SYNCHRONOUS MOTOR USING FERRITE MAGNETS FOR GENERAL PURPOSE ENERGY EFFICIENT DRIVE

B.N. Chaudhari and B.G. Fernandes
Department of Electrical Engineering, Indian Institute of Technology, Bombay
Powai, Mumbai-76, INDIA
Email: bnc@ee.iitb.ernet.in

Abstract
Synchronous motor using ferrite magnets has potential for energy saving in general applications such as fan, pump and compressor drives. Recently(7), a rotor geometry is suggested for this machine which eliminates the drawbacks of the conventionally used rotor geometries and gives higher airgap flux density. The performance of this machine with the proposed rotor geometry is compared with the conventional geometries for the same magnet volume and conductor density, employing field based circuit analysis. The performance of the machine for different operating conditions and asynchronous performance are also presented. The machine is also modified to suit the inverter fed drive.

I. INTRODUCTION

Though, advances in the development of high energy permanent magnets such as Neodymium-Iron-Boron have attracted increased attention in the development and application of permanent magnet (PM) motors, ferrite magnets are the only economical magnets for motors of general applications. In order to design a line start permanent magnet synchronous motor (LSPMSM), magnets need to be buried under iron poles with sufficient space for cage bars. The magnets can be magnetized with their direction of magnetization in radial or in circumferential direction (flux squeezing arrangement). To increase the ratio of magnet width to pole pitch, the magnets are often offset from the radial direction so that they can be extended over the shaft [1]. Flux squeezing is effective with the number of poles being higher than four and requires a non magnetic shaft [2].

Recently, a new rotor geometry is proposed for 4 pole and 2 pole LSPMSM[7]. It is suitable for ferrite or bonded rare earth magnets. It eliminates the drawbacks of the conventionally used rotor geometries and gives higher airgap flux density. In view of the complex geometry, deeper knowledge is obtained here, using FEM. The performance of the machine with this rotor geometry is compared with the conventional geometries employing same magnetic volume and conductor density. Finite element analysis is combined with a lumped parameter circuit model for predicting the performance for different rotors. The performance of the machine with this rotor geometry is studied for different operating conditions using field based analysis. The asynchronous performance is presented and parameter sensitivity analysis is performed.

II. CONSTRUCTION

The stator of the machine is similar to that of a 3 phase induction motor or wound field synchronous motor. The proposed rotor with its direction of magnetization is shown in Fig.1. The mechanical bridges between horizontal and inclined magnets can be designed from mechanical considerations. The leakage due to these bridges is negligible and most of flux which saturates these bridges is the useful flux whereas with all other geometries, this flux is rotor leakage flux. There is no difference in design of line start and variable speed machines but the number of stator turns. The number of stator turns are modified to suit the excitation voltage and available dc link voltage.

III. LUMPED PARAMETER MODEL

The variables can be transformed from stationary reference frame 'abc' to the rotor reference frame 'dq' and the system governing equation can be written as

\[ \begin{bmatrix} V \\ Z \end{bmatrix} = \begin{bmatrix} [R] + \begin{bmatrix} L \end{bmatrix}_p + \begin{bmatrix} [G] \end{bmatrix}_q \end{bmatrix} \begin{bmatrix} i \end{bmatrix} \]

and the torque is given as

\[ T = \begin{bmatrix} i \end{bmatrix}^T \begin{bmatrix} G \end{bmatrix} [\begin{bmatrix} i \end{bmatrix}] + \begin{bmatrix} L \begin{bmatrix} i \end{bmatrix} - L \begin{bmatrix} q \end{bmatrix} \end{bmatrix} \begin{bmatrix} i \end{bmatrix}^T + L \begin{bmatrix} q \end{bmatrix} \begin{bmatrix} q \end{bmatrix} + \begin{bmatrix} L \begin{bmatrix} q \end{bmatrix} \end{bmatrix} \begin{bmatrix} i \end{bmatrix} + \begin{bmatrix} L \begin{bmatrix} q \end{bmatrix} \end{bmatrix} \begin{bmatrix} q \end{bmatrix} + \begin{bmatrix} L \begin{bmatrix} q \end{bmatrix} \end{bmatrix} \begin{bmatrix} q \end{bmatrix} + \begin{bmatrix} L \begin{bmatrix} q \end{bmatrix} \end{bmatrix} \begin{bmatrix} q \end{bmatrix} \]

