Design and Analysis of Switched Reluctance Motor

Major Project Report

Submitted in Partial Fulfillment of the Requirements for Degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(Power Electronics, Machines & Drives)

By

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Certificate

This is to certify that the Major Project Report entitled "Design and Analysis of Switched Reluctance Motor"submitted by **Ms. Khushbu Bhavesh Shah (Roll No: 13MEEP13)** towards the partial fulfillment of the requirements of Master of Technology (Electrical Engineering) in the field of Power Electronics, Machines and Drives of Nirma University is the record of work carried out by her under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Dedicated To

My Beloved

Parents, Brother and Sister

Abstract

Switched Reluctance Motor (SRM) are the increasingly used in industry as well as domestic applications. It is having simple as well as robust construction. It has some limitation such as higher torque ripple, vibration, noise & control complexity. This project work is intended to design and analyze to Switched Reluctance Motor. It is used in centrifugal pumps, fans, automotive application, under water marine drive, washing machine, electrical vehicle and medical application. It gained more importance in recent years due to simple structural properties. Aim of the project is to developed the Computer Aided Design (CAD) program for sizing and performance evolution of Switched Reluctance Motor. Proper value of magnetic loading, electric loading, flux density, material and other variables play an important role in design of the Switched Reluctance Motor. For that, Computer Aided Design (CAD) programming has been carried out for the design of Switched Reluctance Motor. Based on results obtained from CAD, Finite Element Analysis (FEA) is carried out in Speed Software. Finite Element Method (FEM) is used for the analysis of SRM and their motor characteristics are compared with simulation results.

Nomenclature

P_o	Output power
V	Supply voltage in volt
I	Supply current in ampere
N_r	Speed in rpm
P_s	Number of stator pole
P_r	Number of rotor pole
β_s	Number of stator pole arc
β_r	Number of rotor pole arc
E	Desired efficiency
D	Stator diamete
L	Stack length
D_o	Outer diameter
K_2	Constant
β	Maximum flux density
A_s	Specific electric loading
U_r	Permeability of magnetic material core
D_{sh}	Rotor shaft diameter
J	Current density
K_g	Ratio of rotor pole pitch to air gap length
ω_{cs}	Gap left between two adjacent coils
d_e	Density of material
l_g	Air gap length
T_{ph}	Number of turns per pole
h_c	Height of stator coil
ω_{cs}	Width of stator coil

Abbreviations

SRM	Switched Reluctance Motor
CAD	Computer Aided Design
FEM	Finite Element Method
FEA	Finite Element Analysis

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Chapter 1

Introduction

1.1 Introduction of Switched Reluctance Motor

Switched Reluctance Motor (SRM) are the increasingly used in electric motors in industry as well as domestic applications. Its offer reasonable performance, low maintains, simple as well as robots construction, torque-speed curve, stable operation under load and satisfying efficiency. Its higher efficiency, high torque to inertia ratio and thermal toughness are some of the salient advantages of SRM. Use of centrifugal pumps, fans, automotive application, under water marine drive, washing machine, electrical vehicle and medical application. It has gained more importance in recent years due to simple structural properties.

New ideas, materials and components creates many opportunities. It is the motor that determines the characteristics of electric drive. Motor determines the requirement of converter and control techniques. The Switched Reluctance Motor (SRM) is a type of a stepper motor, an electric motor that runs by reluctance torque. DC motor types, power is delivered to windings in the stator rather than the rotor. Simply mechanical design as power does not have to be delivered to a moving part, but it complete the electrical design as some part of switching system needs to be used to deliver power to the different windings.

Construction of SRM

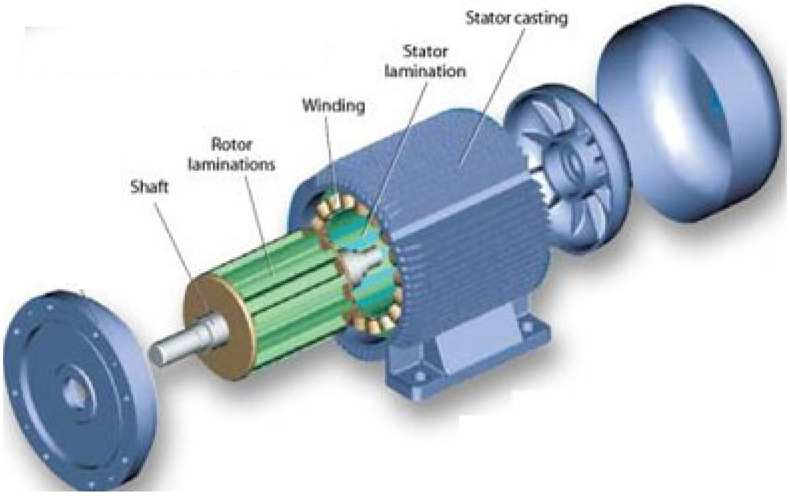


Figure 1.1: Construction of SRM

Basically electrical motor also have two main parts namely stator and rotor. Stator as its name indicates stator is a stationary part of motor. Rotor as its name indicates rotating part of motor. The rotor is connected to the mechanically load through the shaft. This is the simple electrical machine. Switch Reluctance Motor can be traced back to 1842, but the 'reinvention' has been possible to inexpensive, high power switching devices. Windings are on the stator only and no windings or magnets on the rotor, thus saving of materials on the rotor. Rotor conductors are not required because the torque is produced by the tendency of the rotor to obtain position having minimum reluctance. It has salient poles, singly excited, doubly salient, machine. Switched Reluctance Motor is a type of synchronous machine. It has no coils or magnet on the rotor and for its winding of the stator wound field coils of a DC motor. The motor mainly consist of stator and rotor dependent of number of poles. Usually the number of poles on the stator is more than that on the rotor. Main components like stator back iron, stator poles, rotor poles, stator coils, Stator poles and rotor poles are salient type construction and excitation is provided only at stator side. Because of this, Switched Reluctance Motor is known as singly excited doubly salient machine. Stator has winding but not on rotor side. Stators winding on diametrically opposite′s poles are connected in series or parallel to form one phase of the motor.

There are Several combinations of stator and rotor poles are possible, such as 6/4, 8/4, 10/6, 12/6 etc and 4/2 configurations are also possible, but with this it is almost impossible to develop a starting torque when the stator-rotor poles are complectly aligned. The higher number of pole have less torque ripple.

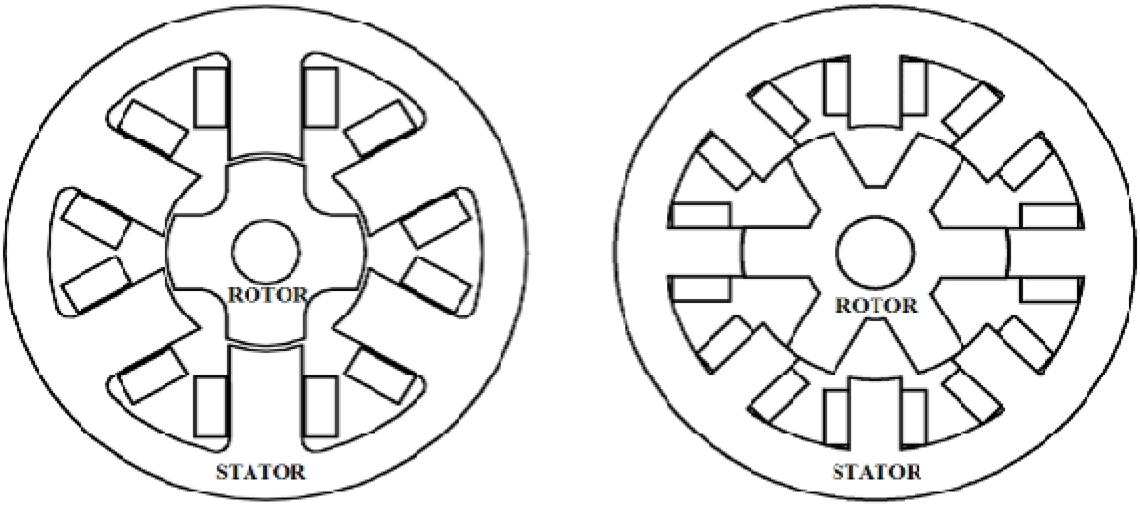


Figure 1.2: Simple Construction of SRM (a) 6/4 pole (b) 8/6 pole

- Depends parameter on SRM configuration:
  - a. Number of stator/rotor poles
  - b. Number of phase
  - c. Number of repetitions
  - d. Connections of the stator windings

Operating Principle:-

Principle of the Switched Reluctance Motor the rotor rotation as switching sequence proceeds in a three phase Switched Reluctance Motor, the rotation direction is opposite to the direction of the excited phase. The switching angle for the phase current is controlled and synchronized with the rotor position, usually by means of a shaft position sensor.

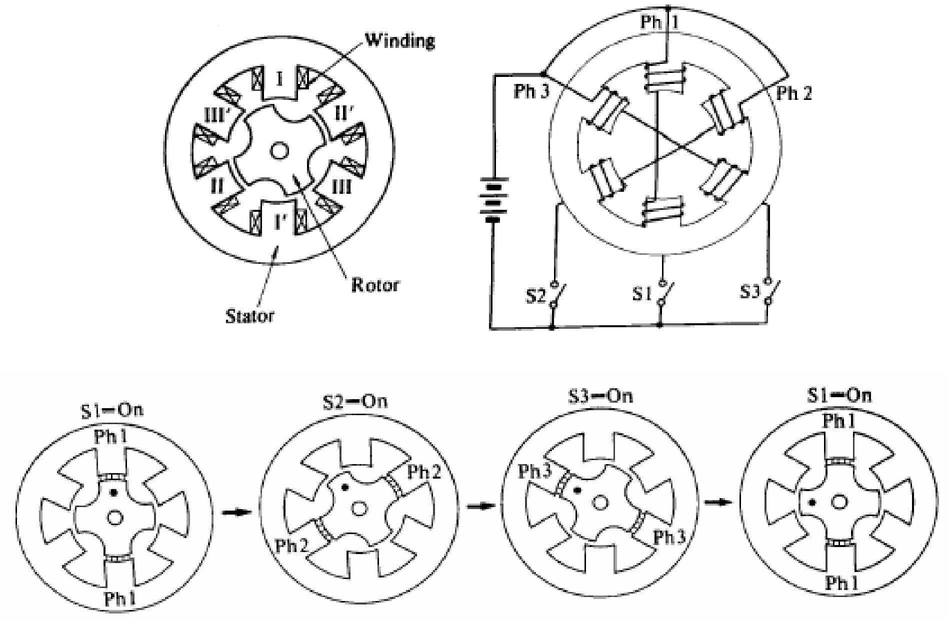


Figure 1.3: Operating Principle

1.2 Types of Switched Reluctance Motor

- Advanced Motors are of following types:

  a. Switched Reluctance Motor

  b. Permanent Magnet Brushless DC motor

  c. Permanent Magnet Synchronous Motor

  d. Flux Reversal Motor

  e. Doubly Salient Permanent Magnet Motor

- Classified based on the motion nature.

  a. Rotating type

  b. Linear type

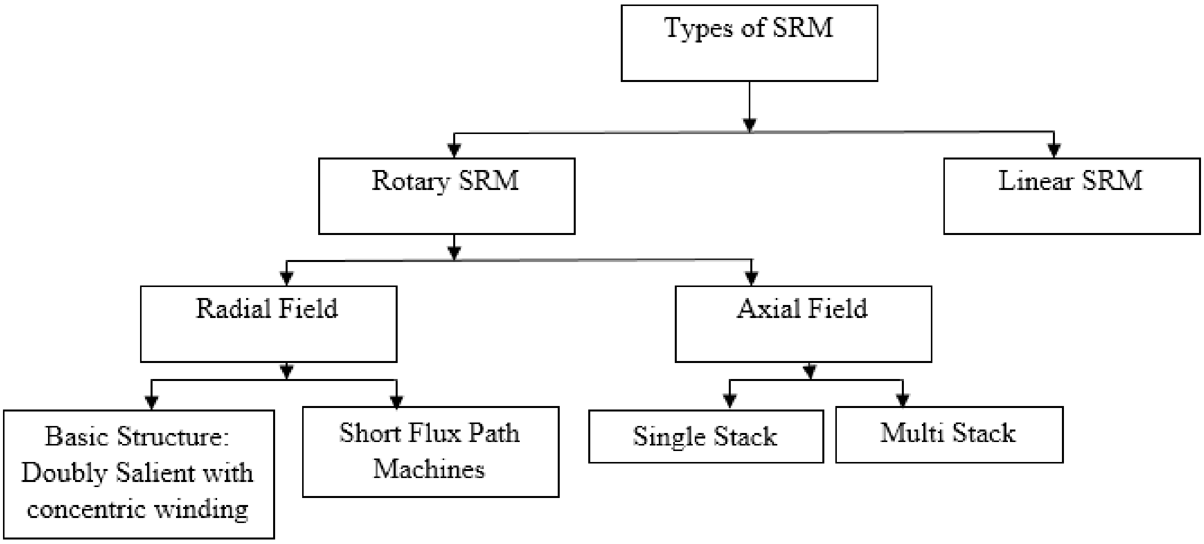


Figure 1.4: Types of SRM

The rotary machine based on Switch Reluctance Motors are classified by the nature of the path of the magnetic field as to its direction with respect to the machine's axial length. In case of the perpendicular magnetic field path to the shaft of the motor, this is classified as radial field. In the case of the flux path is along the axial direction, the machine is named as an axial field Switched Reluctance Motor.

