SWITCHED RELUCTANCE MOTOR: DESIGN, SIMULATION AND CONTROL

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To my wife Nesreen

and my daughter Sara
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ABSTRACT

This thesis presents a design method for a switched reluctance (SR) motor to optimise torque production for two types of 3 phase 6/4 poles SRM and 8/6 poles SRM designs. SR motors require precise control to optimise the operating efficiency; two controllers are proposed and built to operate the switched reluctance motor. The primary objectives of this thesis are:

- To investigate the developed torque optimization for switched reluctance (SR) motors as a function of various dimensions e.g. pole arc/pole pitch variation, stator shape variation and rotor shape variation. This investigation is achieved through the simulation using Finite Element Method (FEM), MATLAB/SIMULINK.

- The two proposed controllers are designed and built to carry out the experimental testing of SRM. The most versatile SRM converter topology is the classic bridge converter topology with two power switches and two diodes per phase. The first controller consists of a Programmable Logic Controller (PLC) and the classic bridge converter, this Programmable Logic Controller uses a simple language (ladder language) for programming the application code, reliable, and contains timers. The second controller consists of a cam positioner, encoder and the classic bridge converter, this cam positioner is easy to be programmed, high-speed operation, and this cam positioner has 8 outputs.

This thesis is organized as follows:

- Chapter 1 describes the background, the present and future trends for the SRM. This chapter shows the design, control, finite element analysis, fuzzy logic control the for a switched reluctance (SR) motor (literature review).
Chapter 2 describes the theory and principle of finite element method, as applied to SR motors.

Chapter 3 describes the simulation results for serious of switched reluctance motor designs by changing (γ) rotor pole arc / pole pitch ratio, and (β) stator pole arc / pole pitch ratio, for 3 Phase, 6/4 Poles SRM and 4 Phase, 8/6 Poles SRM. The results are obtained through finite element method (FEM) and MATLAB-SIMULINK.

Chapter 4 describes the theory of fuzzy logic controller (FLC). This chapter shows the simulation results for the FLC.

Chapter 5 describes the proposed programmable logic controller (PLC), and associated hardware and software. The proposed programmable logic controller produces lower speed. The cam positioner controller produces higher speed; the experimental results for both controllers are presented and discussed.

Chapter 6 describes the summary of results from earlier chapters to draw the final conclusion for the thesis. The recommendations for further research are also discussed.

Appendix A describes the program code for the PLC controller.

Appendix B contains a CD of photos album, video clips for the PLC controller and cam positioner controller.

Appendix C shows the list of the published papers by the author, extracted from this thesis.
STATEMENT OF SOURCES

I declare that the work submitted in this thesis is the result of my investigation and is not submitted in candidature for any other degree. The earlier research work is appropriately acknowledged and cited in the text.

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(Candidate)
GLOSSARY of TERMS and SYMBOLS

ACC  Accumulates value for the timer.
addmf  Add membership function to FIS.
addrule  Add rule to FIS.
addvar  Add variable to FIS.
ALARM  Showing the alarms in any process.
b  terminal number.
B3  Internal relay numbered by 3 used in the processor memory.
Bit  The smallest part in the software program.
B_m  Viscous friction coefficient of the rotor.
B  The flux density (T).
C5  Counter numbered by 5 used in the processor memory.
CDM  Custom Data Monitors.
XIC  Examine if closed instruction.
XIO  Examine if Open instruction.
D  Electric flux density (C/m^2).
\( dA \)  Differential vector element of surface area A.
DCS  Distributed control system.
DDE  Dynamic Data Exchange.
DH^+  Data high for networking.
\( dl \)  Differential vector element of path length tangential to contour C enclosing surface S.
DN  Done instruction bit (bit 13 in the timer control word).
\( dV \)  Differential element of volume V enclosed by surface S.
defuzz  Defuzzify membership function.
evalfis  Perform fuzzy inference calculation.
evalmf  Generic membership function evaluation.
gensurf  Generate FIS output surface.
getfis   Get fuzzy system properties.
e       Slot number.
EN      Enable bit (bit 15 in the timer control word).
F8      Float numbered by 8 used in the processor memory.
FEM     Finite element method.
FIS     Fuzzy Inference System.
FLC     Fuzzy logic controller.
F       The magneto motive force (mmf).
GRT     Greater Than instruction.
I       Current (A).
I/O     Input/Output.
I1      Input image table numbered by 1.
i_{ph}  Phase current (A).
J       Rotor's moment of inertia (kg m^2).
LAD     Ladder file is attribute of program files.
L(\theta,i)  The instantaneous inductance.
LES     Less Than instruction.
LIM     Limit Test instruction.
L_{ph}  Phase inductance (H).
L       Inductance (H).
l       The length of magnetic path (cm).
MMF     Field force (Amp-Turn).
MIMICS  Graphics program to produce artwork to monitor the process.
MOV     Move instruction.
mf2mf   Translate parameters between functions.
mfstrtch Stretch membership function.
newfis  Create new FIS.
N7      Integer numbered by 7 used in the processor memory.
Nr    Rotor pole number.
Ns    Stator pole number.
N_{wn}    The number of turns in the coil side n.
NSTFPI Artificial neural network tuning.
O:e.s/b, I:e.s/b Address for output, address for input.
O0    output image table numbered by 0.
OTE   Output Energise instruction.
OTL   Output Latch instruction.
OTU   Output Unlatch instruction.
PLC   Programmable Logic Controller.
plotfis Display FIS input-output diagram.
plotmf Display all membership functions for one variable.
PRE   Preset value for the timer.
readfis Load FIS from disk.
rmmf  Remove membership function from FIS.
rmvar Remove variable from FIS.
R6    control numbered by 6 used in the processor memory.
r_{ph} Phase resistance (ohm).
RSLogix 5 Rockwell Software Logic 5 suits Allen Bradley PLC 5.
RSLogix 500 Rockwell Software Logic 500 suits Allen Bradley PLC 500.
RUNG  one step in the ladder file.
ℜ    The reluctance (Amp-Turns per Weber).
s    Word number.
s    The edge of the open surface A.
S2    Status file numbered by 2 used in the processor memory.
SCADA Supervisory control and data acquisition.
SCL   Scale Data instruction.
setfis Set fuzzy system properties.
showfis Display annotated FIS.
showrule  Display FIS rules.
writefis  Save FIS to disk.
SRM      Switched reluctance motor.
\(S_{wn}\)  The cross section area of the coil side \(n\).
\(S_b\)    The uniform cross section area in the bar.
\(S\)      The cross section area of the magnetic path.
\(T\)      Developed torque (N·m).
\(T4\)     Timer numbered by 4 used in the processor memory.
Tags      Data from the I/O images of a PLC is transferred to memory and is
           associated with descriptors.
\(T_{ej}\)  Torque generated by the \(j\)th phase (N·m).
\(T_L\)    Load torque (N·m).
TON       Timer On-Delay instruction.
TRENDS    Showing the trends of the process.
TT        Time timing instruction bit (bit 14 in the timer control word).
u_{Lph}   Induced voltage on the phase inductance (V).
u_{ph}    The applied phase voltage (V).
\(\mu\)   The permeability of the material (Tesla-meters per Amp-turns).
\(W_c\)   Co-energy in joule (J).
\(W_f\)   Stored field energy (J).
Word      16 bits.
\(\Delta W_m\)  Work (J).
\(\Delta \theta\)  Infinitesimal displacement.
\(\varepsilon\)  The electrical permittivity of the material (F/m).
\(\varepsilon_0\)  Permittivity (F/m).
\(\theta\)  Rotor position.
\(\theta_j\)  Rotor position with respect to the \(j\)th phase.
\(\Lambda^2\)  The constitutive transformation.
\(\rho\)   Free electric charge density (coulombs per cubic metre).
\( \chi_e \)  The electrical susceptibility of the material (dimensionless).
\( \chi_m \)  The magnetic susceptibility of the material (dimensionless).
\( \omega \)  Rotor's angular speed (radians per second).
\( \lambda(\theta) \)  Flux linkage (weber-turns).
\( \nabla \times \)  The curl operator.
\( \cdot \)  Word delimiter.
\( \nabla \cdot \)  The divergence operator.
\( / \)  Bit delimiter.
\( : \)  Element delimiter.
\( \gamma \)  Rotor pole arc/pole pitch ratio.
\( \beta \)  Stator pole arc/pole pitch ratio.
\( \sigma \)  The conductivity (siemens per meter).
\( \Phi \)  The field flux (Wb).
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CHAPTER 1 INTRODUCTION

The switched reluctance motor (SRM) represents one of the oldest electric motor designs around. A variation on the conventional reluctance machine has been developed and is known as the “switched reluctance” (SR) machine. This development is partly due to recent demand for variable speed drives and partly as a result of development of power electronic drives. The name “switched reluctance”, describes the two features of the machine configuration: (a), switched, the machine must be operated in a continuous switching mode, which is the main reason for the machine development occurred, only after good power semiconductors became available; (b), reluctance, it is the true reluctance machine in the sense that both rotor and stator have variable reluctance magnetic circuits or more properly, it is a doubly salient machine. The switched reluctance motor is basically a stepper motor and has had many applications as both rotary and linear steppers. The idea of using the SR configuration in a continuous mode (in contrast to a stepper mode) with power semiconductor control is due primarily to Nasar [1-2], at that time, only thyristor power semi-conductors were available for the relatively high-current, high-voltage type of control needed for SR machines.

1.1 SWITCHED RELUCTANCE MOTOR

The reluctance motor operates on the principle that a magnetically salient rotor is free to move to a position of minimum reluctance to the flow of flux in a magnetic circuit. Improved magnetic materials and advances in machine design have brought the switched reluctance motor into the variable speed drive market. The simple brushless construction of the motor makes it cheap to build and very reliable in operation. The unipolar current requirements of the phase windings results in a simple and very reliable power converter circuit. The researchers are now focusing on switched reluctance motors and drives with only one or two phase windings so that applications for the technology are being created in low cost, high volume markets such as domestic appliances, heating ventilation and air
conditioning and automotive auxiliaries. In recent years, power transistors, GTOs, IGBTs, and power MOSFETs have been developed in the power ranges required for SRM control [3]. SRM’s eliminate permanent magnets (PMs), brushes and commutators. The stator consists of steel laminations forming salient poles. A series of coil windings, independently connected in phase pairs, envelopes the stator poles. With no rotor winding, the rotor is basically a piece of steel (and laminations) shaped to form salient poles. It is the only motor type with salient poles in both the rotor and stator (double salient). As a result, and also because of its inherent simplicity, the SR machine promises a reliable and low-cost variable-speed drive and will undoubtedly take the place of many drives using the cage induction and DC commutator machines in the near future. The switched reluctance motor is a new entrant in domestic appliance applications. Many electrical machine researchers are investigating the dynamic behaviour of switched reluctance motor (SRM) by monitoring the dynamic response (torque and speed), monitoring and minimising the torque ripple, building different types of controllers to reduce the cost, to increase the general performance of SRM like high reliability and high practicability, to build a better controller for SRM [4-12].

The switched reluctance motor’s (SRM) principle of operation has been known for more than a century, under general name of the doubly salient variable reluctance motor. However, an intensive research on SRM began about thirty years ago, mainly due to the progress in power electronics and microprocessors. Its principal advantages are simple and robust construction, possibility to work at very high rotation speeds, high mechanical torque at low speeds, and simple power electronics driver [13-16].

The conventional way to operate as SRM, is to supply unidirectional current pulses sequentially to each of the SRM phase coils. The current pulse could be controlled by its amplitude and on and off timing. The current pulse form depends largely on the SRM speed, i.e., the voltage drop equivalent to a back electromagnetic force (back emf). Due to its special construction, i.e., the lack of a clear magnetic excitation current and nearly
zero mutual inductance between the SRM phases, the equivalent back emf is due to the change of the self-inductance of the excited phase, during the rotor movement. At low and intermediate rotor speeds, due to a low back emf, the source voltage is sufficient to impose a rather rectangular current pulse though the excited phase coils. At high speeds, the back emf becomes quite large. As a result, the current pulse is no longer rectangular but becomes rather triangular [17-22].

The mechanical torque on the rotor is due to the force exerted by the excited phase of the stator on the rotor salient poles. This force and, as a result, the mechanical torque depend on the number of stator and rotor salient poles, their geometrical dimensions, the number of stator phases, and also the phase current intensity and on/off timing. The SRM could have the largest ratio between the aligned and unaligned phase inductances; this is due to a large angle between the stator as well as rotor poles. The SRM is quite cumbersome to control due to its double saliency and also its inherent strong magnetic nonlinearity [23-29].

The SRM’s rugged construction is suitable for harsh environments such as high temperature and vibration. SRM controllers add to the benefits; since they do not need bipolar (reversed) currents, the number of power-switching devices can be reduced by 50%, compared to bridge-type inverters of adjustable-speed drives. An SRM drive has inherent reliability and fault tolerance, it can run in a “limp-home” mode with diminished performance with one failed transistor in a phase, unlike standard motor drives. The major applications of SRMs include:

(a) General purpose industrial drives
(b) Application-specific drives: compressors, fans, pumps, and centrifuges
(c) Domestic drives: food processors, washing machines, and vacuum cleaners
(d) Electric vehicle application
(e) Aircraft applications
(f) Servo-drives

SR motors offer numerous benefits, such as:

1. Improved performance with much greater torque output and with the same (or slightly higher) efficiencies than “premium efficiency” induction motors, over a wider speed range.

2. Small unit size makes efficient use of materials and low inertia.

3. Low cost, low manufacturing cost, low material cost and low maintenance cost. It does not use expensive magnets.

4. High speed and acceleration capability, up to 100,000 r.p.m (revolutions per minute), with the proper drive [30-32].

5. Most of the heat is generated in the stationary stator, which is relatively easy to cool.

A good machine drive has to meet the general requirements of four-quadrant operation (i.e., forward/reverse and positive or negative torque), with seamless transition between quadrants. True “servo quality” control imposes further requirements of very low torque ripple, rapid dynamic response, good stability, ability to operate at zero speed, and smooth reversing. Even without these servo-quality requirements, optimized performance for simple variable-speed drives requires continuous control of the firing angles (i.e. the switching on/off angles of power semiconductors). The DC commutator motors and the brushless DC motors are well adapted to these advanced requirements because their torque is proportional to current. With vector control (field-oriented control), AC induction motors and PM synchronous motors effectively acquire this characteristic of the DC motors. The equations of the AC motor can be transformed into those of the DC motor by means of reference-frame transformations (the dq-axis transformation). The switched reluctance motor has no dq-axis transformation, and no field oriented control principle has been developed for it [33-34].

The requirements of four-quadrant operation and servo performance can only be met by high-speed real-time controllers which operate with phase currents and voltages directly, and not with slow-varying dq-axis quantities. Such high-speed controls are used in
advanced DC and AC drives already, in order to achieve the highest dynamic performance. What makes the SRM different is that the relationships between torque, current, speed and firing angles (i.e. the commutation angles) are highly nonlinear and vary as functions of speed and load. These highly nonlinear relationships of the SRM are due to its single-excited (exciting the stator only) double salient and highly nonlinear machine characteristics. The generated electrical torque appears to be a high order polynomial of the stator currents with an order equal to or greater than two. Even in the simplest case, the electrical torque is not a linear function of the stator current. Moreover, this torque and current relationship of the SRM is usually not as clear as in any other type of motor. The generated electrical torque is a function of the rotor position. In order to achieve desired torque, the motor has to be operated in a phase-to-phase switching mode based on accurate rotor position information. It increases the complexity of the control algorithm [35-37].

Continuous torque can be produced by intelligently synchronizing each phase’s excitation with the rotor position. By varying the number of phases, the number of stator poles, and the number of rotor poles, many different SRM geometries can be realized. The torque-speed operating point of an SRM is essentially programmable and determined almost entirely by the control. This is one of the features that make the SRM an attractive solution. The envelope of operating possibilities, of course, is limited by physical constraints such as the supply voltage and the allowable temperature rise of the motor under increasing load; in general this envelope is described by figure 1.1. Like other motors, the torque is limited by maximum allowed current, and speed by the available bus voltage. With increasing shaft speed, a current limit region persists until the rotor reaches a speed where the back-EMF of the motor is such that, given the DC bus voltage limitation we can get no more current in the winding, thus no more torque from the motor. At this point, called the base speed, and beyond, the shaft output power remains constant, and at its maximum. At higher speeds, the back-EMF increases and the shaft
output power begins to drop. This region is characterized by the product of torque and the square of speed remaining constant [38-40].

The SRM must obey the laws of physics. The torque in a reluctance motor is developed by virtue of the change in the reluctance with respect to the rotor position. Based on this principle, a reluctance motor is different from other types of electric machines such as the DC machine, synchronous machine and induction machine. The theory of conventional reluctance machines evolved from synchronous machine theory developed in the early 20th century, based on the well-known Park Equations. The basic torque or force production in reluctance machines results from the variation of the stored magnetic energy as a function of the rotor position. This relationship also applies to most electromagnetic relays, holding magnets, solenoid actuators, and other devices where force is produced between two magnetic surfaces, including all machines with saliency. To derive the basic torque equation of the SRM, consider an elementary reluctance

![Figure 1.1: SRM Torque-speed characteristics [40].](image-url)
machine as shown in figure 1.2. The machine is single phase exited; and the excited winding is wound on the stator and the rotor is free to rotate [40-41]. The flux linkage is

$$\phi (\theta) = L(\theta) I$$  \hspace{1cm} (1.1)

where I is the independent input variable, i.e. the current is flowing through the stator and L is the inductance.

A mathematical model of an SRM can be developed, based on the electrical diagram of the motor, incorporating phase resistance and phase inductance. The diagram for one phase is illustrated in figure 1.3. The voltage applied to a phase of the SRM can be described as a sum of voltage drops in the phase resistance and induced voltages on the phase inductance:
Although SR motor operation appears simple, an accurate analysis of the motor’s behaviour requires a formal, and relatively complex, mathematical approach. The instantaneous voltage across the terminals of a single phase of an SR motor winding is related to the flux linked in the winding as illustrated in equation 1.2,

$$V = i R_m + \frac{d\phi}{dt}$$  \hspace{1cm} (1.2)

where, \(V\) is the terminal voltage, \(i\) is the phase current, \(R_m\) is the motor resistance, and \(\phi\) is the flux linked by the winding. Because of the doubly salient construction of the SR motor (both the rotor and the stator have salient poles) and because of magnetic saturation effects, in general, the flux linked in an SRM phase varies as a function of rotor position, \(\theta\), and the motor current. Thus, equation (1.2) can be expanded as:

$$V = i R_m + \frac{\partial\phi}{\partial i} \frac{di}{dt} + \frac{\partial\phi}{\partial \theta} \frac{d\theta}{dt}$$  \hspace{1cm} (1.3)

where, \(\frac{\partial\phi}{\partial i}\) is defined as \(L(\theta, i)\), the instantaneous inductance, \(\frac{\partial\phi}{\partial \theta}\) is the instantaneous back EMF. Equation (1.3) governs the transfer of electrical energy to the magnetic field. In this section, the equations which describe the conversion of the field’s energy into
mechanical energy are developed. Multiplying each side of equation (1.2) by the electrical current \(i\), gives an expression for the instantaneous power in an SRM:

\[
V_i = i^2 R_m + i \frac{d\phi}{dt} \tag{1.4}
\]

The left-hand side of equation (1.4) represents the instantaneous electrical power delivered to the SRM. The first term in the right-hand side (RHS) of equation (1.4) represents the ohmic losses in the SRM winding. If power is to be conserved, then the second term in the RHS of equation (1.4) must represent the sum of the mechanical power output of the SRM and any power stored in the magnetic field. Thus,

\[
i \frac{d\phi}{dt} = \frac{dW_m}{dt} + \frac{dW_f}{dt} \tag{1.5}
\]

where \(\frac{dW_m}{dt}\) is the instantaneous mechanical power, and \(\frac{dW_f}{dt}\) is the instantaneous power. Because power, by its own definition, is the time rate of change of energy, \(W_m\) is the mechanical energy and \(W_f\) is the magnetic field energy. It is well known that mechanical power can be written as the product of torque and speed,

\[
\frac{dW_m}{dt} = T\omega = T \frac{d\theta}{dt} \tag{1.6}
\]

where \(T\) is the torque, and \(\omega = \frac{d\theta}{dt}\) is the rotational velocity of the shaft. Substitution of equation (1.6) into equation (1.5) gives,

\[
i \frac{d\phi}{dt} = T \frac{d\theta}{dt} + \frac{dW_f}{dt} \tag{1.7}
\]
Solving equation (1.7) for torque yields the following equation,

\[ T(\theta, \phi) = i(\theta, \phi) \frac{\partial}{\partial \theta} - \frac{dW_f(\theta, \phi)}{d\theta} \]  

(1.8)

For constant flux, equation (1.8) simplifies to,

\[ T = -\frac{\partial W_f}{\partial \theta} \]  

(1.9)

Since it is often desirable to express torque in terms of current rather than flux, it is common to express torque in terms of co-energy \( W_c \), instead of energy. To introduce the concept of co-energy, first consider a graphical interpretation of field energy. For constant shaft angle, \( \frac{d\theta}{dt} = 0 \), integration of equation (1.7) shows that the magnetic field energy can be shown by a shaded area in figure 1.4 and equation (1.10) [41-42].

\[ W_f = \int_{0}^{\phi} i(\theta, \phi) d\phi \]  

(1.10)

Figure 1.4: Graphical Interpretation of Magnetic Field Energy [40].
For the fixed angle, $\theta$, let the magnetization curve define flux as a function of current, instead of current defined as a function of flux. The shaded area below the curve is defined as the magnetic field co-energy, and shown in figure 1.5 and equation (1.11) [40-42].

