People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
University Amar Telidji- Laghouat

FACULTY: Technology.

DEPARTMENT : Electrotechnic.

MASTER THESIS

Presented by: GUENANE Malek

KERBOUB Mohammed Otmane

DOMAIN: Sciences and Technologies.

SECTOR : Electrotechnic.

OPTION : Electromechanic.

Theme

Modeling and Simulation of Switched Reluctance Motor using Matlab Environment

Submitted on: September 29th, 2020

Jury members :

AMEUR Aissa	Prof	President
BESSEDIK Sid Ahmed	MCA	Examiner
HADJADJ Merouane	MCB	Supervisor
DJEKIDEL Rabah	MCA	Co-supervisor

Promotion 2020

Acknowledgments

No one is perfect and no work is made by a single man.

We would like to dedicate our special thanks to our great supervisors both, Dr. HADJADJ Merouane and Dr. DJEKIDEL Rabah for their endless patience and support which helped us to finish our Master thesis during this difficult times of the coronavirus pandemic. We will never forget their teaching method, that was an inspiration of new experiences.

Must also express our gratitude to all family members, my brother Guenane Farouk and Ferhat Khadidja and the Guendouz brothers Ayoub and Oussama and all of their family members, and to all Ameur family members.

To Mr.Miloudi Elaid, thank you for what you for your dedication and patience during the difficult time of yours. Thank you for all what have done for us.

A special thanks to all friends, Boukhelkhal Kouider, Assameur Tahar, Khachba Messaoud, Rezoug Abdelmadjid, Badreddine Ayoub, Benziane Taha, Lagraa Ghazali and Merad Abdelatif .

To my dear friends Chikhi Moulay Tayeb, Talebahmed Yacine, Boumaaza Bouziane, Allout Abdeslam, Houidane Abdennacer and Bouaakaz Yacine (the order is by the birthdate), you were and still part of my life, both of heart and mind is your home.

To all of our teachers, thank you.

An infinite appreciation goes to our mothers and fathers and to the special grandmothers for their endless support and prayers.

Last but not least, this work is dedicated to you Guendouz Ben Youcef, for all your love and care and support during our childhood and other lifetimes, you were the loving father, the dear uncle, The good brother and the best friend that anyone could want, you were all those .

A lot of thanks and gratitude is not enough for all what you have done for us in our lives, we cannot give you your right, but god can.

Until we meet again, may god help us and have mercy on your soul.

Abstract

This master project consists mainly of two parts, the first part reviews and describes the basic classification of switched reluctance motor, SRM categories, converters, control strategy, and a mathematical approach for modeling the dynamics of switched reluctance motor. This part means to help to understand the working principle and properties of SRM.

The second part of the project describes the simulation of SRM and its control drives based on matlab environment. All simulation results are shown in this part. The simulation results for the specific SRM 6/4 are discussed, and then the current control and speed control are applied, and finally this work ending by a general conclusion.

Key words : switched reluctance motor, modeling the dynamics, control, simulation, matlab environment .

Résumé

Ce projet de mastère se compose principalement de deux parties, la première partie passe en revue et décrit la classification de base du moteur à réluctance commutée, les catégories MRC, les convertisseurs, la stratégie de contrôle et une approche mathématique pour la modélisation de la dynamique du moteur à réluctance commutée. Cette partie vise à aider de comprendre le principe de fonctionnement et les propriétés de MRC.

La deuxième partie du projet décrit la simulation de MRC et de ses commandes de contrôle basées sur matlab environnement. Tous les résultats de la simulation sont présentés dans cette partie. Les résultats de la simulation pour le MRC 6-4 spécifique sont discutés, puis la commande de courant et la commande de vitesse sont appliquées, et enfin le travail se termine par une conclusion générale.

Mots clés: moteur à réluctance commutée, modélisation de la dynamique, contrôle, simulation, matlab environnement.

ملخص

يتكون مشروع الماستر هذا بشكل أساسي من جزأين ، الجزء الأول يستعرض ويصف التصنيف الأساسي لمحرك الممانعة المبدلة وفئات م م م ، والمحولات ، واستراتيجية التحكم ، والنهج الرياضي لنمذجة ديناميكيات محرك الممانعة المبدلة .يعني هذا الجزء المساعدة في فهم مبدأ العمل وخصائص م م م.

يصف الجزء الثاني من المشروع محاكاة م م م وأوامر التحكم الخاصة به بناءً على بيئة ماتلاب . يتم عرض جميع نتائج المحاكاة في هذا الجزء. تمت مناقشة نتائج المحاكاة لـ م م م 6/4 المحدد ثم يتم تطبيق تحكم التيار والتحكم في السرعة ، وأخيراً الاستنتاج.

الكلمات المفتاحية: محرك الممانعة المبدلة ، نمذجة الديناميكيات ، التحكم ، المحاكاة ، بيئة ماتلاب.

Abbreviations

SRM: Switched Reluctance Motor

VRM: variable reluctance motor

EMF : electromotive force

MMF: magneto motive force

CCW: counter clock wise

PM : permanent magnet

AC : alternative current

DC: direct current

DSP: digital signal processors

FEA: finite element analysis

DITC: direct instantaneous torque control

IGBT: insulated-gate bipolar transistor

PWM: pulse width modulation

SR: switched reluctance

Table of content

Acknowledgments II
Abstract III
Abbreviations V
Table of content VI
List of figures IX
List of tables XII
General Overview of Switched Reluctance Machines 1
Chapter I: A Brief Introduction and a Literature Review of SRM 3
I.1. HISTORY 4
I.2. INTRODUCTION 4
I.3. SWITCHED RELUCTANCE MOTOR TOPOLOGIES 5
I.3.1. Single phase motor 6
I.3.2. Two Phase Motor 6
I.3.3. Three Phase Motor 7
I.3.4. Four Phase Motor 7
I.3.5. Five and More Phase Motor 8
I.4. GENERAL OPERATION PRINCIPLES OF THE SWITCHED RELUCTANCE MOTOR 8
I.4.1. Elementary operation of the switched reluctance motor 10
I.4.2. Basic Switched Reluctance Motor Principles 11
I.4.2.1 The Aligned Position (La) 14
I.4.2.2. Intermediate Rotor Positions (Lint) 14
I.4.2.3. The Unaligned Position (Lu) 14
I.4.2.4. SRM Constructions 14
I.4.2.5. Torque – Speed Characteristics 15
I.5. CONCLUSION 17
Chapter II: SRM Mathematical Model 18
II.1. INTRODUCTION 19
II.2. MATHEMATICAL MODEL OF SWITCHED RELUCTANCE MOTOR 19
II.3 BASIC CIRCUITS ANALOGY 20

II.2.1. Inductance 21
II.2.2. Operation of this SRM 22
II.4. EQUIVALENT CIRCUIT OF SWITCHED RELUCTANCE MOTOR 30
II.4.1.Mathematical modeling of switched reluctance machines 30
II.4.1.1 Nonlinear characteristics of switched reluctance machines 30
II.4.1.2 Magnetization curves 37
II.5. CONCLUSION..38
Chapter III: SRM Drive and Simulation Results 39
III.1. INTRODUCTION 40
III.2. CONVERTER STRUCTURES FOR SRM 40
III.2.1. Utility Interface 42
III.2.2. Front-end Circuit 43
III.2.3. Power Converter..43
III.3. CONVERTER CLASSIFICATIONS OF SRM 44
III.3.1. SRM converter by phase switch...44
III.3.2. SRM converter by commutation 45
III.4. BASIC SRM CONVERTERS...46
III.4.1. Two-stage Converter 46
III.4.2. 1.5 Switch/Phase Converter 47
III.4.3. R dump Converter 48
III.4.4. C dump Converter 49
III.4.5. Asymmetric Bridge Converter 49
III.5. CLASSIC CONVERTER TOPOLOGY...50
III.6. CONTROL STRATEGIES 52
III.6.1. Voltage Control of SRM..54
III.6.2. Current Control of SRM 55
III.6.3. Direct Instantaneous Torque Control 56
III.7. SRM SIMULATION MODEL..57
III.7.1. Description of the SRM Model 57
III.7.2. Simulation Results of SRM Without Load 58
III.7.3. Simulation Analysis..62
III.7.4. Simulation results of SRM loaded with 100 N.m 63

III.8. SRM CURRENT CONTROL 66
III.8.1 Current Control Description 66
III.8.3. Simulation results of SRM current control 67
III.9. SRM SPEED CONTROL 71
III.9.1. SRM speed control description 71
III.9.2. Simulation results of SRM speed control 71
III.10. CONCLUSION 75
General Conclusion 76
GENERAL CONCLUSION 77
REFERENCES 79
APPENDIX A 82
APPENDIX B 83

List of figures

Figure I.1. Single phase with 4 rotor poles and 4 stator poles …………………………..........6
Figure I.2. Two phase with 2 rotor poles and 4 stator poles ………………….………..........7
Figure I.3. Three phase with 4 rotor poles and 6 stator poles ……………………….….........7
FigureI.4.geometries of 4 phase motor with 6 rotor poles and 8 stator poles ………………..... .8
Figure I.5. Switched reluctance motor configurations. ……..……………………………….... 10
Figure I.6. Operation of an SRM. (a)Phase c aligned. (b)Phase a aligned …….……………........11
Figure I.7. Three phase 6/4 switched reluctance motor …………………………….....…..12
Figure I.8. (a) Inductance and (b) torque in SRM ……………………………………...13
Figure I.9. The construction of SRM ………………………………………………..........15
Figure I.10. The torque speed of SRM ………………..…………….........………………….....16

Figure II.1. The electric and magnetic circuit ……………………..……………………..…...20
Figure II.2. Cross-section of a 6-4 SR motor (Phase A is at Aligned Position) ……..………...22
Figure II.3 Variation of coil inductance as a function position with linear materials ……….....23
Figure II.4. Variation of torque as a function position with linear materials ………….........24
Figure II.5. SR nonlinear flux – current plot ……………………………………...….............25
Figure II.6. Simplified SR flux current plot …………………………………………...…......27
Figure II.7. Torque zone for 6-4 SRM……………………………………………………..28
Figure II.8. Torque ripple and phases ……………………………………………………......29
Figure II.9. Equivalent circuit of SR motor ……………………………………….……….....31
FigureII.10.Graphic representation of magnetic flux linkage ………………………………......33
FigureII.11.Graphic representation of magnetic energy and co-energy for θ1 position …..…...34
FigureII.12.Graphic representation of magnetic energy and co-energy for θ2 position.. ……....35
FigureII.13.Graphic representation of coenergy variation between angles θ1 and θ2 ………....36

Figure III.1. Component block diagram of conventional SR drive …………...………………41
Figure III.2. Modules of SR Drive …………...…….……………………………………….42
FigureIII.3. Utility interface ……...………………………………………………….………42

Figure III.4. Classification of capacitive type front-end topology…………………………..….43
FigureIII.5.Active type of two capacitors network separated to DC-link ……..……………....44
FigureIII.6. SRM converter classification by phase switch ………..…………………………..45
FigureIII.7.SRM converter classification by commutation type……... ………………………46
Figure III.8. A block diagram of a two-stage converter ……...………………………………...47
Figure III.9. 1.5switch/phase converter….…………………………………………..............48
Figure III.10. R dump converter of SRM …………………………………………………....48
Figure III.11. C dump converter of SRM ……………………………………………………49
FigureIII.12. Asymmetric bridge converter of SRM ………..…………………………….…....49
Figure III.13. Connection of an asymmetric bridge to SRM …………..……………………....50
Figure III.14. Four-quadrant classic converter for a three-phase SRM ………………………..51
Figure III.15. Converter switching operation for motoring of phase A winding……………….52
Figure III.16. Closed-loop speed and current control block diagram of a SRM…………..…...53
Figure III.17. Voltage control technique….……...………………………….…………….…54
Figure III.18. Voltage and current profiles of voltage control technique………………………54
FigureIII.19. current control technique…..55
Figure III.20. Voltage and current profiles of current control technique…..............................56
Figure III.21. Block diagram of DITC...…….......57
Figure III.22. SRM model circuit…………………..……..……………………..….......58
Figure III.23. One phase flux linkage without load……………..……….………………........59
Figure III.24. One phase current without load…….……..……………………………….…....59
FigureIII.25. One phase current ripple without load……………..…..……………………...….60
Figure III.26. Output torque without load……….……………………………………..….......60
Figure III.27. Output torque ripple without load……...……………………………………..….61
FigureIII.28. Motor speed without load……………..………….……………………………….61
Figure III.29. One phase Flux linkage loaded………..…………………………………...……63
Figure III.30. One phase current loaded……..…………………………………………….…...64
Figure III.31. One phase current ripple loaded………..……………………………………...….64
Figure III.32. Output torque loaded……………...………………………………………….......65
FigureIII.33. Output torque ripple loaded………..………………………………………………65
Figure III.34. Motor speed loaded………..……………………………………………………..…66

FigureIII.35. SRM current control simulation circuit………..……………………………….…...67
Figure III.36. SRM phase currents with current control………..……………………………....68
Figure III.37. Current amplitude with current control…………..…………………………..…69
Figure III.38. Electromagnetic torque with current control……………..……………………....69
Figure III.39. Angular velocity with current control …………..……………………………….…...70
Figure III.40. Simulation circuit of SRM speed control …………..…………………….……...71
Figure III.41. SRM phase currents with speed control ……....………………………………...72
Figure III.42. One phase current with speed control …………..………………..………..…...72
Figure III.43. Reference and measured motor speed with speed control ……………………....73
Figure III.44. Rotor angle 74

List of tables

Table II.1**:** Circuits Analogy ………………………………..21

Table II.2**:** Common SRM Configurations …………………………………………….……….....30

General Overview of Switched Reluctance Machines

A reluctance machine is one in which torque is produced by the tendency of its moveable part to move to a position where the inductance of the exciting winding is maximized. This definition covers both switched and synchronous reluctance machines. The switched reluctance motor (SRM), also known as the variable reluctance motor (VRM) was established the mid 1838 but the motor could not realize its full potential until the modern development of the power electronics necessary for satisfactory control of SRM, were not patented until early 1970. The used as a locomotive traction motor. The switched reluctance motor has salient poles on both the rotor and the stator and operates like a variable-reluctance stepper motor except that the phase current is switched on and off when the rotor is at precise positions, which may vary with speed and torque. It is this switching, which gives the switched reluctance motor its name. SRM drives present several advantages as high efficiency, maximum operating speed, good performance of the motor in terms of torque/inertia ratio together with four-quadrant operation, making it an attractive solution for variable speed applications. The very wide size, power, and speed range together with the economic aspects of its construction will give the SRM place in the drives good family [1, 2].

This work focuses on the study of Switched Reluctance Motor. It presents a unified view of the machine and its drive system from all of its system and subsystem aspects. With a careful balance of theory and implementation, we will start to develop the analysis and control of SRMs from first principles, introduces a wide variety of power converters available for driving the SRM, and systematically presents some performance controllers.

The result of this work provides a state-of-the-art knowledge of SRMs, power converters, and their use with controllers. This thesis enables both students and engineers to learn all aspects of SRM drive systems and appreciate the interdependence of the various subsystems in performance optimization.

The purpose of this master thesis is to build a simulation model with MATLAB code for the SRM, to simulate its performance.

To fully understand the principle of SRM, a study literature review for SRM is necessary and very important.

This report has been divided into 3 chapters.

• **Chapter 1:** A brief introduction and a literature review of SRM;

• **Chapter 2:** SRM mathematical model; • **Chapter 3:** SRM drive and simulation results.

Chapter I: A Brief Introduction and a Literature Review of SRM

I.1. HISTORY

The guiding principle behind the SRM drive is that when a magnetically salient rotor is subject to the flow of flux in the magnetic circuit, it tends to move toward the position of minimum reluctance. This phenomenon has been known ever since the first experiments on electromagnetism. In the first half of the 19th century, scientists all over the world were experimenting with this effect to produce continuous electrical motion. A breakthrough came from W. H. Taylor in 1838, who obtained a patent for an electromagnetic engine in the United States. This machine was composed of a wooden wheel on the surface, on which was mounted seven pieces of soft iron equally spaced around the periphery. The wheel rotated freely in the framework in which four electromagnets were mounted. These magnets were connected to a battery through a mechanical switching arrangement on the shaft of the wheel such that excitation of an electromagnet would attract the nearest piece of soft iron, turning the wheel and energizing the next electromagnet in the sequence to continue the motion. However, the torque pulsations were the main drawback of this machine compared to DC and AC machines [3].

At the time, some experts viewed the technology as unfeasible, and practical application has been limited, partly because of control issues and unsuitable application, and because low production numbers result in higher cost [4].

But an others experts show that the Switched Reluctance Motors (SRM) are gaining interest in various applications such as electric vehicle driving system, starter-generators system, and power supply for aerospace applications, because of the many advantages that the SRMs have in comparison to other motors, including their low cost, durability, simple structure and robust construction [5].

I.2. INTRODUCTION

In recent years, much interest has been focused on the use of switched reluctance motors (SRM) in many application areas because of simple motor construction and unidirectional power inverter supply.

Improved magnetic material and advances in machine design have brought the SRM into the variable-speed drive market. Presently demand for SRM is increasing as they offer superior performance with lower price. Other than simplicity and low-cost machine manufacturing, the main motivation toward SRM use is the availability of low-cost power electronic switches, control electronic components, integrated circuits, microcontrollers, microprocessors, and digital signal processors (DSP) [3, 6-7].

In other words, the performances of SRM strongly depend on the applied control. Three main parts can be identified: the motor itself, the power electronic converter, and the controller. The drive system, comprising signal processing, power converter, and motor must be designed as a whole for a specific application.

There is one converter unit per phase. A battery or a rectifier supplies the DC power. The basic principle is simple: each phase is supplied with DC voltage by its power electronic converter unit as dictated by the control unit, developing a torque, which tends to move the rotor poles in line with the energized stator poles in order to maximize the inductance of the excited coils. An important fact is that the torque production is independent of the direction of current, which contributes to the reduction of the number of switches per phase [2-3, 6-7].

I.3. SWITCHED RELUCTANCE MOTOR TOPOLOGIES

As any other motor, the structure of SRM consists of a stator and a rotor. Both stator and rotor are laminated. Stacking the laminations punched from steel lamination with high magnetic quality yields the rotor cores. The stator is formed from punched laminations too bonded into a core, and the coils are placed on each of the stator poles. Each stator pole carries an excitation coil, and opposite coils are connected to form one "phase". There are no windings on the rotor. Paper [8] was presents a novel rotor structure optimized by using the level set method to improve the static torque characteristics of a high speed SRM. It was reported that segmented rotor construction improves the torque output and efficiency. Paper [9-10] discusses a SRM with segmented rotor construction designed for direct drive application. Such a motor has an outer rotor. It is found that in such motors, the torque output increases when there are higher number of rotor segments than stator poles.

SRM can offer a wide variety of aspect ratios and salient pole topologies without affecting performance too much. This means that each application is likely to be better suited for a specific switched reluctance topology.

Paper [10] investigates the influence of physical size of SRM on its output performance, the comparison of magnetic characteristics and energy conversion loops of three SRMs that the output capability of SRM will be reduced in different ways as the motor size is reduced.

I.3.1. Single phase motor

These are the simplest SRM having the advantage of fewest connections between motor and power electronics. For this motor, the quantities of the rotor poles are the same as the stator poles. The disadvantages lie in very high torque ripple and inability to start at all angular positions. Maybe attractive for very high speed applications, but starting problems may preclude their use. Figure I.1 shows the geometries of single phase motor with 4 rotor poles and 4 stator poles [11].

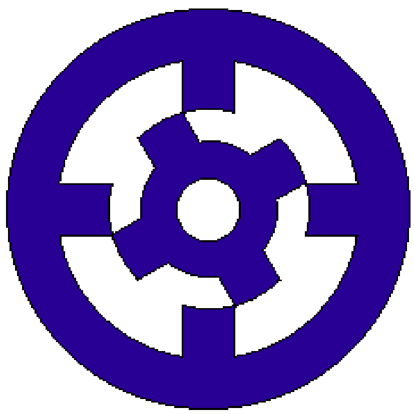


Figure I.1. Single phase with 4 rotor poles and 4 stator poles [11]

I.3.2. Two Phase Motor

Problems of starting compared with single phase machines can be overcome by stepping the air-gap, or providing asymmetry in the rotor poles. This machine may be of interest where the cost of winding connections is important, but again high torque ripple is an important drawback. Figure I.2 shows the geometries of 2 phase motor with 2 rotor poles and 4 stator poles [11].

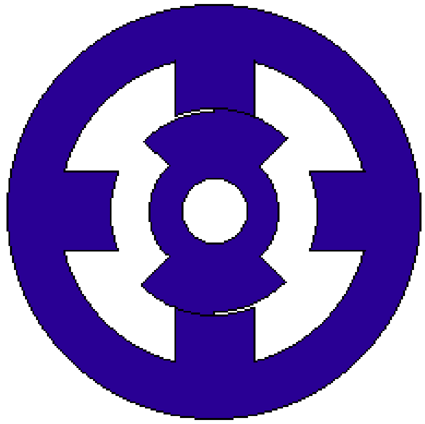


Figure I.2. Two phase with 2 rotor poles and 4 stator poles [11]

I.3.3. Three Phase Motor

The most popular topology of a three phase is the 6/4 form (stator poles = 6 and rotor poles = 4). It represents a good compromise between starting and torque ripple problems and number of phases. Alternative three phase motors with doubled-up pole numbers can offer a better solution for lower speed applications.But again watch-out for torque ripple especially in the voltage control single-pulse operating mode. Figure I.3. shows the geometries of 3 phase motor with 4 rotor poles and 6 stator poles [11].

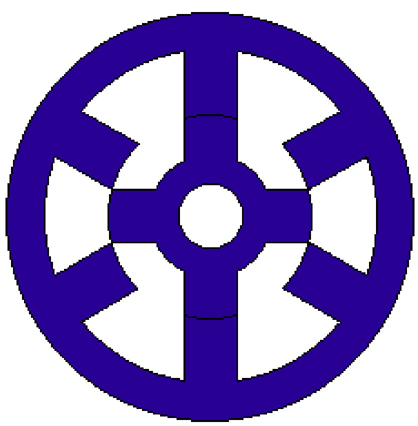


Figure I.3. Three phase with 4 rotor poles and 6 stator poles [11]

I.3.4. Four Phase Motor

The four phase motor is known for reducing torque ripple. The large number of power electronic devices and connections is a major drawback, limiting four phase motors to a specific application field. A practical limitation to consider larger phase numbers is the increase of the converter phase units, hence of the total cost. On another side, Five- and six-phase motors can offer better torque ripple reduction compared with four-phase and three-phase. Figure I.4. shows the geometries of 4 phase motor with 6 rotor poles and 8 stator poles.

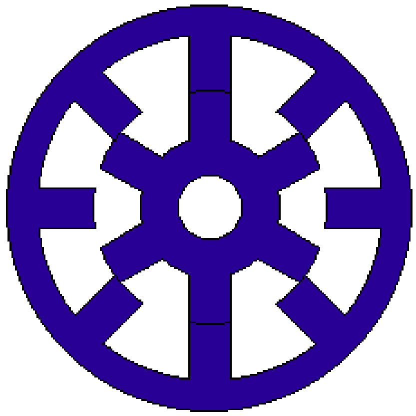


Figure I.4. Shows the geometries of 4 phase motor with 6 rotor poles and 8 stator poles [11].

I.3.5. Five and More Phase Motor

Generally, increasing the number of SRM phases reduces the torque ripple, but at the expense of requiring more electronics with which to operate the SRM. At least two phases are required to guarantee starting, and at least three phases are required to insure the starting direction. The number of rotor poles and stator poles must also differ to insure starting.

Paper [12] presents a technique that uses is performed to develop a new 8-6 pole switched reluctance motor (SRM) in order to improve the magnetic field energy and torque production; and describes the differences of standart 8/6-pole SRM and that newly developed SRM in dynamic characteristics such as magnetic field energy and torque production. In this paper, the finite element analysis (FEA) was used to obtain the nonlinear magnetisation data for application to the modelling.

I.4. GENERAL OPERATION PRINCIPLES OF THE SWITCHED RELUCTANCE MOTOR

A variable reluctance motor has been proposed for variable speed applications. Even though this machine is a type of synchronous machine, it has certain novel features. It has wound field coils of a dc motor for its stator windings and has no coils or magnets on its rotor. Both the stator and rotor have salient poles, hence the machine is referred to as a doubly salient machine. This is the main difference with conventional motors like DC or induction motors which have rotor windings or permanent magnets.

Various options of rotor and stator poles may be used. By increasing the number of phases the torque ripple can be reduced, but more electronic will be needed increasing the whole solution price. A compromise has to be chosen knowing that different number of rotor and stator poles and a minimum of two phases are necessary to start the motor, and three phases to choose the starting direction [1-2].

Such a typical machine is shown in Figure I.5a with, and a modified version of two teeth per pole is shown in Figure I.5b. The rotor is aligned whenever diametrically opposite stator poles are excited. [2]. In a magnetic circuit, the rotating member prefers to come to the minimum reluctance position at the instance of excitation. While two rotor poles are aligned to the two stator poles, another set of rotor poles is out of alignment with respect to a different set of stator poles.

The motor windings are in series with each main power switching device. Then, this set of stator poles is excited to bring the rotor poles into alignment. Likewise, by sequentially switching the currents into the stator windings, the rotor is rotated. The movement of the rotor, hence the production of torque and power, involves switching of currents into stator windings when there is a variation of reluctance; therefore, this variable speed motor drive is referred to as a switched reluctance motor drive [2]

We conclude, the guiding principle behind the SRM drive is that when a magnetically salient rotor is subject to the flow of flux in the magnetic circuit, it tends to move toward the position of minimum reluctance.

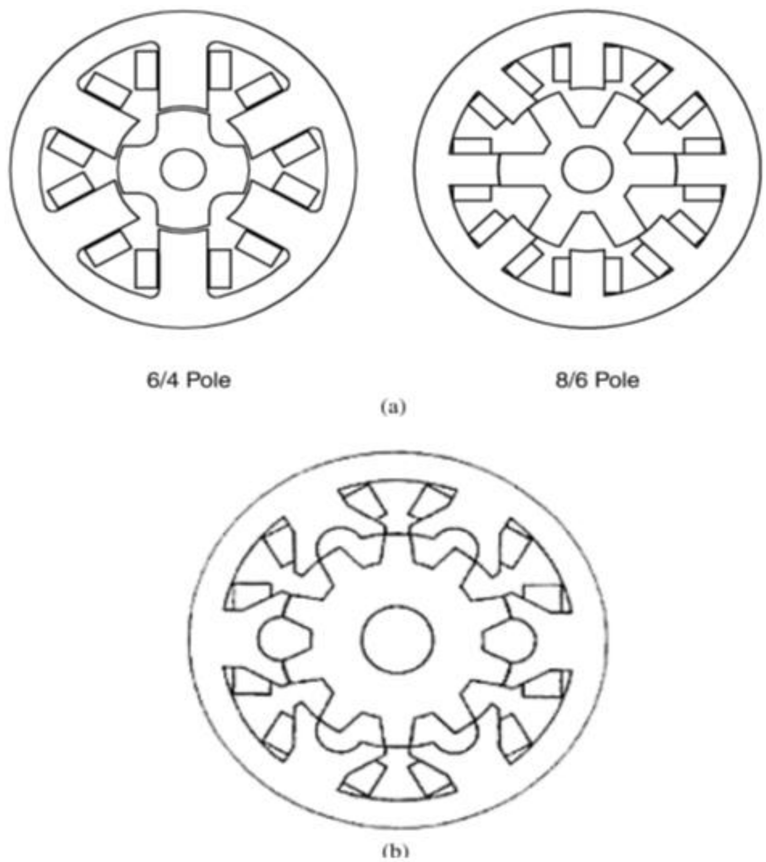


Figure I.5. Switched reluctance motor configurations [2].

