

Finite Element Modeling of an 8/6 Switched Reluctance Machine for an Electromechanical Brake System

by
Matthew C. Bringman
Professor Ali Keyhani

Mechatronics Laboratory
Department of Electrical Engineering
The Ohio State University
Columbus, Ohio 43210

All Rights Reserved by Delphi Automotive and the Ohio State University

May 29, 2001

ABSTRACT

The modern car will soon feature many electromechanical devices on it that will improve the safety, performance and fuel economy for the modern driver. One such device is the electromechanical brake system. Delphi Automotive has designed an electromechanical brake system that uses an 8/6 switched reluctance motor to drive the system. This thesis will concentrate on modeling of the switched reluctance motor that was designed.

First an introduction to and the basic operation of the switched reluctance motor will be explained. The equations that model the voltage, current, torque and speed of the switched reluctance machine will then be derived as functions of the parameters of the machine. The inductance of the machine changes as a function of position and current. The inductance of the motor is periodic with respect to theta so a model will use a Fourier Series to calculate the inductance as a function of theta. After the models and operation of the switched reluctance motor has been explained, the next section will explain the finite element analysis of the machine.

The dimensions of the machine were entered into a computer model and a finite element analysis was performed. Flux2D was used to create two computer models of the motor from the drawings used to build the actual motor. Two models were created with different airgaps to reflect the tolerances that were given on the drawings. Then the motor was rotated through an electrical cycle for different current level and the

inductance was calculated for every degree of rotation. The inductance was then used to calculate the flux linkage in the motor and the results were graphed.

The resulting flux linkages were then graphed with some estimated values that were obtained from an actual motor. These estimated values were used to validate the results that were obtained from the computer simulation. Then the data was compared and differences have been analyzed. The result of this thesis shows that the flux linkage values for both of the methods were very close to each other, but the differences will be examined and explained.

Dedicated to my family
Christa, David, and Peter Bringman

ACKNOWLEDGMENTS

I wish to thank my adviser, Professor Ali Keyhani, for his insight, support and guidance, which made this work possible.

This work was supported in part by the Delphi Automotive Systems, The National Science Foundation: Grant ESC 9722844, 9625662, Department of Electrical Engineering, The Ohio State University. I would also like to thank the Ford Motor Company, TRW, and GE for their support of the work in the Mechatronics Systems Lab. My sincere thanks goes out to Prof. Donald G Kasten for agreeing to be on my Master's Examination Committee.

It was a pleasure working with Bogdan Proca, Paul Gemin, Luris E. Higuera, Geeta Athalye, Min Dai, and Wenzhe Lu.

I would also like to thank Steven Hutchins, Steven Sefton, Doug Pekkanen, Chris Fish, Carrie Fish, and Michael Chakerian for their help and support through the years. Thank you all for your help in completing this project.

VITA

January 7, 1976.....Born – Cincinnati, OH

1999.....B.S.E.C.E., The Ohio State University

1999-2001.....Graduate Research Associate

The Ohio State University

PUBLICATIONS

FIELDS OF STUDY

Major Field: Electrical Engineering

Specialization: Mechatronics, Power Electronics, and Controls

TABLE OF CONTENTS

	<u>Page</u>
Abstract.....	ii
Dedication.....	iv
Acknowledgements.....	v
Vita.....	vi
List of Tables.....	ix
List of Figures	x
 Chapter One.....	 1
Electromechanical Brake System – Introduction and Basics	1
1.1 Introduction	1
1.2 Electromechanical Brake.....	3
1.3 Switched Reluctance Motor.....	7
1.3 Finite Element Analysis and Flux2D	12
1.5 Analysis	13
 Chapter Two.....	 16
Modeling of a Switched Reluctance Machine	16
2.1 Introduction	16
2.2 Model Development	18
2.3 Mathematical Model.....	19
2.4 Inductance Model	20

2.5 Simulation of the Power Converter	20
2.6 Switch Reluctance Machine Modeling.....	22
Chapter Three.....	28
Finite Element Analysis of SR Motor.....	28
3.1 Introduction	28
3.2 Geometry	29
3.3 Parameter	30
3.4 Points	31
3.5 Lines	32
3.6 Regions	33
3.7 Mesh Generator	34
3.8 Material Database	38
3.9 Physical.....	40
3.10 Solve	42
3.11 Results	44
3.12 Draw	49
3.13 Conclusion.....	50
Chapter Four.....	50
Analysis.....	50
4.1 Introduction	50
4.2 Results at Unaligned Position, $\theta=0^\circ$	56

4.3 Results at $\theta=5^\circ$	58
4.4 Results at $\theta=10^\circ$	59
4.5 Results at $\theta=15^\circ$	60
4.6 Results at $\theta=20^\circ$	61
4.7 Results at $\theta=25^\circ$	62
4.8 Results at Aligned Position, $\theta=30^\circ$	63
4.9 Parameter Errors.....	65
4.10 Errors from Estimation.....	65
4.11 Errors from Calculations.....	67
4.12 Conclusion.....	68
Chapter Five.....	69
Conclusion.....	69
5.1 Conclusion.....	69
5.2 Future Work.....	71
Bibliography.....	74
Technical Report.....	76

LIST OF TABLES

<u>Table</u>	Page
Table 2.1 : Turn on/off Angles in Degrees for the Four Phases	21
Table 4.1 : The Mean Error and the Standard Deviation of Flux	53

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
Figure 1.1 : Control Loops for the Electromechanical Brake System	4
Figure 1.2 : 8/6 Switched Reluctance Machine	8
Figure 1.3 : Inductance as a Function of Current and Position	11
Figure 2.1 : $L(\theta, i)$ at Constant Current and Changing θ	23
Figure 2.2 : Location of L_a , L_u , and L_m	24
Figure 3.1 : Points and Lines from Flux2D for the SR Motor	32
Figure 3.2 : Regions Plot from Flux2D for the SR Motor	34
Figure 3.3 : Mesh Nodes Plot from Flux2D for the SR Motor	37
Figure 3.4 : Generated Mesh Plot from Flux2D for the SR Motor	38
Figure 3.5 : B-H Curve for M-19 Non-Oriented Steel	39
Figure 3.6 : Unaligned Position for Phase C	45
Figure 3.7 : Motor at Ten Degrees for Phase C	45
Figure 3.8 : Motor at the Midpoint for Phase C, Fifteen Degrees	46
Figure 3.9 : Motor at Twenty Degrees for Phase C	46
Figure 3.10 : Aligned Position for Phase C	47
Figure 3.11 : Lambda versus Current for Different Positions	49
Figure 4.1 : Lambda Bar(Mean) versus Theta	55
Figure 4.2 : Variance versus Theta	55
Figure 4.3 : Fluxlinkage versus Current at Unaligned Position	57
Figure 4.4 : Fluxlinkage versus Current at Theta equals five degrees	58

Figure 4.5 : Fluxlinkage versus Current at Theta Equals Ten Degrees	59
Figure 4.6 : Fluxlinkage versus Current at Theta equals Fifteen Degrees	60
Figure 4.7 : Fluxlinkage versus Current at Theta equals Twenty Degrees	61
Figure 4.8 : Fluxlinkage versus Current at Theta equals Twenty-five Degrees	62
Figure 4.9 : Fluxlinkage versus Current at Aligned Position	63
Figure 4.10. λ_e versus Current for Different Rotor Position	64
Figure 4.11 : λ_c versus Current for Different Rotor Position	64

Chapter One

Electromechanical Brake System – Introduction and Basics

1.1 Introduction

The systems that are used to control the function of an automobile are becoming more sophisticated everyday. The designs of the past are constantly being improved and updated. The technological sophistication of automobiles has continued to increase, as more and more new technology is being used and invented for use in automobiles. This will continue in the future, and one of the biggest areas of development right now is in the electrification of the automobile. Electrification means that automobiles of the future will replace the old hydraulic steering, braking, and other systems with steer-by-wire and brake-by-wire systems.

These systems in some cases will create improvements in vehicle performance. For instance the brake systems of the future will feature improved anti-lock braking systems because of the faster response of electric control systems and electric motors. The electric control of the motor can oscillate the pressure of the brake pads on the rotor of the wheel much faster than the current hydraulic systems because of the nature of the different systems. The ability to change the pressure more quickly will allow the automobile to slow down more quickly and in a safer manner.

These systems will also be crucial to improving the fuel economy of newer automobiles. In a standard hydraulic steering system the hydraulic pump is hooked up to the engine and constantly circulating fluid in the hydraulic steering system. This constant motion causes the system to draw power from the motor at all times. These electric systems are also smaller and less cumbersome which allows for a slight weight advantage over hydraulic. With the electromechanical brake you can remove the brake booster and the master cylinder from being in alignment with the brake pedal, which will allow the hood to be lowered. The lower hood height would improve the aerodynamics of the automobile and this would improve the fuel economy of the automobile.

Another advantage to the electrification of these systems is the ability to put a computer between the driver inputs and the automobile outputs. This removes the mechanical linkage between the driver and the system. This will allow for the automobile to make corrections to the driver errors and prevent the driver from losing control of the automobile. A simple example of this would be when a automobile goes into a skid. A four-wheel independent brake-by-wire system would have the ability to brake each of the wheels with a different amount of force so that the automobile steers into the skid properly. This type of a system could even compensate for a driver that is unfamiliar with how to react in this situation and prevent them from causing more problems.

Another benefit is that all of the systems would be able to communicate their current states to the other systems. This would create an automobile with overall vehicle dynamic control. This would mean that the throttle-by-wire could talk to the brake system and the steering system. Then if it was detected that the automobile was not

traveling in the intended direction the systems could coordinate their activities and improve the response of the automobile. The steering commands to the tires could be damped so that erratic steering commands would have a reduced impact. Then the throttle-by-wire system could be told to reduce the fuel flowing to the engine, which would cause the engine to slow. Then the brake-by-wire system could be used to put the automobile on the correct path. It would also slow the automobile safely in a manner that would allow for the driver to still retain some control of the automobile. In this way all of the systems of the automobile would work together and gain better vehicle dynamic control than each of the systems could separately. These are only a few of the many reasons that these types of systems will be introduced into the automobile in the coming years. This paper will focus on understanding the operation of a particular brake-by-wire system, the switch reluctance electromechanical brake.

1.2 Electromechanical Brake

The electromechanical brake is a brake-by-wire system that could be used to totally replace the standard hydraulic system that is presently in the cars. The purpose of this machine is to achieve better performance than the current machine without adding much additional cost to the overall manufacturing cost of the car. The parts that will make up the electromechanical brake system will be the brake pedal, digital signal processor, switched reluctance motor, gear train, brake pads and rotor. To achieve this goal the electromechanical brake will have some requirements that will be described in this section.

The first part of the system would be the force input to the system. This input could come from the brake pedal as a driver input or from the computer in charge of the

anti-lock braking system, ABS. This command would be in the form of a voltage input to the digital signal processor, DSP. This input would be equivalent to a clamping force command. This force will be continually changing with conditions and the requirements at the time. This brake command would then be fed to the DSP where the motor control algorithm would determine the operation of the motor. A simple control diagram is shown in Figure 1.1.

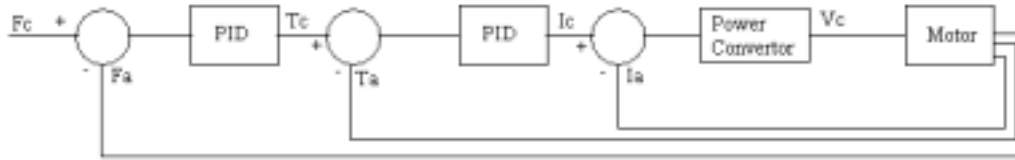


Figure 1.1 : Control Loops for the Electromechanical Brake System

There are essentially three feedback loops in this system that are used to determine the voltage that will be applied to the motor. The outer feedback loop the actual force on the pads would be compared to the commanded force and the DSP would generate a torque command for the motor. Then this torque command would be compared to the current torque on the motor and the DSP would generate a current command to the motor. In the innermost loop the current command would be compared to the current on the motor at the time and this would then be used to determine which of

the phases of the motor should be given voltage. The speed of the digital signal processor would allow all of these processes to occur in a very short loop, and operating the motor at optimal performance.

After the motor receives the proper voltage and torque commands that torque would be translated out onto the wheel. This would be accomplished by attaching the motor shaft to a ball-screw gear train. This would allow for the rotational motion of the shaft of the motor to be transferred into a horizontal motion. This motion would push the pads against the rotor and once the pad came into contact with the rotor, then the motion would generate a clamping force of the pads on the rotor. This force could be measured and fed back to the DSP in a lab environment. However, there will be a problem when the system is actually placed on the car. It will not be possible to place a sensor between the rotor and the pads on the actual wheel of the car. This means that the motor must be controlled without feedback from the wheels.

This is where some of the major control challenges come from in this system. Trying to control this system while only having the current and that voltage available is a very difficult task called sensorless control. Sensorless control of the switched reluctance motor is a very difficult objective. There are many reasons that cause this machine to be very difficult to control with or without feedback.

One problem is the fact that the system is always changing. The brake system is a very dynamic system. There are several modes of operation that must be considered for the system to operate effectively. The first mode is when the command force is first applied to the motor. When this occurs the pads are not touching the rotor. In this mode there will be very little torque required of the motor but it will be required to spin at a

very high rate of speed until the pads come into contact with the rotor. The torque and the direction of rotation are both in the apply direction.

In the second mode the force will be increasing at a desired rate until reaching a set point force. During this portion of operation the motor is not moving very far but it is generating large amounts of torque to produce the clamping force. This is very different from the first mode of operation. The direction of torque and rotation are in the same direction as the previous mode. This mode of operation is called near-zero speed operation and it is where most of the current sensorless techniques tend to fail. Once the set point force is reached the force command is decreased and the motor operates in yet another mode.

In this mode the motor is decreasing slightly the amount of clamping force that is required while still maintaining some force. This operation will require the motor to rotate in the reverse direction while the torque remains in the apply direction. This mode lasts until the commanded force is achieved. Then the motor will go to a fourth mode of operation.

Once the force command is achieved then the motor stops moving but maintains the torque in the apply direction. It will maintain this position until the force command is removed, which is equivalent to the brake pedal being released. This near zero speed operation causes many of the problems with the control of the switched reluctance motor.

Once the force command is released the motor turns in the reverse direction and the torque will be in the reverse direction. This mode will cause the brake pads to release the rotor and allow it to spin freely. This mode will last until there is no longer a

clamping force on the rotor and the pads are a sufficient distance from the rotor. Then the motor will wait for the next force command to come from the brake pedal.

The scenario that was described is for a normal apply cycle. It is important to realize that in the real brake system that any of these modes could come at any time. If a wheel is determined to have stopped spinning at anytime the clamping force to that wheel will be reduced so that the wheel can begin to spin. All the wheels should be spinning at the same speed at all times to have control of the car. Otherwise it is very difficult for the car to be steered, when a wheel is locked up.

