ROTOR RETENTION AND LOSS REDUCTION FOR HIGH-SPEED PERMANENT MAGNET MOTOR GENERATORS

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Abstract:

There are two primary technologies of magnet retention in high speed permanent magnet machines, namely high-strength non-magnetic metal sleeve and high strength composite sleeve. Each offers unique advantages to the system and motor/generator performance. System designers select the optimum approach to meet system performance goals for rotor's tip speeds up to 360 meters/second and operating temperatures up to 230°C

The metal sleeve can be designed to provide some stiffness to the rotor structure. It also acts to effectively shield the magnets from stator's harmonic currents. Eddy currents generated in the metal sleeve due to stator's harmonic currents and stator slotting impede high frequency fields from penetrating the magnets and generate losses. Most of the absorbed energy in the metal sleeve readily dissipates to the cooling medium in the airgap and the rest is conducted to the magnets and/or end supports. Carbon fiber sleeves are significantly stronger and lower density than their metal counterparts thus allow the use of more magnet mass or thinner sleeve for similar magnet volume. The result is smaller magnetic gap and better magnetic performance with carbon fiber sleeves. However, they do not provide any harmonic filtering. Moreover, due to their low thermal conductivity they act as thermal barriers to heat generated in the magnets. Rotor loss reduction and management techniques such as segmenting magnets or conductive layer shielding are frequently employed to enhance system performance when using carbon fiber sleeves.

Introduction:

Electromechanical systems with permanent magnet rotors can operate as motors to convert electrical power into mechanical movement or as generators to convert mechanical movement into electrical power. High speed motors/generators are commonly used in different systems such as expanders in Organic Rankin Cycle waste heat recovery systems, flywheel-based energy storage systems, and electric turbo-charging and supercharging systems for marine engines and high-performance vehicles.

Design details of these systems are beyond the scope of this paper. The focus will be placed on the high-speed rotor which is a critical part of many integrated motor generator systems.

High-Speed Rotor

The invention of permanent magnet brushless motors and generators has led to the development of very high-performance machines with significantly higher operating speed and power density than the earlier mechanically commutated designs. At high operating speeds, however, the design of the rotor assembly becomes increasingly critical. Considerable material and geometric uniformity is required to minimize the inertial force imbalance and the rotor components must be designed to withstand the centrifugal stresses induced by rotation. In addition, rotor's bending stiffness needs to be managed for robust system operation.

The high-speed permanent magnet rotor is composed of a series of permanent magnets (PM) bonded to a center steel hub and retained by a high-strength, non-magnetic sleeve. The high-performance alloy magnets, such as samarium cobalt (SmCo) series or neodymium iron boron (NdFeB) series, are brittle materials, exhibiting relatively low strength. Magnets with low tensile strength require retention to protect them from cracking or lifting-off the steel hub at high speeds. This can be achieved by using a retaining sleeve manufactured from a material with high tensile strength.

The sleeve material and sleeve thickness are determined based on service conditions and strength requirements. High-strength, nonmagnetic materials such as Inconel (Trademark of Special Metals Corporation), titanium alloys and composite materials with carbon and glass fibers are normally considered for retaining sleeves. Magnet retention is provided for tip speeds in excess of 360 meters per second. The designer selects the optimum approach to meet the system performance goals. A schematic of a typical 4-pole rotor and its components are shown in Figure 1.

