MAGNETICS

BUSINESS & TECHNOLOGY

www.MagneticsMagazine.com

a webcom publication

Winter 2005

2005/2006 ANNUAL BUYERS GUIDE ISSUE

Magnets and Their Losses in Large Brushless Motors

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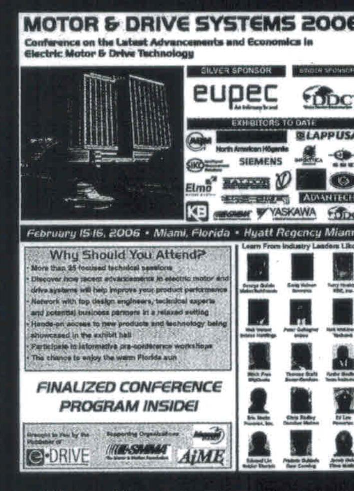

Finalized Program Announced for Motors Conference

See Brochue Inside

Magnets and Their Losses in Large Brushless Motors

Powertec Industrial Motor is a company specialized in designing and making customized brushless DC motor with powers from fractional to 600 Hp. All motors in fabrication here contain permanent magnets. The use of the permanents magnets in the electrical brush and brushless DC motors is very common in our days. A large popularity they have got in making small (fractional Hp) motors. Going to large size of brushless DC motors (i.e. hundreds of Hp) the use of magnets remains still an attractive solution due to the fact that their price cost is not prohibited. However, some precaution must be taken into the account when the use of the magnets is considered such as: the magnet type, its losses and their temperature rise associated. A motor running hot (i.e. winding temperature being 180°C, equivalent to the class F of isolation) may imply a magnet temperature to the same magnitude. Unfortunately, the metallurgical properties of the NdFeB magnets change around 200°C so a margin of safety of only about 20°C of the temperature rise will be left for magnets. But sometimes, the temperature of the magnet will rise more than 20°C due to the magnets looses occurred in them. Thus, the result generates a failure of the magnet and of the motor itself. Fig. 1 shows a failure of the magnet/motor due to the temperature rise. Therefore, the purpose of this article is to enter in the above aspect and highlight suggestions for solving the trade-off issues of making large BLDC motors with surface mounted permanent magnets.

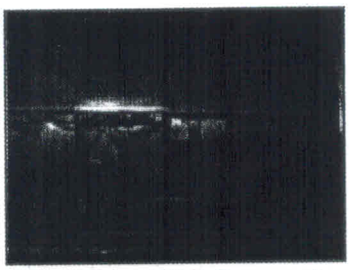

Fig.1. Failed NbFeB magnets due to the temperature rise

Manufacturing Aspects

In the regular construction, the brushless DC motor contains the permanent magnets mounted in the rotor and the three phase windings inserted into the stator stack laminations. The motor is generally packed using a housing and two end bells/plates. The rotor is made-up from a shaft, two bearings, one for each end of the shaft, the rotor laminations or a magnetic hub plus the permanent magnets. The number of the rotor and the stator poles has to be the same in order to get an electromagnetic torque.

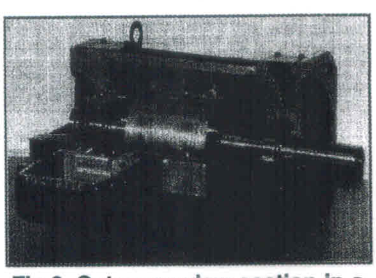

Fig.2. Cut-away view section in a rare-earth brushless motor

In the classical construction, the rotor is concentric with the stator as it is shown in Fig.3. Large motors contain also a terminal box. The commutation and the feedback control can be done using Hall sensors, encoders and resolvers. A resolver is seeing in the Fig. 3 sitting on the terminal box waiting to be mounted along the shaft of the motor.

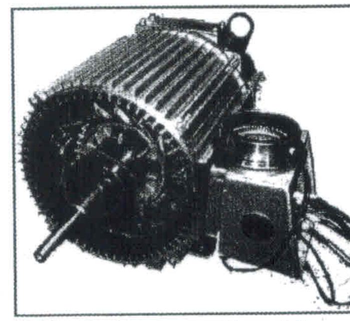

Fig. 3. An opened brushless DC motor

The output power of a motor (the nominal power) is given by the difference between the input power and the losses occurred inside the motor. The two major components of the losses are: the Joule losses (losses occurred in the windings) and the iron losses (the losses occurred in the magnetic circuits of the motor). The desire is to keep the losses at a lower level to get a higher efficiency and less heat dissipated inside the motor. The iron losses are produced by variation of the magnetic field and are due to the hysteresis phenomena of the magnetic material and the eddy currents generates in it. The eddy currents may occur not only in the magnet material but also in the steel hub underlying the magnets, in the magnets and in the retaining sleeve over the magnet if that is conducting.