In this section the basic operation of the electromechanical brake system has been described. The basic operation of all of the parts and how they will interact has been described. In the next section more detail will be given for the switch reluctance motor. The benefits and the problems with the switch reluctance motor will be discussed along with the motivation for the work that is presented here and how it will help to solve some of the problems that are associated with this application of this motor technology.

1.3 Switched Reluctance Motor

The motor that was chosen for study in this project was the 42V 8/6 switched reluctance motor. This motor has eight stator poles and six rotor poles and is shown in the Figure 1.2. This motor will provide the movement and the power for the electromechanical brake. The switched reluctance motor was one of the first types of motor that was invented but for many years it was one of the more difficult motors to control and to design. Developments in power electronics and computer design programs have made it easier to control and improve the design of these motors. There are many reasons that this motor would be desirable for this application.

The first advantage to having a switched reluctance motor is that the rotor of this motor does not have any windings or permanent magnets. There will not be any

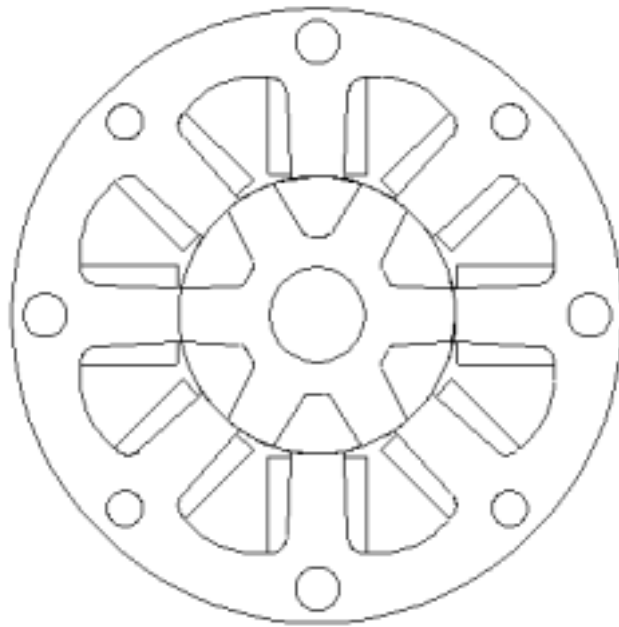


Figure 1.2 : 8/6 Switched Reluctance Machine

i^2r losses on the rotor. It also makes the rotor lighter than the rotor that would be in another type of motor. The rotor is typically made of the same material as that of the stator, laminated steel stacks. This type of rotor is lighter and will allow for the motor to easily change directions during operation. Meaning that if the motor is turning in one direction it will be very easy to change the rotation to be opposite the original direction. This will be helpful when the system is constantly changing directions to apply and release the brakes during an ABS cycle.

A benefit of this machine over a permanent magnet motor is for fault tolerance of the machine. Since there are no magnets on the rotor, if there is a phase-to-phase fault inside the machine then the rotor will rotate freely. In a permanent magnet motor the phase-to-phase fault would cause the machine to operate as a generator with a very low resistance. For this type of fault in a permanent magnet motor, the rotor would not keep turning. This is an important consideration for the brake system. Considering a permanent magnet motor with the brake at full apply and then a fault occurs, this wheel has the potential to stop spinning and lock up because the rotor cannot be back driven by the system. For the same system with a switched reluctance motor the fault would not cause the motor to keep the rotor from reversing direction. The pads would be forced back by external forces. This would keep the wheel from locking up and the car would be more easily controlled.

There are some disadvantages to using this motor as well. Because there are no windings or magnets on the rotor, the field must be generated on the rotor and this will cause the machine to be slightly less efficient. This motor will not be as efficient when compared to a permanent magnet motor. However, the efficiency will still be better than a brush type DC motor.

One of the biggest disadvantages of using this motor is that it is much more difficult to control. Algorithms for control are tough to develop, as is the hardware implementation of them once developed. Applying voltage to the unaligned phase will cause the rotor to move so that the excited phase will be in the aligned position. In order to move the machine properly and get the best performance of the machine, the position must be known at all times to have the proper phase voltage applied at the correct time.

Most of the current methods of control rely on using position encoder feedback to determine the position. This is not a desirable condition for this application.

Another big disadvantage of this type of motor is that the inductance changes as a function of the current and the position. Meaning that at anytime it would be difficult to know what the inductance of the machine is from the voltage and the current. Also with the operating conditions, temperature and loading, it is possible that the resistance on the coil can change by up to 200% of the rated value. Combining that fact with the near zero speed operation and the resistance between phases will probably not be the same at any time. These operating conditions make it very difficult to determine the position of the machine from the voltage and the current. This occurs because one current value could be related to many different possible positions and loading conditions.

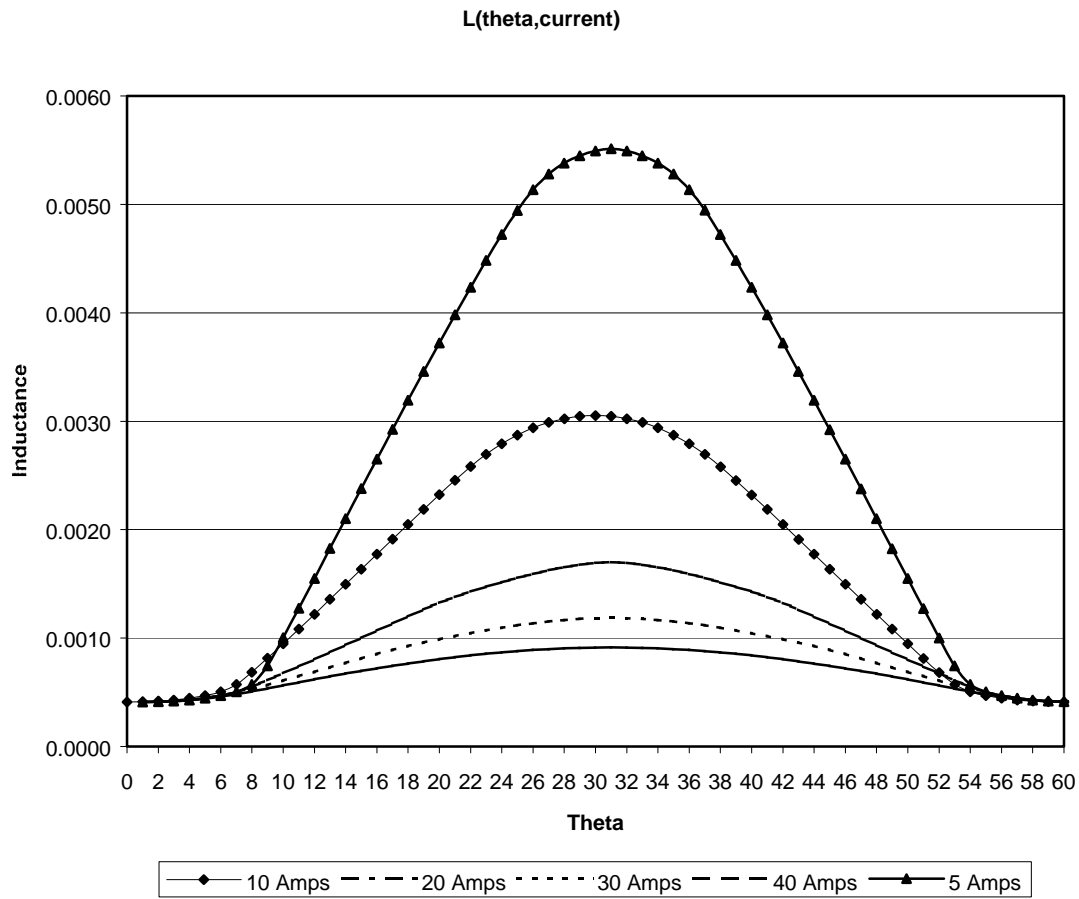


Figure 1.3 : Inductance as a Function of Current and Position

Another disadvantage of the switched reluctance machine is that the inductance is also affected by the manufacturing of the machine. Eccentricity or manufacturing differences due to the tolerances can cause two machines to have different machine parameters. Some of the changes that can occur would be differences in the airgap length, stack length and tooth width. These differences will cause changes in the inductance of the machine and the torque that can be produced. Other changes that could occur could be due to the bearings that are used to hold up the shaft or any other product that is used to make the motor. These changes can be significant enough to affect the

response of the system. One way to fix this would be to set very strict tolerances on all the parts but that would raise the cost, so other methods will be considered.

One solution would be to have all of the controllers tuned to match each of the individual motors. For mass production it would be impossible for each of the controllers to be tuned to the individual motors. It would also cause problems if the motor were ever changed. A way of solving that problem would be to have very tight manufacturing tolerances. This would create a lot of extra cost to produce the motor to those specifications. Another way would be to estimate the values as the machine is running.

If the voltage and the current were measured at each of the position for different loading conditions then the inductance could be estimated for the machine. This estimation has already been performed in the lab and estimated values of inductance and flux linkage have been determined. To validate these estimated results a finite element analysis was performed. The program that was chosen to produce the finite element analysis was Flux2D.

1.3 Finite Element Analysis and Flux2D

Flux2D is a package of software that allows the user to determine the parameters for a machine based on the dimensions of the machine and the operating positions. Then the program will divide the cross-section into many different pieces. At each of the intersections of these pieces it will calculate all of the important values until the numbers match at all the points to a predefined precision. This is the basic premise of how a finite element analysis package works. For Flux2D, the steps will be laid out in a little more detail.

The first step is to enter the important points that will be used to define the boundaries of the machine and determine the scale of the model. This will allow for the definition of the machine in a two-dimensional drawing. These points are entered to scale so that the machine looks reasonable on the monitor. The next step is to section off the machine and define the material properties of the various sections of the machine. Defining the sections as vacuum or as the metal that will be used to create the model so that it can then be simulated. After the materials have been decided on then a phase coil was excited and the machine was simulated. When the simulation is done all of the data is in a huge file to keep all of the data separate. The final step is post processing and it is where the data is taken out of Flux2D format and put into a form that can be used. This whole process will be shown in more detail in the chapter that explains Flux2D. Once the inductance was calculated for the machine then it was a matter of verifying the inductances with results that were obtained from estimation.

1.5 Analysis

Inductance values for this switched reluctance machine were obtained from two different methods. Each of the methods was performed independent of each other so that there results could be compared for similarities and differences that might exist in the inductance that was observed. The results from each of the methods are included in this paper.

One of the methods that was used to determine the inductance was estimation. The voltage and current were recorded for several different positions and for several different loading conditions. These values were then used to estimate the inductance. The results

of many different simulations were averaged so that a better value could be determined and the most noise could be taken out of the system.

The other method that was used is the one that is described in this paper. The inductance was calculated by using a finite element analysis tool. The results were generated at every position θ in an electrical cycle, sixty degrees for an 8/6 switched reluctance machine, and for various loads on the coil in terms of currents. This was done with Flux2D in an attempt to verify the results that were performed experimentally. The results were very close and are shown in a later chapter.

Chapter Two

Modeling of a Switched Reluctance Machine

2.1 Introduction

The SR motor is a motor that was designed many years ago but has only recently begun to be utilized. The developments in power electronics and computer design programs over the years have made it easier to control and improve the design of these motors. The design of the SR motor is different from all other motors in one major way, and that is that the rotor is not wound.

It is made from laminated iron stacks just like the stator core. This motor does not require magnets or wound copper on the rotor to produce the flux to make the motor turn. This occurs because the number of poles on the stator and the rotor is different for a SR motor. For example if there are eight stator poles there will be six rotor poles on the rotor. Typically there are more stator poles than there are rotor poles. This means that in different positions that there is always a set of poles on the rotor that is in an aligned position and a set in an unaligned position. When a set of poles is in the unaligned position that is the position of least inductance or greatest reluctance. Conversely when the poles are in an aligned position they are the point of

greatest inductance or lowest reluctance. Exciting the pole pairs that are in the unaligned position cause the pair to rotate and move to a position that will minimize the reluctance or maximize the inductance. By constantly exciting the unaligned pairs the motor will rotate.

This main design difference leads to many significant advantages for an SR motor when compared to other available motors. Since the rotor does not need to be wound it is not subject to copper, $i^2 R$, losses on the rotor and the weight is significantly reduced. This reduces the effect of inertia on the shaft. This allows the motor to change speeds more quickly than some others. Since the rotor does not have magnets there is no concern about heat demagnetizing the rotor and it can run at higher temperatures. Due to the design of the motor high torque values can be achieved at low speeds, which is beneficial to many applications. By not placing magnets on the shaft some money could be saved during construction of the motors however the airgap needs to be held to a tight tolerance during construction and this will add to the cost.

This main design advantage does cause some problems with the accurate modeling of the SR motor. The difficulty arises from the nonlinear relationship between the flux linkage, current and rotor position. One way to overcome this problem is using finite element modeling, FEM. This approach can be used to predict the actual parameters of the motor before it is created fairly accurately.

2.2 Model Development

The SR motor is more accurately described as a “statically commutated doubly-salient vernier reluctance motor” [2]. That is that the motor that has no windings on the rotor. This motor rotates because the poles try to move to a point where the reluctance is minimized. When this is achieved then another set of poles is excited and the process starts over again. The difference in reluctance is due to the fact that there are a different number of poles on the rotor and the stator.

To model the SR motor, a basic understanding of the operation must first be described. In the motor there will be a set of poles that are in the unaligned position, at the point of maximum reluctance. At this point what happens is that this set of stator poles is excited and the rotor tends to move, so that the reluctance is minimized. This happens when the poles are in the aligned position. To keep the rotor in motion this set of stator poles is turned off and the set that is now in the unaligned position is excited. The excitation of the phases is alternated to keep the rotor in constant motion and helps to maintain quasi-constant torque. Of course it is obvious that this motor is capable of motion in both directions and that is achieved simply by changing the order of excitation and not by the direction of current flow in the motor. The phase voltage only needs to be maintained in a constant direction while a phase is being excited so that the current can build. This model is sufficient for the understanding of the mathematical equations that describe the motion and operation of the SR motor.

2.3 Mathematical Model

A SR motor operates on the principle that positive torque is generated when a current is applied to the phase as the reluctance decreases, and reluctance decreasing is the same as the induction increasing. In the next section all of the equations that explain the operation of the SR motor will be shown.

As in most electric machines, the equation that describes the voltage is developed from Faraday's Law. The Law states that if a time changing field is present in a loop of wire that a voltage will be produced at the terminals. This voltage is related to the voltage by the flux linkage according to the following equation:

$$V = Ri + \frac{d\lambda}{dt}$$

In this case the flux linkage is a non-linear function of excitation current and rotor position. The equation can be broken into components by the chain rule:

$$V = Ri + \frac{d\lambda}{di} \cdot \frac{di}{dt} + \frac{d\lambda}{d\theta} \cdot \frac{d\theta}{dt}$$

In the previous equation, the second to last term is referred to as the transformer voltage because this is the typical voltage that is seen in a rotating machine or even in a transformer. The last term is referred to as the rotational voltage. This term is due to the changing flux that is due to the changing inductance as the motor is rotating. The next step in most cases is to neglect motor saturation which produces the following equation:

$$V = Ri + L(\theta) \frac{di}{dt} + i^2 \frac{dL(\theta)}{d\theta} \cdot \frac{d\theta}{dt}$$

Where the following is true:

$$\frac{d\theta}{dt} = \omega$$

Substituting yields the following equation:

$$V = Ri + L(\theta)\frac{di}{dt} + i^2\omega\frac{dL(\theta)}{dt}$$

This simple model of the SR motor helps to explain its operation; but to accomplish the simulation of this type of a motor and generate results that make sense a better model would have to be used. In the next section the inductance model will be presented in combination with a power converter that can be used to supply the voltage to the motor while maintaining the current at a reasonable level.

