Finite Element Modeling of an Interior Permanent Magnet Synchronous Motor for Calibration and Testing Purposes

AUTHOR **Abhiroop Chattopadhyay**
FACULTY ADVISOR **Professor Ian Brown**

Abstract

This research focuses on the utilization of Finite Element Analysis (FEA) for the modeling of an interior permanent magnet synchronous machine (IPMSM). The long term goal of the project is to model the given motor and simulate its operating conditions using the Finite Element Method (FEM). The FEM solutions will also be used to extract important motor operating conditions and parameters.

Introduction

The focus of this research is to develop and refine accurate electromagnetic finite element models for the interior permanent magnet synchronous motors (IPMSM) that are currently utilized in the Electric Machines Laboratory at the Illinois Institute of Technology.

This project may be categorized in the Energy portfolio of the Engineering Themes as motors of various structures are one of the largest consumers of electrical power in the world. Thus, developing efficient motors is a key aspect in being able to make manufacturing processes cleaner and more sustainable, thereby reducing the environmental impact of the ever growing energy usage of the world. [1] They are also very similar in design to generators, which are the workhorses of the power generation industry as we know it today. As such, gaining a better understanding of motors will help us develop methods to optimize the efficiency of generators as well.

IPMSMs are a relatively recent innovation in the electric machines industry. With the advent of ultra-strong rare earth magnets with high energy products, it has become possible to make electric motors more efficient. Stronger magnets can provide a higher flux density, which directly translates to higher power densities, allowing more power to be packed in smaller volumes. Permanent Magnet (PM) electric motors, today, also have much higher efficiencies and, consequently, see a lot of use in traction applications for hybrid and all-electric drives for vehicles; applications where a wide speed range is desired. [2]

Significant resources are currently being devoted to support research in this area. There is a significant amount of literature in the IEEE Transactions database that is devoted to developing models to obtain accurate simulations for the flux distribution inside PM machines.

This project will be analyzing a specific motor with a unique rotor geometry that includes non-magnetic flux barrier regions in the lamination. These regions are designed to allow the magnetic flux to be focused on to the stator slots and minimize the leakage fluxes. This also helps to reduce the ripple torque of the machine.

The goal for this semester's research was to learn the operation of the Finite Element Analysis (FEA) package JMAG Designer to obtain an understanding of how Finite Element Method (FEM) can be utilized in electromagnetic simulations. The geometry of the motor was set up, materials were selected and some basic simulations were run for the flux density distribution.

It is the author's hope to continue this research in the coming semester to obtain the motor's other operating characteristics to better understanding its behavior under rated operating conditions.

Methods

The specific motor being analyzed is a 3-phase Interior Permanent Machine with 6 poles and 9 slots. The windings are concentrated. The structure of the rotor is shown below.

As may be seen in the geometry of the rotor, the magnet slots are of an unusual shape. Since the magnet is rectangular in cross section, it is intended to fill only the central space which is of uniform cross-section. The remaining slot space is filled with non-magnetic epoxy resin that holds the magnet in place. The concept behind this slot design is that since steel has a much higher magnetic permeability than epoxy resin, the flux will preferentially pass through the steel regions and very little of it would attempt to cross the resin-filled region. This ends up acting as a flux barrier to help direct the magnetic flux. [3]

The figure below is the structure of the stator. The windings are made of copper and the coil windings are concentrated. The space between adjacent coils in a single slot is filled with air and insulation lining. Thus, in terms of the magnetic property of the slot, the permeability of the whole slot area is essentially the same as that of free space.

These geometries were then replicated in the JMAG geometry editor. Manufacturing data such as the type of magnetic steel, the grade of permanent magnets and wiring diagrams was used to model the material properties as accurately as possible. On completion of the geometry, a static study was set up with only one energized magnet pole to observe the flux density distribution. The analysis was run and the results were obtained.

Results

A close-up of the energized magnetic pole and the slot lying closest to it is shown in the adjoining column. The magnetic flux is observed to be mostly contained in the rotor steel and is directed into the stator tooth effectively, with very little of the flux leaking into the air gap of the slot. The grade of steel used here is seen to saturate at approximately 1.44 T. Certain areas of the rotor attain very high magnetic flux densities, with the maximum of 2.4 T, located in the narrow regions between the non-magnetic epoxy regions.

Discussion

Upon analysis of the flux distribution inside the machine, it can be seen that the capability of the non-magnetic regions to channel the magnetic flux is quite pronounced. The flux emerging from the magnet is directed along the direct axis and traverses the air gap to link with the stator tooth. The experimental slot shape is thus justified as fulfilling its role.

