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Simulation of High Temperature Superconducting Hysteresis Motor using MATLAB and COMSOL Multiphysics

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Abstract

In this paper, a 2-pole, 50 Hz high temperature superconducting hysteresis motor has been numerically simulated using finite element method for its performance calculation. In this high temperature superconducting hysteresis motor, conventional copper winding is used in stator and the rotor consists of high temperature superconducting material which possess higher flux density consequently current density gets increased and the developed power also gets increased. To reduce the huge investments, errors and computational time for this work, numerical simulations are preferred over practical experiments. The performance parameters are compared with that of the conventional hysteresis motor in which ferro-magnetic material is used as a rotor. All the simulations are performed using MATLAB and partial differential equation based module of COMSOL Multiphysics software with proper boundary conditions. The simulation result shows a good agreement with the experimental results.

"1. Introduction"

Hysteresis motor is special type of synchronous motor with uniform air gap and there is no dc excitation in the rotor because of the magnetic material used in the rotor. Initially the rotor starts rotating due to the combined effect of hysteresis and eddy currents induced in the rotor. The mechanical torque of this motor is produced in the hardened steel rotor by the action of rotating m.m.f. of the stator winding. The torque is proportional to the area of hysteresis loop. The rotor of hysteresis motor has no winding, no teeth thus it has low noise operation. It has simple structure with conventional stator winding, light weight, high self-starting torque during the run-up, constant speed, moderate start up current that is usually 180% less than the full load current and also pulls wide range of loads with different inertia into synchronism [1-4]. These exclusive advantages make the hysteresis motor especially suitable for wide range of industrial applications such as ATM, air conditioner, entry verification, tele-printer, sound recorder etc. In spite of these advantages, the conventional hysteresis motor still suffers from some limitations. There are different techniques are available to improve performance of the machine. Therefore, improvement in magnetic property of the rotor using different types of rotor materials is one of the techniques. Several international research groups have explored the use of HTS materials in the construction of rotor of hysteresis motors [2], as superconducting materials has the ability to trap the magnetic field as high as possible and carries greater current density at higher magnetic field, high magnetic permeability, high saturation magnetization and low losses. Some exclusive superiority of superconducting synchronous machines over its conventional machines have better torque to volume ratio [1], reduced size and losses for the same power [3],[4]. Nowadays the applications of superconductors in rotating electrical machines are getting more importance, resulting in greater overall efficiency, increased current density, more power output, lower size and weight and better environmental impact. Hysteresis motor with high temperature superconducting rotor instead of rotor with conventional ferromagnetic material has been proved to be the most viable electrical machines with HTS material [4]. In conventional ferromagnetic material hysteresis is a non-linear magnetic property whereas in high temperature superconductors it is an ohmic property and related with the vortices dynamics [4].

The object of this investigation is to design a hysteresis motor with high temperature superconductor in the rotor. The studies of this type of motors through experiments involve huge cost, computational time, errors etc. Therefore finite element based simulation techniques are opted here. Because it is much cheaper to design, simulate and correct the exact model in the computer than to build the real model with mistakes. The results are simulated through the program written in MATLAB and using FEM based software COMSOL Multiphysics.

"2. Modeling of hysteresis motor"

2.1. Conventional hysteresis motor

The stator of hysteresis motor consists of copper winding and it is used to create the rotating magnetic field that drags the rotor. The rotor is made up of hard iron ring with a high degree of magnetic hysteresis. In this case motor shaft is made up of paramagnetic material [4]. The layout of hysteresis motor is shown in Figure (1).

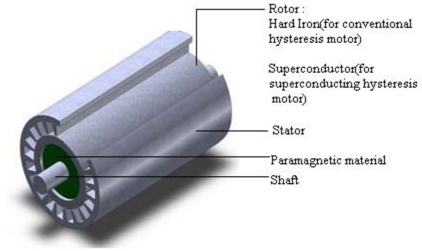

Figure 1. Hysteresis motor layout [4].

2.2. Proposed high temperature superconducting hysteresis motor

Superconducting hysteresis motor is almost identical with conventional hysteresis motor but its rotor is constructed from HTS materials (YBCO). In this motor, stator consists of conventional copper conductors. However, the rotor core is made up of paramagnetic materials, aluminum is used as a paramagnetic material, they provide the mechanical support to the HTS elements [2] and the shaft consists of paramagnetic material such as steel. The cross-sectional view of HTS hysteresis motor is shown in Figure (2). Due to the brittle nature of YBCO materials, a single superconducting cylinder cannot be constructed. So the segments are assembled with non-magnetic materials [2], [4] Figure (3). For large shielding, more segments are advantageous [5]. If the numbers of the circular sectors are increased, the flux distribution inside the HTS rotor is also increased because of the presence of paramagnetic materials between them. But the numbers of circular sectors are limited otherwise flux leakage increases and thus the developed torque of the hysteresis motor will decrease Table (1) with increase of the number of sectors [2].