2.4 Inductance Model

The modeling of an 8/6 Switched Reluctance (SR) Motor is a very difficult task to accomplish based upon the changing inductance in the machine. Not only does the inductance change as a function of position but loading of the machine can also affect the inductance. With the complex commutation of this machine it is not easy to say when to apply a phase voltage to a phase or not. The power converter model will handle this complex switching and the motor template will simulate the operation of the machine. In this section an explanation of the simulation algorithms that will be used in the templates will be explained.

2.5 Simulation of the Power Converter

The power converter determines which if any of the phases should be turned on based on the operating conditions of the motor. At the beginning of the simulation

there are some conditions that need to be initialized. The angle of the motor shaft, $\theta(t=0)$, and the phase currents are all set equal to zero. The values for the bus voltage and the maximum current in the windings are all set to predetermined levels. After these conditions are set then an algorithm is implemented to analyze which phases should be turned on and which should be turned off.

The first information that the converter reads from the motor is the shaft speed of the motor. Then the new motor shaft angle is calculated with the equation:

$$\theta(n+1) = \theta(n) + \omega$$

Then considering each phase independently the value of θ is compared to the turn off and turn on angles for each phase listed in Table 2.1:

	θ_{on}	θ_{off}
Phase A	0	15
Phase B	15	30
Phase C	30	45
Phase D	45	60

Table 2.1 : Turn on/off Angles in Degrees for the Four Phases

and if:

$$\theta < \theta_{off} \text{ and } \theta_{on} < \theta$$

Then for that phase the voltage is turned off. If that condition is not the case then there is still one more condition that must hold. Using a form of hysteresis band control the current is maintained at a safe level for the machine. If

$I_{\text{phase}} < I_{\text{max}}$ and I_{phase} increasing or $I_{\text{phase}} < I_{\text{min}}$ and I_{phase} decreasing

then the voltage for that phase is turned on. Otherwise it is left off so that the current level in the winding will come back down to a safe level. With the proper choice of I_{max} and I_{min} it would be possible to determine an:

$$I_{\text{ave}} = \frac{(I_{\text{max}} + I_{\text{min}})}{2}$$

The power converter now applies the bus voltage to the correct phases and this voltage is passed to the motor. The converter passes the voltage command to the motor and the motor uses these values to calculate values of shaft speed, and phase current back to the converter. Now in the simulation of the motor there are equations that govern the motors operation and in the next section these equations will be explained.

2.6 Switch Reluctance Machine Modeling

The modeling of a switched reluctance motor can become very complicated since the inductance in each phase is a function of the current and the position of the rotor. Since there exists a different number of rotor and stator poles the inductance changes as the poles go from an aligned position to the unaligned position. At the aligned position the inductance is at a maximum, in the unaligned position it is at its minimum, and between the two points the inductance is defined by a non-linear function. In the next section the method for modeling this equation will be explained.

For one phase winding in the stator of the motor the equation that best represents the dynamic characteristics is:

$$V = R \cdot i + \frac{d\lambda}{dt}$$

V represents the phase voltage, R is the winding resistance, i is the winding current, and λ is the flux linkage of the winding.

The flux linkage is a function of the inductance, L, and the current defined as:

$$\lambda = L(\theta, i) \cdot i$$

As seen in Figure 2.1 $L(\theta, i)$ is a periodic function that can be represented by a Fourier series with respect to θ :

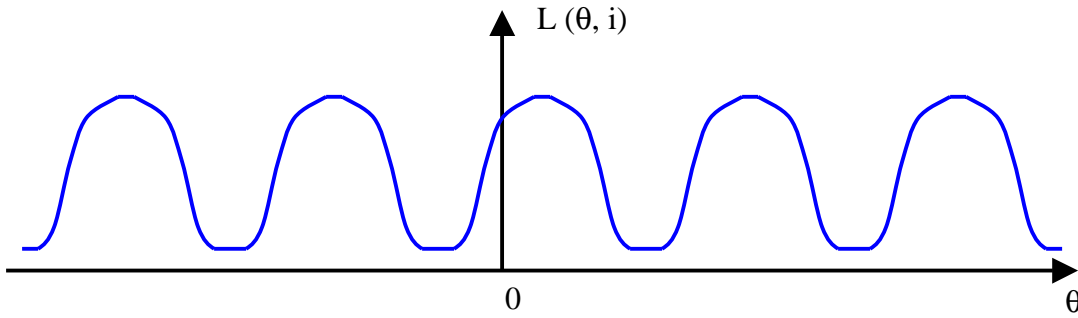


Figure 2.1 : $L(\theta, i)$ at Constant Current and Changing θ

$$L(\theta, i) = \sum_{n=0}^{\infty} L_n(i) \cos(n \cdot N_r \theta + \varphi)$$

N_r is the number of rotor poles in the motor and in this case there are six rotor poles.

For representation of the actual system only the first three terms of the Fourier series are used to compute $L(\theta, i)$ for the motor and the function is centered around the origin, $\varphi=0$, and thus the equation becomes:

$$L(\theta, i) = L_0(i) + L_1(i) \cos(N_r \theta) + L_2(i) \cos(2N_r \theta)$$

At this point the values L_1 , L_2 , and L_3 are unknown machine parameters. Now a method for extracting these values from the actual machine must be found.

By examining the inductance for one phase and period it can be shown that there are three inductance values that can be measured as shown in Figure 2.2.

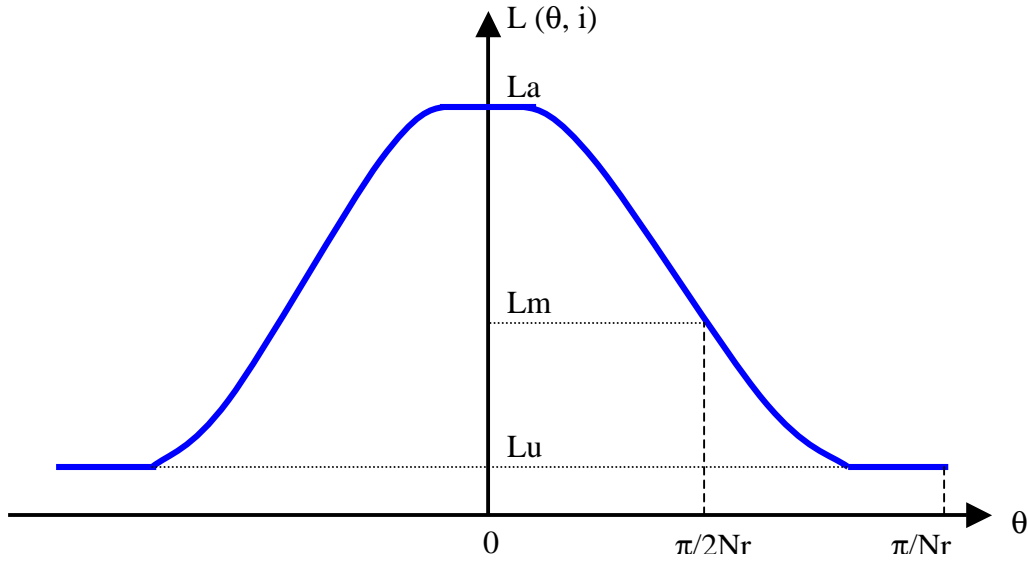


Figure 2.2 : Location of L_a , L_u , and L_m

This figure combined with the location of the terms for L_0 , L_1 , and L_2 produces a relationship between the two sets of terms:

$$L_a = L(0, i) = L_0(i) + L_1(i) + L_2(i)$$

$$L_u = L\left(\frac{\pi}{N_r}, i\right) = L_0(i) - L_1(i) + L_2(i)$$

and

$$L_m = L\left(\frac{\pi}{2N_r}, i\right) = L_0(i) - L_2(i)$$

L_m represents the inductance at the midpoint, $L(\theta_{\text{mid}}=\pi/2N_r)$ between $L(\theta=0)=L_a$ and $L(\theta=\pi/N_r)=L_u$. Using estimation methods it is possible to estimate the values for L_m , L_a , and L_u in an 8/6 switched reluctance machine, so these equations are solved for L_0 , L_1 , and L_2 :

$$L_0 = \frac{1}{2} \left[\frac{1}{2} (L_a + L_u) + L_m \right]$$

$$L_1 = \frac{1}{2} (L_a - L_u)$$

and,

$$L_2 = \frac{1}{2} \left[\frac{1}{2} (L_a + L_u) - L_m \right]$$

Now to estimate the values of L_a , L_m , and L_u it is first necessary to consider their properties. Since L_u occurs at the unaligned position of the machine, this is a position that is unsaturated and the inductance does not depend on the current. It can be treated as a constant with respect to current. On the other hand L_m , and L_a are very strongly dependent on current and must be represented by functions of the current:

$$L_a = \sum_{n=0}^k a_n \cdot i^n$$

and

$$L_m = \sum_{n=0}^k b_n \cdot i^n$$

The coefficients, a_n and b_n where $n=0,...,5$, are determined by curve fitting of data from measurement made on the motor or from finite element analysis.

Now expanding the original equation yields:

$$V = R \cdot i + L \frac{di}{dt} + i \frac{dL}{dt} = R \cdot i + L \frac{di}{dt} + i \left(\frac{\partial L}{\partial \theta} + \frac{\partial L}{\partial i} \cdot \frac{di}{dt} \right)$$

and in simulation

$$\frac{\partial L}{\partial \theta} = -\frac{N_r}{2} [(L_a - L_u) \sin(N_r \theta) + (L_a + L_u - 2L_m) \sin(2N_r \theta)]$$

Using this value in computer simulation it is possible to update the phase currents for the motor. After computing the inductance and the current for each phase it is possible to compute the torque that is generated on the shaft. The torque on the shaft is based on the equation that describes the field coenergy:

$$W_c(\theta, i) = \int_0^i \psi di$$

Then taking the derivative of the coenergy yields the torque:

$$T_e = \frac{\partial W_c(\theta, i)}{\partial \theta} = -\frac{N_r}{4} i^2 [(L_a^{**} - L_u) \sin(N_r \theta) + (L_a^{**} + L_u - 2L_m^{**}) \sin(2N_r \theta)]$$

where

$$L_a^{**} = \sum_{n=0}^k \frac{2}{(n+2)} a_n \cdot i^n$$

and

$$L_m^{**} = \sum_{n=0}^k \frac{2}{(n+2)} b_n \cdot i^n$$

Now by using the torque that is generated on the shaft and the load torque that is present, it is possible to compute the acceleration of the shaft α :

$$\alpha = \frac{1}{J} [T_e - T_L]$$

Now the motor model can be used to calculate all of the values that the power converter needs for the simulation and those values are passed back to the power converter. This is the completion of the first cycle of simulation that is required for the switched reluctance model. In computer simulation the process would start over with the power converter step one, determining which phases should be turned on and which of them should be turned off. Then the rest of the simulation would follow the steps that have been outlined in the rest of this paper and complete the simulation of the SR motor with a power converter.

Chapter Three

Finite Element Analysis of SR Motor

3.1 Introduction

To obtain the parameters of a motor such as inductance or core losses a model of the machine must be created and simulated. The model must contain all of the physical dimensions of the machine so that an accurate result can be obtained. These results then need to be used in a simulation to determine the values of the parameters. For this project the software that was chosen was Flux2D. This package of software is a finite element analysis package that will take all of the physical parameters and then compute the inductance. In this section the details of producing this simulation will be discussed.

There were six main sections of the Flux2D package that were used on this project and they would be geometry, materials database, physical, solve, results, and draw. Each of these parts has a different purpose in the program and must be used to obtain results from Flux2D. They each must be used in order to obtain the results that were required for this paper.

The first one is used to specify most of the dimensions of the cross section of the machine. It is used to create a representation of the machine that can be

simulated. Then in the materials database the magnetic properties of the steel that the rotor and stator are made of can be entered for use in the simulation. In the next step the different regions of the machine are defined as vacuum or as steel in the physical section. In this section the current levels in the phases can be set. Once all of the physical properties are set the solve section is used to determine all of the values of the machine. Once the simulation is done then the results section can be used to compute or display any of the results that would be required. The draw section is used to show any of the plots that are created in any of the sections. It can then save those files for use in other programs. The SR motor that is being study here was put into this model and starting with a description of the geometry each of the sections will be detailed here.

3.2 Geometry

The Geometry section is used for entering the data that will allow for a cross-sectional representation to be entered for the motor that is to be modeled. The five sections that make it up are parameters, points, lines, regions, and mesh generator. These are used to give the program the best picture of the machine possible. They must be used in order, so if a change must be made to the location of a point first the region that it is in must be eliminated and then the lines that are connected to it must be deleted before a change can be made unless the location is dependent upon a parameter that can be changed. With that in mind the first thing to do is to set up all of the parameters that one might use to alter the dimensions of the machine for the different simulations.

3.3 Parameter

This section is used so that parameters that might need to be changed on the model can be changed more easily. Parameters can be anything that needs to be changed or that might need to be labeled. The four parameters that were chosen for this simulation are Theta, Airgap, Rr, and Rs. These were chosen so that the airgap length could be altered to represent the different values that were available due to the tolerances that were given in the drawings that were used to manufacture the motor.

The first parameter that should be used in every simulation is theta. Theta will be used to duplicate the points on the machine. By knowing how many identical teeth are on the rotor or the stator it is possible to know the number of degrees that each of the points will be rotated and how many times. This way there are a fewer number of points that need to be entered but the whole machine is still being put into the simulation.

The rest of the parameters were terms that were used to represent the machine and allow for the machine to change size and airgap if necessary to simulate it properly. Rr represents the outer radius of the rotor. This value was taken from the drawing as a parameter. As part of the machine this dimension could change depending on which end of the tolerances the machine was created. Airgap was used to represent the gap that exists between the rotor and the stator. It is defined by the equation:

$$Airgap = \frac{1}{2}(StatorInnerDiameter - RotorOuterDiameter)$$

The last parameter that was used is the R_s , which was used to define the outer radius of the stator. This way the machine could be changed in size if it was needed. Once the parameters were set then the next step was to create the points.

3.4 Points

In the points section the main objective is to enter enough points into the model so that the geometry will be accurately captured for one rotor and one stator tooth. The first thing that was done was to figure out how many points would be needed for this simulation; nine points were used for a stator tooth, seven for a rotor tooth, and ten per coil that fit around each of the teeth. Then figuring out where all of the points are located using polar coordinates is the next step. This required the examination of the dimensional drawings of the motor and then using trigonometry to calculate where each of the points is located.

