Design of Permanent Magnet Hysteresis Motors

J. Rizk, A. Hellany and M. Nagrial

Abstract— The hysteresis motor is so named because it is producing mechanical torque utilizing the phenomenon of hysteresis. The rotor of a hysteresis motor is a cylindrical tube of high hysteresis loss permanent magnet material without windings or slots. This paper presents the design of a hysteresis permanent magnet motor using the finite element method. The rotor of the machine consists of 36% Cobalt steel alloys with Neodymium Boron Iron permanent magnets. This hybrid motor combines the best performance features of both the typical permanent magnet motors and the conventional hysteresis motors. The finite element method is used to determine the dimensions of the optimal design.

***Keywords*— Hysteresis motors, Permanent magnets.**

I. INTRODUCTION

THE hysteresis motors have many advantages including self-starting, high starting and synchronising torque, constant speed, relatively noiseless operation and robustness of construction [1-4]. The hysteresis motors are generally used in applications requiring constant starting torque and precise speed operation. They are also used to drive loads having high moments of inertia, such as gyroscopes, since they develop their maximum torque during starting [5-6]. These are simple motors that are widely used for fixed frequency timing application such as clocks. There are two different kind of hard magnetic materials in the rotor: a hard magnet material with percentage of cobalt-steel alloys and the Neodymium Iron Boron (NdFeB) magnet (Fig. 1).

The hard magnet is a low coercivity material whose magnetisation state can be influenced by the armature-winding field. The hysteresis in its B versus H loop is used to create a phase difference between the armature winding and rotor magnet fluxes, which will always rotate in synchronism with the rotor lagging by the torque angle.

A simplified explanation of motor operation will assume infinite rotor resistance, that is, no induced rotor currents. The rotor MMF is directly proportional to the magnetic flux [7]. The stator voltage and the spatial flux distribution are nearly sinusoidal, since the applied voltage is sinusoidal. The crucial point is that an angle exists between the flux and the rotor MMF, and thus torque is developed. Significantly, this angle is determined by the hysteresis loop of the rotor material, and it remains constant throughout the acceleration period [8-10]. Also the flux per pole is primarily a function of the rotor material, and therefore it remains essentially constant.

Therefore the voltage induced in the stator windings is independent of rotor speed.

These advantages make the hysteresis motor especially suitable for applications, such as compressors, pumps, timing and recording equipment [11]. Hysteresis motors use the hysteresis characteristics of magnetic materials. It is known the magnetic characteristics of the motor could be easily affected by air gap length and structure dimensions variations [12-14].

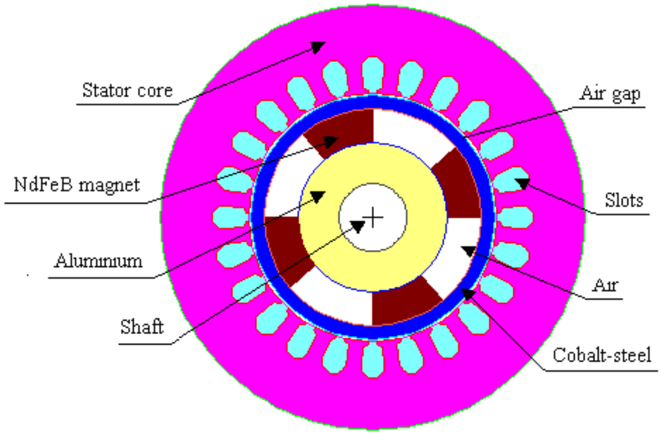

Fig. 1: Cross section of a PM / hysteresis motor

The outstanding special feature of a hysteresis motor is the production of nearly constant, ripple-free torque during starting. Hysteresis motors are widely used in synchronous motor applications where very smooth starting is required, such as in clocks and other timing devices and record-player turntables, where smooth starting torque reduces record slippage. Hysteresis motors are limited to small size by the difficulty of controlling rotor losses caused by imperfections in the stator mmf wave. A 3D finite element study [15] gave a high level of accuracy and a better insight of motor performance.

