International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:6, No:8, 2012

Some Design Issues in Designing of 50KW 50Krpm Permanent Magnet Synchronous Machine

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***Abstract*—**A numbers of important developments have led to an increasing attractiveness for very high speed electrical machines (either motor or generator). Specifically the increasing switching speed of power electronics, high energy magnets, high strength retaining materials, better high speed bearings and improvements in design analysis are the primary drivers in a move to higher speed. The design challenges come in the mechanical design both in terms of strength and resonant modes and in the electromagnetic design particularly in respect of iron losses and ac losses in the various conducting parts including the rotor. This paper describes detailed design work which has been done on a 50,000 rpm, 50kW permanent magnet(PM) synchronous machine. It describes work on electromagnetic and rotor eddy current losses using a variety of methods including both 2D finite element analysis

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

I. INTRODUCTION

RECENTLY a large amount of research effort has been spent on high speed electrical machines. Various ac machines can be used for high–speed applications, such as squirrel cage induction motor, permanent magnet synchronous machines and switched reluctance machines. Many of these alternates, including induction, permanent magnet, axial gap synchronous and switched reluctance machines, are reviewed in [1] from the point of high rotational speed, their characteristics and the advantages and disadvantages of each machine type and the paper shows that PM machines are a good choice for high speed applications. Improvements in high power density and cheap permanent magnet materials are encouraging high speed machine designers to use magnets to energize the rotor. Higher speed means smaller size which can reduce cost and allow benefits in the overall application.

High-speed electrical machines (motor /generator) are used in applications such as fuel pumps, energy storage flywheel, grinding spindle and milling spindles for machine tools, compressor drives, high speed generators which can couple to gas turbines directly without a gearbox and many other applications [3]. A range of factors must be taken into account in the design of a high speed PM machine, such as: the choice of PM material; rotor diameter and length; choice of pole number; rotor strength and rigidity; bearings design and so on. The mechanical, electromagnetic and the thermal behaviour are the challenging areas in high speed PM machines. [1, 4, 5, 6].

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This paper presents a detailed analysis of, electromagnetic, rotor and stator loss during normal operation of a 50,000 rpm, 50KW permanent magnet synchronous machine.

II. GENERAL DESIGN CONSIDERATIONS

The high fields available using permanent magnets for energizing the rotor leads to reduction in rotor volume of [7] which can lead to low cost even taking into account their high cost. Note that reductions in the size of high speed machine make it difficult to distribute the heat, and the additional loss related with high speed tends to decrease the efficiency of the machine. It is possible to use a wide range of different PM materials such as high energy magnets (sintered NdFeB or SmCo) or the low energy magnets (ferrite or bonded NdFeB). The considerations for the choice of PM material take account of good magnet properties, high operations temperature and low cost. A sintered NdFeB was the choice in this design.

Another central issue is the choice of pole number, the lower the pole number of the motor for a given a speed the lower the fundamental frequency. However, the core back thickness of the stator and rotor increases with pole number. Two or four poles are the most common for high speed applications, 2-pole was the choice for the high speed PM in [5] [8] whereas four pole has been chosen in [6, 9]. In this design a 4 pole was the choice to give a smaller core back depth which led to reduction in the outside dimension of the machine if it compared with two pole machine design.

The magnets in high speed machines are usually retained using a sleeve which can be metallic or a composite. In this design a high strength nonmagnetic stainless steel (Inconel) has been used as it has nearly the same yield strength but is much lower cost compared with carbon-fibre. The thickness of the enclosure (sleeve) should be as small as possible because the nonmagnetic sleeve lengthens the effective air gap from a magnetic point of view. A carbon-fibre or glass- fibre sleeve has been used in many designs. A thin carbon-fiber sleeve can make the air-gap smaller which is good for the power density. However, the carbon-fiber works like a thermal insulator. Therefore, special care should be paid to the cooling of the rotor [11].

III. DESIGN OF THE MACHINE

An analytical approach and both 2D and 3D finite element analysis approaches have been used to determine the motor electromagnetic and mechanical quantities. One pole of the two pole field of three phases PM synchronous machine with appropriate boundary conditions is required to be meshed in order to obtain a solution. Figure 1 shows the boundary conditions which can be applied to the machine.

A = 0 is set on the outer surface on the top and down of the machine. The left hand and the right hand surfaces on the bottom have natural boundary condition which will allow flux to flow out normally. The geometry left and right hand surface s also have a periodic boundary conditions with A = A, which means "what happen on this side will be exactly the same on the other side".

TABLE I
ROTOR MATERIAL ELECTRICAL AND MAGNETIC PROPERTIES

Rotor part	1.25e-6	Electrical resistivity ($\Omega \bullet m$)	Relative permeability (μ_r)
magnets	Neodymium iron born	1.6e-6	1.043
sleeve	Non-magnetic Inconel 718 steel		1.0011

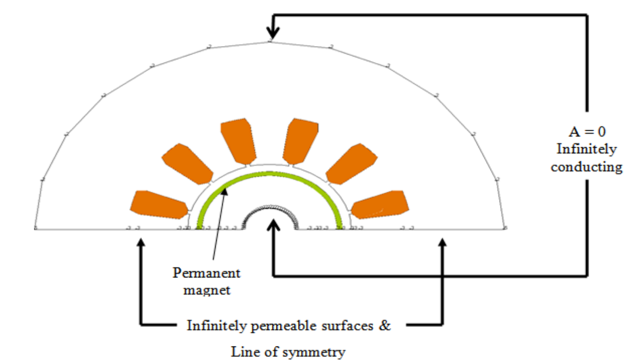

Fig. 1 The boundary conditions applied to the 50kW 50krpm PM machine

A 2 pole 12 slot (PM) Permanent Magnet Synchronous Machine has been designed, Fig.2 shows cross-sectional geometry of magnetic flux plot at no-load of the 2-pole 12 slot ,50,000rpm, 50kW PM synchronous machine.