After defining where these points were to be located for one tooth on the stator and the rotor then the next step was to duplicate these points for all of the teeth on the machine. In this case the SR motor is an 8/6 machine. That means that on the stator there are eight identical teeth and on the rotor there are six identical teeth. Once the points for one whole stator tooth are defined, then the points can be rotated by forty-five degrees seven times and after defining one rotor tooth, the points could be duplicated by rotating the points sixty degrees five times. Now for the machine to take shape you need to connect all of the points with lines.

3.5 Lines

Lines are used to connect the points of the machine together so that the various regions of the machine can be defined. They are also important so that each of the regions can later be defined with the proper physical properties. The different lines that were used to form this machine were the straight line, arc, and circle. Each of these was used to come up with the correct shape. A plot of the motor geometry after all of the points and lines are defined is shown in the following figure.

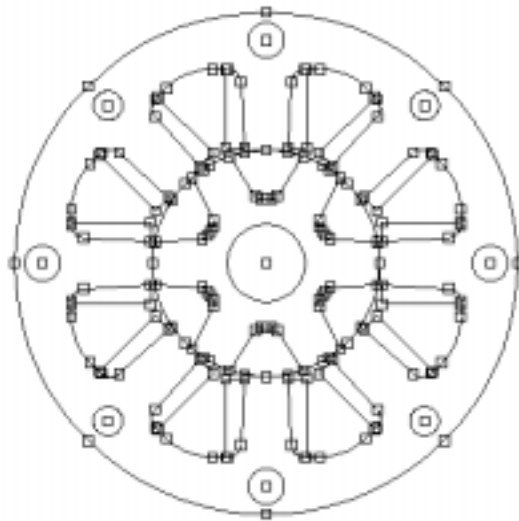


Figure 3.1 : Points and Lines from Flux2D for the SR Motor

3.6 Regions

This section is where each of the different regions of the motor are defined. For example this is where the stator, rotor, slots, and airgap are divided from each other. To be defined as a region it must be completely enclosed by lines in the previous section so that there is no overlap between the lines. Then the steps to define the region are fairly simple. The first step is to create a name for the region, chose a color for that region from the six that are available, and then you click inside the sections of the model that make up that region. When assigning the physical properties to the machine the only way to differentiate between them is by the regions that are created. In most cases it is wise to break up most of the regions so that different properties can be assigned to them later on in the process.

In this model there are twenty-two regions, which are hole, rotorslot, statorslot, airgap, stator, rotor, and the coils. For each of the phases there are four different coil regions so that leads to sixteen different coils, phasex1, phasex2, phasex1p, phasex2p (where x represents the phase a, b, c, or d and p designates prime). These represent the coils of the machine and can be excited to move the machine.

There are two important region names that were recognized by Flux2D and used in this project. Hole and airgap were used to distinguish two regions. The bolt holes and rotor shaft were defined as hole in this simulation. When a region is defined as a hole it is automatically filled with a vacuum and the region called airgap will be allowed to move in the simulation. These are two important things to

understand before attempting to simulate a motor in Flux2D. The regions that make up the machine are shown in Figure 3.2 even though without the various colors it is difficult to see the different regions.



Figure 3.2 : Regions Plot from Flux2D for the SR Motor

3.7 Mesh Generator

After the regions have been selected, the next step is to generate the mesh for the model. Flux2D comes with its own mesh generator but for most applications this mesh is too coarse to get accurate results. The mesh is what is used to create the points where the simulation will check to make sure that the model is accurate. The more points that the mesh has the more accurate the model will be; however this will slow down the computation time as well.

Subdividing the lines that made up the model creates the points that are used to generate the mesh elements. In this simulation two of the subdivision methods were used. The arithmetic and the geometric method were used to divide the lines properly. The arithmetic method takes the number of divisions that is specified and evenly distributes them across the length of the line. The geometric method uses a progressive weight to distribute more of the points on one end of the line. In other words the distance between the points gets longer as each point is placed based on the weight that is specified.

One other thing is that there can only be two sets of elements in the rotating airgap. There are two ways to insure that this occurs. One is to make sure that there are the same number of points of the rotor side and the stator side of the airgap. The second way is proposed by Flux2D and involves the airgap being divided into three sections. The airgap in this project was already very small so the numbers of points on both sides of the airgap were kept the same. For such a small airgap, a mesh point was placed every half-degree. This created a lot of elements but it was needed so that the elements would be considered good elements for this small airgap.

The next step was to subdivide the rest of the lines appropriately so that good results would be obtained. The lines that defined the teeth around the airgap were divided into very small pieces near the airgap because there is a lot of flux that is traveling through these areas. Also anyplace on the model where there was a sharp curve or angle, the pieces of the line were subdivided also. Once the initial subdivision of the lines was completed the mesh was generated.

Once the mesh was displayed the poor elements were displayed in green and total there was about 1000 of them. The elements are triangles and Flu2D defines poor elements as triangles whose angles are too large or too small. The first step was to remove the bad elements that were around the coils. The areas that are green typically need more subdivisions to make the elements acceptable by the Flux2D mesh generator. In the original drawing of the coil there was a small gap between the coil and the tooth where the two came together. To get rid of all of the bad elements the lines would have required many subdivisions. To avoid this problem the area of the coil was kept the same but the small gaps were removed between the tooth and the coil. This still left some bad elements so the lines that were producing these poor elements were then subdivided more and the mesh was regenerated. This was an iterative process that continued until there were nine poor elements out of 12517. It was around .07%, which is very small, and none of the poor elements were near the airgap so the model was allowed to create the mesh file that was needed for simulation. The mesh will be shown in Figure 3.3:

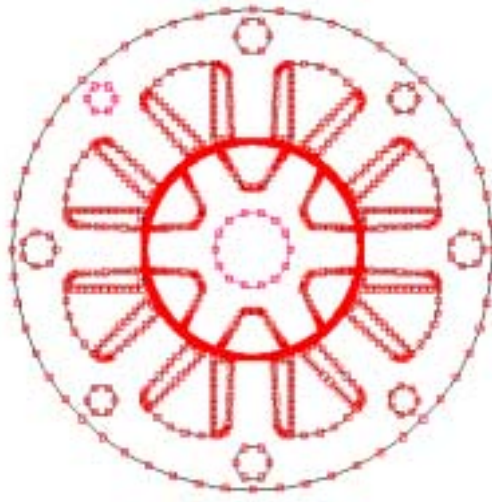


Figure 3.3 : Mesh Nodes Plot from Flux2D for the SR Motor

Mesh generation is the last step in creating the geometry for a model and it is shown in Figure 3.4. Now that the geometry has been created the next step is to create the material that will make up the model.

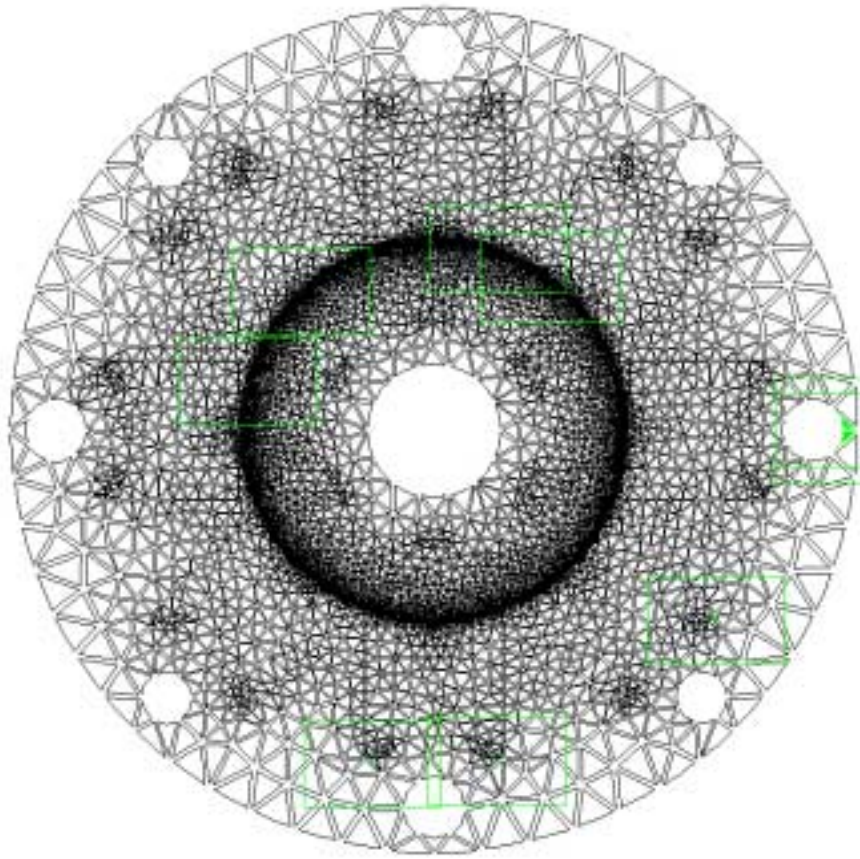


Figure 3.4 : Generated Mesh Plot from Flux2D for the SR Motor

3.8 Material Database

In this section of Flux2D the materials that compose your model can be created with the correct properties. The steel that is created for the simulation must have the same magnetic properties as the steel that was used to make the motor. This way accurate results can be obtained from the simulation. The stator and rotor of the motor were made from M-19 non-oriented silicone steel with C-5 core plate. The magnetic curve for that data is shown in Figure 3.5.

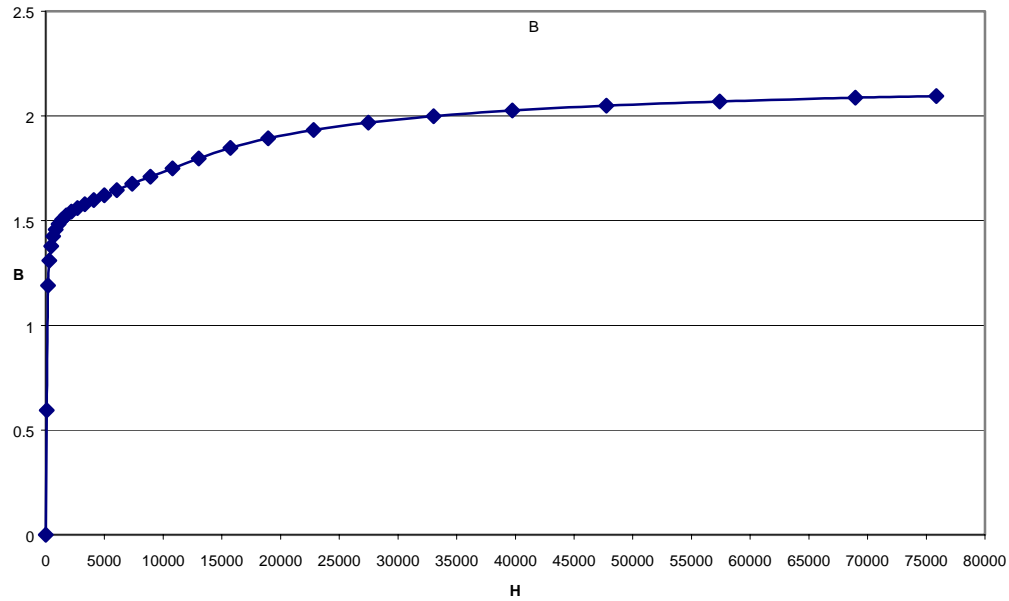


Figure 3.5 : B-H Curve for M-19 Non-Oriented Steel

To enter this data into the material database meant that a new material would have to be created. After choosing the name, the next step was to select the property that would be created for this material. By selecting isotropic μ from the menu and selecting tensor spline as the way that the curve would be defined. The next step was to enter the B-H data for the material. Then the points were plotted on a graph and the spline was chosen. To choose the spline was to select three points and the saturation value. Once those were chosen the program would show the spline that would be chosen for those values. The spline could be adjusted until the proper fit was achieved. Once this was completed then the material was ready to be used in the

model. This material could now be used to assign the magnetic properties to the rotor and the stator of the machine in the physical section of Flux2D.

3.9 Physical

This section is used to assign the properties to the model and to define the type of simulation that will be used. For this simulation a transient magneto-static simulation was performed on the model. With that decision made, the airgap is allowed to move; the results will be obtained for the change that occurs as the motor changes position. Currents can also be assigned to the phases that are of interest and the machine length is also specified at this point.

The first step is to define a new problem and the program will then ask which of the geometries that have been defined will be used for this simulation. After selecting the geometry then the length of the machine will be needed. In this case the machine length was chosen to be equal to the length of the rotor, which was slightly shorter than the length of the stator. Then the problem type is chosen as transient magneto-static. The next step is to define all of the regions with the proper values.

For each of the regions the material that composes it must be assigned in order for the simulation to generate meaningful results. The choices of material in this simulation were steel and vacuum. The stator and rotor regions were composed of the steel that was defined in the materials database and assigned to have no source inside them. There was no external current being put through these particular regions. The statorslot and rotorslot were assigned the same properties of vacuum with no external source. Then all of the coils except phase C were assigned the same

as the rotor and stator slots. Because the coils are not solid metal they are assigned the same properties as air and this has little affect on the simulation results.

Phase C regions were also assigned as a vacuum but with a small difference from the other coils. These coils would be given a current so that they would create a flux path inside the machine. To do this the constant current choice was selected and total value was selected since the current density and the number of turns were known. The value was chosen based on the equation:

$$TotalCurrent = Numberofturns * Current$$

The direction of the current in each of the coils was then chosen so that the flux would flow in the correct direction for the machine operation. In this case phasec1 and phasec2 were given positive current while phasec1p and phasec2p were given negative current values.

The last section that was described in this section was that of the airgap. The section was defined as a y rotating air gap with constant angular velocity. This allows for the rotor of the machine to turn and the results to be generated. The speed that was chosen for this machine was 60 rpm. This value was not very important since is a static simulation and there are no effects of speed. The only reason this was chosen is so that time step could be chosen to get the proper resolution of the results. In this case the results were needed for every degree of rotation, so the time step was calculated to be:

$$timestep = 1 \text{ deg} \cdot \frac{1 \text{ rev}}{360 \text{ deg}} \cdot \frac{1 \text{ min}}{60 \text{ rev}} \cdot \frac{60 \text{ sec}}{1 \text{ min}} = .002778 \text{ sec}$$

With all of the properties assigned to the regions now the boundary conditions were assigned to the motor. The boundary conditions help the model to determine where the flux will travel within the model. In the case of this simulation there is only one type of boundary condition that needed to be created. That was the dirichlet boundaries where the machine would have zero flux passing. The three places that received that boundary condition were the outside diameter of the machine stator, the outer diameter of the shaft inside the rotor, and on all of the outer dimensions on the bolt holes. Each of these regions is assumed to have no flux passing through them. Once the boundary conditions have been created the model is ready to simulate.

This would only simulate the results for one current level and in the SR motor the current directly affects the results that would be gathered for things such as the inductance. To create more models with different currents levels is very simple. Using the modify option in the physical menu, a new model can be created that is based on the previous problem. Then after changing the current in the appropriate phase and accepting the previous boundary conditions the new model could also be simulated. This way many simulations for the same geometry and physical description can be performed at many different currents and the results can be compared.

