Application of High Temperature Superconductor (HTS) to Improve Starting Torque of Three Phase Induction Motor

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Abstract: Efficiency and starting torque are two basic performance criterias of three phase induction motor. Conventionally deep bar rotor or double cage rotor have been used to increase the starting torque of the induction motor. Effective resistance of the deep bar rotor and double cage rotor varies from starting to full load operation. This paper presents application of High Temperature Superconductor (HTS) material in rotor bars and end rings to increase the efficiency and starting torque. Finite element analysis (FEA) is carried out using HTS material in rotor bar and end rings. Performances of 2.2 kW, 415 V, 1440 rpm three phase induction motor using HTS in rotor is compared with the standard induction motor with same volume and specifications. Starting torque is increased by 46.6 % due to application of HTS in end ring and the same is increased by 89.5 % due to application of HTS in end ring as well as rotor bar of induction motor.

Keywords: High Temperature Superconductor (HTS), Finite Element Analysis (FEA), Induction Motor Design.

I. INTRODUCTION

Electrical motors are extensively used in domestic and industrial applications. Electrical motors are an important part of any electrical system because they consume about 65% to 70% of all electricity generated. Among all the motors, induction motors are the most widely used electric motors in all applications. It offers reasonable performance, low maintenance, robust construction, a manageable torque-speed curve, stable operation under load and satisfactory efficiency. Starting torque of three phase induction motor is comparatively low due to poor power factor at starting. In order to enhance performance of three phase induction motor, starting torque should be improved. Resistance of rotor winding is controlled in double cage motor conventionally. Torque speed characteristic and overall performance of induction motor can be significantly improved with the application of HTS material in rotor.

During starting the rotor current of induction motor is high and frequency of induced voltage in rotor is high. This makes HTS tapes quench at the starting of induction motors. Therefore high starting torque can be obtained. As the speed of rotor builds up, HTS tapes which are used as shorted bars become superconducting state again because current and frequency of the rotor circuit decrease gradually. After the HTS tapes recover from quench, resistance of the rotor circuit is completely zero provided the joint resistance between short bars and short rings is neglected. In that case, power loss in rotor circuit which is generated in conventional induction motors is eliminated. In HTS induction motors, large current in rotor circuit can be induced at very low slip because of no resistance. Motor operates at very minimum slip for wide range of load [1`]. A 2.2 kW, 415 V, 1440 rpm three phase standard induction motor motor is designed and analyzed first. The same motor is designed using HTS material in end ring and starting characteristic is analyzed. The same motor is designed using HTS material in end ring as well as rotor bar and starting characteristic is analyzed too. It is observed that starting torque in increased significantly due to application of HTS material.

II. DESIGN OF STANDARD THREE PHASE INDUCTION MOTOR

The main purpose of designing an induction motor is to obtain the complete physical dimensions of all the parts of the machine and performance estimation to satisfy the customer specifications. Following are important design stages:

- A .Main dimensions calculation
- B. Stator design
- C. Rotor design
- D. Performance estimation.

KVA rating of machine of a 3- phase induction motor,

$$Q = 3E_{Ph} \times I_{Ph} \times 10^{-3} \quad kVA \tag{1}$$

Where,
E_{ph} =Induced emf per phase.
I_{ph} =Current per phase.
The output equation of 3-phase induction motor is,

$$Q = C_0 D^2 L n_s \quad kVA \tag{2}$$

$Where, C_0 = Output\ Co-efficient = 11\times 10^{-3} B_{av}\, ac\, K_w$ ¦
B_{av} = Specific magnetic loading
Ac = Specific electric loading
L= Stack length
D = Stator bore Diameter
K_w =Winding Factor
n_s= Synchronous speed in r.p.s.
from equation (2)

$$D^2 L = \frac{Q}{C_0 n_s} \tag{3}$$

D and L are calculated based on assumed ratio between axial length to pole pitch. Dimensions of magnetic circuits are calculated based on flux and permissible flux densities of magnetic materials used in various sections of motor. Numbers of turns per phase are calculated according to voltage rating and conductor size is calculated according to current rating and assumed current density. Performance estimation is carried out considering design details. Algorithm is developed for computer aided design (CAD) of three phase induction motor [3]. Design of 2.2 kW, 415 V, 50 Hz, 4-pole, 3-phase induction motor using M19 magnetic material is done and CAD output is shown in Table I.

