DESIGN AND CONSTRUCTION OF A SINGLE PHASE CLAW POLE PERMANENT MAGNET MOTOR USING COMPOSITE MAGNETIC MATERIAL

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Abstract

To investigate the application of composite magnetic material in electrical machines, a small single phase claw pole permanent magnet motor using this soft material as the stator iron core has been designed and constructed. Based on the three dimensional magnetic analysis the output performance, efficiency, power factor, output and cogging torque are computed.

1. Introduction

Small single phase AC motors are widely used in domestic electrical appliances. In general, these motors are of very low efficiency, typically 30%-50%. A lot has been done to improve the efficiency by using better motors and power electronic variable speed direct drives. When better technology is employed, however, the cost of the product increases accordingly. Therefore, it would be very beneficial to bring the cost down while keeping the improved performance. This can be achieved by using composite soft magnetic materials to reduce the manufacturing cost of high performance motors.

Soft magnetic composite materials produced by power metallurgy techniques have undergone significant development in the past few years because of their unique properties and potential application fields [1,2,3,4]. Compared with electrical steels widely used in rotating machines and transformers, the major advantage of this material is the potential of large volume manufacturing of low cost motors. Because the iron cores and parts are formed in a die, or iso-static press process, and can be combined to form complex net-shape components, the dimensional change are minimized and hence the product costs are greatly reduced. In addition, the powdered nature of the material yields lower eddy current loss and isotropic magnetic properties, and therefore, it is suitable for specially structured, such as claw pole, motors with three dimensional fluxes. The permeability of this material, however, is lower than electrical steels. It is expected that this material would be appropriate for construction of permanent magnet motors, which are not sensitive to the permeability of the core. In the case of surface mounted permanent magnets, the machines have large effective air gaps therefore the reduced permeability is less important than that in armature magnetised machines such as induction and reluctance machines.

In order to make a good use of the material so as to produce motors of low cost and reasonably good performance, suitable topologies must be studied. For this purpose, a small single phase claw pole permanent magnet motor with a composite magnetic core was designed and constructed using SOMALOY™ 500, a magnetic soft composite recently developed by Höganäs AB, Sweden. This new soft composite material has a saturation flux density of 2.37 T at 340 kA/m, maximum relative permeability of 500, and reasonably low core loss at medium frequencies. For core loss prediction, rotational core losses of SOMALOY™ 500 with rotating magnetic fluxes were measured and used in the design [5,6]. A commercial finite element package ANSYS was employed for the optimum design and performance analysis. This paper presents the design, construction and performance analysis of the prototype claw pole armature machine in which the armature is constructed from powder iron composite.

2. Design and Construction of the Prototype

Electrical machines with claw pole rotors have been popular for many years and the typical application is for automobile alternators. The rotor has only one exciting coil housed between the two claw pole pieces to produce a magnetic field with a high number of pole-pairs. The magnetic field changes its direction while crossing the air-gap to the armature which is similar to that of a common three phase synchronous machine.

It is possible that the claw pole structure is used for the armature of a permanent magnet motor. This type has been well known, but the excessive eddy current in the commonly applied solid steel core limits the machine to very small size and/or low speed and causes low efficiency. Because the magnetic field is truly three dimensional, the production of the claw pole arrangement is extremely difficult using lamination.

As discussed in the last section, the unique properties of soft magnetic composite materials make them suitable to manufacture complex structured permanent magnet claw pole motors. It is noted that simply replacing the existing laminated stator iron core with a soft magnetic composite material will result in a loss of performance with very small compensating benefits[3]. Therefore, the topology and dimension of the motor should be arranged to fully take the advantages of the soft magnetic material. The traditional magnetic circuit method was applied in the initial design and then the three dimensional finite method was used to optimize the design and predict the motor performance [7].

Fig.1 shows the magnetically relevant parts of the rotor: a mild steel case and 20 surface mounted NdFeB magnets. In addition, the rotor contains two aluminum end plates.

