Technical analyses of HTS bulk used in a rotating machine

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HTS bulks are used for developing novel rotating machines. In these systems, the qualities of HTS bulk are closely related to the structure, start-up and operation of motors. Based on the experimental results and theoretical simulations, some technical considerations, such as pre-magnetization, dynamic performance and structural strengthening of HTS bulk motor, were discussed in details.

INTRODUCTION

There is a continuing need for new motors with reduced size and weight, higher efficiency, and increased reliability. Commercial HTS bulks provide excellent potential to design high-efficiency motors with improved performance to respond to these new requirements. Based on peritectic solidification processes and different philosophies on improving the performance, various techniques have been adopted to produce large-domain HTS bulks with high Jc. It was reported that MTG-YBCO bulk can trap a strong magnetic field over 1 T at 77 K, which may be dramatically enhanced by irradiation and lowering the temperature. A large light rare-earth (LRE) BCO bulk is believed to trap very high magnetic fields of more than 5 T at 77 K. Such bulks are tried to construct novel rotating machines, such as hysteresis, reluctance, permanent-magnet (PM) and linear motors. At present, a maximum output power of HTS bulk motor has reached 38 kW at 77 K. In these motors, the characteristics of HTS bulk should be fully taken into account in the design, construction and operation. Based on our experiments and theoretical analyses, some technical considerations for HTS bulk motor were proposed and discussed in the paper.

PRE-MAGNETIZATION

As we know, the generated torque of a hysteresis machine is equivalent to the loss in the HTS bulk rotor. It is important to allow adequate fluxes to permeate the rotor. For situations where the penetration is less than optimal, the torque can be increased by partly-magnetization of HTS bulk rotor beforehand. As an alternative to field windings on the rotor, HTS bulks in the form of cylinders carrying currents which circulate an iron member can be used as PM in a synchronous machine. This necessarily requires HTS bulks in the assembly to have trapped a field by means of pre-magnetization. For these kinds of motor, we have no alternative but to perform impulse magnetization by using stator / extra auxiliary coils.

Figure 1 shows an equivalent circuit of pulse magnetizing system. R and L are the external circuit resistance and leakage inductance of the magnetizing coil, The impulse field is generated by discharging a large capacitor bank into the coil. The circuit equation is written as:

$$\oint_c \frac{\partial \vec{A}}{\partial t} \cdot d\vec{s} + (R + R_c)\frac{dQ(t)}{dt} + L\frac{d^2Q(t)}{dt^2} + \frac{Q(t) - Q_0}{c} = 0 \tag{1}$$

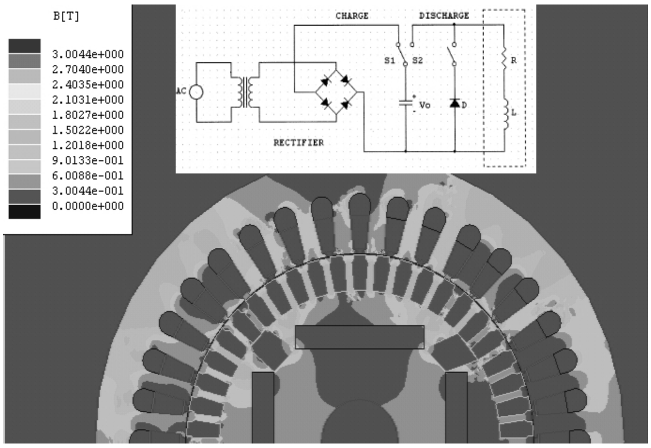

Figure 1 Equivalent circuit of pulse magnetizing system and Instantaneous field distribution inside HTS motor

Table 1 Specification of the analysis model

Section	Item	Value (Unit)
Stator	Number of phases	3
	Number of slots	36
	Outer diameter	245 (mm)
	Inner diameter	162 (mm)
	Number of turn / phase / pole	28 (turn)
Rotor (PM)	Number of pole	4
	Outer diameter	161 (mm)
	Radial thickness	10 (mm)
	Axial Length	58 (mm)
	Residual Flux density	1.0 (T)
Air gap	Mechanical air gap	0.5 (mm)

where A is the magnetic vector potential, R_c is the resistance of the magnetizing yoke, $Q(t)$ and Q_0 are the electric charge of the capacitor at the time t and its initial value. Considering $M(H)$ curve of HTS bulk obtained from Kim model, instantaneous field distributions in the regions of the magnetizing coil and HTS bulks were simulated by FEA method (see Figure 1) using fundamental equations as follows:

$$rot(v rot\vec{A}) = \vec{J}_0 + \vec{J}_e + v_0 rot\vec{M} \qquad \vec{J}_e = -\sigma(\frac{\partial \vec{A}}{\partial t} + grad\,\phi) \qquad div\vec{J}_e = 0 \tag{2}$$

