

Electromagnetic Analysis of Hysteresis Synchronous Motor Based on Complex Permeability Concept

S. M. Mirimani*, A. Vahedi*, M. R. Ghazanchaei* and A. Baktash*

Abstract: Hysteresis motor is self-starting synchronous motor that uses the hysteresis characteristics of magnetic materials to make torque. There are different methods to model this kind of motor and take into account the magnetic hysteresis characteristic of the rotor hysteresis ring. In this investigation the application of complex permeability concept is implemented to model the hysteresis loop and the hysteresis loop in inclined ellipse shape is adopted. To the best knowledge of the authors, this has not been studied before. Based on this concept, simulation of hysteresis motor in conventional configuration is done in order to obtain the output values of motor using 3D Finite Element Model (FEM). This 3D finite element model has high level accuracy and gives better insight of motor performance. Meanwhile, in order to validate the simulation results an experimental set-up is provided and the output values of typical motor are measured. It is shown that there is a good agreement between experimental and simulation results.

Keywords: 3-D Finite Element Method, Complex Permeability, Hysteresis Motor.

1 Introduction

Hysteresis motors have some good characteristics such as soft torque, simple construction with conventional three phase stator windings and self-starting torque. These advantages make the hysteresis motor suitable for some applications such as compressors, pumps, timing, and recording equipment. Although, hysteresis motor in contrast to Permanent Magnet Synchronous Motor (PMSM) has lower output power per unit volume, lower power factor and efficiency and higher magnetizing current [1]. But limitation such as zero starting torque, needs to auxiliary winding for line starting and closed loop control systems have confined the usage of PMSM for special applications. Hysteresis motor overcomes these limitations by using the hysteresis characteristics of the magnetic materials. It should be noted that the magnetic characteristics of the motor could be easily affected by hysteresis material, structural dimensions and winding distributions [2]. To have a good designing for these parameters of machine, it would be desirable to adopt an accurate model for the motor. Analytical methods have been used to study the hysteresis motors frequently. However, these methods are very complex when accurate evaluation of the saturation effects, and

stator and rotor slotting is needed. These problems are overcome by applying numerical methods. Finite element method allows a precise analysis of magnetic devices taking into account geometric details and magnetic nonlinearity. In previous studies, 2D finite element (FEM) techniques for simulating of hysteresis motors have been developed [2-4].

In this paper, the performance characteristics of hysteresis motor through a 3D finite element analysis (FEA) are provided. 3D model has high level of accuracy and gives us a better insight of motor characteristics. Such simulation is based upon Maxwell's field equations considering the case of a circumferential flux type machine at synchronous speed. There are mainly three methods to take into account the magnetic hysteresis of the rotor hysteresis ring. One is based on the approximation of a parallelogram [5] and the second one is the Preisach model [2, 6, 7] and the last one is based on elliptical model [8]. In this study, the application of complex permeability concept is implemented in order to model the hysteresis loop in the shape of inclined ellipse. To the best knowledge of the authors, this has not been studied before.

Finally, in order to validate the simulation an experimental set-up is provided and output characteristics of conventional hysteresis motor are measured. There exists a reasonably close agreement between the FEM results and experimental set-up output characteristics. Furthermore, this study can be used in the design approach and precise analysis of hysteresis motors.

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2 Structure and Winding Configuration

Hysteresis motor is a kind of special motor with outstanding structural features. This type of motor has not slot on its rotor and the rotor structure is quite simple. The structure of a typical two pole hysteresis motor is shown in Fig. 1. The inside surface of the stator has teeth and slots and the conventional three phase windings is implemented in stator. Rotor is generally designed as a cylindrical type motor and made up of two parts. Firstly, hysteresis ring which is the basic element for the torque providing that is made of semi hard magnetic material and can conduct flux circumferentially. Secondly, the hysteresis ring holder; which almost is made of the nonmagnetic material such as aluminum and its alloys. This part of rotor has not any effect on the torque providing and only is the copulative between the rotor and the motor shaft.