.

The stator windings for SRM are concentrated coils, wound over one stator tooth and are designed with either 3, 4 or 5 phases, making them robust and fault tolerant. Single-phase and two-phase designs suffer from high torque ripple and starting issues. Additionally, unlike most rotating machines, the stator and rotor of an SRM will have a different number of poles. The pole counts are usually designated by stator poles / rotor poles. For example, a machine with 6 stator poles (Ns) and 4 rotor poles (Nr) would commonly be designated as a 6/4 machine.

I.4.1. Elementary operation of the switched reluctance motor

Consider that the rotor poles **(r_1)** and **(r_1')** and stator poles **(c)** and **(c_1')** are aligned. Apply a current to phase **(*a*)** with the current direction as shown in Figure I.6a. A flux is established through stator poles **(a)** and **(a')** and rotor poles **(r_2)** and **(r_2')** which tends to pull the rotor poles **(r_2)** and **(r_2')** toward the stator poles **(a)** and **(a')**, respectively. When they are aligned, the stator current of phase ***(a)*** is turned off and the corresponding situation is shown in Figure I.6b. Now the stator winding ***(b)*** is excited, pulling **(r_2)** and **(r_2')** toward **(b)** and **(b')** in a clockwise direction. Likewise, energization of the ***(c)*** phase winding results in the alignment of **(r_2)** and **(r_2')** with **(c)** and **(c')**, respectively. Hence, it takes three phase energizations in sequence to move the rotor by 90^0 and one revolution of rotor movement is effected by switching currents in each phase as many times as there are number of rotor poles. The switching of currents in the sequence acb results in the reversal of rotor rotation is seen with the aid of Figures I.6a. and b [2].

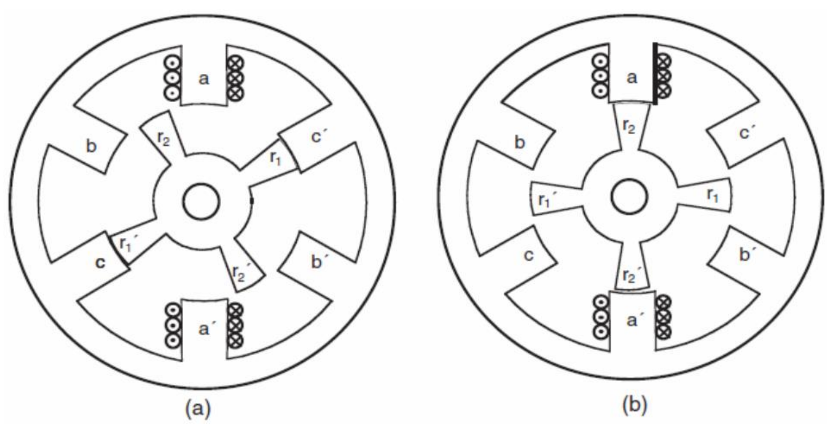


FIGURE I.6. Operation of an SRM. (a) Phase c aligned. (b) Phase a aligned [2]

I.4.2. Basic Switched Reluctance Motor Principles

The SRM is an electric machine that converts the reluctance torque into mechanical power. The basic operating principle of the SRM is quite simple: as current is passed through one of the stator windings, torque is generated by the tendency of the rotor to align with the excited stator pole. The direction of torque generated is a function of the rotor position with respect to the energized phase, and is independent of the direction of current flow through the phase winding. Continuous torque can be produced by intelligently synchronizing each phase's excitation with the rotor position.

In order to operate this machine, we must use power electronic switches. According to the operating principle of the switched reluctance motor, the current flowing in the motor is unipolar

(Can be driven bipolar especially if fully pitched wound where torque is produced by the change in mutual reluctance rather than self-reluctance). for this purpose, we can used a single-ended converters, but the favourite is the two-transistor forward converter topology (asymmetric half-bridge) which has two power switches connected to either end of the power rails and in series with a winding for fluxing the machine and two diodes forming a return path. With modern devices in power electronics as IGBTs, this argument is largely irrelevant especially when compromises are made with respect to torque ripple and acoustic noise. There is a cost disadvantage over a MOSFET inverter since the inherent MOSFET anti-parallel diode cannot be used.

Figure I.7 illustrates the cross-section of a three phase 6/4 SRM, in which the coils of the pole winding are connected in series and *i* is the current of a single phase.

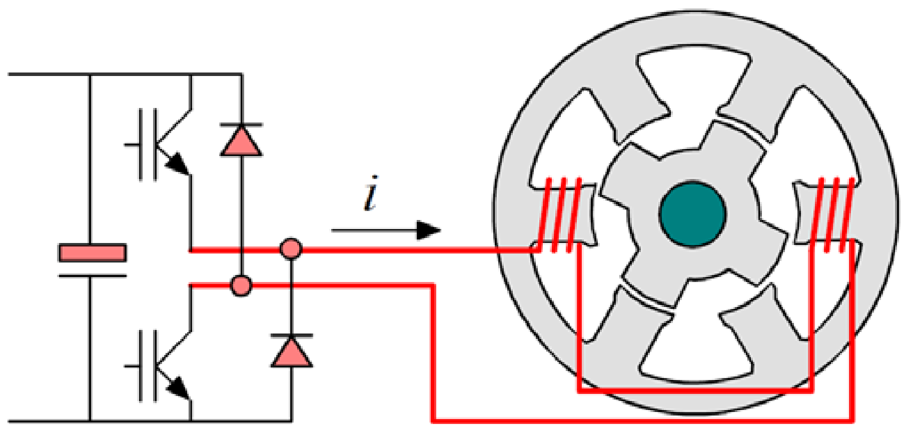
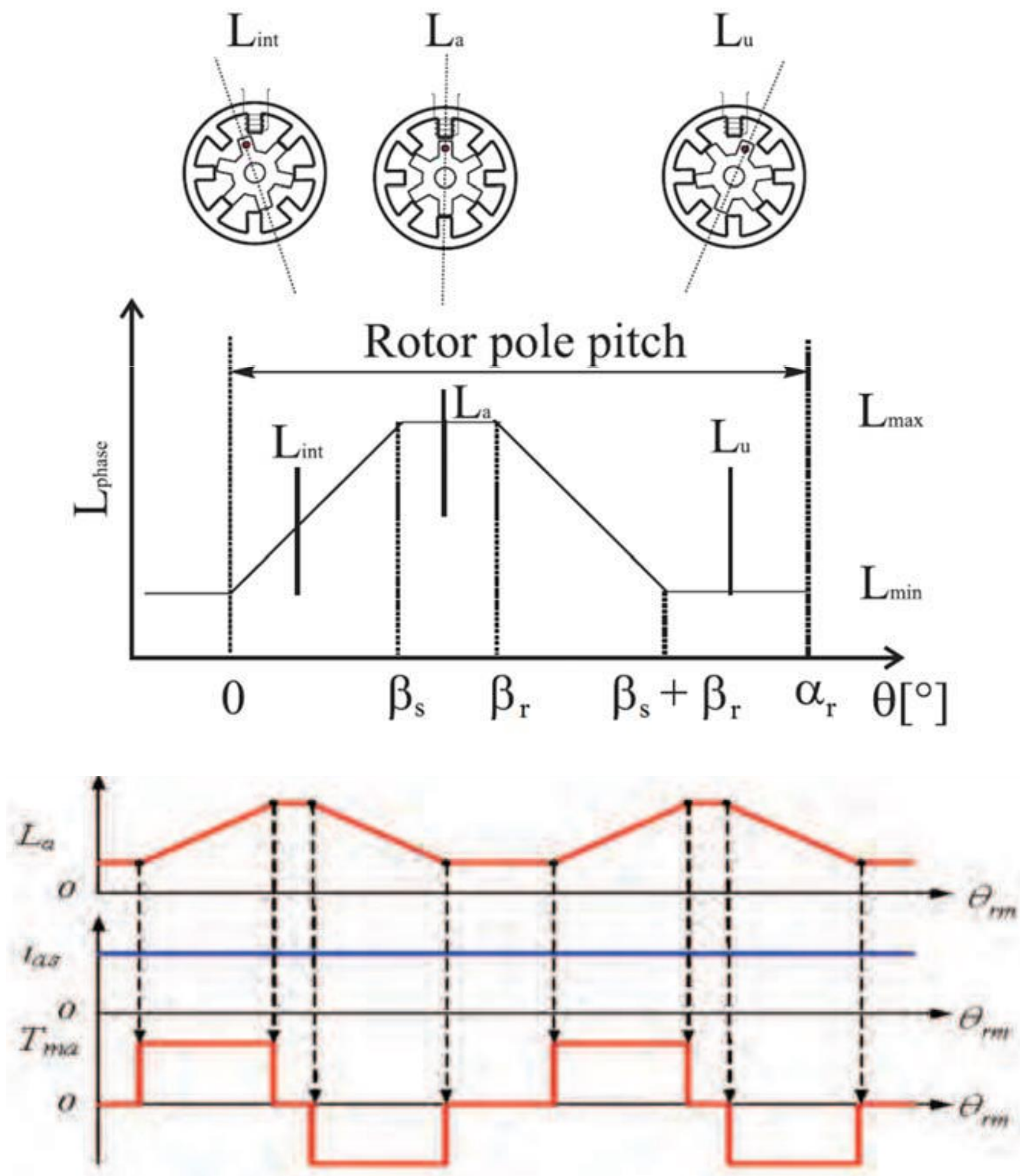


Figure I.7. Three phase 6/4 switched reluctance motor [13]

Although the concept of inductance is not valid for a highly saturated machine like SR motor, the unsaturated aligned and unaligned incremental inductances are the two key reference positions for the controller. The relationship between inductance and torque production according to rotor position is shown in Figure. I.8. there are some advantages of an SRM compared with the other motor type. The SRM has a low rotor inertia and high torque/inertia ratio; the winding losses only appear in the stator because there is no winding in the rotor side; SRM has rigid structure and absence of permanent magnets and rotor windings; SRM can be used in extremely high speed application and the maximum permissible rotor temperature is high, since there are no permanent magnets and rotor windings [13]

A torque is produced when one phase is energized and the magnetic circuit tends to adopt a configuration of minimum reluctance, i.e. the rotor poles aligned with the excited stator poles in order to maximize the phase inductance. As the motor is symmetric, it means that the one phase inductance cycle is comprised between the aligned and unaligned positions or vice versa as. shown in Figure. I.8.



(b)

Figure .I.8. (a) Inductance and (b) torque in SRM [13]

I.4.2.1 The Aligned Position (La)

Consider a pair of rotor and the stator poles to be aligned. Applying a current to phase establishes a flux through stator and rotor poles. If the current continues to flow through this phase, the rotor remains in this position, the rotor pole being "stuck" face to face to the stator pole. This position is called aligned position, and the phase inductance is at its maximum value (*Lmax* or *La*) as the magnetic reluctance of the flux path is at its minimum. [13]

I.4.2.2. Intermediate Rotor Positions (Lint)

At intermediate positions the rotor pole is between two stator poles. In this case the induction is intermediate between the aligned and unaligned values. If there is any overlap at all, the flux is entirely diverted to the closer rotor pole and the leakage flux path starts to increase at the base of the stator pole on one side.

I.4.2.3. The Unaligned Position (Lu)

In the unaligned position, the magnetic reluctance of the flux path is at its highest value as a result of the large air gap between stator and rotor. The inductance is at its minimum (*Lmin* or *Lu*). There is no torque production in this position when the current is flowing in one the adjacent phases. However, the unaligned position is one of unstable equilibrium. The aligned position of a phase is defined to be the situation when the stator and rotor poles of the phase are perfectly aligned with each other (βr-βs), attaining the minimum reluctance position and at this position phase inductance is maximum (*La*). The phase inductance decreases gradually as the rotor poles move away from the aligned position in either direction. When the rotor poles are symmetrically misaligned with the stator poles of a phase ($\beta s+\beta r$), the position is said to be the unaligned position and at this position the phase has minimum inductance (*Lu*). Although the concept of inductance is not valid for a highly saturated motor like SRM, the unsaturated aligned and unaligned incremental inductances are the two key reference positions for the controller. The relationship between inductance and torque production according to rotor position is shown in Figure I.8. [13].

I.4.2.4. SRM Constructions

Constructions of SRM with no magnets or windings on the rotor also bring some disadvantage in SRM. Since there is only a single excitation source and because of magnetic saturation, the power density of reluctance motor is lower than PM motor. The construction of SRM is shown in Figure.I.9. The dependence on magnetic saturation for torque production, coupled with the effects of fringing fields, and the classical fundamental square wave excitation result in nonlinear control characteristics for the reluctance motor. The double saliency construction and the discrete nature of torque production by the independent phases lead to higher torque ripple compared with other machines.

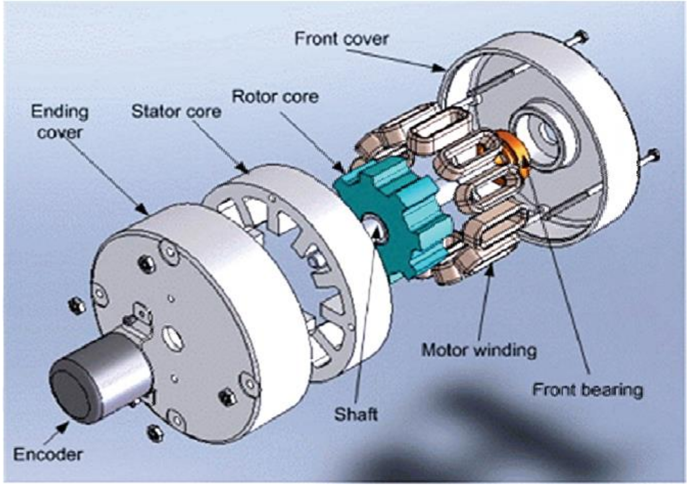


Figure .I.9. The construction of SRM

The higher torque ripple, and the need to recover some energy from the magnetic flux, also cause the ripple current in the DC supply to be quite large, necessitating a large filter capacitor. The doubly salient structure of the SRM also causes higher acoustic noise compared with other machines. The main source of acoustic noise is the radial magnetic force induced. So higher torque ripple and acoustic noise are the most critical disadvantages of the SRM. [13]

I.4.2.5. Torque – Speed Characteristics

The absence of permanent magnets imposes the burden of excitation on the stator windings and converter, which increases the converter kVA requirement. Compared with PM brushless machines, the per unit stator copper losses will be higher, reducing the efficiency and torque per ampere. However, the maximum speed at constant power is not limited by the fixed magnet flux as in the PM machine, and, hence, an extended constant power region of operation is possible in SRM. The torque-speed characteristics of an SRM are shown in Figure.I.10. Based on different speed ranges, the motor torque generation has been divided into three different regions: constant torque, constant power and falling power region. [13]

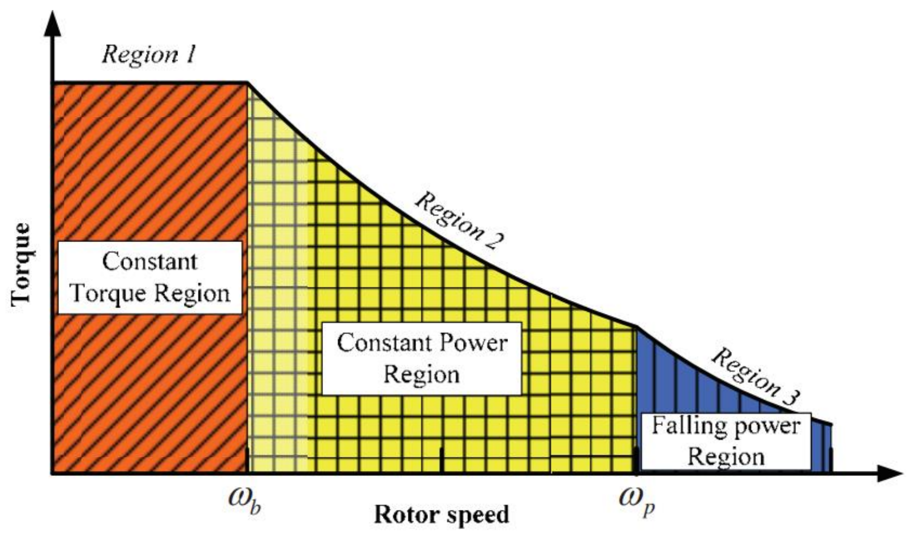


Figure. I.10. The torque speed of SRM

The base speed ω_b is the maximum speed at which maximum current and rated torque can be achieved at rated voltage. Below ωb, the torque can be maintained constant or control the fat-top phase current. At lower speed, the phase current rises almost instantly after the phase switches turn-on since the back EMF is small at this time. So it can be set at any desired level by means of regulators (hysteresis or PWM controller). Therefore, the adjustment of firing angle and phase current can reduce noise and improve torque ripple or efficiency. With speed increase, the back-EMF is increased. An advance turn-on angle is necessary to reach the desired current level before rotor and stator poles start to overlap. The desired current level depends on the speed and the load condition. At the same time, since no current chopping appears during the dwell angle, only the angle control can be used at this stage. So the torque cannot be kept constant and is falling linearly with the speed increase, resulting in a constant power production.

In the falling power region, as the speed increases, the turn-on angle cannot be advanced further. Because torque falls off more rapidly, the constant power cannot be maintained. As the speed grows, the tail current of the phase winding extends to the negative torque region.

The tail current may not even drop to zero. In the high speed operation, the continued conduction of current in the phase winding can increase magnitude of phase current and the power density can be increased [13]

I.5. CONCLUSION

A literature review is proposed in this chapter, it describes the vast topology and the general and basic operation of the switched reluctance motor, and brings the characteristics of the aligned and unaligned position for the rotor of this motor, its number of poles and other specifications of the machine.

Chapter II: SRM Mathematical Model

II.1. INTRODUCTION

As we mentioned in chapter I, the switched reluctance motor also known as the variable reluctance motor (VRM) originated in the mid1830s. As with any other rotating machine, a basic understanding of operating principles can be useful in troubleshooting and repair. One of the most critical things for service center personnel to understand upfront is that these machines cannot be operated without a special drive, which typically would need to be supplied by the end-user or the manufacturer [1]. The machines are structurally simple but can need relatively advanced control for optimum performance.

In this chapter, we will go to describe the mathematical model of switched reluctance motor (SRM). The simplified mathematical model was suitable to simulate the performance of the SRM system and to design its controller. The new simplified model was determined based on the assumption that the SRM phase inductance profiles have triangular waveforms with peak values that depend on the current through the windings when magnetic saturation occurs.

II.2. MATHEMATICAL MODEL OF SWITCHED RELUCTANCE MOTOR

With this new simplified model, we will go to determine the characteristics of SRM. For this study, we based on the assumption that the SRM phase inductance profiles have triangular waveforms with peak values that depend on the current through the windings when magnetic saturation occurs.

The speed and torque control strategy consisted of two simultaneous actions: voltage pulse width modulation (PWM) and adjustment of firing angles as a function of the desired motor speed. for this propose, we will go to simulate the characteristics of speed and torque control of the SRM system that was performed using the new simplified mathematical model.

Additionally, unlike most rotating machines, the stator and rotor of an SRM will have a different number of poles, the pole counts are usually designated by stator poles/rotor poles. For example, a machine with 6 stator poles (N_s) and 4 rotor poles (N_r) would commonly be designated as a 6/4 machine. [1]

Two of the most important characteristics to understand for operation or control of any type of rotating machine are rotational speed and torque. For the SRM, the rotational speed (n) depends on the operating frequency (f) and the number of rotor poles (N_r). If these two variables are known, calculating the rotational speed is straight forward. If we take an example of a 6/4 machine with an operating frequency of 133.33 Hz, the operating speed would be:

$$n = 60.\frac{f}{N_r} = \frac{133.33}{4} = 2000 \ (rpm) \tag{II.1}$$

To understand how the SRM produces torque, it is helpful, to begin with, a review of some basic circuits. [1]

II.3 BASIC CIRCUITS ANALOGY

When introducing magnetic circuits, an analogy is often used with basic electric circuits (see figure II.1). In this electric circuit, the voltage, also called electromotive force (EMF), drives a current (I) which is limited by the total resistance (R_1+R_2). In this magnetic circuit, the magnetomotive force (MMF) drives a magnetic flux (Φ) which is limited by the total reluctance ($\mathcal{R}_{core}$+$\mathcal{R}_{gap}$).

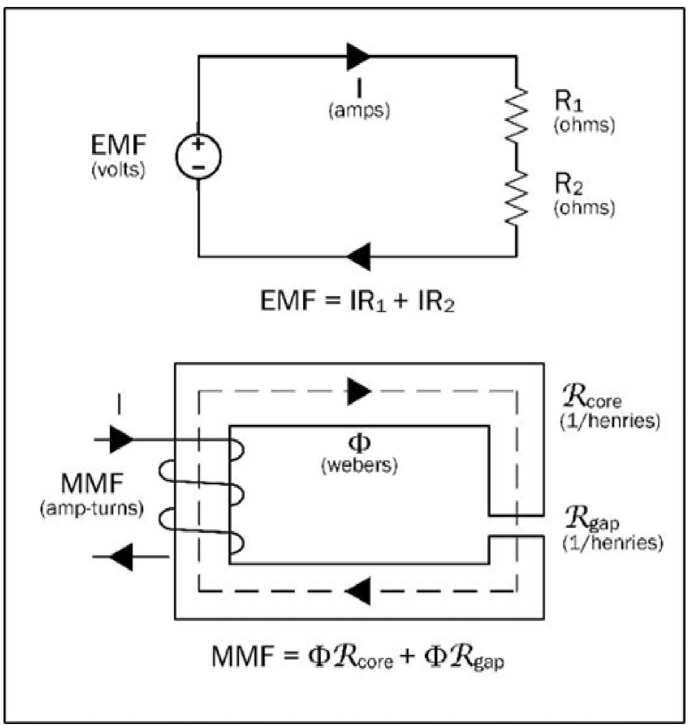


Figure. II.1. The electric and magnetic circuit [14]

For the electric circuit shown in figure (II.1) observe that if the resistance R_1 is much greater than the resistance R_2, the voltage drop due to R_1 will also be much greater than the voltage drop due to R_2. In the magnetic circuit, the same relationship is true. If the reluctance R_{gap} is much greater than the reluctance R_{core}, the MMF drop due to R_{gap} will be much greater than the MMF drop due to R_{core}. Just as with an electric circuit, steel is a much better conductor of magnetic flux than air. Also, as shown in table 1, note that the resistance of an electrical conductor and the reluctance of a magnetic path are both determined by the length (ℓ), cross-sectional area (A), and a factor based on the materials of construction (for electrical resistivity and magnetic permeability). [1]

- **Table II.1: Circuits Analogy**

Electric circuit	Magnetic circuit
EMF in volts	MMF in ampere-turn
Current in amperes	Flux in webers
Resistance in ohms $R = \rho\frac{\ell}{A}$	Reluctance in henries^{-1} $\mathcal{R} = \frac{\ell}{\sigma A}$

II.2.1. Inductance

An additional concept is needed to discuss torque production in the SRM conventionally. Assuming a magnetic circuit is not saturated, we can define an inductance (L), in terms of the number of turns (N) in a winding and the total reluctance ($\mathcal{R}_{total}$) of the magnetic circuit associated with that winding. Inductance is measured in henries (H) and winding inductance is usually small (mH).

$$L = \frac{N^2}{\mathcal{R}_{total}} \tag{II.2}$$

From this, one can see that high reluctance results in low inductance and vice versa. Additionally, the inductance changes with the number of turns squared – a small change in the number of turns result in a large change in the inductance [1].

By analogy, we can study the inductance variation of SMR. Such as the diagram of a switched reluctance motor is shown in Figure (II.2). An important point can be seen in the motor diagram.

The machine has 4 rotor poles and 6 stator poles, which is referred to as a 6-4 SR motor. Each stator pole has a concentrated coil wound on it (not shown in the figure). Two coils on the opposite stator poles are connected in serial or parallel, making one stator phase. There are no windings on the rotor, nor does the rotor have any permanent magnetic material. The stator and rotor are usually both made of laminated silicon steel to diminish Foucault’s current [14].

To develop the expressions of inductance variation and torque of this machine, in first we need to study their operation.

II.2.2. Operation of this SRM

Consider the motor design above. In the position shown, phase B will be excited. The magnetic field created by coil B will cause the rotor to rotate clockwise until two of the rotor poles align with the phase B poles. At this time, phase B can be de-energized and phase C turned on. The rotor will continue to rotate until it aligns with coil C. It should be noted that the magnetic field created by the stator is traveling counter-clockwise, but the rotor moves in a clockwise direction [15].

Calculation of power and torque can be carried out by considering the energy stored in the magnetic field, and the approach differs, depending on whether the operation can be considered as using a linear magnetic system or a saturating nonlinear magnetic material.

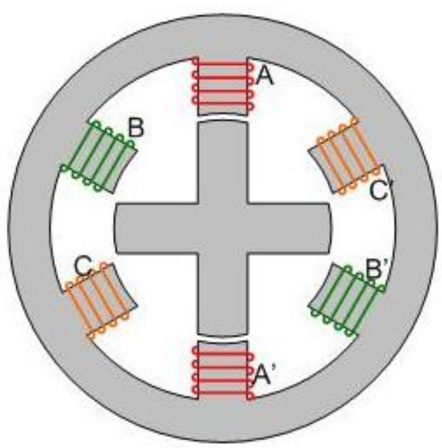


Figure II.2. Cross-section of a 6-4 SR motor (Phase A is at Aligned Position) [15].

A) Linear Analysis

Assuming that the motor doesn't saturate, linear analysis using inductance to find the stored energy is possible. Considering one coil, the inductance will vary approximately sinusoidally with the position, as shown in Figure (II.3). The inductance variation is periodic, depending on the number of rotor poles Pr [15.

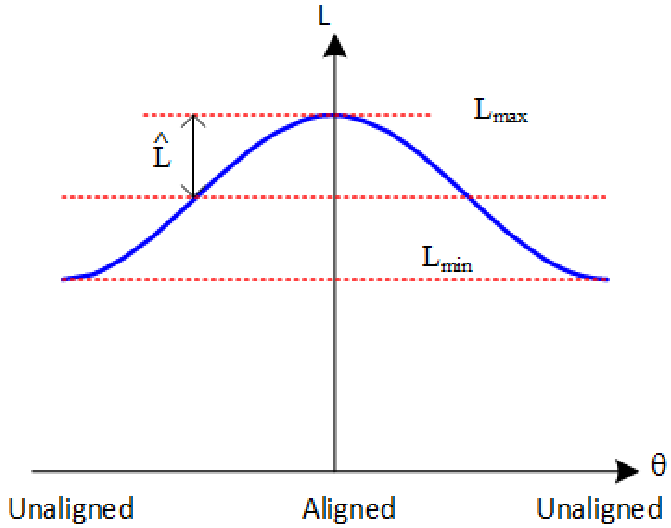


Figure II.3. Variation of coil inductance as a function position with linear materials [15]

The inductance can be written as:

$$L = \bar{L} + \hat{L}.\cos(Pr.\theta_m) \qquad (II.3)$$

$$\bar{L} = \frac{L_{max} + L_{min}}{2} \; ; \; and \quad \hat{L} = \frac{L_{max} - L_{min}}{2} \qquad (II.4)$$

If the coil is conducting current i then the energy stored in the magnetic field is given by:

$$W = \frac{1}{2}.L.i^2 \qquad (II.5)$$

Using the definition of torque as:

$$T = \frac{dW}{d\theta_m} \qquad (II.6)$$

Gives:

$$T = -\widehat{T}.\sin(Pr.\theta_m) \qquad (II.7)$$

$$\hat{T} = \frac{1}{2}.Pr.\hat{L}.i^2 \qquad (II.8)$$

Torque can be plotted as shown in Figure (II.4). Note that the torque waveform repeats Pr times every rotation, due to the symmetry of the rotor.