3.10 Solve

This is the program that actually performs and generates the results for Flux2D. It can be programmed to perform many simulations in a row since the program can take a long time to compute simulations. This is accomplished by using

the batch solver that is included. The first thing that must be done to use the batch solver is to prepare the files. This involves selecting all of the files that need to be processed and then pushing the prepare button. Once the prepare button has been pushed it will ask several questions.

The answers that were used for the results from this simulation will be included here with the paraphrased question. My solution did not utilize the progressive algorithm and set the initial position to negative one degree. This is because the solver rotates the machine one time step before calculating any of the results and the time step that was chosen for the simulations will rotate this machine one degree at each time step. This will get the simulation to start at zero degrees. The next step is the value for the initial time step and for this case it is set to the value that was calculated earlier. The time limit for the computation was set to be equal to 3500 seconds. That is the amount of time that it will take to calculate the answer before stopping the simulation. It was just set large enough so that the calculations would not be affected.

Then the number of time steps that was chosen was thirty-one because it takes sixty degrees to go through one electrical cycle and the machine is symmetrical during the first and second half of this cycle. Then the upper and lower limit for the simulation time step can be set. For this simulation the upper and lower limit were also set to .002778 so that each time step the rotor of the machine would move the same distance. This would give smoother results when looking at the results. The next question was how many time steps to store and all of them are stored. This

makes the most sense for my simulation. The computation that is performed by the solver is iterative so the maximum number of iterations must be set. It was set to fifty a high number so that the solver could perform as many as needed. The precision was set to .001 and this seemed to be an adequate precision for the simulation that was performed. If the results had been very rough or the graphs would have produced jagged lines then the precision could have been increased and the results obtained again.

Once these questions were answered for each of the simulations in the batch it was time to run the simulations. Selecting the simulations that needed to be run and pressing start would run each of the simulations and the results would be stored. These simulations would run without any user input to allow for many hours of computation to be performed. The results from the solver then need to be processed in the results section to be useable in other programs.

3.11 Results

This part is used to display the results that have been computed by the solver. It can display the results to the screen for quick verification or it can be printed to a list, which prints the data to a file that is space delineated. These two options allow for the data to be used in a very user-friendly matter.

The first results that were examined were the equi flux lines for the whole machine at two different time steps to make sure that the flux was traveling in paths that made sense. In Figure 3.6 through 3.10 the plots of the flux lines at each position with phase C excited are shown, to prove that the results seem reasonable.

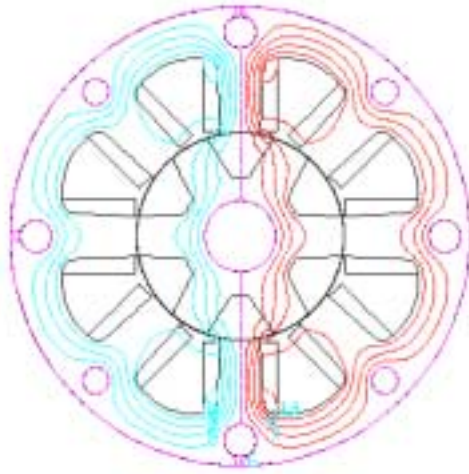


Figure 3.6 : Unaligned Position for Phase C

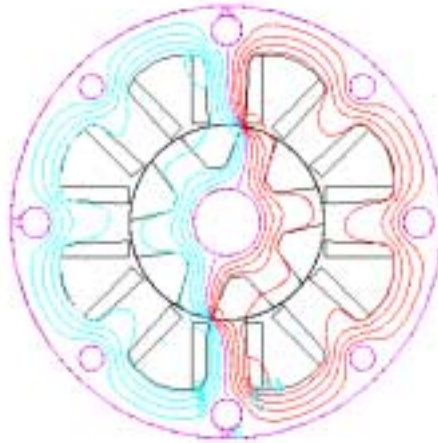


Figure 3.7 : Motor at Ten Degrees for Phase C

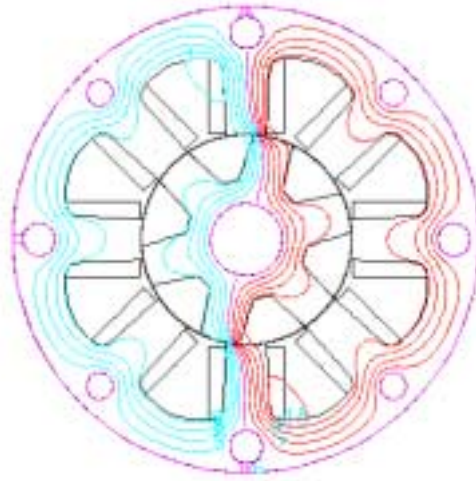


Figure 3.8 : Motor at the Midpoint for Phase C, Fifteen Degrees

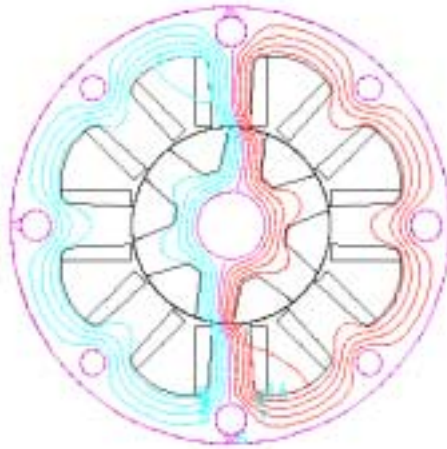


Figure 3.9 : Motor at Twenty Degrees for Phase C

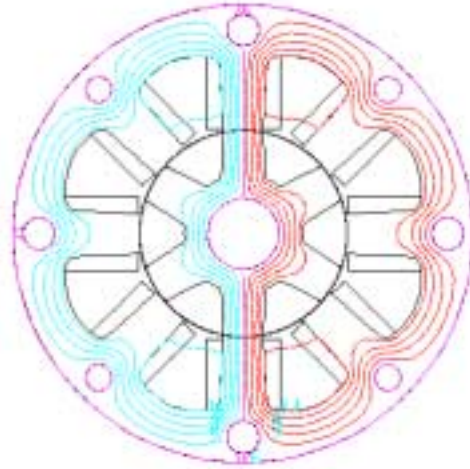


Figure 3.10 : Aligned Position for Phase C

From other papers it was seen that the flux would travel from one pole into the rotor across to the other pole and then back through the stator to the point of origin. It can be seen from the plots that this machine is generating the same results as expected.

Once the flux lines were used to verify that the flux paths were correct, the next simulation that was performed was to calculate the inductance of the machine as phase C went from the unaligned to aligned position. To produce this result time variation was chosen from the menu and the whole time range was selected. Then a group region was selected to include phasec1 and phasec1p. After inputting the

number of turns in each of the coils the inductance was computed at each time step and then put into a space-delineated list with the time step that it was associated with. A list was produced for every current value and then Excel was used to put the data into graphs to show the result.

There are many other results that are computed at each time step but equi flux lines and the inductance are the ones that have been utilized so far in the results. These results that were obtained were put into Excel and the data was processed until the values that were desired were obtained. First the inductance was doubled because the result from Flux2D was for one coil and there were two coils in parallel in this motor arrangement. Then to obtain flux the inductance was multiplied by the current and used to create graphs of λ , which is the flux linkage.

$$\lambda = L \cdot i$$

Where L is the inductance and i is the current in the phase. This was used to compute the flux linkage for various theta values as the current was increased. That graph is shown in Figure 3.11.

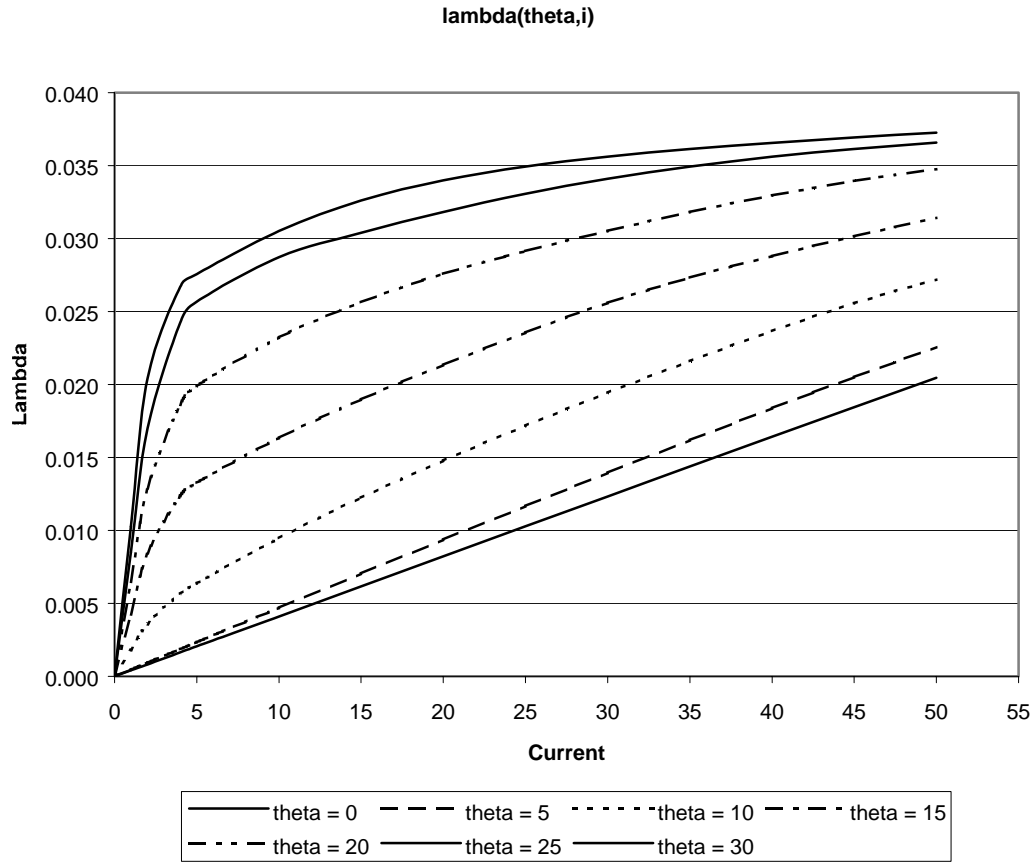


Figure 3.11 : Lambda versus Current for Different Positions

3.12 Draw

This program is used to look at all of the plots that are taken inside the various other Flux2D sections. When a plot is created it is saved inside a .des file that is not accessible by other programs but can be used by draw. Using draw to open the plot files then the individual plots can be saved as files that can be directly imported into a windows file. For this paper many of the plots were cut and pasted into Microsoft Paint. Then the pictures were cropped so that they would be easier to see. Then the

pictures were saved as bitmaps and inserted into the word document. This makes it easier for the work from these programs to be displayed and shown in this type of paper.

3.13 Conclusion

This paper went through the six main sections of Flux2D and showed how each of them could be used to help generate a two-dimensional switched reluctance motor model. It showed how to enter the simple geometry and how to define the different regions in the simulation. After that it went through the steps that were used to create the mesh file so that a good simulation would be made for a motor with such a tiny airgap. It showed how to enter steel characteristics so that the machine would be simulated with the same properties, as the actual machine would have. Then the steps to defining the boundary conditions were explained. After that the steps that were used to generate the results using the batch solver were discussed and how to process the results that are obtained. This section explained the method that was used to generate the Flux2D results that are contained in this paper.

Chapter Four

Analysis

4.1 Introduction

The main tool that was used to produce results that could be analyzed for this motor was Flux2D. It uses finite element analysis to determine motor parameters at defined intervals. The model was also configured for several current levels. At each of the current levels it would step through one electrical cycle or sixty degrees and perform all the calculations. Each step in this simulation was equivalent to one degree. The next step was to use the post processing tools inside Flux2D to obtain the data that was important to this research, the inductance.

There are many different types of post processing that can be performed on the data. To select that the program compute the inductance for a particular phase here are the steps that need to be followed. First after the solver has finished its computations for one particular machine condition the data can be analyzed by starting the results sub program.

Once the results program starts up it will list all of the projects that have finished with computations. Select from the name of the project that needs to be analyzed from the menu. It may take some time to load but then a listing of all of the

time steps will appear on the right hand side menu. Choose one of the time steps and wait for the picture of the machine at that time to load. Then choose time variation from the sub menu and all of the time steps will show up in the sub menu. To select all of the positions that were run in the simulation choose the option whole. Selecting the option for inductance and the menu will list all of the regions that had an active current for the simulation that was run. For these results a group was selected by selecting the positive and the negative sides of one tooth. Then since the current in the coil was entered as a current density, the program will ask for the number of turns per coil. The number was entered for each of the coils and the program was allowed to compute the inductance. This process can take some time, as the computer will calculate the inductance of the coil at every time step.

When finished the data can be displayed to the screen by selecting display and then selecting inductance. When it prompts for a curve to superimpose select quit and a graph of the inductance versus time will be shown on the screen. To get the data to a form that can be used by other programs the data can be printed to a list. The default print option is screen so this must be changed every time that inductance is calculated. Under the option menu select printing mode and then select list. After quitting back to the print and display menu, by selecting print the data will be put into a tab delineated file.

Now to put the data in form to be put into graphs the data was brought into Microsoft Excel. Excel does a nice job of reading in delineated files and putting everything into columns. The final calculation that was performed was to double the

inductance since for each phase there are two coils that are connected in series. The time step was also converted to an angle by knowing how fast the machine would move in each time step:

$$L_{\Phi} = L_{coil} + L_{coil}$$

$$\theta^{\circ} = \frac{\text{sec}}{60 \text{ sec}} \cdot \frac{1 \text{ min}}{60 \text{ sec}} \cdot \frac{60 \text{ rev}}{\text{min}} \cdot \frac{360^{\circ}}{1 \text{ rev}}$$

This would put the data in the form $L(\theta, i)$. To compare this data to estimated data from the machine the flux linkage would have to be calculated by:

$$\lambda = i \cdot L(\theta, i)$$

This process was performed for each of the different cases. There were two cases that were considered in the simulation and the differences between the two was that the air gap distance was changed to reflect the manufacturing tolerances that were set on the machine by the drawings that were used to construct the machine. Each of these was run for current varying from one amp up to fifty amps and for the angle varying through the sixty degrees that makes up the electrical cycle in an 8/6 SR machine. Once this data was arranged, it was then compared to the estimated values.

