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3D Finite Elements Analysis and Experimental Validation for the Consequent Pole PM Machine

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Abstract—
In this paper the Consequent Pole Permanent Magnet (CPPM) machine finite element analysis is presented. Due to the double excitation (PM and field winding) and inherent three-dimensional flux distribution an appropriate numerical analysis must be done so that operating conditions can be predicted. Using this analysis flux distribution, winding inductances, back-emf and other parameters of the magnetic structure are calculated. This work is oriented to obtain parameters and airgap flux control range for the CPPM machine. Experimental verification is made to verify the accuracy of the method when is applied to this type of machine configuration.

Index Terms —**Motor and Generator, Numerical analysis.**

I. Introduction

Accurate machine parameters calculation is required for high performance AC drives, where the operating range and control are highly dependant of them [1]. In fact, speed range and field weakening capabilities of the PM machines are define by the inductances values and the back-emf [2] . Two and three-dimensional FEA allow us to calculate with adequate precision the airgap flux distribution under any operating condition.

It has been shown that the CPPM machine has attractive features for variable speed AC drives applications [3]. Due to the double excitation (PM and field winding) a wide range of airgap flux can be achieved with a modest amount of field MMF. In addition, there does not exist a demagnetization risk for the magnets because the control action is made over soft iron poles rather than over magnet as a regular PM machine . Slip rings, brushes or other mobile contact are not required to transfer energy to the field winding because it is located in the stator. The operation of the CPPM machine involves a three-dimensional flux distribution which increases the analysis complexity. In this Paper a FEA is carried out to obtain an the airgap flux control range, back-emf and *d-q axis* inductances. Maxwell 3D provide the ability to analyze volumetric structures and supplies tools to calculate local and integrals variables. In addition, experimental results are presented from a 3kW prototype built using the consequent pole configuration and field control strategy.

II. Analysis Domain

Figure 1 shows the magnetic structure of the CPPM machine. The machine consists of a rotor divided into two sections. One section has partial surface-mounted permanent magnets, which are radially magnetized, and the other has a laminated iron pole. The stator is composed of a laminated core, solid iron yoke, and a conventional AC three-phase winding allocated in slots around the periphery of the inner diameter. To complete the stator structure, a circumferential field winding is placed in the middle of the stator, which is excited by a DC current.The combination of the PM and field winding fluxes generate a demagnetizing or magnetizing effect on the machine airgap according with the magnitude and direction of the DC current.

III. FEA and Experimental Comparison

A. Flux per pole

The magnetization curve of the CPPM machine represents the relation between the AT field excitation and the flux per pole. This relation shows the airgap flux control range from the maximum subtractive effect of the field flux, (minimum airgap flux) up to maximum additive effect (with maximum airgap flux). Figure 2 shows the flux per pole predicted by 3D-FEA and the experimental flux control capability of the prototype. It can be note that the control provide for the DC field winding allows us to control the airgap flux in a range of +/-40% respect to the no field current conditions. Slightly difference between the actual and predicted slope is found. In effect, 3D-FEA does not consider several practical manufacturing consideration which are present in the actual prototype, such as interlamination airgap and junction between stator lamination and solid core. These are not considered in order to reduce the complexity of the numerical analysis.

B. Back-emf waveform

From Faraday's law, the $back-emf$ induced in a full pitch coil is obtained from

$$e = \frac{\partial \lambda}{\partial t} \qquad (1)$$

where λ are the coil flux linkages.Asumming constant speed, the induced voltage is calculated from the flux distribution at different rotor position and DC field current.

Figures 3, presents the calculated and actual $back-emf$ waveforms. In addition, fundamental harmonics component for the actual and predicted waveforms are also shwon. Close