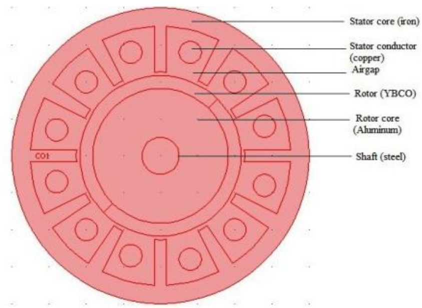

Figure 2. Cross-sectional view of HTS hysteresis motor.

Figure 3. Segmented HTS hysteresis rotor, with two or four segments [4].

Table 1. Analytical high field limits of torque [5]

Number of segments, n	High field torque limit/ Tmax

1	1
2	1
3	0.51
4	0.42
6	0.28
8	0.22

"3. Problem formulation"

The alternating current of different magnitudes is applied in the non-HTS stator of a high temperature superconducting hysteresis motor and thus the rotating magnetic field is produced in the air-gap and trapped field produced in the HTS rotor due to high current carrying property. Then the various parameters of a HTS hysteresis motor are calculated using finite element method that provides a wide range of simulation options for controlling the complexity of both modeling and analysis of a system and similarly, the desired level of accuracy required and associated computational time requirements can be managed simultaneously to address most engineering applications [6]. The simulations are done using MATLAB and finite element method based COMSOL Multiphysics software.

3.1. Formulation of electromagnetic problem

It is known that E-H formulation is the most useful expression of an electromagnetic field [7]. Therefore, the basic electromagnetic equation for the HTS hysteresis motor is expressed as

$$\nabla \times E = -\mu \frac{\partial H}{\partial t}$$

Where, E is electric field vector [V/m] and μ is magnetic permeability of the materials [H/m].

Therefore,

$$\nabla^2 H - \mu\sigma \frac{\partial H}{\partial t} = 0$$

Here, H is magnetic field vector [A/m].

"4. Simulation and results"

The HTS hysteresis motors are numerically simulated using finite element method based software COMSOL Multiphysics that internally compiles a set of PDEs representing the entire model and also provides tools for plotting and post-processing any model quantity or parameter such as surface plot, contour plot, stream-line plot, cross-section plot and animation etc [8],[9]. The specifications of the high temperature superconducting material used in the rotor of the HTS hysteresis motor is shown in Table (2).

Table 2. Specifications of the HTS material used in the rotor.

Name of the sample	YBCO
Outer radius(mm)	21.7

Inner radius(mm)	18.2
Thickness(mm)	3.5
Critical current density(A/m^2)	4×10^7
Critical electric field(V/m)	10^{-4}
Initial Conductivity (S/m)	10^{16}

For the simulation of the HTS hysteresis motor, time dependent solver parameter is used. Where the time stepping is 0:0.001:0.02 (second) and the relative and absolute tolerance is 0.001 second. Figure (4) shows the cross-sectional view of a HTS hysteresis motor and Table (3) gives the geometric data of a HTS hysteresis motor. In Figure (4), C1 is stator outer radius, C2 and C3 is outer and inner radius of HTS rotor respectively, C4 is shaft radius and C5 is the copper conductor radius respectively.

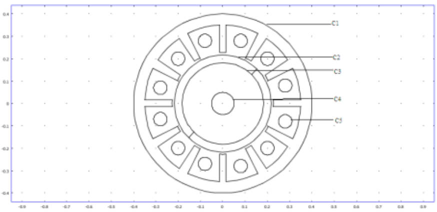

Figure 4. Cross-sectional view of HTS Hysteresis Motor in COMSOL MULTIPHYSICS.

Table 3. Geometry of a HTS hysteresis motor in COMSOL Multiphysics

Name	Radius (mm)	Base	(X,Y)
C1	40	Centre	(0,0)
C2	21.7	Centre	(0,0)
C3	18.2	Centre	(0,0)
C4	5	Centre	(0,0)
C5	3	Centre	(0,0)

To discretize the HTS hysteresis motor into finite elements, mesh statistics are applied. From this mesh statistics Table (4), various parameters are known. Figure (5) shows the mesh of a HTS hysteresis motor.