A table was computed that calculated the mean error and variance between the estimated and the calculated results. At each rotor position the value of the flux for each of the currents was taken. The mean error was calculated by:

$$\bar{\lambda}(\theta) = \frac{1}{9} \sum (\lambda_e(\theta, i) - \lambda_c(\theta, i))$$

$$i = 1, 2, 5, 10, 15, 20, 25$$

Then from the mean and the estimated values the variance and the standard deviation can be computed by:

$$\text{var}(\theta) = \frac{1}{9} \sum (\bar{\lambda}(\theta) - \lambda_e(\theta, i))^2$$

$$\sigma = \sqrt{\text{var}}$$

$$i = 1, 2, 5, 10, 15, 20, 25$$

The results are presented in Table 4.1:

Theta (degrees)	0	1	2	3	4	5	6
Sum of the Error	0.00749	0.00793	0.00936	0.01163	0.01435	0.01753	0.02046
Mean lambda	0.00083	0.00088	0.00104	0.00129	0.00159	0.00195	0.00227
Variance	0.00003	0.00003	0.00004	0.00004	0.00005	0.00005	0.00006
Standard Deviation	0.00569	0.00575	0.00595	0.00627	0.00673	0.00727	0.00796
Theta (degrees)	7	8	9	10	11	12	13
Sum of the Error	0.02257	0.02269	0.02074	0.01874	0.01655	0.01414	0.01154
Mean lambda	0.00251	0.00252	0.00230	0.00208	0.00184	0.00157	0.00128
Variance	0.00008	0.00009	0.00012	0.00014	0.00017	0.00019	0.00022
Standard Deviation	0.00873	0.00969	0.01074	0.01182	0.01286	0.01385	0.01479
Theta (degrees)	14	15	16	17	18	19	20
Sum of the Error	0.00836	0.00492	0.00116	-0.00309	-0.00744	-0.01214	-0.01714
Mean lambda	0.00093	0.00055	0.00013	-0.00034	-0.00083	-0.00135	-0.00190
Variance	0.00025	0.00027	0.00030	0.00033	0.00036	0.00040	0.00043
Standard Deviation	0.01570	0.01657	0.01742	0.01826	0.01909	0.01991	0.02070
Theta (degrees)	21	22	23	24	25	26	27
Sum of the Error	-0.02207	-0.02699	-0.03174	-0.03648	-0.04093	-0.04492	-0.04844
Mean lambda	-0.00245	-0.00300	-0.00353	-0.00405	-0.00455	-0.00499	-0.00538
Variance	0.00046	0.00049	0.00053	0.00056	0.00059	0.00062	0.00064
Standard Deviation	0.02148	0.02223	0.02295	0.02363	0.02425	0.02480	0.02526
Theta (degrees)	28	29	30				
Sum of the Error	-0.05135	-0.05560	-0.05467				
Mean lambda	-0.00571	-0.00618	-0.00607				
Variance	0.00066	0.00069	0.00068				
Standard Deviation	0.02564	0.02623	0.02605				

Table 4.1 : The Mean Error and the Standard Deviation of Flux

From the table it can be seen that the error is relatively small. The estimated data from the real machine and the data that was calculated with Flux2D seem to be very close together. From looking at the data that is presented here it is easy to see that the error starts out small at the unaligned position. Then as the angle increases to eight degrees the mean between the two increases, but after eight the error becomes smaller again. It hits a minimum at fifteen or sixteen degrees and then increases till the aligned position where it attains its largest value. The mean at this point is almost three times the mean at six or seven degrees. This is probably because of saturation in the actual machine that does not occur in the model.

The variance has results that were a little bit different looking than that of the mean. The variance starts off with the smallest value at the unaligned position and increases until the aligned position. This would make sense since the variance is based on the mean and the mean is very large at aligned position. When the mean is large then when the difference between the mean the estimated value is squared that number becomes very large. This will cause the variance to be much larger at the aligned position. The variance at this point is almost twenty-three times the variance at the unaligned position.

As for the mean, the reason for this large increase is probably in the saturation of the actual machine that is not captured by the Flux2D model in its calculations. The actual teeth are probably saturating before the teeth that are in the model. However there might be some error in the estimation as well. The resistance might be changing or other factors might be keeping the value low. This result is probably

also a product of the saturation that is not shown in the Flux2D model. Figure 4.1 and 4.2 show the mean error and the variance versus theta, respectively:

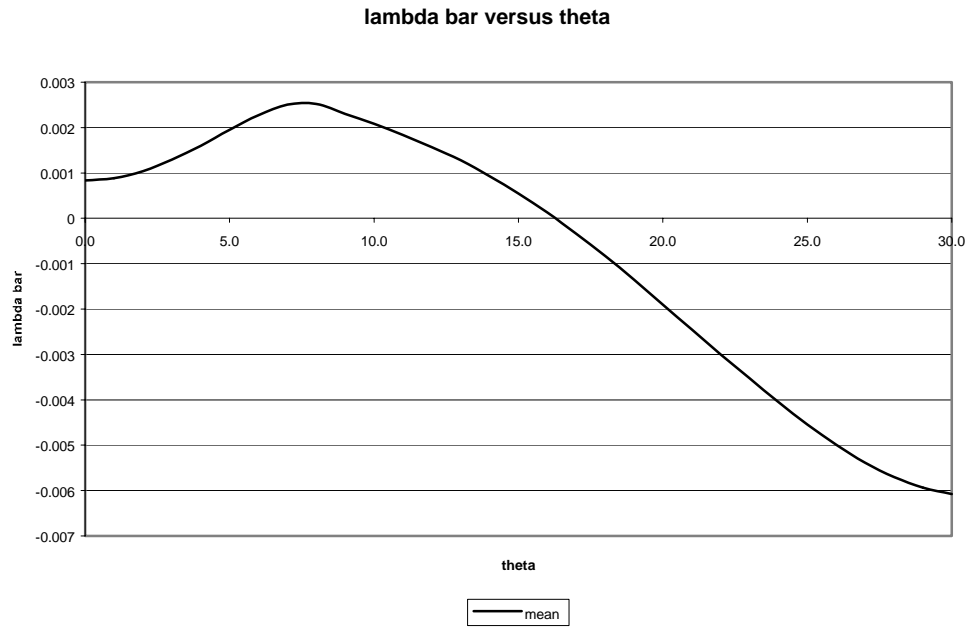


Figure 4.1 : Lambda Bar(Mean) versus Theta

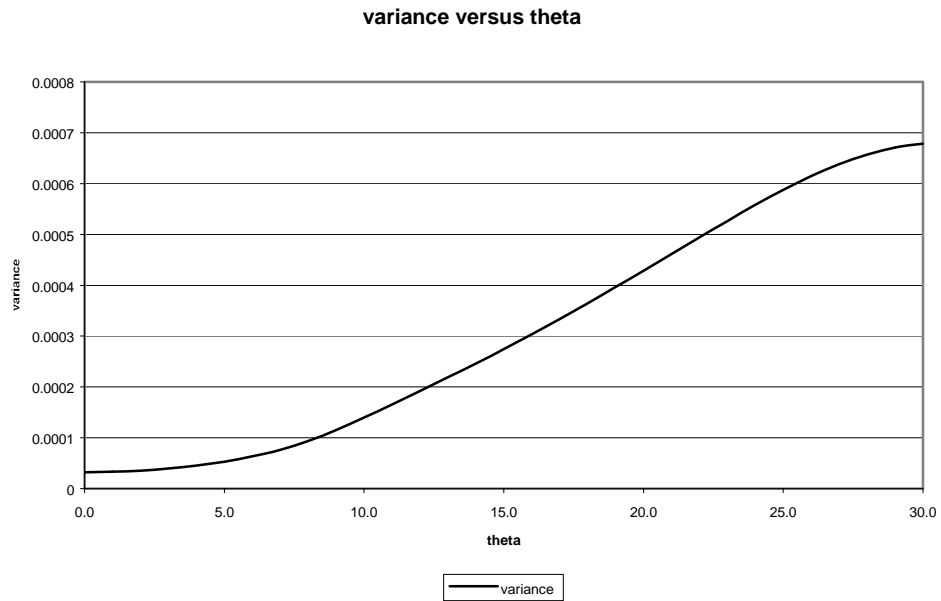


Figure 4.2 : Variance versus Theta

For certain positions of theta there was a graph created of λ versus the current for the estimated values and the two calculated values from Flux2D. These graphs will be shown here and then the results will be discussed for each graph. The differences in the standard deviation and variance will be explained with an understanding of how the actual machine has varied from the machine that was designed on paper. For several positions λ_e and λ_c will be graphed together and errors will be explained. At the end each a graph for λ_e and λ_c will be shown for various rotor positions.

4.2 Results at Unaligned Position, $\theta=0^\circ$

At this position the machine has the lowest value of inductance and the material is totally unsaturated. This will produce an inductance profile that is a straight line. This means that an increase in current will see a proportional increase in flux linkage. This is only true when the machine is in an unsaturated position, the unaligned position. The error between the actual and estimated λ is also very small. Figure 4.3 shows the results.

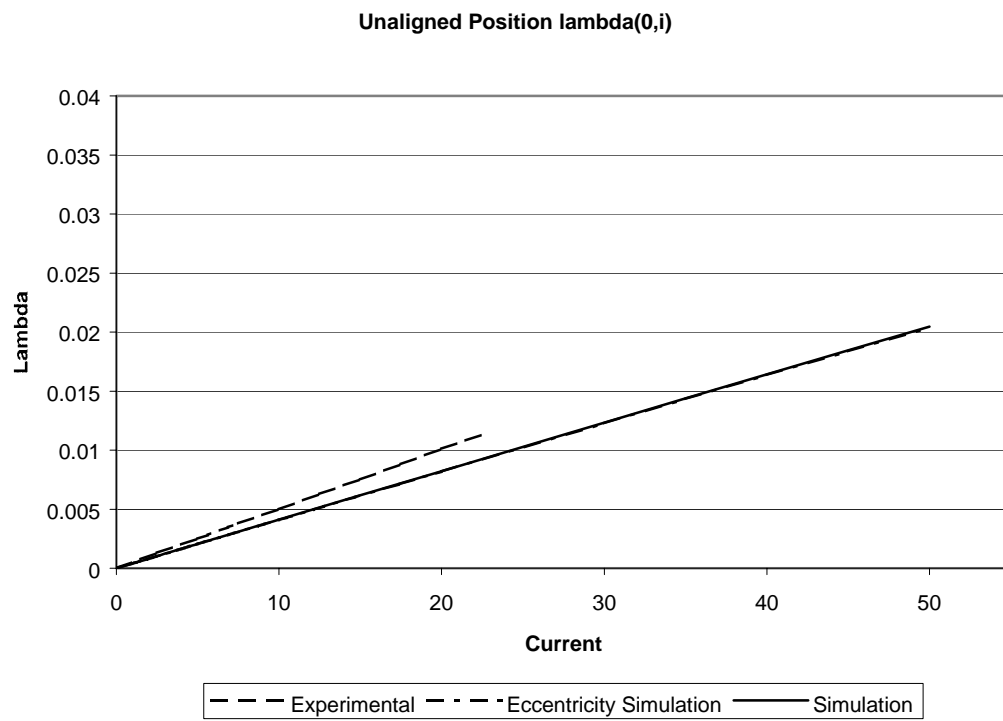
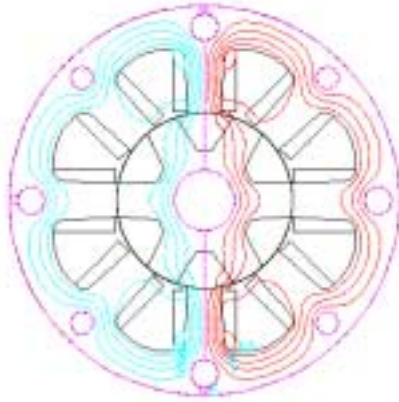


Figure 4.3 : Fluxlinkage versus Current at Unaligned Position

4.3 Results at $\theta=5^\circ$

At this position the machine is still unsaturated. The machine has not saturated and an increase in current will produce an increase in flux linkage for the range of current that is being considered in this report. The deviation from the estimated results has begun to get a bit larger in this graph but for the most part the results are very close.

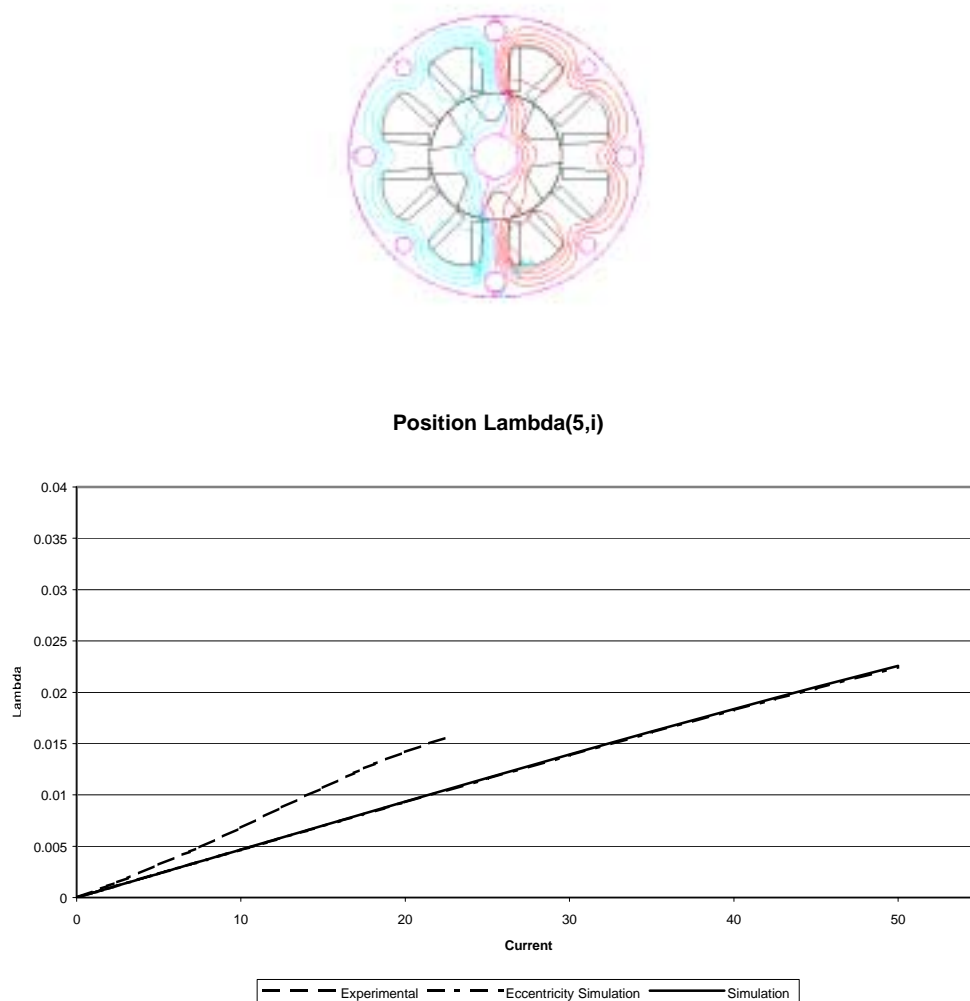


Figure 4.4 : Fluxlinkage versus Current at Theta equals five degrees

4.4 Results at $\theta=10^\circ$

At this position the machine starts to show the effects of saturation. The deviation has grown again but this time it is because the actual model shows that there is a higher flux linkage than Flux2D has calculated. This may be due to sensor noise in the calculated results at the low flux value. The results remain close for this position.

