KARADENIZ TECHNICAL UNIVERSITY
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

MINIMIZATION OF TORQUE RIPPLES AND SPEED CONTROL OF SWITCHED RELUCTANCE MOTOR THROUGH FUZZY LOGIC BASED DIRECT TORQUE CONTROL METHOD

MASTER'S THESIS

Electrical-Electronics Engr. Hafeezul HAQ

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Hafeezul HAQ

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PREFACE

First and foremost, I am very grateful to Allah, the Almighty, the guide of all guides, for giving me the strength and energy to undergo all the challenges in life. Also, I am grateful to Allah for allowing me to complete this work.

Secondly, I would like to thank all my teachers throughout my life. They have taught me to go through life with my own capacity and capability. They made me realize that success is not an easy task but not an impossible one. They have broadened my perspective on life. They have assisted me to be a better person and to face life with courage.

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Finally, I would like to express my deepest appreciation to my beloved Mother. Thank you for your unconditional love and support. It is because of their spirit that I have been encouraged to overcome every challenge that came along my way. They taught me that in every situation I should not withdraw, hold back, or be afraid. They polished me to excel in life.

Hafeezul HAQ

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DECLARATION

I, the undersigned, declare that this study entitled "Minimization of torque ripples and speed control of switched reluctance motor through fuzzy logic based Direct torque control method" completed under the supervision of Assoc. Prof. Dr. Halil İbrahim OKUMUŞ is my original work and has not been presented for a degree in any other university and that all sources of materials used for the study have been duly acknowledged. 21/02/2017

Hafeezul HAQ

CONTENTS

Yüksek lisans Tezi

ÖZET

BULANIK MANTIK TABANLI DOĞRUDAN MOMENT DENETİMLİ ANAHTARLAMALI RELÜKTANS MOTORUN MOMENT DALGALARININ AZALTILMASI VE HIZ KONTROLÜ

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Danışman: Doç. Dr. Halil İbrahim OKUMUŞ
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Anahtarlamalı relüktans motorları (ARM), statoru ve rotoru çıkık kutuptan oluşan ve sadece statorunda sargı bulunduran, rotorunda herhangi bir sargı ya da sürekli mıknatıs bulundurmayan basit yapılı elektrik makinalarıdır. Günümüzde relüktans motorları imalatının basit ve ucuz olması ve küçük hacimde çok yüksek moment üretebilmeleri, güç elektroniği devresinde diğer kollektörsüz motorlara oranla daha az anahtarlama elemanına ihtiyaç duyulması gibi üstünlükleri nedeniyle sanayide sıkça kullanılmaktadırlar. Bu motorların en büyük dezavantajları düşük hızlarda oluşan moment dalgaları ve bu bozukluk sebebiyle meydana gelen akustik gürültüdür. Bu dezavantajı en aza indirgemek için güç elektroniği devreleri kullanılmaktadır. Güç elektroniği sistemi temel olarak rotor pozisyonu, motor akımı ve gerilim değerlerine göre yapılan hesaba dayalı en uygun çıkış dalga şeklini oluşturmayı hedefler.

Bu tezin ana amacı anahtarlamalı relüktans motor sürücüsünün moment darbelerini azaltmak ve sürücünün hızını kontrol etmektir. İlk olarak motorun çalışması, motorun modellemesi, moment dalgalarını oluşturması ve konvertör topolojisini içeren bir literatür çalışması yapılmıştır, ve sonrasında bulanık mantık denetleyici ile doğrudan moment kontrol yöntemi kullanarak anahtarlamalı relüktans motorun hız kontrolü ve moment dalgalarının azaltma çalışmaları yapılmıştır. Bu çalişmalar ve bulanık mantık denetleyici ile doğrudan moment kontrol yönteminin uygulaması MATLAB/SIMULINK ortamında yapılmıştır.

Anahtar kelimeler: Anahtarlamalı Relüktans Motoru, Bulanak Mantık, Doğrudan Moment Kontrol Yöntemi, Moment Dalgalarının Azaltması, Akustik Gürültüler.

Master's Thesis

ABSTRACT

MINIMIZATION OF TORQUE RIPPLES AND SPEED CONTROL OF SWITCHED RELUCTANCE MOTOR THROUGH FUZZY LOGIC BASED DIRECT TORQUE CONTROL METHOD

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The switched reluctance motor has a salient pole stator with concentrated coil and a salient pole rotor which has no winding on it. The motor's doubly salient structure makes its magnetic characteristics highly nonlinear. The switched reluctance motor gains a significant response in industries in the past decade because of its ruggedness, high torque to inertia ratio, simple structure, high reliability and inexpensive manufacturing capability. These features make it a suitable candidate for various applications and electric drives. However in the field of electric drives a switched reluctance motor drive is having doubly salient structure thus it inherently produces high torque ripples and acoustic noise problems and its controlling difficulties that is an undesirable effect for vehicle applications, especially at low speeds. The control of the SRM is also a difficult task. The motor's doubly salient structure make its magnetic characteristics nonlinear. The flux linkage appears to be a nonlinear function of stator current as well as rotor position. Apart from these for suitable control the SRM should be operated in continues phase to phase switching mode.

The main objective of this thesis is to form and test SRM drive to provide a detailed work in this field. First a literature study for switched reluctance motor is carried out which includes its fundamental operation, modelling, and Torque ripple reduction is done from the motor's structure properties, model equations, operations and converter topologies. And secondly, a fuzzy logic controller based direct torque control method is used for speed controlling and for controlling of torque ripples of the 8/6 SRM drive. Modelling and application of fuzzy logic controller based direct torque control method is done in MATLAB/SIMULINK environment.

Key Words: Switched Reluctance motor, Fuzzy logic controller, Direct torque control, Ripple control, Acoustic noise, Torque ripples.

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

N_s	No. of stator pole
N_r	No. of rotor pole
m	No. of phases
L_a	Aligned inductance
L_u	Un-aligned inductance
β_s	Stator pole arc
β_r	Rotor pole arc
P_r	No. of rotor pole
ψ	Flux linkage per phase
e	Induced emf
K_b	Emf constant
P_i	Instantaneous power input
P_a	Air gap power
T_e	Electromagnetic torque
$V_{\alpha s}$	α-axis stator voltage
$V_{\beta s}$	β-axis stator voltage
$V_{\alpha r}$	α-axis rotor voltage
$V_{\beta r}$	β-axis rotor voltage
$i_{\alpha s}$	α-axis stator current
$i_{\beta s}$	β-axis stator current
$i_{\alpha r}$	α-axis rotor current
$i_{\beta r}$	β-axis rotor current
L_s	Stator inductance
L_m	Mutual inductance
R_s	Stator resistance
R_r	Rotor resistance
$\psi_{\alpha s}$	α-axis stator flux linkages
$\psi_{\beta s}$	β-axis stator flux linkages
$\psi_{\alpha r}$	α-axis rotor flux linkages

$\psi_{\beta r}$	β-axis rotor flux linkages
V_s	Voltage space vector
σ	Leakage co-efficient of the motor
p	No. of pole pairs

1. INTRODUCTION

1.1. Overview

The switched reluctance motor is an old member of the electric machine family. The switched reluctance motor can be tracked back to early 19th century. The name switched reluctance comes from two features of the machine configuration "switched" and "reluctance". The word 'switched' comes because the machine can be operated in a continuous switching mode and the word reluctance comes because both the stator and rotor consist of variable reluctance magnetic circuits. It has many advantages like its simple structure, inexpensive to manufacture and its ruggedness. However it also has some disadvantages like acoustic noises and high torque ripples and controlling difficulties which prevent it from being accepted by the industrial applications.

SRM drives are growing rapidly among the other electrical machine drives such as induction motor drive, DC motor and permanent magnet synchronous motor drive. Perhaps a simplest electrical machine according to its construction, where just stator windings and a magnetic rotor are used. And the popularity of these machines are also supported with the development of switching technologies and converters.