![Graphical Interpretation of Magnetic Field Co-energy](image)

Figure 1.5: Graphical Interpretation of Magnetic Field Co-energy [40].

\[
W_c = \int_0^i \phi(\theta, i) \, di 
\]  

(1.11)

From figures 1.4 and 1.5, we see that the area defining the field energy and co-energy can be described by the relation,

\[
W_c + W_f = i\phi 
\]  

(1.12)

Differentiating both sides of equation (1.12) yields

\[
dW_c + dW_f = \phi di + i d\phi 
\]  

(1.13)
Solving for the differential field energy in equation (1.13) and substituting back into equation (1.8) gives,

\[
T = \frac{id\phi - (\phi di + id\phi - dW_c(\theta,i))}{d\theta}
\]  (1.14)

For simplification, the general torque equation, equation (1.14), is usually simplified for constant current. The differential co-energy can be written in terms of its partial derivatives as,

\[
dW_c(\theta,i) = \frac{\partial W_c}{\partial \theta} d\theta + \frac{\partial W_c}{\partial i} di
\]  (1.15)

From equation (1.14) and equation (1.15), it is fairly easy to show that under constant current,

\[
T = \frac{\partial W_c}{\partial \theta}, \text{ i constant}
\]  (1.16)

Often, SRM analysis proceeds with the assumption that, magnetically, the motor remains unsaturated during operation. When magnetic saturation is neglected, the relationship from flux to current is given by,

\[
\phi = L(\theta) \times i
\]  (1.17)

And the motor inductance varies only as a function of rotor angle. Substituting equation (1.17) into equation (1.11) and evaluating the integral yields,

\[
W_c = \frac{i^2}{2} L(\theta)
\]  (1.18)
And then substituting equation (1.18) into equation (1.16) gives the familiar simplified relationship for SRM torque,

\[
T = \frac{i^2}{2} \frac{dL}{d\theta}
\]  

(1.19)

A schematic representation of the lamination pattern of two, three, and four phase switched reluctance motors is shown in figure 1.6. In each of the motors shown in figure 1.6 a coil is wound around each stator pole and is connected, usually in series with the coil on the diametrically opposite stator pole to form a phase winding. The reluctance of the flux path between the two diametrically opposite stator poles varies as a pair of rotor poles rotates into and out of alignment. The inductance of a phase winding is a maximum when the rotor is in the aligned position and a minimum when the rotor is in the non-aligned position. Since inductance is inversely proportional to reluctance a pulse of positive torque is produced if a current flow in a phase winding as the inductance of that phase winding is increasing. A negative torque contribution is avoided if the current is reduced to zero before the inductance starts to decrease again. The rotor speed can be varied by changing the frequency of the phase current pulses while retaining synchronism with the rotor position [43-48].
The absence of permanent magnets or coils on the rotor means that the torque is produced purely by the saliency of the rotor laminations. The direction of torque produced is irrespective of the direction of the flux through the rotor, and hence the direction of current flow in the stator phase windings is not important. The unipolar phase current in the reluctance motor results in simpler and more reliable power converter circuits. By choosing a combination where there are two more stator poles than rotor poles, high torque and low switching frequency of the power converter can be achieved. Figure 1.7 shows the three positions for the SRM. The rotor of an SRM is said to be at the aligned position with respect to a fixed phase if the reluctance has the minimum value; and the rotor is said to be at the unaligned position with respect to a fixed phase if the reluctance reaches its maximum value; otherwise the rotor is said to be at the misaligned position. For an SRM with symmetric structure, i.e. both the stator and rotor poles are distributed symmetrically, respectively; the positions defined above with respect to phase 1 are shown in figure 1.7 [49-50].
Figure 1.7: (a) Aligned Position; (b) Misaligned [Overlap] Position; (c) Unaligned Position.

The reluctance of the flux path varies with rotor position, specifically; the reluctance of any magnetic circuit is given by:

\[ \mathcal{R} = \frac{F}{\Phi} = \frac{Hl}{BS} = \frac{1}{\mu S} \]  

(1.20)

Where \( \mathcal{R} \) is the reluctance, \( F \) is the magneto motive force (mmf), \( \Phi \) is the flux, \( H \) is the magnetizing force in the air gap, \( l \) is the length of magnetic path, \( B \) is the flux density, \( S \) is the cross section area of the magnetic path, and \( \mu \) is the permeability of the magnetic material. The three parameters \( l, S \) and \( \mu \) contribute to the variation of the magnetic circuit reluctance as the angular position of the rotor changes. Before the stator yoke and the rotor yoke overlap, the permeability \( \mu \) is essentially equal to the permeability of the free space \( \mu_0 \), which is very small compared to the permeability of the core material. The reluctance \( \mathcal{R} \) is maximum at the unaligned position and does not vary in the range where no overlapping occurs as the length of the magnetic path \( l \) is constant. From the position where the overlapping occurs to the aligned position, permeability \( \mu \) increases substantially as the overlapping area increases. At the aligned position, the overlapping area reaches the maximum area. Therefore, the permeability \( \mu \) is maximum at the aligned
position, or the reluctance $\mathcal{R}$ reaches its minimum value at this position. In SR motors, the inductance $L$ is more often used instead of the reluctance $\mathcal{R}$, in representing the model or equations of the motor. The relationship between reluctance and inductance is given by:

$$L = \frac{N\Phi}{i} = \frac{N^2}{\mathcal{R}}$$  \hspace{1cm} (1.21)

where $i$ is the phase current and $N$ is the number of turns per phase. When current flows in a phase, the resulting torque tends to move the rotor in a direction that leads to an increase in the inductance. Provided that there is no residual magnetization of steel, the direction of current flow is immaterial and the torque always tries to move the rotor to the position of highest inductance. Positive torque is produced when the phase is switched on while the rotor is moving from the unaligned position to the aligned position. The positive torque is produced when the phase is switched on during the rising inductance consequently, if the phase is switched on during the period of falling inductance, negative torque will be produced. For an SRM with symmetric structure, i.e. both the stator and rotor poles are distributed symmetrically, respectively, the positions defined with respect to phase 1 are shown in figure 1.8. When excited, the rotor of an SRM always tends to achieve the nearest position of minimum reluctance (aligned position), which corresponds to the minimum stored energy in the system [51-53].
Unlike induction motors or D.C. motors, the reluctance motors cannot run directly from an A.C. or D.C. supply. A certain amount of control and power electronics must be present. The power converter is the electronic commutator, controlling the phase currents to produce continuous motion. The control circuit monitors the current and position feedback to produce the correct switching signals for the power converter to match the demands placed on the drive by the user. The purpose of the power converter circuit is to provide some means of increasing and decreasing the supply of current to the phase winding. Many different power converter circuits have been proposed for the switched reluctance motor. The most common power converter for the switched reluctance drive is the asymmetric half-bridge, shown in figure 1.9 for a three phase and a four phase motors. Each asymmetric half-bridge has three main modes of operation. The first, a positive voltage loop, occurs when both switching devices associated with a phase winding are turned on. The supply voltage is connected across the phase winding and the current in the phase winding increases rapidly, supplying energy to the motor. The second mode of operation is a zero voltage loop. This occurs if either of the two switching devices is turned off while current is flowing in a phase winding. In this case the current continues to flow through one switching device and one diode. Energy is neither taken from nor returned to the D.C. supply. The voltage across the phase winding
during this time is equal to the sum of the on-state voltages of the two semiconductor devices. This voltage is very small compared to the supply voltage and so the current in the phase winding decays very slowly. The final mode of operation is a negative voltage loop. Both the switching devices are turned off. The current is forced to flow through both the freewheel diodes. The current in the phase winding decreases rapidly as energy is returned from the motor to the supply. The asymmetric half-bridge thus offers three very flexible modes for current control. The zero voltage loops is very important in minimising the current ripple at any given switching frequency. The zero voltage loops also tend to reduce the power flow to and from the motor during chopping by providing a path for motor current to flow without either taking energy from or returning it to the supply capacitors. The major advantage with this circuit is that all the available supply voltage can be used to control the current in the phase windings. As each phase winding is connected to its own asymmetric half-bridge there is no restriction on the number of phase windings [54-60].

![Power Converter with Asymmetric half-Bridge for 3 and 4 Phase SRM.](image)

The principal advantage is the simple construction of the power electronics driver and the low number of transistors. The efficiency is optimized by minimizing the dwell angle (the dwell angle is the angle traversed while the phase conducts). Some sort of multi-phase operation could be seen when the sequential phase is commutated on before the previous phase was commutated off. A true SRM multi-phase operation is reported by Mecrow [61-63].
1.2 FINITE ELEMENT ANALYSIS

There are many methods available to model the torque-current relationship, such as fuzzy logic, artificial neutral network (ANN) and finite element analysis (FEA) and so on. Finite Element Method (FEM) has gained widespread acceptance and popularity in analytical modelling and performance analysis of SRM. Since then many papers have been published on effect of end core, influence of rotor pole shape on static and dynamic torque characteristic, stator deformation during excitation and rotor eccentricity. Design optimization of SRM has been reported by Faiz, which uses nonlinear theory of torque production [64-66].

Anunugam et al [67] have compared analytical method and FEM method for calculating average torque at different pole arc and pole pitch combinations for a fixed value of air gap length. Also their work lacks a detailed analysis on the optimum geometry of SR motor for different combination of design parameters. The sensitivity study is performed by comparing the average torque developed for different stator as well as rotor pole-arc/pole-pitch ratios and choosing the ratio combination that produces the greatest value of average torque. The sensitivity analysis of SR motor geometry is carried out for stator- and rotor pole-arc/pole-pitch ratio, and radial air gap length as motor design variables. The optimum value of design variables are arrived at by choosing their values for maximum value of average torque developed by the motor. The results of a two-dimensional finite element analysis conducted on an 8/6 switched reluctance motor for studying the effects of air-gap non-uniformity on the overall developed torque profiles [64-73].

1.3 SWITCHED RELUCTANCE MOTORS CONTROL

Motor control speed is achieved by self-tuning fuzzy Proportional Integral (PI) controller with artificial neural network tuning (NSTFPI). Performance of NSTFPI controller is
compared with performance of fuzzy logic (FL) and fuzzy logic PI (FLPI) controllers in respect of rise time, settling time, overshoot and steady state error. The fuzzy set and fuzzy logic theory originally advocated by Zadeh [76], the first FLC’s were employed in slow dynamic industrial-plants. Some applications of FLC’s to motor drive have been reported. Consumer appliances with FLC’s have been also put in the market during the last years. In all these experiences the FLC’s profitably replaced conventional controllers, in general proportional, integral, and derivative (PID) controllers. The use of an FLC significantly changes the approach to the automatic control problems. A genetic algorithm (GA) based adaptive fuzzy logic controller (FLC) has been developed with four-parameter for the speed control of switched reluctance motor (SRM) drive. Different from the conventional control rules expressed by linguistic rules and inferred by Mamdani inference method, the control rules could also be expressed by a set of equations. The advantage of this method is that the complex Mamdani inference process can be avoided and the control rules can be tuned conveniently by adjusting the parameters [79]. FLC is a nonlinear controller which is suitable in controlling SRM. MATLAB/SIMULINK environment to simulate a 6/4-switched reluctance motor has been describes [74-82].

1.4 CONCLUSION

According to the above literature review, it seems that, there is no much work has appeared on the effect of variation of stator-and rotor pole/pole pitch ratio on the average torque developed by the SRM, as well as, no much work has appeared on the switched reluctance motor’s controller, so the project objectives are:

- to propose the best design for the switched reluctance motor depending on the effect of variation of stator-and rotor pole/pole pitch ratio on the average torque developed by the SRM by using the most effective simulation tools.
- to propose a new controller for SRM. These controllers are independently of any other researcher’s work.
This dissertation is structured, documented and written to include the intensive work done in the field of:

- SRM Design.
- Finite Element Method and SRM.
- Fuzzy Logic Controller.
- MATLAB-SIMULINK Environment.

The thesis contains vast amount and considerable contribution in various designs up to 30 of rotors as well as stators of switched reluctance motor (SRM) for 3 phase, 6/4 poles and 8/6 poles types to optimize the developed torque. In addition to implementing and proposing two control systems, PLC and cam positioner with absolute encoder as follows:

- Simulation and execution of Finite Element Method Packages in designing aspects of the key factor for the switched reluctance motor such as $\gamma = \text{rotor pole arc} / \text{pole pitch ratio}$, $\beta = \text{stator pole arc} / \text{pole pitch ratio}$ for 30 different ratio and configurations (shapes and sizes) of switched reluctance motors. This various shapes and sizes of SRM designs show an outstanding contribution to analyse and obtain optimised and best design for SRM. The reason for using variety of switched reluctance motor designs (30 designs with the same air-gap between stator and rotor poles) is to show a good comparison between this study and other researcher’s results.
- Two main types of 3 phase 6/4 poles SRM and 8/6 poles SRM designs were investigated thoroughly to obtain the optimised developed torque.
- The successful use of MALAB and SIMULINK for calculations and prediction of performance of the above designs.
- This thesis contains an extensive work on fuzzy logic control of switched reluctance motor.
CHAPTER 2: FINITE ELEMENT METHOD (FEM)

2.1 INTRODUCTION

Modelling the electrical machines is important and necessary because it saves money and time, in practical to build and fabricate 30 to 40 different motor designs cost money, time, and efforts as well. The finite element method (FEM) has shown its reliability when it deals with electromagnetic design. The electrical machines are modelled by the two-dimensional finite element method. SRM modelling has been going on ever since the motor was in existence and it is necessary as well, the finite element method (FEM) is generally considered to be the preferred approach to determine the static phase flux linkage and torque inside the motor. Various methods to translate static model into dynamic model have also been proposed. Among these, the most widely referred methods are the look-up table based approach of Stephenson and Corda [83], and the analytical expression based approach of Torrey [84]. The look-up table approach can be very accurate but generally slow in simulation due to the retrieval process of the huge tabular data base and intermediate point interpolation routines. Cubic spline technique has been suggested to interpolate the data points to improve the accuracy of the look-up table approach. B-spline based flux linkage analytical expression with respect to phase current is proposed to reduce the data base of look-up table approach, but data point interpolation with respect to rotor position is still necessary [85].

During the past few decades, the numerical computation of magnetic fields has gradually become a standard in electrical machine design. At the same time, the amount of power electronics coupled with electrical machines has continuously increased. The design of converters and electrical machines has traditionally been carried out separately, but the demands for increased efficiency and performance at lower cost push the product development activities towards a combined design process. Especially in large drives and variable-speed drives, both machine and converter must be individually tailored to work
together and thereby guarantee the best possible performance for the application. In the field of complex engineering design problems, the mathematical formulation is tedious and usually not possible by analytical methods. Hence the use of numerical techniques is attractive and useful. Finite element method FEM, which is very powerful tool for obtaining the numerical solution of a wide range of engineering problems. The basic concept is that a body or structure may be divided into smaller elements of finite dimensions called “Finite Elements”. The original body or structure is then considered as an assemblage of these elements connected at a finite number of joints called “Nodes” or “Nodal Points”. The equations of equilibrium for the entire structure or body are then obtained by combining the equilibrium equation of each element such that the continuity is ensured at each node [86-91].

The first major finite element code for general use was NAS-TRAN developed for NASA by the MacNeal-Schwendler Corporation and Computer Sciences Corporation in the mid 1960s. In the late 1960s and into the 1970s, the application of the finite element method required the use of a large mainframe computer. With these machines, it was possible for designers and analysis engineers to use finite element analysis as part of their work without necessarily relying on the support of a finite element specialist. Applications of the finite element method can be divided into two categories, depending on the nature of the problem to be solved. In the first category is all the problems known as equilibrium problems or time-independent problems. These are steady-state problems whose solution often requires the determination of natural frequencies and modes of vibration of solids and fluids. In the second category is the multitude of time-dependent or propagation problems of continuum mechanics [87-95].

The use of finite element method is very popular in the designing of electromechanical and electromagnetic devices. The mathematical algorithm and general conditions of the finite element method has a history of about fifty years. The elements used were triangle, linear two dimensional (x-y) plane elements. The modelling process involves much more
than filling out data records. A good physical understanding of the device and an appreciation of the engineering aspects of the problem are needed. Electromagnetic devices such as electrical machines, transformers, waveguides, and antennas have their behaviour governed by the electromagnetic fields. These fields obey Maxwell’s equations; therefore, in order to be able to predict performance characteristics, it is necessary, in the course of design of these devices to solve the Maxwell equations describing the field. Differential or, alternatively, the integral form of the Maxwell equations has made electromagnetic field computations a heavily mathematically oriented discipline. Before the advent of the computer, recourse to elaborate mathematics had to be made to solve the electromagnetic equations, using solution concepts such as series expansions, separation of variables, Bessel and Legendre polynomials, Laplace transformations, and the like [91-99].

However, the solution of electromagnetic field in the inside of even trivial devices employing these methods is a rather lengthy and cumbersome procedure. Moreover, it happens frequently that no solution is possible without resorting to rather drastic simplifying assumptions concerning device geometry, current or charge distributions, and so on. Fortunately, with the advent of the digital computers and the subsequent advances in computing power, storage devices, as well as developments in numerical techniques, it is now possible to use simple numerical approximation schemes to solve large-scale problems within reasonable time limits [99-102].

2.2 COUPLED FIELD-CIRCUIT PROBLEMS

The coupled field-circuit problems are studied from the viewpoint of electrical machines and converters. The main field of interest is the coupling of two-dimensional finite element analysis with the circuit and control equations. In the early 1980’s, formulations for such coupling were developed for modelling voltage-supplied electrical machines. Inclusion of external circuits with power electronics was presented widely during the late
1980’s and early 1990’s [103]. However, most of the studies concerned rather simple geometries and circuits, because the computational facilities were limited and most of the authors had to develop the program codes themselves. Together with the increasing computational power and development of the software, the complexity of the modelled systems has also increased. Nowadays, the trend is to model large systems as a whole, including electro-magnetic, thermal fields, and kinematics and control systems. However, there is still a lot of work ahead to achieve this goal and the coupling mechanisms need to be studied further [103-104].

