Numerical Assessment of Efficiency and Control Stability of an HTS Synchronous Motor

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Abstract. A high temperature superconducting (HTS) permanent magnet synchronous motor (PMSM) is designed and developed in Cambridge University. It is expected to become cost competitive with the conventional PMSM owing to its high efficiency, high power density, high torque density, etc. The structure and parameters of HTS PMSM are detailed. Both AC losses by transport current and applied filed in stator armature winding of HTS PMSM are also analyzed. Computed and simulated results of the characteristics of the HTS PMSM and conventional PMSM are compared. The improvement on stability of direct torque control (DTC) on the HTS PMSM is estimated, and proved by simulation on Matlab/Simulink.

1. Introduction
Superconductivity has been a hope and vision for a new generation of electrical rotating machinery since the early 1960s [1]. A wholly high temperature superconducting (HTS) permanent magnet synchronous motor (PMSM) is designed and developed in Cambridge University so far [2]-[6]. The high current density obtained by using HTS material in stator armature windings and HTS bulks which can trap a high magnetic field (exceeding 2T at 77K [7]) on the rotor surface make the HTS PMSM possible to achieve very high power density, high torque density. The HTS PMSM is also expected to efficiency-competitive with the conventional PMSM, although some reasonable large AC losses may exist in motor. In addition, the variation of stator resistance is one of most important issues on stability of direct torque control (DTC) of PMSM, particularly at low speed. Very small equivalent stator resistance introduced by AC loss by transport current, especially at low speed, of HTS PMSM is predicted to solve the problem and to consequently improve the stability of DTC.

Firstly, the structure of the HTS PMSM is introduced briefly. Secondly, the AC losses of armature windings by both transport current and applied field are analyzed and estimated. The section 4 investigates efficiency of HTS PMSM. At last, simulation results of DTC of HTS PMSM and conventional PMSM on Matlab/Simulink are illustrated to verify the improvement on stability by HTS PMSM in section 5.

2. Design of the HTS motor
A cross-sectional drawing of the HTS motor is shown in Figure 1. The stator consists of six air core HTS armature windings, and the rotor is made of 75 (15 columns, 5 pieces per column) HTS bulks which are surface mounted and can be magnetized to a four-pole permanent magnet. The photograph of experimental motor sample is shown in Figure 2. On the upside of the rig, there are two magnetizing copper coils which are used for magnetizing HTS bulks on the rotor. The dimension of
magnetizing coil is shown in Figure 3. Pulse field magnetization will be used for magnetization of rotor. The magnetizing coils will generate roughly 1 T of magnetic field which will magnetize the HTS bulk to obtain 0.38 T of magnetic field on average [6]. The stator is on the bottom of the rig. Both of HTS windings and HTS bulks will be immersed into liquid nitrogen (77 K).

Figure 1. Cross-sectional drawing of the HTS motor.

Figure 2. HTS motor prototype.

Figure 3. Dimension of magnetizing coil.

Figure 4. (a) Dimension of the coils; (b) cutaway of the coils.
The armature winding in the HTS motor is composed of six single flat-loop coils which are wound as flat racetrack pancake coils with a bend radius of several centimeters. The racetrack windings and their geometry are shown in Figure 4. Double layers of HTS windings are stacked together to make one racetrack winding. This maximizes the inductance of the winding within the limited geometry. The total number of turns per phase for the stator windings is 200 turns, with 50 turns for each layer. Parameters of the HTS PMSM are listed in Table 1.

Figure 5 gives the Jc dependence on Bz of the superconducting tapes provided by American Superconductor Inc. From the figure we can use Kim model [8] to predict the Jc (Bz) expression as

\[ I_c = \frac{I_0}{1 + 3.93B_z} \]  

where \( I_0 = 100 A \).

![Graph showing Jc dependence on Bz](image)

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<th>Table 1. Parameters of HTS motor.</th>
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<td>Rated stator current (rms)</td>
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<td>d,q axis inductances</td>
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<td>Rotor flux linkage</td>
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![Graph showing AMSC 344 superconductor Ic (B, T) under parallel and perpendicular fields](image)

3. AC loss of HTS armature winding

3.1. Hysteretic Loss by Transport Current

To estimate the hysteretic loss caused by the transport current, we adapted an analytical model to give the prediction [9]. This model starts as an infinite long stack of tapes carrying the same current. The magnetic flux lines lie parallel to the tapes where the flux has not penetrated. In the penetrated part the critical current density \( J_c(x,z) \) flows while a much lower current density \( J_m \) flows in the middle unpenetrated region as shown in Figure 6 and 7 below. \( J_c(x,z) \) is given by the Kim expression (1) in section 2.