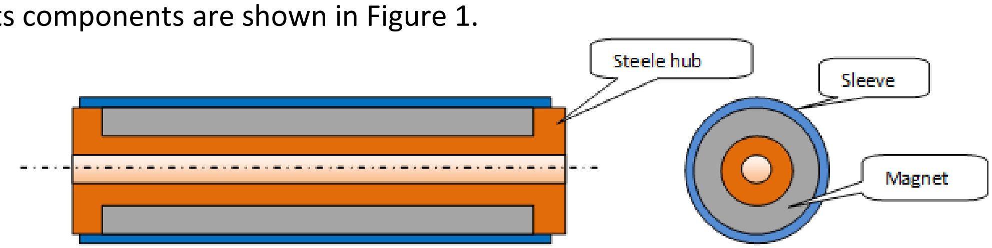

Figure 1

A permanent magnet (PM) motor/generator consists of two basic parts: a stationary stator winding assembly, powered by a multi-phase alternating current to create a rotating magnetic field, and a rotor assembly that contains permanent magnets. The interaction of the stator and rotor fields generates torque. The stator and rotor assemblies are separated by a clearance gap. For a given stator bore diameter, the outer diameter of the rotor magnet needs to be reduced to incorporate the non-magnetic retaining sleeve. The presence of the retaining sleeve increases the stator-rotor effective magnetic gap (i.e., clearance gap plus sleeve thickness). Thus, for a given rotor length and electromagnetic performance, the inner diameter of the magnet is reduced to increase magnet volume. This in turn causes a reduction in rotor hub diameter.

For high-speed rotation, the bending stiffness of the rotor's hub is an important parameter which affects the natural frequencies or modes of vibration. If one of these critical frequencies is in the range of operation, considerable energy can be transferred to the system during a short period of time causing bearing damage or catastrophic failure of the shaft. Therefore, rotors are designed to be stiff and lightweight for high-speed applications. In conjunction with dynamic requirements, the retaining sleeve is designed to have high strength to resist hoop stresses and apply sufficient compression on the magnet assembly to eliminate the possibility of “lift-off” at high rotational speeds that would cause the rotor to go out of balance.

The state of stress in a rotor with a center hole spinning at high speed will be considered next to demonstrate the requirements posed on the sleeve. The radial and hoop stresses in the rotor can be approximated by the following equations assuming material continuity and homogeneity [1]:

$$\sigma_r = \frac{(3+\nu)}{8} * \rho * \omega^2 * [r_1^2 + r_4^2 - r^2 - (\frac{r_1^2 * r_4^2}{r^2})] \qquad \text{(Equation 1)}$$

$$\sigma_\theta = \frac{(3+\nu)}{8} * \rho * \omega^2 * [r_1^2 + r_4^2 + (\frac{r_1^2 * r_4^2}{r^2}) - \frac{(1+3\nu)}{(3+\nu)} * r^2] \qquad \text{(Equation 2)}$$

where

σ_r =radial stress at a radial distance r
σ_θ =hoop stress at a radial distance r
ν = Poisson’s ratio
ρ = density
ω = angular velocity
r_1 = radius of rotor center hole
r_4 = radius of sleeve outer surface

Figure 2 shows radial and hoop stress distributions of a representative rotor at 125 krpm.
where

r_2 = radial distance to hub-to-magnet interface
r_3 = radial distance to magnet-to-sleeve interface