The usual approach is the magnetic vector potential formulation with filamentary and solid conductors. The filamentary conductors, sometimes referred as stranded conductors, consist of several turns of thin wire carrying the same current. In order to simplify the analysis, the eddy currents in filamentary conductors are not taken into account, but a constant current density is assumed. In the solid conductors, or conductors, eddy currents represent a significant part of the total excitation and they cannot be omitted from the analysis. The numerical solution of the coupled problem is generally accomplished directly or indirectly. The difference lies in, whether the field and circuit equations are solved simultaneously or sequentially. When the time constants in the sub-domains differ significantly from each other, it is advantageous to decouple the domains and utilize different time steps. Another major advantage is that the decoupled models can be constructed separately by the experts in different fields. Several types of coupled problems have been classified on the basis of physical, numerical or geometrical coupling. When considering the coupling between magnetic fields and electrical circuits, the coupling is physically strong, which means that they can not be considered separately without causing a significant error in the analysis. However, they can be analysed indirectly in the case of different time constants [103-104].
2.2.1 Numerical Methods

In the time-stepping analysis of FEM-based nonlinear differential equations, the solution process requires methods for modelling the time-dependence, handling the nonlinearity and solving the resulting system of equations [105]. The simple difference methods, like backward Euler, Galerkin or Crank-Nicholson, are the most commonly used methods for the time-stepping simulation. While these utilize results from two adjacent time steps, there are also numerous multi-step methods performing numerical integration over several time steps and providing higher accuracy. When phenomena of substantially different time scales are coupled together, the problem is mathematically considered as stiff. Most of the multi-step methods usually fail for such problems, but the implicit difference methods often converge [105-107].

For nonlinear equations, an iterative scheme is required for the numerical solution. The classical Newton-Raphson method, with its several modifications, is used widely for this purpose, as well as the block iterative Picard methods. In order to improve the convergence, the iteration is often damped by relaxation procedures. The final system of equations arising from the finite element method is typically symmetric and positive definite. When coupled field-circuit problems are considered, however, the system of equations is indefinite and often ill-conditioned. This must be taken into account in choosing suitable methods for preconditioning and factorization [110-112].

2.2.2 Modelling by Field and Circuit Equations

In the finite element model of an electrical machine, the magnetic field is excited by the currents in the coils. However, it is often more appropriate to model the feeding circuit as a voltage source, which leads to the combined solution of the field and circuit equations. At first, time harmonic formulations using complex variables were presented for sinusoidal supply. Then time-stepping simulation was derived in order to model arbitrary
voltage waveforms or transients. The phase windings in the stator and rotor are generally modelled as filamentary conductors, and the rotor bars in cage induction machines or damper windings in synchronous machines are modelled as solid conductors with eddy currents [112-113].

2.2.3 Coupling with External Circuits

The inclusion of external circuits is relatively simple, since it only requires adding new elements into the circuit equations of the windings. For this purpose, many authors have presented general methods, in which any circuit models composed of resistors, inductors, capacitors, diodes or other semiconductors can be coupled with the electromagnetic model of the electrical machine. The mathematical formulations for the circuit equations are usually based on loop currents or nodal voltages, but most of the formulations combine both approaches. The main reason for this is that the currents of filamentary conductors and inductances, as well as the voltages of solid conductors and capacitances, are the most natural selections for unknown variables in the coupled formulation, and therefore result in the minimum number of equations. A generalized formulation for coupling two-dimensional finite element analysis with solid or filamentary conductors using sinusoidal voltage or current sources has been presented. Further method for time-stepping analysis has been developed to allow resistive and inductive components in the external circuit. The unknown variables of the formulation were the magnetic vector potential, current in the filamentary conductors and inductors, and voltage drop over the solid conductors. Many authors have considered the field-circuit coupling from the circuit theoretical point of view. The methods presented, were based on the state-space approach, where the inductor currents and capacitor voltages were considered as the unknown variables in the circuit model. Wang [16] formulated the field equations to represent a multi-port circuit element, which was coupled to the electric circuit by the currents and voltages of the filamentary and solid conductors [114-118].
2.2.4 Coupling with Power Electronics

The simulation of power electronics together with electrical machines can be carried out in several ways. The simplest approach is to define the supply voltage waveform with respect to time or position and use this pre-defined supply in the simulation. However, modelling the real interaction between the electrical machine and the converter also requires models for the semiconductors. Usually, the switching elements are represented in the circuit model as binary-valued resistors, the value of which depends on the state of the switch. A distinction is often made between diodes and externally controlled switches because of the differences in defining the switching instant. In the simulation of diodes, the time step must be adapted to the switching instants in order to prevent negative overshoots in the current. For the externally controlled switches, synchronization of the time steps is simple, since the switching instants are already known in advance [119-121].

The diodes were modelled as binary-valued resistors and the time steps were selected according to the rate of change in the magnetic properties and the switching instants of the rectifier. A field-circuit simulation of a load-commutated inverter supplying a permanent magnet motor has been presented. Switches were modelled as binary-valued resistors, and the converter operation was divided into conduction and commutation sequences. The resistance and inductance values in the phases were changed according to the states of the switches. The method was developed further and the state-space approach was adopted. Developing a general method using an automatic procedure to construct the state-space equation for arbitrary circuit topologies and demonstrated the method by simulating a fly-back converter with a saturable transformer. Linear forces and movement was included for modelling contactors and, finally, the method was extended for rotating machines by taking into account the polyphase structures and rotational movement [122-130].
2.3 FINITE ELEMENT MODEL FOR ELECTRICAL MACHINES

In the model of the electrical machine, the magnetic field in the iron core, windings and air gap is solved by the two-dimensional finite element method and coupled with the voltage equations of the stator and rotor windings. The resulting equations are solved by a time-stepping approach, while the Newton-Raphson iteration is utilized for handling the nonlinearities [131-133].

2.3.1 Maxwell’s equations

The magnetic field in an electrical machine is governed by Maxwell’s equations:

\[ \nabla \times \mathbf{H} = \mathbf{J} \quad (2.1) \]

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2.2) \]

where:

- \( \mathbf{H} \) is the magnetic field strength
- \( \mathbf{J} \) is the current density
- \( \mathbf{E} \) is the electric field strength
- \( \mathbf{B} \) is the magnetic flux density.

It is assumed that the polarization and displacement currents are negligible because of the low frequencies used with the electrical machines. Therefore, those components are omitted from equation (2.1) and the analysis is referred to as quasi-static.

Using the reluctivity \( \nu \), we have the material equation

\[ \mathbf{H} = \nu \mathbf{B} \quad (2.3) \]
where \( v \) is a material-dependent, possibly nonlinear function of the magnetic field. The magnetic vector potential \( A \) defines the magnetic flux density as:

\[
B = \nabla \times A
\]  

(2.4)

and the substitution of (2.4) and (2.3) into (2.1) gives the fundamental equation of the vector potential formulation for magnetic field

\[
\nabla \times (v \nabla \times A) = J
\]  

(2.5)

The two-dimensional model is based on the assumption that the magnetic vector potential and current density have only z-axis components and their values are determined in the xy-plane as shown below:

\[
A = A(x, y) e_z
\]  

(2.6)

\[
J = J(x, y) e_z
\]  

(2.7)

where \( e_z \) denotes the unit vector in the z-axis direction. As a result, equation (2.5) becomes:

\[
- \nabla \cdot (v \nabla A) = J
\]  

(2.8)

### 2.3.2 Source of the Field

Although the two-dimensional analysis will be utilized, let us first consider a general case. The current density on the right-hand side of equation (2.5) can be determined from the material equation:
\[ J = \sigma E \]  

(2.9)

where \( \sigma \) is the conductivity. Combining (2.2) with (2.4) gives

\[ \nabla \times E = -\frac{\partial}{\partial t} \nabla \times A \]  

(2.10)

This is satisfied by defining the current density as:

\[ J = -\sigma \frac{\partial A}{\partial t} \sigma \nabla \phi \]  

(2.11)

where \( A \) is the electric scalar potential.

### 2.3.3 Material Properties

The magnetic properties of the laminated iron core are modelled by the reluctivity \( \nu \), which is a single-valued nonlinear function of the flux density \( B \), thus excluding the effect of magnetic hysteresis from the analysis. Since the eddy currents are greatly reduced by the laminated structure, the conductivity is set to zero in the laminated iron core. The shaft and pole shoes, which are typically made of alloy steel, are modelled as conductive iron with a nonlinear magnetization curve. Resulting from the analysis above, the magnetic field in different materials can be presented in the form:

\[-\nabla.(\nu \nabla A) = \begin{cases} 
0 & \text{in air and laminated iron} \\
N_w i_w / S_w & \text{in phase windings} \\
-\sigma \frac{\partial}{\partial t} A + \sigma U_b / I_b & \text{in rotor bars} \\
-\sigma \frac{\partial}{\partial t} A & \text{in conductive iron}
\end{cases} \]  

(2.12)
2.3.4 Stator Windings

The computational model of the electrical machine can be greatly improved by coupling the circuit equations of the stator windings with the two-dimensional field equation (2.12). In the circuit equations, the dependence between current and voltage is solved and the circuit quantities are coupled with the magnetic field by means of flux linkage. Also, the end-windings outside the core region are modelled by including an additional inductance in the circuit model.

\[ U_b = l_b \int_{s_b} \frac{\partial A}{\partial t} ds + R_b i_b + L_{be} \frac{di_b}{dt} \]  \hspace{1cm} (2.13)

where \( R_b \) denotes the resistance of the bar including the end region. All the rotor bars are connected by short-circuit rings in both ends of the rotor core. This is taken into account by defining the end-ring resistance \( R_{sc} \) and the end-ring inductance \( L_{sc} \)

\[ u_{sc} = R_{sc} i_{sc} + L_{sc} \frac{di_{sc}}{dt} \]  \hspace{1cm} (2.14)

where \( u_{sc} \) and \( i_{sc} \) are vectors of voltage and current in the end-ring that connects the bars to each other. The phase windings in the stator consist of several coils connected in series and distributed in several slots in the stator core. When the number of positively oriented coil sides is \( N_{pos} \) and the number of negatively oriented coil sides is \( N_{neg} \). Integration of the current density over all the coil sides in a phase winding gives a voltage equation

\[ u_w = l_w \left[ \sum_{n=1}^{N_{pos}} \frac{N_{wn}}{S_{wn}} \int_{S_{wn}} \frac{\partial A}{\partial t} ds - \sum_{n=1}^{N_{neg}} \frac{N_{wn}}{S_{wn}} \int_{S_{wn}} \frac{\partial A}{\partial t} ds \right] + R_w i_w + L_{we} \frac{di_w}{dt} \]  \hspace{1cm} (2.15)
where \( l_w \) is the length of the coils in the core region, \( N_{wn} \) is the number of turns in the coil side \( n \) and \( S_{wn} \) is the cross section area of the coil side \( n \). Voltage \( u_w \) is applied to the whole winding and current \( i_w \) flows through all coils that belong to the phase winding. Resistance \( R_w \) includes all coils and the end region outside the iron core. \( L_{we} \) is the inductance outside the core region. Several different methods can be utilized in the numerical solution of the magnetic field equation (2.12), such as reluctance networks, the boundary element method, finite difference method or finite element method. In this work, the numerical analysis is based on the finite element method (FEM). The two-dimensional geometry is covered by a finite element mesh, consisting of first or second-order triangular elements.

2.4 MOTION AND ELECTROMAGNETIC TORQUE

Unless a constant speed is assumed, the movement of the rotor during time steps is solved from the equations of motion:

\[
J \frac{d\omega_m}{dt} = T_e - T_L
\]  
(2.16)

\[
\omega_m = \frac{d\theta_m}{dt}
\]  
(2.17)

where \( J \) is the moment of inertia, \( \omega_m \) is the angular speed and \( \theta_m \) is the angular position of the rotor. \( T_e \) is the electromagnetic torque and \( T_L \) is the load torque. The new position of the rotor is determined at the beginning of each time step and a new mesh is created in the air gap. The electromagnetic torque is determined by the virtual work principle

\[
T_e = \frac{\partial}{\partial \theta_m} \int_{\Omega} \left( \int_0^H \mathbf{B} \cdot d\mathbf{H} \right) d\Omega
\]  
(2.18)
where the integration area covers only the air gap. The implementation for finite element analysis follows the approach presented by [107], in which the virtual movement is determined by means of a coordinate transformation matrix without altering the air-gap mesh.

2.5 ANSOFT SOFTWARE & FINITE ELEMENT ANALYSIS

Figure 2.1 shows the flow charts of the general procedure for solving the electrostatic or electromagnetic problems. The general procedure summarized below can be used to create a model of a 2d structure for computing the electric or the magnetic fields. This general procedure is to create and solve models of 2d structures; select the type of electric or magnetic field solver, and then select the desired solver. Depending on the Maxwell 2d package, different electric or magnetic field solvers may be available.

Select the type of model to be created, choose drawing, a menu appears, choose XY plane to create a Cartesian model, where the 2d model represents the XY cross-section of structure that extends infinitely long in the z-direction. Choose RZ plane to create an axisymmetric model, where the 2d model represents the cross-section that is revolved around an axis of symmetry; create the geometric model of the structure. Choose define model, and from the menu that appears:

- Choosing the model to create (or modify) the individual objects that make up the 2d cross section of the device for which fields are to be computed. Assign materials to objects in the structure. Choosing set up materials to specify the material attributes of objects (such as relative permittivity, relative permeability).

- Defining the desired sources (electromagnetic excitations) and boundary conditions for the model. Choosing set up boundaries/sources to describe the behaviour the electric or magnetic field at object interfaces and the edges of the problem region.
Compute other quantities of interest during the solution process. Quantities include forces, torques, matrices, or flux linkage. Choosing set up executive parameters, and from the menu that appears; choosing matrix to compute a capacitance, inductance, impedance, admittance or conductance matrix for conductors in the structure. Choosing force to compute the force on selected objects due to the electric or magnetic field in the structure.

- Choosing the torque to compute the torque on selected objects due to the electric or magnetic field in the structure. Choosing core loss to compute the core loss for a system of objects. Choosing flux linkage to compute a value for the flux linkage across the line. Choosing current flow to compute the current flow across a line (or lines). Enter refinement criteria for the various field solvers and specify whether an adaptive analysis should be performed. Choosing set up solution / options to enter this information (in most cases, accept the defaults). To compute fields over a two dimensional space, Maxwell 2d first creates a finite element mesh that divides the structure into thousands of smaller regions.

- The field in each sub-region (element) can then be represented with separate polynomial. In an adaptive analysis, the field simulator automatically refines the field solution in regions where error is highest. Optionally, it can be refining the model’s finite element mesh manually to increase the density of the mesh in areas of interest.

- For transient problems, define the motion parameter of the objects in the model. Choose set solutions/motion setup to describe the motion parameters. Compute the desired field solution and any requested parameters (force, torque). by choosing solve to generate the solutions, after the solutions are completed, the following step has to be follow:
• Choosing the post process to display contour, shaded, and arrow plots of the electromagnetic field patterns and to manipulate the corresponding field solutions. Mathematical operations are allowing computing any quality of interest that can be derived from the basic electromagnetic fields. Choose solutions at the top of the executive commands window to view the final results from any force, torque, flux linkage, current flow, or matrix computation. In general, the commands in this procedure must be chosen in the sequence listed.

Figure 2.2 shows the details of a finite element mesh in which more than 15 thousands elements are used in ten passes to represent the cross-section of a switched reluctance motor. The mesh is refined in the regions where the flux density is expected to be high; where there is rapid spatial variation of the field; and in the air-gap. The stator coil-side is represented by a simple geometrical shape. For accurate work it is important to try to reproduce the exact cross-section of the coil, and even of each conductor within it, especially for the calculation of the total flux-linkage of the coil. The total flux-linkage is the sum of the flux-linkage of all the individual loops of wire, and these are generally not equal because the flux density varies considerably across the cross-section of the slot, particularly in the unaligned position.
Figure 2.1: Sequence of Solving a Problem.
The accuracy of finite-element software depends on the skill of the user and on the nature of the problem. The choice of the angular displacement of the rotor ($\Delta \theta$) is very important to determine the accuracy and the time of the simulation.

Figure 2.2: Finite Element Method Mesh for 3 Phase, 6/4 Poles SRM [134].
2.6 CONCLUSION

The Finite Element Method (FEM) can be used to solve any problem that can be formulated as a field problem. It can produce accurate and reliable results when designing electromagnetic devices. FEM can be utilized by using different computer software. It is a valuable design tool, provided it is used correctly and can save money, materials and time. FEM is a very useful tool in the solution of electromagnetic problems.

The development of software products has increased dramatically in the last 20 years. Finite element analysis would not be where it is today if computers had not proliferated and become faster and less expensive to an extent almost beyond belief. FEM can produce accurate and reliable predictions of the device parameters, and the validity and accuracy of the model. Its solutions rely on an accurate representation of the problem and correct analysis procedures. The design of electromagnetic devices requires accurate calculation of the design parameters.
CHAPTER 3: SIMULATION RESULTS

The conventional method for the design of switched reluctance motors is to maximize the overall static average torque or minimize the torque ripple by using optimal machine geometry and control strategies. However, for a commercially viable variable-speed SRM, the design goal is not only to meet the torque requirements at both low and high speeds, but also to minimize the total cost of the motor and power electronics. This thesis presents the torque optimization of a SRM by using a finite-element analysis. The effects of different rotor and stator shapes and sizes on the performance were investigated. Finite element method was used to simulate each shape of SRM, while various stator/rotor shapes are analysed keeping the same ampere-turns for various SRM shapes. The investigation was performed on 3 phase, 6/4 poles base design, with various configurations as follows:

- Changing the shape and size of the rotor and stator.
- Dimensional variations for stator and rotor poles and yoke size.

3.1 SRM DESIGN

The investigation for the developed torque of the base design for 3 phase, 6/4 poles SRM has been performed by the finite element method. The cross section for the base 3 phase, 6/4 poles is chosen to perform the simulation tests. Figure 3.1 shows the flux linkage versus current variation for 3 phase base SRM 1 from 0.1 to 10 amperes, while the rotor rotates from unaligned to aligned positions in step of 6.5°. The winding turns of each phase are 150 turns with current is 1 ampere as shown in figure 3.1 to investigate this study. ATs are varied from 30 to 210 ampere-turns. The rotor is rotated from unaligned to aligned position to find the developed torque on each rotor displacement angle. The base SRM design is referred as SRM 1.
Figure 3.1: Flux versus Current for 3 Phase base SRM 1.

Figure 3.2 shows the developed torque on the rotor versus rotor angle displacement for phase A, while the ATs are varied from 30 to 210 in step of 30 ATs. As expected, the torque increases with increasing MMF. The highest developed torque occurs at 210 ampere-turns. Phase A is activated when the rotor angle displacement varied from 0º to 45º. The maximum developed torque for phase A occurs at 25º due to flux density at these displacement angles. All the simulation results are taken when the rotor is turned from unaligned to aligned positions. Figure 3.3 shows the flux density when the rotor angle displacement is equal to 25º.
Figure 3.2: Torque versus Rotor Angle Displacement at Different MMF for the SRM 1.
Figure 3.3: Flux Distribution for the SRM 1 (at 25° rotor position)

Figure 3.4 shows the developed torque versus the ATs, while the displacement angle is varied. The position between the aligned and unaligned positions is also referred as “intermediate position“.
Figure 3.4: Torque versus MMF at Different Rotor Angles for SRM 1.
3.2 SIMULATION AND ANALYSIS.