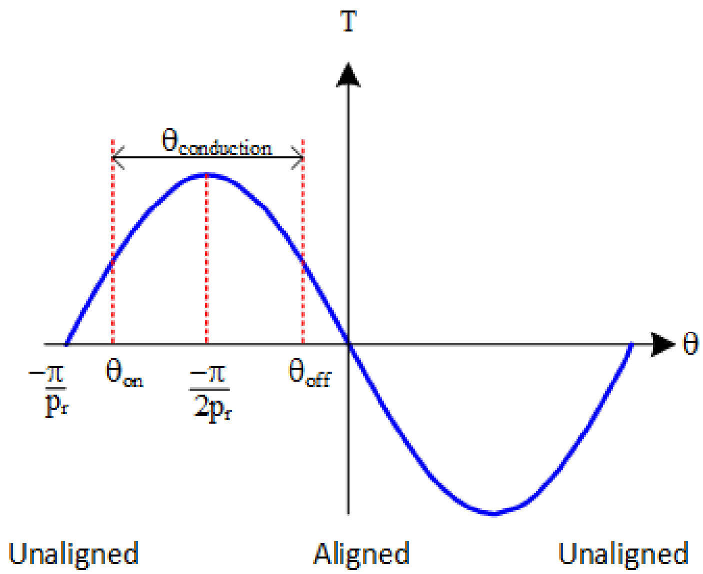


Figure II.4. Variation of torque as a function position with linear materials [15]

If the machine has Np phases, then each phase will conduct for 1/Np of the periodic rotation angle of 2π/Pr. Each stator coil conducts for a period of :

$$\theta_{conduction} = \frac{2\pi}{Pr.Np} \tag{II.9}$$

The peak torque occurs when the rotor pole is $\pi/2.Pr$ away from the rotor pole. For the torque when one phase is turned on to equal the torque when the previous phase is turned off, the turn-on and turn-off torques should be equal. Therefore each coil should conduct for an angle that is symmetric about the peak torque position. The current through a coil should be turned on when the rotor is at a position [16].

$$\theta_{on} = -\frac{\pi}{2.Pr} - \frac{\theta_{conduction}}{2} \tag{II.10}$$

And stop conducting at an angle:

$$\theta_{off} = -\frac{\pi}{2.Pr} + \frac{\theta_{conduction}}{2} \tag{II.11}$$

Relative to each pole. $\theta_{conduction}$, θ_{on}, and θ_{off} are angles in mechanical radians and can also be quoted in mechanical degrees.

For the case of a 3-phase 6-4 SR motor, $\theta_{conduction}$ = 30° , θ_{on} =37.5° and θ_{off} = -7.5°

The average torque T_{ave} can be found by integrating the torque over the conduction period:

$$T_{ave} = \frac{1}{\theta_{conduction}} \cdot \int_{\theta_{on}}^{\theta_{off}} -\hat{T}.\sin(Pr.\theta_m).d\theta \qquad \text{(II.12)}$$

B) Nonlinear Analysis

Unfortunately, many real machines operate in saturation, and analysis of energy stored using inductance is invalid. In this case, it is important to consider energy as the integral of current concerning flux [16]:

$$W = \int i.d\lambda \qquad \text{(II.13)}$$

In SR motor operation there are three distinct steps during a current cycle:

1. Current is turned on instantaneously (with no movement)
2. Current is held constant while the rotor moves
3. Current is switched off instantaneously (no movement)

These three stages are represented on the flux-current plot in Figure (II.5).

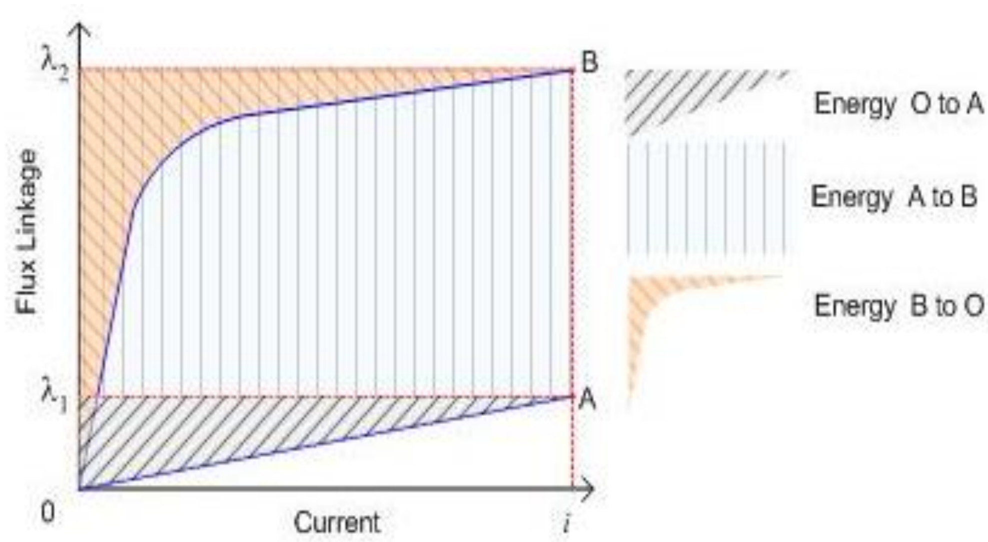


Figure II.5. SR nonlinear flux – current plot [15]

In a plot of flux vs current, the integral for energy is given by the area to the left of the flux-current plot. The integrals for the three distinct steps are shaded on the diagram.

1. Current increases from 0 to i_1, unsaturated, and flux increases to λ_1
2. Current is constant at i_1. As the rotor moves into alignment, the flux linkage increases to λ_2, and the iron in the machine becomes saturated.
3. Current is switched off. The stored energy from point (i_2, λ_2) is returned to the supply.

Net energy can be found from

$$W = W_1 + W_2 + W_3 \qquad \text{(II.14)}$$

Where the energy at each step is calculated using equation (II.13)

Note that in step 3, the integral will result in a negative value for *W3* as energy is returned to the supply. The total energy is equal to the area enclosed by the flux-current loop; a machine with a large enclosed area transfers more energy in a given switching cycle.

Average torque over one conducting period is given by

$$T_{ave} = \frac{W}{\theta_{conduction}} = \frac{W_1 + W_2 + W_3}{\theta_{conduction}} \qquad \text{(II.15)}$$

Power can be found from energy transfer over the time of the cycle.

$$P = T_{ave}.\omega_m = \frac{W}{t_{conduction}} \; ; \; \omega_m = \frac{\theta_{conduction}}{t_{conduction}} \qquad \text{(II.16)}$$

C) Linearized Approach

The nonlinear flux-current plot is often approximated as being made up from 4 straight lines as shown below. This makes a calculation of the stored energy much simpler.

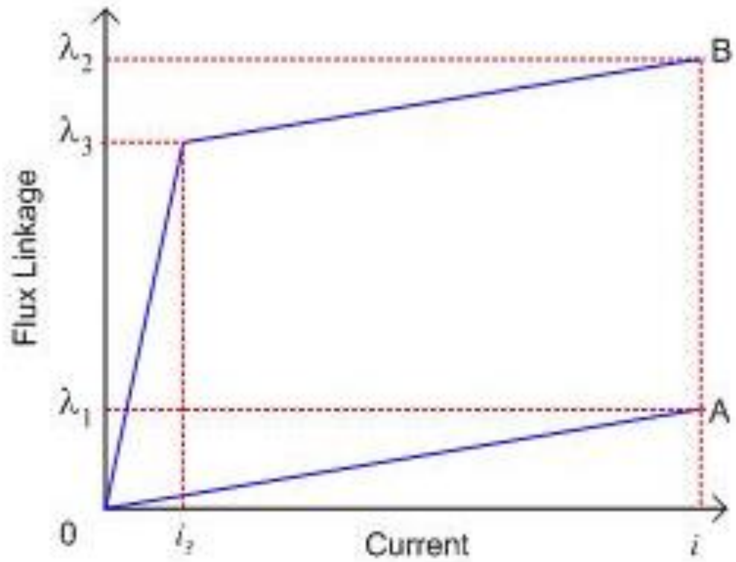


Figure II.6. Simplified SR flux current plot [15]

In Figure (II.6.):

$$W_1 = \frac{1}{2}\, i_1 \lambda_1 \tag{II.17}$$

$$W_2 = i_1 (\lambda_2 - \lambda_1) \tag{II.18}$$

$$W_3 = -\left(\frac{1}{2}\, i_3 \lambda_3 + \frac{1}{2} (i_1 - i_3) (\lambda_2 - \lambda_3) + i_3 (\lambda_2 - \lambda_3)\right) \tag{II.19}$$

D) Discussion

Let's look at a practical 6-4 machine which has three-phase windings, 6 stator poles, and 4 rotor poles,(see Figure II.2.) We will assume motoring operation in the counterclockwise (CCW) direction and isolate 1 phase winding, shown in red. When the stator pole is located directly between two rotor poles, this is called the unaligned position (see Figure II.7A.). In this position, inductance is at a minimum, and energizing the phase winding shown will produce no torque.

If the rotor is displaced from the unaligned position some CCW distance (see Figure II.7B.), a torque will be produced tending to align the closest rotor pole with the energized stator pole. The blue shaded region shown here is called the torque zone and this is the angle through which the phase winding shown will be energized. [1]

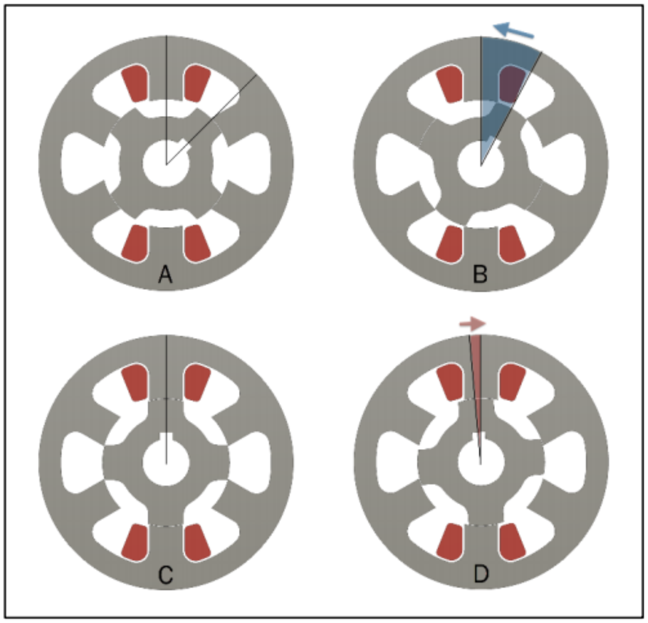


Figure II.7. Torque zone for 6-4 SRM [1]

The position shown in Figure II.7C is referred to as the aligned position. In the aligned position, inductance is maximum and there is no reluctance torque produced since the poles are aligned. Note that if this phase winding remained energized as the rotor passed through the aligned position as shown in Figure II.7D. the torque produced would act as a restoring torque, pulling the rotor backward in the clockwise direction until it returned to position figure II. 7C. So, just before the rotor reaches the aligned position, the phase winding shown would be de-energized and the next phase winding in the direction of rotation would be energized through its torque zone, continuing operation in the desired CCW direction. The average torque produced by the SRM through one torque zone depends on the winding current (i) and the change in the inductance (L_{max} - L_{min}) over the angle swept ($\Delta\theta$). This average torque can be expressed as:

$$T = \frac{1}{2}.i^2.\frac{L_{max} - L_{min}}{\Delta\theta} \qquad \text{(II.20)}$$

An important thing to note is that through the torque zone, the magnitude of inductance is not as important as the range of inductance. The range of inductance (L_{max} - L_{min}) is sometimes referred to as saliency. Additionally, the torque is proportional to the square of the current, if the core is not saturated. Unlike most stator windings, another interesting characteristic of the SRM is that the polarity of the winding does not affect the torque direction. [1] Torque ripple is a major issue in SRM design, as is the control of acoustical noise. This is a significant problem with single- and two-phase designs but it can be an issue with more phases as well. With three-phase machines, the pole widths must be chosen carefully to minimize this.

Figure II.8 demonstrates how torque ripple is reduced as the number of phases increased from three to five. This is very similar to adding more commutator segments per pole in a DC machine.

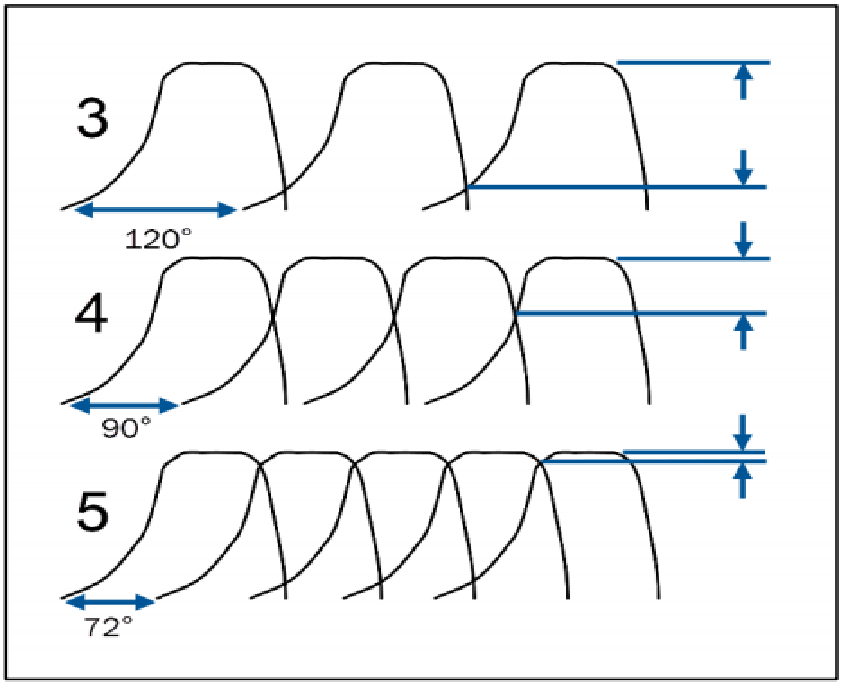


Figure II.8. Torque ripple and phases [1]

Aside from the reduction of torque ripple, using four or five phases has another advantage in that multiple phases can be energized for short periods. However, as the number of phases increases, the cost and complexity of the drive also increase. The number of stator poles (Ns) must be a multiple of the number of phases. Some common configurations are shown in table 2. Other options are possible, but these combinations are often found in practice. [1]

- **Table II.2**: Common SRM Configurations

Phases	Ns-Nr
3	6-2, 6-4, 6-8, 12-8, 18-12, 24-16
4	8-6, 16-12
5	10-4, 10-6, 10-8

To energize the appropriate phase winding while the rotor is within its torque zone as shown in Figure II.8., the rotor position must be known with great accuracy. This is most often done by using rotor position sensors such as encoders or Hall effect sensors, which add cost and decrease reliability. Sensorless control is of great interest to SRM designers and a common approach is to use the inductance and stator current to estimate flux linkage but operating with the core near or in saturation makes this challenging. [1]

II.4. EQUIVALENT CIRCUIT OF SWITCHED RELUCTANCE MOTOR

II.4.1.Mathematical modeling of switched reluctance machines

II.4.1.1 Nonlinear characteristics of switched reluctance machines

To simplify the analysis of the nonlinear characteristics intrinsic to SRMs, consider some simplifications:

1. The magnetic coupling between phases is negligible,
2. There are no Eddy current and hysteresis losses,
3. The phase resistance is constant,
4. The phase inductance depends on the rotor position and the phase current.

With the assumptions made, an elementary circuit of one SRM phase may be derived as in FigureII.9. The sum of the resistance voltage drop and the change rate of flux linkage must be equal to the applied voltage to a motor phase; thus equation. (II.21) can be derived, where V is the voltage applied to the phase, i is the phase current, R is the phase resistance, λ is the phase flux linkage, θ is the rotor position, and e is the back electromotive force [16].

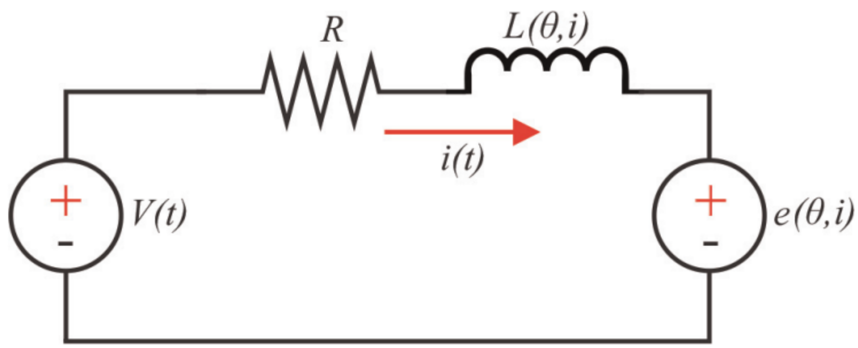


Figure II.9. Equivalent circuit of SR motor [16]

So, the linear analytical model of the SRM can be described by three differential equations, which can be classified as the voltage equation, the emotional equation, and the electromagnetic torque equation.

So in SRM, The applied voltage to a phase is equal to the sum of the resistive voltage drop and the rate of change of flux linkages as given below:

$$V = R\,.\,i + \frac{d\lambda(\theta, i)}{dt} \qquad (II.21)$$

So λ is Flux Linkage per Phase;

While excluding saturation and mutual inductance effects, the flux in each phase is given by the linear equation (II.22). Where λ can be expressed as the product of inductance and winding current:

$$\lambda(\theta, i) = L(\theta, i).\, i \qquad (II.22)$$

As well as, L is the inductance per phase dependent on the rotor position and phase current.

We can note that the phase inductance varies according to the rotor position, because of the reluctance variation, and according to the phase current due to the magnetic saturation. Furthermore, both the rotor position and the phase current may vary with time.

Substituting equation (II.22) into equation (II.21) and expanding, the phase voltage equation can be extended into equation (II.23) the voltage equation we can be rewritten as:

$$\begin{cases} V = R.i + L(\theta,i) . \dfrac{di}{dt} + i.\dfrac{dL(\theta,i)}{dt} \\ V = R.i + L(\theta,i) . \dfrac{di}{dt} + i.\dfrac{d\theta}{dt}\dfrac{dL(\theta,i)}{d\theta} \\ V = R.i + L(\theta,i) . \dfrac{di}{dt} + i.\omega\dfrac{dL(\theta,i)}{d\theta} \end{cases} \qquad (II.23)$$

In equation (II.23), the mechanical speed is given by the variation of the rotor position by time: $\omega = d\theta/dt$. Thus, note that the phase voltage is composed of three components. The first term is the voltage drop in the phase resistance, the second term is the voltage drop in the phase inductance, and the third term is the induced back electromotive force, or back-emf (***e***). The back-emf (***e***) is highlighted in equation (II.24) to focus on the perception of the direct relationship between the rotor speed and the back-emf(***e***) [16]:

$$e = i.\omega\frac{dL(\theta,i)}{d\theta} = k_b.\omega.i \ ; \quad So \quad k_b = \frac{dL(\theta,i)}{d\theta} \qquad (II.24)$$

In equation (II.23), the three terms on the right-hand side represent Resistive voltage drop, Inductive voltage drop & Induced EMF ‘ e ’ respectively. The instantaneous input power P_i can be written as:

$$P_i = V.i = R.i^2 + L(\theta,i).i.\frac{di}{dt} + i^2.\omega\frac{dL(\theta,i)}{d\theta} \ ; \quad So \quad t = \frac{\theta}{\omega} \qquad (II.25)$$

This equation is in the familiar form found in introductory electro-mechanics texts, implying that the input power is the sum of the winding resistive losses given by $R.i^2$, the rate of change of the field energy given by $p[L(\theta, i) \cdot i^2]$, and the air gap power, P_a, which is identified by the term $[i^2 pL(\theta, i)]/2$, where p is the differential operator, d/dt.

During the phase energization, a certain amount of magnetic flux linkage is generated. As the magnetic circuit depends on the rotor position, the amount of flux linkage generated depends on the electric current and rotor position. The magnetic flux characteristics according to the electric current are known as magnetization curves and can be used to model the SRM dynamics. The modeling procedure will be explained in detail further in this chapter. Magnetization curves of a generic SRM are presented in Figure II.10. Note that the magnetization curves are obtained as the magnetic flux, versus the DC electric current in one phase, for a fixed angle (θ) [16].

When the phase current is low, the SRM works out of the saturated region. However, recall that usually, SRMs work in the saturated region. Furthermore, the alignment and misalignment angles are marked in Figure II.10 along with two intermediate angles (θ1 and θ2).

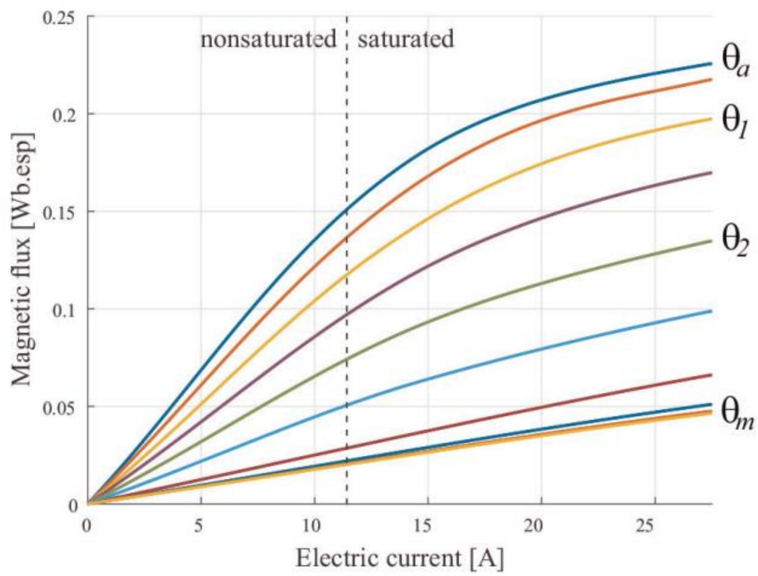


Figure II.10. Graphic representation of magnetic flux linkage [16]

In Figure II.11 we can look at the magnetization curve for the intermediate angle θ1. For a given point P_1 in the curve, there is an electric current value I1 and a corresponding flux linkage value λ_1. In any case, the electric energy applied to the winding is stored in the form of magnetic energy (hatched region $O\lambda_1P_1$).

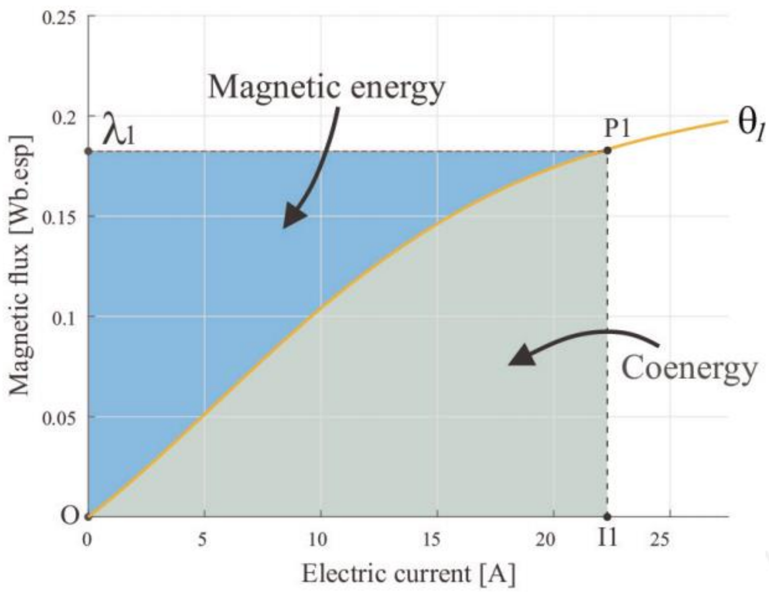


Figure II.11. Graphic representation of magnetic energy and co-energy for θ1 position [16]

Because the reluctance varies with rotor position and magnetic saturation is part of the normal operation of SR motors, there is no simple analytical expression for the magnetic field produced by the phase windings. The energy conversion of SR motors is hereby analyzed in this section by a general energy conversion approach presented in [14]. The flux linkage is a nonlinear function of both phase current and rotor position. Because of the large air gap, the magnetization is low and does not reach saturation at the unaligned position. Therefore, the magnetization curve is essentially linear as a function of current at $\theta = \theta_{unaligned}$. In contrast, the magnetization curve at the aligned position is heavily saturated because of the small air gap [14].

So the stored magnetic energy (Wf) is calculated as [14,16] :

$$Wf = \int_0^t V.i.dt = \int_0^t \frac{d\lambda}{dt}.i.dt = \int_0^{\lambda_1} i.d\lambda(\theta, i) \qquad (II.26)$$

Wf is termed the stored field energy because its value turns out to be the magnetic energy stored in the rotor/stator iron and the air gap. With the rotor is locked, it is also equal to the electric energy supplied to the phase winding during the time interval in which the phase flux linkage λ builds up from 0 to λ_1 [14].