Table 4. Mesh statistics of HTS hysteresis motor

Mesh statistics	2-dimensional
Solver	Time dependent solver
number of elements	17432
number of degree of freedom	34754
number of boundary elements	1234
solution time	26.219 s
Processor	Intel(R) Core(TM)2Quad @2.50GHz

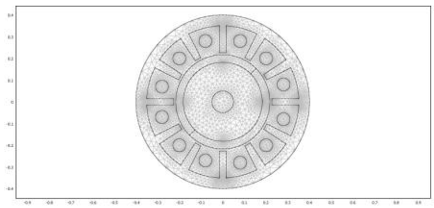

Figure 5. Mesh of a HTS hysteresis motor.

The solution time is changed due to change in the values of various parameters but the number of elements and number of degrees of freedom will remain same unless the geometry is changed. Dirichlet condition is applied in the outer boundary and shaft and Neumann condition is applied in other boundaries.

4.1. Magnetic flux distribution in HTS hysteresis motor

The surface plot of electric field (V/m) in a HTS hysteresis motor is shown in Figure (6). It is observed that two poles have been created. The stator current produces rotating field in the air gap between the stator and the rotor, which in turn induces currents in the superconductor and the HTS rotor is magnetized. Due to the high current leading ability, most of the fluxes are trapped in the HTS hysteresis rotor. This phenomenon is shown in the plots of magnetic flux density (B) of a HTS hysteresis motor in Figure (7) and magnetic field (H) plot of HTS hysteresis motor in Figure (8). It is observed that the magnetic flux distribution is maximum inside the HTS rotor compared to the other region.

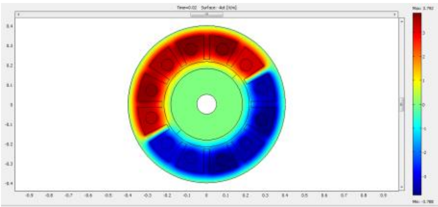

Figure 6. Electric field of a HTS hysteresis motor.

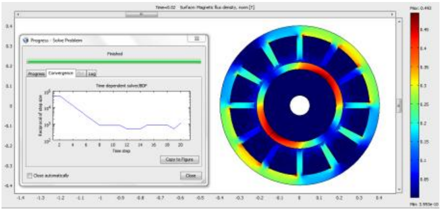

Figure 7. Magnetic flux density of a HTS hysteresis motor.

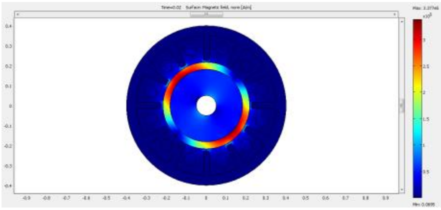

Figure 8. Magnetic field of a HTS hysteresis motor.

4.2. Effects of applied current on torque of a HTS hysteresis motor

The torque in hysteresis motor is calculated using the relation, $T = \left(\frac{1}{2\Pi}\right) P V_r A_h$, [10],[11]

where, P is number of pole pairs, V_r is volume of the HTS rotor and A_h is area of the hysteresis loop in the HTS rotor. MATLAB program has been developed to draw the torque in the motor. As shown in Figure (9), the torque changes almost linearly with the applied current, that is the common feature of any hysteresis motor [10]. The simulation result shows a good agreement with the experimental results [11],[12].

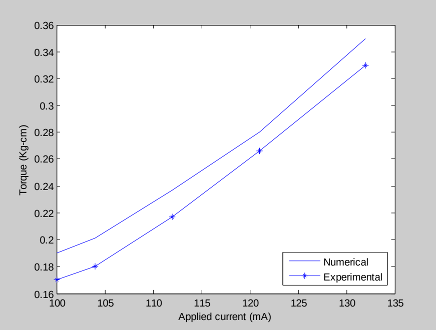

Figure 9. Simulation and experimental results of torque vs. current plot of a HTS hysteresis motor.

"5. Conclusion"

In this paper, modeling of high temperature superconducting hysteresis motor is presented and numerically simulated using MATLAB and COMSOL Multiphysics and then compared with the experimental results of conventional hysteresis motor. All the simulation results are verified with the experimental results. So the application of MATLAB and COMSOL Multiphysics software for performance calculation of hysteresis motor with high temperature superconducting element in the rotor is justified and helps in the numerical analysis of various parameters with different geometrical configurations.

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