Figure 3.5 shows the different switched reluctance motor designs investigated by the finite element method. First the simulation has been performed on different shapes of SRM 1, SRM 2, SRM 3, SRM 4, and SRM 5 by rotating each rotor in steps of 2° from aligned position to unaligned position or visa-versa. Two designs were added by increasing the metal percentage for the rotor of SRM 1 (the tested motor). In the SRM 1 the iron percentage for the rotor is 62%, whereas the iron percentage in SRM 6 is increased to 76%, iron percentage is further increased to 91% in SRM 7. Out of seven investigated SRM models, it is found that the developed torque for the SRM 1 (the base SRM) is still the best. Figure 3.6 shows the flux line distribution for the tested SR motors, the flux line distribution for SRM 3 and SRM 4 are nearly the same, so choose SRM 3 to show the flux line distribution for both. The highest flux line distribution from this simulation test is established in the SRM 1. γ = rotor pole arc / pole pitch ratio, β = stator pole arc / pole pitch ratio.
Figure 3.5: Seven Cross Sections Views with Different Shape and Sizes for 3 Phase, 6/4 Poles SRM.
Table 3.1 shows the flux linkage (Wb) for different SRM, SRM 1 has the highest flux density.
Figure 3.7 shows the developed torque versus the rotor displacement angle for seven models of SRM. The developed torque will vary according to the rotor angular displacement. The highest developed torque occurs when the rotor position is 25°. The developed torque starts to decline when the rotor rotates toward the aligned position. At this position the activated phase winding around the stator pole is disconnected, and the next phase winding for the next stator pole is activated. All the different rotor shapes and sizes having the same ampere-turns of 150. Increasing the iron rotor percentage in SRM 6 and SRM 7, still SRM 1 develops the highest torque as shown in figure 3.7. The torque developed in the switched reluctance motor is a function of flux density and rotor angle, the simulation results show the developed flux density by the above designs are low due to rotor geometry.

Table 3.1 Flux Linkage for Different SRM Designs

<table>
<thead>
<tr>
<th>SRM</th>
<th>Flux Linkage (Wb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRM 1</td>
<td>0.031</td>
</tr>
<tr>
<td>SRM 2</td>
<td>0.024</td>
</tr>
<tr>
<td>SRM 3</td>
<td>0.019</td>
</tr>
<tr>
<td>SRM 4</td>
<td>0.017</td>
</tr>
<tr>
<td>SRM 5</td>
<td>0.023</td>
</tr>
<tr>
<td>SRM 6</td>
<td>0.0279</td>
</tr>
<tr>
<td>SRM 7</td>
<td>0.0292</td>
</tr>
</tbody>
</table>
Table 3.2 shows the developed Torque versus rotor angle displacement for seven SRM designs when the rotor moves from unaligned to aligned positions.

<table>
<thead>
<tr>
<th>Rotor Angle</th>
<th>Torque (Nm) SRM 3</th>
<th>Torque (Nm) SRM 2</th>
<th>Torque (Nm) SRM 1</th>
<th>Torque (Nm) SRM 4</th>
<th>Torque (Nm) SRM 5</th>
<th>Torque (Nm) SRM 6</th>
<th>Torque (Nm) SRM 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>0.12</td>
<td>0.62</td>
<td>0.049</td>
<td>0.15</td>
<td>0.613</td>
<td>0.594</td>
</tr>
<tr>
<td>4</td>
<td>0.2</td>
<td>0.22</td>
<td>0.86</td>
<td>0.1</td>
<td>0.249</td>
<td>0.87</td>
<td>0.823</td>
</tr>
<tr>
<td>6</td>
<td>0.25</td>
<td>0.27</td>
<td>0.98</td>
<td>0.16</td>
<td>0.329</td>
<td>0.966</td>
<td>0.914</td>
</tr>
<tr>
<td>8</td>
<td>0.3</td>
<td>0.32</td>
<td>1.05</td>
<td>0.22</td>
<td>0.401</td>
<td>1.02</td>
<td>0.928</td>
</tr>
<tr>
<td>10</td>
<td>0.35</td>
<td>0.36</td>
<td>1.09</td>
<td>0.28</td>
<td>0.502</td>
<td>1.05</td>
<td>0.968</td>
</tr>
<tr>
<td>12</td>
<td>0.39</td>
<td>0.402</td>
<td>1.11</td>
<td>0.34</td>
<td>0.542</td>
<td>1.07</td>
<td>0.971</td>
</tr>
<tr>
<td>14</td>
<td>0.42</td>
<td>0.436</td>
<td>1.13</td>
<td>0.398</td>
<td>0.611</td>
<td>1.1</td>
<td>0.978</td>
</tr>
<tr>
<td>16</td>
<td>0.46</td>
<td>0.471</td>
<td>1.16</td>
<td>0.44</td>
<td>0.717</td>
<td>1.123</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>0.5</td>
<td>0.51</td>
<td>1.18</td>
<td>0.477</td>
<td>0.764</td>
<td>1.111</td>
<td>1.02</td>
</tr>
<tr>
<td>20</td>
<td>0.537</td>
<td>0.547</td>
<td>1.2</td>
<td>0.508</td>
<td>0.853</td>
<td>1.153</td>
<td>1.04</td>
</tr>
<tr>
<td>22</td>
<td>0.582</td>
<td>0.587</td>
<td>1.22</td>
<td>0.553</td>
<td>0.965</td>
<td>1.173</td>
<td>1.043</td>
</tr>
<tr>
<td>24</td>
<td>0.628</td>
<td>0.632</td>
<td>1.24</td>
<td>0.642</td>
<td>1.12</td>
<td>1.192</td>
<td>1.04</td>
</tr>
<tr>
<td>26</td>
<td>0.607</td>
<td>0.608</td>
<td>0.9</td>
<td>0.73</td>
<td>1.225</td>
<td>1.06</td>
<td>0.92</td>
</tr>
<tr>
<td>28</td>
<td>0.197</td>
<td>0.195</td>
<td>0.6</td>
<td>0.122</td>
<td>0.5</td>
<td>0.288</td>
<td>0.204</td>
</tr>
<tr>
<td>30</td>
<td>0.08</td>
<td>0.079</td>
<td>0.4</td>
<td>0.047</td>
<td>0.07</td>
<td>0.158</td>
<td>0.069</td>
</tr>
<tr>
<td>35</td>
<td>0.05</td>
<td>0.04</td>
<td>0.15</td>
<td>0.02</td>
<td>0.03</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>40</td>
<td>0.01</td>
<td>0.01</td>
<td>0.05</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>45</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
To discuss the developed torque results theoretically, figure 3.8 shows an ideal situation, while in reality the inductance and torque are nonlinear functions of the current and rotor position. This ideal inductance profile of the SRM is assumed to produce torque in the conventional drives. The rotor position is defined as the mechanical angle from the polar axis of phase \( a \) to one of the inter-polar axes of the rotor. At zero degree, the inductance of phase \( a \) is the lowest and the inter-polar axis of the rotor is aligned with the polar axis of phase \( a \). At the points where inductance is the highest, a set of rotor poles are in full alignment with two opposite stator poles. If a phase is excited when its inductance is rising, positive torque is produced while negative torque is produced during the falling slope of the inductance. The torque is proportional to the square of the phase current as given in equation (3.1). Hence, the direction of the current is arbitrary. To move the rotor
by 90° in the counter clockwise direction, it takes three phase excitations in the sequence of \( a-b-c \) and one revolution of the rotor needs four sets of the same sequences. Similarly, three phase excitations in the sequence of \( c-b-a \) are necessary for the movement of the rotor in the clockwise direction. The total output torque generated by this scheme is given in (3.1). It is the sum of the torques produced by the sequentially excited phases [135].

\[
T_c = \sum_{k=a,b,c} \frac{1}{2} \frac{\partial L_k}{\partial \theta} i_k^2
\]  

(3.1)

where \( \frac{\partial L_k}{\partial \theta} \) is the rate of change of self inductance with respect to rotor position and \( i_k \) is the phase current. From the relationship between the self inductance to rotor position shown in figure 3.8, the rate of change of self inductance with respect to rotor position can be approximated as a piece-wise linear function as shown in equation 3.2;

\[
\frac{\partial L_a}{\partial \theta} = \begin{cases} 
\frac{L_{\max} - L_{\min}}{\theta_2 - \theta_1} & \text{for } \theta_1 \leq \theta \leq \theta_2 \\
-L_{\max} - L_{\min} & \text{for } \theta_3 \leq \theta \leq \theta_4 \\
0 & \text{otherwise}
\end{cases}
\]  

(3.2)

However, in an actual machine it is not possible to achieve such an ideal inductance profile [135].
The leakage flux plays an important role in determining inductance in the unaligned and partially aligned positions when the stator and rotor poles are not fully overlapping. Furthermore, for rectangular currents, it is observed that torque is produced in a pulsed form resulting in a large torque ripple due to the limited bandwidth of current control loop. Increased audible noise and fatigue of the rotor shaft are drawbacks of this operation. More importantly, rectangular currents cannot produce electromagnetic torque without ripple even if zero tracking error is achieved in the current control loop due to the non-ideal inductance profile. With this control scheme, mutual coupling is neglected. Only one phase is excited at a time except during the short commutation period. The torque ripple caused by the mutual coupling is usually small compared with the torque

Figure 3.8: Conventional Operation of the SRM [135].
error caused by incorrect current commands and the limited bandwidth of the current control loop.

3.3 EFFECTS OF DIMENSIONAL VARIATIONS

From the previous investigation, it is found that the base SRM generates the highest developed torque. The results for dimensional variations of rotor, stator poles and yoke size to achieve the higher developed torque are discussed below [136-142].

3.3.1 Dimensional Variations for Rotor Pole

The effects of the dimensional variation of pole arc/pole pitch ratio $\gamma$ of the rotor for the base switched reluctance motor are investigated. The ampere-turns for all models are kept the same. Leaving the pole arc/pole pitch ratio ($\beta$) of the stator and the yoke geometries with the same dimensions for the base SRM, while, increasing or decreasing the pole arc/pole pitch ratio $\gamma$ of the rotor pole and studying the influence of these changes on the motor torque. Table 3.3 shows the developed torque for different SRM by changing $\gamma$. The air-gap between stator and rotor poles is 0.4 mm. $\gamma = \text{rotor pole arc} / \text{pole pitch ratio}.$

Table 3.3: Torque Development for Different SRM Designs

<table>
<thead>
<tr>
<th>Switched Reluctance Motor</th>
<th>pole arc/pole pitch ratio ($\gamma$)</th>
<th>Torque (N.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRM 16</td>
<td>0.25</td>
<td>0.691</td>
</tr>
<tr>
<td>SRM 15</td>
<td>0.36</td>
<td>0.845</td>
</tr>
<tr>
<td>SRM 14</td>
<td>0.37</td>
<td>0.891</td>
</tr>
<tr>
<td>SRM 13</td>
<td>0.38</td>
<td>0.895</td>
</tr>
<tr>
<td>SRM 12</td>
<td>0.4</td>
<td>0.887</td>
</tr>
<tr>
<td>SRM 11</td>
<td>0.42</td>
<td>0.876</td>
</tr>
<tr>
<td>SRM 1</td>
<td>0.44</td>
<td>0.848</td>
</tr>
<tr>
<td>SRM 8</td>
<td>0.48</td>
<td>0.739</td>
</tr>
<tr>
<td>SRM 9</td>
<td>0.5</td>
<td>0.740</td>
</tr>
<tr>
<td>SRM 10</td>
<td>0.74</td>
<td>0.578</td>
</tr>
</tbody>
</table>
Figure 3.9 shows the cross sections for four SRM designs. The widest rotor pole pitch ($\gamma$) is 0.74. The rotor pole width is wider than the stator pole width and also wider than the rotor pole of the base SRM. In this design, the developed torque has the lowest value. The range for increasing the rotor pole arc/pole pitch ratio $\gamma$ varies between 0.44 to 0.74 as shown in table 3.2.
Figure 3.10 shows the graphical results of the torque development for five different SRM designs after increasing the rotor pole arc/pole pitch ratio $\gamma$ from 0.44 to 0.5 in steps of 0.2 (increasing $\gamma$ tests). Investigating the influence of these incremental steps on the developed torque, it is found that torque decreases as soon as the $\gamma$ increases. The rotor pole widths for these models are wider than the rotor pole width for the base SRM. The mmf for wider and narrower rotor pole width is 150 AT.

Figure 3.11 shows the graphical results of the torque developed versus rotor displacement angles for the SRM model when the rotor pole arc/pole pitch ratio $\gamma$ is equal to 0.48. Changing the mmf from 30 to 210 ampere-turn in step of 30 ampere-turn, it was found that torque increased as soon as the ampere-turns are increased.
Figure 3.11: Torque versus Rotor Position Displacement for Different MMF of the Wider Rotor Pole Width SRM 9 ($\gamma = 0.48$).

Figure 3.12 shows the torque developed versus different mmf in the rotor pole width SRM when the rotor pole arc/pole pitch ratio $\gamma$ is equal to 0.48. For each mmf, the rotor position displacement is changed from aligned to unaligned positions in step of 5º; rotating step has been chosen randomly. The lowest developed torque is obtained at aligned and unaligned positions, in the intermediate positions the rotor developed higher torque values.
Figure 3.12: Torque versus MMF at Different Rotor Positions for SRM ($\gamma = 0.48$).

Figure 3.13 shows the flux line distribution for the base design and the widest rotor pole design. Figure 3.14 shows the cross sections for four SRM of the narrower rotor pole width i.e. the rotor pole width is narrower than the stator pole width and rotor pole arc/pole pitch ratio $\gamma$ varies from 0.44 to 0.25 in random steps as shown in table 3.2. The rotor pole width for these designs is narrower than the rotor pole width of the base model. $\gamma$ for SRM 1 is 0.44, $\gamma$ for SRM 11 is 0.42, $\gamma$ for SRM 13 is 0.38, and the last lowest possible value for rotor pole width of SRM 16 is 0.25 (decreasing $\gamma$). The air-gap between stator and rotor poles is 0.4 mm.
Figure 3.13: The Flux Line Distribution for SRM 1 (Base) and SRM 10 (increasing $\gamma$).
Figure 3.14: Four Cross Sections of SRM Designs (decreasing $\gamma$).

Figure 3.15 shows the flux distribution for various designs. The developed torque increased more than the base SRM and reached the highest value in SRM 13 ($\gamma = 0.38$).
Figure 3.16 shows the graphical results of the torque developed for four different SRM models after decreasing the rotor pole arc/pole pitch ratio $\gamma$ from 0.44 (SRM 1) to 0.42 (SRM 11), 0.38 (SRM 13) and 0.25 (SRM 16) (decreasing $\gamma$). Investigating the influence of the rotor pole arc/pole pitch ratio $\gamma$ on the developed torque, it is found that torque increases for designs 11 and 13 when $\gamma$ equal 0.42 and 0.38 and the torque starts to decrease with increasing $\gamma$. The reason for this behaviour is the saturation of the magnetic field curves the inductance profile between aligned and unaligned position, causing the flux linkage to be lower, which occurred on SRM 15 and 16, because the size of the rotor poles is smaller. As expected and according to equation 3.1, 3.3 and the values of the flux linkage for SRM 15 and 16 as shown in table 3.4, the total output torque generated by these designs are low. The rotor pole width for these designs is wider than the rotor pole width for the base SRM. The mmf for wider and narrower rotor pole width is 150 AT. Figure 3.17 shows the torque developed versus rotor displacement angles in SRM 13 at $\gamma$ equals 0.38, with variable mmf. As expected, it is found that developed torque increases as soon as the ampere – turns are increased. Table 3.4 shows the flux distribution for all SRM designs.
Table 3.4: Flux Linkage for various SRM Designs

<table>
<thead>
<tr>
<th>Switched Reluctance Motor</th>
<th>Flux Linkage (Wb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRM 16</td>
<td>0.025</td>
</tr>
<tr>
<td>SRM 15</td>
<td>0.03</td>
</tr>
<tr>
<td>SRM 14</td>
<td>0.0326</td>
</tr>
<tr>
<td>SRM 13</td>
<td>0.0327</td>
</tr>
<tr>
<td>SRM 12</td>
<td>0.032</td>
</tr>
<tr>
<td>SRM 11</td>
<td>0.032</td>
</tr>
<tr>
<td>SRM 1</td>
<td>0.031</td>
</tr>
<tr>
<td>SRM 8</td>
<td>0.027</td>
</tr>
<tr>
<td>SRM 9</td>
<td>0.0271</td>
</tr>
<tr>
<td>SRM 10</td>
<td>0.021</td>
</tr>
</tbody>
</table>

Figure 3.16: Torque versus Rotor Position for Four SRM Designs (decreasing γ).
Figure 3.17: Torque versus Rotor Position for Different MMF for SRM 13 at $\gamma = 0.38$.

Figure 3.18 shows the developed torque versus different mmf for the SRM 13 at various angles, while the rotor pole arc/pole pitch ratio $\gamma$ is equal to 0.38. For each mmf, the rotor is moved from aligned to unaligned positions. The lowest developed torque is obtained at aligned and unaligned positions, in the intermediate positions the rotor developed higher torque.
Figure 3.18: Torque versus MMF at different Rotor Positions for SRM 13 ($\gamma = 0.38$).

Figure 3.19 shows the graphical results of the average developed torque versus the rotor pole arc/pole pitch ratio $\gamma$. Each value of the rotor pole arc/pole pitch ratio $\gamma$ represents different SRM design. Increasing $\gamma$ between (0.44 to 0.75) will reduce the developed torque, while decreasing $\gamma$ between (0.44 to 0.38) will increase the developed torque and the developed torque reaches the highest value when $\gamma$ equals to 0.38. Decreasing $\gamma$ further from 0.38 to 0.25 will reduce the developed torque as shown in figure 3.19.
3.3.2 Effect of Variations for Stator Pole

Further simulation study is carried out to find the effect of stator pole /pole pitch ratio ($\beta$) on the developed torque. The pole arc/pole pitch ratio of the rotor $\gamma$ and the yoke geometries are the same as the base SRM. The pole arc/pole pitch ratio ($\beta$) of the stator is varied to study the influence of these changes on the developed torque. Different values of the stator pole arc/pole pitch ratio ($\beta$) are chosen in eleven random steps started from 0.25 to 0.74.

Table 3.5 shows the various values of stator pole arc/pole pitch ratio ($\beta$); each ($\beta$) represents SRM design. The first motor SRM 1 is the base SRM with $\beta$ equal 0.44. The air-gap between stator and rotor poles is 0.4 mm. The stator pole width for SRM 17 to SRM 22 are wider than the stator pole width of the base SRM 1, in this design the developed torque reaches the lowest value. The range for increasing the stator pole arc/pole pitch ratio ($\beta$) varies between 0.46 to 0.74. The effects of the dimensional
variation of the pole arc/pole pitch ratio ($\beta$) of the stator on the developed torque for the base switched reluctance motor are investigated. All the models for this study are set on the same value for the ampere-turns as in the previous case. Each value of the rotor pole arc/pole pitch ratio ($\beta$) represents a single SRM design.

Table 3.5: $\beta$ for various SRM Designs

<table>
<thead>
<tr>
<th>Switched Reluctance Motor</th>
<th>Stator pole arc/pole pitch ratio ($\beta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRM 17</td>
<td>0.46</td>
</tr>
<tr>
<td>SRM 18</td>
<td>0.48</td>
</tr>
<tr>
<td>SRM 19</td>
<td>0.5</td>
</tr>
<tr>
<td>SRM 20</td>
<td>0.6</td>
</tr>
<tr>
<td>SRM 21</td>
<td>0.7</td>
</tr>
<tr>
<td>SRM 22</td>
<td>0.74</td>
</tr>
<tr>
<td>SRM 1</td>
<td>0.44</td>
</tr>
<tr>
<td>SRM 23</td>
<td>0.42</td>
</tr>
<tr>
<td>SRM 24</td>
<td>0.4</td>
</tr>
<tr>
<td>SRM 25</td>
<td>0.38</td>
</tr>
<tr>
<td>SRM 26</td>
<td>0.28</td>
</tr>
<tr>
<td>SRM 27</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Figure 3.20 shows the graphical results of the torque development for four different SRM designs after increasing the stator pole arc/pole pitch ratio ($\beta$) from 0.44 to 0.5 in step of 0.2 (increasing $\beta$ tests). The first cross section design is SRM 1 with $\beta$ equal 0.44, ($\beta$) for SRM 18 is 0.48, ($\beta$) for SRM 19 is 0.5, ($\beta$) for SRM 22 is 0.74. It is found that average developed torque for SRM 19 has the highest value out of all the tested SRM and even more than the developed torque of the base SRM design. The stator pole width for these designs is wider than the stator pole width for the base SRM. The mmf for wider and narrower stator pole width is 150 AT.
Figure 3.20: Torque versus Rotor Position for Four SRM Designs (increasing $\beta$).