To calculate the hysteretic loss in each cycle, we just need to know the magnetic field and current density distribution of the stack when the transport current is at its peak value. Then we integrate \( J_c(x,z)\cdot E(x,z) \) over the critical region of the stack and over time, we can get the initial hysteretic loss per unit length of the stack [9], [10],

\[ Q_0 = 2 \int_{-b}^{b} \int_{-c}^{c} J_c(x,z) \cdot |B_x(x,z)| \cdot (a-x) dx dz \]  

where \( Q_0 \) is the hysteretic loss when the transport current is ramped from zero to its peak value.
The hysteretic AC loss $Q$ per unit length in a full cycle will be four times the initial magnetization loss [11], i.e. $Q=4Q_0$. If we multiple $Q$ by the mean circumference of the racetrack coil, we can get the AC loss per cycle. $Q_{coil}=QC$ where $C$ is the mean circumference of the coil.

In our race track coil, the distance between the two tracks and the radius of the semi-circle is much larger than the width of the tape, thus it is accurate enough to use the model above to estimate the hysteretic loss of the coil. Moreover, by symmetry we can regard the double pancake coil as a single pancake model given that the gap between the pancakes is much smaller than the width of the tape. Therefore we can put in the following parameters from our coil into analytical model

$$A_{Immb} = 50, 102, 2.0, 7.82$$

The hysteretic loss of the coil is determined by 1.17 J/cycle/m. The effective length of winding is 0.618 m. Hence, the transport power loss can be determined as

$$P_{trans} = 6 \times 1.17 \times 0.618 \cdot \frac{P \omega_r}{60} = 0.145 \omega_r \quad (W) \quad (3)$$

where $P$ is the number of pole pairs and $\omega_r$ is the rotor speed in rpm. The equivalent stator resistance of HTS PMSM can be derived consequently as

$$R = \frac{P_{trans}}{3I_{rms}^2} = \frac{0.145}{3 \times (50 / \sqrt{2})^2} \omega_r = 3.87 \times 10^{-5} \omega_r \quad (\Omega) \quad (4)$$

where $I_{rms}$ the rms value of stator current in one phase. Equation (4) indicates the stator resistance of HTS PMSM is proportional to the speed rather than a constant as the resistance of conventional copper winding. For example, at 1500 rpm, the stator resistance of HTS PMSM can be determined as

$$R = 3.87 \times 10^{-5} \times 1500 = 0.0580 \quad (\Omega)$$

3.2. Hysteretic Loss by Applied Field

It is not difficult to adapt this model to simulate the situation of a stack of tapes magnetized in an applied uniform magnetic field $B_z$. In the magnetization process, there will be no transport currents in the tapes but only magnetization current which has a different sign in the two critical regions. In the middle subcritical region, there will be no magnetic field, and $J_m$ will also be zero since the applied field has not penetrated here. The formula to calculate AC loss is still the same. Figure 8 shows the details.

The perpendicular magnetic field to the stack of tapes, which is also parallel to the radius of the coil, is an AC field with 0.1 T as the peak value. Thus we use 0.1 T as $B_z$ in the model. The result is 0.440 J/cycle/m. The effective length of winding is 0.618 m. Hence, the magnetization power loss can be determined as
\[
P_{mag} = 6 \times 0.440 \times 0.618 \cdot \frac{P_{rot}}{60} = 0.0543\omega_r (W)
\]  

Figure 8. The critical and unpenetrated regions in the coil under an applied field.

4. Efficiency of the HTS motor

The electromagnetic torque of no-salient PMSM can be determined as

\[
T = \frac{3P}{2} \left[ \lambda_d i_q + (L_d - L_q) i_d i_q \right] = \frac{3P}{2} \lambda_d i_q
\]  

where \(L_d\) and \(L_q\) are the d, q axis inductances, \(i_d\) and \(i_q\) are the d, q axis stator currents, \(\lambda_d\) and \(\lambda_q\) are the d, q axis stator flux linkages.

In the constant torque region, the value of \(i_d\) is zero, \(i_q\) equals to the total current which is 50 A. Hence the rated electromagnetic torque of the HTS PMSM can be determined as

\[
T = \frac{3 \times 2}{2} \times 0.675 \times 50 = 101 Nm
\]

At 1500rpm, the rated power of the HTS PMSM can be determined as

\[
P = T \cdot \omega_r = 101 \times 50\pi = 15.86 kW
\]

In order to assess the efficiency of HTS PMSM, a similar rating (15 kW/100 Nm) conventional PMSM in [13] is used for comparing to the HTS PMSM. For conventional PMSM, the main electrical and magnetic losses are copper loss and iron loss in stator armature winding which can correspond to hysteretic loss by transport current and hysteretic loss by applied field in stator armature winding of HTS PMSM. The copper loss is independent of speed and iron loss is proportional to speed, both of them in [13] are as follows:

\[
P_{copper} = 587 (W)
\]

\[
P_{iron} = 167 \cdot \frac{\omega_r}{1500} (W)
\]

where 587 and 167 are the copper loss and iron loss in watts at 1500 rpm, full load respectively.