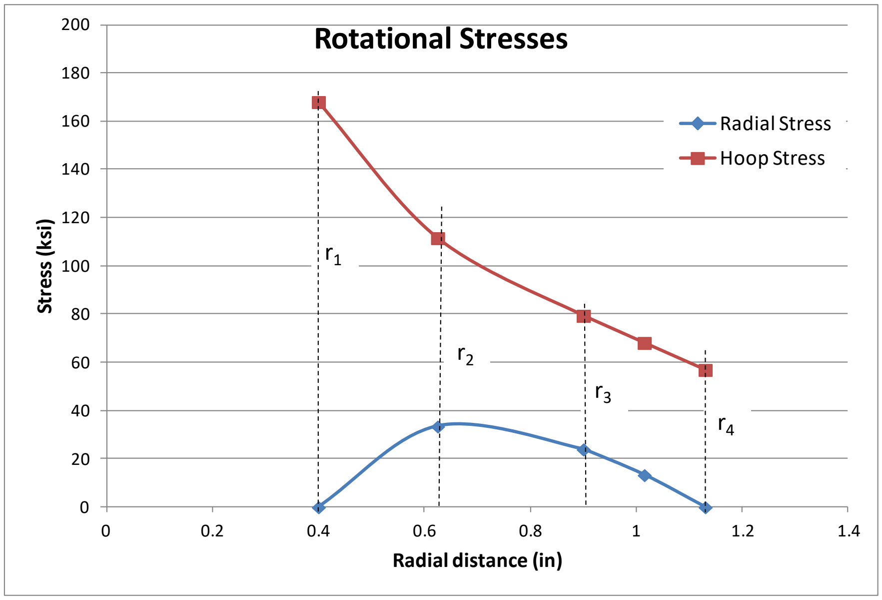

Figure 2

Figure 2 suggests that at hub-to-magnet interface, "r2", there will be considerable amount of tensile stress in the radial direction which will de-bond the magnets and cause magnet lift-off. Such a deformation will produce rotor imbalance and lead to catastrophic failure. Thus, the sleeve is designed to have high strength to resist hoop stresses and apply sufficient compression on the magnet assembly to eliminate "lift-off" at high rotational speeds. To achieve this, rotors are sleeved with sufficient pre-stress.

The following four approaches are commonly used to introduce pre-stress during the sleeving process:

1) ***Thermal Shrink-fit***

For this process the sleeve is designed with an interference fit where the inner diameter of the sleeve (r_2-Δr) is smaller than the outer diameter of the magnet assembly (r_2). This process is typically used for metallic sleeves the sleeve is expanded thermally while the hub with permanent magnets is cooled to reduce its outer diameter. After the shrink-fit process as the temperature of the rotor assembly equalizes, the core expands, and the sleeve shrinks in size producing compressive pre-stresses at the magnet/sleeve interface.

Hydraulic Shrink-fit

For this process special machines are used to apply differential pressures on the sleeve, higher pressure on the inner surface and ambient pressure on the outer surface. The sleeve expands due to this pressure differential and allows the insertion of the rotor core in place. After proper positioning of the sleeve the device is de-pressurized to achieve the shrink fit. This approach requires more extensive tooling and is considered more suitable for high volume production.

2) ***Shrink-fit with Axial Compression***

This process is primarily used for segmented composite sleeves where the rotor is lubricated, and the sleeve segments are forced onto the rotor. Similar to Process #1 the sleeve is designed with an interference fit and is expanded with a conical nose piece to slide over the rotor.

3) ***Direct Wound Composite Sleeves***

For this process carbon or glass fibers pre-impregnated (pre-preg) in a thermoplastic or thermoset material in the form of a unidirectional tape is wound on rotor assembly with some tension to compress the magnets against the steel hub. If the matrix is thermoplastic (e.g. PEEK), it needs to be heated above the melting temperature during sleeving for proper consolidation. The thermoset matrix is only partially cured to allow easy handling. Hence, composite sleeve built with a thermoset pre-preg material will require an oven cure.

Radial stresses in a pre-stressed rotor at high speed are shown in Figures 3. These plots were generated for the same rotor shown in Figure 1 after applying a carbon-fiber composite sleeve. Pre-stress in the composite sleeve was optimized to apply adequate compression on magnets and eliminate the possibility of magnet lift-off at high speeds. As shown in Figure 3, the magnets ($r_2 > r > r_3$) remain under radial compression at high speed.