Figure 3.21 shows four cross sections of SRM designs (decreasing $\beta$). Decreases the rotor pole arc/pole pitch ratio ($\beta$) from 0.44 (SRM 1) to ($\beta$) equals 0.42 for SRM 27, ($\beta$) equals 0.4 for SRM 28, ($\beta$) equals 0.38 for SRM 29, ($\beta$) equals 0.28 for SRM 30 and the last lowest possible value for ($\beta$) for SRM 31 is 0.25. Investigating the influence of the rotor pole arc/pole pitch ratio ($\beta$) on the developed torque, it is found that developed torque decreases as soon as $\beta$ decreases. The stator pole width for these designs is wider than the stator pole width for the base SRM. The mmf for wider and narrower stator poles
widths is 150 AT. Figure 3.22 shows the flux distribution for four SRM designs. It was found that flux distribution for the base SRM has the highest value in comparison with the SRM designs for decreasing $\beta$ tests.

![Four Cross Section Designs of SRM (Decreasing $\beta$)](image)

SRM 1 ($\beta = 0.44$)  
SRM 25 ($\beta = 0.38$)  
SRM 26 ($\beta = 0.28$)  
SRM 27 ($\beta = 0.25$)

Figure 3.21: Four Cross Section Designs of SRM (Decreasing $\beta$).
Table 3.6 shows the flux distribution developed in eleven SRM designs by increasing and decreasing $\beta$ with rotating the rotor from unaligned to aligned positions. The flux linkage value is varied according to $\beta$. Equation 3.1 and this table is controlling the developed
torque in these designs. Figure 3.23 shows the developed torque in various (decreasing and increasing) $\beta$, each $\beta$ represent SRM design.

Table 3.6: Flux Linkage (Wb) for Various SRM Designs

<table>
<thead>
<tr>
<th>Switched Reluctance Motor</th>
<th>Flux linkage (Wb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRM 17</td>
<td>0.031</td>
</tr>
<tr>
<td>SRM 18</td>
<td>0.0322</td>
</tr>
<tr>
<td>SRM 19</td>
<td>0.0325</td>
</tr>
<tr>
<td>SRM 20</td>
<td>0.03</td>
</tr>
<tr>
<td>SRM 21</td>
<td>0.029</td>
</tr>
<tr>
<td>SRM 22</td>
<td>0.0285</td>
</tr>
<tr>
<td>SRM 1</td>
<td>0.031</td>
</tr>
<tr>
<td>SRM 23</td>
<td>0.03</td>
</tr>
<tr>
<td>SRM 24</td>
<td>0.029</td>
</tr>
<tr>
<td>SRM 25</td>
<td>0.0285</td>
</tr>
<tr>
<td>SRM 26</td>
<td>0.021</td>
</tr>
<tr>
<td>SRM 27</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Figure 3.23: Torque versus ($\beta$).
The developed torque in table 3.7 is shown as a function of \( \beta \).

<table>
<thead>
<tr>
<th>Torque (Nm)</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55</td>
<td>0.25</td>
</tr>
<tr>
<td>0.58</td>
<td>0.28</td>
</tr>
<tr>
<td>0.78</td>
<td>0.38</td>
</tr>
<tr>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>0.83</td>
<td>0.42</td>
</tr>
<tr>
<td>0.85</td>
<td>0.44</td>
</tr>
<tr>
<td>0.86</td>
<td>0.46</td>
</tr>
<tr>
<td>0.88</td>
<td>0.48</td>
</tr>
<tr>
<td>0.89</td>
<td>0.5</td>
</tr>
<tr>
<td>0.83</td>
<td>0.6</td>
</tr>
<tr>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>0.78</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Figure 3.24 shows the cross section for two SRM designs. First design is developed the highest torque with pole arc/pole pitch ratios \( \beta \) equal 0.5. The second design is developed the lowest torque with pole arc/pole pitch ratios \( \beta \) equal 0.25.

Figure 3.24: a) SRM 27 \( \beta = 0.25 \), b) SRM 19 \( \beta = 0.5 \).
Figure 3.25 shows the graphical results for three SRM designs. Developed torque is analysed for the SRM 1 and SRM 19 when the rotor rotates from 0° to 45°. These designs have nearly the same developed torque in the zone between 0° to 14°. The developed torque for SRM 19 starts to decrease slightly when the rotor rotates from 14° to 28°; finally the developed torque of SRM 19 is higher than the developed torque of the base design SRM 1 while the rotor rotates from 28° to 45°. Now comparing SRM 1 and SRM 27, the developed torque for the SRM 27 is less than the developed torque of the SRM 1 while the rotor rotates from 0° to 8°. The developed torque for SRM 27 is higher than the developed torque of the SRM 1, while the rotor rotates from 8° to 22°. Finally the developed torque for the SRM 27 is lower than the developed torque of the SRM 1 when the rotor rotates from 22° to 45°.

Figure 3.25: Torque versus Rotor Angle Displacement for Three SRM Designs.
3.4 OPTIMIZED DESIGN FOR 3 PHASE SRM.

Torque optimization has been achieved as shown individually by dimensional variation on the stator, the rotor poles and yoke size of the SRM. After gathering the results of the highest developed torque for the stator, the rotor poles and yoke size, a new SRM 28 optimized design is obtained. Figure 3.26 shows the base design and the optimized design SRM 28. The stator pole arc/pole pitch ratio (β) for the optimized SRM is 0.5; the rotor pole arc/pole pitch ratio γ for optimized SRM is 0.38.

![Figure 3.26: a) Base Design SRM 1, b) Optimized Design SRM 28.](image)

Figure 3.27 shows the graphical results for developed torque for the reference base SRM design and the optimized SRM design. Developed torque is analysed when rotating the rotor from 0° to 45° for the optimized and base models. The torque developed in the optimized design is less than the torque developed in the base design when rotor rotates from 0° to 5°; the torque developed for optimized design is higher than the developed torque for the base design when the rotor rotates from 5° to 45°.
Figure 3.27: Torque versus Rotor Angle Displacement for SRM 1 and SRM 28.
Figure 3.28a shows the flux line distribution through the yoke, stator pole, air-gap, and rotor for 3 phase, 6/4 poles base cross-section design SRM 1. Figure 3.28b shows the flux line distribution through the yoke, stator pole, air-gap and rotor for 3 phase, 6/4 poles optimized cross-section design SRM 28.

![Figure 3.28: a) Flux Line Distribution for 3 Phase, 6/4 Poles Base Design SRM 1; b) Flux Line Distribution for 3 Phase, 6/4 Poles Optimized Design SRM 28.](image)

### 3.5 OPTIMIZED DESIGN FOR 4 PHASE, 8/6 POLES SRM

Since the torque optimization is performed by dimensional variation for stator, rotor poles of 3 phase, 6/4 SRM as discussed in previous steps, so the same proposed dimensional variation method are implemented for 8/6 poles base SRM 29. Figure 3.29a shows two types of cross sections for SRM, the base design 4 phase, 8/6 poles SRM 29, while figure 3.29b shows the optimized design for 4 phase, 8/6 poles SRM 30. Table 3.8 shows $\beta$ and $\gamma$ values for the base design 4 phase SRM 29 and the optimized design 4 phase SRM 30.
Figure 3.29: a) Base Design of SRM 29, b) Optimized Design SRM 30.

Table 3.8: β and γ values for the base and the optimized designs 4 Phase SRM.

<table>
<thead>
<tr>
<th>(β) and (γ) \ SRM</th>
<th>SRM 29 (4 phase base SRM)</th>
<th>SRM 30 (4 phase optimized SRM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The stator pole arc/pole pitch ratio (β)</td>
<td>0.44</td>
<td>0.5</td>
</tr>
<tr>
<td>The rotor pole arc/pole pitch ratio (γ)</td>
<td>0.44</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Figure 3.30 shows the comparative base design SRM 29 and optimized design SRM 30. As soon as the mmf varies from 200 to 1000 AT, the developed torque for optimized SRM 30 is higher slightly than the developed torque of base SRM 29. The developed torque of the optimized SRM 30 increases rapidly compared with the developed torque of the base SRM 29 between 1000 to 4000 AT.
Figure 3.30: Average Torque versus Ampere-Turn for 4 Phase SRM 29 and 30.
Figure 3.31a shows the flux line distribution through the yoke, stator pole, air-gap, and rotor for 4 phase, 8/6 poles base SRM 29, while Figure 3.31b shows the flux line distribution through the yoke, stator pole, air-gap, and rotor for 4 phase, 8/6 poles optimized SRM 30.

Figure 3.32 shows the flux linkage versus current variation for 4 phase base SRM 29 from 0.2 to 10 amperes, while the rotor rotates from unaligned to aligned positions in step of 4.2°.
Figure 3.32: Flux Linkage versus Current for 4 Phase base SRM 29.
3.6 SIMULATION RESULTS BY MATLAB

MATLAB SIMULINK package is used to simulate the SR motor. The SRM designs were simulated with the MATLAB SIMULINK package and look up table of the torque \( \tau (\theta, I) \) is used to represent the simulation, torque is a function of rotor position and current, which is extracted from the numerical data of the motor design by a finite elements method. The look up table from SIMULINK library is used to represent the developed torque in the 3 phase base SRM 1 and optimized SRM 28, as the displacement angles are considered as a row parameters (horizontal parameters), that varied between (0° to 45°), and the mmf is considered as column parameters (vertical parameters), which is varied between (30 to 210 AT).

\[
T = T_e - T_l = J \frac{d\omega}{dt}
\]

(3.3)

This simulation is based on equation (3.3), where \( T \) is the torque, \( T_e \) is the electromechanical torque, \( T_l \) is the load torque, which is assumes to be zero, \( \omega \) is the rotational velocity of the shaft, \( J \) momentum of inertia. Figure 3.33 shows how to multiply the developed torque table of SRM1 by momentum of inertia \((1/J)\), then through single and double integration, \( \omega \) and \( \theta \) have been obtained.

Figure 3.33: Block Diagram for 3 Phase, 6/4 Poles Base SRM 1.
Since the torque is a function of rotor angle displacement as shown in figure 3.34a and ampere turn (AT) as shown in figure 3.34b, these two inputs are used to feed the look up table (2D).

![Figure 3.34: a) Angle displacement, b) AT, Inputs of Look-up Table for Base SRM 1.](image)

Figure 3.34: a) Angle displacement, b) AT, Inputs of Look-up Table for Base SRM 1.

Figure 3.35 shows the two inputs (rotor displacement angle) and AT (ampere/turn) and the output is the developed torque values allocated in the table. For example if the rotor is in the aligned position (0°), which is shown in the row parameters and the value of (AT) varies from 30 to 210, which is shown in the column parameters, then the output (developed torque) is allocated in table parameters.

![Figure 3.35: Look-up Table (2-D) for the Base SRM 1.](image)

Figure 3.35: Look-up Table (2-D) for the Base SRM 1.
The output of integrator 4 is (ω) as shown in figure 3.36a when the rotor moved from unaligned to aligned positions for different mmfs. The output of integrator 3 is θ as shown in figure 3.36b when the rotor moved from unaligned to aligned positions.

Figure 3.36: a) (ω) versus time, b) θ versus time of the Base SRM 1.

Figure 3.37 shows how to multiply the developed torque table by momentum of inertia (1/J), then by performing single and double integration on the result, (ω) and θ have been obtained. The same procedure is used to find (ω) and θ for the optimized SRM by implementing equation (3.4) and using the numerical extracted data of the 3 phase optimised design SRM 28, which is found by finite elements method.

Figure 3.38a shows the simulation results for (ω) of the optimized SRM 28 when the rotor moved from unaligned to aligned positions for different mmfs. Figure 3.38b shows the simulation results for θ of the optimized SRM 28 when the rotor moved from unaligned to aligned positions for different mmfs. It is obvious that the speed obtained from the optimized SRM 28, is higher than the speed obtained for the base SRM 1 as shown in figure 3.38 and figure 3.36 respectively.
Figure 3.37: Block Diagram for 3 Phase, 6/4 Poles Optimised SRM 28.

Figure 3.38: a) $\omega$ versus time, b) $\theta$ versus time of the Optimised SRM 28.
Since the speed for the proposed 3 phase, 6/4 poles SRM 28 has a higher developed torque and speed than the base SRM 1, so same procedure is used for MATLAB-SIMULINK package implementation on the model of 4 phase, 8/6 poles base SRM 29 and proposed (optimized) SRM 30. Figure 3.39 shows the implementation of the mathematical torque equation in block diagram form on the 4 phase, 8/6 poles base SRM 29. The table of the developed torque as a function of rotor angle and current $T(\theta, I)$ is extracted from the numeric data of the base SRM 29 by a finite element method.

Figure 3.40 shows the implementation of the mathematical torque equation in block diagram form on the 4 phase, 8/6 poles proposed (optimized) SRM 30.
Figure 3.41 shows the simulation results for the base 4 phase, 8/6 poles SRM 29 when the rotor moved from unaligned to aligned positions for different mmfs. Figure 3.42 shows the simulation results for the optimized (proposed) 4 phase, 8/6 poles SRM 30 when the rotor moved from unaligned to aligned positions for different mmfs.
Figure 3.41: a) $\omega$ versus time, b) $\theta$ versus time of the Base 4 Phase, 8/6 Poles SRM 29.

Figure 3.42: a) $\omega$ versus time, b) $\theta$ versus time of the Optimized (Proposed) 4 Phase, 8/6 Poles SRM 30.
3.7 CONCLUSIONS

The incremental torque percentage for the optimized design 3 phase SRM 28 is 11.5% greater than the developed torque of the base design 3 phase SRM 1. The incremental torque percentage of the optimized design for 4 phase SRM 30 is 12.9% greater than the developed torque of the base design for 4 phase SRM 29. MATLAB-SIMULINK package is employed in this study relied on the results extracted from finite element method to show the speed of the optimized design 3 phase SRM 28 is greater than the speed of the base design 3 phase SRM 1 and the speed of the optimized design 4 phase SRM 30 is greater than the speed of the base design 4 phase SRM 29. The chosen base SRM has been modified to achieve an optimized SRM where flux line distribution finds a better path to develop a stronger torque that attracts the rotor; this is the reason why the optimum ratios in the design of the switched reluctance machines arise. Reducing the area too much caused magnetic saturation of the rotor.
CHAPTER 4: FUZZY LOGIC CONTROL of SRM

4.1 INTRODUCTION

Fuzzy logic is a powerful problem-solving methodology with a myriad of applications in embedded control and information processing. Fuzzy logic provides a remarkably simple way to draw definite conclusions from vague, ambiguous or imprecise information. In a sense, fuzzy logic resembles human decision making with its ability to work from approximate data and find precise solutions. Unlike classical logic which requires a deep understanding of a system, exact equations, and precise numeric values, fuzzy logic incorporates an alternative way of thinking, which allows modeling complex systems using a higher level of abstraction, originating from our knowledge and experience. In 1965 Lotfi A. Zadeh published his seminal work "Fuzzy Sets" which described the mathematics of fuzzy set theory, and by extension fuzzy logic. This theory proposed making the membership function (or the values false and true) operate over the range of real numbers [0.0, 1.0]. New operations for the calculus of logic were proposed, and showed to be in principle at least a generalization of classic logic [76,143].

Areas in which fuzzy logic has been successfully applied are often quite concrete. The first major commercial application was in the area of cement kiln control, an operation which requires that an operator monitor four internal states of the kiln, control four sets of operations, and dynamically manage 40 or 50 "rules of thumb" about their interrelationships, all with the goal of controlling a highly complex set of chemical interactions. One such rule is "If the oxygen percentage is rather high and the free-lime and kiln-drive torque rate is normal, decrease the flow of gas and slightly reduce the fuel rate. The objection has been raised that utilizing fuzzy systems in a dynamic control environment raises the likelihood of encountering difficult stability problems: since in control conditions the use of fuzzy systems can roughly correspond to using thresholds, there must be significant care taken to insure that oscillations do not develop in the "dead
spaces” between threshold triggers. This seems to be an important area for future research. Other applications, which have benefited through the use of fuzzy systems theory, have been information retrieval systems, a navigation system for automatic cars, a predictive fuzzy-logic controller for automatic operation of trains, laboratory water level controllers, feature-definition controllers for robot vision, and more [144-145].

4.2 FUZZY BLOCK AT THE MATLAB PROMPT

The MATLAB fuzzy logic toolbox library contains the fuzzy logic controller with rule viewer blocks. It also includes a membership functions sub library that contains SIMULINK blocks for the built-in membership functions. Figure 4.1 shows the fuzzy logic controller with rule viewer block is an extension of the fuzzy logic controller block. Starting build the fuzzy controller with rule viewer block or o initialize the fuzzy logic controller blocks (with or without the rule viewer), by entering the name of the structure variable describing FIS (Fuzzy Inference System). This variable must be located in the MATLAB workspace.

For most fuzzy inference systems, the fuzzy logic controller block automatically generates a hierarchical block diagram representation of your (Fuzzy Inference System) FIS. This automatic model generation ability is called the fuzzy wizard. The block diagram representation only uses built-in SIMULINK blocks and therefore allows for efficient code generation. The fuzzy wizard can not handle FIS with custom membership functions or with AND, OR, IMP and AGG functions outside of the following list:

- or Method: max
- and Method: min, prod
- imp Method: min, prod
- agg Method: max

In these cases, the fuzzy logic controller block uses the S-function to simulate the FIS.
Fuzzy theory holds that all things are matters of degree, and also reduces black-white logic and mathematics to special limiting cases of grey relationships. The multi-valued fuzziness corresponds to degrees of indeterminacy or ambiguity, partial occurrence of events or relations. Zadeh [76,143] extended the bivalent indicator function $I_A$ of non-fuzzy subset $A$ of $X$,

$$I_A(x) = \begin{cases} 1 & \text{if } x \in A \\ 0 & \text{if } x \notin A \end{cases} \quad (4.1)$$

To a multi-valued indicator or membership functions $m_A: X \rightarrow [0, 1]$. This allows us to combine such multi-valued or fuzzy sets with the point-wise operators of indicator functions, where:

$$\mu_A: X \rightarrow [0, 1] \quad (4.2)$$

Figure 4.2 shows the membership function (MF): A MF is a curve that defines how each point in the universe of discourse is mapped to a value between 0 and 1. This value is called membership value or degree of membership.
Figure 4.2: The Membership Functions of x in A

Figure 4.3 shows an example of fuzzy sets, let’s define a Fuzzy Number as a fuzzy set into real axis $\mathbb{R}$ that:

1. It is normal set, that is, there exist at least one element $x \in \mathbb{R}$ such that $A(x) = 1$
2. $\forall \delta \in [0,1], \forall x, y \in \mathbb{R}: \mu_A(\delta \cdot x + (1-\delta) \cdot y) \geq \min(\mu_A(x), \mu_A(y))$

Example: let’s define two fuzzy numbers “Approximity 4”, semantic label is AP-4 “Approximity 7”, semantic label is AP-7

Where: $\mu_{\text{AP-4}}(6) = 0.4$, and $\mu_{\text{AP-7}}(6) = 0.7$

Figure 4.3: Fuzzy Numbers as Fuzzy Sets.