These equations describe steady state as well as transient conditions. The parameters in these equations change with load due to the magnetic saturation. The loading method which takes variation in excitation voltage with load and cross coupling effects into account is employed to predict machine parameters[4,5]. These parameters are used to predict the synchronous performance by setting p=0 and \( i_p = i_q = 0 \). The parameter variation for new rotor is shown in Fig.2. Excitation voltage remains almost constant in the working range. Saturation has significant effect in quadrature axis. It is observed that unusual dip in excitation voltage and crest in direct axis reactance are reduced. This is due to the reduction in rotor leakage flux. The armature reaction has same direction in iron pole and saturating bridges near shaft i.e. either it is magnetizing or demagnetizing in both. In conventional geometries, armature reaction has different directions in these regions, i.e. if it is...
magnetizing in pole region, it is demagnetizing in bridges. To identify the improvement in energy saving potential of the machine with new rotor, the synchronous performance for different rotors is obtained and shown in Fig.3. The proposed rotor gives at least 4% higher efficiency and 9% higher power factor when compared with conventional spoke type configuration. The increase in pull out torque is around 10%. In order to get insight the machine performance is studied for different operating conditions such as change in voltage, frequency and speed. The efficiency and power factor of the machine for different operating conditions are given in Fig.4-6. As shown in the Fig.4, there is considerable change in machine power factor for different voltage. This is due to fact that machine is very sensitive to the difference in excitation voltage and supply voltage. The effect of change in air gap flux level is also studied varying the stator conductor density and is indicated in Fig.7. It shows that with the increase in air gap flux levels, the power factor and efficiency decrease but the torque to weight ratio of the machine increases. This is obvious as the flux contribution from the rotor is constant. Any increase in air gap flux level increases the magnetizing component of stator current and hence decreases the efficiency and power factor.

IV. ASYNCHRONOUS PERFORMANCE

Quasi dynamic analysis approach with pseudo constant speed characteristics is used to predict the starting performance of the machine[6]. It permitted the parametric sensitivity analysis for finalizing the rotor design. The asynchronous performance for new rotor geometry is shown in Fig.8. The available induction motor stampings are machined to accommodate the magnets. However, this cage design could give the starting torque equal to rated torque. Line start PMSM needs double cage arrangement for good asynchronous performance[1,6]. The double cage rotor is also designed for this machine which could give starting torque equals to the rated torque of the machine.

V. VARIABLE SPEED MACHINE

One of the important constrain in the design of line start permanent magnet synchronous motor is the ratio of excitation voltage to air gap voltage. It should be in the range of 0.3-0.8 to reduce the initial braking torque due to magnets. For the inverter driven variable speed applications, the machines can be designed such that the open circuit flux density nearly approaches the air gap flux density. This can give almost unity power factor operation which is necessary to reduce the inverter ratings. The stator design is modified to suit the variable speed operation. The design parameters are, stack length = 100 mm, stator turns = 268, Vline = 180 V, Excitation voltage = 100 V. The performance of the machine is shown in Fig.9.

VI. EXPERIMENTAL RESULTS

A 1/2 hp motor is fabricated and tested for different operating conditions. The synchronous performance of the machine for different voltage variations is given in Fig.10 as an example. The power factor at rated conditions is 0.87 and efficiency is 91%. As expected machine power factor is very sensitive to voltage variations. It improves for undervoltage as the machine is underexcited.

VII. CONCLUSIONS

New rotor geometry which uses both radially and circumferentially magnetized magnets is studied both for line start and inverter driven PMMSM, which concentrates flux effectively and gives at least 22% higher air gap flux density compared to other geometries for same magnet volume. Also, the draw back of conventional flux squeezing geometries regarding shaft material is removed. The synchronous performance of the machine with proposed 4 pole rotor is compared with conventional rotors for same magnet volume and conductor density using field based circuit analysis. Simulation results show 4% improvement in efficiency and 9% improvement in power factor when compared with spoke type configuration. The increase in pull out torque is up to 10%. The 4 pole machine is studied in details for different operating conditions. The machine is fabricated and has shown energy saving potential when compared to general purpose induction motor. The pay back period for the machine is 8 months with a duty of 10 hrs/day. The stator design is modified to suit inverter driven drive. The machine with specially designed inverter indicated economic feasibility in variable speed drive.

REFERENCES

Fig. 1: (a) New rotor with direction of magnetization (b) Open circuit flux plot

Fig. 2: (a) Synchronous performance of new rotor (b) Parameter Variation 1. Excitation Voltage 2. Xd and 3. Xq

Fig. 3: Efficiency and power factor for different rotors
RMF: Radially magnetized ferrite magnets
RMB: Radially magnetized bonded magnets
CMF: Circumferentially magnetized ferrite magnets
NEWF: New rotor with ferrite magnets

Fig. 4: (a) Torque and Input Power (b) Efficiency and Power factor for different supply voltages.
Fig. 5: Efficiency and power factor for different frequencies (voltage constant)

Fig. 6: Efficiency and Power Factor for different frequencies (V/F constant)

Fig. 7: Efficiency and Power Factor at different air gap flux levels (stator turns variation)

Fig. 8: Asynchronous Performance

Fig. 9: Performance of cageless rotor
1. Torque, 2. line current, 3 Input power

Fig. 10: Experimental results
(a) Power factor for different voltages
(b) Torque for different voltages