The hatched area limited by the points OP_1I_1 represents the co-energy (W_f'). The co-energy has no physical meaning. On the other hand, the mechanical work realized by the machine in a given period of time is equal to the variation in co-energy during the same period. The co-energy can be calculated as [14, 16]:

$$W_f' = \int_0^{I1} \lambda(\theta, i).di \tag{II.27}$$

Now, assume that the rotor position is driven to the second intermediate angle θ2 and the current is maintained I1, as in Figure II.12. The new magnetic energy will be calculated as the region limited by the points $O\lambda_2P_2$ and the co-energy as the region is limited by the points OP_2I_1. Then, one can calculate the co-energy variation, that is, the mechanical work realized to take the rotor from position θ_1 to position θ_2:

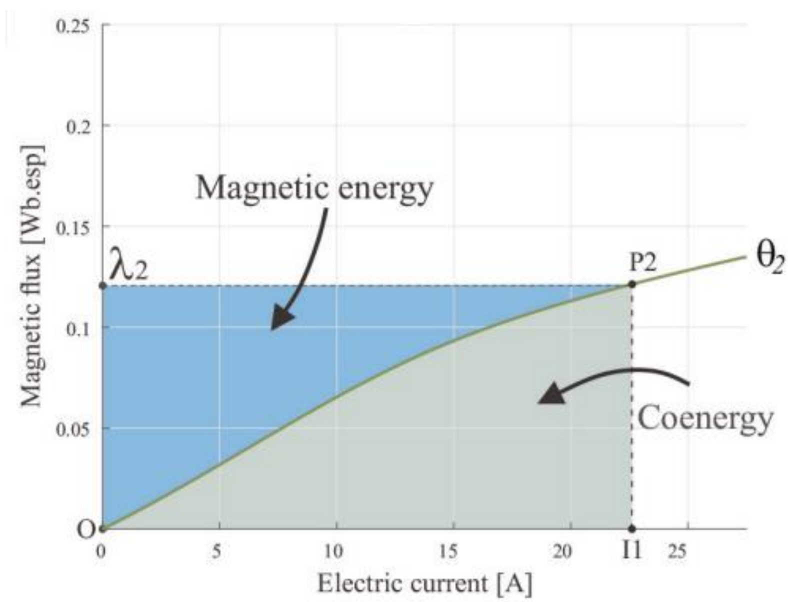


Figure II.12. Graphic representation of magnetic energy and co-energy for θ2 position [16]

Figure II.13 shows the co-energy variation as the hatched area is limited by the points OP_1P_2. The variation of the electric energy (ΔWe) applied is calculated as in equation. (II.28), where L_1 and L_2 are the phase inductance in positions θ_1 and θ_2 for the current I_1, respectively.

$$\Delta We = \int_0^t V.i.dt = \int_0^t \frac{d\lambda}{dt}.i.dt = I_1.(\lambda_2 - \lambda_1) = (L_2 - L_1).I_1^2 \tag{II.28}$$

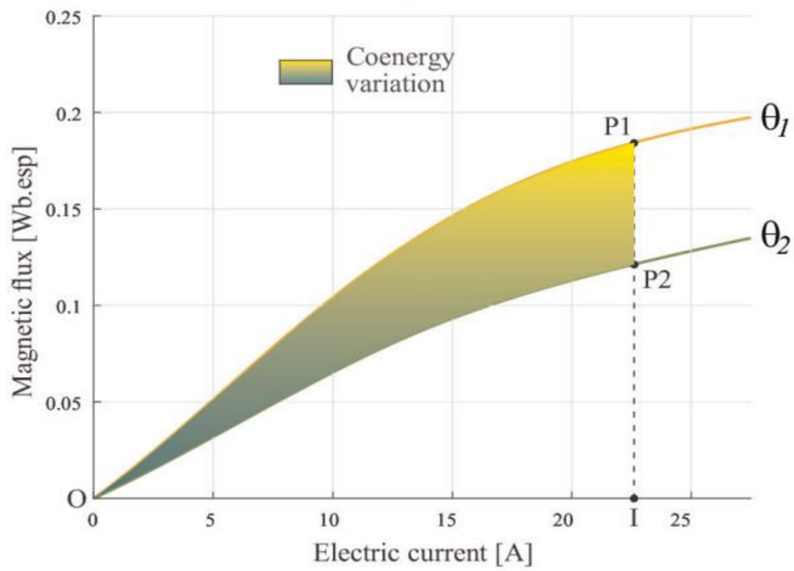


Figure II.13. Graphic representation of coenergy variation between angles θ1 and θ2 [16].

Considering the variation in the linear portion of the magnetization curve, the coenergy variation is half the variation of electric energy applied to the phase winding, as in equation. (II.29):

$$W_f' = \frac{1}{2}(L_2 - L_1).I_1^2 \tag{II.29}$$

The average electromagnetic torque ($\overline{T}$ produced when an electric current I_1 flows through a phase winding is given by equation II.30:

$$\overline{T} = \frac{\Delta W_f'}{\Delta\theta} = \frac{1}{2}.I_1^2\left(\frac{\Delta L}{\Delta\theta}\right) \tag{II.30}$$

Considering infinitesimal variations, the instantaneous electromagnetic torque (Te) can be calculated as in equation II.31, where i is the instantaneous direct current (DC) in the phase :

$$T_e = \frac{dW_f'(i,\theta)}{d\theta} = \frac{1}{2}.i^2\left(\frac{dL(i,\theta)}{d\theta}\right) \tag{II.31}$$

Observing equation (II.31), some information may be inferred. First, torque production does not depend on the electric current direction but has a quadratic relation with its amplitude. Moreover, the produced torque direction depends strictly on the inductance derivative at the energizing moment, while the inductance is a function of rotor position and electric current. The air gap power is the product of the electromagnetic torque and rotor speed given by:

$$P_a = \omega . T_e \quad \text{(II. 32)}$$

The mechanical equation is :

$$J . \frac{d\omega}{dt} = T_e - T_l - f . \omega \quad \text{(II. 33)}$$

Where J - the moment of inertia, f - the friction coefficient, T_l is the torque load and Te is the total torque.

The nonlinearities caused by the saturation and reluctance variation during the rotor excursion are carried to the magnetization curves, electric current, and electromagnetic torque characteristics. For this reason, a well-founded model is of utmost importance for studies covering SRM dynamics and control [16].

II.4.1.2 Magnetization curves

The acquisition of the magnetization curves Φ (I, θ) is crucial to model the electrical and mechanical behaviors of switched reluctance machines (SRM) as these machines operate essentially in the saturation region. As aforementioned, more precise magnetization curves can be obtained through experimental tests. These tests are implemented to obtain the curves for specific rotor positions. The indirect methods consist of using the static torque characteristics to acquire the magnetization curves and may lead to substantial variation if mechanical deviations occur. The direct methods, conversely, consist of applying a voltage to the SRM winding and determining the magnetic flux. One simple way to obtain the magnetization curves is to apply sinusoidal AC voltage to the machine winding in different positions. Once the root means square current (Irms) and the lag angle between voltage and electric current (θl) are known, one can calculate the flux linkage as:

$$\Phi = L . I = \frac{V_{rms} . \sin(\theta_l)}{I_{rms} . 2\pi . f} . I_{rms} \quad \text{(II. 34)}$$

This method returns errors if magnetic saturation occurs, which generally happens when working with SRMs. To work around this issue, the most implemented method is the blocked rotor test, as discussed in previous literature. Thus, in this chapter, the blocked rotor test will be used. This test consists of locking the rotor in place while applying voltage steps for each position. The electric current and voltage signals must be stored to calculate the magnetic flux. Once the phase resistance is known, the magnetic flux is given by [16]:

$$\Phi(t) = \int_0^t (V - R.i).dt \qquad (II.35)$$

The model accuracy is directly related to the number of curves and points in each curve. However, setting up the experiment for each angle and voltage is cumbersome. Hence, an automatic system can be developed to obtain the magnetization curves for as many positions as desired.

This completes development of the equivalent circuit and equations for evaluating electromagnetic torque, air gap power, and input power to the SRM both for dynamic and steady-state operations.

II.5. CONCLUSION

In this chapter circuits analogy for a 6-4 switched reluctance motor was proposed, describing how the electromagnetic torque is produced and the relationship between, the fundamental physical phenomena surrounding it, using a mathematical approach.

Chapter III: SRM Drive and Simulation Results

III.1. INTRODUCTION

Switched Reluctance Machines are receiving significant attention from industries, because of its simple structure; inexpensive manufacturability and reliability make it superior to other electric machines. Hence, it has rigid structure and is suited for high-speed driving applications. In driving control, it possesses highly developed torque and acceleration capabilities. A new practical and simple approach to model the SRM was developed based on three assumptions one operates in linear region of B-H curve, second the inductance offered by the winding will remains constant at its minimum value during the unaligned position and third the reluctance of iron is negligible with respect to air gap. The employed converter is simple topology and has fault tolerance. However, the doubly salient structure of SRM makes it have many inherent drawbacks, such as higher torque ripple, vibration, and acoustic noise. In addition, the nonlinear winding inductance and non-ideal winding current waveform render its dynamic modeling and high-performance control more difficult to achieve. Thus many key affairs must be treated. The typical ones include motor design, power circuit design and switching control, proper rotor position sensing and commutation setting, dynamic modeling, current control, speed control, commutation shift. A suited converter for switched-reluctance machine generating quasi-square winding current waveform is needed. The asymmetric bridge converter with 2N (N = phase number) switches possesses the most flexible winding current PWM switching control capability. Therefore, it is normally adopted, especially the SRM drive with regenerative braking capability. [17]

In This chapter we will go to present a new simulation of Switched Reluctance Motor (SRM) using Matlab environment. This simulation method has many advantages: it is free from complicated mathematical expressions, can be applied widely, and saves run time. In this simulation, we are using 6-4 SRM, moreover, this simulation method can be easily realize various SRM model. The detailed modeling process, computer simulation and test results are presented.

III.2. CONVERTER STRUCTURES FOR SRM

The selection of converter topology for a certain application is an important issue. Basically, the SRM converter has some requirements, such as:

- ✓ Each phase of the SR motor should be able to conduct independently of the other phases. It means that one phase has at least one switch for motor operation.

- ✓ The converter should be able to demagnetize the phase before it steps into the regenerating region. If the machine is operating as a motor, it should be able to excite the phase before it enters the generating region.

In order to improve the performance, such as higher efficiency, faster excitation time, fast demagnetization, high power, fault tolerance etc., the converter must satisfy some additional requirements. Some of these requirements are listed below. Additional Requirements [13]:

- ✓ The converter should be able to allow phase overlap control.
- ✓ The converter should be able to utilize the demagnetization energy from the outgoing phase in a useful way by either feeding it back to the source (DC-link capacitor) or using it in the incoming phase.
- ✓ In order to make the commutation period small the converter should generate a sufficiently high negative voltage for the outgoing phase to reduce demagnetization time.
- ✓ The converter should be able freewheel during the chopping period to reduce the switching frequency. So the switching loss and hysteresis loss may be reduced.
- ✓ The converter should be able to support high positive excitation voltage for building up a higher phase current, which may improve the output power of motor.
- ✓ The converter should have resonant circuit to apply zero-voltage or zero-current switching for reducing switching loss.

The block diagram of a conventional SRM converter is shown in Figure III.1. It can be divided into: utility, AC/DC converter, capacitor network, DC/DC power converter and SR motor.

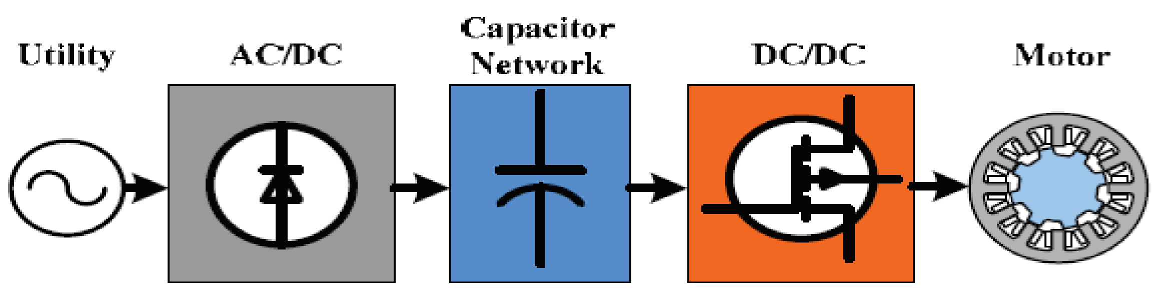


Figure III.1. Component block diagram of conventional SR drive [13]

The converter for SRM drive is regarded as three parts: **the utility interface**, **the front-end circuit** and **the power converter** as shown in Figure III.2. The front-end and the power converter are called as SR converter.

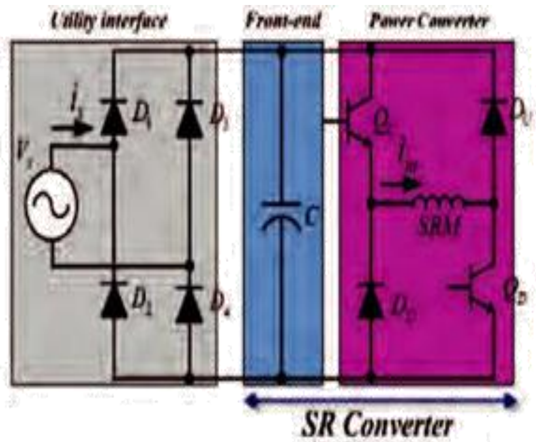


Figure III.2. Modules of SR Drive [13]

III.2.1. Utility Interface

The main function of utility interface is to rectify AC to DC voltage. The line current input from the source needs to be sinusoidal and in phase with the AC source voltage. The AC/DC rectifier provides the DC bus for DC/DC converter. The basic, the voltage doubler and the diode bridge rectifier are popular for use in SR drives.

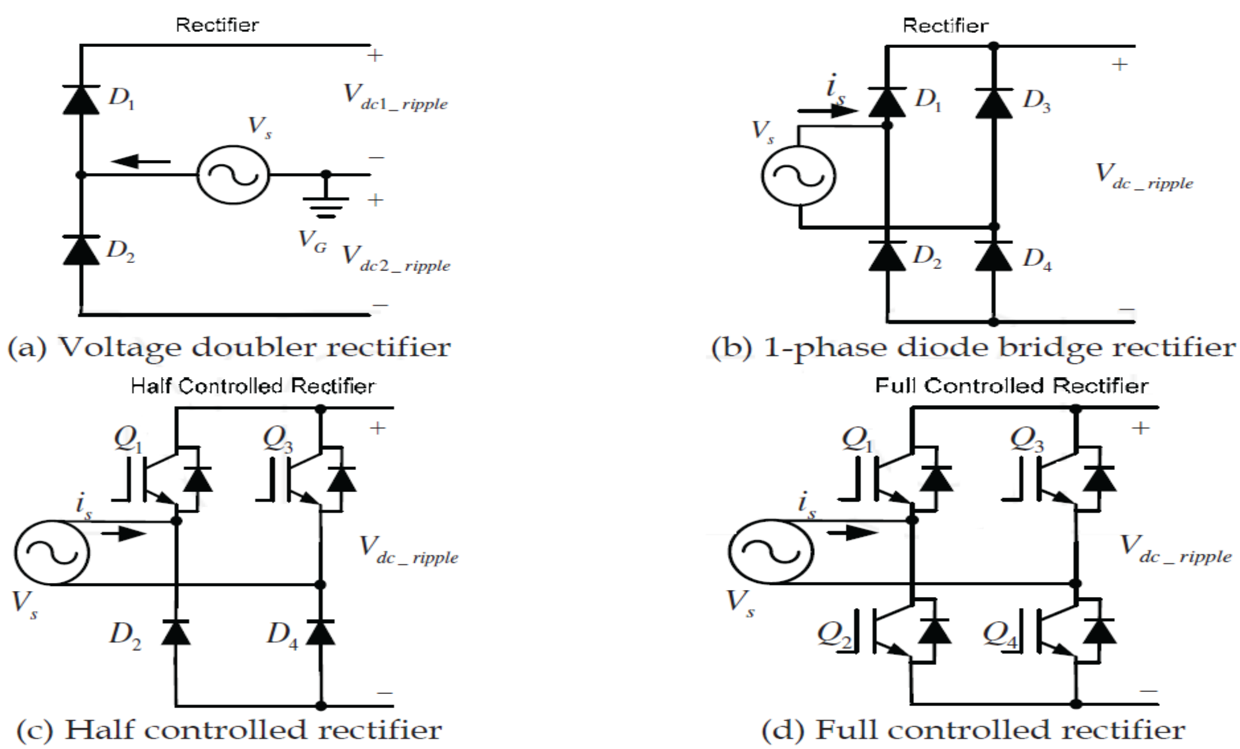


Figure III.3. Utility interface [13]

III.2.2. Front-end Circuit

Due to the high voltage ripple of rectifier output, a large capacitor is connected as a filter on the DC-link side in the voltage source power converter. This capacitor gets charged to a value close to the peak of the AC input voltage. As a result, the voltage ripple is reduced to an acceptable valve, if the smoothing capacitor is big enough. However, during heavy load conditions, a higher voltage ripple appears with two times the line frequency. For the SR drive, another important function is that the capacitor should store the circulating energy when the phase winding returned to.

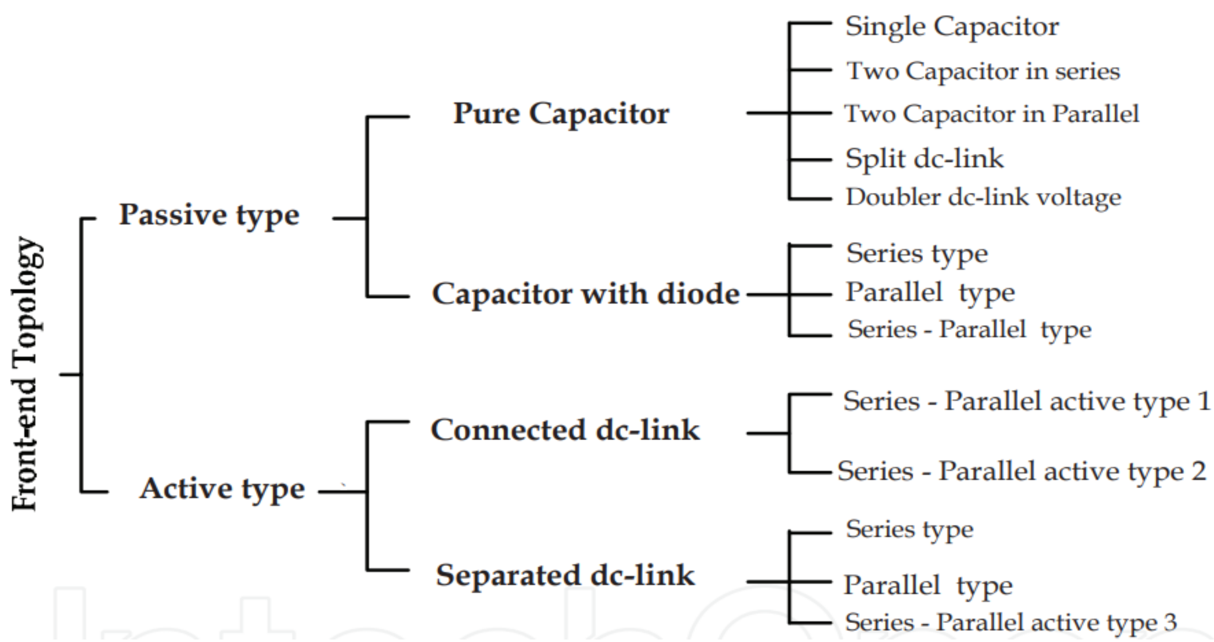


Figure III.4. Classification of capacitive type front-end topology [13]

For more details, you can read the reference [13]. We cannot present here all circuits capacitors connections, because the details lead the work a very long.

III.2.3. Power Converter

The power circuit topology is shown in Figure III.5. where five types of DC-DC converter can be used are shown.

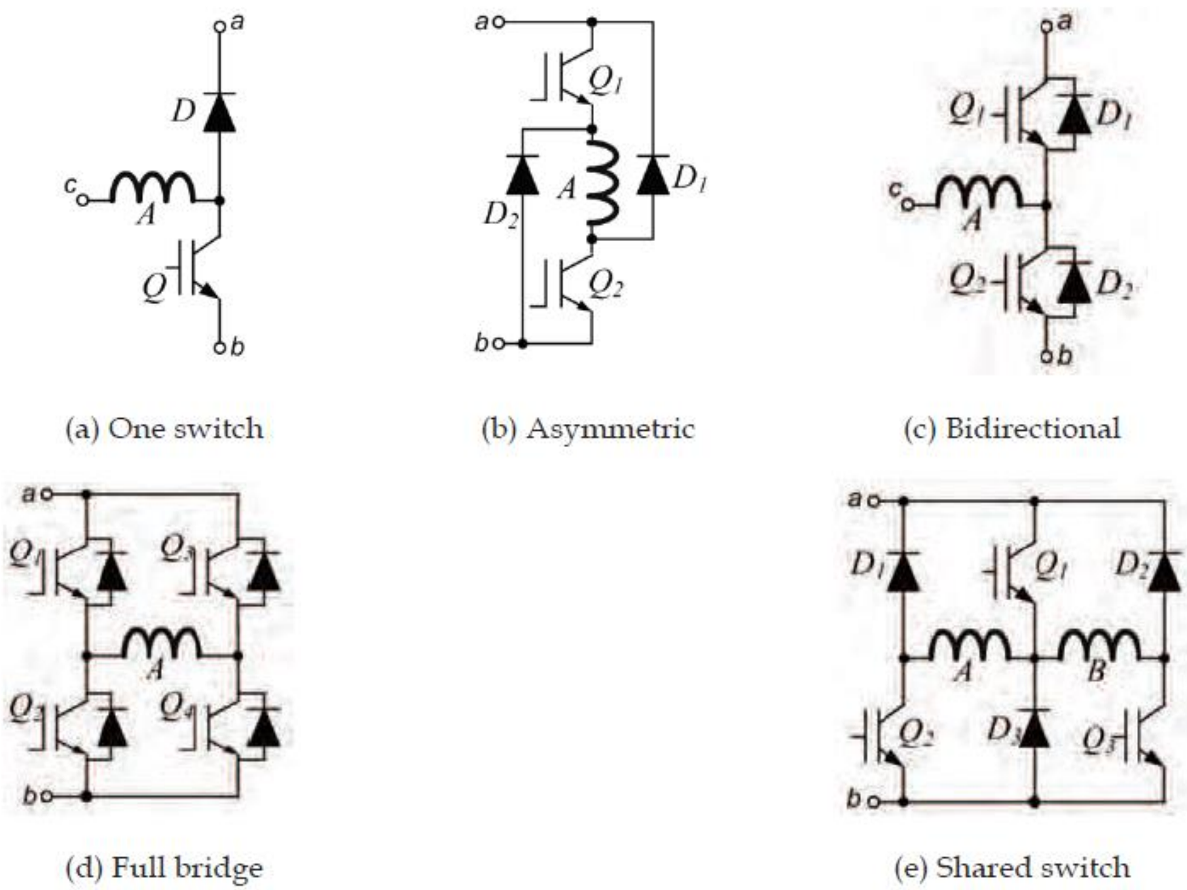


Figure III.5. Active type of two capacitors network separated to DC-link [13]

III.3. CONVERTER CLASSIFICATIONS OF SRM

One of the well-known classifications of SRM converters only considering the number of power switches and diodes and diodes is introduced .Different from the classifications, a novel classifications, which focuses on the characteristics of the converters. [13]

III.3.1. SRM converter by phase switch

The classification of SRM converter focuses on the number of power switches and diodes. These options have given way to power converters topologies with q, (q+1), 1.5q and 2q switch topologies where q is the number of motor phases. These configurations are classified and listed in Figure III.6. A two-stage power converter configuration which does not fit in this categorization based on the number of machine phases is also included. [13]

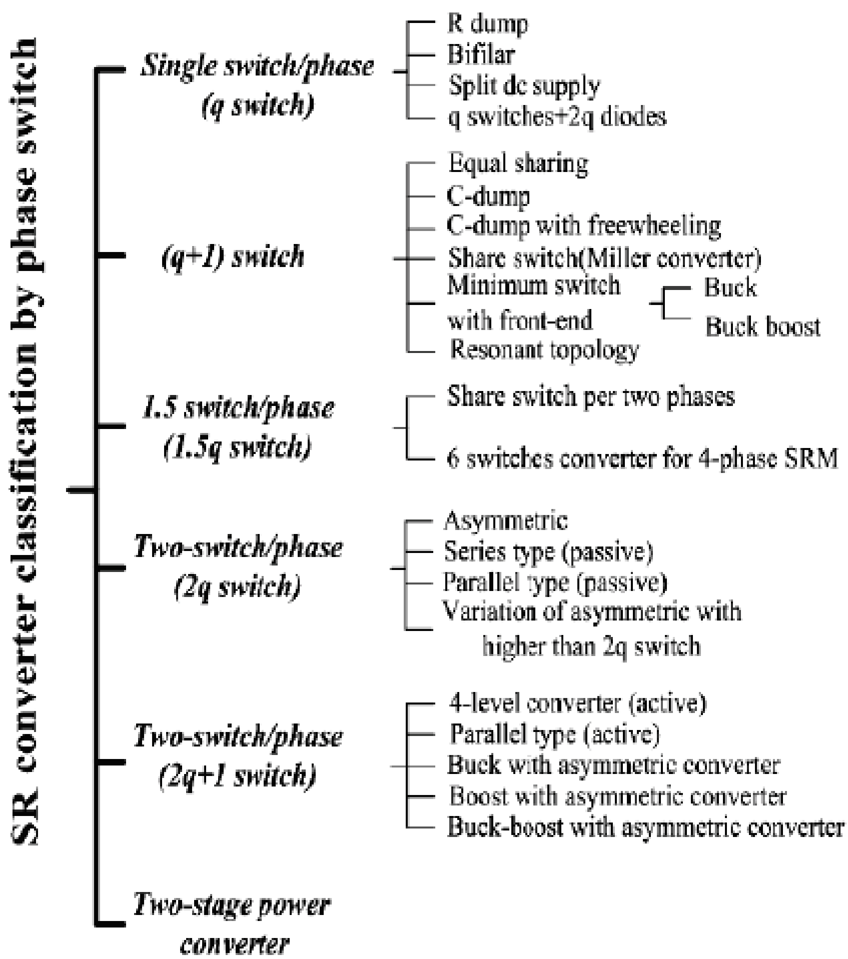


Figure III.6. SRM converter classification by phase switch [13].

All the converter topologies, except the two-stage power converter, assume that a DC voltage source is available for their inputs. This DC source may be from batteries or most usually a rectified AC supply with a filter to provide a stable DC input voltage to the SR converters.

Even though it is easy with the classification to find the number of semiconductors and the cost by counting the number of active components, it does not show important characteristics of a power converter, and the voltage ratings forth e power switches and diodes are difficult to consider. [13]

III.3.2. SRM converter by commutation

Different converters which have the same number of switches may obtain different performance and characteristics. From this point of view, such a classification is not useful for finding the characteristic of an SRM converter. The three types in the classification were presented as: extra commutation, half bridge and self-commutation. In the extra commutation circuit, the capacitive, the magnetic and dissipative circuit is included. However, the distinction between three types in the classification is not clearly defined. Conventionally, the half bridge and the self-commutation circuit also need a large capacitor in the front-end. They could also be classified as capacitive circuit. Moreover, the characteristic of circuits which contain one or more inductances is not shown (Figure III.7.) in the classification. [13]

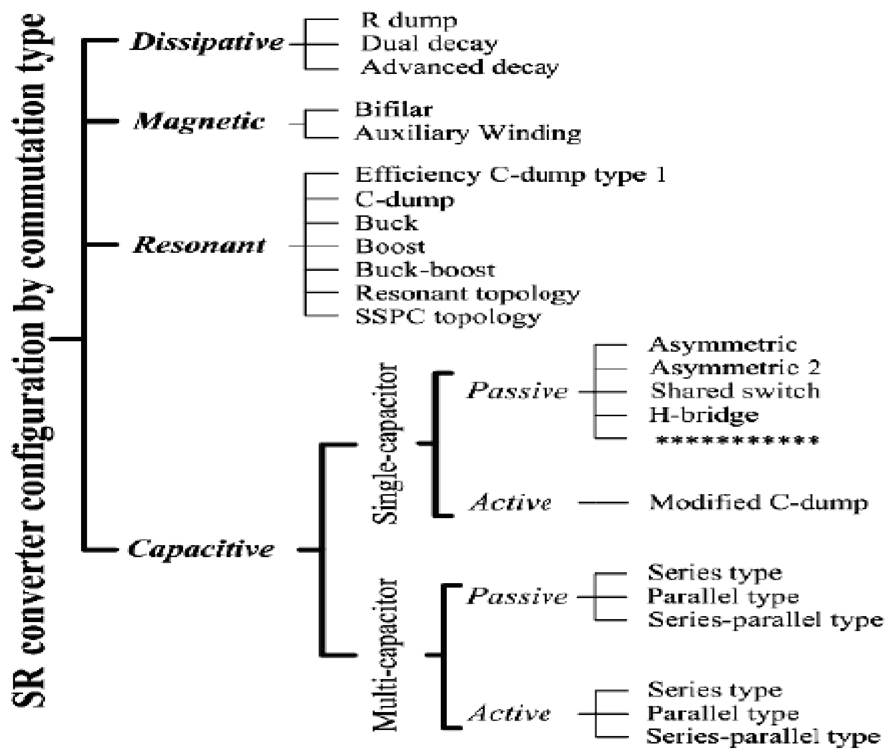


Figure III.7. SRM converter classification by commutation type [13]

III.4. BASIC SRM CONVERTERS

Some of the converter topology from each classification, that are two-stage power converters, asymmetric bridges, R dump converter, and C dump converter, is expressed briefly as follows.