1.3 Features of Switched Reluctance Motor

Advantages:-

- Extremely high speeds are possible.
- There is no magnet on rotor maximum permissible working temperature is higher than in Permeant Magnet (PM) motors.
- Mechanically robust, & naturally high speed operation.
- Under fault condition short circuit current is minimum.
- Saving in material on the rotor.

- No crawling or cogging torque.
- High reliability.
- Machine construction is simple and low-cost because of the absence of rotor winding and permanent magnets.
- Bidirectional current are not necessary, which facilitates the reduction of the number of power switches in certain applications.
- Low rotor inertia and a high torque/inertia ratio.
- Extremely high speeds with a wide constant power region are possible.
- Fault in one phase does not affect other phase.

Disadvantages:-

- High torque ripple.
- Acoustic noise is high.
- Line-start capability.
- Position information is required to controlling.
- Requires an electronic power converter to run.
- The higher torque ripple also cause the ripple current in the DC supply to be quite large, necessity large filter capacitor.

Applications:-

- Washing machines
- Automotive applications
- Vacuum cleaners
- Fans
- Centrifugal pumps

- Small appliances
- Electric vehicles

1.4 Scope of Work

Aim of the design is to obtained energy efficiency motor. The work is divided into two parts. The design of Switched Reluctance Motor will be carried out by conventional method. The Computer Aided Design (CAD) programming is carried out for the whole design of Switched Reluctance Motor (SRM). The CAD program will be validated using F.E. software. The design will be validated from CAD as well as Finite Element (FE) software. It is always desirable to achieve higher operational efficiency.

1.5 Literature Survey

Literature survey plays a very important role in project. Literature survey consists of Switched Reluctance Motor (SRM) related papers that include different topologies for performance improvement, energy efficiency of motor and design procedure for the Switched Reluctance Motor. Papers were taken from IEEE conference proceedings, journal proceedings and other standard publications.

R.Krishnan, **Design of Switched Reluctance Motor** [1]

This book Switched Reluctance Motor Drives describe various content of Switched Reluctance Motor: modeling, simulations, analysis, design and application. Authors explain very clearly about stator design, rotor design and performance calculation of Switched Reluctance Motor. Performance Improvement of Switched Reluctance Motor.

N. K. Sheth, **K. R. Rajagopal**, **Computer Aided Design of Multi-phase Switched Reluctance Motor** [2]

This paper Better approach for calculation of the outer dimensions, phase inductance, flux linkage and losses, and also a different concept for calculating the average torque of the motor are incorporated in the CAD program.

Liuchen chang, **Design Procedure of A Switched Reluctance Motor for Automobile Application** [3]

This paper explain the process, empirical method, finite element method and analytical method has been applied. The empirical formulas as established by design experts yield a preliminary design. Torque characteristics, flux and flux linkages of SRMs can be calculated by Finite Element Method for various stator current excitations and rotor position angles.

R. Arumugam, **and James F.Lindsay, Design Procedure for Switched-Reluctance Motors** [4]

This paper explains gained attention in the variable speed drive. The saving in manufacturing cost of the motor due to its simplicity of construction and use of minimum number of switching devices in the drive circuit are two important factors in its compared to any other motor drive. The design is based on the output equation similar to that of conventional Ac machines.

N. K. Sheth and K. R. Rajagopal, **Optimum Pole Arcs for a Switched Reluctance Motor for Higher Torque With Reluctance Ripple** [5]

In this paper explain has applications in low power servomotor to high power traction drive. It can run with either an ac or switched dc power source. The significant difference between the average torques obtained methods suggests that the method put forward by the valid and accurate results.

Nimit. K. Sheth, **K. R. Rajagopal**, **Estimation of Core Loss in a Switched Reluctance Motor Based on Actual Flux Variations** [6]

In this paper explain loss calculated based on the actual waveform of flux in the various parts of the motor gives more accurate results than the core loss calculated based on the assumption of triangular flux in stator pole.

N. C. Lenin, **R. Arumugam**, **A Unified Design Procedure for Switched Reluctance Motor** [7]

In this paper explain following the design of the machine, finite element software is used to analyze the machine. From the design parameter, aligned inductance, unaligned inductance and average torque are calculated analytically and compared with finite element analysis results. In this motor is simulated using the developed nonlinear model in matlab environment for better control operation.

Caio A. Ferreia, **William D. Jones**, **Detailed Design of a 30-kW Switched Reluctance Starter/Generator System for a Gas Turbine Engine Application** [8]

In this paper explain the systm consist of a SR machine directly coupled to the gas turbine engine. The design objective, hardware, control algorithms and test result for a Switched Reluctance starter/generator system.

Pavol Rafajdus, **Adrin Peniak Optimization of Switched Reluctance Motor Design Procedure for Electrical Vehicles** [9]

In this paper explain optimization process of Switched Reluctance Motor (SRM) during design procedure. This optimization process uses finite element method (FEM) to improve motor performances and properties. On the base of four phase 8/6 SRM analytical design given by known equations and formulas, some improvements and materials utilization are obtained by optimization process. This design was optimized by means of multi objective design process to improve its output power, electromagnetic torque. In the future, the losses, efficiency and thermal analysis will be taken into account of this design procedure.

Liuchen Chang , **Switched Reluctance Motors: Small Motors of the Next Generation for Automobiles** [10]

In this paper the development in Switched Reluctance Motors (SRM) for applications in automotive small motor drives. For advanced small motors with low cost, high reliability, low acoustic noise, long life cycle, variable speed capability, integrated protection functions and high efficiency, SRMs present an alternative choice.

Bingni Qu, jiancheng song, Jianbin Zheng, Torque Ripple Minimization in Switched Reluctance Machine by Pole Arcs Design [11]

In this paper the pole arc design is limited by turn-on angle, turn-off angle and other parameters. Advanced turn-off angle is used to reduce torque ripple during phase commutation. The SRM designed based on this technique can be controlled by relatively simple strategy.

Chapter 2

Design Procedure of SRM

The Switched Reluctance Motor are widely used and their functioning is better known. They are generally composed of two parts; one is stator that contains the slots in which there are the phase′s conductors, while the other is a rotor which the permanent magnets.

Output Equation:-

The output equation for the length, bore diameter,, magnetic, speed, & electric loadings to the output of the machine. The conventional motors are designed starting from the output equation. A same development of the output equation for Switch Reluctance Motor (SRM) will make the design straight forward. Output equation of Switch Reluctance Motor will be significantly varies from that of the conventional motor, their similarities. The output equation for Switched Reluctance Motor is given below.[1]

$$P_d = k_e k_d k_1 k_2 \beta A_s D^2 L N_r \tag{2.1}$$

Where, k_e = Efficiency

$k_d = \frac{\theta_i q P_r}{360}$ = Duty cycle

θ_i = Angle of induction profile

q = No. of stator phase

P_r = No. of rotor pole

$k_1 = \frac{\pi^2}{120}$

$k_2 = 1 - \frac{1}{\sigma_s \sigma_u}$

σ_s= Ratio of saturated aligned inductance to unsaturated aligned inductance

σ_u= Ratio of unsaturated aligned inductance to saturated unaligned inductance

β= Flux density

A_s= Electric loading

D= Bore diameter

L= Stator axial length of pole

N_r= Rotor speed in rpm

2.1 Calculation of Main Dimensions

Length and Diameter:-

Switch Reluctance Motor (SRM) is generally used as a variable-speed device, it has appropriate a base speed specification. Generally the motor has been accepted deliver the rated torque and hence the rated output power. The rated output which keep the stack length as a multiple of rotor bore diameter, the following is obtained:[1]

$$L = kD \tag{2.2}$$

Output power equation:

$$P_d \propto k_2 D^3 \tag{2.3}$$

D is evaluated if the k and rated speed are known. It is possible to start the iterative process of design with reasonable values. The range lies between 0.45 to 0.75. The values of β is taken as the maximum for the core material. The value of electrical loading as ampere-conductor lies between

$$16000 < A_s < 90000$$

As per the equation values bore diameter D is obtained. The ratio of the length to bore diameter k is decided by the nature of the application and space constraints. For non-servo applications,

$$0.25<k<0.70$$

For servo applications,

$$1<k<3$$

Number of Turns Per Phase:-

$$A_s = \frac{2T_{ph}i}{\pi D} \tag{2.4}$$

For the current value given, T_{ph} can be calculated. The size of conductor is select such that the availability space of winding. The current density is obtained maximum permissible amount, that is dependent on the methods used for the cooling for motor. If there are no limitations on the outer side diameter the space of the winding can be calculated from the number of turns, the cross-section area of the conductors, and the thickness of the insulation. Stator pole height derived from the winding space. Specific electric loading and bore diameter, the product of i & T_{ph} is a constant. The value bore diameter and electric loading, satisfy the following mutually contradictory demands:[1]

a. Small current implying a larger number of turns

b. Small values of resistance and inductance of the winding implying a smaller number of turns

2.2 Stator Design

Thickness of Stator Back Iron:-

The thickness is obtained on the based on the value of the maximum flux density in it and by the additional factor of minimum vibration to reduce noise. The stator poles the flux density approximately half in the stator back iron. An allowance provide slightly greater share of the pole flux. The pole flux density have to accommodate with stator pole arcs. If ω_s is the pole width given in terms of pole arc as follows:

$$\omega_{sp} = D \sin \frac{\beta_s}{2} \tag{2.5}$$

There fore the back iron thickness has to be a minimum of 0.5 ω_{sp} . Due to mechanical robustness and minimization of vibration value in range lies:

$$\omega_{sp} > b_{sy} > 0.5\ \omega_{sp}$$

Selection of higher value for b_{sy} than its minimum.