3 FEM Model

Since the presentation of the theory of hysteresis torque by Steinmetz in 1908, many authors analyzed the hysteresis machine based on the approximation of representing the hysteresis loop. The hysteresis loop was replaced by inclined ellipse by Teare, Roberts, Miyairi and Robertson in their analysis of the hysteresis motor.

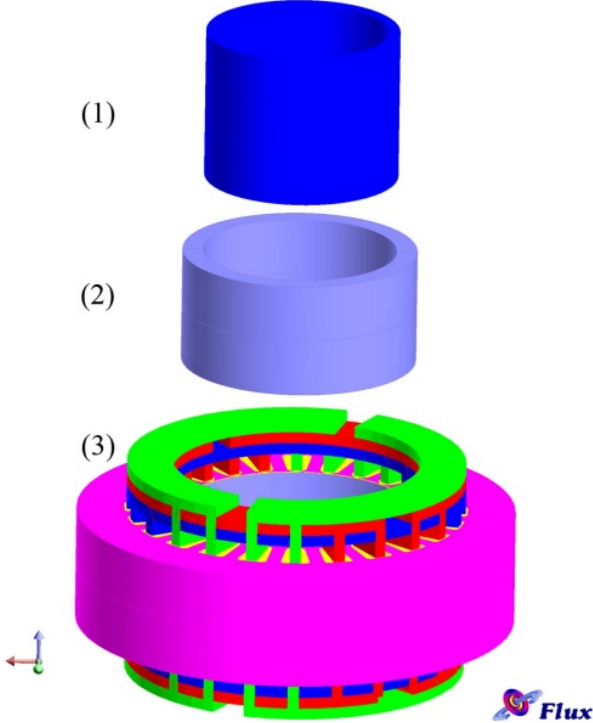


Fig. 1 different parts of hysteresis motor (1) Holder, (2) Hysteresis ring, (3) Stator and winding

In this study, a complex permeability is used to predict the hysteresis loop in hysteresis motor for first time. The aim of the following discussion is to investigate the validity of such application. A useful tool for dealing with magnetic effects is the complex permeability. While at low frequencies in a linear material the magnetic field and the auxiliary magnetic field are simply proportional to each other through some scalar permeability, at high frequencies these quantities will react to each other with some lag time [9]. These fields can be written as phasors, such that:

$$H = H_0 e^{j\omega t} \quad , \quad B = B_0 e^{j(\omega t - \delta)} \quad (1)$$

where δ is the phase delay of B from H . Understanding permeability as the ratio of the magnetic field to the auxiliary magnetic field, the ratio of the phasors can be written and simplified as:

$$\mu = \frac{B}{H} = \frac{B_0 e^{j(\omega t - \delta)}}{H_0 e^{j\omega t}} = \frac{B_0}{H_0} e^{-j\delta} \quad (2)$$

So that the permeability becomes a complex number. By Euler's formula, the complex permeability can be translated from polar to rectangular form:

$$\mu = \frac{B_0}{H_0} \cos \delta - j \frac{B_0}{H_0} \sin \delta = \mu' - j\mu'' \quad (3)$$

The ratio of the imaginary to the real part of the complex permeability is called the loss tangent:

$$\tan \delta = \frac{\mu''}{\mu'} \quad (4)$$

which provides a measure of how much power is lost in a material versus how much is stored.

Fig. 2 helps us to exploit desired parameter as a function of H_{max} , H_c and B_{max} [9, 10].

$$|\mu_r| = \frac{\mu}{\mu_0} = \frac{B_{max}/H_{max}}{\mu_0} \quad (5)$$

$$\delta = \sin^{-1} \left(\frac{H_c}{H_{max}} \right) \quad (6)$$

$$\mu_r' = |\mu_r| \cos(\delta) \quad (7)$$

$$\mu_r'' = |\mu_r| \sin(\delta) \quad (8)$$

where δ is hysteresis lag angle between flux density and magnetic field intensity, μ_r is the relative permeability, μ_r' and μ_r'' are the real and imaginary parts of complex permeability.