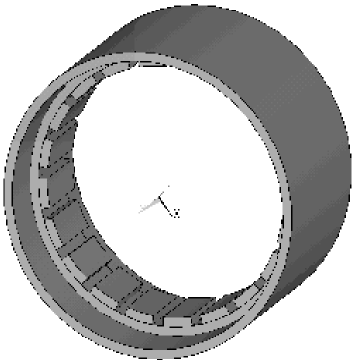

Fig.1 Geometry of the rotor yoke and magnets

Fig.2 shows the magnetically relevant parts of the stator: two claw pole wheels of soft magnetic composite materials and the shaft of steel. The stator winding is housed between the two claw pole wheels. The stator winding is a concentrated single phase coil and the manufacturing cost is low because of simple winding techniques. This greatly simplifies the winding operation and allows considerably a high fill factor to be achieved.

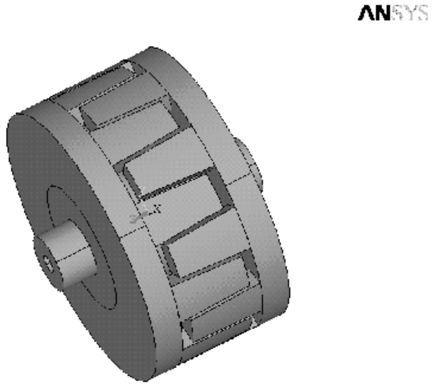

Fig.2 Geometry of the stator iron core and shaft

3. Numerical Calculation by 3D-FEM Analysis

It is evident that the complicated shape of a claw pole machine leads to a truly 3 dimensional way of the magnetic flux. Therefore, it is necessary that three dimensional finite element analysis be conducted for an accurate determination of the parameters and performances of the electrical machine.

Fig.3 presents the finite element model with 13350 tetrahedral elements and 2642 nodes for the field calculation consisting only of one pole-pair pitch because of its symmetry. The constraints are described by periodical boundary conditions in equation 1.

$$U_m(r,\theta+\Delta\theta,z)=U_m(r,\theta,z) \tag{1}$$

where $\Delta\theta = 36^o$ is the angle of one pole-pair pitch, the original point of the cylindrical coordinate is located at the centre of the motor.

It can be noted that the main airgap and the magnets have been meshed much more densely than other regions. In calculating magnetic energy stored in the machine, these two parts take up the major part and their accuracy will be the key factor to the results of magnetic energy and cogging torque.

It may be possible to analyse the field in one pole pitch [8], the constraints of half periodical boundary conditions are described in equation 2.

$$U_m(r,\theta+\Delta\theta,z)=-U_m(r,\theta,-z) \tag{2}$$

where $\Delta\theta = 18^o$ is the angle of one pole pitch.

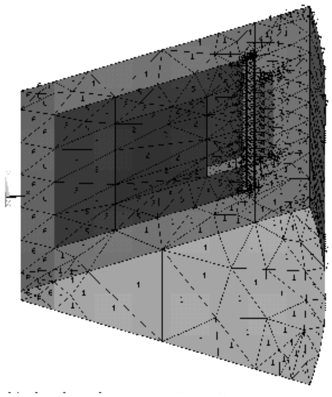

Fig.3 Finite element mesh with material codes, where (1) air, (2) winding, (3) and (4) permanent magnets, (5) soft magnetic composite (6) steel (7) mild steel

When the magnetic field distribution inside the electrical machine is figured out, the flux linkage, induced EMF and reactance of the stator winding, and then the performance can be calculated.

3.1 No-load Flux Linkage of the Stator Winding

When the rotor rotates, the flux passing through the stator winding and the induced EMF vary. $\theta = 0^o$ is supposed at the place the magnets share the same axes with the stator claw poles respectively, where the main magnetic circuit has the highest permeability and the stator winding links the maximum magnetic flux. The no-load flux linkage waveform of the stator winding is plotted in Fig. 4 which clearly shows the flux linkage and then the induced EMF are sinusoidal waveforms.