where J_0, J_e are the exciting and eddy current density, v, σ, ϕ, M and v_0 are the reluctivity, conductivity, electric scalar potential, magnetization of HTS bulk and reluctivity of vacuum respectively. Our analytical model is shown in Table 1. HTS bulks in the rotor were magnetized successively pole by pole using each neighboring stator coils. It was observed that the required magnetizing mmf is generally higher since the stator coils are further from HTS bulk in the rotor, whilst the problem may be aggravated by the presence of iron components which may shunt the magnetic field and / or cause eddy-current screening of iron rotor. The field penetration was initially inhibited by eddy currents induced in the rotor core, and gradually began from HTS bulks' flanks near flux barriers containing no magnetic material. The pole transition region is the most difficult to be magnetized since the radial alignment of the magnetizing field is very poor. It is desirable to make the pole width similar to the HTS bulk width in order that magnetizing fluxes flow HTS bulk regions uniformly.

Theoretically, HTS bulks could be magnetized to saturation by increasing the capacitance. The magnetized volume can be calculated from $M(H)$ curve. However, our experiments indicated that the thermo-magnetic instability occurs during impulse magnetization, and results in a drastic reduction of magnetization due to a strong heating of HTS bulks, which may be well described by the flux-creep model. Prominent fringing effects would be exhibited as the iron core becomes saturated, causing an uneven magnetization of HTS bulks. One impulse field configuration exists to make the remnant magnetization maximal. Additional 2-3 pulses would be helpful to improve the magnetization by further flux penetration. So an optimum pre-magnetization strategy, in terms of the level of saturation achieved, should be selected subject to constraints such as the subsequent temperature rise in HTS bulks due to flux movements, and the peak current withstand of stator / auxiliary coils. Larger number of stator coil-turns is better to reduce eddy current in the rotor. Some other issues may require consideration, such as the possible insulation degradation due to large induced emf, mechanical shocking to the bearings, and effects of the impulse on Hall devices and any other drive electronics which are housed within the motor case.

DYNAMIC PERFORMANCE

It was proven that the shielding-currents redistribute with time inside HTS due to dynamic disorder. The law of distinct regions has obvious differences, which is attributed to local distributions of effective pinning energies. It is possible to improve the time stability of the magnetization profile by consciously introducing ordered-array pinning centers, but the energy dissipation cannot be completely avoided by the quenched disorder. Once the motor runs, HTS bulk in the rotor will also be exposed to a complicated rotating field produced by the stator currents, which isn't always sinusoidal and sometimes contains harmonics. The onset of flux penetration into HTS bulk happens if only the angle of the rotating field exceeds some threshold value. The dynamic magnetic behavior and the losses strongly rely on the flux-cutting effect and anisotropy of HTS as well as the instantaneous direction of rotating-field. Rotating fluxes would penetrate $\sqrt{2}\sim\sqrt{3}$ times further than an alternating field with the same magnitude. The magnetic instability may extend to inner regions quickly by correlated flux motion. The induced unsymmetrical magnetization / magnetic shield levels of HTS bulk in the rotor have an effect on dynamic performances such as torque ripples and unbalanced magnetic force acting on the rotor. As for the HTS PM motor, torque pulsation and the unbalanced magnetic force can be calculated by [1]

$$T = r\sum_{i=1}^{u}\frac{1}{\mu}\left[B_n^{(i)}B_s^{(i)}\right](Dl_i)\ \ [\mathrm{Nm}] \qquad f_b = \sum_{i=1}^{u}\frac{1}{2\mu}\left[\left(B_n^{(i)}\right)^2-\left(B_s^{(i)}\right)^2\right](Dl_i)\ \ [\mathrm{N}] \tag{3}$$

where u is the number of incremental integration path l on the rotor surface, μ stands for permeability, r is the rotor radius, D is the stator core length, B_n and B_s are the normal and the shear component of average flux density on an incremental integration path. The simulation result of torque ripple was shown in Figure 2 for our motor model. It can be seen that the harmonics of torque pulsation change due to the asymmetric magnetization distribution. Furthermore, it was observed that the difference of force in the opposite direction at HTS inner surfaces is greater than that of symmetric magnetization. The increase of the unbalanced force will affect the bearing life cycle and the vibration in the motor drive.

It is general preferable to eliminate pulsating torque by improving the machine design. The screening current in HTS bulk keeps a value larger than a critical threshold J_0 for all times, i.e. $J_s(t)/J_0 \le 1-\phi_{\max}$, where $\phi_{\max}$ is the maximum value of the instability parameter. As a precaution for the safety of motor, a lost of synchronization caused by a fault in the control must be considered, especially the most critical condition when the stator and rotor fluxes are in phase opposition. The stator current is limited so that the power losses do not exceed the cooling power. The increase in heat transfer coefficient of HTS would result in smaller $\phi_{\max}$, improving stability. In order to reduce HTS magnetization degradation, non-linear magnetic bypass by magnetically soft material can be used at the opposite of the edge of HTS bulk. The configuration of slotless motor seems to be more adaptable for HTS bulk motor. Meanwhile, active cancellation control-based techniques may be adopted for minimizing pulsating torque, which depend on accurate knowledge of machine parameters provided by either careful tuning or adaptive control [2].