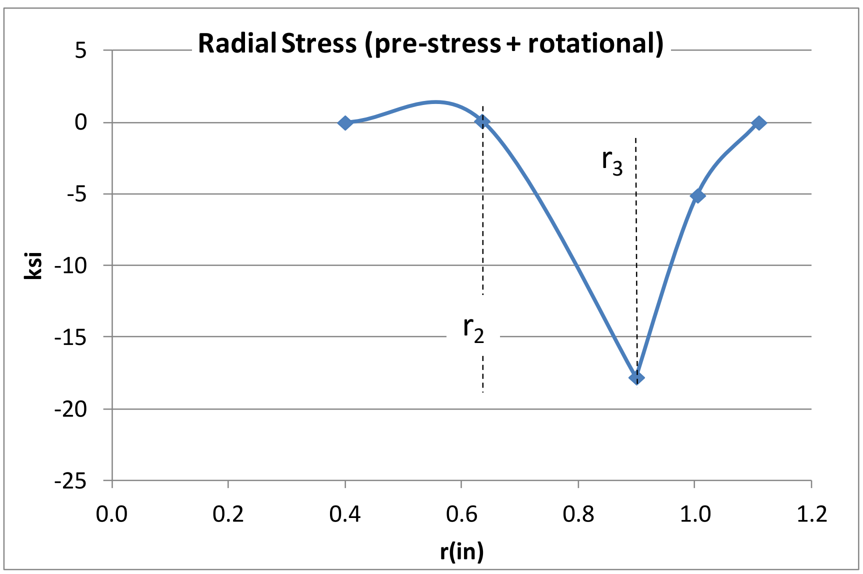

Figure 3

Rotor Tip-Speed, Figure-of-Merit and Efficiency

Since power is proportional to torque times rotational velocity, operating at high speed reduces the torque required for a fixed output power. Machines are normally sized according to the level of operational torque. Thus, high speed machines are much smaller in size and therefore more power dense when compared to equivalent-power low-speed machines. High speed machines are typically designed to operate at same speeds as aerodynamic components (i.e., turbines, compressors), eliminating the need for step up gearboxes and allowing for robust systems integration. Design of these types of machines must address the challenges that are introduced due to complex vibration modes within the yield and ultimate strength of rotor materials. Rotor design, rotor materials, and rotor damping must be optimized together to overcome these challenges. Composite sleeves with carbon fiber filaments are normally used due to their light weight and high strength. Reducing the weight in high speed rotors has two benefits; the natural frequencies are increased and the inertial loading which produces stresses in the material is minimized. Composite rotors are designed to enable the production of greater amounts of energy per unit weight and achieve maximum rotational speeds. Furthermore, fiber reinforced composite rotors have been shown to fail in a less destructive manner than metallic rotors.

Rotor-Tip-Speed (RTS) and Figure-of-Merit (FOM) are frequently used as objective metrics to evaluate and rank high speed motors. RTS and FOM are defined as

$$RTS = \omega * r_4 \quad \text{(Equation 3)}$$

$$FOM = kW * (krpm)^2/1{,}000{,}000 \quad \text{(Equation 4)}$$

where

ω = angular velocity
r_4 = outer radius of sleeve
kW= power generated/consumed by the system at its rated condition
krpm = revolutions per minute/1000

Table 1 provides these metrics for representative systems where rotors are retained with carbon fiber sleeves.

System	Power(kW)	Rotor speed (krpm)	RTS (ft/s)	FOM
ZH350	175	52.5	830	0.48
TA-60	60	105	871	0.66
TA-100	100	74	772	0.55
MTR100	100	105	848	1.10

Table 1

Rotor tip speeds for systems provided in Table 1 are within 20%. Comparing the ZH350, with an FOM of 0.48, and the MTR100 with an FOM of 1.1, tip speeds are within 2.1% of each other. While not directly comparable to sleeve stresses, it is in the least clearly indicative that both composite sleeves are operating at similar stress conditions, and that factors other than rotor containment stress and retention capability are driving FOM in these systems. The data clearly indicates the range of FOM is significant, and dependent on the system design requirements. It is also clear, looking specifically at the MTR100 design, that the sleeving technology is able to achieve a FOM of greater than 1.0, more than twice the FOM value of ZH350 system. It should be noted that there are inherent limitations in such simplistic metrics. Design parameters including bearing attributes, items installed on the shaft, operating conditions, temperature range, etc. can influence the maximum rated operating speed, and thus these metrics. In addition, systems are not designed to maximize such metrics, but optimized to best meet the overall performance and cost requirements.

Loss Reduction in High Speed Rotors

The loss generated by induced eddy currents in the rotor's retaining sleeve, steel shaft and permanent magnets is typically a small percentage of the machine's total loss. However, removing the heat from the rotor to ensure reasonable operating temperatures of its components is an engineering challenge. Thus, reduction of rotor losses at high speeds becomes an important task. Major contributors of rotor loss can be categorized in three groups: (a) no-load rotor eddy current loss caused by the existence of stator slots, (b) on-load rotor eddy current loss induced by harmonics resulting from non-sinusoidal or discrete winding distribution, which is also called space harmonics, and (c) on-load rotor eddy current loss induced by the time harmonics of the phase currents due to pulse width modulation (PWM). The rotor loss can be predicted using FEA based on measured current waveforms or estimated current with total harmonics distortion (THD) [2].