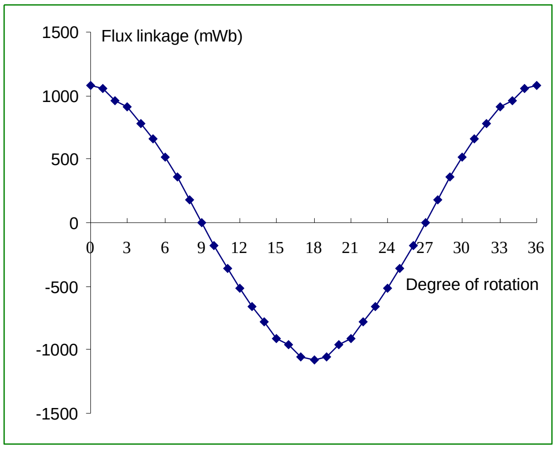

Fig.4 No-load flux linkage of the stator

The induced stator emf is determined by

$$E_1 = \frac{\omega_1 N_1 \phi_m}{\sqrt{2}} \quad (3)$$

where $\omega_1 = 2\pi f_1$ is the angular rotor speed in electrical radians per second, f_1 the frequency of the induced stator emf in Hertz, N_1 the number of turns of the stator winding, and ϕ_m the magnitude of the magnetic flux linking the stator winding due to the permanent magnets, which can be obtained from the results of field analysis at no-load.

3.2 Cogging Torque

Cogging torque is caused by the tendency of the rotor to line up with the stator in a particular direction where the magnetic circuit has the highest permeability. The Cogging torque arises from the reluctance variation of the magnetic circuit as the rotor rotates and exists even when there is no stator current.

The finite element method can provide an accurate and simpler approach to cogging torque from the determination of electromagnetic field distribution. There are two available calculation methods: the Maxwell stress tensor and the gradient of coenergy. Since the second is more accurate and simpler, it is used although it is a bit of computationally expensive.

For a conservative electromagnetic system, the torque in a rotating machine can be expressed as the derivative of magnetic energy, with respect to angular displacement:

$$T = -\frac{dW}{d\theta} \quad (4)$$

This derivative can be calculated approximately as the variation of magnetic energy against the angular displacement of the rotor:

$$T = -\frac{\Delta W}{\Delta\theta} = -\frac{W_2 - W_1}{\theta_2 - \theta_1} \quad (5)$$

Fig.5 shows the variation of the total energy depending on the rotor position . The characteristic curve was obtained by rotating the rotor with 0.9 deg.

Fig.6 shows the cogging torque variation versus the rotor position. There is no cogging torque at these positions: θ=0°, θ=9° and θ=18°. From the curve, it can be seen that θ=9° is a stable equilibrium point whereas θ=0° and θ=18° are unstable ones. This means that the rotor will stay at the point, where the axes of the permanent magnets lies in the middle of those of the claw poles when no stator current is applied.