Even its construction is simple but its controlling is quite difficult task since the phase energizing should be done at right time and angle in order to have less torque ripple and speed oscillation. Another big issue is the double salient construction of both stator and rotor, so that torque production by separate phase became a cause of high torque ripples. It also produces ripples in current in DC supply and demand a large filter capacitor. In other side torque ripples also produce acoustic noise due to the induction of radial magnetic forces.

Fortunately, the power electronics and converter topologies recently have a good advancement and it became possible to control these type of machines and to overcome the problems. These motors become competitive with the other motors in most industrial applications.

In summary, switched reluctance motors are robust, cheap, have no winding in the rotor, and have a simple construction and fault tolerance. However for a controlled speed and torque, the stator current must be turned off and on at a right time and right rotor position to produce the desired torque which requires a precise control algorithm.

1.2. Advantages, Limitations and Applications of SRM

1.2.1. Advantages

a. In switched reluctance motor, the rotor consists of steel laminations without any conductors or permanent magnet and the phase winding exists only on stator, so the SRM has several advantages over conventional motors.
b. Because of no winding in the rotor, the copper and heat losses are reduced and the efficiency of the SRM drive increases. So SRM maintains a high efficiency over wide speed and load range.
c. Because of no winding or permanent magnet in the rotor, no brushes on the stator and its salient rotor poles make the SRM rotor inertia less than that of conventional motor. So SRM accelerates more quickly with respect to other motors.
d. Because of the absence of winding on rotor, brush and commutator, it can run up to high speed. It can also run at low speed with full rated torque.
e. The absence of rotor winding results in the reduction of the cost of SRM drive.
f. It can be operated in four quadrants, which means it can be operated in forward or backward direction. These motors can be operated in both motoring and generating mode of operation.
g. Its rugged construction makes it suitable for operation in high temperature and vibrating zone.
h. Its cooling is easy because most of losses occurs in stator.
i. Torque produced in SRM drive is independent of the polarity of the phase current so the power converter becomes simplified with a reduced number of semi converter switches.

1.2.2. Limitations of the SRM

With the above advantages, the SRM drive also has some disadvantages and limitations. Some of those are as following:

a. Switched reluctance motor drives have double salient structure so it causes inherent torque ripple and acoustic noise.
b. The converter used for SRM drive requires high kVA rating.
c. Switched reluctance motor drive cannot operate directly from AC or DC supply, it requires current pulse signal for torque production.
d. Requirement of rotor position sensor, and high torque ripples and acoustic noise limit the switched reluctance motor drive in some applications.

1.2.3. Application of Switched Reluctance Motor

a. Switched reluctance motors have greater potential in motion control and give high performance in harsh conditions like temperature and dusty environment.
b. Using in Electric Vehicles.
c. Household appliances like vacuum cleaner and washing machine, food processors.
d. Aerospace.
e. Variable speed and servo type applications.
f. Compressors, fans, pumps, centrifuges.
g. General purpose industrial drives.

1.3. Torque Ripples and Its Reduction

Torque ripples are the main problem of SR motors which limit their applications. Torque ripples are produced because of double salient structure of the machine. Because the torque production mechanism in SRM drive is basically successive excitations of each stator phase, the double salient structure inevitably results in the torque pulsation between two successive excitations. These torque ripples are controlled by motor design and advance control methods.

1.4. FLC based DTC of Switched Reluctance Motor

Direct torque control method is also used for controlling the torque ripples produced in switched reluctance motor. DTC is an advanced vector control method. In this method, by controlling the magnitude of stator flux linkage and the position of stator flux vector the torque is controlled.

1.5. Objectives

a. To study operation principle of switched reluctance motor and to obtain the mathematical model of SRM.
b. To observe the changes in its characteristics by changing the turn-on and turn-off angles.
c. To observe by using fuzzy logic controller how the actual speed tracks the reference speed.
d. To implement the direct torque control method to reduce the torque ripples and to control the speed of SR motor drive.
e. To design fuzzy logic controller for controlling torque and speed of switched reluctance motor.

2. OPERATION, MODELING AND SIMULATION OF SWITCHED RELUCTANCE MOTOR

2.1. SRM Configuration

Switched reluctance motor is made up of laminated stator and rotor with N_s= 2mq poles on stator and N_r poles on rotor, where 'm' represents number of phases and each phase is made up of concentrated windings on '2q' stator poles. The stator of SRM is salient pole with concentrated winding and the rotor is salient pole with no winding or permanent magnet. It means switched reluctance motor is having double salient pole structure and is single excited with different numbers of rotor and stator pole. The main common stator and rotor poles configuration are 6/4, 8/6, and 10/8. The each two opposite diametrically poles of stator are connected in series to form a single phase. It means that 8/6 stator/rotor pole configuration represent the 4 phase configuration of SRM. The cross section of these motors are shown below in Fig. 2.1[39].

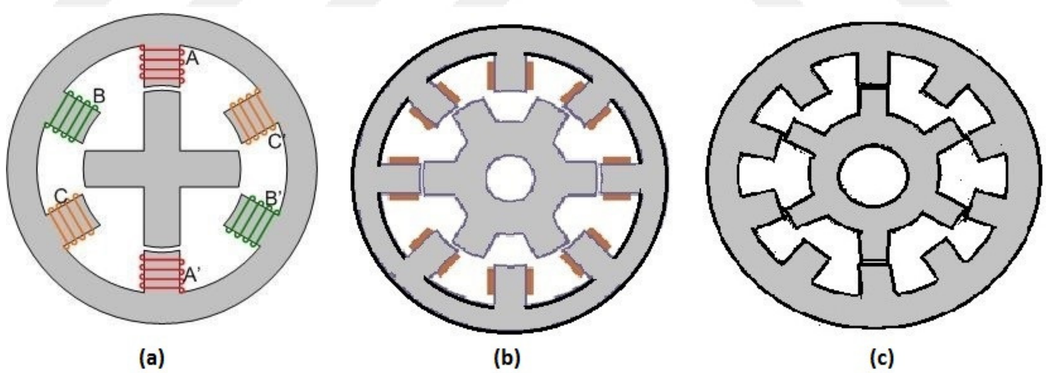

Fig. 2.1. Configuration of SRM. (a) 6/4 (b) 8/6 (c) 10/6

2.2. Principle of operation

A magnetic reluctance which gives rise in order to form stable equilibrium position in an electromagnetic system is the main principle of operation of switched reluctance motor. When the two opposite poles are excited, it attracts the nearest rotor poles in order to produce torque. When these rotor poles get aligned with stator pole, then the stator energized pole become de-energized and its adjacent stator pole gets pulse and becomes energized and thus it attracts the other pair of rotor poles. By to this way the torque is produced in switched reluctance motor and it start running.

When both the stator and rotor poles get parallel to each other, this means they are aligned. Then that position is called aligned position. During aligned position the phase inductance reaches its maximum value while reluctance reaches to its minimum value. When the rotor pole moves away from its aligned position, the phase inductance decreases gradually. When the rotor becomes unaligned from stator pole then the phase inductance reaches to its minimum value while reluctance reaches to its maximum value [40].

The cross section of a three phase switched reluctance motor is shown in Fig. 2.2. For the continuous rotation of SRM, every phase winding must be energized by a suitable current at a suitable rotor angle. So with the rotation of rotor the excitation is changing phase to phase sequentially [40].

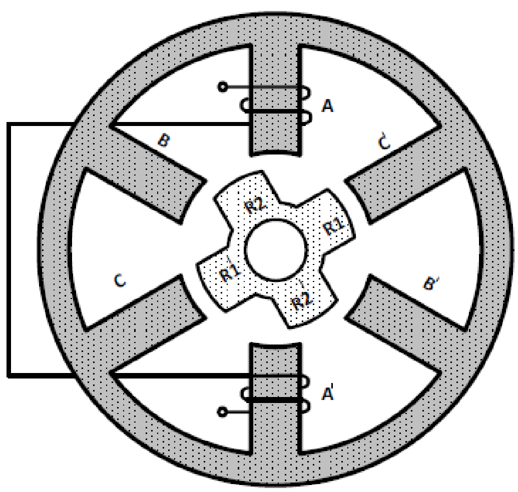

Fig. 2.2. Cross section of a three phase SRM, unaligned position [40]

Consider that the stator pole A-A' and the R_2-R_2' pole of the rotor are in an unaligned position. By applying current to phase winding A, it become energized, flux passes across the stator pole A-A' and R_2-R_2' pole of the rotor. By this, a force is produced which causes the rotor pole R_2-R_2' to rotate towards the stator pole A-A'. When the rotor pole R_2-R_2'

becomes aligned with the stator pole A-A', the current to stator pole is turned off. This rotation is shown in Fig. 2.3.