TABLE I CAD OUTPUT

Stator outer diameter(mm)	206.1
Stator inner diameter(mm)	105
Number of turns	427
Conductor's cross section area(mm^2)	0.674
Depth of stator core(mm)	13
Width of stator teeth(mm)	7
Stack length(mm)	125
Length of air gap(mm)	0.43
Total loss(kW)	0.488
Output power(kW)	2.2
Input power(kW)	2.688
Full load efficiency (%)	81.83

Finite element analysis is carried out to validate CAD procedure. FEA results are shown below.

TABLE II FEA RESULT

Stator outer diameter(mm)	206.1
Stator inner diameter(mm)	105
Number of turns	427
Conductor's cross section area((mm^2)	0.674
Depth of stator core(mm)	13
Width of stator teeth(mm)	7
Stack length(mm)	125
Length of air gap(mm)	0.43
Total loss(kW)	0.490
Output power(kW)	2.2
Input power(kW)	2.68
Full load efficiency (%)	81.80

A comparison of CAD and FE results is given in Table III. It is observed that the results are within the acceptance tolerance; however, the minor difference between the two can be attributed to the empirical design coefficients and formulae used in the CAD program.

TABLE III A COMPARISON OF CAD AND FEA RESULTS

Performance	**CAD**	**FEA**
Full load efficiency (%)	81.83	81.80
Power factor	0.80	0.814
Total loss(kW)	0.488	0.490
Output power(kW)	2.2	2.2
Input power(kW)	2.688	2.68
Flux density in stator core(Wb/m^2)	1.30	1.12
Flux density in stator teeth(Wb/m^2)	1.60	1.62
Flux density in rotor teeth(Wb/m^2)	1.30	1.35
Flux density in air gap(Wb/m^2)	0.45	0.44

Figure 1 shows the flux density plot of induction motor designed using M19 magnetic material. Flux densities in various sections is as per assumed flux densities.

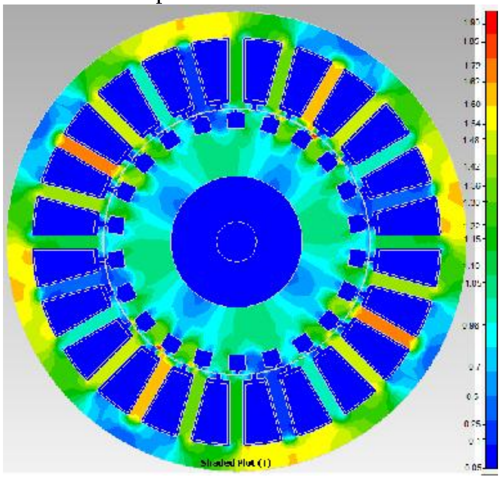

Fig.1 Flux density plot

III. GENERAL CONCEPTS OF SUPER CONDUCTORS

Super conductors are high current density conductors of electricity, until a critical temperature (T_c) or current level (ρ_c) is exceeded. There are generally two types of super conductors.

(1) Low temperature super conductor. The LTS has critical temperature T_c = 20K (-253ºC).

(2) High temperature super conductor. The HTS has critical temperature T_c = 90K (-183ºC).

Above T_c or ρ_c the superconductor "quenches" and becomes a "normal" conventional conductor.