It is well-known that the hysteresis motors produces the torque by magnetic hystere sis. Because of this, it has many advantageous features including self-starting, high starting and pull- in torque, constant speed, low noise operation and robustness of the construction. However, there are the

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disadvantages including low output , low efficiency, and low power-factor [16].

II. TORQUE CALCULATION

The rotor supports a mechanical load torque that tries to slow the motor down. However, the flux linkage interaction between the stator and rotor provides energy to coerce the rotor to continue running at the stator excitation rate. The load torque is removing mechanical energy from the motor while the stator coils are injecting higher amount of electrical energy to compensate the mechanical energy and different losses. The motor has two sources of energy storage: electrical and mechanical. The electrical energy driving the motor is either stored in the magnetic field or dissipated as heat through the coil resistance.

The output energy of an electrical motor is a combination (multiplication) of the torque and the speed. The torque is in N. m and the speed is in rad/s.

The electrical energy (the input energy of the motor) is higher than the mechanical energy (the output) by the amount of the total energy losses in the machine.

It could be easy to work with power that is the time rate of the energy. Mechanical power is defined as force times velocity, so the motor's mechanical power will be torque times the angle rate:

$$Pm = T\, d\theta /dt \qquad (1)$$

Electric power equals current times voltage, and since voltage is the time rate of change of flux, electric power is:

$$Pe = I\, d\lambda /dt \qquad (2)$$

The total power stored in the motor is the difference between electric and mechanical power. This stored power is a differential function of λ and θ:

$$dW(\lambda,\theta)/dt = id\lambda - Td\theta /dt \qquad (3)$$

Since *dW/dt* is the stored power in the motor, it is easy to imagine that with added current or voltage, power would increase. On the other hand, if the rotor is allowed to torque, T, in the direction coerced by the magnetic field, then the stored energy is expended as kinetic energy so that *dW/dt* would decrease. That's why the mechanical power is negatively defined: it is the output of the motor. The expression for conservation of energy:

$$dW(\lambda,\theta) = id\lambda - Td\theta \qquad (4)$$

λ and θ are considered independent variables. Thus, energy *W* can be expressed as:

$$dW(\lambda,\theta) = id\lambda/dt - Td\theta/dt \qquad (5)$$

A partial differential equation could be concluded as:

$$dW(\lambda,\theta) = id\lambda - Td\theta \qquad (6)$$

And its solution is presented as the values for the current and the torque λ

$$i = dW(\lambda,\theta)/d\lambda \qquad (7)$$

$$T = - dW(\lambda,\theta)/d\theta \qquad (8)$$

$$dW(\lambda,\theta)/dt = id\lambda - Td\theta /dt \qquad (9)$$

In a very similar way, the co-energy W' is determined as

$$W' = \lambda i - W \qquad (10)$$

And the flux linkage and the torque are defined as

$$\Lambda = dW'(i,\theta)/d\lambda \qquad (11)$$

$$T = - d W'(i,\theta)/d\theta \qquad (12)$$

Expression 12 is the equation used to calculate the torque by calculating the flux linkage, λ, for the motor as a function of current *i* and θ.. Integrating the flux linkage to get the expression for co-energy and by the differential of the co-energy with respect to θ, the torque could be defined.

The finite element method (FEM) is a powerful numerical technique for obtaining approximate solutions to boundary-value problems of mathematical physics. Engineers and researchers use it as a tool to solve a wide range of problems.

The finite element method can be used to change the structure of the machine, the material properties, and the excitation in the rotor and/or in the stator of the machine. In finite element analysis, the energy derivative is obtained by the sum of the contributions from each element in the airgap to obtain the total torque.