Stator Coil Dimension:-

The dimension of the stator coil given by width ω_c and length , h_c from the conductor cross section a_c determine by the number of turns per phase and the current density, T_{ph}. Let ω_{cs} is the gap between the two adjacent coils. A stator coil area is given, in terms of no. of turns and cross section are of the conductor, by:[1]

$$h_c\omega_c = \frac{a_cT_{ph}}{2} \tag{2.6}$$

The maximum ω_c is derived by selecting to the periphery of the stator bore & removing the motor pole arcs and gap between coils and dividing the remaining by 2Ps coils. Then,

$$\omega_c = \frac{\pi D - P_s[\beta_s\frac{D}{2} + \omega_{cs}]}{2P_s} \tag{2.7}$$

Combining both equations, the available coil height is determined:

$$h_c = a_cT_{ph}[\frac{P_s}{\pi D - P_s[\beta_s\frac{D}{2} + \omega_{cs}]}] \tag{2.8}$$

Stator Pole Height:-

The height of stator pole and coil height both are near about equal but the coil has to be required a small space is near the pole face. The coil at the root is not usually tight fitting, that′s why some more space is lost which is taken into calculation of the stator pole height. Considers all these factors and the need for a smaller length of the pole, the pole height in terms of the coil height h_c is derived by

$$h_c < h_s < 1.4\ h_c$$

Outer Diameter of Stator Lamination:-

$$D_0 = D + 2b_{sy} + 2h_s \tag{2.9}$$

2.3 Rotor Design

Rotor Back Iron Thickness:-

The structural & operating flux-density is dependent on the rotor back iron thickness, b_{ry} . The stator back iron thickness and neither has to half of the stator pole width or to be equal to the minimum value equal. Ratio between the aligned and unaligned inductances, range of values has to be selected for the larger air-gap but at the same time, minimum vibration in the rotor. The thickness of rotor back iron is,

$$0.5\ \omega_{sp} < b_{ry} < 0.75\ \omega_{sp}$$

Rotor Pole Height:-

As per the equation rotor pole height is given the air gap length l_g,bore diameter D, thikness of rotor back iron b_{ry}, and diameter of the rotor shaft diameter D_{sh}, the rotor pole height is:[1]

$$h_r = [\frac{D - 2b_{ry} - 2l_g - D_{sh}}{2}] \tag{2.10}$$

Where , D_{sh} = Rotor shaft diameter

Length of air gap

$$l_g = \frac{\pi D}{P_r K_g} \tag{2.11}$$

The equation of air gap length is given above. The K_g is ratio of rotor pole pitch to air gap Length. The range of K_g is lies between:

$$50 < K_g < 300$$

2.4 Selection of Material

Non-Oriented Silicon Steel:- The high performance M 19-29 non-oriented silicon steel magnetic material are plays a significant role in the improvement of the motor performance. Respect to this goal, its main features are the magnetic permeability and the specific losses. Moreover, the choice of a suitable electrical steel depends on several aspects such as cost, workability, annealing (when needed), "business tradition" and storehouse demands. The iron loss per kg for different material at 1.5 T flux density is shown below Table 2.1.

Table 2.1: Selection of material property

Material with Grade	**Iron loss W/kg**
M 15-26	3.30
M 15-29	3.08
M 19-24	4.05
M 19-26	3.28
M 19-29	3.17
M 27-24	4.55
M 27-26	3.70
M 27-29	3.36
M 36-24	4.72
M 36-26	3.74
M 36-29	3.69
M 43-26	3.28
M 45-24	5.04
M 45-29	3.65
M 47-24	4.30
M 47-26	4.48

2.5 Inductance Calculation

The torque characteristics dependent on rotor position as a function of current & flux linkages. The limitations of this motor drive & control possibilities, neglecting the fringing effect. The changes in the inductance profile are determined in terms of the

No. of the rotor poles, stator pole arcs & rotor pole arcs. The rotor pole arc to be higher than the arc of the stator.[1]

There are two types of inductance calculation.

- Aligned inductance
- Unaligned inductance

$$\theta_1 = \frac{1}{2}[\frac{2\pi}{P_r}] - (\beta_s + \beta_r) \tag{2.12}$$

$$\theta_2 = \theta_1 + \beta_s \tag{2.13}$$

$$\theta_3 = \theta_2 + (\beta_r - \beta_s) \tag{2.14}$$

$$\theta_4 = \theta_3 + \beta_s \tag{2.15}$$

$$\theta_5 = \theta_4 + \theta_1 = \frac{2\pi}{P\ _r} \tag{2.16}$$

Where β_s is pole arc of the stator and β_r is pole arc of the rotor, and P_r is the No. of the rotor poles.

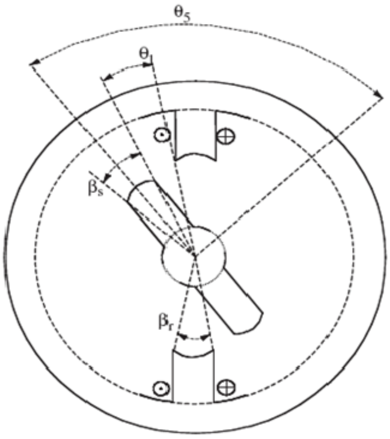


Figure 2.1: Rotor Position

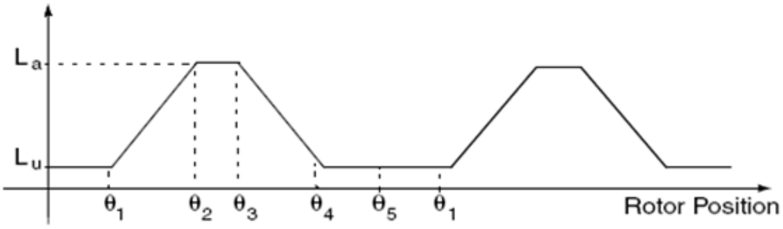


Figure 2.2: Profile of Inductance

2.5.1 Unaligned Inductance

Here, seven flux paths are shown below in figure 2.3. The calculation of unaligned inductance is done by flux paths.

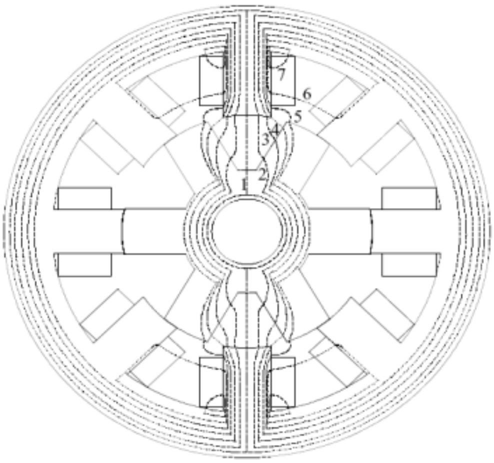


Figure 2.3: Unaligned Inductance

2.5.2 Aligned Inductance

The 8/6 machine is consider for of aligned position. The flux in the machine consists of flux path 1 to flux path 7, identified for the unaligned position. Flux path 1 consists of the majority of the flux and is mutual flux connecting the stator and rotor. Flux path 7 has leakage flux only when connecting the excited poles with adjacent poles

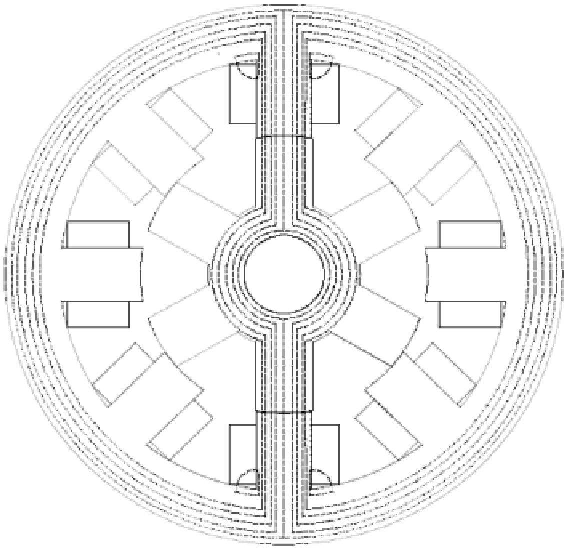


Figure 2.4: Aligned Inductance

and carries only a small flux. The derivations for these two flux paths are given separately.

For aligned inductance calculation, the reluctance of flux path 1 and flux path 7 is calculated and inductance of both paths is calculated.

2.6 Performance Estimation

Calculation of Core Loss:-

First we find the volume of material for particular section. Then the density of material multiplied to the volume of material so we get the weight of material. Then the core loss per kg for material is found out by the graph of core loss per k_g flux density.

Core Loss of Stator Pole

$$V_{sp} = (\frac{0.5 P_r P_s D L B_{sr} h_s}{10^9}) \tag{2.17}$$

where , V_{sp} = Volume of stator pole

$$C_{sp} = V_{sp} d_e C_{sp} \tag{2.18}$$

where , C_{sp} = Core loss per k_g stator pole material

d_e = Density of core material

Core Loss of Stator Yoke

$$V_{sy} = (\frac{2P_r(0.5D_o - b_{sy})\frac{2\pi}{P_s}b_{sy}L}{10^9}) \tag{2.19}$$

where , V_{sy} = Volume of stator yoke

$$C_{sy} = V_{sy} d_e C_{sy} \tag{2.20}$$

where , C_{sy} = Core loss per k_g stator yoke material

Core Loss of Rotor Pole

$$V_{rp} = [\frac{P_r P_s (0.5D - l_g) B_{rr} h_r L}{10^9}] \tag{2.21}$$

where , V_{rp} = Volume of rotor pole

$$C_{rp} = V_{rp} d_e C_{rp} \tag{2.22}$$

where , C_{rp} = Core loss per k_g for rotor pole material

Core Loss of Rotor Yoke

$$V_{ry} = [\frac{b_{ry} L\pi(D - 2L_g - 2h_r D_{sh})}{10^9}] \tag{2.23}$$

where , V_{ry} = Volume of rotor pole

$$C_{ry} = V_{ry} d_e Cry \tag{2.24}$$

where , C_{ry} = Core loss per k_g for rotor yoke material

Total Core Loss

$$C_o = C_{sp} + C_{sy} + C_{rp} + C_{ry} \tag{2.25}$$

where C_o = Total core loss

Copper Loss Calculation:-

Following equation to be calculated in copper loss ,

$$l_m = (\frac{2L + 2\omega_{sp} + 4\omega_c}{1000}) \tag{2.26}$$

where, l_m = Length of mean turn

$$R = (\frac{r_e l_m 1000000}{a_c}) \tag{2.27}$$

where , a_c = Cross section area of conductor

r_e = Resistivity of coil material

$$C_u = T_{ph} R I^2 \tag{2.28}$$

where C_u = Total copper loss

Calculation of Efficiency:-

Total losses = Core losses (C_o) + Copper losses (C_u)

$$Efficiency = \frac{Outputpower}{Outputpower + Losses} \tag{2.29}$$

Chapter 3

Computer Aided Design of SRM

3.1 Introduction

Motors are being used in domestic as well as in industries for the various purposes. So the designing of the motor is carried out manually by mathematical equations. But for the accurate performance of the machine is usually evaluated using Computer Aided Design (CAD) method. With this Computer aided design (CAD) method, the effect of a single parameter on the dynamical performance of the machine can be effectively studied by using a computer programming language. It is important to have the knowledge of parameters of the machine to design reliable and an efficient machine. MATLAB is a language of technical computing software that provides platform for perform various mathematical analysis. It is easy to use and simple to understand. It use for design of motor, electronic circuit analysis and other network analysis. In this program we implement input data of Switched Reluctance Motor (SRM) and calculate the Main Dimension, Aligned inductance calculation, Unaligned inductance calculation, Copper loss, Core loss and Efficiency.

3.2 Flow-Chart of CAD for SRM

Specifications of the motor, efficiency and input data are given initially. After selection of motor topology some of the parameters should be assumed for the particular application. On the basis of the initially assumed and input data, main dimensions of the motor are calculated. There after stator design, rotor design and inductance Calculation and performance calculations are done.