Different types of HTS material

The development of superconductor rotating machines has been pursued since low temperature superconductors (LTS), which operate at 4 K, became available in the mid-1960s. The small thermal margin and the complex and expensive cooling systems of these early LTS devices prevented market acceptance. It was not until the advent of HTS, which operate at 30-40 K and have simpler cooling systems that economically viable superconductor rotating machines became possible [2]. In the last few years, a number of HTS rotating machines have been demonstrated in the US and Europe and several other projects are currently in advanced development stages. Today, large, high-torque ship propulsion motors (36.5 MW, 120 RPM), large turbo-generator prototypes (100 MVA, 3600 RPM) and grid stabilization devices (10 MVAR, 1800 RPM dynamic synchronous condensers) are under development and are expected to become commercially available over the next 1 to 3 years. High power density, better starting torque, higher efficiency and greater durability are benefits driving the development of these HTS machines.

Bi-2223: "First Generation Wire"

The high temperature superconductor $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$, commonly called Bi-2223, is the commercially available HTS wire, which is known as first generation (1G) HTS wire. The composite structure of 1G HTS wire is composed of 30% to 40% Bi-2223 embedded in a silver alloy matrix. The maximum current density corresponds to an engineering critical current density of close to 18,000 A/cm^2, and high critical current density (j_c) of 45,000 A/cm^2. Bi-2223 wire also shows good performance in higher fields at lower temperatures.

Bi-2212 Wire

A Bi-2212 round wire of high critical current density (j_c) in high magnetic field has been developed. It can carry more than 200 kA/cm^2 in a magnetic field of 10 T and 180 kA/cm^2 in a magnetic field of 20 T at 4.2 K, which exceeds the current-carrying capability of all conventional metallic superconductors.

YBCO Wire

The high temperature superconductor $YBa_2Ca_3O_{7-x}$, which is called as YBCO, is the second generation (2G) superconducting material. This YBCO is the alternative to Bi-2223 1G HTS material. The cost of 2G wire is expected to provide similar or improved electrical properties at 2-5 times lower than 1G HTS wire.

IV. APPLICATION OF HTS IN INDUCTION MOTOR

2.2 kW, 415 V, 1440 rpm three phase induction motor is designed using HTS in rotor bar and end rings keeping same design variables. The FEA is carried out for standard induction motor and induction motor using HTS.

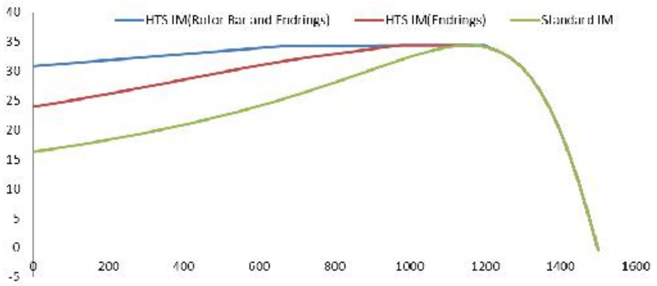

Fig. 2 Comparison of starting torque
(X axis: 1 cm= 200 rpm, Y axis: 1 cm= 5 Nm.)

The above graph shows that by inserting the HTS material in place of conventional copper in end rings of induction motor, the starting torque of the motor is increased form 16.3 Nm. to 23.9 Nm. With the application of HTS material in end rings as well as rotor bar, starting torque is increased form 16.3 Nm. to 30.9 Nm. The comparative FEA is carried out for the same motor and results are shown below table.

TABLE IV FEA RESULTS USING HTS MATERIAL

Motor Parameters	**Standard IM**	**HTS IM (end rings)**	**HTS IM (Rotor bars and end rings)**
Torque (N.m.)	15	15	15
Starting Torque (N.m.)	16	24	31
Output (kW)	2.2	2.2	2.2
Input (kW)	2.67	2.66	2.65
Copper Losses (kW)	0.343	0.333	0.323
Iron Losses (kW)	0.130	0.130	0.130
Efficiency (%)	82	82.5	83

V. CONCLUSION

Starting torque is one of the important performance parameter of induction motor. Deep bar rotor and double cage rotor are conventional techniques used to improve starting torque. Application of HTS material is recent technique. FEA is carried out using HTS conducting material in place of normal copper in rotor bar and end ring keeping other design parameters same. It is observed that starting torque is significantly improved due to application of HTS material and efficiency is marginally improved.

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BIOGRAPHIES

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