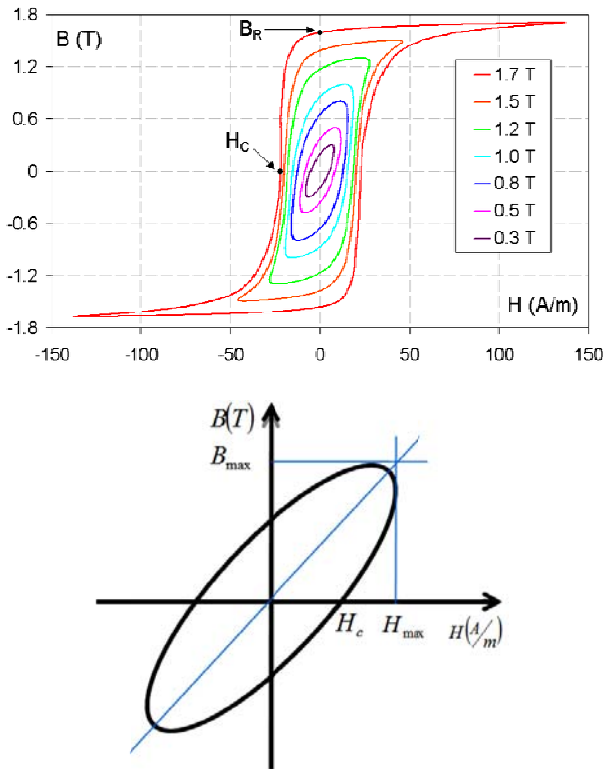


Fig. 2 Inclined hysteresis loop approximation

As shown in Fig. 2, for a hysteresis material there is different hysteresis loop. In order to choose an accurate loop regarding to magnetic circuit that hysteresis material is in, an iteration method is used that is illustrated with a flow chart in Fig. 3. In the first iteration, a random hysteresis ring is selected. So, all the hysteresis ring elements have the arbitrary permeability. From the FEA, the maximum flux density for the circumferential direction in the hysteresis ring region can be obtained. Now, the maximum flux density obtained from FEA is checked with previous value and this procedure continues until the convergence criterion is satisfied. If the analysis is completed, torque of motor can be evaluated. It is so important to select an accurate hysteresis loop since the output torque of the motor is proportional to the area of hysteresis loop [10] regarding Eq. (5).

$$T = \frac{1}{2\pi} p \cdot V_r \cdot E_h \quad (9)$$

where, p is number of pole pairs, V_r the hysteresis ring volume and E_h is the area of hysteresis loop. It is seen that this procedure is so accurate and hysteresis loop modeling with complex permeability has close agreement with real motor tests. As mentioned before, a 3D finite element model is implemented in order to simulate of proposed motor. This 3D model has high level of accuracy and gives us a better insight of motor performance [9]. Finite element method is based on

Maxwell's equations. The following Maxwell equations are relevant to steady state applications [11].

$$\nabla \times H = J, \quad (10)$$

$$\nabla \cdot B = 0, \quad (11)$$

$$B = \nabla \times A. \quad (12)$$

In order to have high level of accuracy the automatic mesh diagram is not used and a mesh diagram is designed manually. Pentagon element in stator and hexagonal element is used in rotor in order to constitute the mesh diagram. The total number of nodes is about 90000 that lead to high level of accuracy. Meanwhile, for boundary conditions, the homogenous Dirichlet condition is adopted on the infinite box that encompasses the motor. This simulation is based on circuit coupled model that the phase voltage is the input quantity. Fig. 4 shows the circuit coupled model that is used in this study.