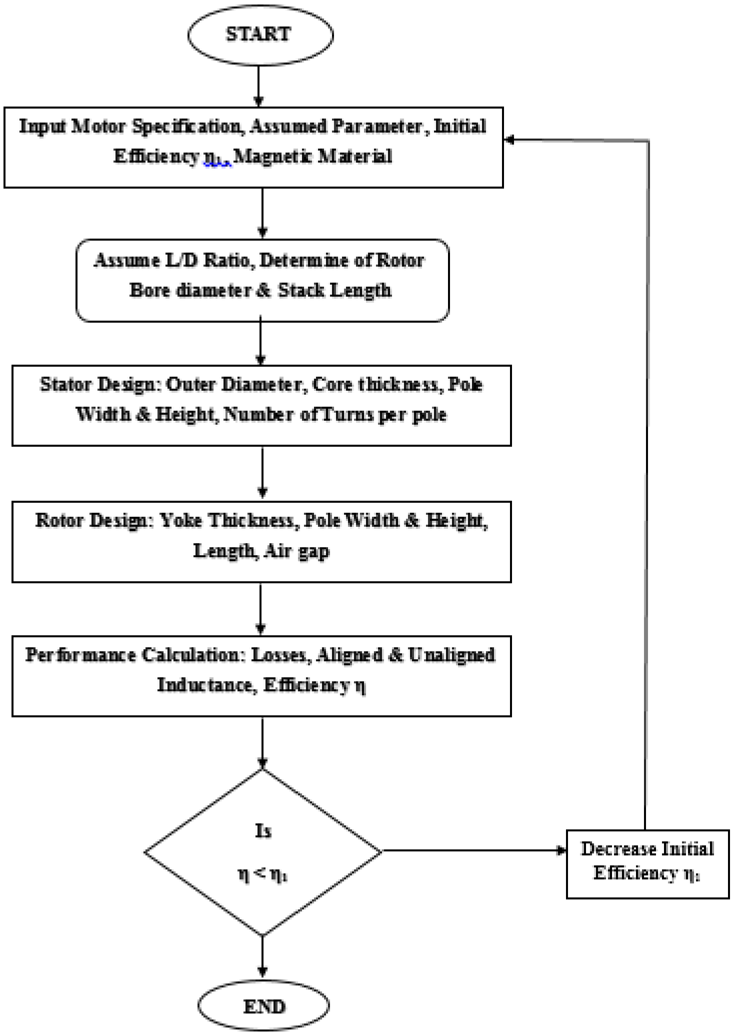


Figure 3.1: Flow Chart of CAD for SRM

3.3 CAD of 250 W, 6/4 pole, 12.8 V, 3600 rpm of SRM

Input Data

The input to the CAD program is as shown in below.[3]

Parameters	**Rating**
Output power (P_o)	250 W
Supply voltage (V)	12.8 V
Supply current (I)	39 A
Speed (N_r)	3600 rpm
No. of stator pole (P_s)	6
No. of rotor pole (P_r)	4
Stator pole arc (β_s)	30.13°
Rotor pole arc (β_r)	32.40°
Assume efficiency (E)	85%
Constant (K_2)	0.5987 mm
Flux density (β)	1.5 T
Permeability of magnetic material (U_r)	1900
Specific electric loading (A_s)	16000 A/mm^2
Stack length to bore diameter (K=L/D)	0.59 mm
Ratio of stator core thickness to stator pole width (b_{syr})	0.6 mm
Gap left between two adjacent coils between (ω_{cs})	5 mm
Current density (J)	5.5 A/mm^2
Ratio of height of stator pole to height of stator coil (h_{sr})	1.125 mm
Ratio of rotor core thickness to stator pole width (b_{ryr})	0.5275 mm
Ratio of rotor pole pitch to air gap length (K_g)	95.93 mm
Rotor shaft diameter (D_{sh})	7.84 mm
Density of material (d_e) (Stainless Steel)	7600 kg/m^3
Core loss per kg for stator pole material (C_{sp})	17 W/kg
Core loss per kg for stator yoke material (C_{sy})	3.2 W/kg
Core loss per kg for rotor pole material (C_{rp})	4.5 W/kg
Core loss per kg for rotor yoke material (C_{ry})	0.88 W/kg
Resistivity of coil material (ρ_e)	1.72$\times$ 10^{-8} Ωm

Output Data

The results obtained from developed CAD program is as shown in the output data.

Parameters	**Value**
Rotor bore diameter (D)	48.86 mm
Stack length (L)	28.82 mm
Outer diameter (D_o)	96.56 mm
Stator core thickness (b_{sy})	7.62 mm
Width of stator coil (ω_c)	3.868 mm
Height of stator coil (h_c)	14.429 mm
Number of turns per pole (T_{ph})	16 Turns
Height of stator pole (h_s)	16.23 mm
Rotor core thickness (b_{ry})	6.69 mm
Length of air gap (l_g)	0.40 mm
Rotor pole height (h_r)	13.41 mm
Unaligned inductance of flux path (L_{u1})	0.0000048 H
Unaligned inductance of flux path (L_{u2})	0.0000038 H
Unaligned inductance of flux path (L_{u3})	0.0000060 H
Unaligned inductance of flux path (L_{u4})	0.0000093 H
Unaligned inductance of flux path (L_{u5})	0.0000018 H
Unaligned inductance of flux path (L_{u6})	0.0000056 H
Unaligned inductance of flux path (L_{u7})	0.0000053 H
Total unaligned inductance (TL_u)	0.000053 H
Aligned inductance of flux path (L_{a1})	0.000448 H
Aligned inductance of flux path (L_{a1})	0.000051 H
Total core loss (T_{co})	24.38 W
Total copper loss (T_{cu})	26.55 W
Efficiency (η)	83.07%

3.4 CAD of 3.73 kW, 8/6 pole, 655 V, 1500 rpm of SRM

Input Data

The input to the CAD program is as shown in below.[2]

Parameters	**Rating**
Output power (P$_o$)	3.73 kW
Supply voltage (V)	655 V
Supply current (I)	13 A
Speed (N$_r$)	1500 rpm
No. of stator pole (P$_s$)	8
No. of rotor pole (P$_r$)	6
Stator pole arc (β_s)	22°
Rotor pole arc (β_r)	26°
Assume efficiency (E)	86%
Constant (K$_2$)	0.521 mm
Flux density (β)	1.5 T
Specific electric loading (A$_s$)	25000 A/mm^2
Stack length to bore diameter (K=L/D)	1.2 mm
Ratio of stator core thickness to stator pole width (b$_{syr}$)	0.7186 mm
Gap left between two adjacent coils between (ω_{cs})	7 mm
Current density (J)	5.13 A/mm^2
Ratio of height of stator pole to height of stator coil (h$_{sr}$)	1.26 mm
Ratio of rotor core thickness to stator pole width (b$_{ryr}$)	0.63 mm
Ratio of rotor pole pitch to air gap length (K$_g$)	70 mm
Rotor shaft diameter (D$_{sh}$)	33.33 mm
Core loss per kg for stator pole material (C_{sp})	6.5 W/kg
Core loss per kg for stator yoke material (C_{sy})	1.5 W/kg
Core loss per kg for rotor pole material (C_{rp})	0.6 W/kg
Core loss per kg for rotor yoke material (C_{ry})	0.4 W/kg

Output Data

The results obtained from developed CAD program is as shown in the output data below

Parameters	**Value**
Rotor bore diameter (D)	100.00 mm
Stack length (L)	120.00 mm
Outer diameter (D_o)	201.12 mm
Stator core thickness (b_{sy})	13.8131 mm
Width of stator coil (ω_c)	6.610 mm
Height of stator coil h_c	29.166 mm
Number of turns per pole (T_{ph})	304 Turns
Height of stator pole (h_s) (h_s)	36.75 mm
Rotor core thickness (b_{ry})	12.11 mm
Length of air gap (l_g)	0.7535 mm
Rotor pole height (h_r)	20.8419 mm
Unaligned inductance of flux path (L_{u1})	0.00807 H
Unaligned inductance of flux path (L_{u2})	0.00604 H
Unaligned inductance of flux path (L_{u3})	0.01188 H
Unaligned inductance of flux path (L_{u4})	0.02567 H
Unaligned inductance of flux path (L_{u5})	0.00387 H
Unaligned inductance of flux path (L_{u6})	0.01480 H
Unaligned inductance of flux path (L_{u7})	0.35725 H
Total unaligned inductance (TL_u)	0.10607 H
Aligned inductance of flux path (L_{a1})	0.3283 H
Aligned inductance of flux path (L_{a1})	0.0804 H
Total aligned inductance (TL_a)	0.4087 H
Total core loss (T_{co})	233.06 W
Total copper loss (T_{cu})	232.71 W
Efficiency (η)	88.89%

3.5 CAD of 55 kW, 6/4 pole, 784 V, 3500 rpm of SRM

Input Data

The input to the CAD program is as shown in below.

Parameters	**Rating**
Output power (P_o)	55 kW
Supply voltage (V)	784 V
Supply current (I)	94 A
Speed (N_r)	3500 rpm
No. of stator pole (P_s)	6
No. of rotor pole (P_r)	4
Stator pole arc (β_s)	30°
Rotor pole arc (β_r)	32°
Assume efficiency (E)	90%
Constant (K_2)	0.74 mm
Flux density (B)	1.5 T
Specific electric loading (A_s)	56000 A/mm^2
Stack length to bore diameter (K=L/D)	1.70525 mm
Ratio of stator core thickness to stator pole width (b_{syr})	0.5672 mm
Gap left between two adjacent coils between (ω_{cs})	5 mm
Current density (J)	5.5 A/mm^2
Ratio of height of stator pole to height of stator coil (h_{sr})	1.05 mm
Ratio of rotor core thickness to stator pole width (b_{ryr})	0.5212 mm
Ratio of rotor pole pitch to air gap length (K_g)	247.4 mm
Rotor shaft diameter (D_{sh})	53 mm
Core loss per kg for stator pole material (C_{sp})	26.8 W/kg
Core loss per kg for stator yoke material (C_{sy})	7.1 W/kg
Core loss per kg for rotor pole material (C_{rp})	3.1 W/kg
Core loss per kg for rotor yoke material (C_{ry})	0.9 W/kg

Output Data

The results obtained from developed CAD program is as shown in the output data.

Parameters	**Value**
Rotor bore diameter (D)	126.10 mm
Stack length (L)	215.03 mm
Outer diameter (D_o)	238.72 mm
Stator core thickness (b_{sy})	18.512 mm
Width of stator coil (ω_c)	14.00 mm
Height of stator coil (h_s)	35.99 mm
Number of turns per pole (T_{ph})	204.39 Turns
Height of stator pole h_s	37.79 mm
Rotor core thickness (b_{ry})	17.010 mm
Length of air gap (l_g)	0.40 mm
Rotor pole height (h_r)	19.14 mm
Unaligned inductance of flux path (L_{u1})	0.0059 H
Unaligned inductance of flux path (L_{u2})	0.0010 H
Unaligned inductance of flux path (L_{u3})	0.0012 H
Unaligned inductance of flux path (L_{u4})	0.0020 H
Unaligned inductance of flux path (L_{u5})	0.0005 H
Unaligned inductance of flux path (L_{u6})	0.0016 H
Unaligned inductance of flux path (L_{u7})	0.0071 H
Total unaligned inductance (TL_u)	0.0197 H
Aligned inductance of flux path (L_{a1})	0.0401 H
Aligned inductance of flux path (L_{a1})	0.0161 H
Total aligned inductance (TL_a)	0.0562 H
Total core loss (T_{co})	792 W
Total copper loss (T_{cu})	578 W
Efficiency (η)	97.56%

3.6 CAD Results and Validation

The comparison between three different motor ratings are small rating of 250 W, medium rating of 3.73 kW and large rating of 55 kW of Switched Reluctance Motor are listed in below table 3.1.

Table 3.1: Comparison of three different motor rating

Parameters	**Symbol**	**Rating-I**	**Rating-II**	**Rating-III**
Output power	P_o	250 W	3.73 kW	55 kW
Output voltage	V	12.8 V	655 V	784 V
Speed	N_r	3600	1500	3500
Torque	T	0.6 Nm	24.99 Nm	149.8 Nm
Rotor bore diameter	D	48.86 mm	100.00 mm	126.10 mm
Stack length	L	28.82 mm	120.00 mm	215.03 mm
Outer diameter	D_o	96.56 mm	201.12 mm	238.72 mm
Air gap length	l_g	0.40 mm	0.75 mm	0.4 mm
Unaligned inductance	L_u	0.000053	0.0311 H	0.0197 H
Aligned inductance	L_a	0.00049	0.1013 H	0.0562 H
Efficiency	η	83.07%	88.89%	97.56%

The CAD output shows that

- As the power rating increase the efficiency also increase.