III. SIMULATION RESULTS

This paper presents the results of using the finite element method in the design of PM hysteresis motors. The method is used in the design optimisation of the motor to obtain the optimum size of the hysteresis magnet material and of Neodymium Iron Boron (NdFeB) magnets. The finite element method is also used to determine the optimum permeability of the Cobalt-steel magnet material. The average magnetic flux density in the air gap B is used as the objective function for optimisation.

The rotor of the designed machine consists of an aluminium ring around the shaft, the hysteresis material and the Neodymium Boron Iron magnet [11]. The magnets are arranged within the hysteresis material. Moreover the Neodymium Iron Boron magnets are separated by 4 air gaps as shown in Fig. 1. The NdFeB magnet's size, the permeability and the thickness of the hysteresis magnet are the variable parameters for the optimal design. A standard stator frame for a 3-phase induction machine rated at 415 volts, 550W, 50 Hz, delta connected 4-pole is employed.

Firstly the variation of the magnetic flux density in the air gap B_g with variations of above mentioned three parameters is investigated. Then, depending on the sensitivity to the change of given parameter, the number of variations and the steps between subsequent variations are chosen. This procedure resulted in 15 different geometrical versions of the rotor. The results of these investigations are summarised in Fig. 2 to 4

a) *Influence of Magnet Length*

The magnetic flux density in the airgap is linearly proportional to the magnet length, which is not surprising because a wider magnet produce a higher magnet flux per pole. In comparison with other parameters, the length of NdFeB has the greatest influence on the magnetic flux density in the airgap. Fig. 2 shows how the magnetic flux density in the airgap is changed with increasing NdFeB length.

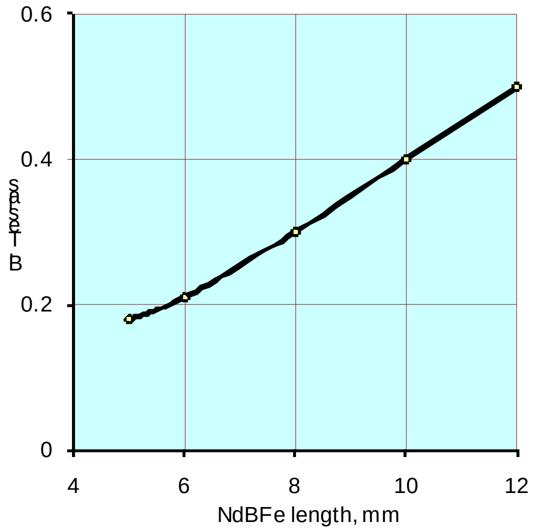


Fig. 2: Magnetic flux density versus magnet length

b) *Influence of Hysteresis Magnet Permeability*

Cobalt is a ferromagnetic metal with a specific gravity of 8.9. Pure cobalt is not found in nature, but compounds of cobalt are common. Small amounts of it are found in most rocks, soil, plants and animals. In nature, it is frequently associated with nickel, and both are characteristic minor components of meteoric iron. Cobalt has a relative permeability two thirds that of iron.

The finite element method is used to determine the optimal permeability of the hysteresis materials. Extensive simulations have been performed on a model of a hysteresis motor. The permeability is only the variable parameter while other parameters are kept constant. The optimal permeability of the hysteresis material is 18 (Fig. 3). The hysteresis material can be made of 36 % Cobalt-steel alloys.