Also note the high magnetic flux density provided by the rare-earth magnet. Generating the same amount of flux in a wound rotor synchronous machine would involve supplying a significant amount of current to the field windings, which

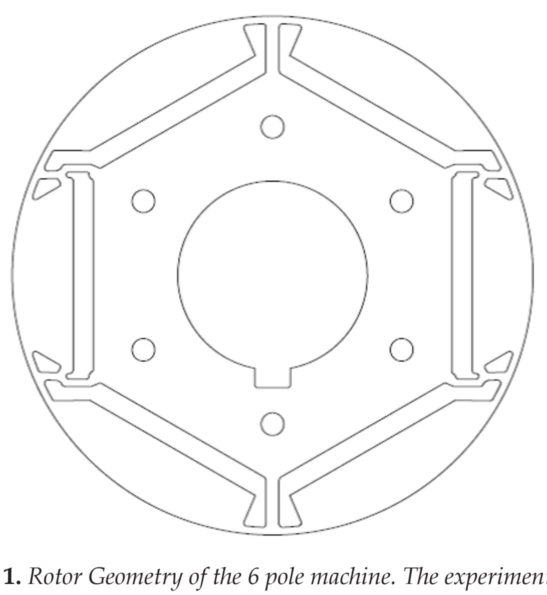

Figure 1. *Rotor Geometry of the 6 pole machine. The experimental 'flux lensing' structures of the slots are visible here.*

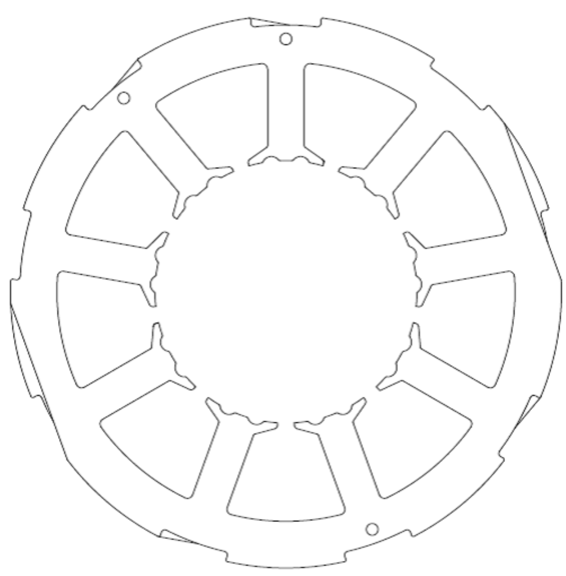

Figure 2. *The 9 Slot structure of the stator.*

are a source of ohmic losses. Thus, the use of rare-earth magnets allows motors to run at higher efficiencies.

Proposed future work in this project is to expand the simulation to the whole machine geometry and obtain various other operating characteristics such as cogging torque, radial and tangential air gap flux densities, open circuit phase voltages, electromagnetic torque production, and Maximum Torque Per Ampere (MTPA) angles for different current values. To better understand the power conversion process in the motor, the air gap flux quantities will be of importance. The electromagnetic torque production will be useful in obtaining the values of current phase angles when average torque generation is maximized. Harmonic analysis of the various quantities will also be conducted to understand which of the primary harmonics are responsible for the power conversion process.

Based on a set of simulations run as part of the graduate coursework for ECE 539, some examples of the above characteristics – simulated for a different motor - are shown below.

The induced voltages are a useful measure of which harmonic order is most prevalent to power conversion and which ones may contribute to losses.

The MTPA angles are useful in understanding how the phase angle of the 3-phase input current affects the average torque production of the machine.

The future scope of the project is to extract these data from the FEM simulation to better understand this specific motor's capabilities.