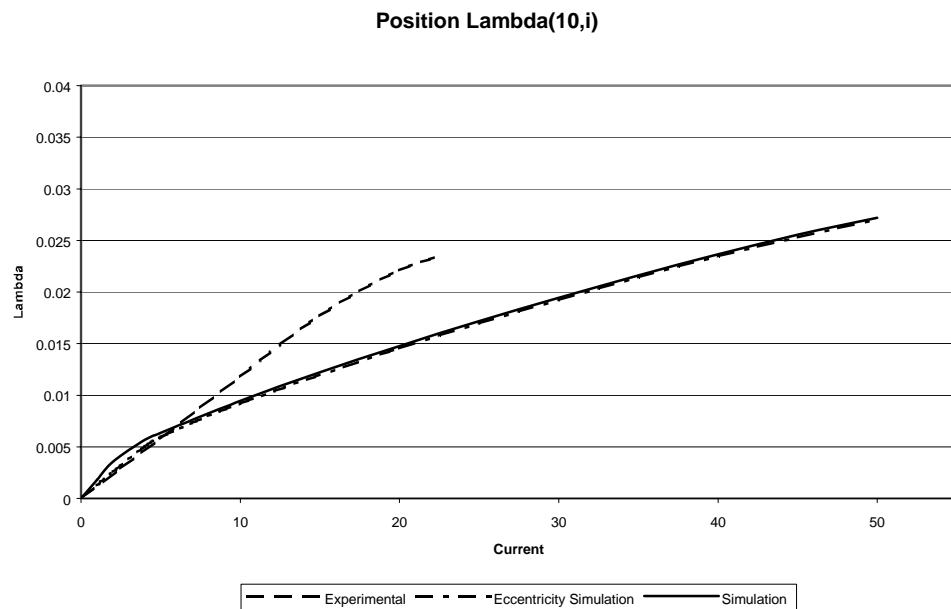
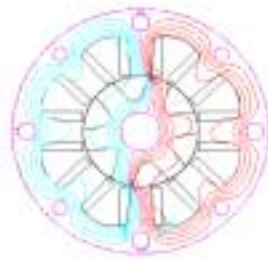


Figure 4.5 : Fluxlinkage versus Current at Theta Equals Ten Degrees

4.5 Results at $\theta=15^\circ$

At this position the effects of saturation are evident. There is no longer a proportional flux gain with current increase, meaning that the machine flux is saturating the metal. The estimated and calculated come very close to each other in this section, which is shown in the previous tables.

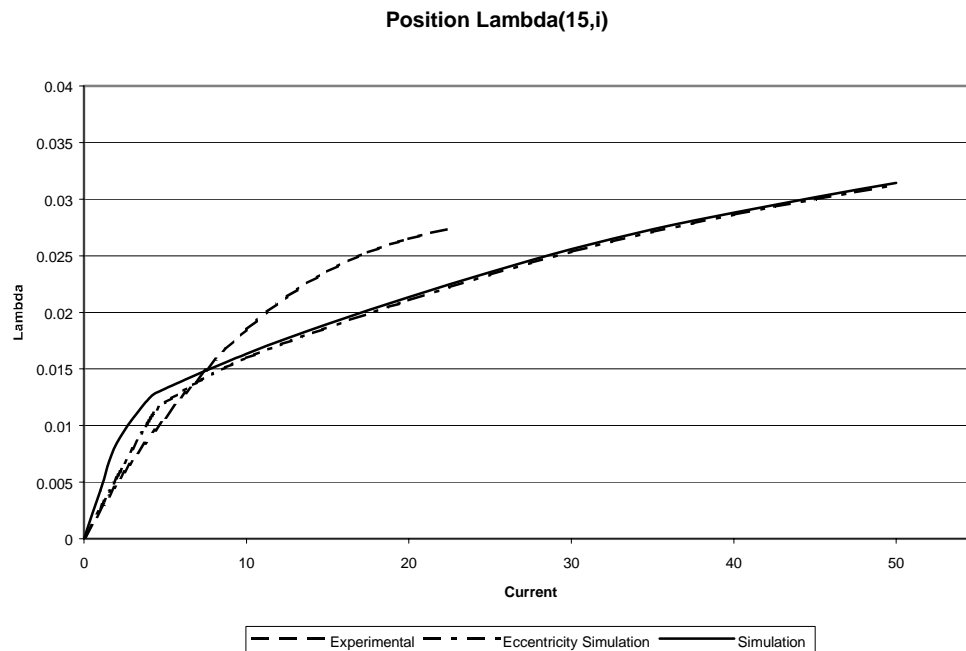
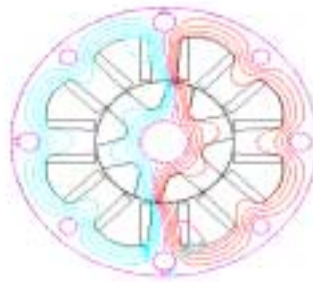


Figure 4.6 : Fluxlinkage versus Current at Theta equals Fifteen Degrees

4.6 Results at $\theta=20^\circ$

At this position the effects of saturation have increased. The saturation effect is more predominate in the estimated values, meaning that Flux2D is not accounting enough for the saturation. Even with this at low current the graphs are almost on top of each other.

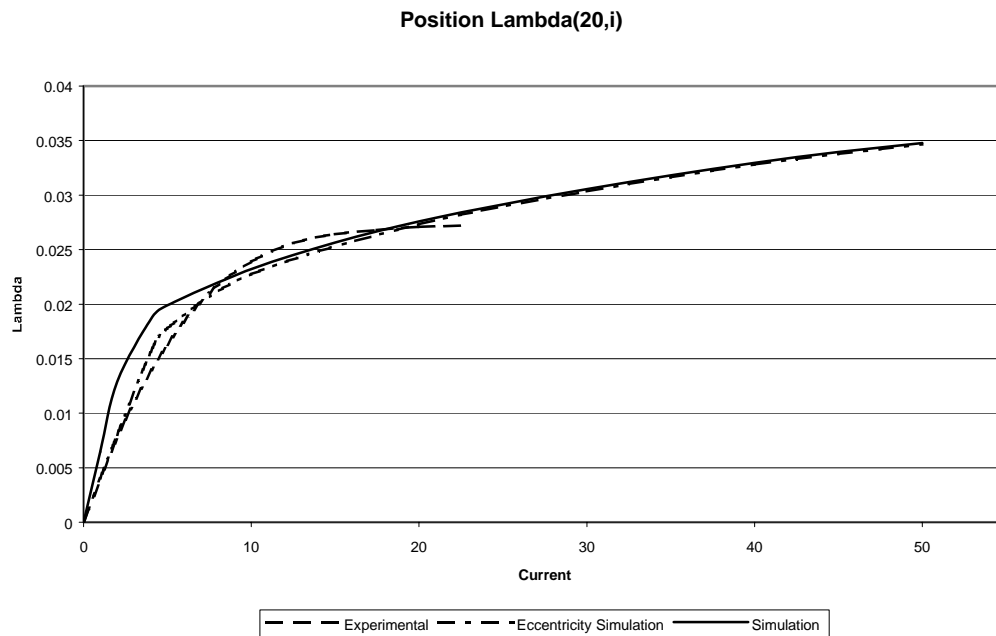
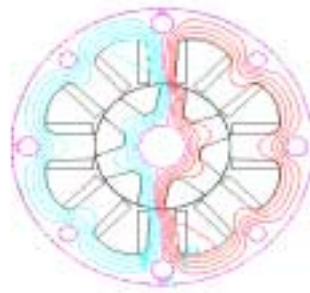


Figure 4.7 : Fluxlinkage versus Current at Theta equals Twenty Degrees

4.7 Results at $\theta=25^\circ$

At this position the two graphs seem to be getting further apart. At higher currents the estimated values become almost a horizontal line, which means that there is no increase in flux with an increase in current but Flux2D is still calculating a flux increase with current increase and two things are causing the graphs to get further apart.

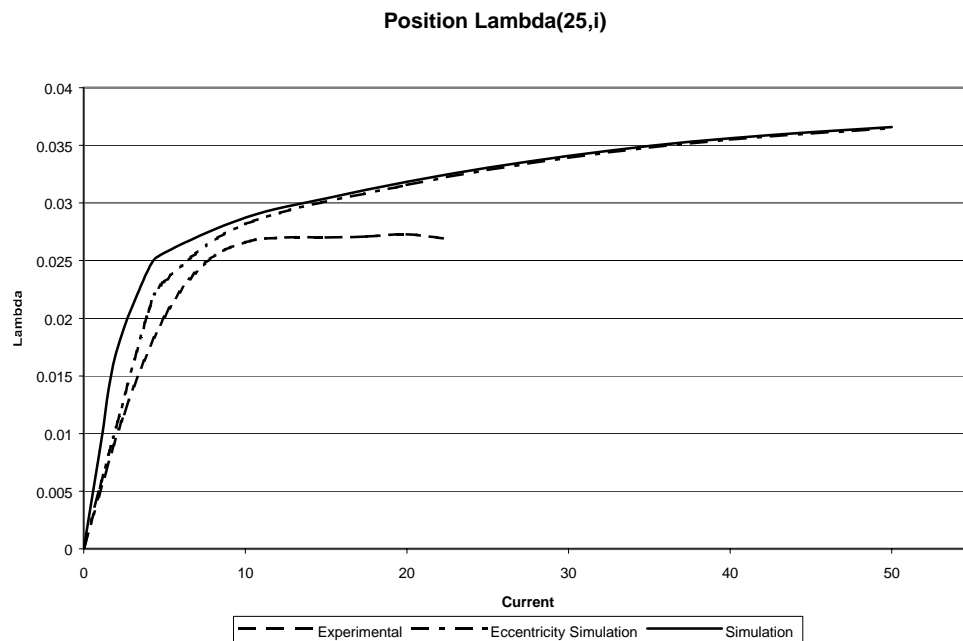
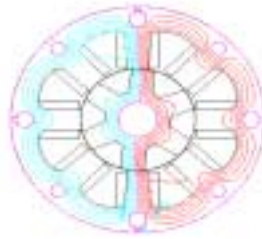


Figure 4.8 : Fluxlinkage versus Current at Theta equals Twenty-five Degrees

4.8 Results at Aligned Position, $\theta=30^\circ$

At this point the inductance of the machine is maximized and the machine should be fully saturated. Both of the graphs show this but the estimated values show more saturation than the calculated values. The table showed the most error between these two points and it is easily seen on the graph.