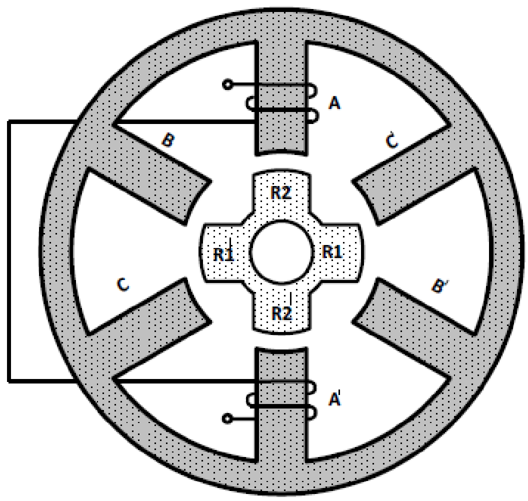

Fig. 2.3. Cross section of a three phase SRM, aligned position [40]

When the rotor is in aligned position, the inductance becomes maximum and the reluctance becomes minimum. In unaligned position the inductance is minimum and the reluctance is maximum. The current to the stator poles is applied through switching converter in step. That's why it is called switched reluctance motor [40].

2.3. Relationship between Inductance and Rotor Position

The characteristics of torque can be obtained by the relationship of flux linkages and the rotor position as a function of the current. The number of rotor poles and the rotor and stator pole arc determine the changes in inductance. Below are some angles derived from Fig. 2.4 and Fig. 2.5.

$$\theta_1 = \frac{1}{2}\left\{\frac{2\pi}{P_r} - (\beta_s + \beta_r)\right\} \qquad (2.01)$$

$$\theta_2 = \theta_1 + \beta_s \qquad (2.02)$$

$$\theta_3 = \theta_2 + (\beta_r - \beta_s) \qquad (2.03)$$

$$\theta_4 = \theta_3 + \beta_s \tag{2.04}$$

$$\theta_5 = \theta_4 + \theta_1 = \frac{2\pi}{P_r} \tag{2.05}$$

Where β_s and β_r are the stator and rotor pole arc and P_r is the number of rotor poles.

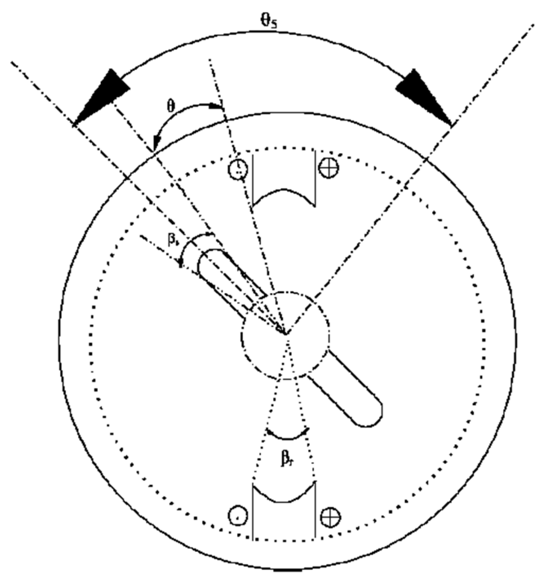

Fig. 2.4. Basic rotor position in a two pole SRM [40]

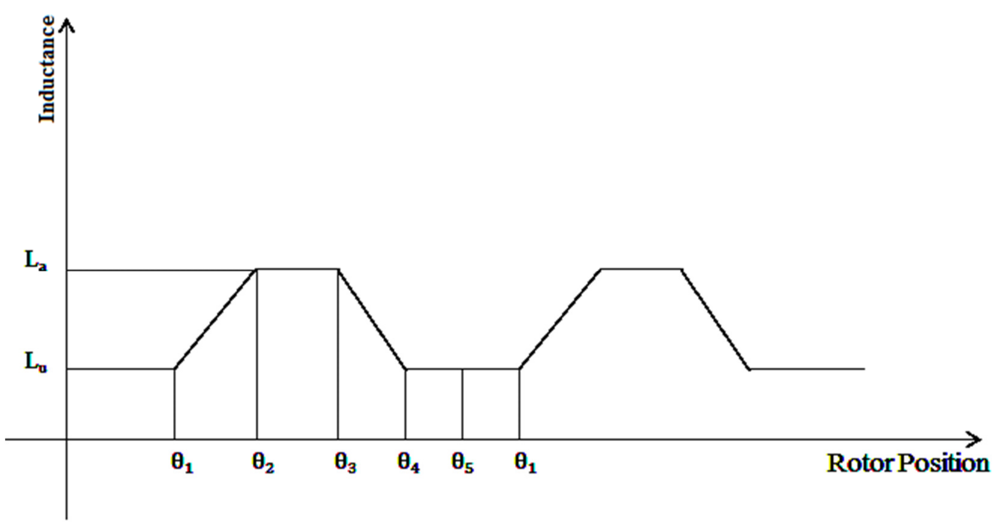

Fig. 2.5. Inductance profile of switched reluctance motor [40]

a. **0-θ_1 and θ_4-θ_5:** This is the unaligned position region. Thus inductance in this region is minimum and almost constant. This minimum inductance is called unaligned inductance, L_u. In this region the torque production is almost zero.

b. **θ_1 -θ_2:** In this region the rotor pole is crossing the stator pole. So the flux flows in stator and rotor lamination in this region. So the inductance starts to increase with respect to rotor pole position and it results in a positive slope. In this region positive torque is produced. This region is up to the point where rotor pole completely overlaps the stator pole.

c. **θ_2 -θ_3:** In this region the rotor pole is completely aligned with stator pole. The flux in this region is very high so the inductance produced is very high in this region. This inductance is called aligned inductance, L_a. As torque depends on the rate of change of inductance so the torque in this region is almost zero even the current is present.

d. **θ_3 -θ_4:** In this region the rotor is going away from stator pole. In this case the aligned position is going to unaligned position so the inductance starts to decrease and a negative slope is produced and results in a negative torque.

In real it is not possible to achieve the ideal inductance profile due to saturation.

2.4. Types of Switched Reluctance Motor

The switched reluctance motors are classified according to nature of the motion (rotating or linear). The linear switched reluctance motors are used for servo purposes. The main classification of switched reluctance motor is shown in Fig. 2.6.

2.4.1. Rotary Switched Reluctance Motors

The rotary switched reluctance machines are further classified by the direction of its magnetic field path with respect to the axial length of the machine. If the magnetic field path is perpendicular to the machine shaft, i.e. the magnetic field path is along the radius of the cylindrical rotor and stator, this type of machine is classified as radial field switched reluctance machine. If the magnetic flux path is along the axial direction, the machine is called axial field switched reluctance machine. The axial field SRMs are suitable for such application where the total length may be constrained, such as in a ceiling fan or in a propulsion application. The main disadvantage of this type of SRM is that the stator lamination have to be folded one on top of the other unlike the simple stacking of lamination in the radial field type. The converter and controller configuration are the same for the both [41].