III.4.1. Two-stage Converter

In a two-stage converter, power conversion is realized as bidirectional that is transferring energy from SRM to grid and from grid to SRM. The block diagram of two-stage topology is shown in Figure III.8. Has been shown that when the SRM is used as a generator, prime mover is attached to SRM and inverter is used to obtain three-phase voltage for grid integration. However, when the SRM is used as a motor, rectifier is used to feed SRM from the three-phase grid and load is replaced with prime mover. [18]

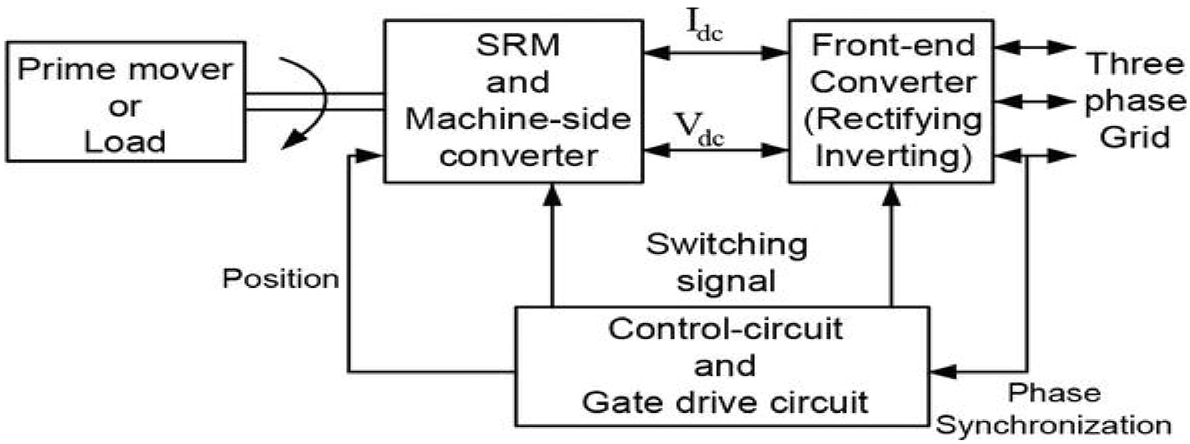


Figure III.8. A block diagram of a two-stage converter [18]

III.4.2. 1.5 Switch/Phase Converter

The 1.5 q converter that is shown in Figure III.9. is just suitable for SRM that has even number of phases. Energizing for each phase, 1.5 switch and diodes are required. The operation of 1.5 switch converter is described as follows. To energize phase a, S_1 and S_5 is turned on, while S_3 and S_6 is turned off. At that time, phase c current freewheels over D_5. After that, for energizing phase b, S_2 and S_6 have to be turned on when S_5 has to be turned off and current of phase a flows from S_1 to D_5. Then, phase c should be energized by turning on S_3 and S_5 while turning off S_6 and S_1. Furthermore, phase b current flows from S_2 to D_6 and phase a current freewheels over D_1. At last, to energize phase d, S_6 and S_4 should be turned on after turning off S_5 and S_2. Besides, phase c current flows from S_3 to D_5, while phase b current freewheels over D_2. [18]

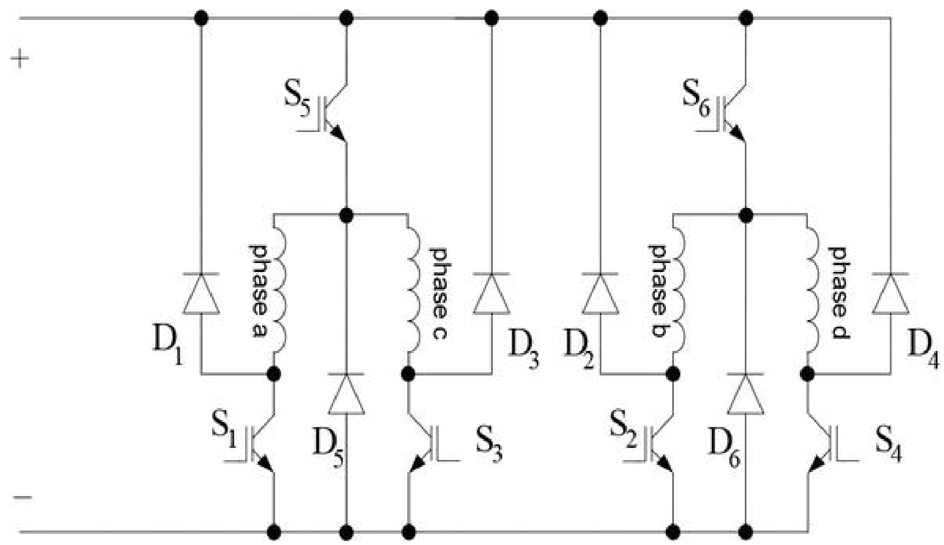


Figure III.9. 1.5 Switch/Phase converter [18]

III.4.3. R dump Converter

R dump converter is shown in Figure III.10. Operation of R dump converter can be summarized as follows. After each power switch turns off, current passes through the diodes and charge C; then, current flows through R and resets the energy in phase windings. Due to the use of R for extinguishing energy of phase windings, energy is dissipated and overall efficiency reduces. [18]

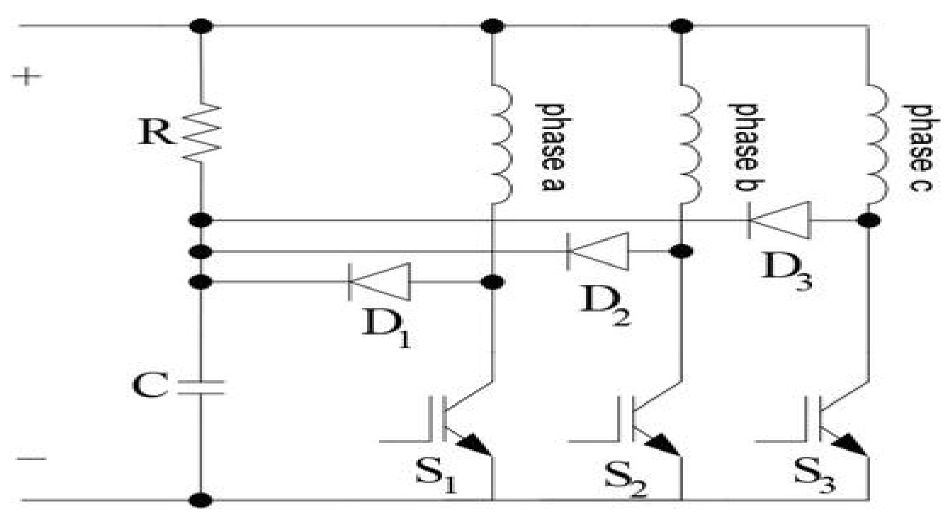


Figure III.10. R dump converter of SRM [18]

III.4.4. C dump Converter

Figure III.11. shows a C dump converter. In C dump converter, energy recovery process is being done by S_4, D_4, L, and C. Operation is briefly as follows: firstly the energy of phase windings is stored on C and then by switching on S_4, stored energy on C is sent to DC source or phase windings over L and D [18]

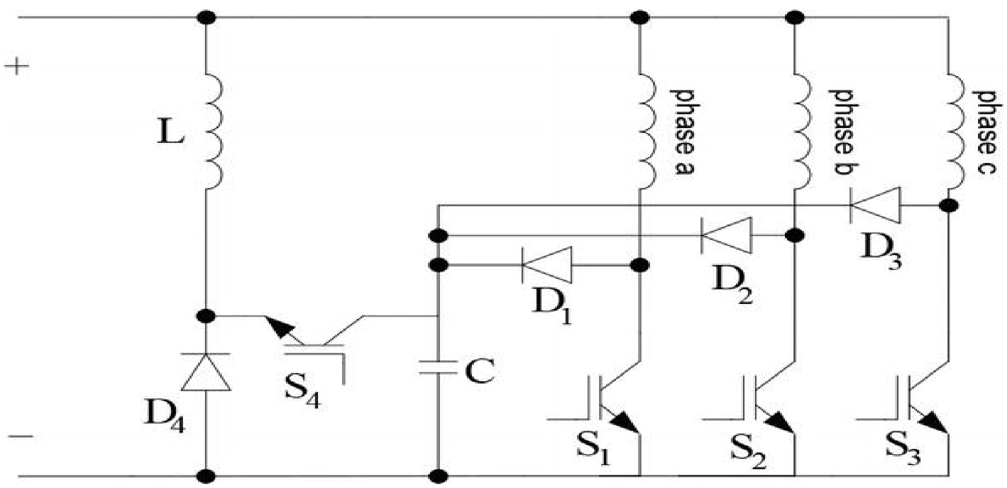


Figure III.11. C dump converter of SRM [18]

III.4.5. Asymmetric Bridge Converter

In asymmetric bridge converter that is shown in Figure III.12. for each phase of SRM, there are two power switches and two diodes.

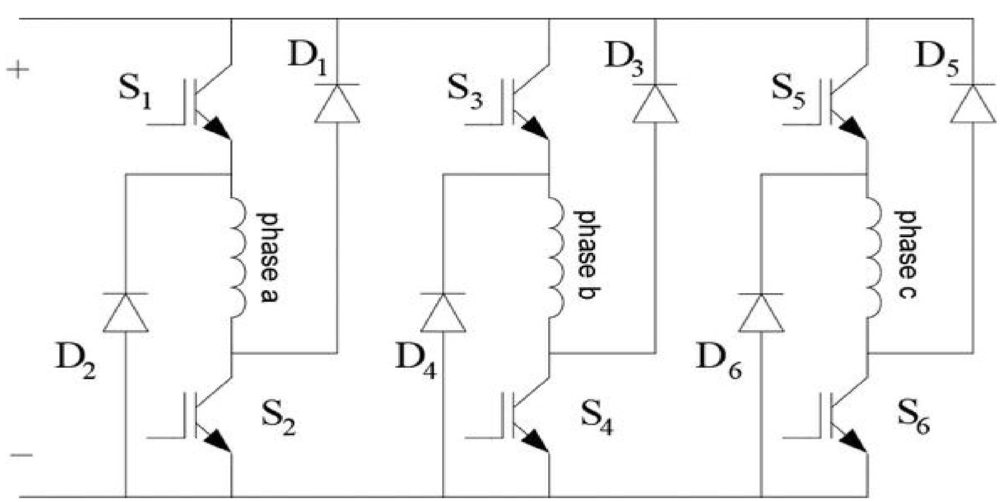


Figure III.12. Asymmetric bridge converter of SRM [18]

The sample connection of switches and diodes to one phase of SRM is shown in Figure III.13. It is also seen from the same figure that SRM has six stator and four rotor poles.

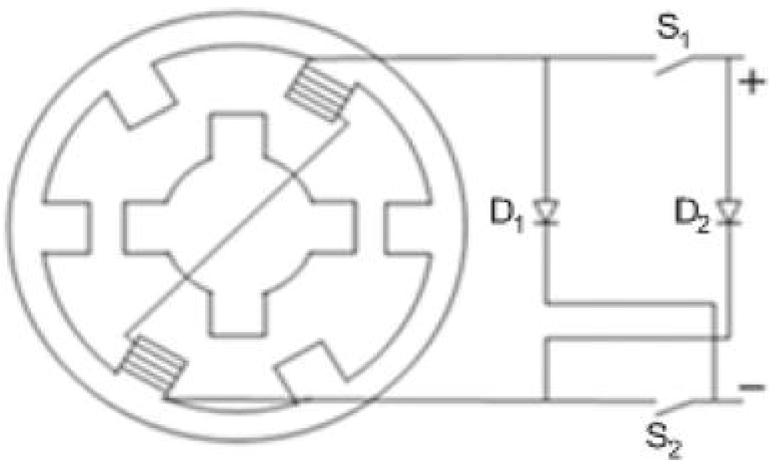


Figure III.13. Connection of an asymmetric bridge to SRM [18]

Basically, the definition of Figure III.13. and the operation of asymmetric bridges are as follows: windings are placed mutually on stator poles and they are connected in series to compose N and S poles. After energizing phase one winding with S_1 and S_2 switches, current flows from DC power supply to phase winding. When switches turn off, current flows through D_1 and D_2 diodes and negative voltage is applied to phase winding that causes decreasing of winding current. So, energy turns back to power supply [18]

III.5. CLASSIC CONVERTER TOPOLOGY

Since the torque developed in an SRM is independent of the direction of current flow, unipolar converters are sufficient to serve as the power converter circuit for the SRM. The most flexible and versatile four quadrant SRM topology is the classic bridge converter, which has two transistors and two freewheeling diodes per phase as shown in Figure III.14. The transistor switches are turned on and off in each phase based on the controller output for torque and speed control of the SRM. [19]

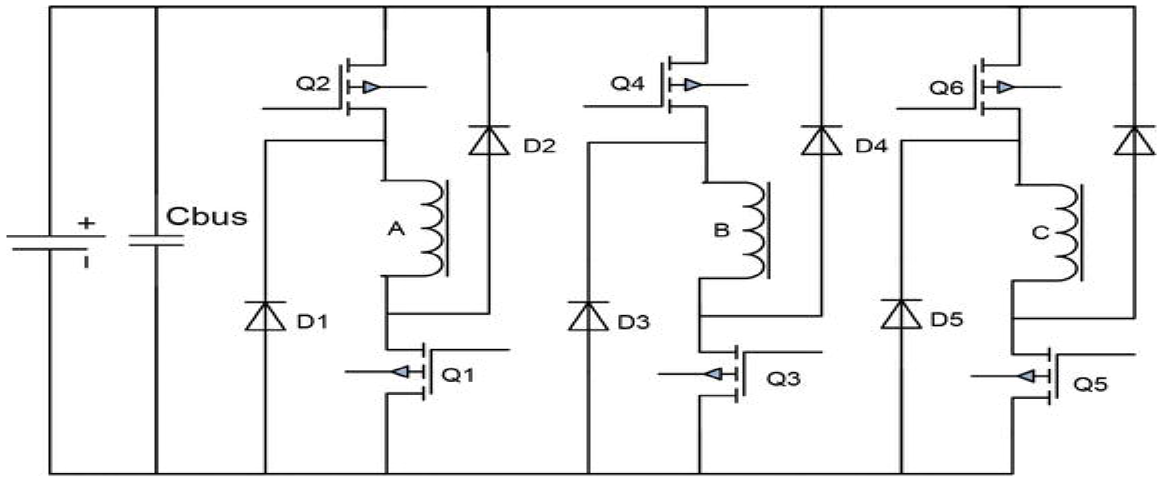


Figure III.14. Four-quadrant classic converter for a three-phase SRM [19]

There are three modes of converter operation in each phase: magnetization, freewheeling, and demagnetization.

1. Magnetization period for motoring is when both the switches are turned on and the energy is transferred from the source to the motor phase winding as shown in Figure III.15 (a). For generation, the phase winding of the motor is excited initially to generate higher back-emf than the DC-link voltage ($+V_{dc}$) with the machine driven by a prime mover. The generated energy is delivered to the electrical side achieving generation.

2. Freewheeling, for motoring operation at lower speeds, is accomplished by keeping one of the switches on and switching the other switch as shown in Figure III.15 (b). With only one switch on, the motor phase gets slowly demagnetized through the respective antiparallel freewheeling diode. For generating operation, one of the switches is turned off, whereas the other switch is turned on and off. With only one switch on, the motor phase gets slowly magnetized through the respective antiparallel freewheeling diode.

3. Demagnetization is achieved by applying a negative DC-link voltage to the phase winding with the two switches turned off as shown in Figure III.15(c) helps in fast decay of current flowing through both the diodes. [19]

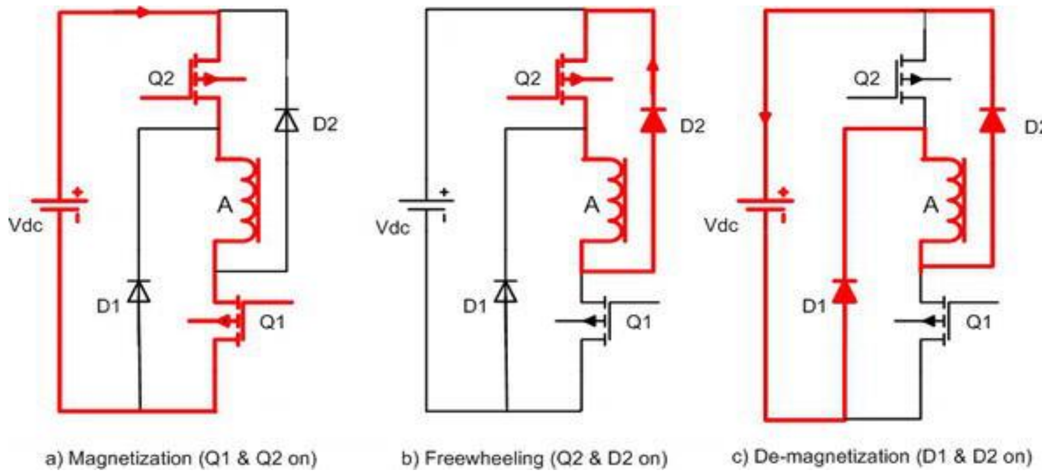


Figure III.15. Converter switching operation for motoring of phase a winding [19]

The chopping operation involves switching of the transistors connected to the phase winding accordingly for current regulation depending on the motoring or generating operation. The possible phase voltages in this Pulse Width Modulation (PWM) operation would be $+V_{dc}$ (for magnetization), 0 V (freewheeling), and $-V_{dc}$ (for demagnetization). The phase current control is set by three levels, which include the reference current value "I_{ref}" and the upper and lower hysteresis band limits. The hysteresis band value is chosen based on the peak current value of the machine. The chopping operation is implemented for torque control below the based speed.

The single-pulse mode of operation is possible when the machine is operated at high speeds. The possible phase voltages in this operation would be $+V_{dc}$ (for magnetization) and $-V_{dc}$ (for demagnetization). The current regulation is not possible in this operation because in motoring there may not be sufficient time to reach the desired current level at high speeds or in generating, when demagnetization occurs, there is no control over the diodes. The main advantage of this converter is its ability for independent control of each phase, which is particularly important when phase overlap is desired. It is more suitable for high-voltage, high-power drives. [19]

III.6. CONTROL STRATEGIES

The effective performance characteristics from an SRM drive system can be obtained by proper positioning of the phase excitation pulses relative to the rotor position. The commutation angles (turn-on angle "θ_{on}," turn-off angle "θ_{off}"), total conduction period, and the magnitude of the phase current "I_{ref}" determine the average torque, torque ripple, and other performance parameters. The complexity of finding the control parameters depends on the chosen control method for a particular application. At low speeds, the current rises almost instantaneously after turn on because of the negligible back-emf and the current must be limited by either controlling the average voltage or by regulating the current level. As the speed increases, the back-emf increases and opposes the applied DC-link voltage. Phase advancing is necessary to establish the phase current at the onset of rotor and stator pole overlap region. Voltage PWM is used to force maximum current into the machine to maintain the desired torque level. [19]

The block diagram for the general closed-loop speed and current control of the SRM is shown in Figure III.16. In speed control applications, an outer speed loop is added to the faster inner current loop. The inner loop creates desired currents in the stator windings necessary to achieve the desired speed specified by the outer loop. The inner current loop is implemented by current regulation, which consists of the current controller, the power converter, the SRM stator windings and the current sensing devices for feedback control. For current control, a simple hysteresis controller is illustrated here for simplicity and PI controller for outer speed control. [19]

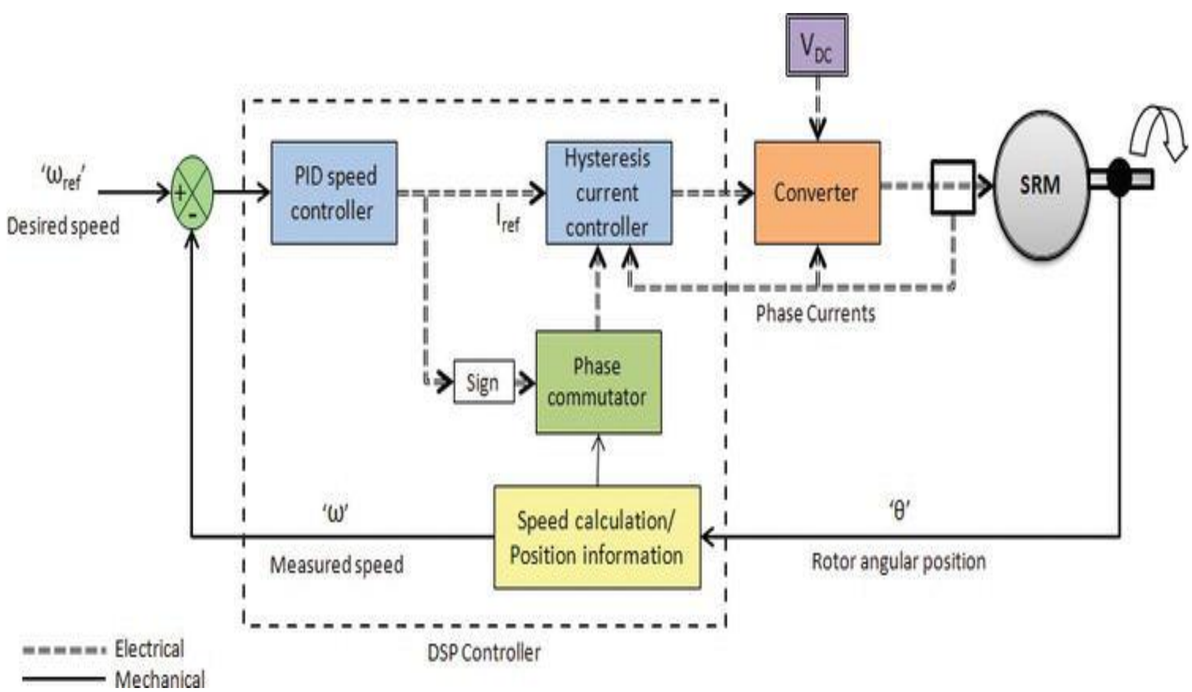


Figure III.16. Closed-loop speed and current control block diagram of a SRM. [19]

III.6.1. Voltage Control of SRM

In voltage control techniques, the voltage applied to the motor phases is constant during the complete sampling period of the speed-control loop. The commutation of the phases is linked to the position of the rotor. The voltage applied to the phase is directly controlled by a speed controller. The speed controller processes the speed error (the difference between the desired speed and the actual speed) and generates the desired phase voltage. The phase voltage is defined by a PWM duty cycle implemented at the DC Bus voltage of the SR inverter.

The phase voltage is constant during a complete dwell angle. The technique is illustrated in FigureIII.17. The current and voltage profiles can be seen in Figure III.18. The phase current is at its peak at the position when the inductance starts to increase (stator and rotor poles start to overlap), due to the change in the inductance profile. [20]

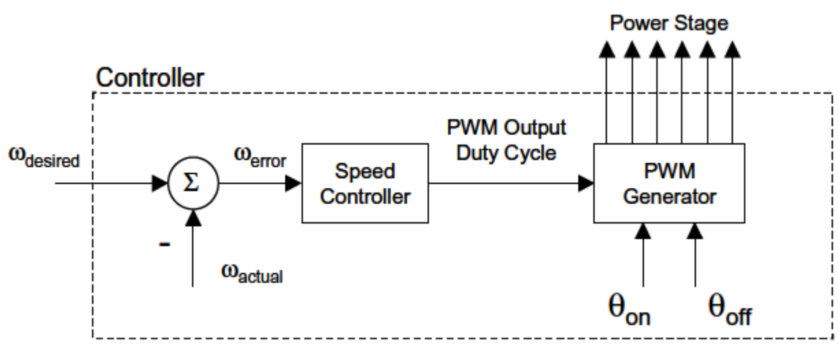


Figure III.17. Voltage control technique [20]

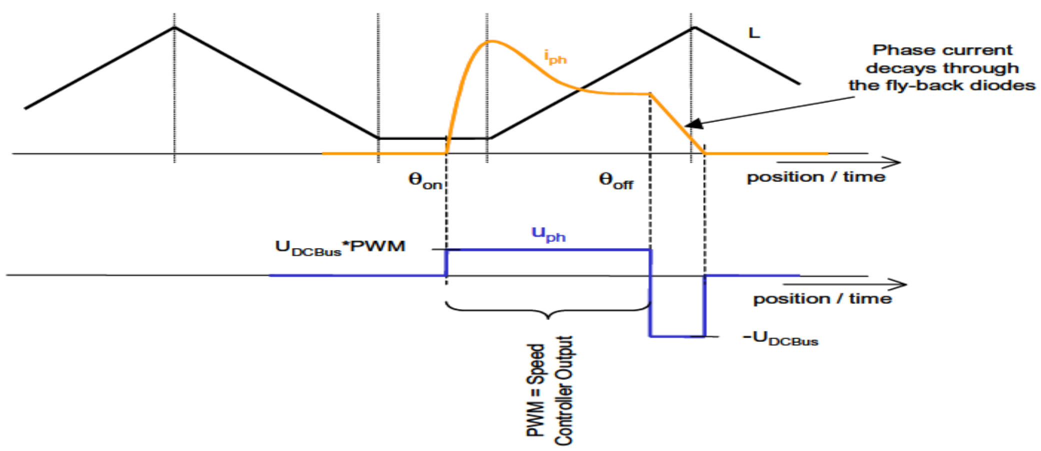


Figure III.18. Voltage and current profiles of voltage control technique [20]

III.6.2. Current Control of SRM

In current control techniques, the voltage applied to the motor phases is modulated to reach the desired current at the powered phase. For most applications, the desired current is constant during the complete sampling period of the speed control loop. The commutation of the phases is linked to the position of the rotor.