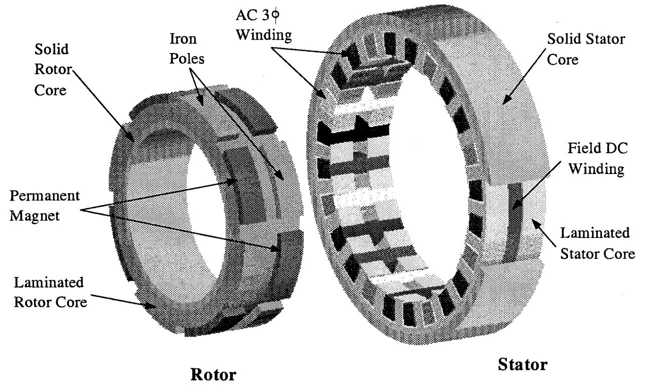

Fig. 1. Magnetic structure of the CPPM machine

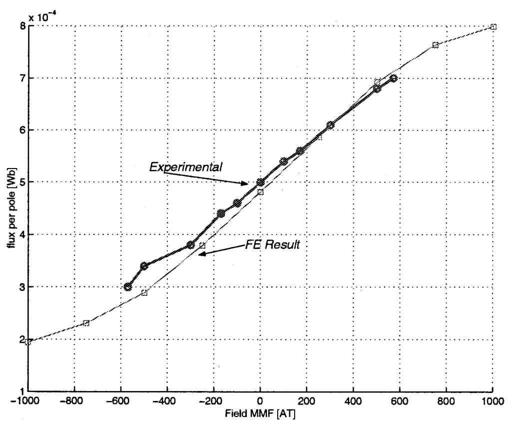

Fig. 2. Flux per pole: FEA and measured values comparison

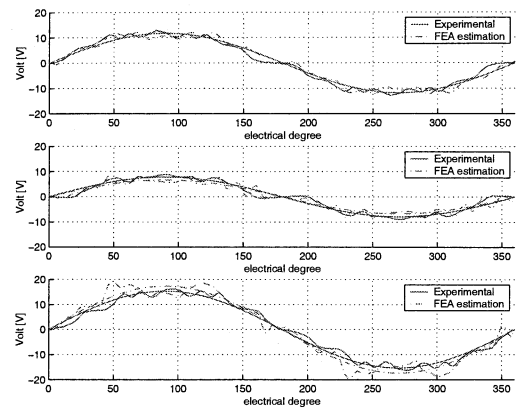

Fig. 3. Back-emf waveform (actual and predicted) as a function of field current

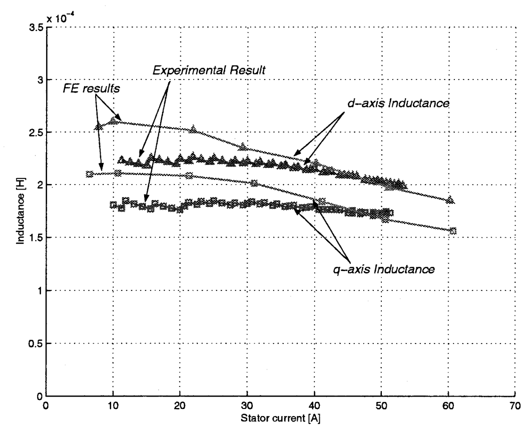

Fig. 4. Variation of $d - axis$ and $q - axis$ d-a axis inductances under stator current variation.

agreement are found between experimental and 3D-FEA result. Fundamental components for no-field current match almost exactly with the actual $back - emf$. There are slightly differences when field current is circulating, which is predicted from figure 2. In fact, underestimation for magnetizing and overestimation for demagnetizing effect of the field current are predicted from the flux per pole vs. field current characteristic. This discordance is related with the FE model and the simplification applied to reduce its complexity.

C. $dq - axis$ Inductances

In order to determine the $dq - axis$ inductances, the following equation are evaluated [4].

$$L_d = \frac{\lambda_d - \lambda_{pm}}{i_d} \quad and, \quad L_q = \frac{\lambda_q}{i_q} \qquad (2)$$

Figure 4 summarize the $dq - axis$ inductance variation as the stator current changes. As is predicted, $d - axis$ inductance results higher $q - axis$ one. In general PM machines present a lower L_d due to the high PM reluctance. However, for the CPPM machine iron pole represent a very low reluctance path for the $d - axis$ flux, which result in a inverse relation between $d - axis$ and $q - axis$ inductances. Some disagreement are found for the inductances calculation. At low current, more flux is predicted than the actual values due to interlamination of the stator stack. In fact, Solid stator iron is assumed for the FEA model which presents lower reluctance. At High current saturation makes the numerical result closer to the experimental.

IV. Conclusions

Experimental tests demonstrate that the CPPM machine can control the airgap flux in a wide range. Over +/- 40% with respect to the no-field current condition can be achieve using the DC field current. It appears feasible to control the airgap flux by varying the field current in variable speed applications. Close agreement between actual and predicted back-emf waveform. CPPM machine exhibits inverse relation between L_d and L_q, respect to the traditional surface mounted PM machines, due to iron pole presence.

References

[1] Z.Q. Zhu, G.W. Jewell, D. Howe, "Finite Element Analysis in the Design of Permanent Magnet Machines, " IEE Seminar on Currente Trends in the Use of Finite Element (FE) in Electromewchanical Design Analysis, 2000.

[2] R. F. Schiferl, T. A. Lipo, "Power Capability of Salient Pole Permanent Magnet Synchronous Motor in Variable Speed Drive Applications, " IEEE Transactions on Industry Applications. Vol 26, No. 1, January/February 1990, pp.115-123.

[3] J.A. Tapia, F. Leonardi, T.A. Lipo, "Consequent Pole Permanent Magnet Machine With Field Weakening Capability." IEEE International Electric Machines and Drives Conference, IEMDC 2001. Cambridge. pp 126-131.

[4] E.C. Lovelace, T.M. Jahns, J.H. Lang, "Impact of Saturation and Inverter ost onInterior PM Syncronous Machine Drive Optimization ." IEEE T-IA, Vol. 36, No. 3 May/june 2000 pp 723-729.