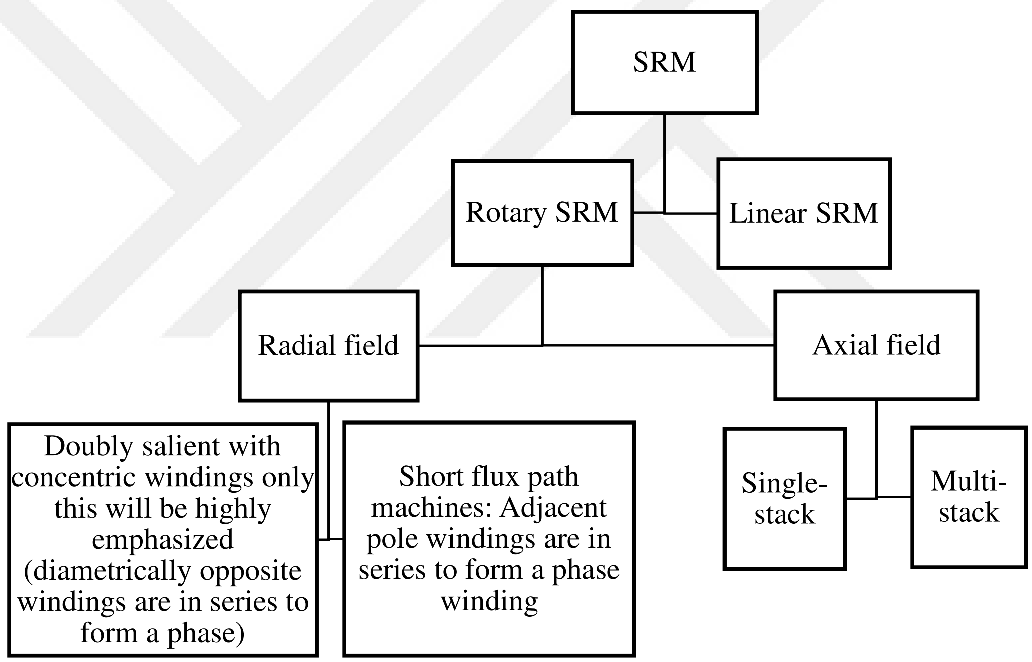

Fig. 2.6. Classification of Switched Reluctance Motor

2.4.2. Linear Switched Reluctance Motors

Linear switched reluctance motors are mainly used for machine tool drives because by using this there is no need of mechanical subsystem of gears and rotary to linear motion converters. By using linear motors, the position accuracy is improved. The linear switched reluctance motor is shown in Fig. 2.7.

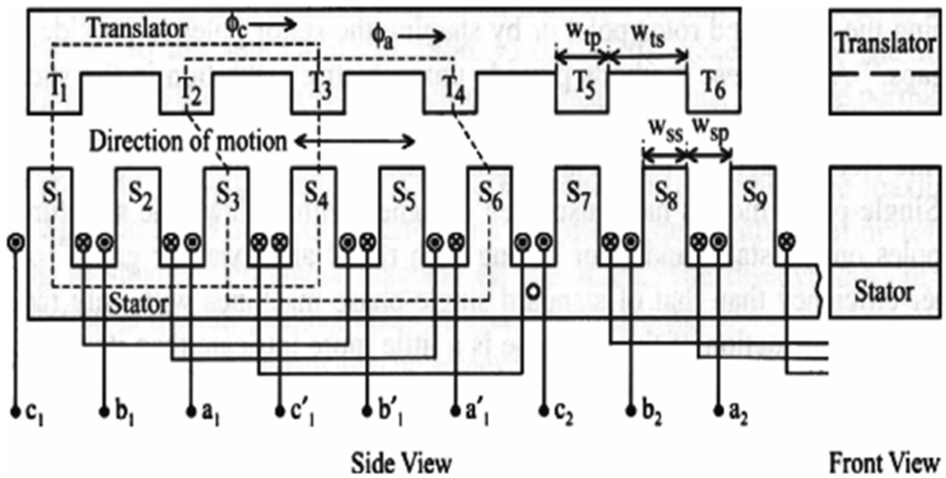

Fig. 2.7. Three phase Linear Switched Reluctance Motor [41]

In linear switched reluctance motor, windings are either on stator or on translator (the moving part) whereas in rotary motor, the windings are always on stator. Regardless of the windings the fixed part is always called stator or track and the moving part is called translator. There are two main classification of linear switched reluctance motor, longitudinal flux and transverse flux.

The linear switched reluctance motor may also have either two stator or two translators to make a doubly sided linear switched reluctance motor. Its advantage is high force density and lower inductance with respect to single side linear switched reluctance motor [41].

2.5. Mathematical Modelling of Switched Reluctance Motor

For an accurate analysis of the motor behavior, it is needed to obtain a relatively complex mathematical approach. Across the terminals of a SRM drive, the instantaneous voltage depends on its flux linked by the winding and the resistance of the winding. The flux linkages are composed of two variables, the current 'i' and the rotor position i.e. angle 'θ'. The mathematical model describing the equivalent circuit for one phase is shown in Fig.2.8.

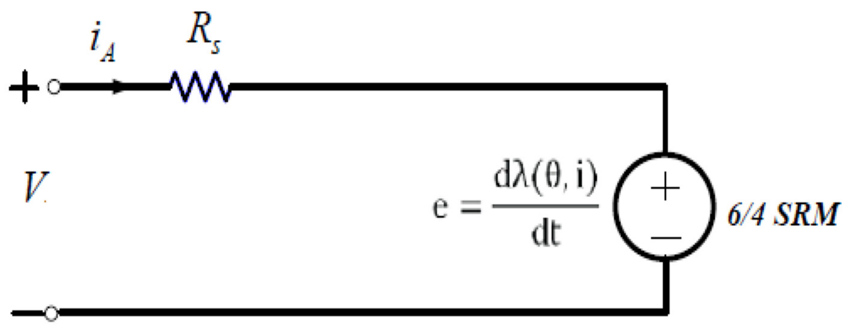

Fig. 2.8. Equivalent circuit of one phase of Switched Reluctance Motor

$$V = R_s i + \frac{d\lambda(\theta, i)}{dt} \quad (2.06)$$

Where 'V' is the applied phase voltage, 'R' is the phase resistance, and 'λ' is the flux. The flux is the product of inductance and winding current.

$$\lambda(\theta, i) = iL(\theta, i) \quad (2.07)$$

Substituting this into (2.06).

$$V = R_s i + \frac{dL(\theta, i)i}{dt} = R_s i + L(\theta, i)\frac{di}{dt} + i\frac{d\theta}{dt}\frac{dL(\theta, i)}{d\theta} \quad (2.08)$$

$$V = R_s i + L(\theta, i)\frac{di}{dt} + i\frac{dL(\theta, i)}{d\theta}\omega_m \quad (2.09)$$

Here this equation consists of three terms which are resistive voltage drop, inductive voltage drop and induced emf.

The induced emf is represented as:

$$e = i\frac{dL(\theta, i)}{d\theta}\omega_m = K_b \omega_m i \quad (2.10)$$

From (2.09) we can get the instantaneous power by multiplying both side with *i.*

$$P_i = Vi = R_s i^2 + iL(\theta, i)\frac{di}{dt} + i^2\frac{dL(\theta, i)}{d\theta}\omega_m \quad (2.11)$$

The energy stored in an inductor is represented as:

$$W = \frac{1}{2} L(\theta, i) i^2 \tag{2.12}$$

The power for an inductor is given as the rate of change of energy over time so the power is given by:

$$P_L = \frac{d}{dt}\left[\frac{1}{2} L(\theta, i) i^2\right] = \frac{1}{2} i^2 \frac{dL(\theta, i)}{dt} + L(\theta, i) i \frac{di}{d\theta} \tag{2.13}$$

$$P_L = \frac{1}{2} i^2 \omega \frac{dL}{d\theta} + Li \frac{di}{d\theta} \tag{2.14}$$

According to law of conversation of energy, the mechanical power can be found by subtracting the winding resistance losses, 'Ri^2', and the losses due to inductance that is (2.14) from the instantaneous power. So by subtracting these two values from (2.11), we get the mechanical power as: [5]

$$P_m = \frac{1}{2} \frac{dL(\theta, i)}{d\theta} \omega_m i^2 \tag{2.15}$$

The mechanical power is also expressed as the product of electromagnetic torque and rotor speed so we can calculate the switched reluctance motor torque as.

$$T_e = \frac{P_m}{\omega_m} = \frac{1}{2} i^2 \frac{dL(\theta, i)}{d\theta} \tag{2.16}$$

The torque is directly proportional to the square of current. The torque will be unidirectional whether current is positive or negative. But the torque is also directly proportional to $dL(\theta,i)/d\theta$. So if the value of $dL(\theta,i)/d\theta$ is positive, the torque produced will be positive that means the motoring will be created and the electrical power will be converted to mechanical power. If the value of $dL(\theta,i)/d\theta$ is negative then the torque produced will also be negative that means the generator action will occurs and the mechanical power will be converted back to electrical power [5].