Let $X$ and $Y$ is a couple of universes of discourse. Fuzzy relation $R$ between $X$ and $Y$ is defined as a fuzzy set such that:

$$R = \{ ((x, y), \mu_R(x, y)) | (x, y) \in X \times Y \}$$ (4.3)
\[ \mu_R : X \times Y \rightarrow [0, 1] \]  

(4.4)

Let A and B be fuzzy sets such that \( A \subseteq X \) and \( B \subseteq Y \), and \( (x, y) \in X \times Y \). AND connective can be accomplished through next fuzzy relation:

\[ \mu_{\text{AND}}(x, y) \rightarrow \min \{ \mu_{\text{AND}}(x), \mu_{\text{AND}}(y) \} \]  

(4.5)

That describes how much \( x \) belongs to A and \( y \) belongs to B.

OR connective can be accomplished through next fuzzy relation:

\[ \mu_{\text{OR}}(x, y) \rightarrow \max \{ \mu_{\text{OR}}(x), \mu_{\text{OR}}(y) \}, \]  

(4.6)

That describes how much \( x \) belongs to A or \( y \) belongs to B.

Figure 4.4 shows how the connectives work. The upper part of the figure displays plots corresponding to the two-valued truth tables, while the lower part of the figure displays how the operations work over a continuously varying range of truth values A and B according to the fuzzy operations defined above.
Figure 4.4: Logical Instruction Connective

Let’s define the T-norm application as, \( t: [0, 1] \times [0, 1] \rightarrow [0, 1] \) with the next properties:

1. Mono-tonicity, that is, not decreasing in each argument: when \( x \leq y \) and \( w \leq z \), then \( t(x, w) \leq t(y, z) \)

2. Commutatively:

\[
t(x, y) = t(y, x), \quad \forall x, y \in [0, 1]
\]

(4.7)

3. Associatively:

\[
t(t(x, y), z) = t(x, t(y, z)), \quad \forall x, y, z \in [0, 1]
\]

(4.8)

4. Boundary:

\[
t(x, 0) = 0 \text{ and } t(x, 1) = x, \quad \forall x \in [0, 1]
\]

(4.9)
T-norms are used instead of classical intersection operator:

\[ \mu_{A \cap B}(x) = t(\mu_A(x), \mu_B(x)) \quad (4.10) \]

(Maximum) \( s(x, y) = \max(x, y) \) \quad (4.11)

(Limited sum) \( s(x, y) = \min(1, x + y) \) \quad (4.12)

(Algebraic sum) \( s(x, y) = x + y - x \cdot y \) \quad (4.13)

(Sum) \[ s(x, y) = \begin{cases} 
\max(x, y) & \text{when } \min(x, y) = 0 \\
1 & \text{othercase} 
\end{cases} \quad (4.14) \]

That is to say, the associated S-norm can be defined for a specified T-norm. Since intersection and union operators can be understood as classical ones, T-norm and S-norm operators are defined in order to obtain more generality. Several parameterized T-norm and dual T-norm have been proposed providing different ways to vary the "gain" of the function [76,146-149].

Fuzzy inference procedure works like in classical theory as shown in table 4.1:

<table>
<thead>
<tr>
<th>Antecedent:</th>
<th>“IF x is A THEN y is B”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consequent:</td>
<td>“y is B”</td>
</tr>
</tbody>
</table>

If-Then rules will be used to make something useful with fuzzy logic. A single fuzzy If-Then Rule assumes the appearance: IF (x is A) THEN (y is B), where A and B are linguistic values defined by fuzzy sets in the ranges X and Y (universes of discourses). The 'IF' part is called the antecedent while 'THEN' part is called the consequent or
conclusion. The antecedent is an interpretation that returns a single number between 0 and 1. The consequent is an assignment that brings up the entire fuzzy set B to the output variable y. Interpreting an If-Then rule implies different parts: first evaluating the antecedent which involves fuzzifying the input and applying any fuzzy operator, and second, applying that result to the consequent (implication) [150].

When the antecedent is a fuzzy statement so that is true to some degree of membership, then the consequent is also true to that same degree. Both antecedent and consequent rules can have multiple parts, e.g.: “IF temperature is warm AND pressure is increasing THEN sky is grey AND wind is strong ”. In this case, all parts of the antecedent can be calculated simultaneously and resolved to a single number using the fuzzy AND-operator defined above. The consequent specifies a fuzzy set assigned to the output so that the implication function must modify that fuzzy set to the degree specified by the antecedent. The most common way to modify the output fuzzy set is truncation using MIN function or scaling using PROD function. Figure 4.5 shows the application of MIN function as implication operator on the If-Then rule, “IF (Temperature is warm OR Pressure is increasing) THEN Sky is grey”. Implication operator might also be defined in several ways such as proposed by Mamdani etal. [150].
In general, one rule by itself does not do much good. What is needed: are two or more rules that can play off one another. The output of each rule is a fuzzy set, but in general the output for an entire collection of rules to be a single number as shown in figure 4.6. Therefore, all these fuzzy sets are distilled into a single crisp result by aggregating it into a single output fuzzy set. Aggregation only occurs once for each output variable, so that, aggregation results is one fuzzy set for each output variable. The order in which the rules are fired or executed is not important because aggregation method is commutative.
4.3 FUZZY LOGIC CONTROLLER STRUCTURE

Figure 4.7 shows how the fuzzy logic controllers (FLC) use fuzzy logic as a process of mapping from a given input (crisp numerical value) to an output (signal control $u$). This process has a basic structure that involves a fuzzifier, an inference engine, a knowledge base (rule data base), and a defuzzifier, which transforms fuzzy sets into real numbers to provide control signals.
Figure 4.8 shows the block diagram of the fuzzy logic controller.
In order to clarify the structure of an FLC controller, Table 4.2 shows the five linguistic fuzzy sets. Let E and DE be the red input labels corresponding to e signal and its variation. FLC output consists of a signal control u named U (the green label) as shown in table 4.2. Let it be assumed that fuzzy linguistic sets are already defined and the rules are as follows:

Sample Rule: “IF (E is NS AND DE is NS) THEN U is NM”. First step is to take E and DE and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions.

The inputs are always a crisp numerical values limited to the universes of discourse of the inputs (in this case the interval is assumed to be between -3 and 3) as shown in figure 4.9. Therefore, fuzzification procedure is only a function evaluation or a lookup table operation. Once the inputs have been fuzzified, the degree to which each part of the antecedent has been satisfied for each rule is known. If the antecedent of a given rule has more than one part, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. This number will then be applied to the output function. Suppose the next input values are: e = 0.2, and de = 1.4. These two values are located on the horizontal axis of figure 4.9, by dropping a vertical axis on the two values the output is shown in table 4.3.
Figure 4.9: The Fuzzy Linguistic Sets.

Table 4.3: Calculation for the Mentioned Example

<table>
<thead>
<tr>
<th>Variable</th>
<th>Degree of membership</th>
<th>$E = 0.2$</th>
<th>$E = 1.4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{NM}(e)$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\mu_{NS}(e)$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\mu_{ZE}(e)$</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\mu_{PS}(e)$</td>
<td>0.2</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>$\mu_{PM}(e)$</td>
<td>0.4</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

The general degree of membership values are shown in table 4.4.
Figure 4.10 shows the fuzzy values related to output $U$ as follows:

PS activation degree is 0.6, and PM activation degree is 0.4 ($\max\{0.4, 0.2, 0.2\} = 0.4$). Defuzzification method: Calculation of $u_0$ will be calculated using middle of maximum, centroid, and largest of maximum. The largest maximum value between the membership PS and PM shown is 0.6 (PS), so the chosen output fuzzy set is PS. The middle of maximum of PS fuzzy set is $u_0 = 1$ as shown in figure 4.10.

<table>
<thead>
<tr>
<th>EAE</th>
<th>NM</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>NM</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ZE</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>PS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>PM</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.4: Degree of Membership Values
4.4 SIMULATION RESULTS FOR FLC OF 3 PHASE, 6/4 POLES SRM.

4.4.1 System Operating Rules

According to figure 4.7, the value of error:

\[ e\omega = \omega_{\text{ref}} - \omega_{\text{actual}} \]  \hspace{1cm} (4.15)

\[ \text{error-dot} = d(\text{error})/dt. \]  \hspace{1cm} (4.16)

Output: conclusion & system response:

- **Input 1:** Error = NB (Negative big), NM (Negative medium), NS (Negative small), ZE (Zero), PS (Positive small), PM (Positive medium), PB (Positive big).
- **Input 2:** Error-dot = NB (Negative big), NM (Negative medium), NS (Negative small), ZE (Zero), PS (Positive small), PM (Positive medium), PB (Positive big).
- **Conclusion:** Output = (NB, NB, NB, NB, NM, NS, ZE) = (NB, NB, NB, NM, NS, ZE, PS) = (NB, NB, NM, NS, ZE, PS, PM) = (NB, NM, NS, ZE, PS, PM, PB) = (NM, NS, ZE, PS, PM, PB, PB) = (NS, ZE, PS, PM, PB, PB) = (ZE, PS, PM, PB, PB, PB).

Figure 4.11 shows the rule structure, the linguistic rules describing the control system consist of two parts; an antecedent block (between the IF and THEN) and a consequent block (following THEN). Depending on the system, it may not be necessary to evaluate every possible input combination. Since some may rarely or never occur. By making this type of evaluation, usually done by an experienced operator, fewer rules can be evaluated, thus simplifying the processing logic and perhaps even improving the FL system performance.
<table>
<thead>
<tr>
<th>Antecedents block</th>
<th>Consequent block</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. If (ew is NB) and (cew is NB) then (output_current is NB) (1)</td>
<td></td>
</tr>
<tr>
<td>2. If (ew is NB) and (cew is NM) then (output_current is NB) (1)</td>
<td></td>
</tr>
<tr>
<td>3. If (ew is NB) and (cew is NS) then (output_current is NB) (1)</td>
<td></td>
</tr>
<tr>
<td>4. If (ew is NB) and (cew is ZE) then (output_current is NB) (1)</td>
<td></td>
</tr>
<tr>
<td>5. If (ew is NB) and (cew is PS) then (output_current is NM) (1)</td>
<td></td>
</tr>
<tr>
<td>6. If (ew is NB) and (cew is PM) then (output_current is NS) (1)</td>
<td></td>
</tr>
<tr>
<td>7. If (ew is NB) and (cew is PB) then (output_current is ZE) (1)</td>
<td></td>
</tr>
<tr>
<td>8. If (ew is NM) and (cew is NB) then (output_current is NB) (1)</td>
<td></td>
</tr>
<tr>
<td>9. If (ew is NM) and (cew is NM) then (output_current is NB) (1)</td>
<td></td>
</tr>
<tr>
<td>10. If (ew is NM) and (cew is NS) then (output_current is NB) (1)</td>
<td></td>
</tr>
<tr>
<td>11. If (ew is NM) and (cew is ZE) then (output_current is NM) (1)</td>
<td></td>
</tr>
<tr>
<td>12. If (ew is NM) and (cew is PS) then (output_current is NS) (1)</td>
<td></td>
</tr>
<tr>
<td>13. If (ew is NM) and (cew is PM) then (output_current is ZE) (1)</td>
<td></td>
</tr>
<tr>
<td>14. If (ew is NM) and (cew is PB) then (output_current is PS) (1)</td>
<td></td>
</tr>
<tr>
<td>15. If (ew is NS) and (cew is NB) then (output_current is NB) (1)</td>
<td></td>
</tr>
<tr>
<td>16. If (ew is NS) and (cew is NM) then (output_current is NB) (1)</td>
<td></td>
</tr>
<tr>
<td>17. If (ew is NS) and (cew is NS) then (output_current is NM) (1)</td>
<td></td>
</tr>
<tr>
<td>18. If (ew is NS) and (cew is ZE) then (output_current is NS) (1)</td>
<td></td>
</tr>
<tr>
<td>19. If (ew is NS) and (cew is PS) then (output_current is ZE) (1)</td>
<td></td>
</tr>
<tr>
<td>20. If (ew is NS) and (cew is PM) then (output_current is PS) (1)</td>
<td></td>
</tr>
<tr>
<td>21. If (ew is NS) and (cew is PB) then (output_current is PM) (1)</td>
<td></td>
</tr>
<tr>
<td>22. If (ew is ZE) and (cew is NB) then (output_current is NB) (1)</td>
<td></td>
</tr>
<tr>
<td>23. If (ew is ZE) and (cew is NM) then (output_current is NM) (1)</td>
<td></td>
</tr>
<tr>
<td>24. If (ew is ZE) and (cew is NS) then (output_current is NS) (1)</td>
<td></td>
</tr>
<tr>
<td>25. If (ew is ZE) and (cew is ZE) then (output_current is ZE) (1)</td>
<td></td>
</tr>
<tr>
<td>26. If (ew is ZE) and (cew is PS) then (output_current is PS) (1)</td>
<td></td>
</tr>
<tr>
<td>27. If (ew is ZE) and (cew is PM) then (output_current is PM) (1)</td>
<td></td>
</tr>
</tbody>
</table>
28. If (ew is ZE) and (cew is PB) then (output_current is PB) (1)
29. If (ew is PS) and (cew is NB) then (output_current is NM) (1)
30. If (ew is PS) and (cew is NM) then (output_current is NS) (1)
31. If (ew is PS) and (cew is NS) then (output_current is ZE) (1)
32. If (ew is PS) and (cew is ZE) then (output_current is PS) (1)
33. If (ew is PS) and (cew is PS) then (output_current is PM) (1)
34. If (ew is PS) and (cew is PM) then (output_current is PB) (1)
35. If (ew is PS) and (cew is PB) then (output_current is PB) (1)
36. If (ew is PM) and (cew is NB) then (output_current is NS) (1)
37. If (ew is PM) and (cew is NM) then (output_current is ZE) (1)
38. If (ew is PM) and (cew is NS) then (output_current is PS) (1)
39. If (ew is PM) and (cew is ZE) then (output_current is PM) (1)
40. If (ew is PM) and (cew is PS) then (output_current is PB) (1)
41. If (ew is PM) and (cew is PM) then (output_current is PB) (1)
42. If (ew is PM) and (cew is PB) then (output_current is PB) (1)
43. If (ew is PB) and (cew is NB) then (output_current is ZE) (1)
44. If (ew is PB) and (cew is NM) then (output_current is PS) (1)
45. If (ew is PB) and (cew is NS) then (output_current is PM) (1)
46. If (ew is PB) and (cew is ZE) then (output_current is PB) (1)
47. If (ew is PB) and (cew is PS) then (output_current is PB) (1)
48. If (ew is PB) and (cew is PM) then (output_current is PB) (1)
49. If (ew is PB) and (cew is PB) then (output_current is PB) (1)

Figure 4.11: The Rule Structure.

Table 4.5 shows the rule matrix for the FLC. The antecedents linguistic variables (ew, cew) are represented by the yellow highlighted zones and the consequent linguistic variables are represented by green highlighted zones. Both of them are represented by seven triangular membership functions. Error-dot = d(error)/dt, Speed error = ω_{ref} - ω_{actual}
4.4.2 Membership Functions

Fuzzy logic controller generates current reference changes ($\Delta I_{\text{ref}}$) based on speed error $\omega$ and its changes $\Delta \omega$. $\omega$ has its minimal value when the motor speed has its nominal value, 850 rad/sec, and is inverted to −850 rad/sec, so according to equation 4.15, then the speed error equals:

$$\omega = (-850) - (850) = -1700 \text{ rad/sec}$$

The maximum value, +1700, is obtained in the opposite situation as shown in figure 4.12
The changes of speed error \( e_{\omega} \) and according to equation (4.16) can be written in another form:

\[
\begin{align*}
  e_{\omega} &= e_{\omega}(k+1) - e_{\omega}(k) \\
  &= e_{\omega}(k+1) - e_{\omega}(k) \\
  &= (\omega_{ref} - \omega(k)) - (\omega_{ref} - \omega(k - 1)) \\
  &= - (\omega(k) - \omega(k - 1)) = -\Delta \omega
\end{align*}
\]

Substituting equation (4.15) and (4.17) into equation (3.4):

\[
T = T_e - T_i = J \frac{d\omega}{dt}
\]

\[
j \frac{\Delta \omega}{\Delta t} = \tau \Rightarrow \Delta \omega = \frac{\Delta t}{j} \tau
\]

\[
\left| e_{\omega} \right| = \frac{\Delta t}{j} \tau = \frac{0.0013}{0.01 \times 10^{-2}} \times 1.5 = 20 \text{ rad/sec/sec}
\]
\[ \Delta t = 0.0013 \text{ sec}, \ J = 0.01 * 10^{-2} \text{ kg m}^2, \ \tau = 1.5 \text{ Nm} \]

\( \Delta t \) is the interruption time, \( J \) is the moment of inertia, \( \tau \) is the developed torque in Nm and maximum absolute value for the \( \Delta I_{\text{ref}} \) universe was obtained by trial and error. The initial limits for the universes after some manual changes of the antecedents (\( e_\omega \), \( c e_\omega \)) and consequent (\( \Delta I_{\text{ref}} \)) were:

\[
\begin{align*}
  e_\omega &= -850, 850 \text{ rad/sec}; \\
  c e_\omega &= -20, 20 \text{ rad/sec/sec}; \\
  \Delta I_{\text{ref}} &= -1.5, 1.5 \text{ A}.
\end{align*}
\]

Figure 4.13 shows the membership function for the antecedent, the second input is the change in the speed error.

![Figure 4.13: Change of Speed Error (ce_\omega)](image-url)
Figure 4.14 shows the membership function for consequent linguistic variable. \(\Delta I_{\text{ref}}\) is the output of the FLC.

![Membership function plots](image)

**Figure 4.14: Member Function for Output.**

### 4.4.3 Defuzzification

Figure 4.15 shows \(\Delta I_{\text{ref}}\) generation by FLC, as soon as any antecedent’s linguistic variables change or both \((e\omega\text{ or }ce\omega\text{ or both})\) during the process, then the output \(\Delta I_{\text{ref}}\) changes accordingly. For example if the red line on speed error \((e\omega)\) or the red line on the change of speed error \((ce\omega)\) is varied, then \(\Delta I_{\text{ref}}\) will vary accordingly. Results appear at the bottom of the third columns. The simulation results for 3 phase, 6/4 poles SRM are shown in figures 4.15, 4.16, 4.17, and 4.18.
Figure 4.15: Rules Viewer for SRM Fuzzy Logic Controller for 3 Phase, 6/4 Poles SRM (Simulation Results).
Figure 4.16 shows the surface viewer for FLC for 3 phase, 6/4 poles switched reluctance motor. Two inputs ($e_\omega$, $ce_\omega$) are represented by the x-axis, while the output is represented by the y-axis as shown in this figure.

Figure 4.16: Surface Viewer for SRM Fuzzy Logic Controller for 3 Phase, 6/4 Poles SRM (Simulation Results).
Another simulation results in figures 4.17 and 4.18 simultaneously, which show this control performance when there is a change in load and in speed reference. At first, 0.1 Nm load is applied to this motor, at 0.27s, load is increased to 1 Nm, requiring higher torque. At 0.61 s, speed reference is decreased to 80 rads and in consequence current decreases for des- acceleration.