The voltage applied to the phase is controlled by a current controller with an external speed control loop. The speed controller processes the speed error (the difference between the desired speed and the actual speed) and generates the desired phase current. The current controller evaluates the difference between actual and desired phase current and calculates the appropriate PWM duty cycle. The phase voltage is defined by a PWM duty cycle implemented at the DC Bus voltage of the SR inverter. Thus, the phase voltage is modulated at the rate of the current control loop. This technique is illustrated in Figure III.19. The processing of the current controller must be linked to the commutation of the phases. When the phase is turned on (commutated), a duty cycle of 100% is applied to the phase. The increasing actual phase current is regularly compared to the desired current. As soon as the actual current slightly exceeds the desired current, the current controller is turned on. The current controller controls the output of the duty cycle until the phase is turned off (following commutation). The procedure is repeated for each commutation cycle of the motor. The current and voltage profiles can be seen in Figure III.20. Ideally, the phase current is controlled to follow the desired current. [20]

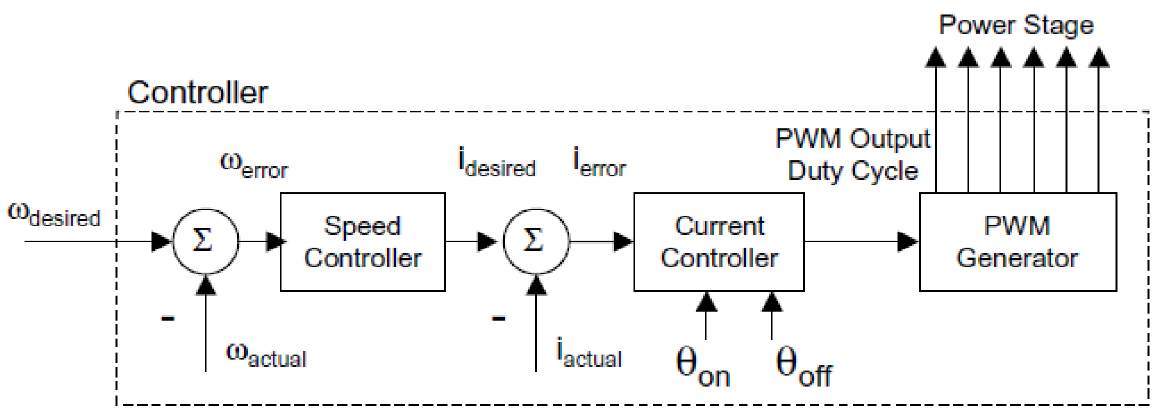


Figure III.19. Curent control technique [20]

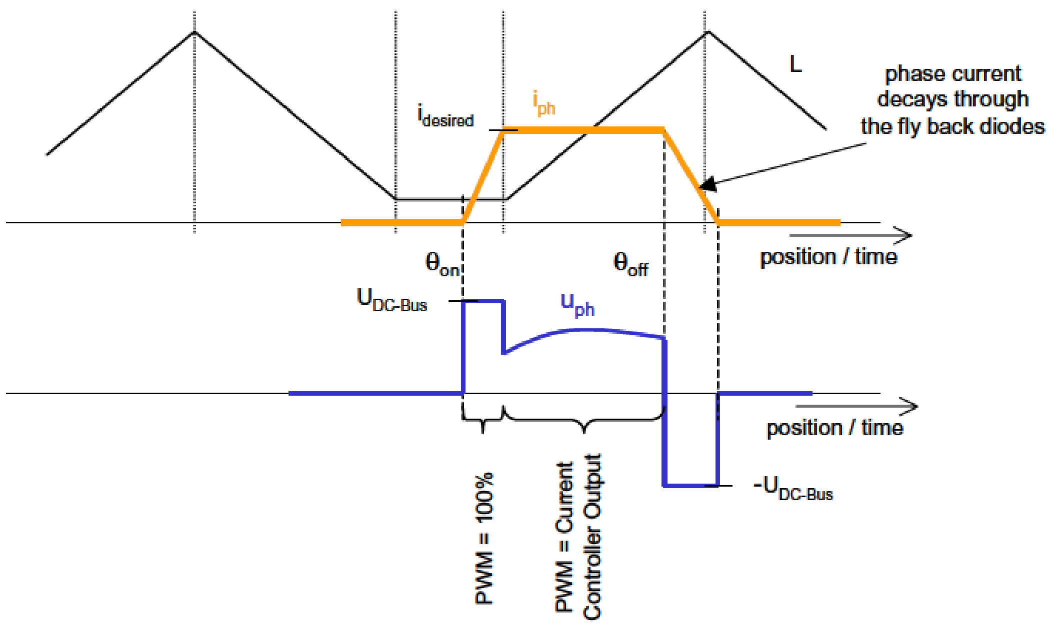


Figure III.20. Voltage and current profiles of current control technique [20]

III.6.3. Direct Instantaneous Torque Control

Direct instantaneous torque control strategy as shown in Figure III.21 can be explained as follows. The reference torque is compared with the actual torque and given to a hysteresis torque controller, which outputs in torque increase or decrease signal. The output of the torque hysteresis is given to switching control unit. Switching control unit does the following operations: it detects the outgoing and incoming phases based on the position sensor signal, turn-on and turn-off angles of the converter. Next states of both incoming and outgoing phases are determined on the information obtained from instantaneous torque, command torque, and present states of incoming and outgoing phases so as to control the torque within its set band. The asymmetrical converter used to excite the phases of the motor has three possible switching States, i.e., 1, 0, and -1 [21]

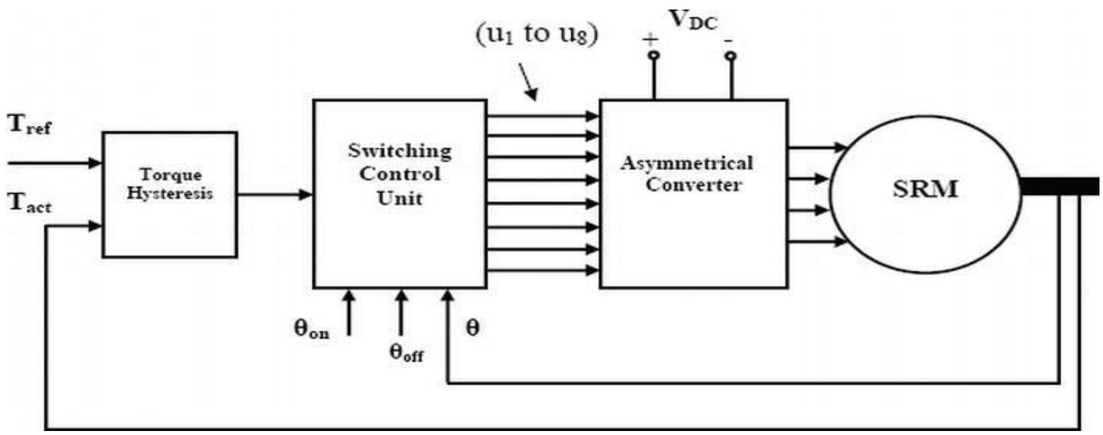


Figure III.21. Block diagram of DITC [21]

In single-phase conduction, any one phase is excited, and the total torque is developed by that phase only. If the torque is less than the reference torque, the controller selects State as 1 and if it is more than the reference torque State is made to −1. State 0 is not used in this scheme. During phase commutation, two phases conduct simultaneously, and the torque of the two consecutive phases is controlled to control the total torque. The torque is maintained within hysteresis band, by changing the States of the outgoing and incoming phases between 1 and −1, depending on the value of instantaneous torque. [21]

III.7. SRM SIMULATION MODEL

III.7.1. Description of the SRM Model

The SRM is fed by a three-phase asymmetrical power converter having three legs, each of which consists of two IGBTs and two free-wheeling diodes. During conduction periods, the active IGBTs apply positive source voltage to the stator windings to drive positive currents into the phase windings. During free-wheeling periods, negative voltage is applied to the windings and the stored energy is returned to the power DC source through the diodes. The fall time of the currents in motor windings can be thus reduced. By using a position sensor attached to the rotor, the turn-on and turn-off angles of the motor phases can be accurately imposed. These switching angle can be used to control the developed torque waveforms. The phase currents are independently controlled by three hysteresis controllers which generate the IGBTs drive signals by comparing the measured currents with the references. The IGBTs switching frequency is mainly determined by the hysteresis band. SRM model circuit is shown in Figure III.22.

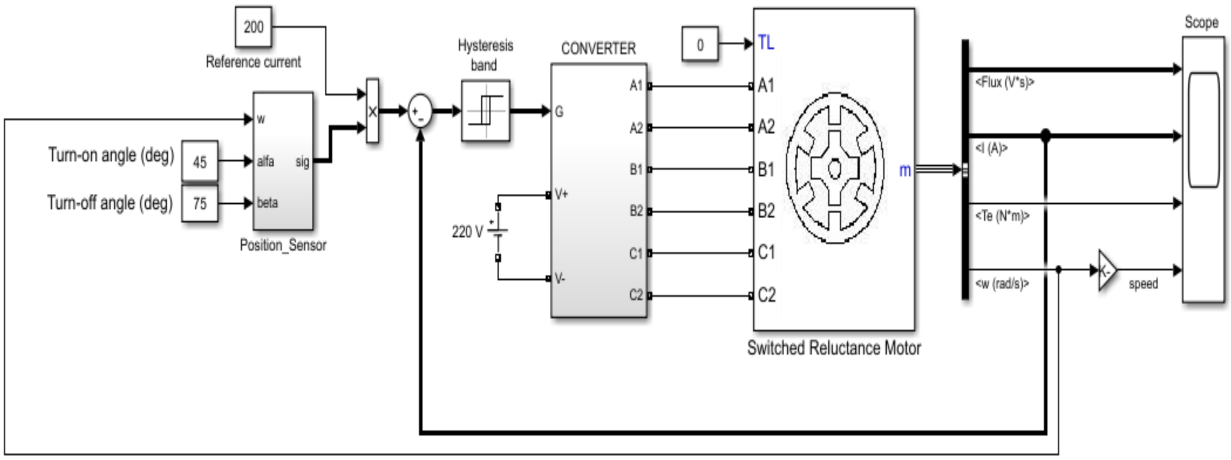


Figure III.22. SRM model circuit

III.7.2. Simulation Results of SRM Without Load

SRM is simulated using MATLAB/Simulink the different appearing simulation results will be discussed.

- Figure III.23. Shows the simulation result of one phase flux linkage without load.
- Figure III.24. Shows the simulation result of one phase current without load.
- Figure III.25. Shows the simulation result of one phase current ripple without load.
- Figure III.26. Shows the simulation result of the output torque without load.
- Figure III.27. Shows the simulation result of the output torque ripple without load.
- Figure III.28. Shows the simulation result of the motor speed without load.

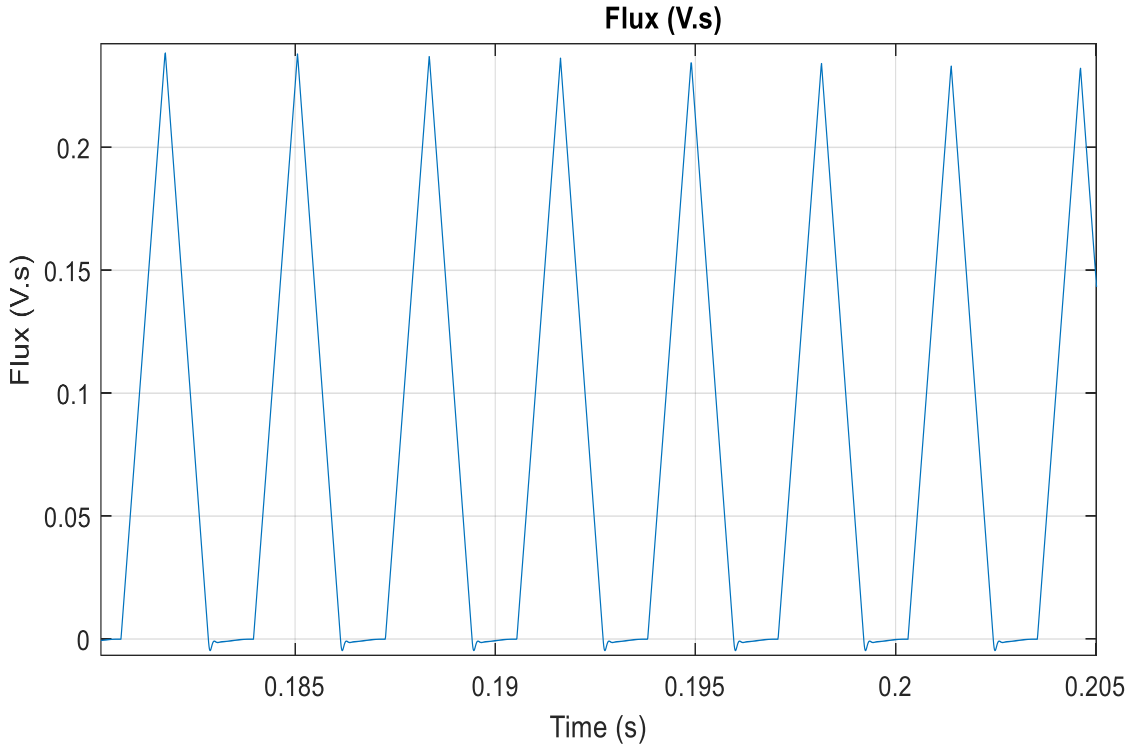


Figure III.23. One phase flux linkage without load

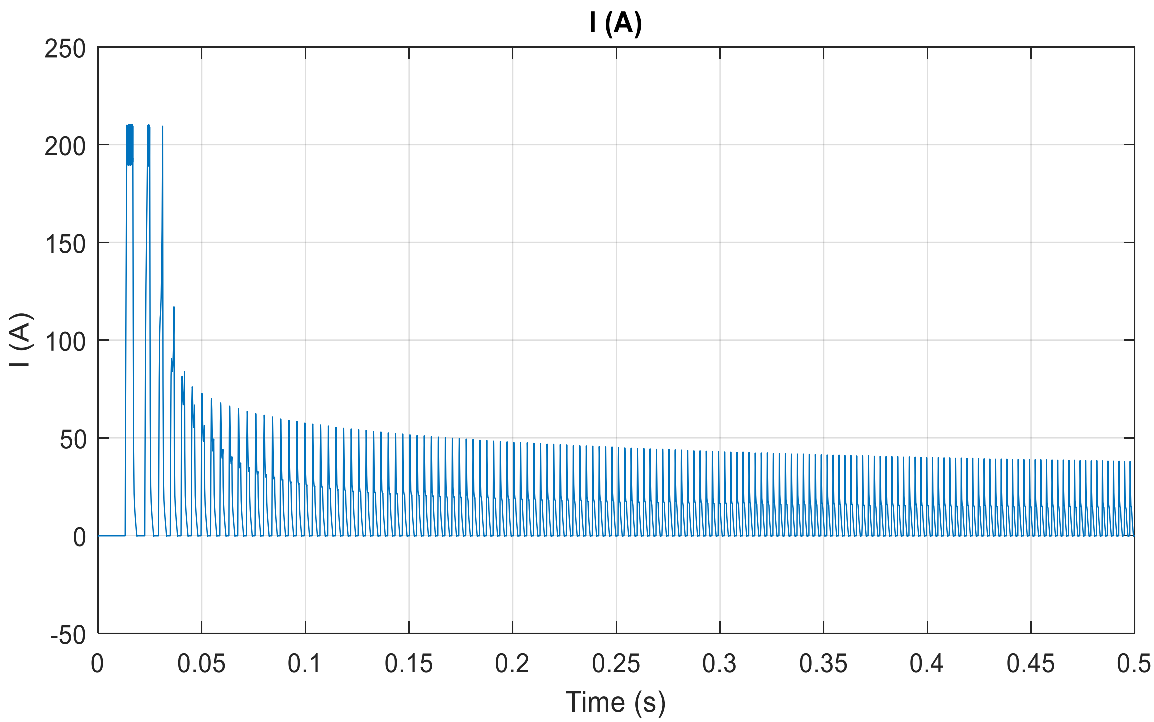


Figure III.24. One phase current without load

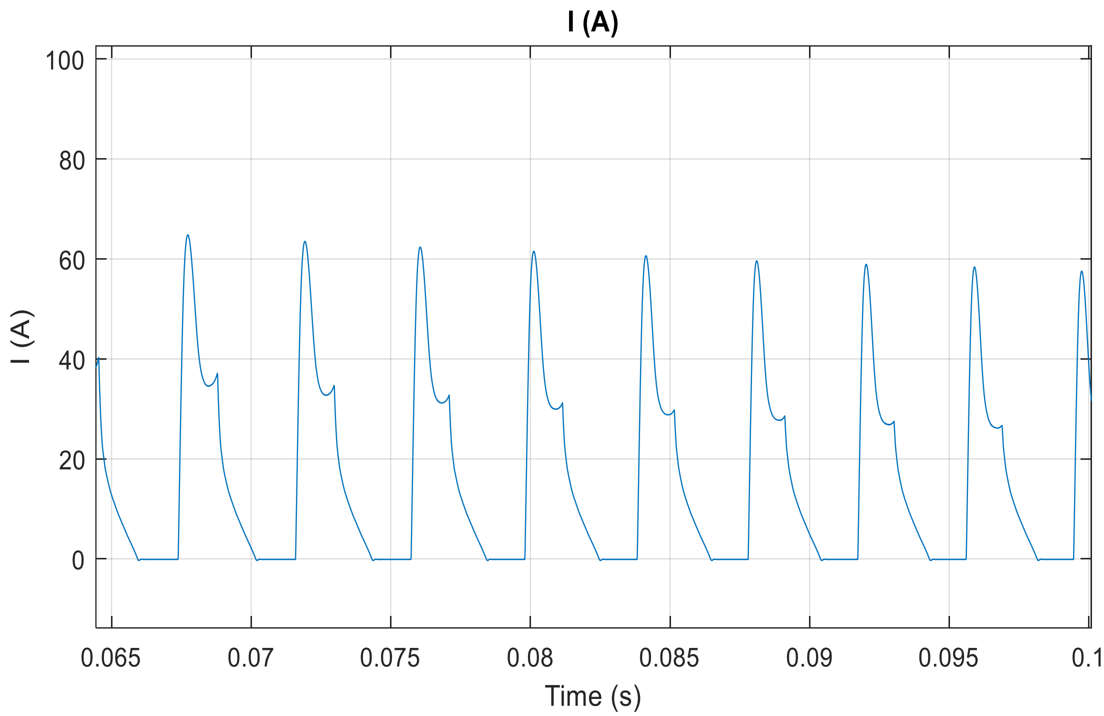


Figure III.25. One phase current ripple without load

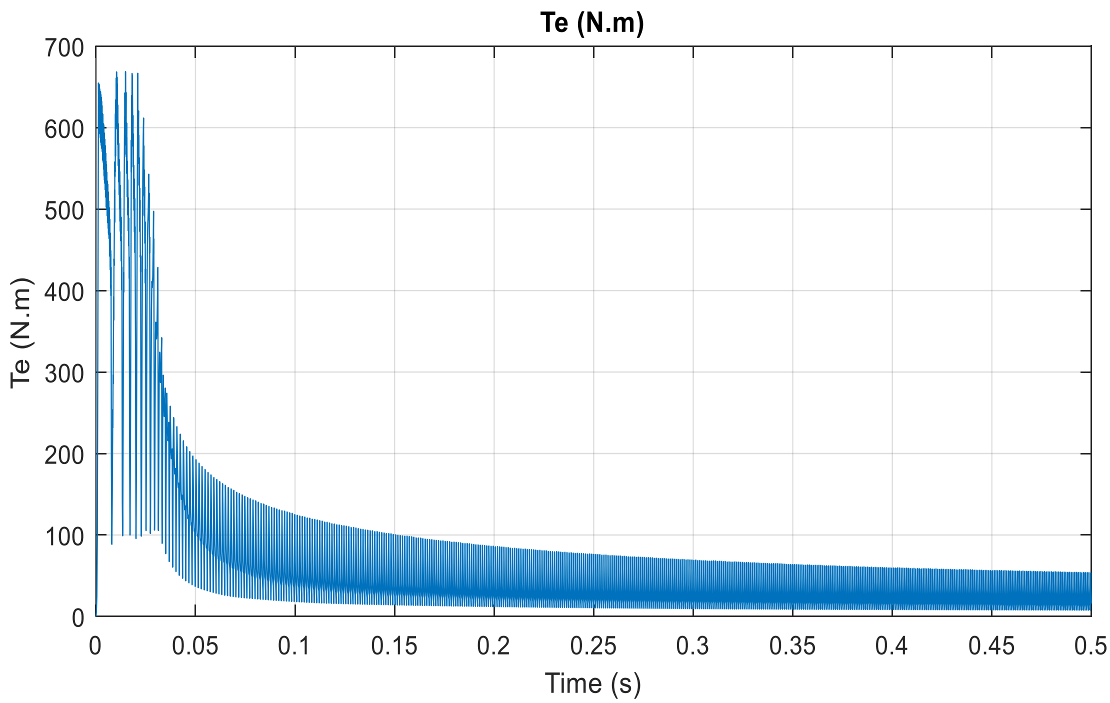


Figure III.26. Output torque without load

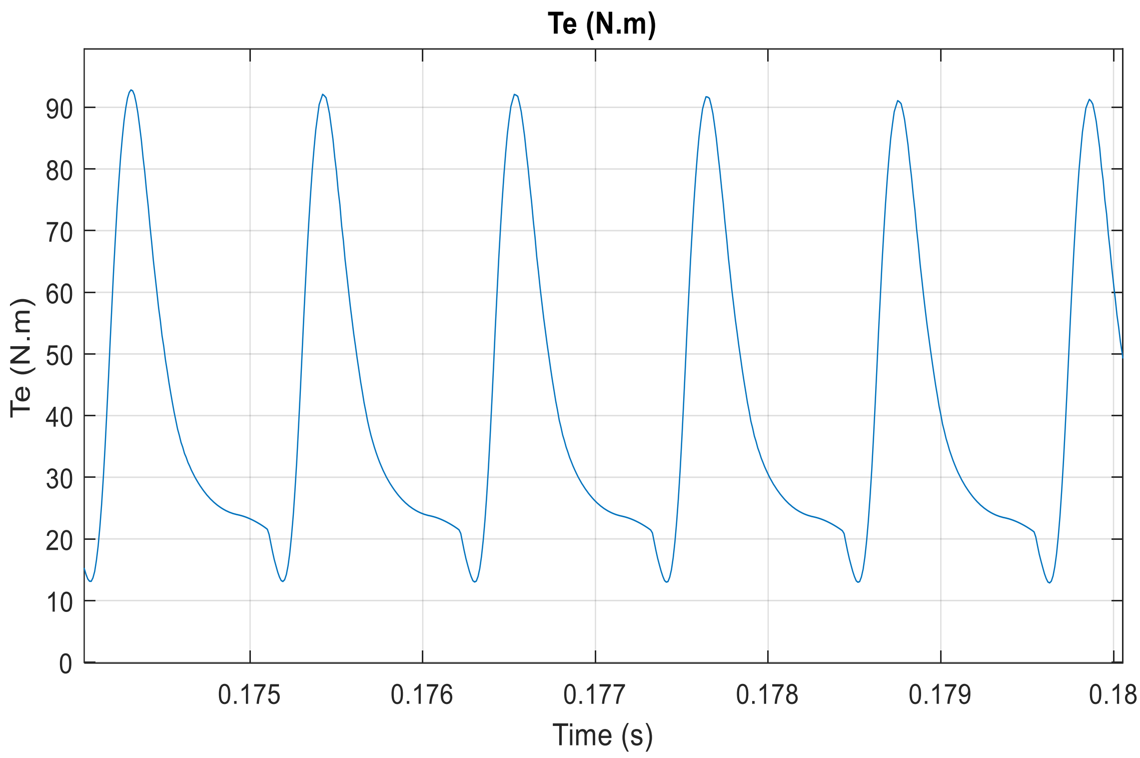


Figure III.27. Output torque ripple without load

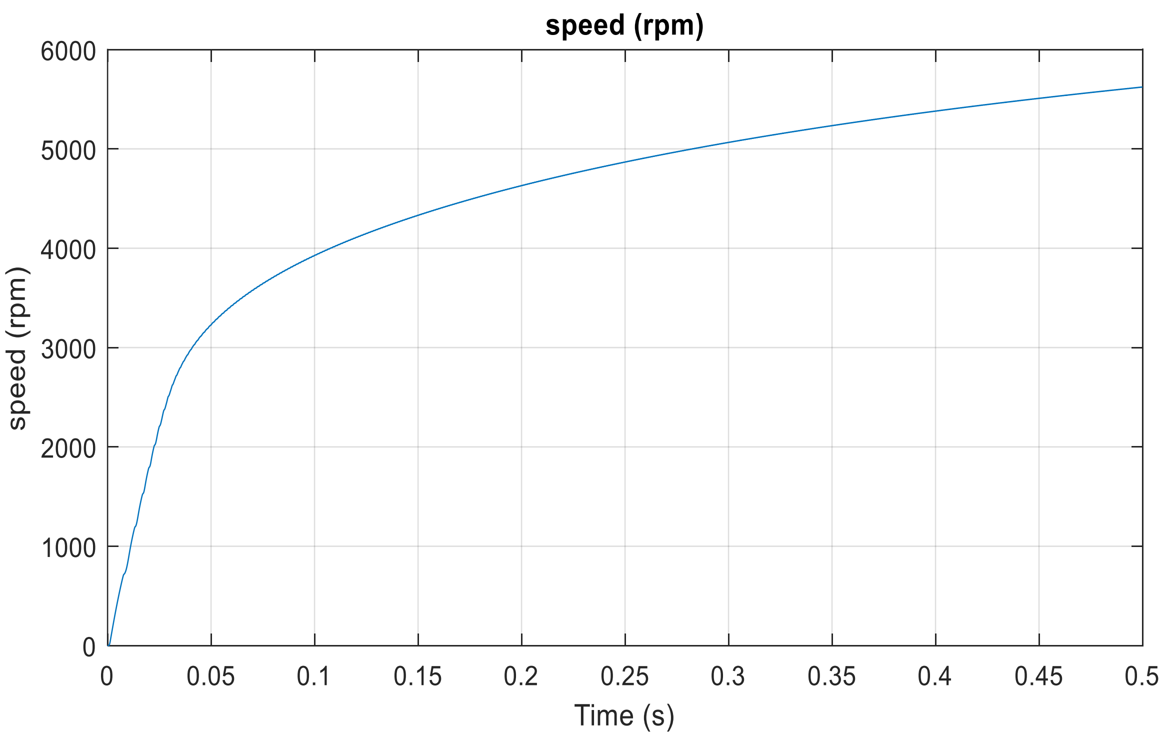


Figure III.28. Motor speed without load

III.7.3. Simulation Analysis

In this model, a DC supply voltage of 220 V is used. The converter turn-on and turn-off angles are kept constant at 45° and 75°, respectively, over the speed ranges. The reference current is 200A and the hysteresis band is chosen as ± 10A, a very light load was chosen. Since only the currents are controlled, the motor speed will increase according to the mechanical dynamics of the system. The SRM drive waveforms (magnetic flux, phase currents, motor torque, and motor speed) are displayed on the scope. As can be noted, the SRM torque has a very high torque ripple component which is due to the transitions of the currents from one phase to the following one. This torque ripple is a particular characteristic of the SRM and it depends mainly on the converter s turn-on and turn-off angles. In observing the drive's waveforms, we can remark that the SRM operation speed range can be divided into two regions according to the converter operating mode: current-controlled and voltage-fed.

A) Current Controlled Mode

From stand still up to about 3000 rpm, the motor's emf is low and the current can be regulated to the reference value. In this operation mode, the average value of the developed torque is approximately proportional to the current reference. In addition to the torque ripple due to phase transitions, we note also the torque ripple created by the switching of the hysteresis regulator. This operation mode is also called constant torque operation.

B) Voltage-fed Mode

For speeds above 3000 rpm, the motor's emf is high and the phase currents cannot attain the reference value imposed by the current regulators. The converter operation changes naturally to voltage-fed mode in which there is no modulation of the power switches. They remain closed during their active periods and the constant DC supply voltage is continuously applied to the phase windings. This results in linear varying flux waveforms as shown on the scope. In voltage-fed mode, the SRM develops its 'natural' characteristic in which the average value of the developed torque is inversely proportional to the motor speed. Since the hysteresis regulator is inactive in this case, only torque ripple due to phase transitions is present in the torque waveforms.