Magnet Aspects

The magnet material resistivity is higher for Ferrite than NdFeB magnets. As a comparison, the NdFeB material has a resistivity of about 1.5 μΩm representing a very low number as compared to Ferrite (>10^4 Ωm.) This makes the large solid magnets very susceptible to the generation of large eddy currents, and hence large power losses, in the magnets themselves. These eddy currents primarily are a function of magnet geometry, flux excursion, speed, PWM current ripple (chopping frequency), stator current magnitude, the resistivity of the material, air-gap length and slot opening [1]. The magnetic field produced by the stator is not constant and the rotor magnets are nearby the stator. Thus, the AC flux may penetrate to some degree into the magnets producing losses in them and obtaining a temperature rise of the rotor magnets above the acceptable limits. If the magnets are made of an electrically conductive material such as neodymium-iron-boron (NdFeB), then eddy currents will flow in response to the driving flux. There will be loss in magnets associated with these eddy currents. Even through the magnitude of the AC flux penetrating the magnets is small, if the resistance of the magnet material is also small and the current path is large, then the loss can be significant. In some cases this loss may have a relative small impact on the overall machine efficiency but not always. Also, the motor drive currents contain time harmonics causing eddy current losses in the magnets. Therefore, a careful consideration in the design process of the magnets losses may be required to avoid the failure modes associated with demagnetization. To calculate and get the feeling of the magnitude for the magnet losses, a formula like the one from the Eq. 1 may be uses [2]. It is derived from the similar equation used to calculate losses in the magnetic circuit (iron losses) and rotor cans. This simplified expression is appropriate when the skin-depth is comparable to the conductor thickness such as a magnetic steel lamination and the hysteresis. The eddy current coefficients are determined experimental for the magnet material in use.

$$Magnet\_Loss = K_{hm} * I * f + K_{em} I^2 * f^2$$

where: K_{hm} is the magnetic hysteresis coefficient; K_{em} is the magnetic eddy current coefficient; f frequency; I phase current;

Equation 1

R_m, the magnet resistance is calculated assuming it equivalent with a conductive loop with the length equal to the length of the outer periphery and an area equal to the thickness multiplied by half the magnet width [3]. When transferred across the air-gap to the equivalent number of direct-axis stator turns, this can be represented as a resistance R_{me}, connected across the direct-axis magnetizing inductance in the equivalent-circuit models for brushless permanent magnet motor.

The representation from Eq.2 of the magnet conductivity is valid when the penetration depth at the maximum frequency

$$R_{me} = \left(\frac{16\ k_w N}{\pi^2 \sin\alpha}\right)^2 \frac{R_m}{P}$$

where: k_w = the winding factor, incorporating the distribution, pitch and skew factors; N = the number of turns per phase; α = half of angular magnet span (in electrical degrees); P = number of magnet poles;

Equation 2

is large in comparison with the magnet radial thickness.

The eddy current losses in the segmented permanent magnets (PM) of a brushless motor may be estimated [4] using the graph from Fig. 4. It can be seen that cutting in half the magnet along the pole-arc the magnet, the losses in magnet are drop to almost to half.

A large number of magnet segments (higher than 4) along the pole-arc does not decrease significant the magnet losses. However, the use of a large number of segments is not recommended because the manufacturing aspect of the motor is complicated and expensive.

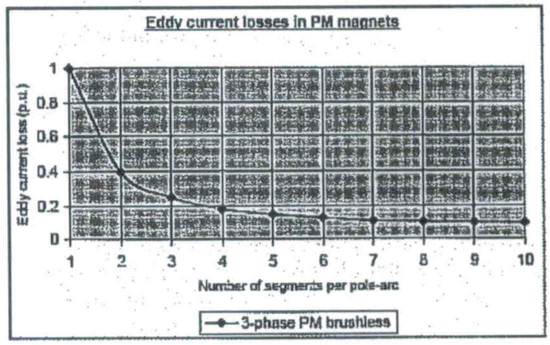

Fig.4 The eddy current losses in permanent magnets

Discussions

The eddy current loss in the permanent magnets of brushless AC machines is usually neglected by many engineers, since the fundamental air-gap field usually rotates in synchronism with the rotor and time harmonics in the current waveform and space harmonics in the winding distribution are generally small. Unfortunately, this may not be true, in special if the size of the motor is large. The rotor temperature rise, although influenced by the stator side temperature, is predominantly due to local loss generation within the rotor itself [5]. A higher magnet temperature generates a weaker magnetic field produced by the magnets in the motor air-gap. Thus, the output torque/power developed by the motor is decreased. An increase of the input current to compensate the loss in torque may make the story worst. A higher current generates a higher loss and temperature rise in the motor resulting in after all runaway and demagnetization of the magnets.