2.6. Converters Used for Switched Reluctance Motor

For a smooth rotation and for an optimal torque output phase to phase switching in switched reluctance motor is precisely timed with rotor position. Rotor position feedback or sensor-less feedback method is required for proper control. This phase to phase switching is obtained by power semiconductors. The so called power semiconductors refer to the circuits called power converters which are used for the SRMs switching requirements.

Generally there are two main classes of switching converters, dependent and independent structure, according to the criterion whether it makes the control between the successive excited phases independent or not. Generally the dependent structure topology needs less powerful semiconductor devices than the independent structure.

As the torque produced in switched reluctance motor drive is independent of the polarity of the excitation current, so the SRM drive needs only one switch per phase. This is opposite to AC motor drives where they need at least two switches per phase for current control. Moreover in AC drives the windings are not in series with the switches, leading to irreparable damage in short through faults. The SRM drives always have a phase winding in series with a switch. In case of short through fault, the rate of rise in current is limited by the inductance of winding and provide time to initiate protective relaying to isolate the faults. The phases of the SRM are independent so in case of one winding failure, uninterrupted operation of the motor drive is possible, though with reduced output power [41].

2.6.1. Converter Configuration

In SRM drives, there is complete independence to each phase winding for control and torque generation because the mutual coupling between phases is negligible in SRM drives. Despite its advantageous, a lack of mutual coupling needs a careful handling of the stored magnetic field energy. During commutation of a phase, the magnetic field energy has to provide with a path, otherwise it generates an excessive high voltage across the winding which further results in the failure of switching converters. The handling of this energy result with a unique but numerous converter topology for SRM drives. The energy could be freewheeled, results in partially converting mechanical to electrical and partially dissipating it in the machine windings. Another option is to return it back to dc source either by electronic or electromagnetic means. All of these options result in power converter topologies with q, q+1, 1.5q and 2q switch topologies, where *'q'* is the number of machine phases. This configuration is shown in Fig.2.9.

Some converters which have the same number of switches may contain different characteristics. So the converters are also classified according to the commutation type. An SR converter configuration according to commutation is shown in Fig. 2.10 [41].

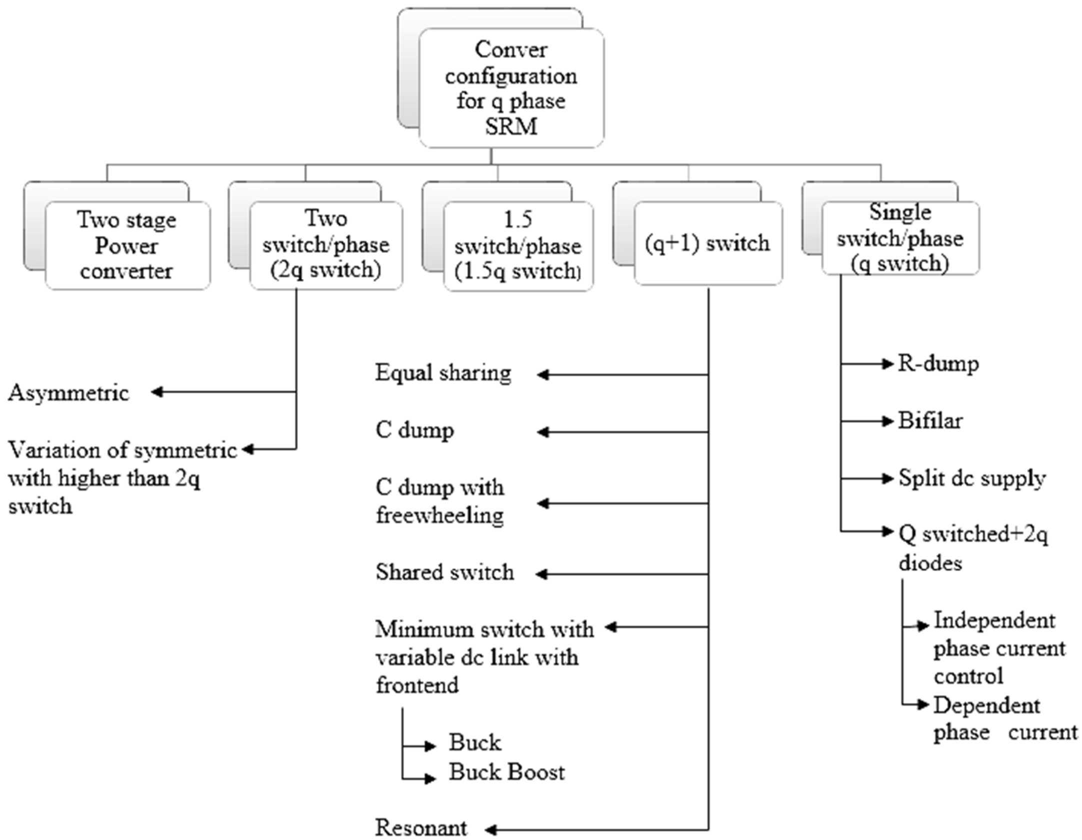

Fig. 2.9. Classification of Power converters for Switched Reluctance Motor

Based on commutation type the four major types are dissipative, magnetic, resonant and capacitive type.

The dissipative type dissipates its stored energy in a phase resistor, in an external resistor or using both of them. This type of converter is simple, having low cost and less amount of semiconductor components.

The magnetic type using a closely coupled second winding for the dissipation of stored energy. The main advantage is simplicity. The one switch per phase power circuit can be used with it. However the coupled extra winding increases the weight and cost of the motor and converter [41].

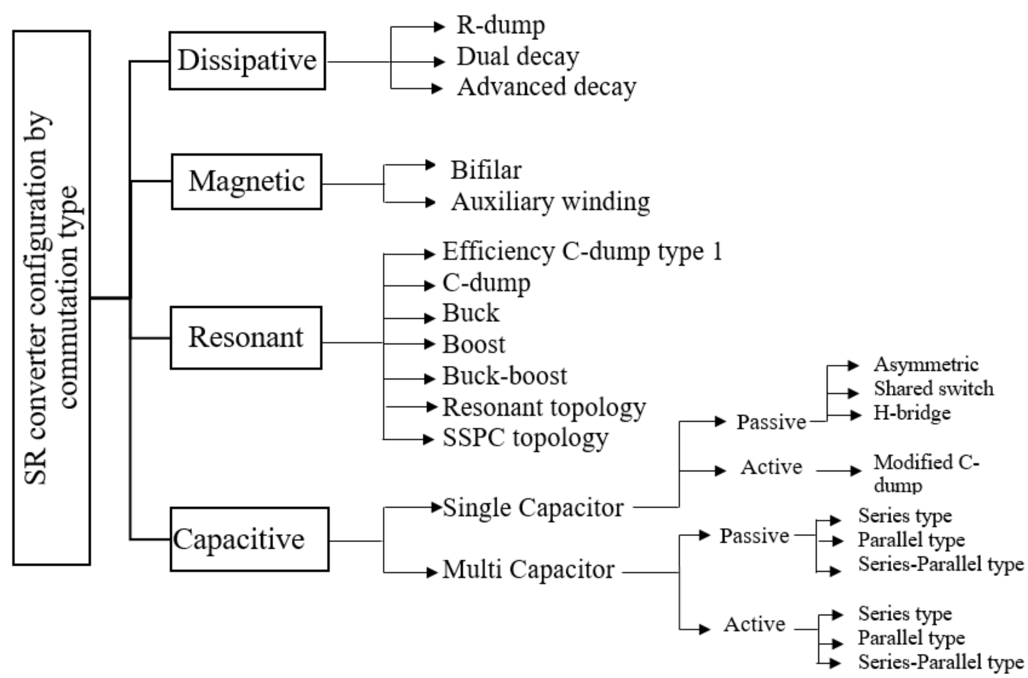

Fig. 2.10. SRM converter configuration according to communication

The resonant type uses one or more than one external inductors for buck, boost or resonant purpose. The inductance, the diode and the power switch form a snubber circuit. So the dump voltages can be easily controlled and low voltages is easily boost. The main advantage is that the phase voltages can be regulated by snubber circuit. However the inductor increase the weight and the cost of converter [41].