III.7.4. Simulation results of SRM loaded with 100 N.m

- Figure III.29. Shows the simulation result of one phase flux linkage loaded with 100 N.m.
- Figure III.30. Shows the simulation result of one phase current loaded with 100 N.m.
- Figure III.31. Shows the simulation result of one phase current ripple loaded with 100 N.m.
- Figure III.32. Shows the simulation result of the output torque loaded with 100 N.m.
- Figure III.33. Shows the simulation result of the output torque ripple loaded with 100 N.m.
- Figure III.34. Shows the simulation result of the motor speed loaded with 100 N.m.

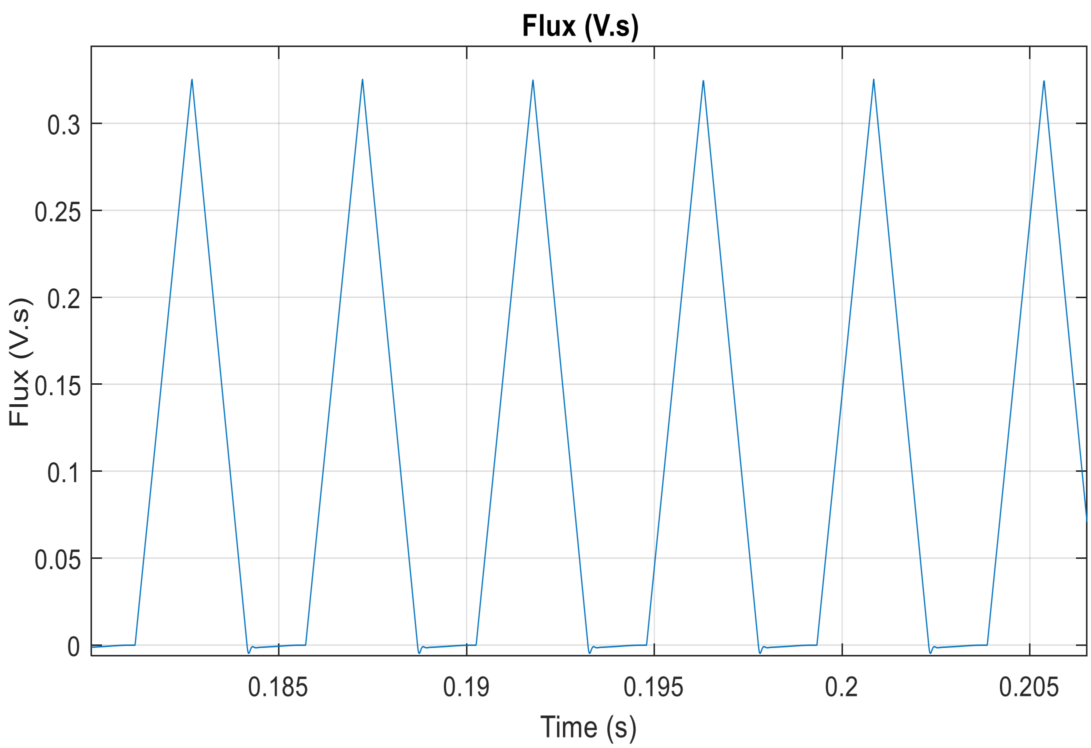


Figure III.29. One phase Flux linkage loaded

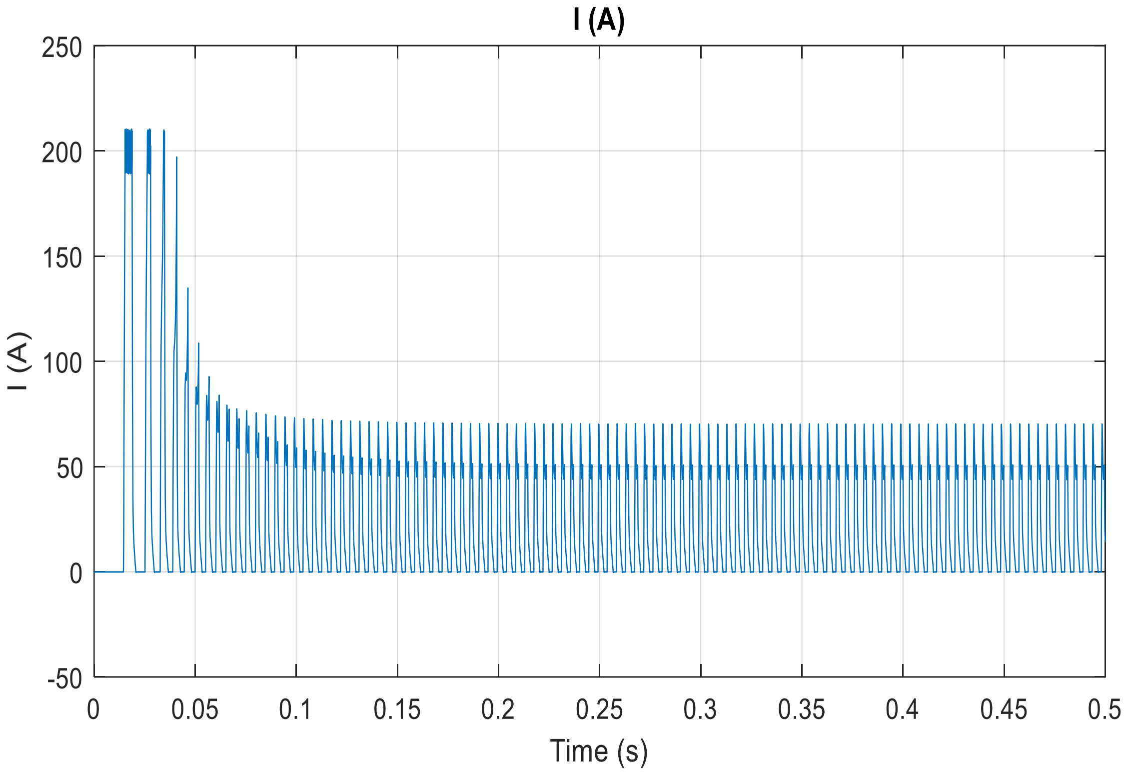


Figure III.30. One phase current loaded

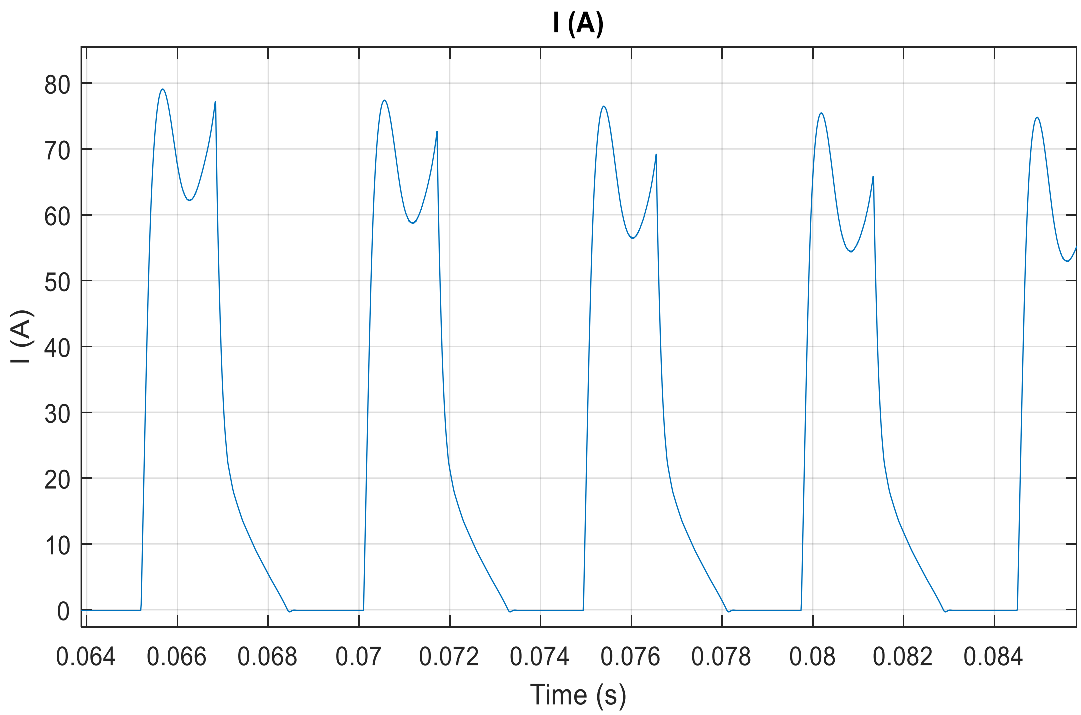


Figure III.31. One phase current ripple loaded

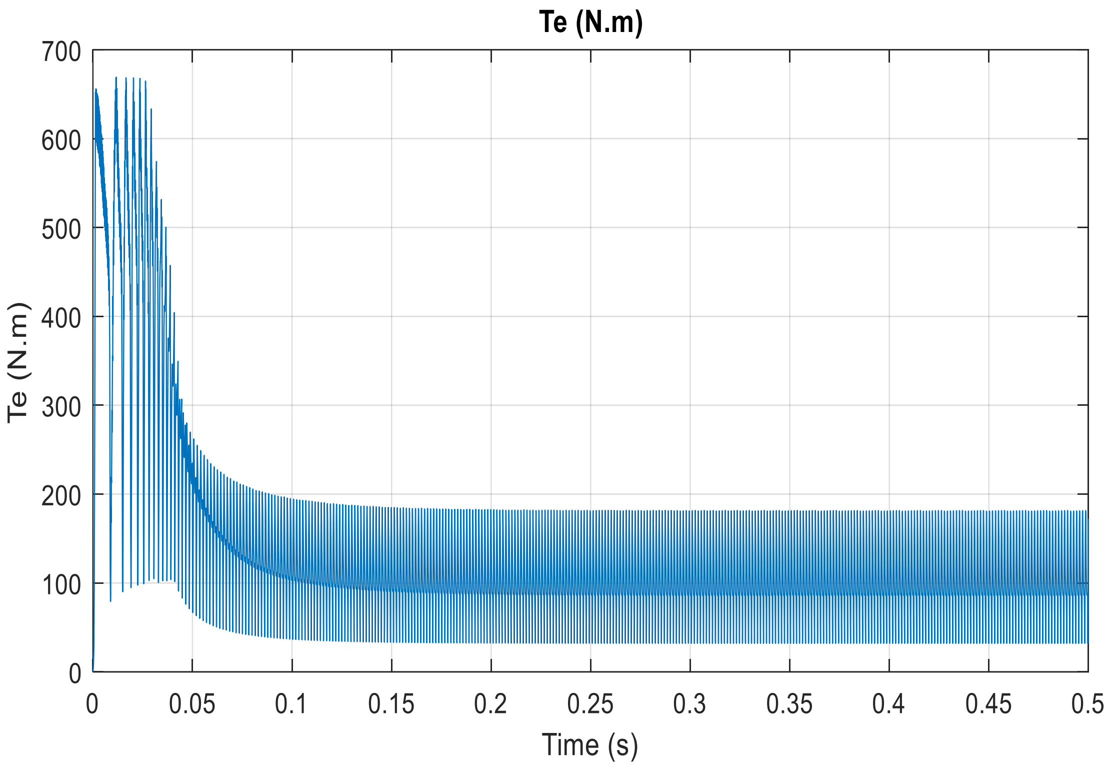


Figure III.32. Output torque loaded

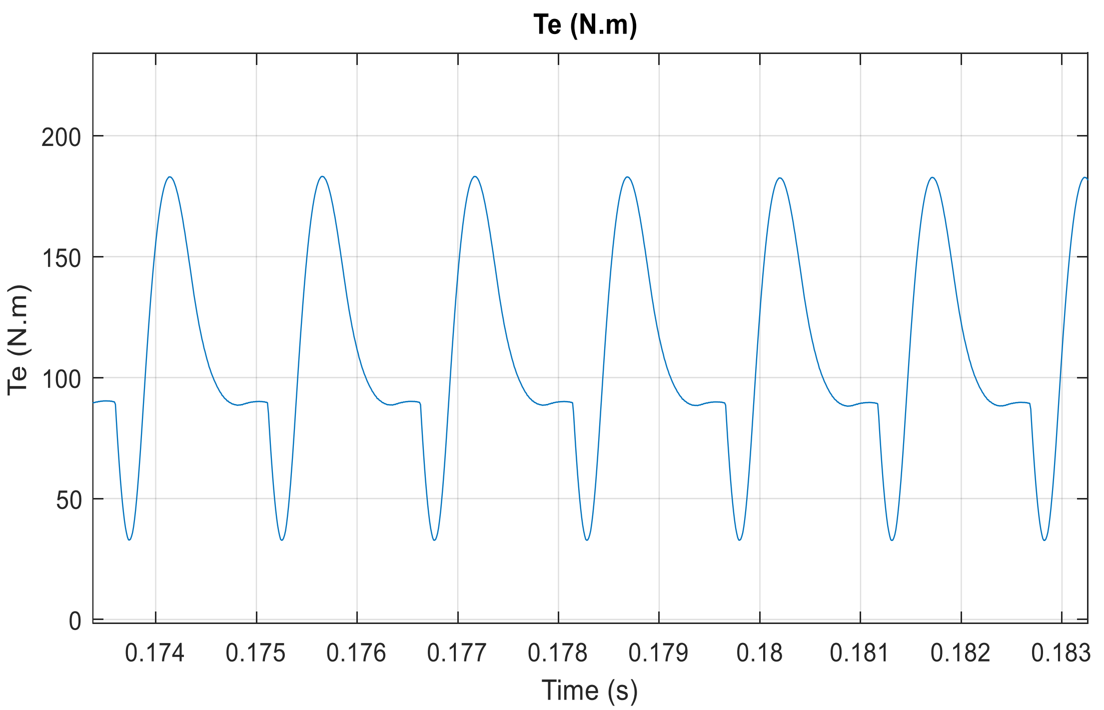


Figure III.33. Output torque ripple loaded

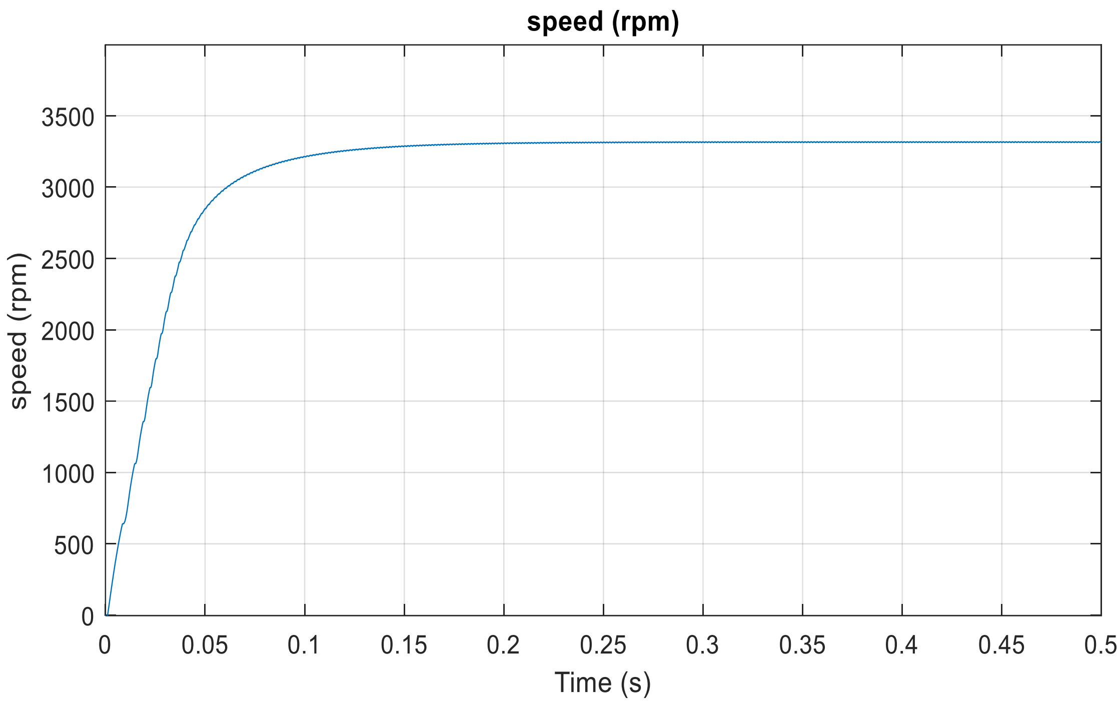


Figure III.34. Motor speed loaded

There is slight difference in the values of flux linkage with or without load, and a major change of phase current, torque and motor speed values.

The high torque inertia stays the same (650 N.m) then it decreases and stood up at almost 200 N.m.

The motor speed reaches to 3500 rpm (6000 rpm without load).

III.8. SRM CURRENT CONTROL

III.8.1 Current Control Description

A DC voltage source feeds the SRM through a controlled three-arm bridge. An ideal angular velocity source provides the load. The converter turn-on and turn-off angles are maintained constant. A PI-based current controller regulates the current amplitude. The simulation circuit of SRM current control is shown in Figure III.35.

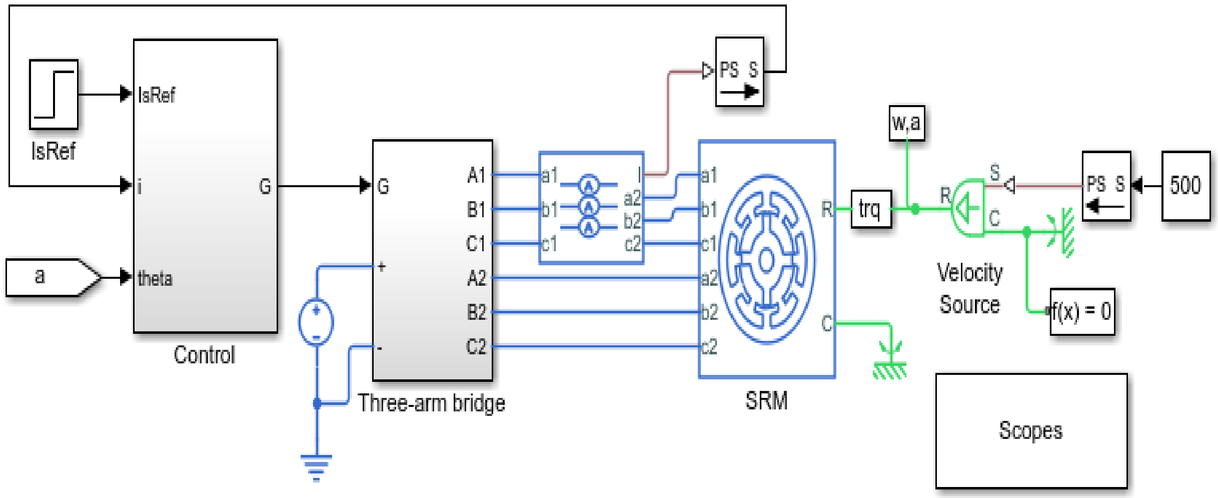


Figure III.35. SRM current control simulation circuit

The SRM current controller performs with a proportional-integral (PI) current control for the switched reluctance motor. it includes pulse width modulation (PWM).

The PWM generation signal is for high side switching devices. When the control signal is greater than the carrier counter value, the PWM generator outputs 1. Otherwise, it outputs 0.

The controller gains for SRM current control are shown in appendix A.

III.8.3. Simulation results of SRM current control

- Figure III.36. Shows the simulation result of SRM phase currents with current control.
- Figure III.37. Shows the simulation result of the current amplitude with current control.
- Figure III.38. Shows the simulation result of the electromagnetic torque with current control.
- Figure III.39. Shows the simulation result of the rotor angular velocity with current control.

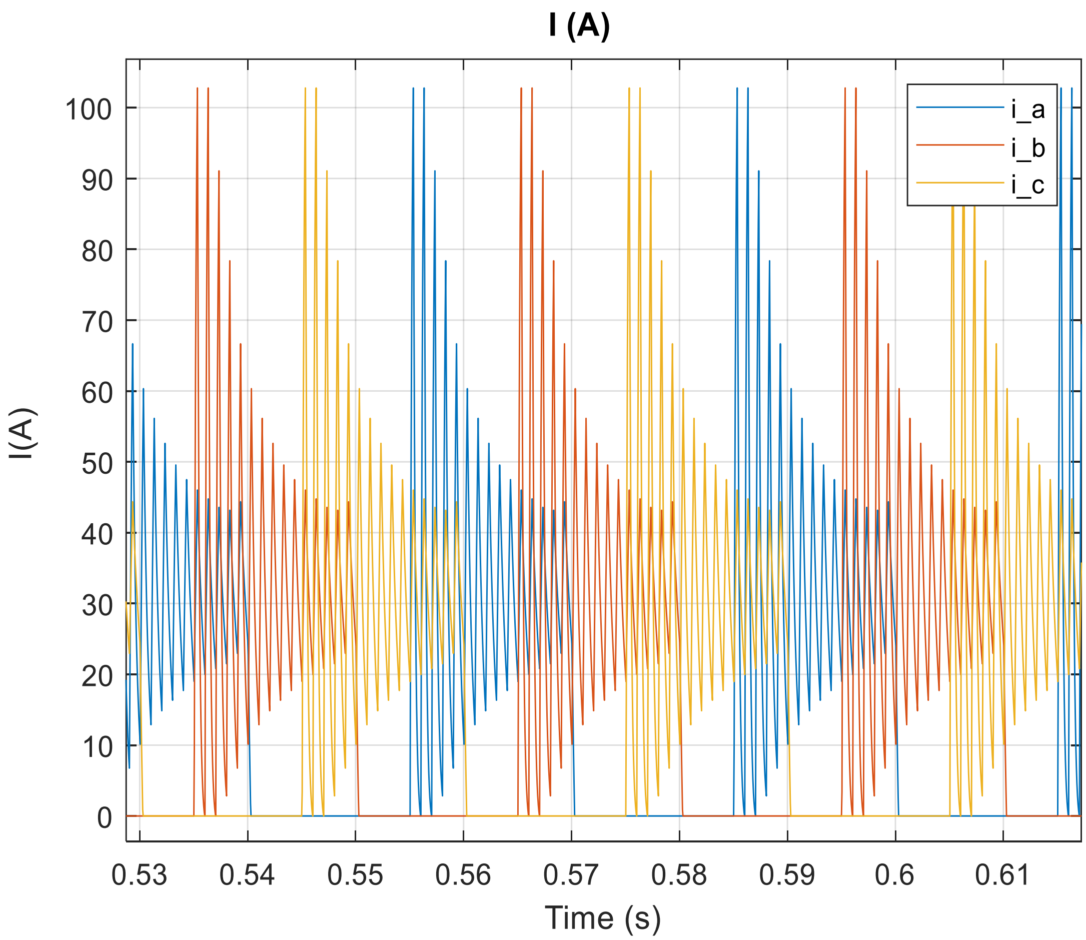


Figure III.36. SRM phase currents with current control

In Figure III.36 SRM phase currents are shown. It is seen that three-phase currents are balanced. This figure shows the influence of the hysteresis current control on the shape of phase current. It can be noticed that the hysteresis band does not remain constant.

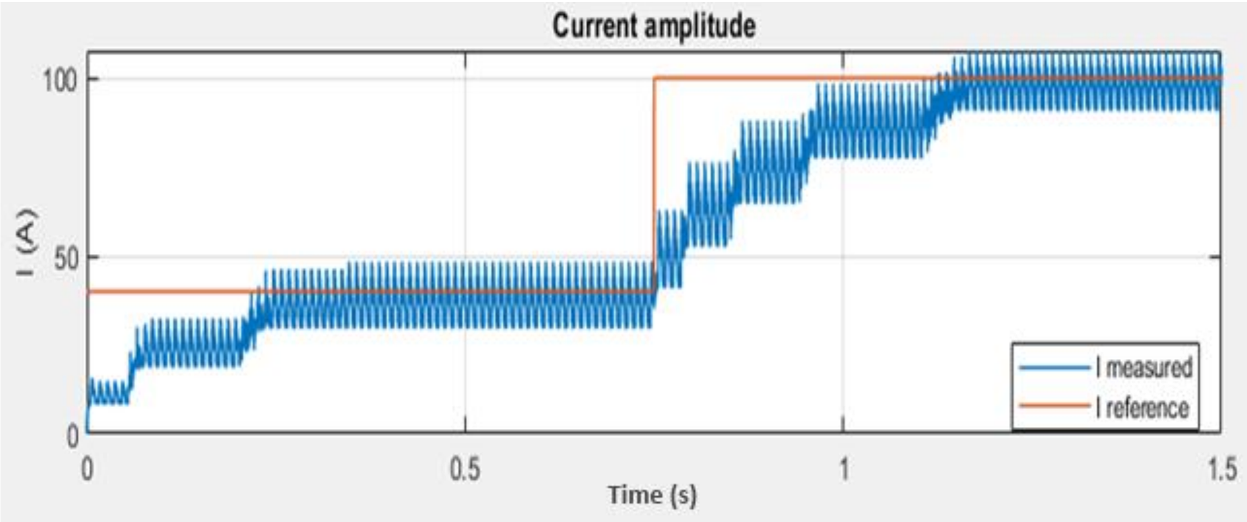


Figure III.37. Current amplitude with current control

SRM current amplitude is shown in Figure III.37., it is understood that SRM reference current is changed from 40 to 100A at 0.75s, the measured current follows it with maximum ±10A ripple.

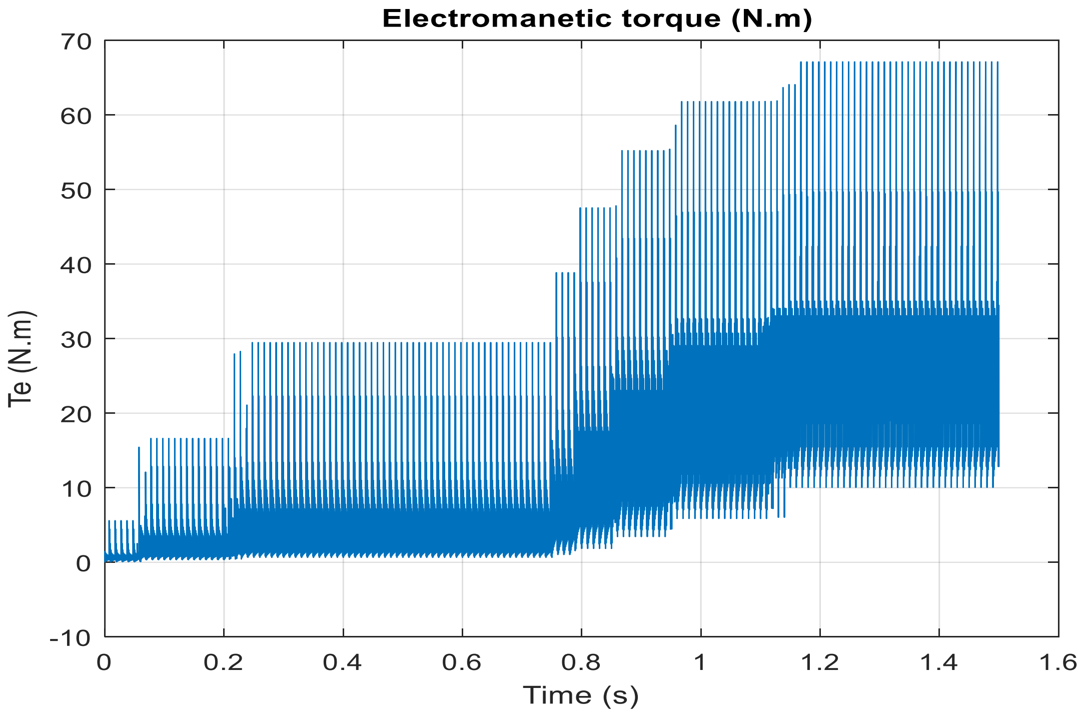


Figure III.38. Electromagnetic torque with current control

SRM torque per phase is shown in Figure III.38. It can be noticed that the current control influence the phase torque the same as the phase current.