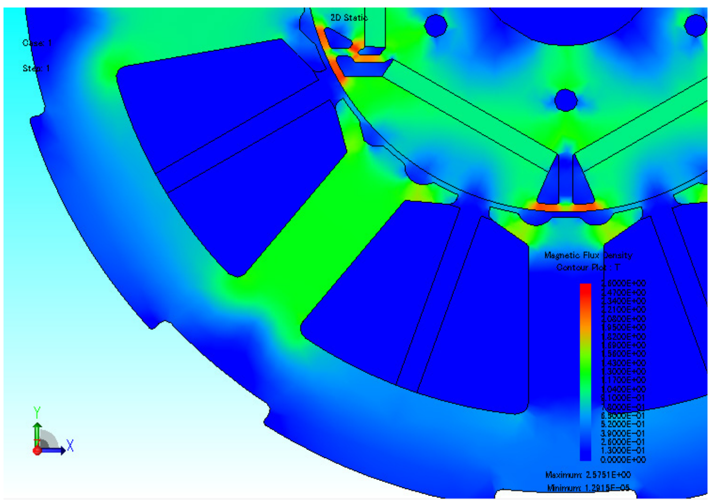

Figure 3. *Magnetic flux density distribution around one pole of the machine.*

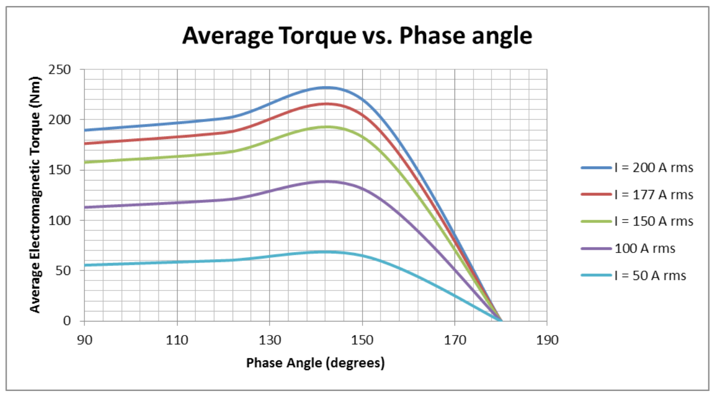

Figure 6. *Average torque generated by the machine as a function of phase angle of the current. Plotted for different values of operating current.*

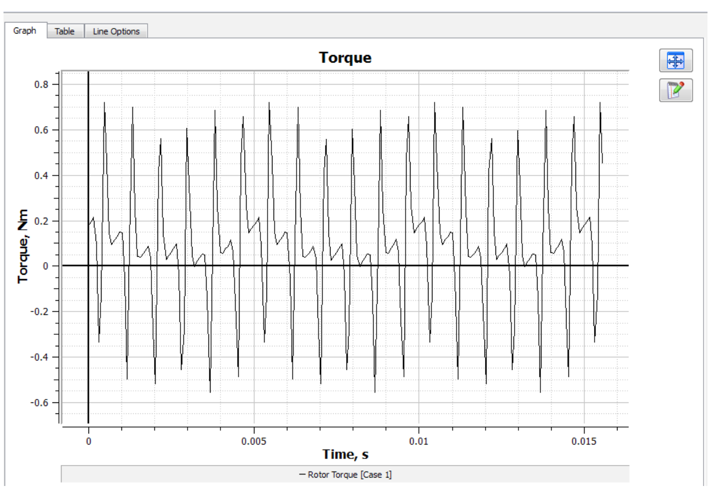

Figure 4. *Plot of cogging torque for the motor as a function of time.*

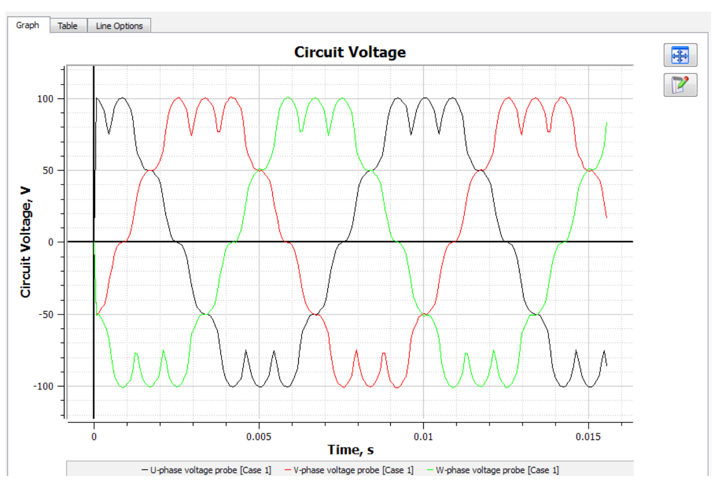

Figure 5. *Plot of the 3-phase open circuit induced voltage of the motor.*

Conclusion

An FEA model of a particular motor with an experimental rotor magnet slot structure was created and simulated. The magnetic flux density distribution of the machine was obtained and the expected behavior of the slot structure was validated by the simulation. The advantage of rare-earth magnet usage in IPM machines was also explored.

Tasks for future scope of the project have also been laid out. These include extraction and harmonic analysis of various quantities in interest with regards to the power conversion process in the electric motor.

Acknowledgements

I would like to express my gratitude for the sponsorship support provided by the ACE Undergraduate Research Program. Thanks also go out to the project mentor Dr. Ian P. Brown, Assistant Professor in the Electrical and Computer Engineering department at IIT for his guidance and support with the project. Special mention is made of the course ECE 539 – Computer Aided Design of electric Machines for laying the theoretical foundations of the research project.

A note of thanks also to my colleague Anthony Krueger, for all the help he provided with the software suite JMAG.

References

1. Pyrhönen, J., Jokinen, T., Hrabovcová, V., Design of Rotating Electrical Machines. Wiltshire: John Wiley and Sons, Ltd., 2008

2. Rahman, F., and Dutta, R.; A new rotor design of interior permanent magnet machine suitable for wide speed range. IECON IEEE. 1193-1201, 2003.

3. Fang, L., and Hong, J. ; Flux barrier design technique for improving torque performance of interior permanent magnet synchronous motor for driving compressor in HEV. VPPC IEEE. 1486-1490, 2009.

4. Alotto, P., Barcaro, M., Bianchi, N. and Guarnieri, M. Optimization of IPM motors with machaon rotor flux barriers. CEFC IEEE, 1, 2010.