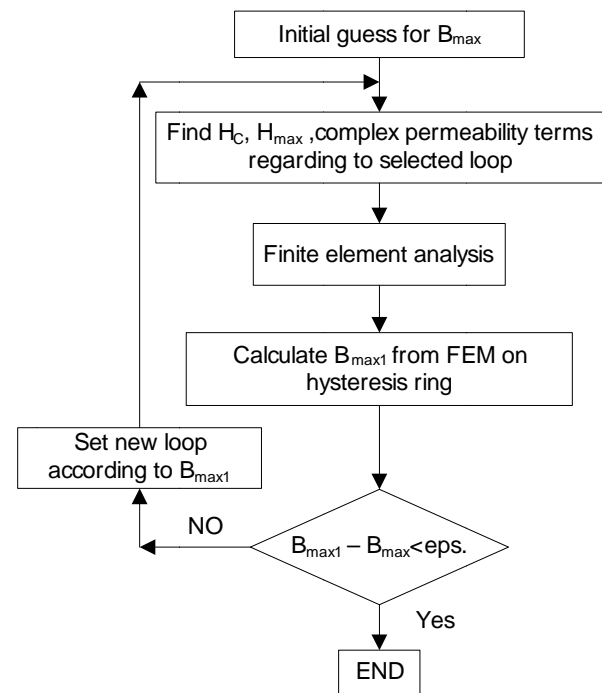


Fig. 3 Flow chart for accurate hysteresis selection

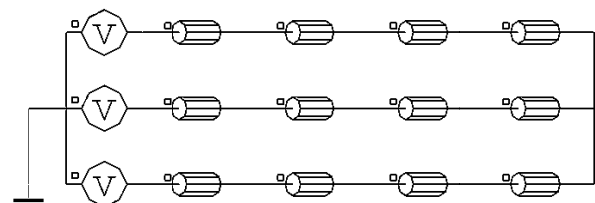


Fig. 4 Circuit coupled model used in simulation

4 Experimental Set-Up

The tests have been done on a prototype circumferential hysteresis synchronous motor that is shown on Fig. 1. The parameters of motor are given in Table 1.

In this set-up voltage, current are measured with a high resolution oscilloscope for a constant load with 0.011(Nm) torque. Output quantities of prototype motor are shown in Table 2.

5 Simulation Results

Based on the above respects, finite element simulation for prototype circumferential flux hysteresis motor has been done. It must be noted that half of the motor is analyzed because of the magnetic periodicity of the motor. Fig. 5 shows the mesh diagram of motor.

Table 1 Motor features

Quantity	Value
Line RMS voltage(V)	150
Rated phase current (A)	0.6
Frequency(Hz)	400
Speed(rpm)	24000
Phase connection	Y
Pole pairs	1
Holder thickness	1
Air gap length (mm)	1.5
Ring thickness (mm)	1
Outer diameter of stator(mm)	93
Inner diameter of stator(mm)	50.4
Stator stack height(mm)	25
Number of slots	24
Number of turns per coil	115
Fill factor	0.5
Phase resistance at 400Hz(Ω)	30

Table 2 Output quantities of prototype motor

Quantity	Hysteresis motor outputs
Steady state Load torque (Nm)	0.0110
Steady state current (A)	0.443
P input(Watt)	68.6
Power factor	0.596
Efficiency (%)	40.2

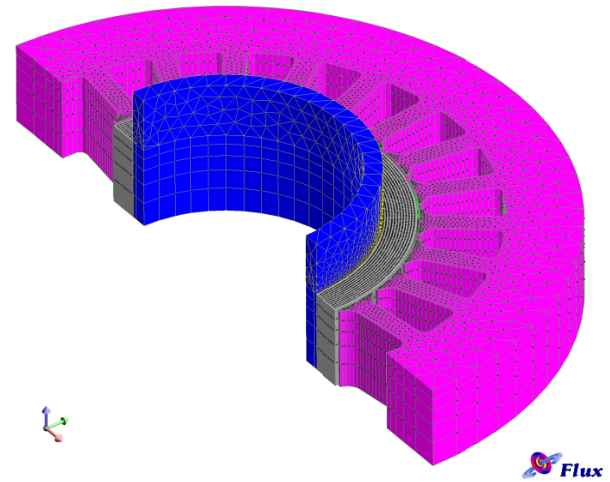
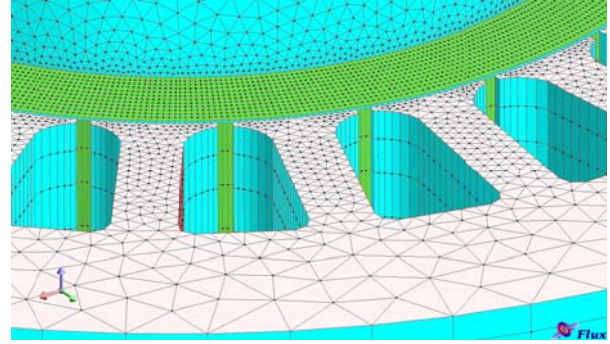