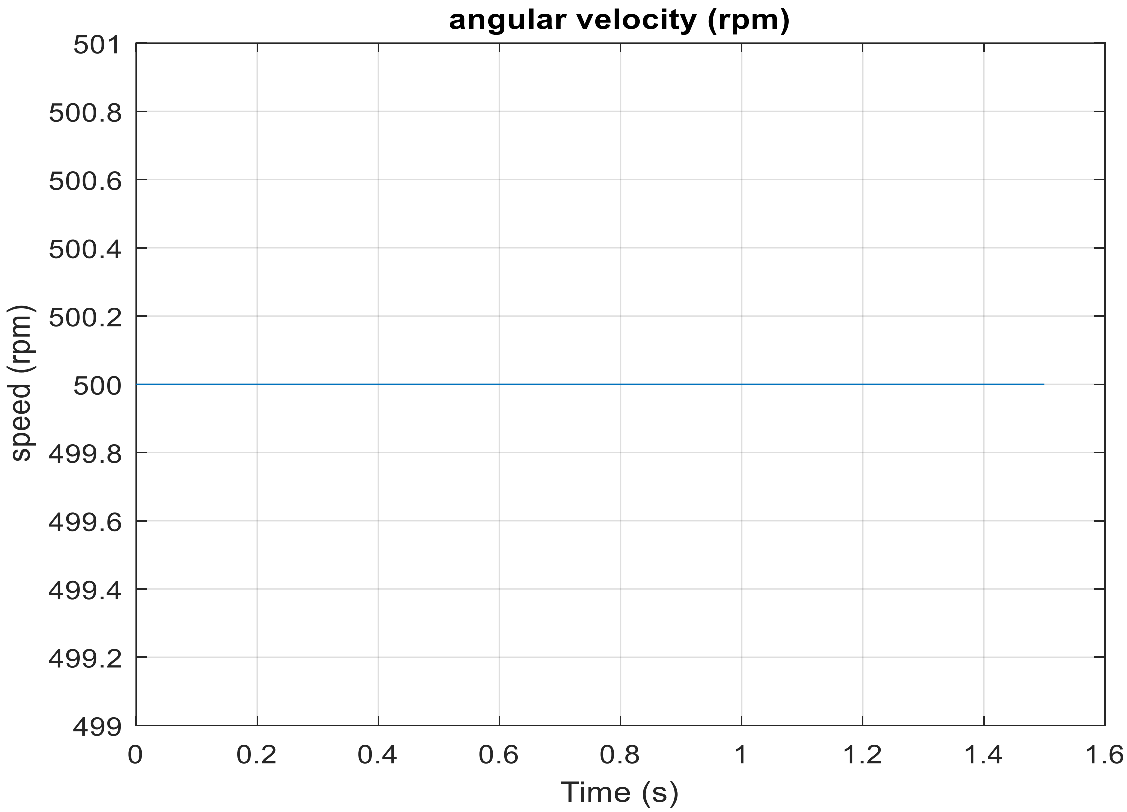


Figure III.39. Angular velocity with current control

In Figure III.39. The speed is set to be constant during the cycle.

From the figures above it'll be deduced:

- The source is ideal in a sense that it is assumed to be powerful enough to maintain the velocity constant regardless of the torque exerted on
- The controlled current function in two zones due to the hysteresis controller.
- Furthermore, current-controlled SRM that is driven using asymmetric bridge converter
- As a result, SRM current is controlled as desired.

III.9. SRM SPEED CONTROL

III.9.1. SRM speed control description

Based on electrical drive system, a DC voltage source feeds the SRM through a controlled three-arm bridge. The converter turn-on and turn-off angles are maintained constant.

The controller gains for SRM speed control are shown in appendix A.

The simulation circuit of SRM current control is shown below in Figure III.40.

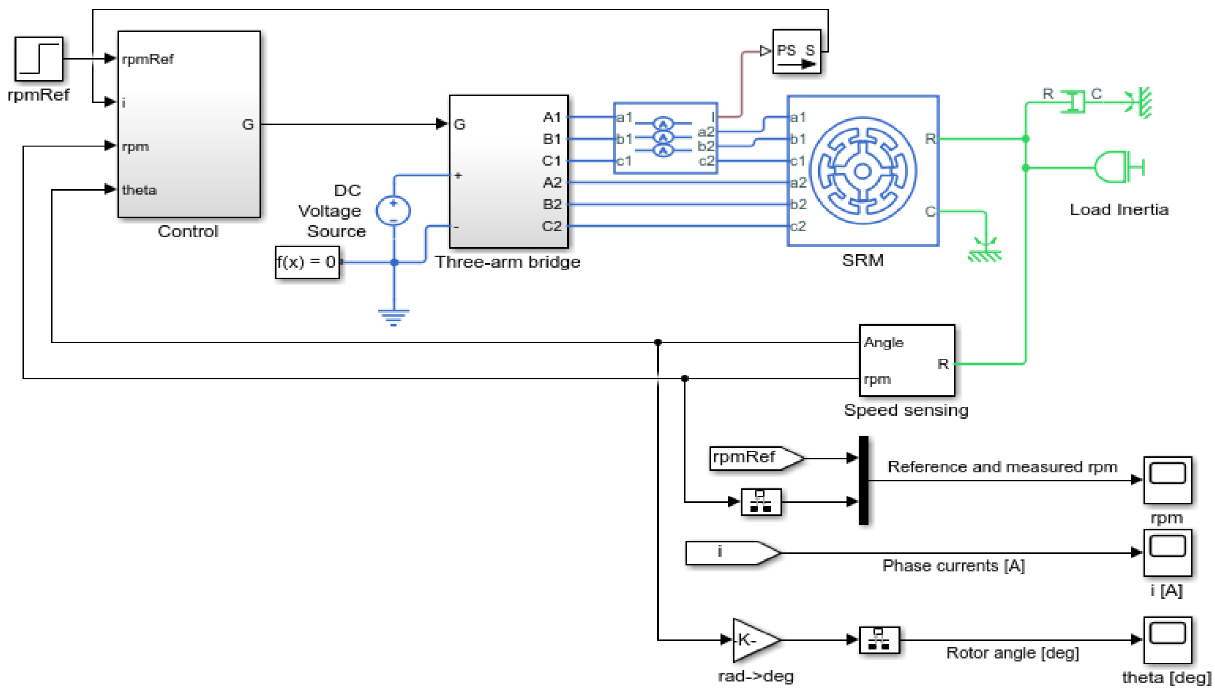


Figure III.40. Simulation circuit of SRM speed control

III.9.2. Simulation results of SRM speed control

The figures below shows the results after controlling the rotor speed in a switched reluctance motor

- Figure III.41. Shows the simulation result of SRM phase currents with speed control.
- Figure III.42. Shows the simulation result of one phase current with speed control.
- Figure III.43. Shows the simulation result of the reference and measured motor speed with speed control.

- Figure III.44. Shows the simulation result of the rotor angle with speed control.

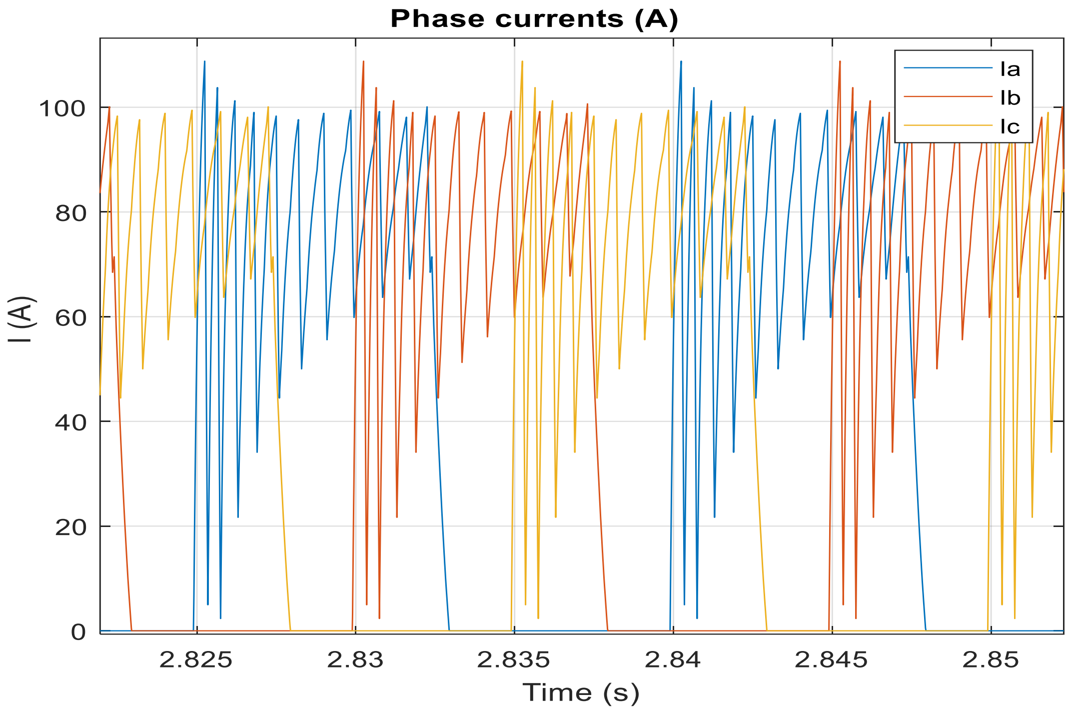


Figure III.41. SRM phase currents with speed control

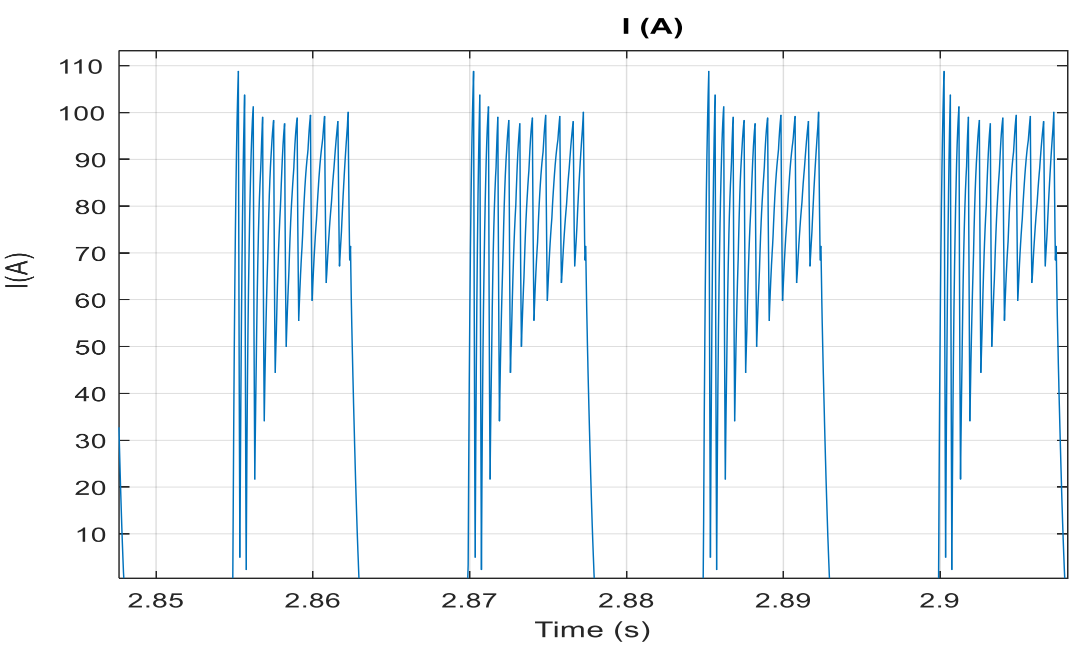


Figure III.42. One phase current with speed control

Figure III.41.and Figure III.42. shows that the speed controller generates a reference current for each SRM phase the SRM phase current seem to be disturb and that's because it has two zones of ripple .one is high and the other is a bit low, due to the hysteresis controller.

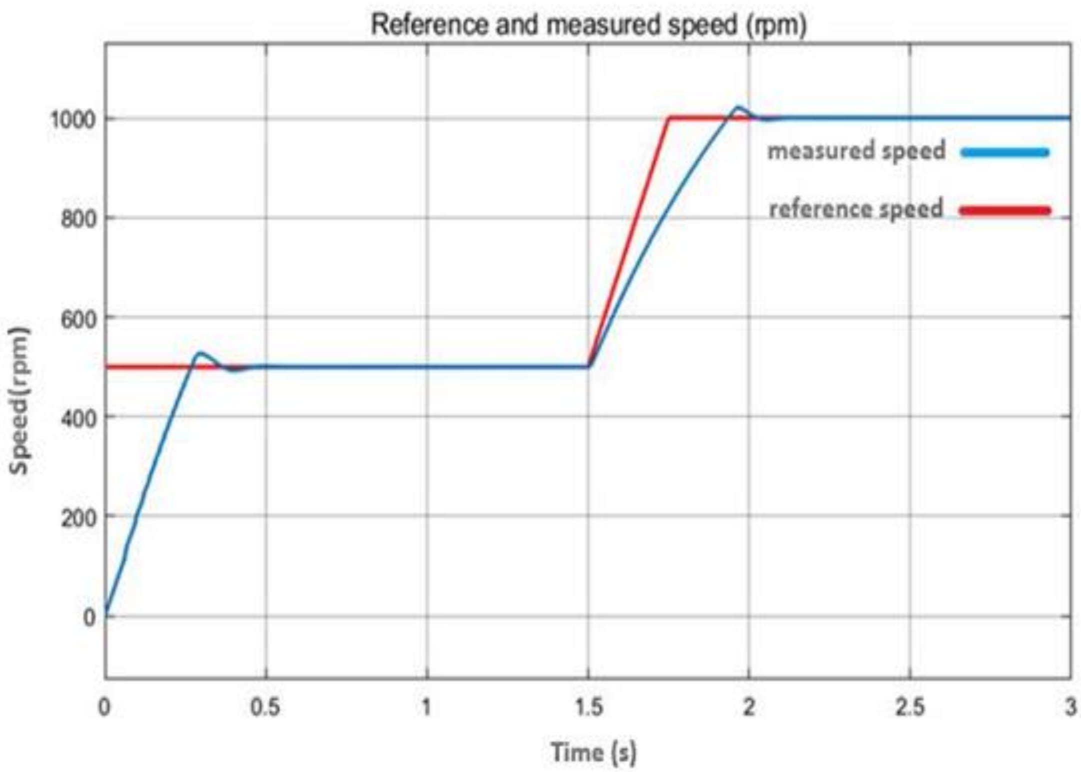


Figure III.43. Reference and measured motor speed with speed control

Figure III.43 shows the SRM speed control result, the speed changes from 0 rpm to 500 rpm and then increases to 1000 rpm. The simulation result proves that the controller is able to track the reference speed closely; the response of the drive is good. The SRM reaches its reference speed in 0.5s. The speed presents a small disturbance that is fast re-established by the controller, this type of control is variable speed control.

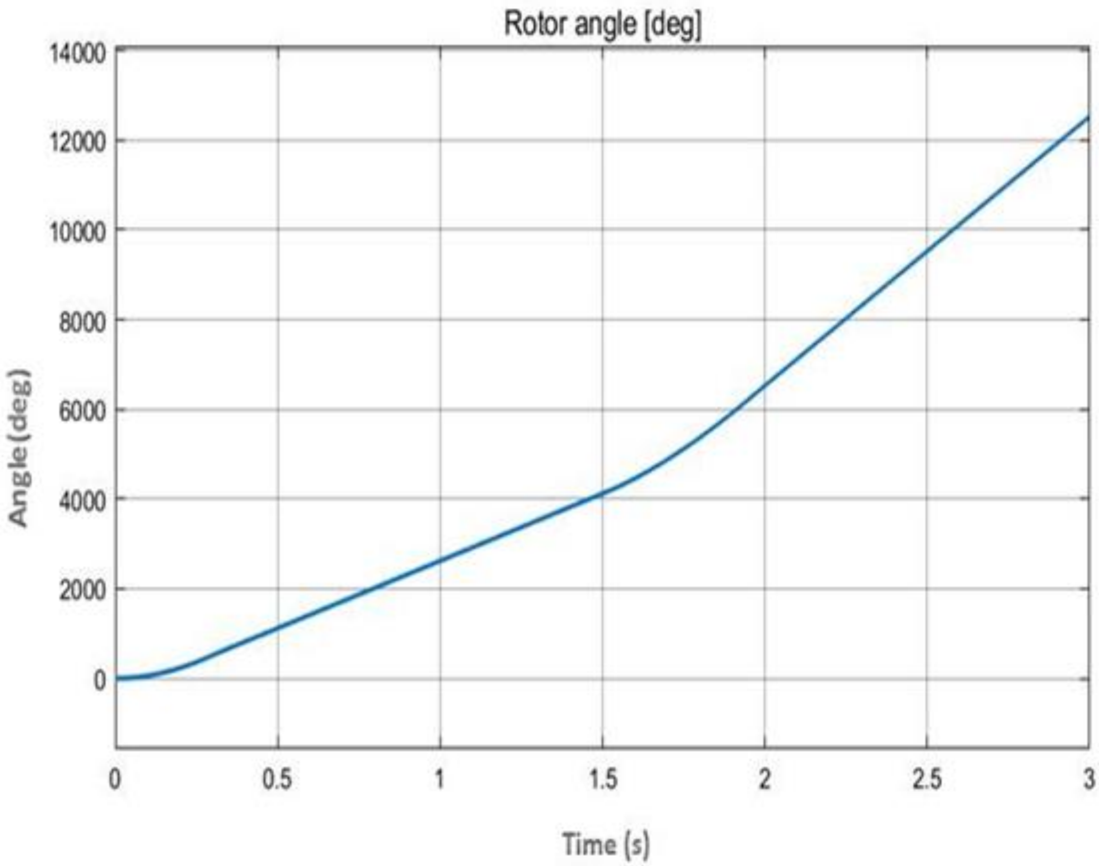


Figure III.44. Rotor angle

Figure III.44. shows the rotor angle, in simple words it shows the number of rotor turns during the cycle, for example at 1.5s the rotor made 11 full turns, these results are obtained from a speed sensor .

III.10. CONCLUSION

The potential of switched reluctance motor is highly greater in variable speed applications. At the same time SRM can operate in all the four quadrants. This chapter mainly contain of two parts, the first part introduces the SRM drive system, its structure and basic topologies of it, and the second one is the simulation results for SRM model and its control system as current control and speed control, the first simulation shows that SRM performs with wide speed range and a high torque to inertia ratio, but it comes along a high torque ripple, the different results of the controllers shows that the potential of switched reluctance motor is highly greater in variable speed applications.

General Conclusion

GENERAL CONCLUSION

The main goal of this thesis is to build up and to simulate of a practical SRM drive system by using Matlab/Simulink, a literature study was done about the fundamental operation of SRM to introduce the basic principles of switched reluctance motor, main motor and converter structure and topologies, and the mathematical approach. SRM was disintegrated for estimating its parameters such as aligned and unaligned position, number of poles configurations and other specifications of this machine.

The dynamic response of the machine was investigated under different working conditions such as no load and loaded operation, the linear mathematical model of a 6-4 SRM was designed in Matlab/Simulink to implement speed and current controllers that are used in the simulation.

The torque production in switched reluctance motor structures comes from the tendency of the rotor poles to align with the excited stator poles. However, because SRM has doubly salient poles and non-linear magnetic characteristics, the torque ripple is more severe than these of other traditional motors. The torque ripple can be minimized through magnetic circuit design or drive control. By controlling the torque of the SRM, low torque ripple, noise reduction or even increasing of the efficiency can be achieved. There are many different types of control methods. In chapter III, detailed characteristics of each control method are introduced in order to give the advanced knowledge about current stator, flux magnetic, speed rotor and torque control method in SRM drive. It's noted that the torque ripple is created by the switching of the hysteresis regulator. The results demonstrated that the speed controller could control the actual speed well; the PI speed controller has a good speed response and the ability to achieve stability.

From all of the above, SRM advantages are as follows:

- Simple structure
- Low manufacturing cost
- High efficiency
- Wide speed range
- High torque to inertia ratio.

However its disadvantages are:

- High torque ripple
- Difficulties to establish the mathematical model
- Vibration and acoustic noise (to see their sources, check appendix B)

- ✓ <u>For the future works:</u>

In SRM drives, both the average torque and torque ripple are affected by the turn-on and turn-off angles and by the current waveforms in the motor phases, and these characteristics change as a function of the motor speed. In many applications, it is highly desirable to have highest torque/ampere ratio and lowest torque ripple and this over a widest speed range possible. The SRM torque characteristic can be optimized by applying appropriated pre-calculated turn-on and turn-off angles in function of the motor current and speed.

REFERENCES

[1] Mike Howell ’’Getting to Know Reluctance Machines’’. Technical Support Specialist EASA St. Louis, MO. Reimagined An Online Event June 15, 2020.

[2] Krishnan R. ‘’Switched Reluctance Motor Drives: Modeling, Simulation, Analysis, Design, and Applications’’. CRC Press, Taylor & Francis Group, Boca Raton, Florida, 2001.

[3] HISTORY OF SWITCHED RELUCTANCE MACHINE (Electric Motor)". what-when-how.com. Retrieved 2020-07-25.

[4] "IEEE Edison Medal Recipients". www.ieee.org. Archived from the original on 19 May 2020.

[5] Wei Ye, Qishuang Ma and Poming Zhang. ‘’ Improvement of the Torque-Speed Performance and Drive Efficiency in an SRM Using an Optimal Torque Sharing Function’’. Applied Science. 2018, 8, 720; doi:10.3390/app8050720.

[6] http://www.dce.edu.in/question-bank/ee6703-sem-eee-viist-au-unit-iii.pdf

[7] A. Derdiyok1, N. Inanh, V. O zbulur and M. O. Bilgih.’’IMPROVING PERFORMANCE OF SWITCHED RELUCTANCE MOTOR BY FUZZY LOGIC CONTROLLER’’ international journal of robust and nonlinear control. Int. J. Robust Nonlinear Control 9, 307—317 (1999).

[8] V. Rallabandi, and B. G. Fernandes, “Design procedure of segmented rotor switched reluctance motor for direct drive applications,” *IET Electr. Power Appl.,* vol. 8, iss. 3, pp. 77-88, 2014.

[9] B. C. Mecrow, E. A. El-Kharashi, J. W. Finch, and A. G. Jack, “Preliminary performance evaluation of switched reluctance motors with segmental rotors,” IEEE Trans. Energy Convers., vol. 19, no. 4, pp. 679-686, Dec. 2004.

[10] T. S. Low, H. Lin, and S. X. Chen, “Analysis and comparison of switched reluctance motors with different physical sizes using a 2D finite element method,” IEEE Trans. Magn., vol. 31, no. 6, pp. 3503-3505, Nov. 1995.

[11] Fleadh, Switched Reluctance Motor Drives, [Online]. Available: http://www.fleadh.co.uk/srm.htm

[12] DURMUS UYGUN, CANER AKÜNER, MEHMET YUMURTACI, ‘’ A New Construction of Switched Reluctance Motor Improving Magnetic Field Energy and Torque

Production’’. Proceedings of the 6th WSEAS International Conference on Applications of Electrical Engineering, Istanbul, Turkey, May 27-29, 2007.

[13] JIn-Woo Ahn (February 10th 2011). Switched Reluctance Motor, Torque Control, Moulay Tahar Lamchich, IntechOpen, DOI: 10.5772/10520. Available from: https://www.intechopen.com/books/torque-control/switched-reluctance-motor.

[14] Carlos Morón, Alfonso Garcia, Jose Andrés Somolinos, ‘’Mathematical Model Switched Reluctance Motor’’ Proceedings of the 4th International Conference on Materials and Applications for Sensors and Transducers. Engineering Materials Vol 644 (2015) pp 87-91.

[15] Internet site, https://people.ucalgary.ca/~aknigh/electrical_machines/other/sr.html.

[16] Marcelo Vinícius de Paula,Thiago de Almada Lopes, Tárcio André dos Santos Barros, Paulo Sergio Nascimento Filho and Ernesto Ruppert Filho,’’ Mathematical Modeling of Switched Reluctance Machines’’. Development and Application DOI: http://dx.doi.org/10.5772/intechopen.89061.

[17] Chang-Ming Liaw, Min-Ze Lu, Ping-Hong Jhou and Kuan-Yu Chou (September 9th 2020). Some Basic and Key Issues of Switched-Reluctance Machine Systems, Modelling and Control of Switched Reluctance Machines, Rui Esteves Araújo and José Roberto Camacho, IntechOpen, DOI: 10.5772/intechopen.89169. Available from: https://www.intechopen.com/books/modelling-and-control-of-switched-reluctance-machines/mathematical-modeling-of-switched-reluctance-machines-development-and-application.

[18] Erdal Şehirli and Meral Altınay (June 21st 2017). Current-Controlled SRM Fed by Three-Phase Boost PFC, Switched Reluctance Motor - Concept, Control and Applications, Ahmed Tahour and Abdel Ghani Aissaoui, IntechOpen, DOI: 10.5772/intechopen.69150. Available from: https://www.intechopen.com/books/switched-reluctance-motor-concept-control-and-applications/current-controlled-srm-fed-by-three-phase-boost-pfc

[19] Sandeep Narla (June 21st 2017). Four-Quadrant Control of Switched Reluctance Machine, Switched Reluctance Motor - Concept, Control and Applications, Ahmed Tahour and Abdel Ghani Aissaoui, IntechOpen, DOI: 10.5772/intechopen.69228. Available from: https://www.intechopen.com/books/switched-reluctance-motor-concept-control-and-applications/four-quadrant-control-of-switched-reluctance-machine.

[20] Radim Visinka, Design of a Motor Control Application, 3-Phase Switched Reluctance (SR) Sensorless Motor Control Using a56F80x, 56F8100 or56F8300 Device, Freescale Semiconductor, Inc. February 2005.

[21] Srinivas Pratapgiri (June 21st 2017). Direct Instantaneous Torque Controlled Switched Reluctance Motor Drive for Fan Type Load and Constant Torque Load, Switched Reluctance Motor - Concept, Control and Applications, Ahmed Tahour and Abdel Ghani Aissaoui, IntechOpen, DOI: 10.5772/intechopen.69280. Available from: https://www.intechopen.com/books/switched-reluctance-motor-concept-control-and-applications/direct-instantaneous-torque-controlled-switched-reluctance-motor-drive-for-fan-type-load-and-constant

APPENDIX A

Parameters of SRM

Stator poles	6
Rotor poles	4
Phases	3
Input voltage	220 v
Stator resistance	0.05 Ω
Inertial	0.05 kg.m²
Friction	0.02 N.m.s
Turn on angle	45°
Turn of angle	75°
Estimated speed	6000 rpm

Controller Gains for SRM Current Control

$K_p = 0.001$

$K_i = 0.05$

$K_{aw} = 1000$

Controller Gains for SRM Speed Control

$K_p = 2.5$

$K_i = 100$

APPENDIX B

Vibrations and Acoustic Noise

Noise sources can be divided into four broad categories: magnetic, mechanical, aerodynamic, and electronic. [2]