Chapter 4

Finite Element Analysis of SRM

4.1 Introduction of Speed Software

Motor design with SPEED software is interactive and fast. It is simply a specialized calculating tool to assist the design engineer with initial sizing and preliminary design of motors by providing a simple intuitive interface and quick simulation. Common features of Speed Software:

- Quick data entry and modification, and for quick simulation.
- Simulation is based upon classical theory and equivalent circuit models.
- Simulations vary by program but include ideal, time-stepping, dynamic, thermal and line-start in one package.
- Simulation includes the motor drive as well as the electromagnetic aspects.
- Extensive written manuals and on-line help are provided.
- Material database contain information about steels, magnets and brushes.
- Effects of switching on motor characteristics due to inverter fed phases.

Data input in to speed software: The data obtained from the program is entered into speed software. The data is entered into outline editor and template editor. The dynamic analysis shows the result of current and torque profile of SRM. The material

to be used for stator and rotor is selected from editor tool box containing the material assign option and simulation is performed.
For Outline editor R_{sh} , R_o , R_1 , R_2 , and R_3 must be in increasing order.
For Template editor in dimensional parameter enter the value of L_{stk} , in winding parameter select the bare diameter and enter the value of diameter of wire. Then the number of turns per pole N_p value put.

4.2 FE Analysis of 250 W, 6/4 pole, 12.8 V, 3600 rpm of SRM

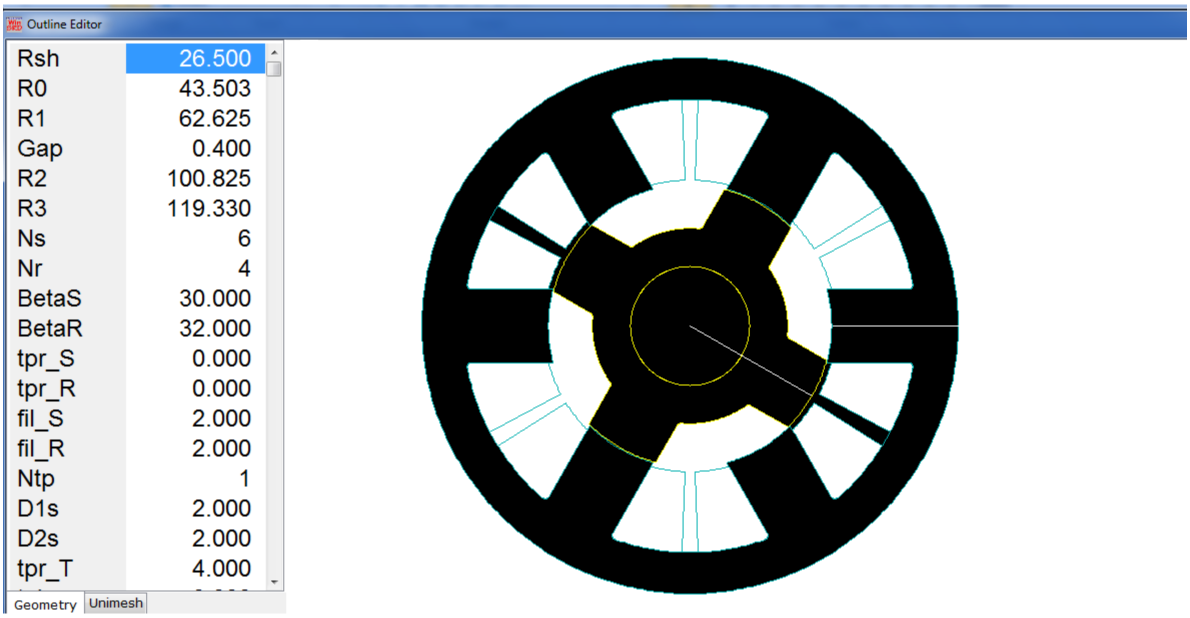
The model of small rating Switched Reluctance Motor 250 W, 6/4 pole, 12.8 V, 3600 rpm is made in speed software using main dimensions obtained from CAD program. Analysis of torque, current and flux linkage, copper loss, core loss and efficiency is carried out.

Input Data for Model

Parameters	**Value**
Output Power (P_o)	250 W
Supply voltage (V)	12.8 V
Supply current (I)	39 Amp
Speed (N_r)	3600 rpm
No. of stator pole (P_s)	6
No. of rotor pole (P_r)	4
Stator pole arc (β_s)	30.13°
Rotor pole arc (β_r)	32.40°
Shaft diameter (D_{sh})	7.84 mm
Rotor bore diameter (D)	48.86 mm
Stack length (L)	28.82 mm
Outer diameter (D_o)	96.56 mm
Air gap length (l_g)	0.40 mm

Output Data obtained from FE Analysis

Parameters	**Value**
Current (I)	39 Amp
Torque (T)	0.56 Nm
Flux (β)	1.5 T
Total Core loss (T_{co})	21.15 W
Total Copper loss (T_{cu})	20.76 W
Efficiency (η)	85.64%



Rsh	26.500
R0	43.503
R1	62.625
Gap	0.400
R2	100.825
R3	119.330
Ns	6
Nr	4
BetaS	30.000
BetaR	32.000
tpr_S	0.000
tpr_R	0.000
fil_S	2.000
fil_R	2.000
Ntp	1
D1s	2.000
D2s	2.000
tpr_T	4.000

Figure 4.1: Model of 250 W, 6/4 pole of SRM

The phase current vs rotor position with flux-linkage and inductance characteristics of the motor is obtained from the FE analysis. Fig 4.2 shows the value of peak current i.e. 39 A which is nearly equal to the input current. The results of FE analysis are compared with the corresponding values obtained from CAD program.

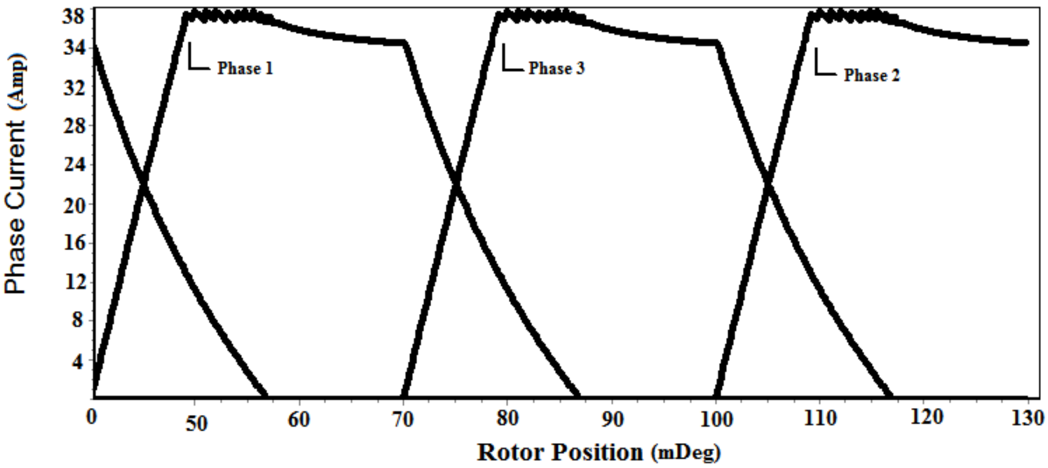


Figure 4.2: Phase current vs rotor position

The average torque is determined by actual phase inductance and flux linkage for different rotor positions and excitation. CAD results are nearly matching with the Finite Element Analysis. Fig 4.3 shows that available torque will be 0.56 Nm.

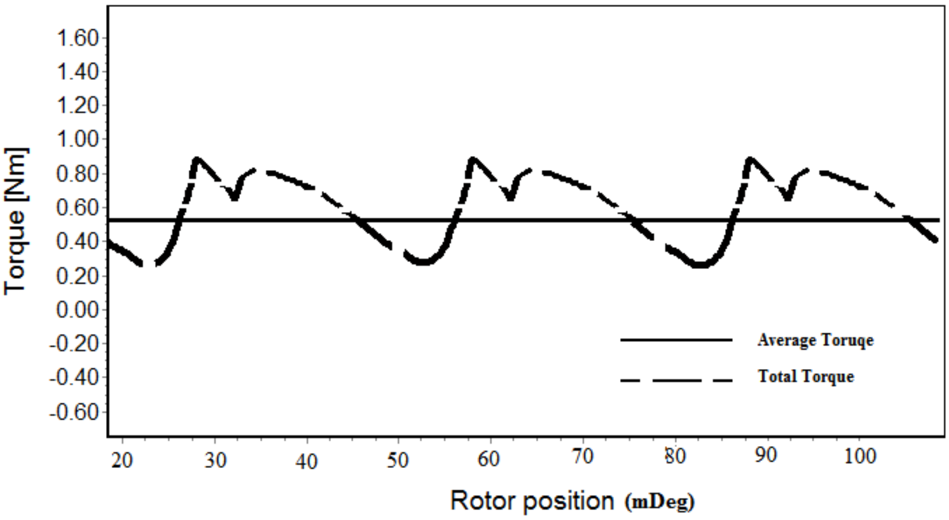


Figure 4.3: Torque vs rotor position

The flux density profile of the stator pole of the motor, the peak value of which as per the CAD program is 1.5 T. Fig 4.4 shows the current vs flux linkage characteristics. The FE analysis of the designed motor for efficiency, core losses, copper losses, have to be calculated.

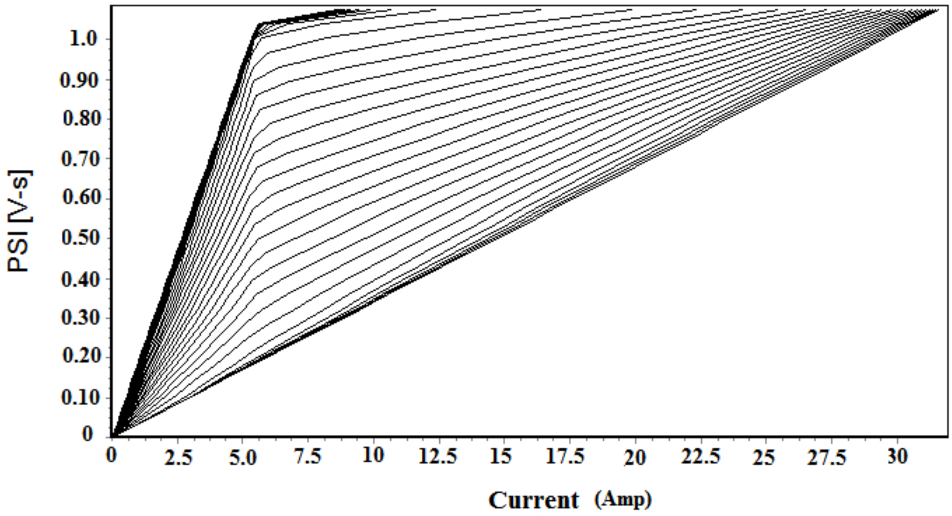


Figure 4.4: Flux-linkage vs current

4.3 FE Analysis of 3.73 kW, 8/6 pole, 655 V, 1500 rpm of SRM

The model of medium rating of Switched Reluctance Motor for 3.73 kW, 8/6, 655 V, 1500 rpm is made in speed software package using main dimensions which get from the obtained output results of the Computer Aided Design (CAD) program. The Analysis of torque, current and flux linkage, copper loss, core loss, efficiency is carried out.

