundary conditions exist on the bottom surfaces of the left and right hands, allowing flux to flow normally. The left and right hand geometry surfaces have periodic boundary conditions with A = A, which indicates "what happens on this side will happen precisely the same on the other side."

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Table 1: Rotor Material Electrical and Magnetic Properties

Rotor part	**1.25e-6**	**Electrical Resistivity (∧ • m)**	**Relative permeability(μ r)**
Magnets	Neodymium iron born	1.6e-6	1.043
Sleeve	Non-magnetic Inconel 718 steel		1.0011

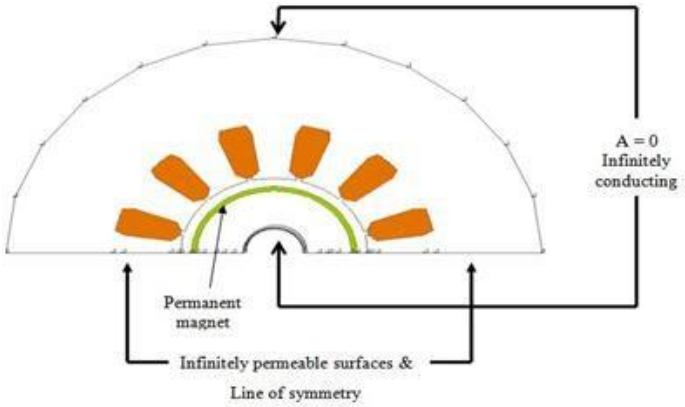


Fig. 1 the boundary conditions applied to the 50kW 50krpm PM machine

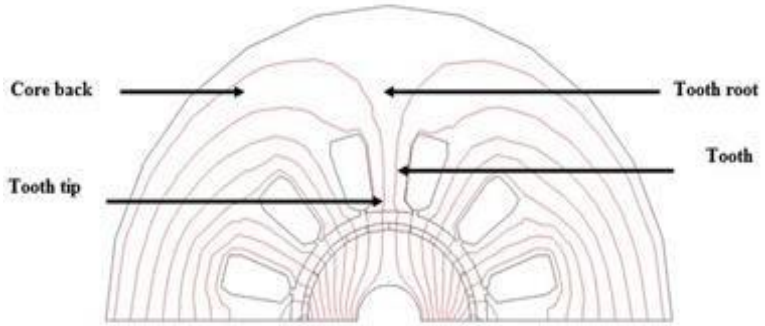


Fig. 2 No-load flux of 50,000rpm, 50KW Permanent Magnet Synchronous Machine

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A permanent magnet synchronous machine with two poles and twelve slots (PM) has been built. Figure 2 illustrates the cross-sectional geometry of the magnetic flux plot at no-load of the 2-pole
12 slot, 50,000rpm, 50kW PM synchronous machine. At no-load, the stator core back has the highest flux density.

The flux densities of the analytical solution match the FE flux density solution quite well. For an output power of 50kW at speed of 50 Krpm the torque has to be 9.55 Nm, which produced by peak sinusoidal phase current of 57.7 A. The torque can be calculated using "equation (1)" and as it has been assumed that the air gap flux density which calculated from the analytical model is a square wave (0.452T). Therefore, the calculated torque was 7.47 Nm, which less than the expected torque (9.55 Nm), this is because a square wave air gap flux density value is used, but if the 1st harmonic of this square wave is used, air gap flux density will be (0.575T), and the calculated torque will be 8.94 Nm

$$Torque = Bilr \qquad (1)$$

The final machine has an active length of 157 mm and a stator outside diameter of 179 mm.

A. Rotor

Mechanical factors such as centrifugal force (mechanical stress), critical speed, inner bearing diameter, and manufacturability all influence rotor diameters. The shaft is composed of non- magnetic Stainless Steel with a diameter of 30 mm. On the top of the shaft is the rotor core back. Because of its residual flux density, a high energy rare earth magnet such as sintered NdFeB was chosen to achieve the maximum torque density (1.2 T). By minimising the centrifugal force stress on the magnet, an inconel alloy 718 retention sleeve is employed to fix the magnet to the rotor core back. The outer diameter of the rotor is 113.46mm.

B. Stator

As is well known, the stator is made up of two parts: the stator core back and the winding. In terms of losses, both are optimum (iron loss and copper loss). 6.5 mm 0.10 m m Because of its highsaturation flux density and low loss, silicon steel is employed as the rotor and stator core back material.

ROTOR EDDY CURRENT LOSS

The induced eddy currents in the rotor magnets, in any conducting magnet sleeve, and in the rotor body (if not laminated) cause a heat loss in the rotor. Rotor loss generally increases with the square of

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speed and is usually only a problem in high speed machines, the main source of rotor losses are the stator-slot harmonics caused with the pulsation of magnetic field by the stator slot opening, the second source is the time harmonics associated with non- sinusoidal supply voltage. Produced A 2-D FE approach is used to estimate the rotor eddy current loss in the rotor. Material properties in table 1 are used in the FE program. Fig. (3 -a, b) illustrates the field from the 5th harmonic (ten-pole) magnetic field and the seventh harmonic (fourteen-pole) magnetic field with frequency of 1200 Hz and 857.14 Hz respectively. A skew in the magnetic field can be seen in Fig. (3 -a, b), this is due to the interaction between the magnetic field source and the eddy current reaction field. This effect is often called eddy current drag and manifests itself as a drag torque. This drag torque applied to the rotating rotor results in power loss ($P=T\omega$) and manifests as heat [13]. From FE the first significant harmonic is the 23rd with total loss of 72.49 W and the second significant harmonic is the 5th with total loss o f
39.19 W the third significant harmonic is the 7th with total of 22.8 W.