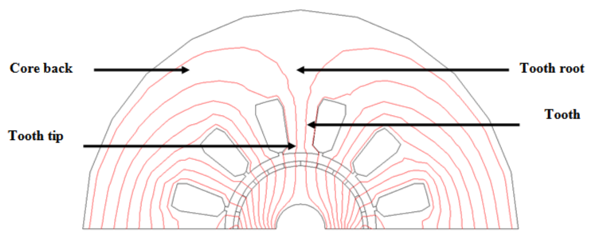

Fig. 2 No-load flux of 50,000rpm, 50KW Permanent Magnet Synchronous Machine

The peak flux density at no-load motor occurs in the stator core back.

The flux densities of analytical solution agree well with the FE flux density solution.

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

$$Torque = Bilr \tag{1}$$

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

A. Rotor

Rotor dimensions are generally governed by mechanical aspects such as centrifugal force (mechanical stress), critical speed, inner of bearing diameter and manufacturability. The shaft with diameter of 30 mm is made from non-magnetic Stainless Steel. The rotor core back is located on the top of the shaft. In order to get a highest torque density, high energy rare earth magnet like sintered NdFeB was the choice because of it is residual flux density (1.2 T). An inconel alloy 718 retaining sleeve is used to fix the magnet to the rotor core back by limiting the centrifugal force stress on the magnet. The outer rotor diameter is 113.46mm.

B. Stator

As it is known that the stator contains a two parts which are stator core back and the winding. Both are optimized with respect to the losses (iron loss and copper loss). 0.10 mm 6.5 Silicon Steel is used as rotor and stator core back material because of high saturation flux density and low loss.

IV. 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 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=Tω) 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.

V. Iron Losses Estimation

Core losses are important at higher speeds and normally the second major loss component in AC machines. Normally, a core loss in the stator is caused by the fundamental-frequency variation of the magnetic field. The prediction of stator iron losses is very important for high speed motors. The total iron loss is commonly expressed in the following form for sinusoidal varying magnetic flux density with frequency is:

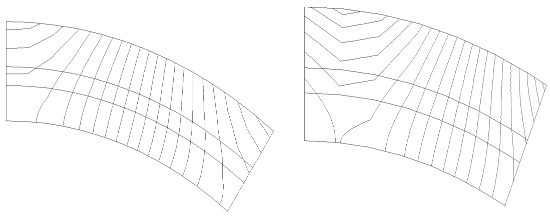

Fig. 3 a,b. 10 and 14 pole resultant magnetic field plot

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

Where: B = max flux density (T).

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

The technique which has been used to estimate the iron loss is by selecting a area of the machine (for example the teeth and core back of the armature) then finding the peak flux density by checking from the flux plot, then using the frequency from the particular speed of rotation to estimate iron loss using manufactures curves to fit equation (2). In order to find the loss at frequency of 500Hz, a genetic algorithm program has been used.

Electrical steel manufacturers' data sheets curves give the value of iron loss against flux density for range of operating frequencies. Genetic algorithm program used a typical values of the constant loss as starting point along with equation 2 in the frequency domain, calculated loss is compared to the data that provided by the manufactures to determine the best loss constant values, this method has been used in Genetic algorithm method has been used to determine the loss constant values of 0.10 mm 6.5 % silicon steel. Table II shows the loss constant values calculated by the genetic algorithm.

TABLE II
CORE LOSS CONSTANTS FOR 0.10 MM 6.5 % SILICON STEEL

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

As can be seen in the stator flux plot of no-load 50KW PM machine, the peak flux density in the stator occurs within the stator core back. Flux density does however vary with position. The no-load iron loss for the 50kW machine assuming 0.1 mm 6.5 % silicon steel lamination and rotor speed of 50,000rpm are estimated to total 36.2 W at no-load.

The 50KW machine has 1 turns/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) with 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, The copper loss is 3.59W per phase. The conductor diameter should be not much larger than one skin depth, as the center of the conductor will not use, Fig 4.

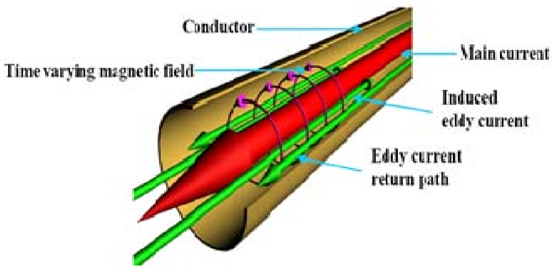

Fig. 4 The effect of time varying current on a conductor

The skin depth in copper at 883.3Hz is 2.46mm. A proximity loss has been estimated, a 2-D FE program giving; a total proximity loss of 3.4 KW is calculated which is high. By breaking the round conductor into many strands each of which is smaller than the skin depth and then twisting them so that every strand occupies all positions in the bundle equalizing the induced field in every strand and thus allowing the main current to spread out evenly between each strand so called Litz wire. The proximity loss is then reduced [14]. Litz wire is chosen with 260 strands and a strand diameter of 0.222mm, the total proximity loss is then reduced to 13.1 kW.

VI. Conclusion

In high speed operation many issues arise and must be carefully studied in order to ensure a successful design. A high speed high power 50krpm, 50kW PM synchronies machine design has been presented in this paper. The losses caused by the high frequency operation are minimized by optimizing the winding and the stator core material, the losses in copper winding due to high speed frequency currents and magnetic field from the PM are calculated and estimated using 2-d FE models.

The total copper loss is reduced by using Litz wire. Also the iron loss is reduced by using 0.1 mm 6.5 % silicon steel lamination.

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