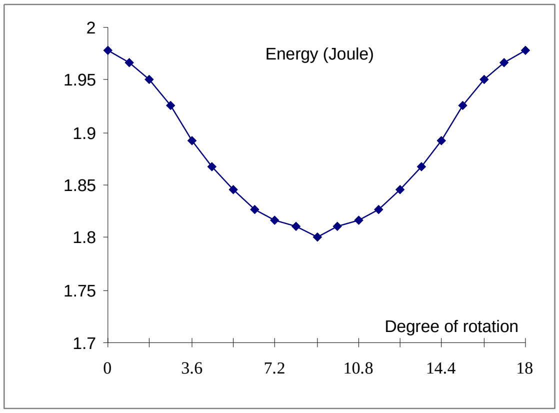

Fig.5 Total magnetic energy versus rotation angle

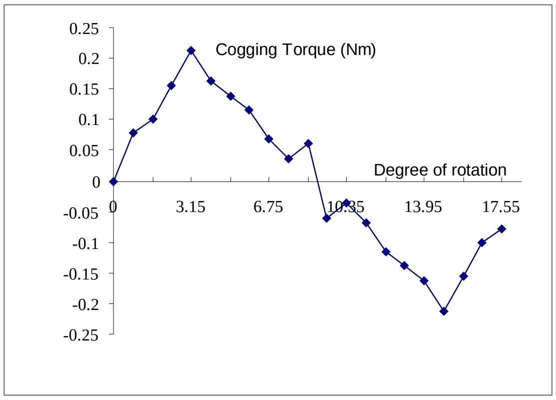

Fig.6 Cogging torque versus rotation angle

4. Performance Calculation

When the stator winding resistance R_1 and reactance X_1 are calculated, the electromagnetic power versus the load angle characteristic can be obtained from equation (6) and plotted in Fig.7.

$$P_{em} = \frac{E_1\left[V_1\left(R_1\cos\delta + X_1\sin\delta\right) - R_1E_1\right]}{R_1^2 + X_1^2} \qquad (6)$$

When δ=86.7° electrical, the electromagnetic power of the motor reaches the maximum value 72.5 W, and the corresponding maximum electromagnetic torque is 2.31 Nm.

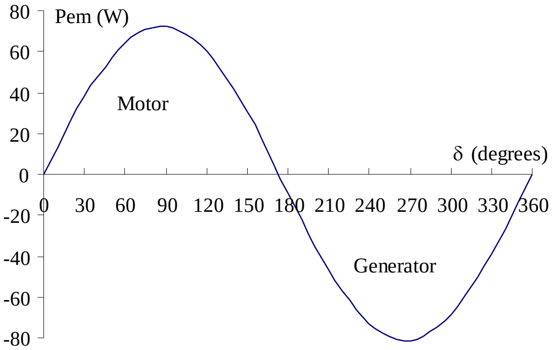

Fig.7 Electromagnetic power versus load angle

Fig.8a presents the input power, output power, stator current, efficiency, and power factor of the motor against the load angle and Fig.8b presents the electromagnetic and output torque curves.

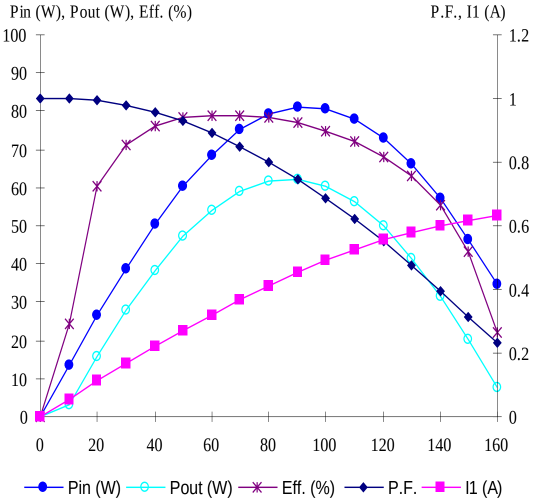

Fig.8a Motor input power, output power, stator current, efficiency and power factor versus load angle

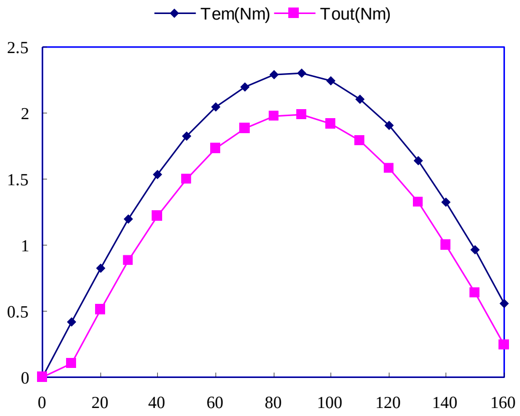

Fig. 8b Electromagnetic and output torques versus load angle

5. Conclusion

A small permanent magnet claw pole motor has been designed that uses and exploits the benefits of soft magnetic powder composite materials by the commercial three dimensional finite element package ANSYS. The prototype is being constructed in the workshop at UTS and the motor performance is expected comparable to that of similar motors with solid steel cores.

6. Acknowledgment

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