There are several methods of reducing rotor losses. Reducing the stator slot opening and increasing the magnetic gap between rotor and stator can reduce no-load rotor loss. Increasing the number of slots per pole and using fractional winding can also reduce rotor loss caused by the space harmonics of the armature winding. Increasing the switching frequency and using external line inductors can reduce rotor loss caused by time harmonics of the phase currents [2].

High-speed PM rotors are built with either metal sleeves or carbon fiber sleeves. One of the advantages of a metal sleeve is that it also acts as a harmonic filter to the PM's by eddy currents being generated in the sleeve. The metal sleeve rejects high frequency fields from entering the magnets and generating losses. The loss generated in the metal sleeve can be readily removed by the cooling medium typically exist in the machine's airgap. CF sleeves do not provide any such harmonic filtering. Moreover, due to their low thermal conductivity they act as thermal barriers to heat generated in the magnet and cooling medium in the air gap. Minimizing loss in the magnets therefore is critical.

Magnet losses in rotors with CF sleeves due to induced eddy currents can be reduced by the use of segmented magnets. The effect of axial and circumferential segmentation of the magnets on rotor losses was the focus of numerous studies [3, 4, 5, 6]. A more cost-effective approach of filtering total harmonic distortion (THD) and significantly reducing the operating temperature of the rotor at high speed was investigated. In this novel methodology, a metal shield with high thermal conductivity is applied over the magnets. A composite sleeve of high strength carbon-fiber is then applied over the rotor to retain the assembly at very high speeds.

This configuration allows the metal shield to filter high frequency harmonics and then conduct the heat to both ends of the rotor that are exposed to cooling media such as bearings oil or air gap cooling , thus reducing direct heating of the permanent magnets and dissipating any internally generated heat as a result of the filtering. The metal type and thickness of the metal shield depends on the THD of the machine and is determined by an analysis.

An experiment was conducted to demonstrate the effectiveness of this novel methodology. Two almost identical rotors were manufactured; one with the metal shielding applied between the permanent magnets and the composite sleeve and the other without the metal shielding. The magnet and sleeve OD of these rotors were kept exactly the same for easy comparison of test results. Moreover, to reduce the number of uncertainties both rotors were driven side by side with the same dynamometer. Table 2 presents test results.

Parameter	Unit	Rotor without Metal Shield			Rotor with Metal Shield		
Speed	krpm	50	70	80	50	70	80
Fundamental Current	A pk	250	250	216	243	246	211
Torque	Nm	8.0	8.0	6.9	7.7	7.8	6.7
Estimated output shaft power	kW	41.6	58.3	57.5	40.5	57.3	56.2
Sum of harmonic currents	A pk	16.7	17.9	18.8	17.4	21.8	22.3
THD	%	6.7%	7.2%	8.7%	7.1%	8.9%	10.6%
Cold Back EMF	Volts/krpm	2.81	2.81	2.81	2.83	2.83	2.83
Hot Back EMF	Volts/krpm	2.67	2.63	2.60	2.79	2.78	2.78
Back EMF reduction	%	5.2%	6.4%	7.5%	1.4%	1.8%	1.8%
Estimated avg rotor temp	C	149	180	207	55	64	64

Table 2

Results presented in Table 2 suggest that the rotor with metal shielding between the magnets and the composite sleeve runs significantly cooler than that with no metal shielding under various conditions. Dynamometer parameters were kept the same for fair comparison. For the same amount of coolant air entering both systems at the same temperature, the air temperature exiting the system with metal shielded rotor is significantly lower than that with the baseline rotor with no shielding. This observation also suggests that the metal shielding effectively reduces the rotor losses.

In conclusion, various advanced magnets retention techniques and rotor loss reduction methods can be used to achieve optimal high-speed permanent magnet motor and generator designs. The current capability of the composite sleeving technology is not the limiting factor in the design of high-speed rotors. Improvements are being introduced in magnet retention technology by developing novel processes to manufacture composite sleeves using high strength thermoset unidirectional fiber tows. Optimization of rotor designs with advanced magnet retention technologies and loss reduction techniques enhances motor/ generator system performance and ensures robust high-speed operations.

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