Without field weakening, the rotor of synchronous motor rotates synchronously to the stator field, thereby no magnetic loss is on permanent magnets mounted on rotor of conventional PMSM, and no hysteretic loss by applied field on YBCO bulks mounted on rotor of HTS PMSM either.

Apart from electrical and magnetic losses, both HTS PMSM and conventional PMSM contain mechanical losses such as windage loss and bearing loss, and cooling loss by cooling system. Furthermore, to investigate the overall efficiency, it is also important to consider the drive loss such as inverter loss, filter loss, etc.

For HTS PMSM, a circulation cooling system is necessary to keep the temperature of liquid nitrogen constant. The circulation cooling system of HTS PMSM is assumed to have a constant output power of 50 W and an efficiency of 60\%, that is same as the fan cooling conventional PMSM [13], hence

\[
P_{cool} = \frac{50}{60\%} = 83 (W)
\]
The windage losses of both HTS and conventional PMSM are assumed to 5 W at 1500 rpm and proportional to the third power of speed [13]:

$$P_{\text{windage}} = 5 \left( \frac{\omega_r}{1500} \right)^3 \text{ (W)}$$  \hspace{1cm} (11)

The bearing losses of both HTS and conventional PMSM, that is proportional to speed, are assumed to 50 W at 1500 rpm. Hence,

$$P_{\text{bear}} = 50 \cdot \frac{\omega_r}{1500} \text{ (W)}$$  \hspace{1cm} (12)

The inverter losses mainly consist of switching loss and conduction loss of power devices. Since the conventional PMSM normally has lower rotor flux than HTS PMSM, it has to increase the pole numbers (8 poles used in [13]) and stator current to obtain the same torque rating. Increasing of pole numbers and stator current can increase the switching loss, conduction loss as well as the harmonics. The inverter loss in [13] is approximately 460 W. For same modulation ratio, the inverter loss of HTS PMSM is about 220 W. Both of them are assumed to be independent of speed.

Therefore, from equation (3), (5), (7), (8) ~ (12), the overall efficiency of HTS PMSM and conventional PMSM at full load can be expressed respectively as follows:

$$\eta_{\text{HTS}} \% = \left( 1 - \frac{P_{\text{cool}} + P_{\text{inv}} + P_{\text{copper}} + P_{\text{trans}} + P_{\text{bear}} + P_{\text{windage}}}{T \omega_r} \right) \cdot 100\%$$  \hspace{1cm} (13)

$$\eta_{\text{HTS}} \% = \left( 1 - \frac{P_{\text{cool}} + P_{\text{inv}} + P_{\text{trans}} + P_{\text{mag}} + P_{\text{bear}} + P_{\text{windage}}}{T \omega_r} \right) \cdot 100\%$$  \hspace{1cm} (14)

Figure 9 illustrates the overall efficiency performance of HTS PMSM and the conventional one at a range of speed (20-5000 rpm). At 1500 rpm, the overall efficiency of HTS PMSM and conventional PMSM are 95.8% and 91.4% respectively, and the difference between efficiency of HTS motor and conventional one is much smaller as speed approaching to 5000 rpm. However, below 1000 rpm, the efficiency of conventional motor falls down dramatically with speed decreasing. From 1000 rpm to 200 rpm, the efficiency of conventional motor decreases from 87.8% to 44.6%, and the efficiency of HTS motor only declines from 94.9% to 83.3%. Obviously, the efficiency of HTS motor is increasingly competitive as speed decreasing. At 1500 rpm, the efficiency ratio of HTS motor and
conventional motor is only 1.05. However, when HTS motor operates at the efficiency of 75% where speed is 127 rpm, the efficiency of conventional motor is only 13.5%, where the efficiency of HTS motor is more than 5 times of conventional one, and when operating speed drops down to 100 rpm where the conventional motor even cannot rotate at all, the HTS motor still own the efficiency as high as 68.8%. The efficiency of conventional PMSM is much poorer at low speed than HTS PMSM, because the copper loss as one of main losses, that is unlike hysteretic loss by transport current which is proportional to speed, is independent of speed. Therefore, the HTS PMSM has much wider operating speed range than conventional PMSM.