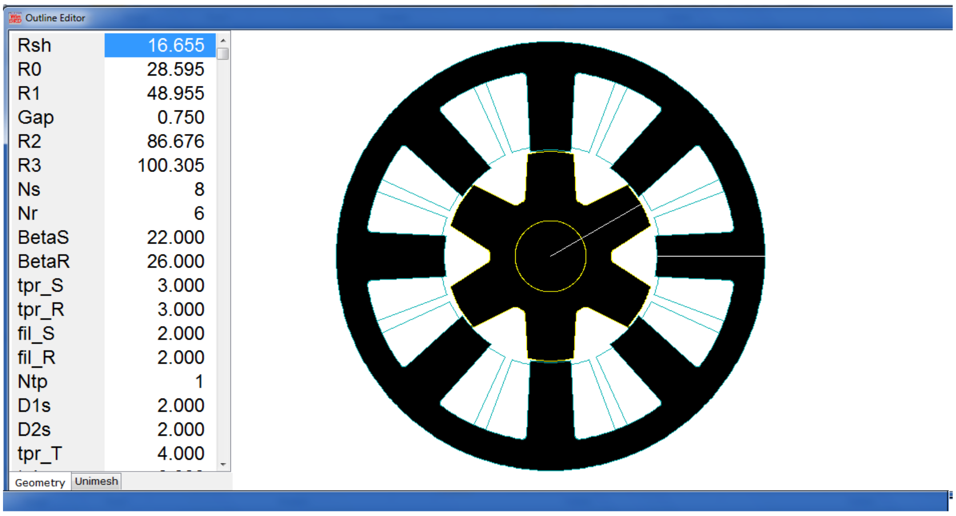
Input Data for Model

Parameters	**Value**
Output Power (P_o)	3.73 kW
Supply voltage (V)	655 V
Supply current (I)	13 Amp
Speed (N_r)	1500 rpm
No. of stator pole (P_s)	8
No. of rotor pole (P_r)	6
Stator pole arc (β_s)	22°
Rotor pole arc (β_r)	26°
Shaft diameter (D_{sh})	33.33 mm
Rotor bore diameter (D)	100.00 mm
Stack length (L)	120.00 mm
Outer diameter (D_o)	201.867 mm
Air gap length (l_g)	0.7535 mm

Output Data obtained from FE Analysis

Parameters	**Value**
Current (I)	13 Amp
Torque (T)	24.5 Nm
Flux (β)	1.5 T
Total Core loss (T_{co})	200.00 W
Total Copper loss (T_{cu})	235.26 W
Efficiency (η)	89.55%

The medium rating of model of 3.73 kW, 8/6 pole, 1500 rpm as shown in below fig. 4.5



Rsh	16.655
R0	28.595
R1	48.955
Gap	0.750
R2	86.676
R3	100.305
Ns	8
Nr	6
BetaS	22.000
BetaR	26.000
tpr_S	3.000
tpr_R	3.000
fil_S	2.000
fil_R	2.000
Ntp	1
D1s	2.000
D2s	2.000
tpr_T	4.000

Figure 4.5: Model of 3.73 kW, 8/6 pole of SRM

The phase current vs rotor position with flux-linkage and inductance characteristics of the motor is obtained from the FE analysis. Fig 4.6 shows the value of peak current i.e. 13 A which is nearly equal to the input current. The results of FE analysis are compared with the corresponding values obtained from CAD program.

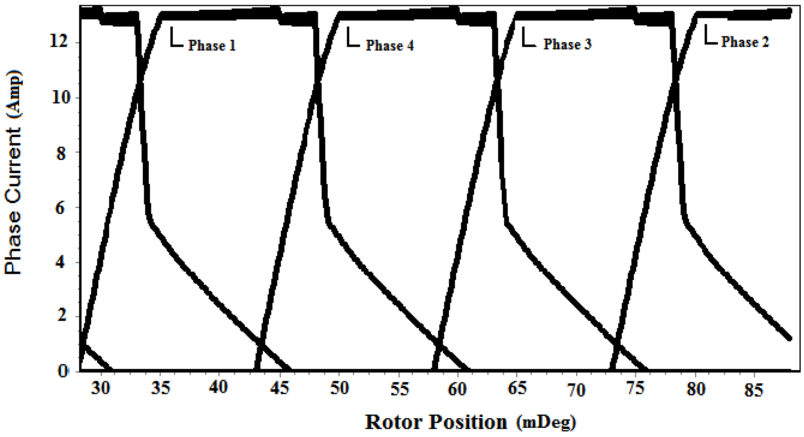


Figure 4.6: Phase current vs rotor position

The average torque is determined by actual phase inductance and flux linkage for different rotor positions and excitation. CAD results are nearly matching with the Finite Element Analysis. Fig 4.7 shows that considering the instantaneous rise and the phase current, the available torque will be 24.5 Nm.

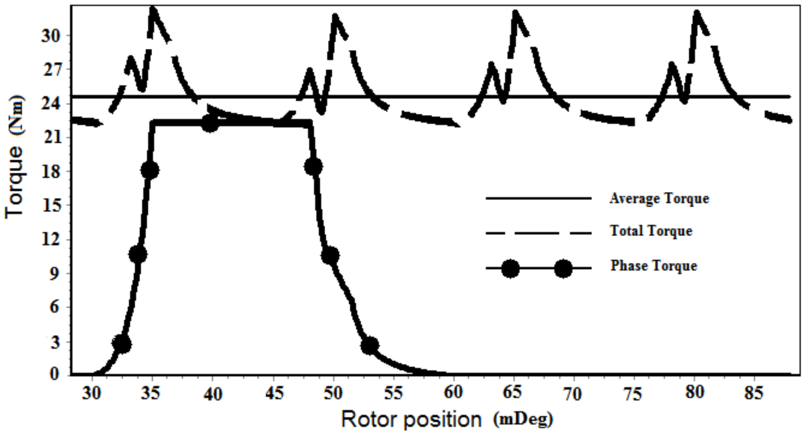


Figure 4.7: Torque vs rotor position

The flux density profile of the stator pole of the motor, the peak value of which as per the CAD program is 1.56 T. Fig 4.8 shows the current vs flux linkage characteristics. The FE analysis of the designed motor for efficiency, core losses, copper losses, have to calculated to the based on the actual current and flux density rather than using conventional methods.

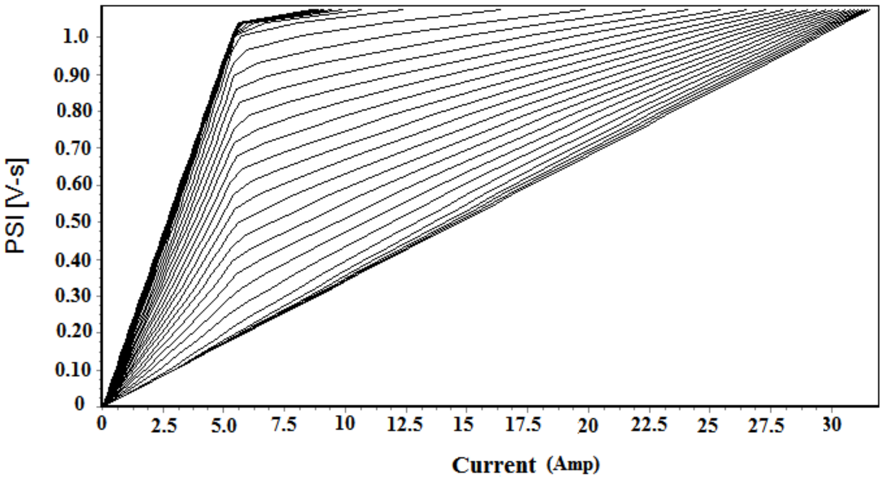


Figure 4.8: Flux-linkage vs current

4.4 FE Analysis of 55 kW, 6/4 pole, 784 V, 3500 rpm of SRM

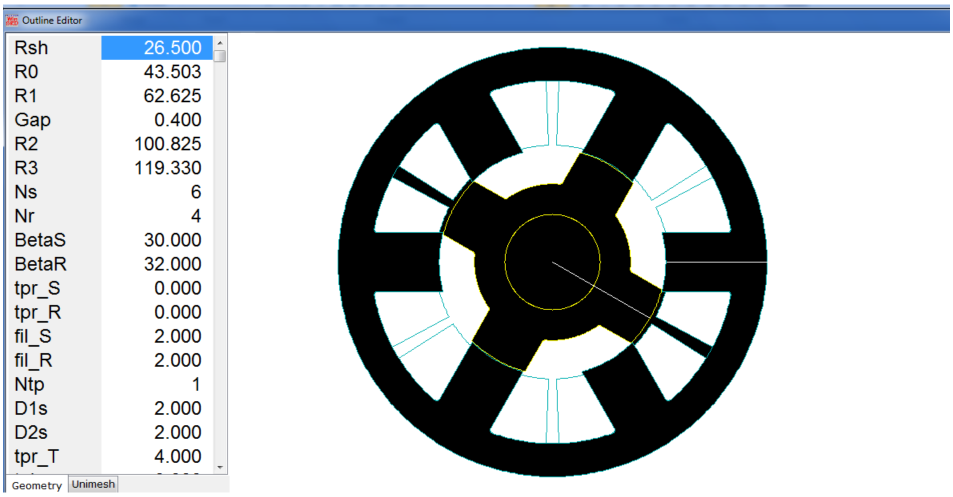
The model of large rating Switched Reluctance Motor 55 kW, 6/4, 784 V, 3500 rpm is made in speed software using main dimensions which get from CAD program.

Input Data for Model

Parameters	**Value**
Output Power (P_o)	55 kW
Supply voltage (V)	784 V
Supply current (I)	94 Amp
Speed (N_r)	3500 rpm
No. of stator pole (P_s)	6
No. of rotor pole (P_r)	4
Stator pole arc (β_s)	30°
Rotor pole arc (β_r)	32°
Shaft diameter (D_{sh})	53 mm
Rotor bore diameter (D)	126.10 mm
Stack length (L)	215.03 mm
Outer diameter (D_o)	238.72 mm
Air gap length (l_g)	0.40 mm

Output Data obtained from FE Analysis

Parameters	**Value**
Current (I)	94 Amp
Torque (T)	149.8 Nm
Flux (β)	1.5 T
Total Core loss (T_{co})	780 W
Total Copper loss (T_{cu})	582 W
Efficiency (η)	97.52%



Rsh	26.500
R0	43.503
R1	62.625
Gap	0.400
R2	100.825
R3	119.330
Ns	6
Nr	4
BetaS	30.000
BetaR	32.000
tpr_S	0.000
tpr_R	0.000
fil_S	2.000
fil_R	2.000
Ntp	1
D1s	2.000
D2s	2.000
tpr_T	4.000

Figure 4.9: Model of 55 W, 6/4 pole of SRM

The phase current vs rotor position with flux-linkage and inductance characteristics of the motor is obtained from the FE analysis. Fig 4.10 shows the value of peak current i.e. 93 A which is nearly equal to the input current. The results of FE analysis are compared with the corresponding values obtained from CAD program.

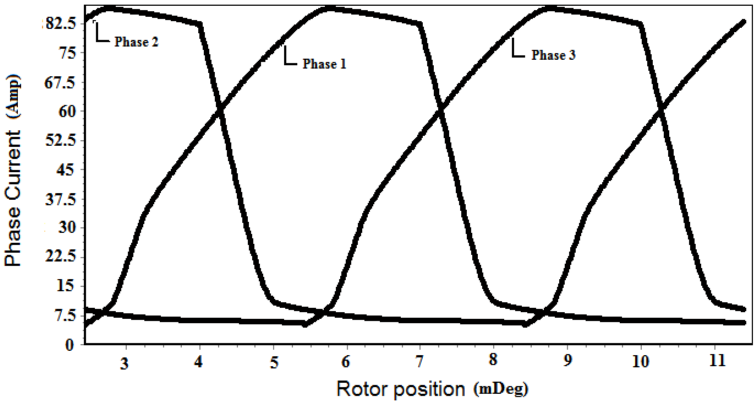


Figure 4.10: Phase current vs rotor position

The average torque is determined by actual phase inductance and flux linkage for different rotor positions and excitation. CAD results are nearly matching with the Finite Element Analysis. Fig 4.11 shows that considering the instantaneous rise and the phase current, the available torque will be 24.5 Nm.