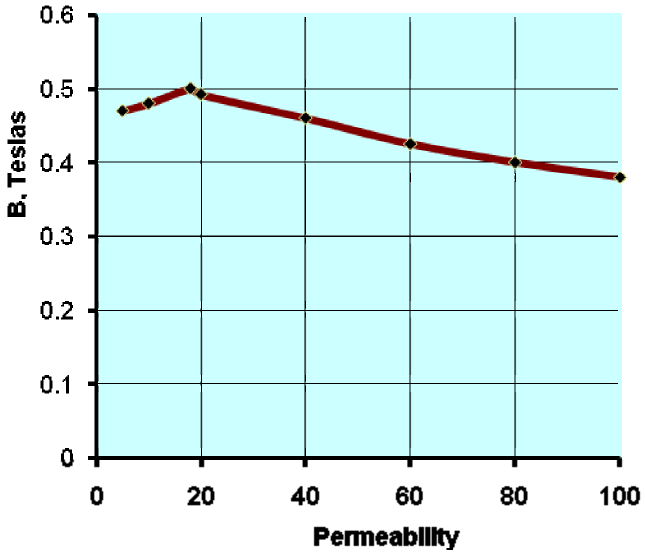


Fig. 3: B versus hysteresis material permeability

c) *Influence of Hysteresis Material Thickness*

The magnetic flux density (B) in the airgap of the hysteresis motor is slightly decreased with increasing the thickness of the hysteresis material (Fig. 4). The minimum thickness of the hard magnet material will be limited by the mechanical strength.

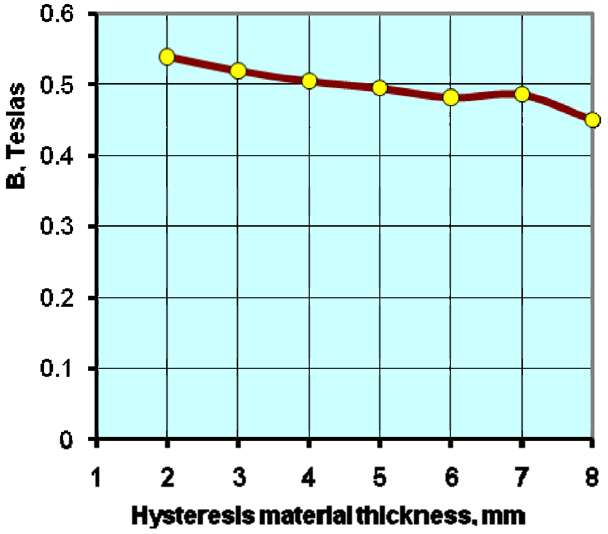
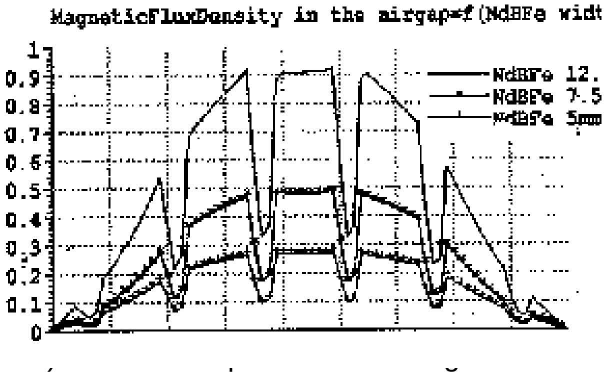


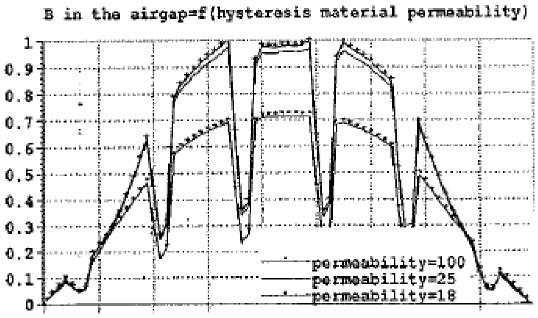
Fig. 4: B versus hysteresis material thickness

Fig.5 shows the magnetic flux density around the air gap of the machine with the variation of different design parameters. Only one pole is considered because of the symmetry.