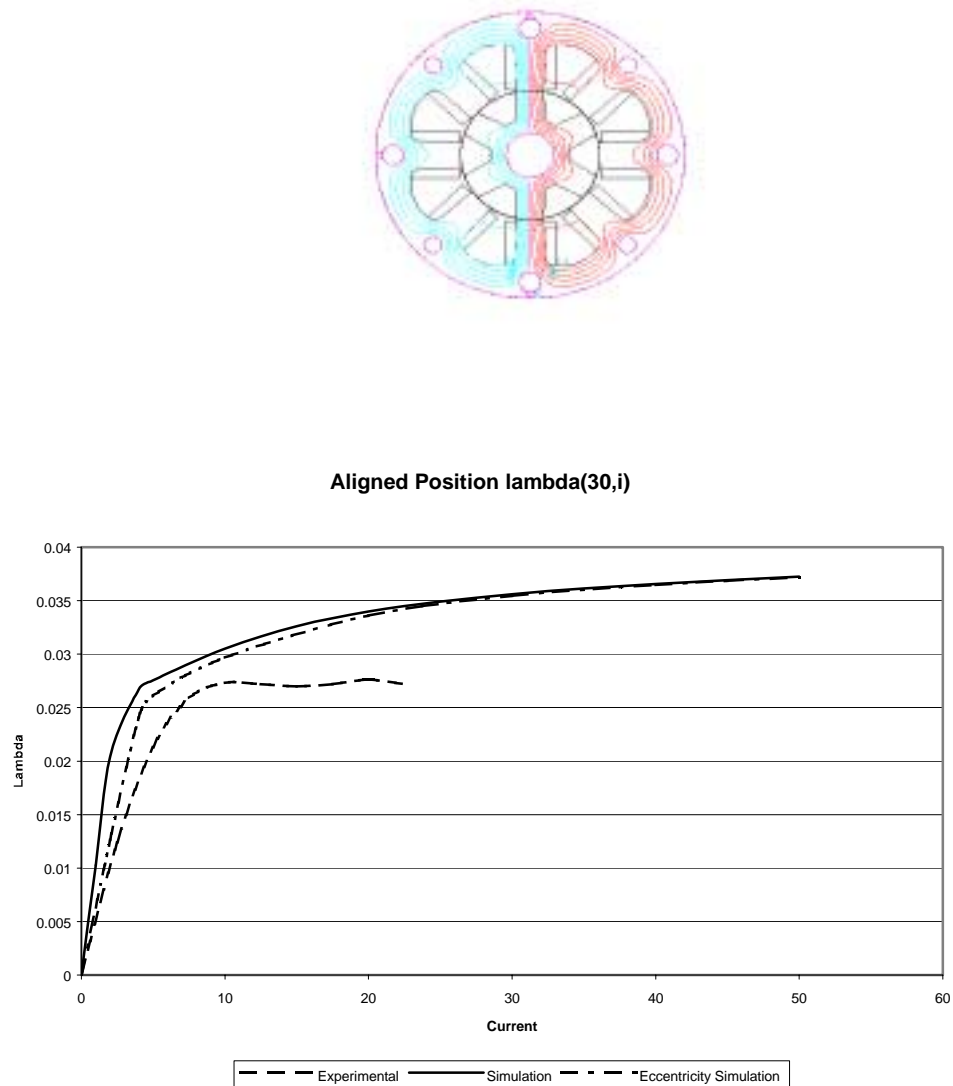


Figure 4.9 : Fluxlinkage versus Current at Aligned Position

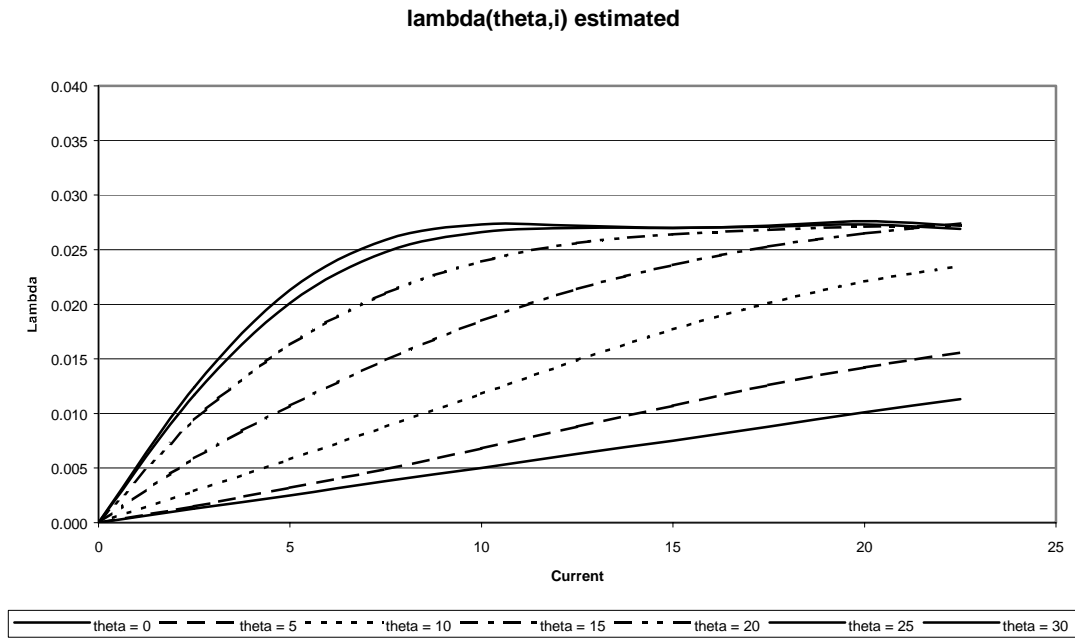


Figure 4.10. λ_c versus Current for Different Rotor Position

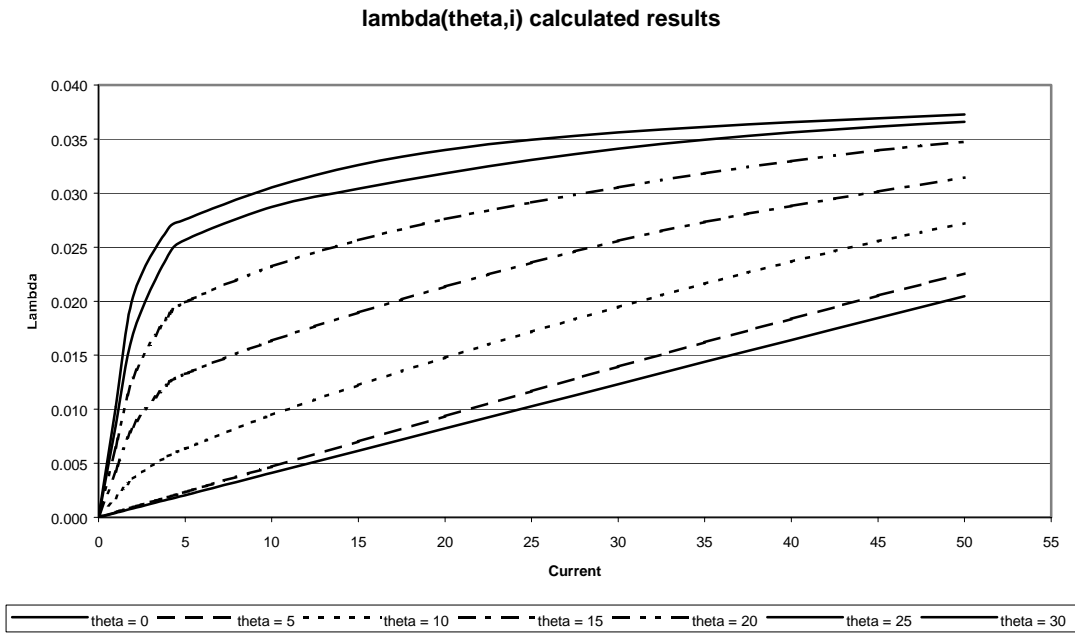


Figure 4.11 : λ_c versus Current for Different Rotor Position

In a SR motor the flux linkage can be graphed as a function of rotor position and current. This means that it changes depending on the rotor and the current in the machine at the time. By comparing the estimated and calculated values of λ versus current at many different positions the variation can be studied. The points where they overlap and the points where the graphs diverge can be studied. It is also important to realize that with both sets of data there could be errors.

4.9 Parameter Errors

Errors could exist in both of the values that are presented in this report. Each of them has different kinds of errors that are related to them. Estimation would have error from the noise in the system and from the methods that are employed to reduce the noise. The calculated results from Flux2D will be off because it does not totally represent the real life machine effects. However, it is important here that each of the errors be presented and discussed here, so that a clear understanding of the results can be obtained

4.10 Errors from Estimation

There are many types of errors that exist when a parameter is to be estimated. One error that can be present is due to measurement noise. Noise can come from the sensors that are used for the measurement of the voltage and current in the phase or it can come from the machine itself. The machine parameters change as a function of heating of the machine that happens when the machine is loaded and these changes can introduce an uncertainty into the estimation. Noise can affect the results and cause them to be skewed one way or another.

Another error that could be present in the estimated results is the method that was used to model the inductance. At certain current levels there was a voltage and current applied to the motor and the inductance was estimated. This was done many times so that an average inductance could be determined from the tests. Then taking the averages at these points a curve was fitted to produce the inductance at all the other points. This method could also produce some errors in the estimated results. This error can be minimal if the number of samples was high enough and the inductance was calculated at enough points to accurately capture all of the dynamics of the inductance. This should be the case for this estimation.

There is one more thing that might add to the error between the estimated values and the calculated values and that is machine eccentricity. Eccentricity is the physical differences that exist in the mechanical dimensions of the machine. There will be differences between motors that are created because of machining tolerances and the parts that are used to put the machine together. The rotor and stator diameter could be different, the teeth could be machined wider, or the bearings that hold the shaft could be slightly out of round. This is just a short list of all of the things that could be different between two machine and these types of things will affect the airgap distance or the saturation effect of a tooth. All of this will affect the inductance and flux linkage from one machine to another and will cause the estimated results to be different from the calculated values.

4.11 Errors from Calculations

It is also important to understand that the numbers that were generated using Flux2D will have some error associated with them as well. It would be hard to get a piece of software that would generate results that were exactly representative of the results from an actual motor but as seen in the graphs the results are pretty good. In this section some of these errors were shown.

From looking at the graphs compared to the estimated value the first error is very obvious. The effect of saturation is represented in the calculated results but not to the degree that the estimated values show. In an actual motor, saturation causes the flux linkage to become almost perfectly horizontal with respect to current and this means that there is no more flux possible even if you add huge amounts of current to the machine. Flux2D still has a slope to the flux linkage line. Meaning that if enough current is added that it is still possible to get additional flux linkage out of the machine.

Flux2D also would have trouble representing any machining differences that might have occurred when the actual machine was built. Any losses outside of the machine would be hard to duplicate in these calculations. The leads that connect the motor to the voltage and current measurement devices would be one of the things that would not be able to model inside Flux2D. If a power converter used there might be some losses here also that would be impossible to duplicate inside Flux2D. These are just a few of the things that a Flux2D model would not be able to account for when calculating the inductance.

4.12 Conclusion

These are just some of the errors that are present in the two methods that were used to calculate the inductance. These errors are related to the strength and weakness of each of the methods. In estimation there are real world errors that can affect the results, such as noise and curve fitting. In the calculated results there are problems with accurately representing the physical realities of the machine and the saturation that would occur in the machine. These things are difficult to represent in a Flux2D model and might cause the results to be in error.

In this section some of the differences between the two results from the calculated and estimated values have been explained. The results that were obtained are still very reasonable and the values are very close together. This shows that a FEA could lead to results that are very close to reality and allow for analysis of the machine before they are built.

Chapter Five

Conclusion

5.1 Conclusion

The systems that are used to control the function of an automobile are becoming more sophisticated everyday. The designs of the past are constantly being improved and updated. The sophistication of automobiles has continued to increase, as more and more new technology is being used and invented for use in automobiles. The implementation of the electromechanical braking system will improve the response time of the braking system and will make cars much safer in the future.

As explained previously the brake system is very complicated and this makes the system very difficult to model accurately. This type of a system also calls for a very robust control algorithm that will not rely on direct force feedback from the controller. Most of the control algorithms for a switched reluctance motor rely on an encoder and a flux table lookup procedure to determine the operation of the motor.

This type of control will not be very beneficial in this application because of the high integration error that is present in the flux model under low speed and high load conditions. This type of control will not produce very good results. In order to more accurately control the motor the parameters could be estimated online and then the control algorithm could be updated. This would allow the control algorithm to more accurately predict the functioning of the motor, but before this there must be some understanding of the motor model.

This type of algorithm will be very difficult to write without first understanding the model of the motor that will be used to operate the system. To understand the operation of the motor, the first step is to accurately model the motor. In this case the motor was modeled using finite element analysis software called flux2D. The parameters of the motor were observed and the machine was fully modeled. Then the model of the motor from the computer simulation was to be verified. The verification of the model would come from a comparison to estimated parameters of the machine.

This verification was comprised of a detailed analysis of the two sets of results to determine that amount of correlation between the two sets of data. By performing some analysis on the data it is easy to see that the two sets of results, estimated and calculated data, contained values that were very close to each other so it is reasonable to assume that the values are probably correct. This comparison was also to show how the parameters of the machine might change from one motor to another. This was a little inconclusive because it was obvious that there were some differences between the data. One way to explore this more conclusively would be to have

another machine built and estimate the inductance on that machine. Then using the data from those two machines it might be possible to determine how what was different in the construction of these two machines.

5.2 Future Work

The purpose of this work was to explain the model of the switched reluctance motor and how to use finite element analysis software to calculate the parameters of the motor at different operating points. The first thing that was presented was the electromechanical brake system and the reasons that this work would be helpful. Then the system was broken down into its individual components and each one was explained. After understanding the system, one of the elements, the switched reluctance motor, was more closely examined. The background and model of the switched reluctance motor was presented. Then the operation of the finite element analysis software, flux2D, was explained. The results from the calculations of the software were then presented together with the estimated values from a real motor. These results were then analyzed and some conclusions were made to the validity of the results that were obtained.

Now that this part has been completed the work is not completed. There is more work that could be done with these models that have been computed. More work could be done with the model to more accurately reflect the actual machine.

The motor could be dismantled and the dimensions of the machine could be checked to determine how it compares to the drawings that were used to construct the computer model.

If the same estimations could be performed on several motors that were constructed to be identical then some sort of average estimated parameters could be generated. Once this was accomplished then it might be possible to adjust the motor model so that the computer simulation would produce results that were more similar to the actual motor. The airgap, length, tooth width, or material properties in the computer model could be scaled to more accurately reflect the way the motor will be constructed. This would be difficult to perform accurately and some extensive testing would have to be performed with many size and types of motors before conclusions could be drawn on all type of switched reluctance motor.

Another obvious extension of this work would be to study which of the tolerances on the machine needs to be set the most accurately. This would all the builder of the motor to understand which of the dimensions were the most important to the successful control of the motor. Taking the flux linkage tables from these models and modifying this model in many ways other ways could accomplish this. Then using these tables to run simulations of the motor on the computer using the flux table lookup simulator of the motor. By keeping the control algorithm the same for all of the different tables and then comparing the responses that are generated by the different tables. This could give some understanding of how the differences in the

machine will affect the response of the motor. Then the flux tables for many motors could be generated.

Switched reluctance motors are simple motors to construct and operate under normal lab conditions. However, to use and control these motors in a mass production system would be very difficult because of the many factors that change the parameters of the motor. There is still much work to be done in this area but this was a necessary step to verify the results of the estimation and it will lead to further exploration in this area.

BIBLIOGRAPHY

- [1] Finite Element Design and the Artificial Neural Network Modeling of a Switched Reluctance Machine, Handoko Gunawan, The Ohio State University, 1996, Faculty Advisor: Dr. Ali Keyhani
- [2] Miller, T. J. E., Switched Reluctance Motor Drives: A Reference Book of Collected Papers, Intertec Communications Inc. Publishers, Ventura CA, 1988.
- [3] Sizing Program for Switched Reluctance Motors, Wenzhe Lu, The Ohio State University, 1999, Advisor: Dr. Ali Keyhani
- [4] Y. Hayashi and T.J.E. Miller, ‘ A new approach to calculating core losses in the SRM’ *IEEE Transactions on Industry Applications*, vol. 31, no.5, pp. 1039-1046, September/October 1995.
- [5] Materu, P.N., Krishnan, R., “Estimation of switched reluctance motor losses”, *IEEE Transactions on Industry Applications*, vol. 28, no. 3, pp. 668-679, May/June 1992.
- [6] Magsoft Corporation, ‘Finite Element Analysis Software Reference Manuals’, *Magsoft Corporation, Troy, NY, April 1995*.
- [7] Fahimi, B., Johnson, J. P., Ehsani M., “Artificial Intelligence Approach to Controlling SRM Drives with Manufacturing Imperfections”, *Emerging Technologies and Factory Automation*, vol. 2, pp. 623-628, 1996.
- [8] Fahimi, B., Suresh, G., Ehsani, M., “Review of sensorless control methods in switched reluctance motor drives”, *IEEE Conference Record of the 2000 Industry Applications Conference*, vol. 3, pp. 1850 – 1857, 2000.
- [9] Suresh, G., Fahimi, B., Rahman, K.M., Ehsani, M., “Inductance based position encoding for sensorless SRM drives”, *IEEE Power Electronics Specialists Conference*, vol. 2, pp. 832-837, 1999.
- [10] Husain, I., Ehsani, M., “Rotor position sensing in switched reluctance motor drives by measuring mutually induced voltages”, *IEEE Transactions on Industrial Applications*, vol. 23, no. 3, pp. 623-628, May/June 1994.

- [11] Dawson, G. E., Eastham, A. R., Mizia, J., "Switched reluctance motor torque characteristics: finite element analysis and test results", *IEEE Transactions on Industrial Applications*, vol. 30, no. 3, May/June 1987.
- [12] Toliyat, H. A., Al-Nuaim, N. A., "Simulation and detection of dynamic air-gap eccentricity in salient-pole synchronous machines", *IEEE Transactions on Industrial Applications*, vol. 35, no. 1, pp. 86-93, January/February 1999.
- [13] Toliyat, H. A., Al-Nuaim, N. A., "A novel method for modeling dynamic air-gap eccentricity in synchronous machines based on modified winding function theory", *IEEE Transactions on Energy Conversion*, vol. 13, no. 2, pp. 156-159, June 1998.
- [14] Seker, S., "Determination of air-gap eccentricity in electric motors using coherence analysis", *IEEE Power Engineering Review*, pp. 48-50, July 2000.
- [15] Toliyat, H. A., Al-Nuaim, N. A., "Simulation and detection of dynamic air-gap eccentricity in salient pole synchronous machines", *IEEE Industry Applications Society Annual Meeting*, pp. 255-261, October 1997.
- [16] Marques Cardoso, A. J., Saraiva, E. S., "Computer-aided detection of airgap eccentricity in operating three-phase induction motors by park's vector approach", *IEEE Transactions on Industry Applications*, vol. 29, no. 5, pp. 897-901, September/October 1993.
- [17] DeBortoli, M. J., Salon, S. J., Burow, D. W., Slavik, C. J., "Effects of rotor eccentricity and parallel windings on induction machine behavior: a study using finite element analysis", *IEEE Transactions on Magnetics*, vol. 29, no. 2, March 1993.
- [18] Marques Cardoso, A. J., Saraiva, E. S., "Predicting the level of airgap eccentricity in operating three-phase induction motors, by park's vector approach", *IEEE Conference Record of the Industry Applications Society Annual Meeting*, vol. 1, pp. 132-135, 1992.
- [19] Miller, T. J. E., ' Switched Reluctance Motors and Their Control' , *Magna Physics Publishing*, 1993