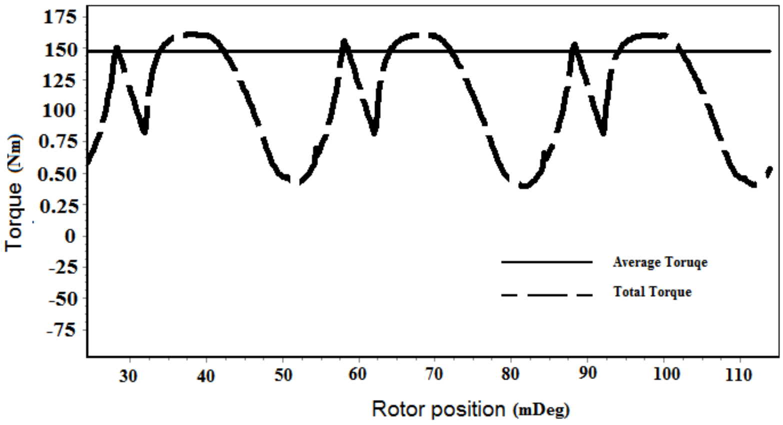


Figure 4.11: Torque vs rotor position

The flux density profile of the stator pole of the motor, the peak value of which as per the CAD program is 1.56 T. Fig 4.12 shows the current vs flux linkage characteristics. The FE analysis of the designed motor for efficiency, core losses, copper losses, have to calculated.

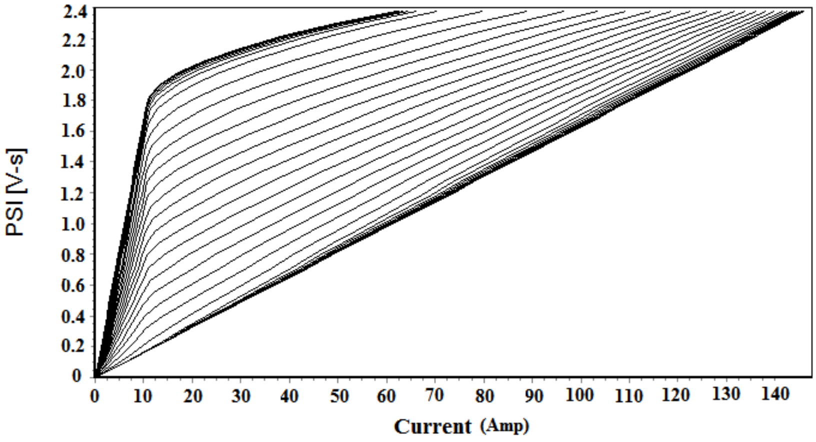


Figure 4.12: Flux-linkage vs current

4.5 Comparison of Result Obtained from CAD & FE Analysis

A. Comparative Analysis of 250 W, 6/4 pole, 12.8 V, 3600 rpm of SRM

The comparative result from the CAD and FEA is as listed in table.

Parameters	CAD	FEA
Torque (T)	0.6 Nm	0.58 Nm
Air Flux density (β)	1.5 T	1.5 T
Total Core loss (T_{co})	24.38 W	21.154 W
Total Copper loss (T_{cu})	26.55 W	20.76 W
Efficiency (η)	83.07%	85.64%

B. Comparative Analysis of 3.73 kW, 8/6 pole, 655 V, 1500 rpm of SRM

The comparative result from the CAD and FEA is as listed in table.

Parameters	CAD	FEA
Torque (T)	24.99 Nm	24.5 Nm
Air gap Flux density (β)	1.5 T	1.5 T
Total Core loss (T_{co})	233.06 W	200.00 W
Total Copper loss (T_{cu})	232.71 W	235.26 W
Efficiency (η)	88.94%	89.55%

C. Comparative Analysis of 55 kW, 6/4 pole, 784 V, 3500 rpm of SRM

The comparative result from the CAD and FEA is as listed in table.

Parameters	CAD	FEA
Torque (T)	150 Nm	149.8 Nm
Air gap Flux density (β)	1.5 T	1.5 T
Total Core loss (T_{co})	792 W	780 W
Total Copper loss (T_{cu})	578 W	582 W
Efficiency (η)	97.56%	97.58%

The comparative analysis of three different rating such as a small rating of 250 W, medium rating of 3.73 kW, and large rating of 55 kW of Switched Reluctance Motor (SRM). It is observed from the comparative results that data obtained from Finite Element Analysis (FEA) matches with the Computer Aided Design (CAD) results.

Chapter 5

Reduction of Torque Ripple

5.1 Introduction

Torque ripple is an effect seen in many electric motor designs, referring to a periodic increase or decrease in output torque as the motor shaft rotates. The conventional way to operate a Switched Reluctance Motor consists in supplying unidirectional current pulses sequentially to each of the Switched Reluctance Motor phase coils. The current pulse could be controlled by its amplitude and on and off timing. The torque ripple is defined as the difference between the maximum and minimum torque expressed as a percentage of average torque during steady state operation.

$$\%_{Ripple} = \frac{\tau_{max} - \tau_{min}}{\tau_{avg}} \times 100 \tag{5.1}$$

5.2 Torque Ripple Minimization Techniques

Changing Stator and Rotor Pole Arc:-

The changing stator and rotor pole arc, the inductance profile of SRM change due to the torque of SRM change. The inductance profile part of θ_2 to θ_3 is changed by stator and rotor pole arc. So that time gets more for energy dissipation of inductance of stator coil.[12]

$$\beta_s, \beta_r \geq \frac{2\pi}{\frac{P_s, P_r}{2}} \tag{5.2}$$

$$\beta_s + \beta_r \leq \frac{2\pi}{P_r} \tag{5.3}$$

Here for 4-phase 8/6 SRM is taken as an example. Because the stator windings are inductive, the phase current is not a square waveform and requires rising and declining time. Fig. 5.2 shows that θ_{on} has to lead θ_1 in order to establish flat current at θ_1, which means that the following inequality constraint should be satisfied.

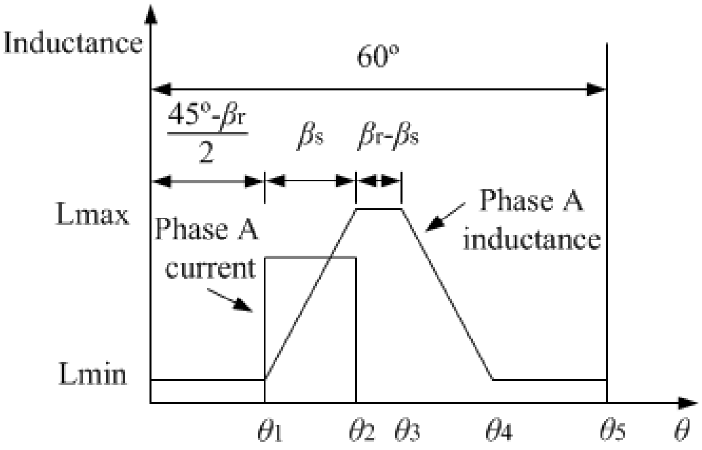


Figure 5.1: Ideal phase current

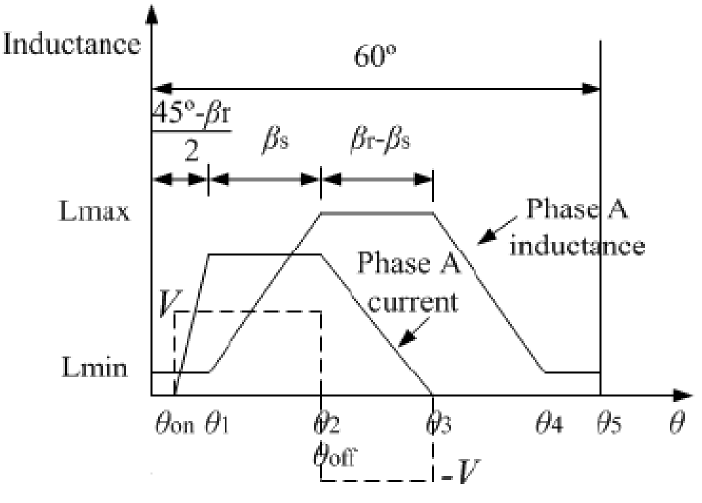


Figure 5.2: Actual phase current

Tapered Angle of Stator and Rotor Pole:-

The changing tapered angle of stator and rotor pole of the cross section area of stator and rotor pole is increased. So the reluctance decreased and the inductance increased because of that the average torque of motor increased and torque ripple can be minimized.

Changing Turn-off and Turn-on Angle:-

The inductance of stator coil the time get more for current to reach at peak value. The torque equation has two terms one is current and another is change of inductance with respect to rotor position. If change of inductance with respect to rotor position is zero then the torque become zero. By advance turn on angle technique, the rising edge of current is on the part of no change of inductance with respect to rotor position. When change in inductance with respect to rotor position is positive at that time current reach at its peak value. So that the maximum average torque get. By this method of changing turn-off and turn-on angle the torque ripple can minimized.

Changing Pole Tip Shape Design:-

The pole tip shape is changed and by this the flux linkage is increase. The inductance increase and average torque is increased. By changing pole tip shape, the torque ripple can minimized.

5.3 Comparative Result of Torque Ripple Reduction

A. Torque Ripple Minimization of 250 W, 6/4 pole, 12.8 V, 3600 rpm of SRM

Graph of Torque Vs rotor position of the 250 W, 6/4, 12.8 V, 3600 rpm Switched Reluctance Motor (SRM) is as shown in below Fig 5.3 The graph is clearly shows that the maximum instantaneous value of the torque is 0.90 Nm and minimum instantaneous value of the torque is 0.40 Nm. So, the average value of the torque is

0.56 Nm.

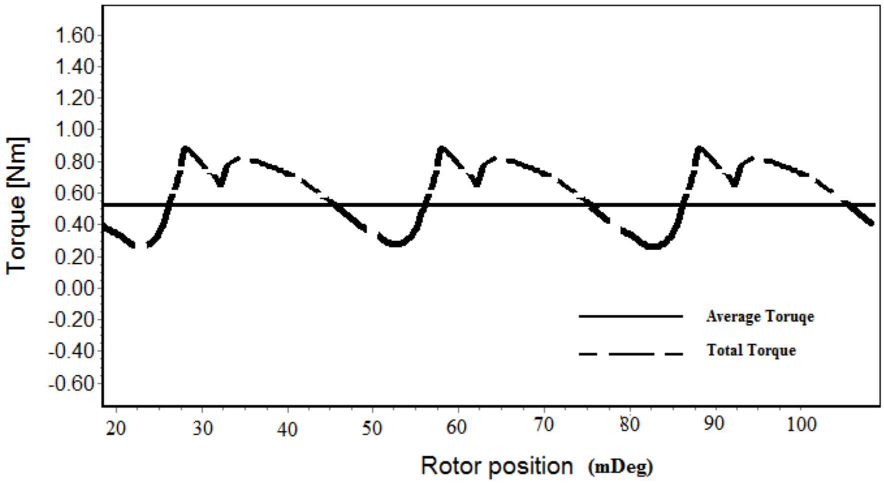


Figure 5.3: Original torque profile of 250 W, 6/4 pole, 12.8 V, 3600 rpm of SRM

By changing stator and rotor pole arc, changing turn on and turn off angle and tapered stator and rotor pole torque profile is improved which as shown in fig 5.4. The comparison of torque ripple obtained for original data & improved data is as shown Table 5.1.