Fig. 5 Mesh diagram of simulated motor

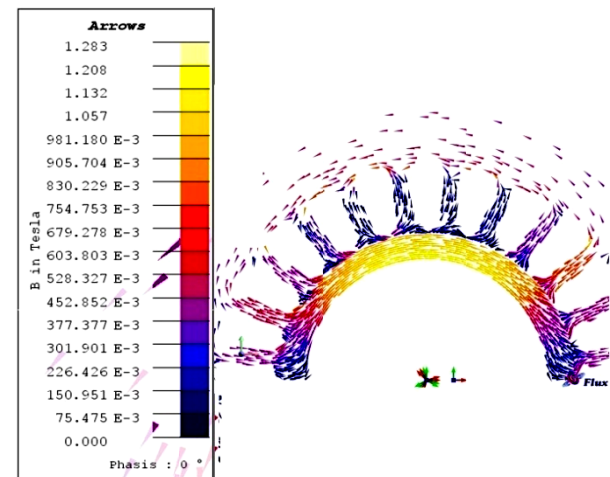


Fig. 6 distribution of the circumferential flux

Fig. 6 shows the flux density of motor. As said before, flux lines are circumferentially through the hysteresis ring.

Fig. 7 shows the isovalues diagram of flux density in Stator and rotor.

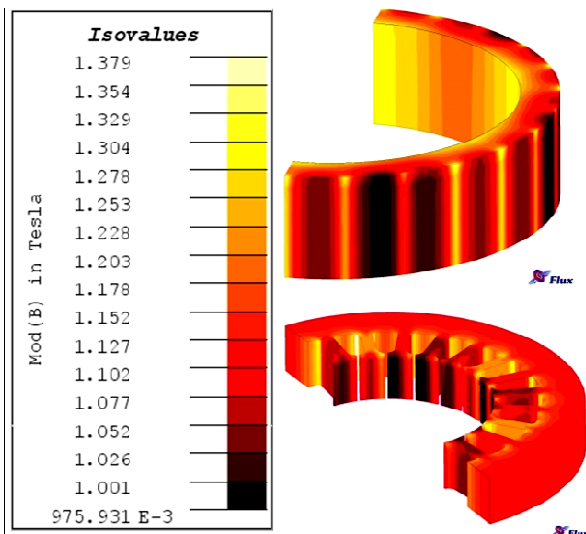


Fig. 7 Isovalues diagram of flux density of rotor and stator

Table 3 Simulation results for Hysteresis motor

Quantity	values
Steady state torque (Nm)	0.0112
Steady state current (A)	0.435
P input(Watt)	66.7
Power Factor	0.59
Efficiency (%)	42

As seen in Fig. 7, hysteresis ring at synchronous speed is exactly like a permanent magnet. Based on flux density distributions the output quantities of motor are obtained and shown in Table 3.

As seen from Tables 2 and 3, there is a close agreement between output quantities of actual motor and simulated one.

6 Conclusion

In this paper, a novel finite element analysis model is presented for accurate analysis of the hysteresis motor. The steady state characteristics of the motor were calculated. A hysteresis loop in an inclined ellipse shape is adopted to approximate the real hysteresis loop. An iteration method is implemented to model the accurate loop. The simulation based on dimensions of a typical motor is done. In order to investigate the accuracy of the model an experimental set-up is provided and output quantities of prototype motor are measured. It was shown that there is reasonably agreement between simulation results and motor quantities.

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