Figure 4.17: Speed versus Time for 3 Phase, 6/4 Poles SRM (Simulation Results).
Figure 4.18: Current Reference versus Time for 3 Phase, 6/4 Poles SRM (Simulation Results).
4.5 CONCLUSIONS

This chapter presents the use of fuzzy logic control (FLC) for switched reluctance motor (SRM) speed control. The FLC performs a PI-like (Proportional-Integral) control strategy. The performance of the drive system is evaluated through digital simulations through the toolbox SIMULINK of the MATLAB program. This choice is taken because this software has a good tool box and performance to undertake the task. The simulated SRM has a structure of 3 phase 6/4 poles and 4 phase 8/6 poles. Simulation is based on equation (3.4), the torque table as a function of angle and current $\tau(\theta, I)$. The table is extracted from the numeric data of the SRM designs created by finite element method. The speed of the mentioned SR motors is determined by using the MATLAB-SIMULINK package as discussed earlier in chapter 3. FLC is employed and generated current reference variations, based on speed error and its change, the objective of the FLC achieves a good performance and accuracy. FLC has performed well for the speed control of SRM, overcoming its nonlinearities.
CHAPTER 5: CONTROLLERS AND EXPERIMENTAL RESULTS FOR SRM [152-156].

5.1 SRM CONTROLLER USING PLC

The need for experimental results requires building a controller to the existing 4 phase, 8/6 poles SRM with aids of the tools in the university’s laboratory to design and propose it without relaying or depending on any researcher or previous work. Studying the structure of the mentioned switched reluctance motor, the feeding voltage needs to be applied to each phase in an interval time. The starting point for feeding this voltage to each phase is important to be specified, called this point a “zero reference”, and it proposed and implemented by means of proximity switch and a hole in the rotor disk as shown later in this chapter. At this location (zero reference) or starting point, the feeding voltage needs to be applied to phase (A) for an interval time, at the end of this time, the feeding voltage is disconnected from phase (A) and applied to phase (B) and so on. Since this type of work needs a fast processor, the need for PLC is brought up to build a proposed controller from the tools in university’s laboratory.

The control system is achieved by means of a Programmable Logic Controller (PLC) such as the Allan Bradley 500 series, for hardware. The SLC 500 line offers a range of choices in memory, I/O capacity, instruction set, and communication ports to allow tailoring a control system to the exact application requirements. These products have a strong reliability history covering hundreds of thousands of installations in a broad range of applications. SLC 5/04 processors allow to configure modular controllers of up to 4096 inputs plus 4096 outputs and a memory of 16 K, 32K, and 64K words. They have all the feature of the SLC 5/03 processor plus a faster communication port and shorter execution times (bit-instruction execution times of 0.37 ms). Instead of a DH port, the SLC 5/04 has built-in DH+ port for communication with other SLC 5/04 and PLC.
processors, operator interfaces, and programming terminals. Communication via the DH+ network is three times faster than DH-485 communication. Simple and affordable processors with broad capabilities to address applications such as material handling, HVAC control, assembly operations, small process control, and SCADA applications, the SLC 500 processor can be used for assembly operations and small process control as well. Thus the PLC 500 is chosen to control the 4 phase, 8/6 poles SRM [157-164].

Figure 5.1 shows the block diagram of the control system used for the SRM. The PLC reads the data that comes from the zero reference input (digital input); it starts according to the application program to set an output to control the process or any machine through the interface relays to the converter, which deliver the supply DC voltage to the specified winding coil. As a result the torque is generated to attract the rotor toward the activated coil and moving it from unaligned to aligned position. As soon the rotor and stator poles are aligned with each other, the voltage will be disconnected from the specific coil winding and it will activate the next coil and so on for the rest of phases. The PLC will activate and deactivate the control signal for each phase according to the PLC program. The communication between a PC and the PLC can be achieved by using RSLogix 500 (Rockwell Software), which contains RSLinks (Rockwell Software) [165-169].

![Figure 5.1: The Block Diagram of the Control System of the SRM.](image-url)
Figure 5.2 shows the layout of the I/O boards (slots 0 - 5). The processor card is located in slot 0, Slot 1 is not used. Input cards, which consist of digital inputs, located in slot 2, used only one single proximity switch as a zero reference input. The co-relation of both the proximity switch and the program will determine the correct selection of output solid state relay, as the specific coil winding activates. Having decided which phase should come on line first; the processor through slot 3 activates the coil to that particular phase.

<table>
<thead>
<tr>
<th>Power Supply for SLC 500</th>
<th>Slot 0</th>
<th>Slot 1</th>
<th>Slot 2</th>
<th>Slot 3</th>
<th>Slot 4</th>
<th>Slot 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor</td>
<td>Not used</td>
<td>Input</td>
<td>Output</td>
<td>Not used</td>
<td>Not used</td>
<td>Not used</td>
</tr>
</tbody>
</table>

Figure 5.2: SLC 5/04 Controller Board Layout.
Figure 5.3 shows the experimental 4 phase, 8/6 poles SRM. The PLC for 4 phase, 8/6 SRM is considered here. Since only a single coil set is activated at any one time to generate a moving field, so the sequence of the activated phases are A, B, C and D. The stator phase configuration is shown as a pair to form a single phase.

Zero reference is important to start firing the voltage to the phase A stator windings. Determine the right stator winding to get activated; rotor pole must be close to stator pole. To attain this configuration, a hole was made in the round disc on the rotor and proximity switch was installed on the cover of SRM as shown in figure 5.4. When the rotor turns the proximity switch detects the hole in the round disc. The status of this proximity switch will be ON i.e. logic 1. When the proximity switch sees the hole, then
the switch goes off or logic 0 as shown in figure 5.5. In this situation the rotor pole is close to the stator pole (unaligned position), and the DC voltage is fed to winding A. The rotor will be attracted to the phase A (aligned position) by the developed torque. According to the program code, phase B will be energized and phase A de-energized and so on for the other phases. The voltage firing sequence in this program code depends on the constant time value for the four phases, it means that at zero reference or starting point, the feeding voltage needs to be applied to phase (A) for an interval time (same specific time) for each phase, at the end of this time, the feeding voltage is disconnected from phase (A) and applied to phase (B) and so on.

Figure 5.4: The Hole in the Round Disc.
Figure 5.6 shows the flow chart for the firing sequence to the four windings of the 4 phase 8/6 SRM. The requirement of this type of controller for start up is that the proximity switch has to be in OFF position (logic 0). In this position the stator and rotor poles are in unaligned position and controller will send an output signal to the converter to apply DC voltage to winding A. As a result the developed torque attracts the rotor from unaligned position to aligned position within an interval of 0.01 sec. At the end of this time frame, the applied DC voltage is disconnected from winding A and applied to winding B for next time frame of 0.01 sec. At the end of this time frame the DC voltage is disconnected from winding B and applied to winding C for an interval of 0.01 sec, and so on. This set up time is found by trial and error, in the beginning this time has been set up for 10 seconds, the switched reluctance motor is not started, reduces the time to 0.01 sec, the lowest value (for each phase) in the used PLC, then the motor rotates with the best speed, this PLC can perform. The proximity switch is considered as a zero reference for start up only. This is been done by drilling a hole through the motor cover and a rotor disk as shown in figure 5.5, and inserted the proximity switch to detect the rotor disc, if the proximity switch is not detecting a rotor disk, which means the proximity switch is facing the hole (indication light of this switch is off) this method is used for both
controllers, then the voltage applies to phase A for 0.01 sec, at the end of this interval, it disconnects and connects to phase B and so on.

Figure 5.6: Flow Chart of SRM Controller (PLC).
5.2 SRM CONVERTER TOPOLOGY FOR PLC.

The basic requirement for the converter of the SRM to be built is that, each phase of the SRM should be able to conduct independently of the other phases. The most versatile SRM converter topology is the classic bridge converter topology with two power switches and two diodes per phase as shown in figure 5.7. This type of converter has been used for both the PLC and the cam positioner controllers. Figure 5.8 shows the four modes of operation in this converter.

During the conduction mode of winding L1 for phase A, both switches (Q1 and Q5) are in ON state. The input dc source magnetizes this phase. This mode is usually initiated before the start of the rotor and stator pole overlap, so that the phase current reaches the reference value before the phase inductance begins to increase. This helps to reduce the torque ripple. When current reaches the reference value, the converter steps into current regulation mode. In this mode, the current is maintained at the reference value by switching one of the phase switches while leaving the other one continuously ON until the commutation time starts. Both the phase switches are turned OFF to initiate the commutation.

During the commutation, the off-going phase winding sees a voltage of $-24V_{dc}$. While one phase is demagnetizing, another phase is magnetized. This helps to reduce the torque ripple during the commutation. The advantages of this converter topology are:

- Control of each phase is completely independent of the other phases.
- The voltage rating of all the switching devices and diodes is $24V_{dc}$, which is relatively low.
- The converter is able to freewheel during the chopping period at low speeds, which helps to reduce the switching frequency and thus the switching losses of the converter.
The energy from the off-going phase is transferred back to the source, which results in useful utilization of the energy. The main disadvantage of this topology is the higher number of switches required in each phase which makes the converter expensive. Also, for low-voltage applications the forward voltage drops in two devices may be significant compared to the available dc bus voltage.

The connections of the PLC output card and the converter are:

1. The MOSFET (Q1 & Q5) are getting the control signal from the output terminal O3:0/0 of card #3 located in the PLC.
2. The MOSFET (Q2 & Q6) are getting the control signal from output terminal O3:0/1 of card #3 located in the PLC.
3. The MOSFET (Q3 & Q7) are getting the control signal from output terminal O3:0/2 of card #3 located in the PLC.
4. The MOSFET (Q4 & Q8) are getting the control signal from output terminal O3:0/3 of card #3 located in the PLC.
Figure 5.7: SRM Classic Converter.
Figure 5.8: The Four-Modes of Operation of Classic Converter.
5.3 EXPERIMENTAL RESULTS FOR PLC.

Figure 5.9 shows the overview of the SRM and PLC controller. The controller is a PLC 50/4 CPU, the internal minimum time base for this processor is 0.01 sec. Three inputs (switches) located in the monitoring panel are connected to the input cards. Four outputs are connected to the control side of the converter.

The converter supplied the DC voltage to an individual phase A or B or C or D of SRM according to the program used for the PLC. The power supply employed for this SRM was $50\, V_{dc}$. The monitoring panel is to monitor which phase is activated by connecting the dual outputs from the output terminal for the output card of the PLC. The first output is connected to the specific MOSFETs and the second output is connected to the bulb on the monitoring panel, and so on for all phases to watch the firing pulse sequence on the windings of the SRM. The speed of the switched reluctance motor by this controller is low speed operation [Appendix A].

Figure 5.10 shows the output card #3 sending four outputs, O3:0/0, O3:0/1, O3:0/2 and O3:0/3 to the interface relays R1, R2, R3 and R4 located in the monitoring panel. The interface relays and according to the program passes the $24\, V_{dc}$ to the control side of the converter. The converter passes the DC voltage supply to the assigned winding of the SRM [Appendix A].
Figure 5.9: 4 Phase, 8/6 Poles SRM and the PLC controller [Appendix A].
Figure 5.10: 4 Phase, 8/6 Poles SRM and its PLC controller.
Figure 5.11 shows the speed versus torque characteristics for the SRM driven by programmable logic controller. The speed of the SRM varies from 50 to 100 RPM, while the voltages are varying from 40 to 60 $V_{dc}$ at a minimum experimental torque of 0.04 Nm. The speed reduces to a range of 30 to 16 RPM for the same applied voltage range at the maximum experimental torque of 0.5 Nm.
5.4 CAM POSITIONER CONTROLLER

The exact choice of the turn-on and turn-off angles and the magnitude of the phase current, determines the ultimate performance of the switched reluctance motor. The commutation angles are also called firing angles. Usually it involves the resolution of two conflicting concerns - maximizing the torque output of the motor or maximizing the efficiency of the motor. In general, the efficiency is optimized by minimizing the dwell angle (the dwell angle is the angle traversed while the phase conducts), and maximum torque is achieved by maximizing the dwell angle to take advantage of all potential torque output from a given phase.

The PLC controller drives the SRM at low speed and hence useful for low speed applications. Since the produced speed by PLC is low and the need of an efficient controller, which performs higher speed, so the next goal is to design and fabricate a new controller, using the same converter, but not a PLC driven. The electronic cam positioner and absolute encoder were employed in this type of controller. The terminals of absolute encoder are connected to the electronic cam positioner to get the exact position of rotor. The output of the cam positioner in this controller is 24 V$_{dc}$ delivered to the control side (MOSFETS inputs) of the converter according to the set values of the dwell angle (firing angle) for each phase.

Figure 5.12 shows the block diagram of control system used for SRM. The absolute encoder reads the rotor angle displacement and sends data to the electronic cam positioner, which is used as a controller. The zero degree for the rotor location is set on the electronic cam positioner. According to the firing angle program, DC voltage is fed to control side of the converter (input terminals of the MOSFET). The MOSFET will not turn ON until the control signal from the electronic cam positioner is turned ON. As a result, the DC power supply will be fed to SRM windings. The developed torque attracts the rotor toward the activated coil and moves it from intermediate (misaligned) to aligned
positions. Soon the rotor and stator poles are aligned to each other. At this position the voltage will be disconnected from the specific coil winding and will activate the next coil of following phases, controlled by the firing angle program.

![Diagram of the block diagram for the control system of SRM](image)

Figure 5.12: The Block Diagram for the Control System of SRM.

5.5 TRACKING SYSTEM FOR THE ROTOR POSITION.

Figure 5.13 shows the flow chart of cam positioner controller. It is important to check the proximity switch in its off status. In this position the rotor pole is not aligned with the stator pole, which is considered as a starting point for adding voltage to phase A. So the DC voltage supply is applied to the stator winding (A, A-) when the rotor angle displacement equal to zero degrees. The absolute encoder will send the rotor location to the electronic cam positioner (the controller) to switch on the control voltage to the converter and cut off when the rotor angle displacement equals 15 degrees according to the firing angle program for step one as shown in figure 5.14. At this angle, the DC voltage supply is applied to the stator winding (B, B-) and is cut off when the rotor angle displacement equal 30 degrees. At this angle the DC voltage is applied to the stator winding (C, C-) and is cut off when the rotor angle displacement is 45 degrees. At this angle the DC voltage is applied to the stator winding (D, D-) and is cut off when the rotor angle displacement is 60 degrees. At this angle the DC voltage is applied again to the
stator winding (A, A-) and cut off when the rotor angle displacement is 75 degree. This sequence continues until one revolution of 359 degree. Practically the maximum value of 360 degrees can not set, because it means zero as well and the zero has been used in the program, so the last value set to 359 degrees. The dwell angle = off angle – on angle.

![Flow Chart of the Cam positioner controller.](image)

Figure 5.13: Flow Chart of the Cam positioner controller.
Using the same method, has been used in PLC controller to locate the zero degree position or the starting position to apply the voltage to the first phase (phase A), but using different controller (cam positioner). The black hole shown in figure 5.15 next to the rotor pole is facing a proximity switch. At this position; the electronic cam positioner is programmed for zero degree of rotor position. Since the torque is a function of stator current and the rotor angle displacement (θ), the rotor location needs to be known at any time. The rotor position is found by finding the zero degree position as discussed earlier. At this location, the DC voltage is fed to winding A, B, C and D. The motor used is the same 4 phase, 8/6 poles SRM as used with the PLC controller.

In figure 5.15a, assume that only phase A is excited (switched ON). Since the rotor is at the misaligned position. The rotor will turn clockwise to the aligned position in figure 5.15b as this is the nearest aligned position; then phase A is switched OFF so that the current in phase A is $i_{a} = 0$ and phase B is switched ON (excited) so that the rotor moves to the next aligned position as shown in figure 5.15c. The rotor will keep its clockwise rotation from its current misaligned position as shown in figure 5.15c to the next nearest aligned position as shown in figure 5.15d for the next excited phase. The rotor will keep its clockwise rotation as shown in figure 5.15e (the end of the rotation cycle), the same rotation cycle starts again. Therefore, the stator exciting sequence A, B, C, D, then back to A, will generate clockwise rotation. The stator phase excitation sequence frequency can change the speed of the SRM drive.
Figure 5.15: Exciting Sequence a, b, c, d, and e for Clockwise Rotation.
5.6 THE FIRING ANGLE SEQUENCE FOR THE ELECTRONIC CAM POSITIONER

To explain the suggested firing angle program, it is better to show the three positions for the 8/6 poles SRM. Figure 5.16 shows both the stator and rotor poles with the positions defined with respect to phase A. Figure 5.16a is the aligned position, while figure 5.16b shows the unaligned position and figure 5.16c shows the intermediate (misaligned) position.

![Figure 5.16: Structure of an 8/6 SRM: a) Aligned position, b) Unaligned position, c) Misaligned position](image)

From the misaligned position of the rotor and stator poles, the firing angle sequence program can be built. One single revolution is equal 360 degrees, and as the 8/6 SRM motor has 4 phases, the number of degrees allocated to four phases is 60 degrees. Figure 5.17 shows the dwell angles for step 0 and step 1 for four phases and they are:

The firing angles of phase A for step 0 is: $\theta_{on} = 0^\circ$, $\theta_{off} = 15^\circ$.
The firing angles of phase A for step 1 is: $\theta_{on} = 60^\circ$, $\theta_{off} = 75^\circ$.
The firing angles of phase B for step 0 is: $\theta_{on} = 15^\circ$, $\theta_{off} = 30^\circ$.
The firing angles of phase B for step 1 is: $\theta_{on} = 75^\circ$, $\theta_{off} = 90^\circ$.
The firing angles of phase C for step 0 is: $\theta_{on} = 30^\circ$, $\theta_{off} = 45^\circ$. 

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The firing angles of phase C for step 1 is: $\theta_{on} = 90^\circ$, $\theta_{off} = 105^\circ$.
The firing angles of phase D for step 0 is: $\theta_{on} = 45^\circ$, $\theta_{off} = 60^\circ$.
The firing angles of phase D for step 1 is: $\theta_{on} = 105^\circ$, $\theta_{off} = 120^\circ$.

Figure 5.17: Firing Angle Sequence of the 4 Phases for Step 0, and Step 1.
Table 5.1 shows the code for the firing angle that programmed the electronic cam positioner for controlling the 4 phase 8/6 poles SRM.

### Table 5.1: Firing Angle Sequence for the Electronic Cam Positioner

<table>
<thead>
<tr>
<th>Phase</th>
<th>Step 9</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
<th>Step 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>15</td>
<td>60</td>
<td>75</td>
<td>120</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td>190</td>
<td>240</td>
<td>255</td>
<td>300</td>
<td>315</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>15</td>
<td>30</td>
<td>75</td>
<td>90</td>
<td>135</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>195</td>
<td>210</td>
<td>255</td>
<td>255</td>
<td>315</td>
<td>350</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>45</td>
<td>90</td>
<td>105</td>
<td>150</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>210</td>
<td>225</td>
<td>270</td>
<td>285</td>
<td>330</td>
<td>345</td>
</tr>
<tr>
<td>D</td>
<td>45</td>
<td>60</td>
<td>105</td>
<td>120</td>
<td>165</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>225</td>
<td>240</td>
<td>285</td>
<td>300</td>
<td>345</td>
<td>350</td>
</tr>
</tbody>
</table>

### 5.7 SRM AND ITS CAM POSITIONER CONTROLLER.

Figure 5.18 shows a view for the SRM and its cam positioner controller. The motor is the same 4 phase, 8/6 poles SRM. The controller is an electronic cam positioner, that can be easily be configured. Proximity switch is used to identify the zero degree for the rotor as discussed earlier in this chapter. Four outputs are connected to the control side of the converter.

The converter is supplying the DC voltage to each individual phase A, B, C or D of SRM according to the firing angle sequence program of the electronic cam positioner. The power supply employed for this SRM is (50-150) $V_{dc}$. However the maximum applied voltage is 95 $V_{dc}$. Four outputs are connected to the input control of the MOSFET converter. The speed of the switched reluctance motor through this controller is more than 3070 RPM [Appendix B].
Figure 5.18: A View of SRM and the Cam positioner controller with Measuring Devices [Appendix B].