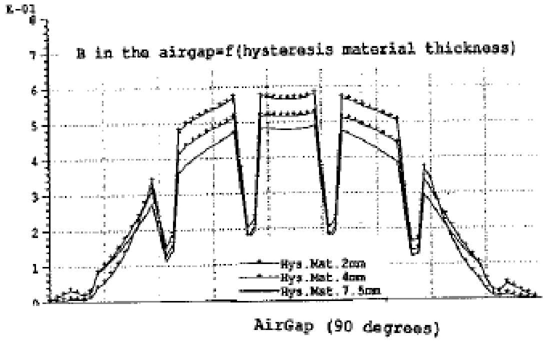
IV. FINAL ROTOR DESIGN

From the above studies, one could draw the following conclusions that in an ideal rotor the NdFeB should be as long as possible. The hard magnetic material should be as thin as possible and the permeability of the hard magnetic material should be about 18. Taking into account the result of a finite element analysis as well as the mechanical constrains the final optimal rotor design is shown in Fig. 6. Fig. 7 shows the distribution of the magnetic flux in the machine. The machine dimensions and design data are given in tables 1 and 2.





b) Function of hysteresis material permeability



c) Function of hysteresis material thickness

Fig. 5: Magnetic flux density versus different parameters

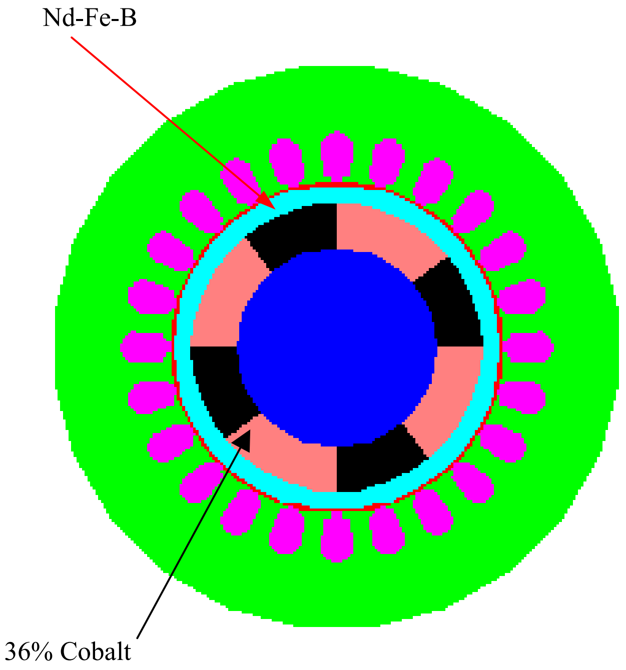


Fig. 6: Optimal Hybrid PM / hysteresis machine

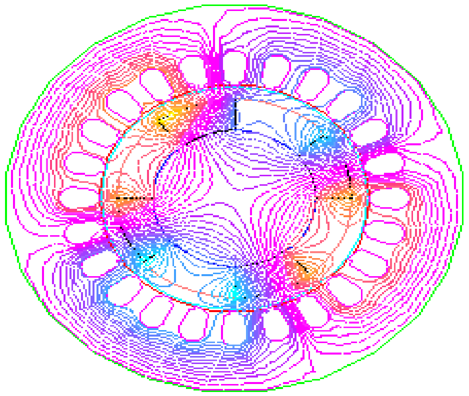


Fig. 7: Magnetic flux distribution in the motor

Table 1: Design dimensions of PM / hysteresis motor

Stator	
Stator inner diameter	63.0 mm
Core length	50.0 mm
Number of slots	24
Number of poles	2

Rotor	
Rotor outer diameter	62.2 mm
Thickness of rotor ring	15 mm
Hysteresis ring thickness	4 mm
Airgap length	0.4 mm

The pertinent properties of the rotor materials are given in Table 2

Table 2: Properties of hysteresis and permanent magnet materials

Properties	36% Cobalt steel	NdFeB
Hysteresis Loss (J/cycle/cm)	0.09	
Residual flux density (kG)	9.6	11.38
Coercive force (kOe)	0.24	10.84
Recoil permeability	18.0	1.07
Energy product (MGOe)	1.0	31.1

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