Most eddy current loss occurs within the magnets where the loss has to be avoided as it can cause demagnetization. The total eddy current loss caused by most significant harmonics is 1.057 KW. For a 50 KW electrical machine with rotor size of (157mm axial length and 113.46 mm diameter) this is a very low. A smaller slot opening or increasing the air gap length is the choice to reduce eddy current caused by tooth ripple harmonic, also changing the winding type or breaking up the eddy current path is another choice to reduce eddy current loss caused by stator winding harmonic.

IRON LOSSES ESTIMATION

At higher speeds, core losses are significant, and they are usually the second most significant loss component in AC machines. The fundamental-frequency change of the magnetic field causes a core loss in the stator in most cases. For high- speed motors, the prediction of stator iron losses is critical. For sinusoidal variable magnetic flux density with frequency, the total iron loss is generally represented as follows:

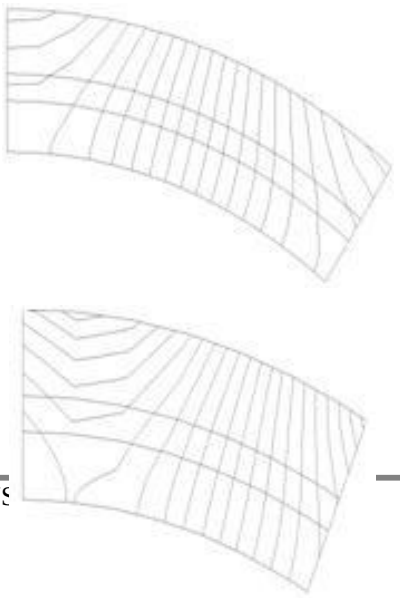


Fig. 3 a,b. 10 and 14 pole resultant magnetic field plot

Where: B = max flux density (T).

F = frequency (Hz). k_h ,α , k_d , k_e hysteresis, domain and eddy current losses

The method for estimating iron loss has been to pick a part of the machine (for example, the teeth and core back of the armature), check the flux plot for the peak flux density, then use the frequency from the particular speed of rotation to estimate iron loss using manufacturers curves to fit equations (2). A genetic algorithm programmer was utilized to find the loss at a frequency of 500Hz.

The curves on the data sheets of electrical steel producers show the value of iron loss vs flux density for a variety of operating frequencies. This method has been used to determine the loss constant values of 0.10 mm 6.5 percent silicon steel. Genetic algorithm programme used a typical values of the constant loss as a starting point along with equation 2 in the frequency domain, calculated loss is compared to the data provided by the manufactures to determine the best loss constant values. The loss constant values derived by the genetic algorithm are shown in Table II.

Table II Core Loss Constants for 0.10 MM 6.5 % Silicon Steel

$$Iron\ \ Loss\ p_{iron}\left(\frac{watt}{kg}\right) = k_h B^{\alpha} f + k_d (Bf)^{1.5} + k_e (Bf)^2 \quad (2)$$

Core Loss Constant	0.10 mm 6.5 % silicon steel
hysteresis constant (K_h)	0.0092
Steinmetz ( )	1.8819
domain constant (K_d)	1.53e-4
eddy loss constant (K_e)	3.9863e-6

The peak flux density in the stator occurs within the stator core back, as shown in the stator flux plot of a no-load 50KW PM machine. Flux density, on the other hand, varies with position. The no- load iron loss for the 50kW machine is predicted to be 36.2 W at no-load, assuming 0.1 mm 6.5 percent silicon steel lamination and a rotor speed of 50,000rpm.

The 50KW machine has 1 turn/coil (making 8 turns per phase connected in parallel, which has been chosen to give a back emf of 331.69V rms line, against a dc link voltage of 469V), each turn of 3.59mm diameter of round copper conductor carrying current of 40.8 rms A, the phase resistance is 2.15e-3 Ohm, and the phase resistance is 2.15e-3 Ohm. The copper loss per phase is 3.59W. Because the conductor's centre will not be used, the diameter of the conductor should be no more than one skin depth, Fig 4.

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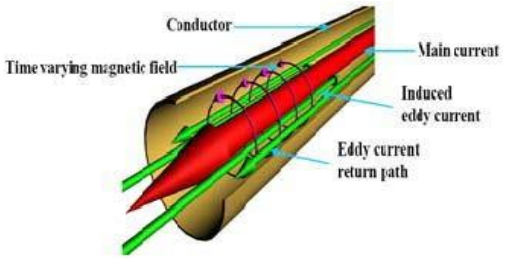


Fig. 4 The effect of time varying current on a conductor

At 883.3Hz, the skin depth in copper is 2.46mm. A proximity loss was calculated using a 2-D FE software, yielding a total proximity loss of 3.4 KW, which is quite high. The spherical conductor is broken into several strands, each smaller than the skin depth, and then twisted so that each strand occupies all locations in the bundle, equalising the induced field in each thread and therefore allowing the main current to spread out evenly between each strand. After that, the proximity loss is minimised [14]. The overall proximity loss is decreased to 13.1 kW by using Litz wire with 260 strands and a strand diameter of 0.222mm.

CONCLUSION

Many challenges arise in high-speed operation and must be thoroughly investigated in order to assure a successful design. This paper presents a design for a high-speed, high-power 50krpm, 50kW PM synchronies machine. The losses in copper winding owing to high speed frequency currents and magnetic field from the PM are calculated and approximated using 2-d FE models.

The use of Litz wire reduces overall copper loss. The use of 0.1 mm 6.5 percent silicon steel lamination also reduces iron loss.

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