The stored energy in capacitive converter is fed directly back to the boost capacitor, the dc link capacitor or to both of them. Compared to other converters one extra component is added to main circuit which increases the losses of converter. In this type, the stored energy is easily feedback using only phase winding therefore the capacitive converter is more effective.

2.6.2. Asymmetric Bridge Converter

Fig. 2.11(a) shows the asymmetric bridge converter for one phase of switched reluctance motor drive. The similar converter is connected with the rest of phases. The circuit has two switches i.e. two transistors, the turning ON these both transistor will circulate a current in the related phase of SRM drive. The T_1 and T_2 are turned off when the current rises the commanded value. The energy stored in the motor winding will keep the current to flow in the same direction until it is depleted so the diode D_1 and D_2 will become forward biased resulting to recharging of the source. It decreases the current and the current come to the level of command. This operation is explained in Fig. 2.11(b).

Assuming that for motoring action a current of magnitude I_p is required to flow during the positive inductance slope. The A-Phase current command is generated with a linear inductance profile. Here at the beginning and commutation both time the phase advancing is neglected. The current command i_a^* is enforced with a current feedback loop for comparing with the phase current i_a. The current error is processed through a hysteresis controller with a current window of Δi. if the current error exceed -Δi, the switches T_1 and T_2 turned off simultaneously.

Hysteresis controller is implemented here because of its simplicity. At that time, the diodes D_1 and D_2 conduct and take the current to dc source by completing the path.

Now the voltage of phase A becomes negative and is equal to the source voltage, V_{dc}. At the same time the energy stored is sent to the source, thus the energy is exchanged during one cycle between the load and source repeatedly. After the initial start at the time of turn-on and turn-off of transistors the machine winding has a double rate of change of the dc link voltage, resulting in a higher deterioration of insulation. Thus this control strategy (strategy I) generate more ripples which reduce the life of the dc source capacitor and it also increase the losses in switching of the power switches. So it need an alternating switching strategy.

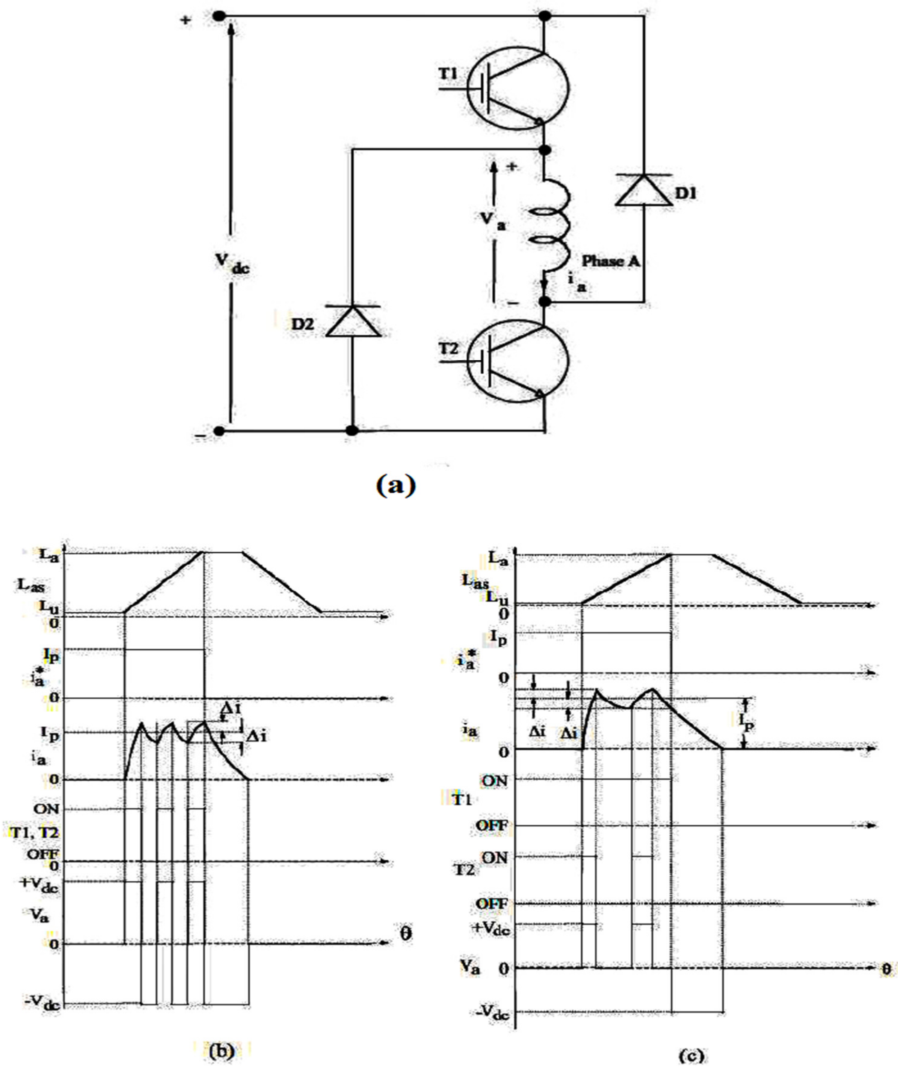

Fig. 2.11. (a) Asymmetric converter for SRM drive. (b) Operational waveforms of the asymmetric bridge converter (strategy I). (c) Operational waveforms of the asymmetric bridge converter (strategy II)

The energy stored in the phase A can be circulated in itself by turning off T_2 only (strategy II). Now in this case the current will flow and will complete its path through T_1, phase A and D_1, the latter having forward biased soon after T_2 is turned off. If we neglect the voltage drop across diode and transistor the winding voltage becomes zero, which is shown in Fig.2.11(c). It will decrease the current magnitude from $I_p+\Delta i$ to $I_p-\Delta i$ in a short time than the previous strategy. This case reduces the switching frequency and by this the switching losses also reduce.

When the current command become zero, the both of transistors turned off simultaneously. At the same time the voltage across the winding is $-V_{dc}$ until the D_1 and D_2 conduct, and after it becomes zero. During the off time of T_2 when T_1 is on, the voltage across T_2 is equal to the source voltage. Therefore the power switches and diodes have to be rated to a minimum of source voltage.

Similarly, the current rating of the diodes can be evaluated. While the current is circulating for a longer time compared to recharging the source, it has an advantage of converting this stored energy to mechanical work. While this form of control can be used for current control and the recharging of source is advantageous when the current has to be turned off rapidly.

Such a time come when the inductance profile becomes straight or is starting of a negative slope. Any further conduction of current in this time causes a loss of energy and production of the negative torque, which reduce the average motoring torque. It is to note that this converter needs two diodes and two transistors for each phase, resembling the conventional ac motor drives [41].

2.7. Simulation of Switched Reluctance Motor Drive

2.7.1. Block Diagram of Switched Reluctance Motor Drive

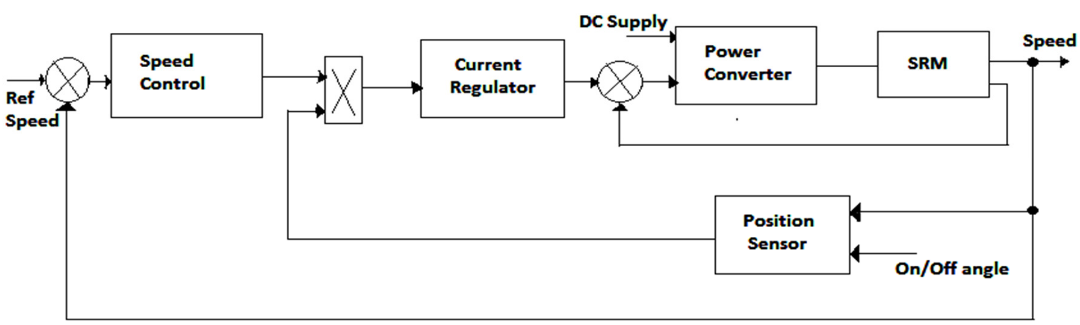

Fig. 2.12. Block diagram of SRM drive

This is a close loop control circuit of the switched reluctance motor drive. The actual speed will track the reference speed and the machine will remain in synchronous. For speed control here proportional- integral controller or fuzzy controller can be used. The speed controller gives a controlled error signal, further it is combined with angle at multiplexer to give the current signal. The signal further compared with the actual current signal to get a pulse signal for the gate of power converter. In power converter the bridge converters are used. For three phase motor three, for four phase motor four and for five phase motor five bridge converters are used.