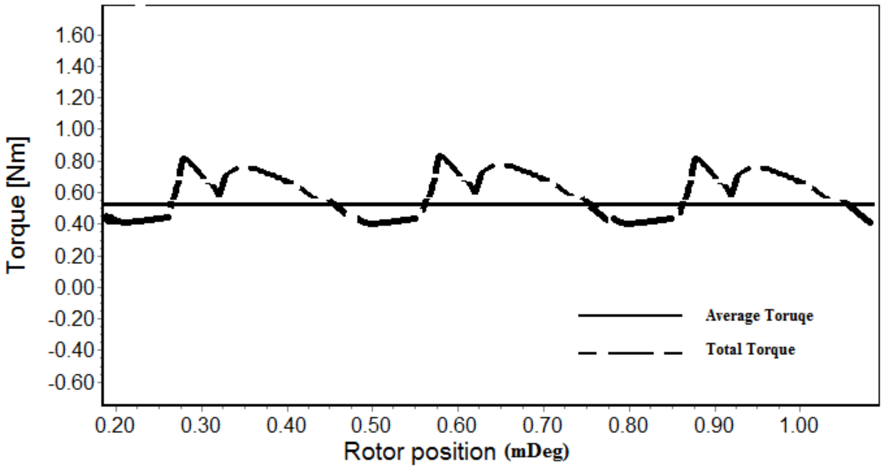


Figure 5.4: Improved torque profile of 250 W, 6/4 pole, 12.8 V, 3600 rpm of SRM

Table 5.1: Comparison of torque ripple obtained for original data & improved data

Parameter	Original	Improvement
No. of stator pole arc	30.13°	32.05°
No. of rotor pole arc	32.40°	34.02°
Turn on angle	40	44.03
Turn off angle	70	70
Average Torque Nm	0.56	0.56
Torque	89.28%	71.42%

B. Torque Ripple Minimization of 3.73 kW, 8/6 pole, 655 V, 1500 rpm of SRM

Torque Vs rotor position is shown in Fig 5.5 maximum instantaneous torque is 32 Nm and minimum instantaneous torque is 22.5 Nm. Average torque is 24.5 Nm.

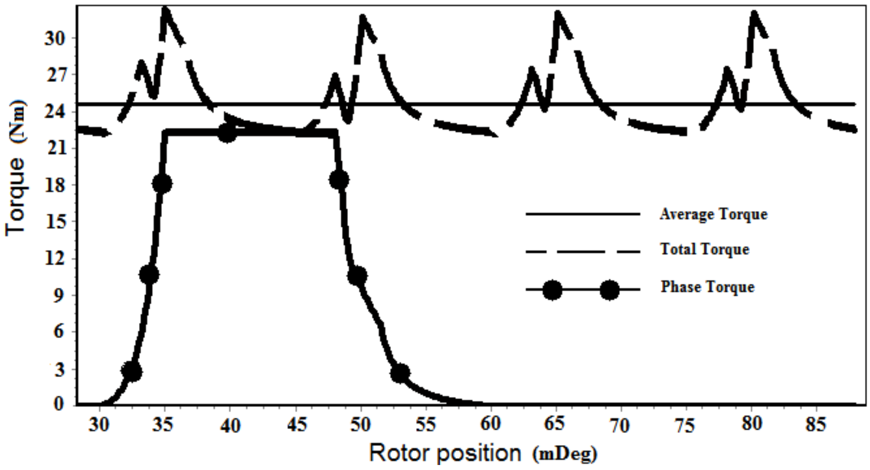


Figure 5.5: Original torque profile of 3.73 kW, 8/6 pole, 655 V, 1500 rpm of SRM

By changing stator and rotor pole arc, changing turn on and turn off angle and tapered stator and rotor pole torque profile is improved which as shown in below fig 5.6. The comparison of torque ripple obtained for original data & improved data is as shown Table 5.2.

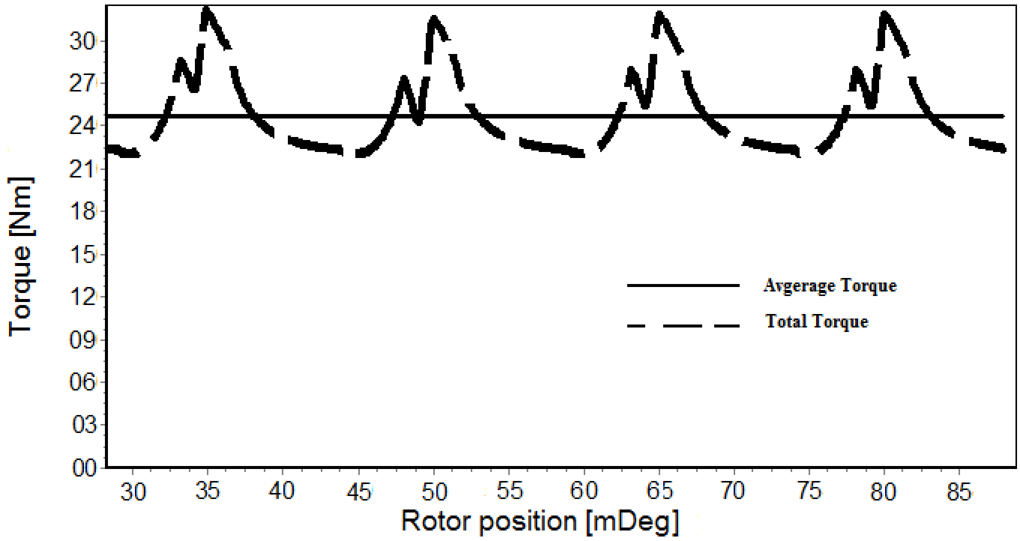


Figure 5.6: Improved torque profile of 3.73 kW, 8/6 pole, 655 V, 1500 rpm of SRM

Table 5.2: Comparison of torque ripple obtained for original data & improved data

Parameter	Original	Improvement
No. of stator pole arc	22°	22°
No. of rotor pole arc	26°	26.4°
Average Torque Nm	24.5	24.8
Torque ripple	38.77%	38.30%

C. Torque Ripple Minimization of 55 kW, 6/4 pole, 784 V, 3500 rpm of SRM

Graph of Torque Vs rotor position of the 55 kW, 6/4 pole, 784 V, 3500 rpm Switched Reluctance Motor (SRM) is as shown in below Fig 5.7. The graph is clearly shows that the maximum instantaneous value of the torque is 161 Nm and minimum instantaneous value of the torque is 45 Nm. So, the average value of the torque is 149.8 Nm.

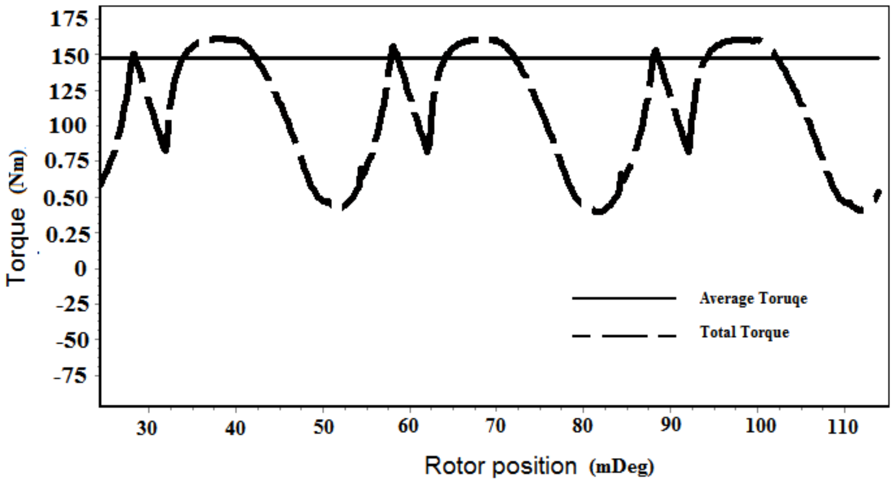


Figure 5.7: Original torque profile of 55 kW, 6/4 pole, 784 V, 3500 rpm of SRM

By changing stator and rotor pole arc, changing turn on and turn off angle and tapered stator and rotor pole torque profile is improved which as shown in fig 5.8. The comparison of torque ripple obtained for original data & improved data is as shown Table 5.3.

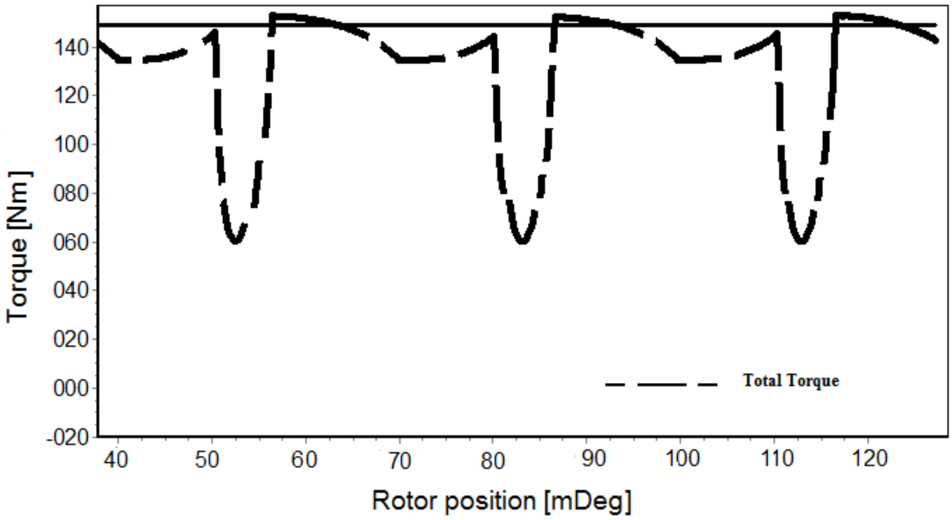


Figure 5.8: Improved torque profile of 55 kW, 6/4 pole, 784 V, 3500 rpm of SRM

Table 5.3: Comparison of torque ripple obtained for original data & improved data

Parameter	Original	Improvement
No. of stator pole arc	30°	31.8°
No. of rotor pole arc	32°	33.45°
Turn on angle	24.20	37.5
Turn off angle	69.90	83.55
Average Torque Nm	149.8	150
Torque	77.43%	61.33%

Above graph shows improved torque profile of 55 kW, 784 V, 6/4 pole, 3500 rpm of Switched Reluctance Motor.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

A procedure for the design of a SRM has been described. Selection of values through simple analytical techniques has been carried out. The material which is used in yoke and poles of stator and rotor are chosen to get desired efficiency. The calculations of inductance is done according to different flux paths for aligned and unaligned inductance position of rotor. The CAD programming is done for SRM and it is appropriately validated for three different motor ratings. The data obtained from CAD program for 250 W, 3.73 kW and 55 kW SRM is used as input data using speed software and its analysis is carried out. It is also observed that results from CAD shows good agreement with the results obtained from Speed Software. From above results it is observed that Core loss, copper loss and efficiency are calculated and verified. Average values of electromagnetic torque and phase current obtained from waveforms matches with the rated values of motor and in turn this values are fairly matching with output of CAD Program. The torque ripple minimization method for SRM is applied successfully. After detailed analysis of the modified models, based on the result the techniques are validated.

6.2 Future Work

Detailed analysis to enhance the performance with regards to efficiency of Switched Reluctance Motor (SRM).

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[11] R.T.Naayagi , V.Kamaraj ”Optimum pole arcs for Switched Reluctance Machine with reduced ripple”-IEEE Transactions on Volume:39,2005

[12] Bingni Qu , Jianbin Zheng ”Torque Ripple Minimization in Switched Reluctance Machine by Pole Arcs Design”-IEEE Transactions,2009

Appendix A

List of Publication

[1] Tejas H. Panchal, Amit N. Patel, Khushbu B. Shah:"Sizing and Finite Element Analysis of Switched Reluctance Motor". Published in International Journal of Computer Applications in Engineering Sciences, ISSN: 2231-4946, VOL V, Issue I, JAN-MAR 2015,pp.6-9.