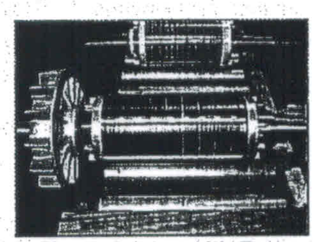

Fig. 5. A rotor with Rare Earth magnets segmented along the axial direction

Fig. 5 shows and rotor with the poles made-up from NdFeB magnets segmented along the rotor axis. The segments are electrical insolated one to the others and also to the magnetic circuit of the rotor. To get that electrical isolation, the classical glue may not work. This technique of segmenting only along the axial direction may be good if the size and speed of the rotor is small. The size of magnet pieces are higher in large motors and therefore, the magnet losses due to eddy currents can be high pushing the magnet temperature up to 200°C.

An increase in temperature from eddy-current losses can demagnetize the magnets and high temperature may weaken structural adhesives, leading to the magnets detaching from the rotor backing iron [6] if not mechanically restrained with suitable banding. Therefore, for large rotors/motors running at high speeds the segmenting of the magnets is recommended to be done along both directions: axial and circular. An example of

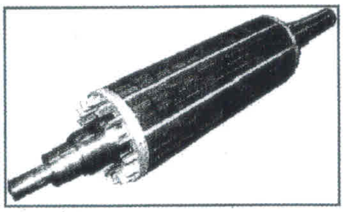

Fig. 6. A rotor with NdFeB magnets segmented along the axial and circular direction

this kind of rotor is shown in the Fig. 6. Thus, cutting or laminating the magnets will reduce these losses in the same manner as the stator losses are reduced by laminating the stator core. Therefore a rotor made of large arcs will have more losses than a rotor made-up of many small pieces.

Also, the electrical isolation of each piece of magnet is important too. To completely insulate the magnets from each other as well as from the laminated core the ``E'' Coat may work the best where adhesion on the coating to the magnet is of utmost importance as well as obtaining optimum corrosion resistance. Unfortunately, a rotor made as the one presented in the Fig. 6 is very costly. In order to avoid high costs, a rotor with ferrite magnets may be used instead. Due to the higher electrical resistivity of the Ferrite compared to the rare earth magnets, the ferrites are currently in use in most high speed application at Powertec Industrial motors. The eddy currents in this type of magnet are much lower that the NdFeB. Thus, the magnet size can be higher and segmentation on a circular direction may not be necessary. Also, the electrical isolation of the magnets may be waived too.

A rotor with ferrite magnets is shown in the Fig. 7. The losses in BDLC can be reduced further using laminated rotor backing-iron.

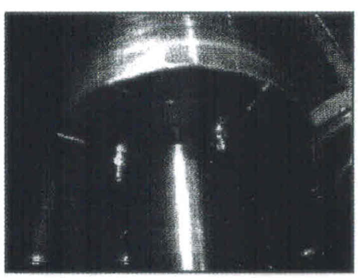

Fig. 7. A rotor with ferrite magnets segmented along the axial direction

Lamination is essential for PWM controlled drives to minimize loss in the back iron. A minimization of phase current ripple magnitude by the drive converted scheme is recommended if the rotor loss must be much lower. The lower the PWM frequency is the higher the current ripple and the magnetic losses are therefore increased. Also, the magnet losses are higher on 6-step than sine wave drives. A sinusoidal stator current is ideal for low rotor losses. Assuming that none of the above options are available or enough to decrease the eddy current loss in a rotor, than, increasing both the magnet thickness and air-gap length may be a good step.

Conclusions

1. Rotor lamination is essential for PWM controlled drives to minimize loss in the back iron; 2. Cutting or laminating the magnets will reduce magnets losses in the same manner as the stator losses are reduced by laminating the stator core. Therefore a rotor made of large arcs will have more losses than a rotor made-up of many small pieces. If the segment magnets are not used a sinusoidal stator current is recommended. 3. For the high-speed brushless DC machines, the increase of the resistivity of the permanent magnet material (using Ferrite magnets instead of NdFeB) will results in a lower magnet loss due to the eddy currents. 4. The eddy current losses in the rotor can be reduced by increasing the magnet thickness and air-gap length simultaneously. 5. As a rule of thumb, a cut in half of the magnet along the arc pole reduces to approximately half the magnet losses due to the eddy currents in that magnet pole.

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