2.7.2. Simulation of SRM Drive

The switched reluctance motor drive in Simulink environment is shown in Fig.2.13. This drive is without control.

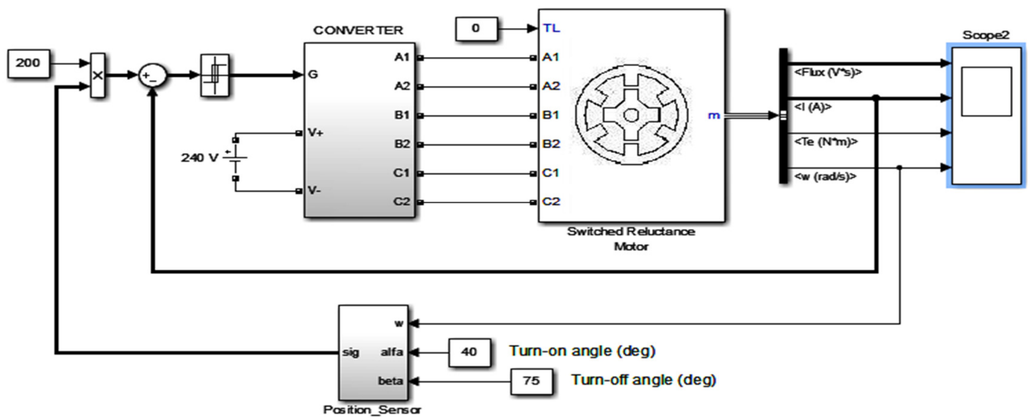

Fig. 2.13. Simulink diagram of SRM drive

Here in this diagram a three phase Switched Reluctance Motor is simulated with a given speed of 200 rad/s. The motor is 60kW, transistor's turn ON and turn OFF angles are 40 and 75 respectively. The input voltage to SRM is applied through three phase asymmetric power converter having three legs, each leg is consist of two IGBTs and two freewheeling diodes. At the time of conduction the active IGBT conducts and applies the positive voltage to the phase winding to drive current. During freewheeling period the diodes conduct and return back the stored energy to dc source. By attaching a position sensor to the rotor, the turn OFF and turn ON angles of the motor phases can be accurately imposed. These angles control the torque waveforms.

In this circuit a dc source of 240V is used. The turn ON and turn OFF angle for the converter is kept constant at 40 and 75 degree respectively. The reference current here is

200A and the hysteresis band is +10 to -10. The SRM is started by applying a step reference to the input. Here, in this circuit only the current is controlled and the speed is uncontrolled, it increase according to the dynamics of the motor. The drive waveforms, magnetic flux, phase currents, motor torque, and motor speed are displayed on scope. From here it can be observed that the SRM has a high torque ripples and it depends on the converter turn ON and turn OFF angles. The output waveform are shown in below Fig.2.14.

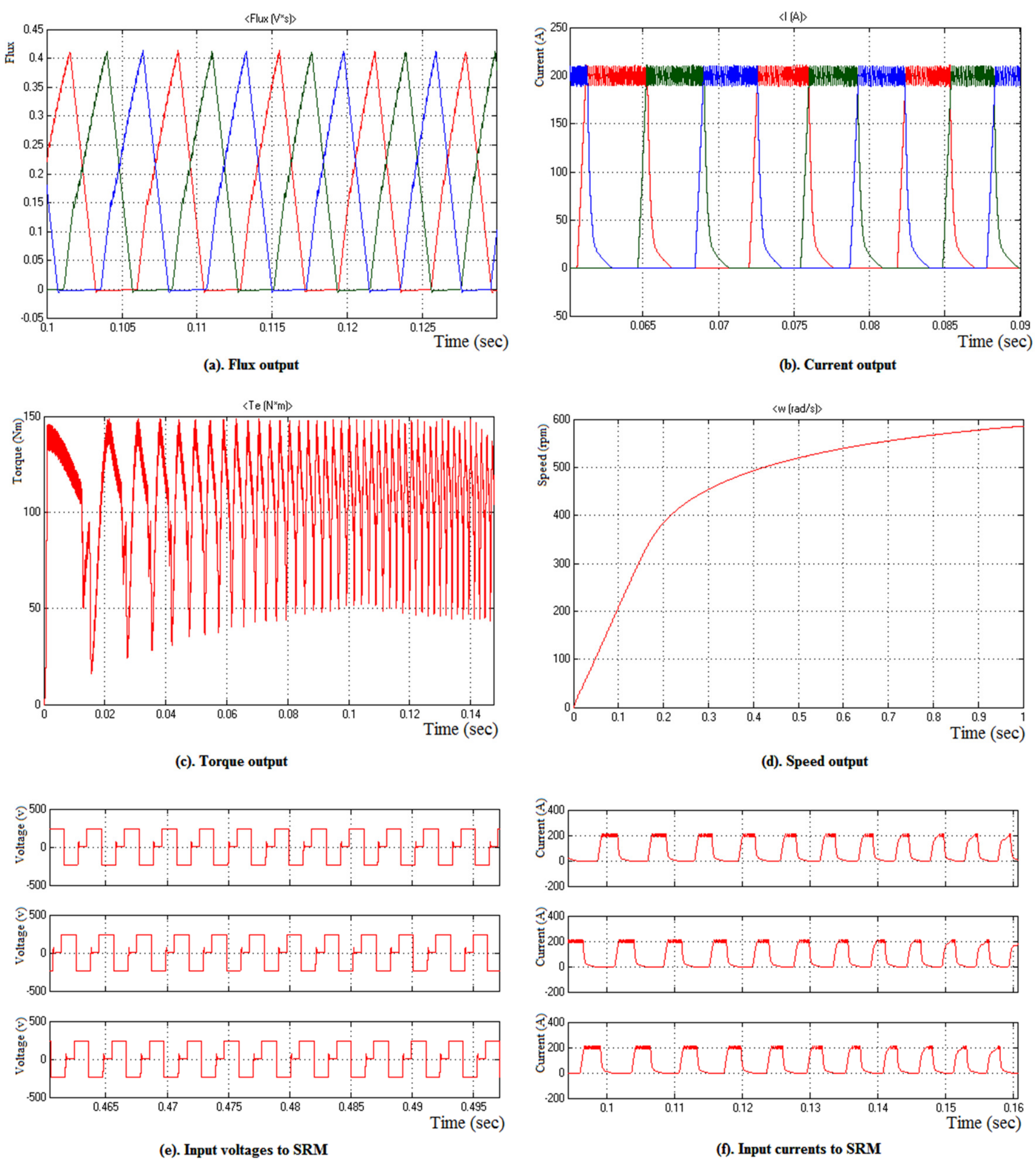

Fig. 2.14. Simulation waveforms of SRM, (a) Flux waveform (b) Current waveform (c) Torque waveform (d) Speed waveform (e) Input voltages to SRM (f) Input currents to SRM

3. MINIMIZATION OF TORQUE RIPPLES OF SWITCHED RELUCTANCE MOTOR DRIVE

3.1. Introduction

The switched reluctance motor has limited application because of its large amount of torque ripple. Due to this large amount of torque ripple it produces high noise and vibration. So for the minimization of these high amount of torque ripple various techniques have been proposed for switched reluctance motor drive. These techniques are mainly divided in two main categories which are the design of the motor shape and the optimization of control techniques.