5. Stability of control system

Direct torque control (DTC) is considered as one of the best alternatives for motor drive designers to get a fast torque response. DTC uses no current controller and no motor parameters other than the stator resistance, which yields a faster torque response and a lower parameter dependence than with field oriented control (FOC) [14]. However, there are some problems associated with this method of control. Error in the estimation of stator flux linkage due to variation of stator resistance is one of the most important problems [15].

The basic principle of DTC is to obtain selected stator voltage vectors from the errors between the reference and actual torque and stator flux linkage. The reference torque is generated by the difference between the reference and actual speed, and the reference stator flux linkage can be set directly. The stator flux linkage is estimated by integrating difference between the input voltage and the voltage drop across the stator resistance given by equation (15)

\[
\lambda_s = \int (v_s - Ri_s) dt = \int (v_s - Ri_s) dt + \lambda_s|_{t=0} \tag{15}
\]

where \(\lambda_s\) is the stator flux linkage, \(v_s\) is the stator voltage in one phase. In the stator \(\alpha\beta\) frame, the torque can be estimated as

\[
T = \frac{3}{2} P \left( \lambda_{\alpha} i_\beta - \lambda_{\beta} i_\alpha \right) \tag{16}
\]

where \(\lambda_{\alpha}, \lambda_{\beta}\) are the stator flux linkage vector in \(\alpha\beta\) frame respectively, and \(i_\alpha, i_\beta\) the stator current vector in \(\alpha\beta\) frame respectively. The classic DTC scheme of PMSM is shown in Figure 10.

For the conventional motor, the stator resistance highly affects the stator flux vector, especially at low speed. The voltage drop across stator resistance at low speed is considerable and probably is comparable to the back EMF. The drive system will be unstable, even absolutely crash, if the actual stator resistance value deviates from the one used in the estimator Eq. (15), because errors between the reference and actual torque and stator flux linkage become quite large at low speed and high load. The stator resistance may change by about 1.5-1.7 times of its nominal value due to skin effect and change of temperature [16].

For the HTS motor, the change ratio of equivalent stator resistance is extremely large, e.g. nearly 0-100% from zero to rated speed, or from no load to full load. However, the maximum stator resistance is much smaller than the conventional copper resistance, e.g. 0.058 \(\Omega\) at 1500rpm for the proposed HTS motor, even though the controller uses a null \(R\), the effect of stator resistance variation on stability of DTC will be very low consequently, even be neglectable. Furthermore, what is on the contrary compared to conventional motor is that the stator resistance variation affects the stator flux linkage more and more lowly as the operating speed decreasing, since the equivalent stator resistance is reducing as well.
To verify such an improvement by HTS PMSM, DTC of both a 12 kW conventional PMSM and the proposed HTS PMSM are designed and simulated on Matlab/Simulink. The parameters of HTS PMSM and conventional PMSM are listed in Table 1 and Table 2 respectively. In simulation, the stator resistance of conventional PMSM is increased by 50%, and the controller uses the nominal R described in Table 2, and the equivalent stator resistance R of HTS PMSM is proportional to the operating speed as Eq. (4), the controller uses a null R. Figure 11 shows the simulation results of the conventional PMSM and the HTS PMSM operated at full load and different speeds respectively. Obviously, the stator flux linkage locus of conventional PMSM deviates from the ideal locus and the deviation is larger with speed lower. Consequently the torque increasingly vibrates that will result in speed vibration as well. On the other hand, there is nearly no deviation appeared on the stator flux linkage locus of HTS PMSM, and no vibration on torque either (increasing of torque ripple with operating speed decreasing is not the vibration) at all operating speeds. Therefore, the DTC of HTS PMSM is much more robust and its stability is not sensitive to the operating speed.

6. Conclusions
In this paper, the numerical assessment of an HTS PMSM and conventional one in terms of efficiency and stability of DTC is presented. The proposed HTS PMSM is more efficient, particularly at low speed. DTC of HTS PMSM will be more robust due to smaller and speed proportional resistance in HTS armature winding. To obtain the more precise result, the experimental assessment is necessary. The practical test of the proposed HTS PMSM will be processed soon.

![Figure 10. The classic DTC scheme of PMSM.](image)

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<th>Table 2. Parameters of a 12kW conventional PMSM.</th>
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Figure 11. Effect of stator resistance variation on stability of DTC (flux linkage and torque): (a) conventional PMSM, 50% increased R, 1500 rpm, (b) conventional PMSM, 50% increased R, 500 rpm, (c) conventional PMSM, 50% increased R, 300 rpm, (d) HTS PMSM, 1500 rpm, (e) HTS PMSM, 500 rpm, (f) HTS PMSM 300 rpm. (red: ideal value; blue: actual value).

References