5.8 SRM CONVERTER TOPOLOGY FOR THE CAM POSITIONER CONTROLLER.

The converter for this controller is the same as used earlier and shown in figure 5.7 except the control signals are taken out from the output terminals of the cam positioner, as illustrated below in table 5.2:
Table 5.2: Controlling Map for the MOSFETs

<table>
<thead>
<tr>
<th></th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>Q5</th>
<th>Q6</th>
<th>Q7</th>
<th>Q8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output terminal 1 of the cam positioner controls</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output terminal 2 of the cam positioner controls</td>
<td></td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output terminal 3 of the cam positioner controls</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output terminal 4 of the cam positioner controls</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.9 CAM POSITIONER CONTROLLER HARDWARE.

Figure 5.19 shows the SRM and the hardware of the controller. The controller consists of:

1. Zero reference proximity switch, which is responsible for finding the zero rotor position. As soon as the zero rotor position is detected by the cam positioner, it is no longer used.

2. Absolute encoder shaft is coupled to the SRM rotor and the electronic rotor position is transferred to the electronic cam positioner through a cable attached between the cam positioner and the encoder.

3. According to the firing program electronic cam positioner will send a control voltage to the MOSFET converter. Used four outputs from this device, each output will activate according to the rotor position.

4. The converter used here is the same converter as for the PLC controller except the control signals is fed from the cam positioner instead from the output card of the PLC.

5. $24\,V_{dc}$ control voltage is supplied to the electronic cam positioner, and zero proximity switch.

6. $(50 – 150)\,V_{dc}$ main supply is responsible for feeding the four phases of SRM. The voltage will be applied to the appropriate phase according to the rotor position. The
speed of the SRM with this controller reaches 3070 RPM according to the applied voltage to the stator winding, which varies between 20 to 95 V\textsubscript{dc}.

![Diagram](image)

Figure 5.19: SRM and Cam positioner Controller Hardware.
5.10 EXPERIMENTAL RESULTS

5.10.1 Torque/Current Characteristics.

The experimental performance of SRM using the cam positioner is performed and shown in the following figures. The speed produced by the cam positioner controller varied from 100 to 3070 RPM according to the applied voltage to the stator winding, which started from 20 to 95 V\textsubscript{dc}, while the PLC controller produced a low speed. The controllers are discussed earlier in this chapter. Figure 5.20 shows the torque versus current, the higher developed torque is occurred while the applied voltage is 85 V\textsubscript{dc} according to the added load.

![Figure 5.20: Torque versus Current for the SRM.](image-url)
5.10.2 Speed/Torque Characteristics.

Figure 5.21 shows the speed versus torque characteristics for the SRM. The speed of the SRM is varied from 600 to 3070 RPM, while the voltages are varying from 20 to 85 V\textsubscript{dc} at a minimum experimental torque of 0.8 Nm. The speed reduced to a range of 1750 to 130 RPM for the same applied voltage range at the maximum experimental torque of 2.3 Nm.

Figure 5.21: Torque versus Speed for the SRM Driven by Cam Positioner.
5.10.3 Maximum Efficiencies for 4 Phase SRM.

Table 5.3 shows the efficiencies results of applying different voltages to the stator winding. Best efficiency for the SRM is 82% when the applied voltage to the stator winding is 85 V\textsubscript{dc}. The worst efficiency is 56.1% when the applied voltage is 20 V\textsubscript{dc}; the second worst efficiency is 62.7% when the applied voltage is 30 V\textsubscript{dc}. While the investigation is carried out, the applied loads are varied from (2 to 5.2) ampere, for each applied voltage. During the test, increasing the applied voltage to (90 and 95) V\textsubscript{dc}, the SRM developed less torque, and the efficiency is dropped, due to motor saturation.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Maximum efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.561</td>
</tr>
<tr>
<td>30</td>
<td>0.627</td>
</tr>
<tr>
<td>40</td>
<td>0.7</td>
</tr>
<tr>
<td>50</td>
<td>0.724</td>
</tr>
<tr>
<td>60</td>
<td>0.753</td>
</tr>
<tr>
<td>70</td>
<td>0.763</td>
</tr>
<tr>
<td>80</td>
<td>0.79</td>
</tr>
<tr>
<td>85</td>
<td>0.82</td>
</tr>
<tr>
<td>90</td>
<td>0.762</td>
</tr>
<tr>
<td>95</td>
<td>0.746</td>
</tr>
</tbody>
</table>
Figure 5.22 shows the maximum efficiencies versus different voltages applied to the stator winding. In each applied voltage, the maximum efficiency is recorded. The maximum efficiency occurred when the applied voltage equals $85 \ V_{dc}$. 

![Graph showing maximum efficiencies versus supply voltage](image_url)

**Figure 5.22: Maximum Efficiencies at Different Voltages.**
5.11 CONCLUSIONS

Two controllers have been built for the tested 4 phase, 8/6 poles SRM; programmable logic controller is the first used hardware. A programmable logic controller (PLC) or programmable controller is a small computer used for automation of real-world processes, such as control of machinery on factory assembly lines. The PLC usually uses a microprocessor; the program is usually created by a skilled engineer at an industrial site, rather than a professional computer programmer. The second employed controller is cam positioner with 8 outputs controller and absolute encoder, with 8 outputs, a simple procedure used for setting the firing angle program. The maximum efficiency occurred when the applied voltage equals 85 Vdc. The lowest efficiency occurred when the applied voltage equals 20 Vdc. The PLC controller suits the low speed applications, while the cam positioner controller suits the high speed applications.

The simulation results in chapter 3 and 4 are performed for more than 30 designs, the capital cost for fabricating all these models is very expensive in order to perform an experimental test on each model and compare it with the same simulated model in chapters 3 and 4, since the simulation results are acceptable, accomplished and finished the simulation results to this extent. Proposed, designed and built two controllers from existing tools like PLC, Cam positioner and 4 phase, 8/6 poles switched reluctance motor. The bottom line is to build and propose our own controllers with no aids from any other researchers work; the motor’s controller is not commonly used as well. The first controller drives the switched reluctance motor with a low speed performance, it is economically high price in real life, however the second controller drives the switched reluctance motor with a high speed performance, so this controller has good and higher efficiency. The expected and actual experimental results are very close for the second controller, because this controller relied on the tracking system for its rotor angle displacement.
Since current $I(\theta, \phi)$, is a function of rotor position and flux linkage, and torque $\tau(\theta, I)$, is function of rotor position and current. The experimental tests based on firing angle interval, which varies between (10-30) degree, found the best interval is 15 degree to perform better torque. For example if the firing angle for applying voltage on phase A is at 0 degree, then the firing angle for cutting off the voltage on phase A is at 15 degree. The second factor, which has an influence on the developed torque, is the current (load condition). The input power is function of applied voltage and the current. The output power is a function of the developed torque.

The efficiency is obtained by finding the input power and the output power. Increasing the applied voltage from 20 to 85 $V_{dc}$ and increasing the load conditions according to each applied voltage, the efficiency increases because the input power incremental reading was less than the output power incremental reading, till the applied voltage increases to 90 $V_{dc}$ and the load conditions increases as well, the input power incremental reading is more than the output power incremental reading, so the efficiency decreases due to the saturation occurred in the switched reluctance motor, same thing happening when increasing the applied voltage to 95 $V_{dc}$, and load conditions, the input power incremental reading is further more than the output power incremental reading, so the efficiency decreases further less due to more saturation occurred in the switched reluctance motor.
CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6.1 CONCLUSIONS

The researchers and scientists in the field of electrical machines have significant researches to introduce the switched reluctance motor (SRM) to the electrical machines family with affordable cost. These machines are eliminating rotor losses due to the absence of rotor conductors. The efficiency of a machine is the function of the distribution of the magnetic iron in machine, the effects of such distribution results in changing the machine’s efficiency.

The Finite element method (FEM) in principle can be used to solve any problem that can be formulated as a field problem. It can produce accurate and reliable results when designing electromagnetic devices. FEM can be utilized by using different computer softwares. It is a valuable design tool, provided it is used correctly and can save money, materials and time. FEM is a very useful tool in the solution of electromagnetic problems.

The development of software products has increased dramatically in the last 25 years. Finite element analysis would not be where it is today if computers had not proliferated and become faster and less expensive. FEM can produce accurate and reliable predictions of the device parameters, and the validity and accuracy of the model. Its solutions rely on an accurate representation of the problem and correct analysis procedures. The design of electromagnetic devices requires accurate calculation of the design parameters.

Finite element method is extensively employed in the design of electrical machines and other electromagnetic and magnetic systems. The finite element method provides an accurate and simple approach to parameters evaluation from the determination of electromagnetic field distribution. In this study, FEM is used in designing different
shapes and sizes of switched reluctance motor. This study is investigated on 3 phase 6/4 poles SRM and 4 phase 8/6 poles SRM to optimize the developed torque. The effects of dimensional variation of pole arc/pole pitch ratio for the rotor and stator have an influence on the developed torque optimization for the base switched reluctance motor.

The SRM design with rotor pole arc/pole pitch ratio (\(\gamma\)) of 0.38 develops a higher torque in comparison with the base SRM using \(\gamma\) of 0.44. The SRM with \(\gamma\) of 0.74 has the lowest developed torque. The results for the stator pole arc/ pole pitch ratios (\(\beta\)) are presented in the following three SRM designs. First design is the base SRM 1 with stator pole arc/pole pitch ratios (\(\beta\)) of 0.44, second design is the wider (best) stator pole arc/pole pitch ratios (\(\beta\)) of 0.5, the third design is the narrower (worst), with stator pole arc/pole pitch ratios (\(\beta\)) of 0.25.

An optimised design for 3 phase 6/4 SRM 28 is worked out by combining the best designs of the dimensional variation for its rotor and stator poles. Torque developed for the base and optimised designs are compared through rotating the rotor from (0 to 45) degrees. The torque developed in the optimized design is less than the torque developed in the base model when rotor rotates from (0 to 5) degrees; the torque developed for optimized design is higher than the developed torque for the base design when the rotor rotates from (5 to 45) degrees.

The optimized 3 phase SRM design has 11.5\% more developed torque than the base 3 phase SRM design. This study and investigation is carried out by choosing aspecific 3 phase, 6/4 poles and 4 phase, 8/6 poles SRM models and changing it with different shapes and sizes by using FEM, comparing the modified models results with the base models results. The chosen base SRM has been modified to achieve an optimized SRM where flux line distribution finds a better path to develop a stronger torque that attracts the rotor. Reducing the area too much caused magnetic saturation of the rotor. While various stator/rotor shapes were set at the same values of ampere-turns, the MMF is
varied from 30 to 210 ampere-turns in steps randomly of 30 ampere-turns for all SRM shapes.

The same method for the torque optimization of the dimensional variation of the stator, rotor poles and yoke size is used in 4, phase 8/6 poles SRMs. The best designs for the rotor, stator poles and yoke size of 4 phase, 8/6 poles SRMs are combined to introduce the optimized SRM design. As soon as the mmf varies from 200 to 1000 ampere-turns, the developed torque for the optimized SRM is slightly higher than the developed torque of the base SRM. The developed torque of the optimized SRM increases rapidly compared with the developed torque of the base SRM 29 in range of 1000 to 4000 Ampere-Turn. The incremental torque percentage for the optimized SRM 30 while the MMF varied in a range of 200 to 4000 ampere-turn is 12.9%. The number of turns for the base SRM is 280 and current is 5A, the MMF is 1400 Ampere-Turn. At this value the incremental torque percentage for the optimized SRM is 8%. The fuzzy logic controller (FLC) generates current reference changes ($\Delta I_{ref}$) based on speed error $e_\omega$ and its changes $ce_\omega$. Speed error $ew$ has its minimal value when the motor speed has its nominal value, 850 rad/sec, and is inverted to – 850 rad/sec, the maximum value, +1700, is obtained in the opposite situation.

The first control system for the SRM used a PLC to control the SRM. The PLC reads the data that comes from the zero reference input (digital input); it starts according to the application program to set an output to control the process or any machine through the interface relays to the converter, which deliver the supply DC voltage to the specified winding coil. The converter used in both controllers is a classical converter i.e eight MOSFET and eight diodes. The speed generated for the 4 phase 8/6 poles SRM by this controller is 100 RPM.

The second control system for the SRM used a cam positioner and absolute encoder. The absolute encoder read the rotor angle displacement sending data to the electronic cam
positioner, which is used as a controller. Having set the zero degrees for the rotor location on the electronic cam positioner, the rotor started to move according to the firing angle program by sending an output DC voltage to the winding A, B, C and D simultaneously. The speed of the SRM with this controller varied from 130 to 3070 RPM according to the applied voltage to the stator winding, is tested over the range of (20 to 95) \( V_{dc} \). The lowest efficiency of 56% occurred, when the applied voltage is 20 \( V_{dc} \). Each voltage is applied to the stator winding and the SRM with loads varied from 1 ampere to slightly above 5 ampere. The original efficiency of the base motor is 76%. The best efficiency for the tested motor by using the proposed cam positioner controller is 82% while the applied voltage to the stator winding is 85 \( V_{dc} \). The efficiency has been improved by 6%.

6.2 RECOMMENDATIONS FOR FUTURE WORK.

Since the maximum efficiency produced by the cam positioner controller for the 4 phase 8/6 poles SRM is 82%, it is recommended that different types of switched reluctance machines such as 12/10 poles and 10/8 poles to be driven by the cam positioner controller. Study and compare the developed torque and efficiencies of these machines driven by this controller and compare it with the developed torque and efficiencies for these machines of their original controller.

Further research should continue to achieve the optimum design for SRMs. Different sizes and configuration could be investigated, e.g. normal configuration has more stator poles than rotor poles. The opposite configuration such 4/6 or 6/8 poles and so on could be studied. Further study is recommended for odd and even poles combination of the stator and rotor such as 3/2 poles, 5/2 poles, 8/3 poles and so on to achieve the optimization of the developed torques and efficiencies. Study and work are recommended for 4 phase, 8/2 poles SRM. Further work is recommended to investigate the PM/SRM (hybrid) motor. This machine is a combination of a permanent magnet and reluctance machine. It employs small amount of permanent magnet materials in the rotor of the SRM and provides better performance.
APPENDIX A: PROGRAM CODE.

The code has been divided into four ladders, to explain it easier.

A.1 Ladder 2 (the Main Ladder):

The main ladder consists from three rungs. Figure A.1.1 shows the first rung 002 with input instruction B3:0/15 (Timer Option Enabled) is picked off; as a result subroutine 3 is activated. The flow of the logical instructions is started from the left to the right, if the instructions on the left hand side are true (1), then the instruction on the right hand side will be true as well (1).

![Figure A.1.1: Subroutine 3.](image)

Figure A.1.1: Subroutine 3.

Figure A.1.2 shows the first rung 003 with input instruction B3:0/15 (Timer Option Enabled) is picked off; as a result subroutine 4 is activated.

![Figure A.1.2: Subroutine 4.](image)
Figure A.1.3 shows the first rung 004 with input instruction B3:0/15 (Timer Option Enabled) is picked off; as a result subroutine 5 is activated.

![Figure A.1.3: Subroutine 5.](image)

### A.2 Ladder 3 (the Firing Sequence):

Figure A.2.1 shows the how to start the program to scan the running program. The first input instruction is the normally stop switch I:2/4. Data reading for this input is logic 1. The second input is the normally open and data reading for this input is logic 0. When push button is pressed, logical data goes on. The last input signal is; the zero proximity switch and supposed to be OFF while proximity switch is looking for the hole in the round disk of the rotor. If the logical status for all the inputs is ON, then the output instruction B3:0/10 should be on.

![Figure A.2.1: Start up the Program.](image)

Figure A.2.2 shows how to stop the program, by pressing the stop instruction input I:2/4, this will unlatch B3:0/10 and program is stopped.
Figure A.2.2: Stop the Program.

Figure A.2.3 shows the first firing sequence order. The first input instruction is an EQUAL instruction. The integer file N7:0, which is located at source A (0) is equal to source B (0) and the ignition input from the program start up. Phase 1 will move to N7:0, which means that phase A is activated.

Figure A.2.3: Starting the Firing Sequence 1.

Figure A.2.4 shows the second firing sequence order, the first input instruction is an EQUAL instruction. The integer file N7:0, which is located at source A (1) is equal to source B (1). Phase 2 will move to N7:0, which means that phase B is activated.
Figure A.2.4: Starting the Firing Sequence #2.

Figure A.2.5 shows the third firing sequence order. The integer file N7:0 is located at source A (2) equal to source B (2). Phase 3 will move to N7:0, activating phase C.

Figure A.2.5: Starting the Firing Sequence 3.

Figure A.2.6 shows the fourth firing sequence order. The integer file N7:0 is located at source A (3) is equal to source B (3). Phase 4 will move to N7:0, leading to phase D being activated.
A.3 Ladder 4 (the Output):

Figure A.3.1 shows the activation of phase A. When the firing sequence for phase A latches, the output of phase A is activated. This control signal will switch on the DC supply of converter to phase A.

Figure A.3.2 shows the activation of phase B. When the firing sequence for phase B latches, the output of phase B is activated. This control signal will switch on the DC supply of converter to phase B.
Figure A.3.2: Activating Phase B.

Figures A.3.3 and A.3.4 show the activation of phases C & D respectively, which switch the DC supply to these phases.

Figure A.3.3: Activating Phase C.
A.4 Ladder 5 (the Timers):

Figure A.4.1 shows how the activation of phase A is achieved within the time frame of 0.01 sec. If the firing sequence of phase A is ON, then source A is equal source B in the EQUAL instruction, i.e. when both sources equal to 1, then the timer T4:10 with base time of 0.01 sec will start to accumulate the preset value of this timer to the value of 1 * time base (time base = 0.01 sec). This value is the best value for the four phases of SRM for this type of processor (SLC 5/04 CPU) to let the rotor runs in a certain speed; this conclusion is drawn from the experimental trials of first controller.
Figures A.4.2, A.4.3 and A.4.4 show how the activation of phases B, C & D are achieved within time frame of 0.01 sec. If the firing sequence of phase B is ON, source A is equal source B in the EQUAL instruction, i.e. when both sources equal to 1, the timer T4:11 with base time of 0.01 sec will start to accumulate the preset value of this timer for the value of 1 * time base (time base = 0.01 sec). For phase F, the timer is in T4:12 and for phase D, it is in timer T4:13.

**Figure A.4.2: Operating Time Zone for Phase B.**

**Figure A.4.3: Operating Time Zone for Phase C.**
Figure A.4.4: Operating Time Zone for Phase D.

Figure A.4.5 shows the activation of the internal relay of phase A. If the accumulated time equals the preset time of T4:10, then the DONE bit of this timer turns on, as a result the internal relay B3:0/0 (inside the processor) of phase A (position 1) turns on as well.

Figures A.4.6, A.4.7 & A.4.8 shows the activation of the internal relay of phases B, C & D respectively. If the accumulated time equals the preset time of T4:11, then the DONE bit of this timer turns on, as a result the internal relay B3:0/1 (inside the processor) of phase B (position 2) turns on as well. In the case of phase C, the preset time is T4:12 and the position is 3 and for phase D the timer is T4:13 and the position is 4.
Figure A.4.6: Internal Relay Activation of Phase B.

Figure A.4.7: Internal Relay Activation of Phase C.

Figure A.4.8: Internal Relay Activation of Phase D.
APPENDIX B: VIDEO CLIPS AND PHOTOS

Attached CD contains:

- Video clips for low speed controller.
- Video clips for second controller.
- Photos for the stator and rotor for 4 phase 8/6 poles SRM.

To watch the video clip we need a window media player program installed on PC, double click on requested file. Thanks.
APPENDIX B: VIDEO CLIPS AND PHOTOS

Can be viewed separately at University of Western Sydney Library
APPENDIX C: PUBLISHED WORK

This research has resulted in eleven conferences papers and they are:


REFERENCES.


[34] J.V. Byrne and M.F. McMullin, "Design of a Reluctance Motor as a 10 kW Spindle Drive", in Proc. of Motorcon ’82, Geneva, Switzerland, September 1982.