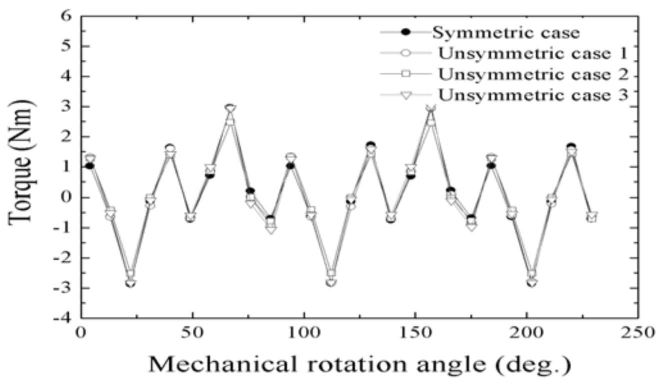

Figure 2 Torque ripple at 1500 rpm. Unsymmetric cases are that 10% degradation of trapped fields happened in one pole (1) and adjacent/opposite two poles (2)/(3), respectively

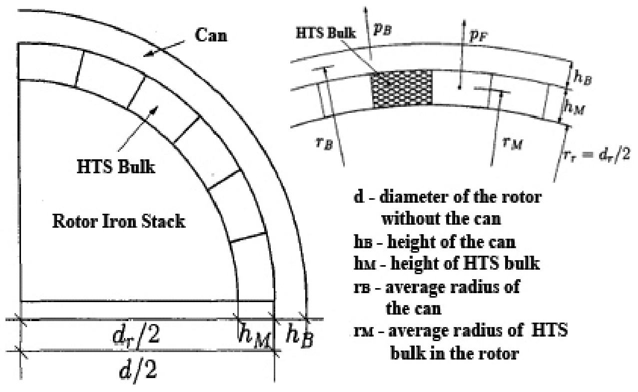

Figure 3 Cutout of the rotor with HTS bulk and the can

STRUCTURAL STRENGTHEN

In high speed applications, the rotor must have sufficient mechanical strength to withstand large magnetic pressures and centrifugal forces during pre-magnetization and rotation. However, HTS bulk exhibits poor mechanical characteristics: a low value of Young's module and brittleness. The fracture strength for MTG YBCO is just about 40 MPa. All the solutions using shaft notches and keys lead to unfavorable stress concentration. Any discontinuity in magnetic circuit is more vulnerable to the magnetization / magnetic shield degradation of HTS bulk. Our experiments showed epoxy-impregnation and joining is one of the feasible and effective methods in toughening, reinforcing and combining HTS bulks as well as locking HTS bulks and shaft. As an index of structural feasibility, the static safety coefficient can be evaluated by the maximum Von Mises stress amount in HTS bulk over the material crack stress.

Magnetic and nonmagnetic thin cans can be fitted around the HTS bulk to provide the rotor with the required mechanical strength (see Figure 3). The residual pressure p_{res} for fixing HTS bulks to the rotor surface must be larger than zero, and the tangential strength must be lower than the material limit, i.e.

$$p_{res} = 2\sigma h_B d^{-1} - 4\pi^2 n_{os}^2 \left(r_M \rho_M h_M + r_B \rho_B h_B\right) > 0 \qquad d\left(2h_B\right)^{-1}\left[2\sigma h_B d^{-1} + 4\pi^2 n_{os}^2 \left(r_M \rho_M h_M + r_B \rho_B h_B\right)\right] < \sigma_{\text{limit}} \qquad (4)$$

where σ, ρ_M, ρ_B and n_{os} are the initial tangential tension within the can, the mass densities of HTS bulk and the can as well as an over-speed of 120% of the nominal speed for the motor, respectively. An increase in the magnetic can thickness increases flux leakage between the poles, with the result that the airgap flux density and the synchronous torque are reduced. The pulsations of flux density in the rotor would cause eddy currents in the HTS and in the can. Rotor losses are particularly undesirable in HTS bulk motor since the can is heated and in direct contact with HTS bulks. Comparatively, the use of a nonmagnetic can avoids short-circuit of magnetic fluxes, but reduces the overall output of motor. So an optimal design requires careful consideration of the conflicting requirements of high output and acceptable losses.

CONCLUSION

The optimal impulse pre-magnetization strategy should be selected for theses constraints such as the temperature rise of HTS bulk, peak current withstand of magnetizing coils and mechanical strength of the motor. The asymmetrical magnetization / magnetic shield levels of HTS bulk have serious effects on dynamic performances of the motor. It is necessary to improve the motor design pertinently or apply active control schemes to eliminate induced pulsating torques. Epoxy-impregnation and the application of can may be the feasible and effective methods to strengthen the HTS bulk rotor.

ACKNOWLEDGMENT

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