There are some mechanical design techniques like increasing the air gap between the stator and rotor pole, pole shaping technique and skewing the rotor. We can minimize the torque ripple by these techniques but there is a big disadvantage of these methods that is the maximum achievable torque is reduced due to an increase in effective air gap.

In addition to these methods, we can also minimize the torque ripples by electronic control techniques in a wide operating range. In order to reduce torque ripples the most popular electronic control techniques are, changing the supply voltage, changing the turn-on and turn-off angles of the converter and current levels. But these techniques also have some limitations. So in order to improve the performance of switched reluctance motor it is required to apply the advanced control strategy.

The production of torque ripples and the advanced control methods for torque ripples minimization are discussed below.

3.2. Origin of Torque Ripple

Because of doubly salient structure of the motor, a large amount of torque ripple is produced in switched reluctance motor. The discrete and nonlinear torque production mechanism in the motor proves to be another reason for ripples in the torque. Therefore, the instantaneously produced torque is the sum of individual phase torques. Dependency of torque on current magnitude and rotor position when operated with flat topped currents would also result in torque ripple. In conventional AC motors, the torque is produced due to interaction of two fluxes which are smoothly revolving around the reference frame and can be made constant by subsequent frame transformation. Absence of such reference frame transformation to eliminate the rotor position dependency due to salient nature of the SRM insists on the control on an instantaneous basis for minimization of torque ripple. Torque ripple is calculated as the difference between the maximum and minimum instantaneous torque expressed as a percentage of the average torque during steady state operation. Mathematically, percentage torque ripple is expressed in equation 3.01.

$$Torque\ ripple\ (\%) = \frac{T_{inst}(max) - T_{inst}(\mathrm{min})}{T_{avg}} \times\ 100 \qquad (3.01)$$

Where T_{inst} is the instantaneous torque and T_{avg} is the average torque [11].

3.3. Influence of Design Parameters on Torque Ripple

The torque ripple can be evaluated from the torque dips in the static characteristics. Torque dip is the difference between the peak value of a phase and the torque at an angle where two overlapping phases produce equal torque at equal levels of current. When the supplying torque from the incoming phase become deficient, torque dip occurs. Torque ripple occur mainly in the overlap region as the torque production shifts from one phase to another. The value of overlap angle is given by the formula.

$$Overlap\ angle = \min(\beta_s \beta_r) - \frac{2\pi}{N_r N_s} \qquad (3.02)$$

Where N_s is the number of stator poles, N_r is the number of rotor poles, ‘βs’ is the stator pole arc and ‘βr’ is the rotor pole arc. The overlap increases with the increase in rotor and stator poles. The overlap angle is proportional to the value of rotor and stator pole arc. The increase in pole arc also increase the overlap angle and decrease the torque ripple. The large value of βs and βr reduce the maximum and minimum inductance value of the winding [1].

$$\min\left(\beta_s, \beta_r\right) > \frac{2\pi}{qN_r} \tag{3.03}$$

The number of overlap in the phase torque increases with the number of phases (q). The increase in the value of q would increase the number of legs in the inverter which increase the drive complexity and the cost. As the torque developed in the motor is on stroke basis, the overlap angle depends on the stroke angle or step angle.

$$step\ angle = \frac{2\pi}{qN_{rep}N_r} \tag{3.04}$$

Where N_{rep} represents the number of pole pairs per phase. A low value of step angle will increase the overlap angle and influences the frequency of control per revolution. Higher number of strokes would reduce the torque ripple with high value of rotor poles Nr which reduce the rotor saliency, increase VA rating of the inverter, switching frequency and copper loss. Direct measurement of torque overlap is given by the inductance overlap ratio (K_L) which is defined as the ratio of inductance overlap of adjacent phases to the angle over which the inductance is changing.

$$K_L = 1 - \frac{\epsilon}{\min\left(\beta_r, \beta_s\right)} \tag{3.05}$$

Where ϵ is the stroke angle. The torque dip decreases with the high value of K_L. Further, it improves the average torque [1].

Another reason of the torque ripples is the fringing of flux before the overlap of stator teeth and rotor teeth. These fluxes make the current nonlinear and result in variation of torque. Thus it could be concluded that the torque dip depends on the stator-rotor pole overlap angle, pole geometry, material properties, number of phases and number of poles. The fringing flux are shown in Fig. 3.1.

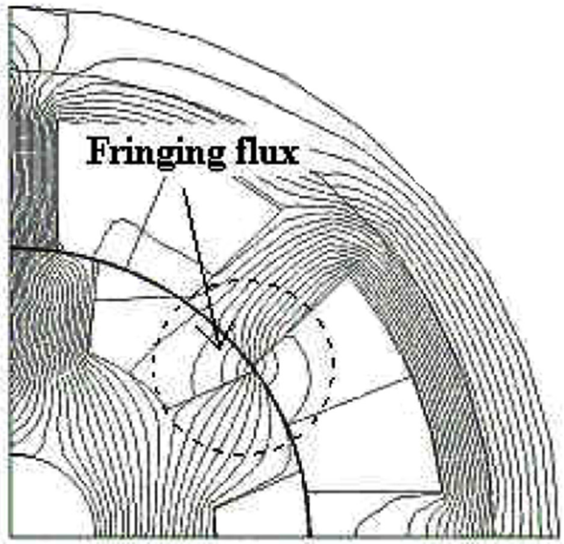

Fig. 3.1. Fringing flux lines of an analytical model [1]

3.4. Motor Design Optimization

The change in magnetic design is common to reduce the torque dips by shape optimization. The shape optimization is achieved by changing:

i. The stator & rotor diameters and stake length.
ii. Stator and rotor pole arc.
iii. Stator and rotor pole shapes.
iv. Number of phases and repetitions [1].

From Eq. 3.05, the torque overlap can be increased by widening the stator and rotor pole arcs. Naayagi et.al has found optimized value of Pole arcs using Genetic Algorithm. The chosen objective function is to optimize the value of flux linkage and Inductance overlap ratio KL. The constraints considered are, rotor pole arc βr should be higher than stator pole arc βs, and rotor pole arc should be greater than stator pole arc. The optimized design values were modelled using Finite Element Analysis (FEA) based CAD package. It was observed that optimization of flux linkage improves the motor torque and maximization of K_L has led to 72.19% lesser torque dip [1].

3.5. Torque-sharing Function

An efficient method for minimization of torque ripples is the torque sharing function (TSF) method, in which the torque produced in every individual phase is tracked. This method is managed by the static characteristics of the motor. The TSF is a function of turn ON angle, overlap angle and motor speed. This method uses the complicated algorithms or distribution function to distribute each phase torque and obtain current command. These current commands are then used to control the phase torque by current controller. The TSF method uses pre-measured non-linear torque characteristic, and simply divided torque sharing curve used for constant torque generation. Torque sharing function is simple, powerful and popular method among the indirect torque control methods. It simply uses a torque sharing curve for generation of constant torque. And the phase torque can be assigned to each phase current to control smoothing torque. But the phase torque has a relationship of square to phase current and the current ripple should be keep small enough to generate smooth torque so the frequency of current controller should be increased [1].

Fig. 3.2 shows the block diagram of torque sharing function method. The input torque reference is divided into three-phase torque command according to the rotor position. And then according to the rotor position, these torque references are changed to current command signals in the 'torque to current' block. Since the output torque is determined by the inductance slope and phase current, the inductance slope is changed by rotor position, and the reference current of each phase is determined by the target torque and rotor position. The switching rule generates an active switching signal of asymmetric converter according to current error and hysteresis switching table [7].

In the overlap region of inductances, the output torque is generated by two phase current together. Fig.3.3 shows the inductance profile for the three phase SRM, linear and cosine TSF curves. The region 2 denotes the one phase activation area. Region 1 and region 3 are two phase activation area denoted as the commutation region. The TSF is constant in every torque sharing function in one phase activation region. But is different in the commutation region. The linear TSF has constant slope of torque in commutation region. This is a very simple method but the generation of linear torque slope in commutation region is very difficult due to the nonlinear inductance characteristics.

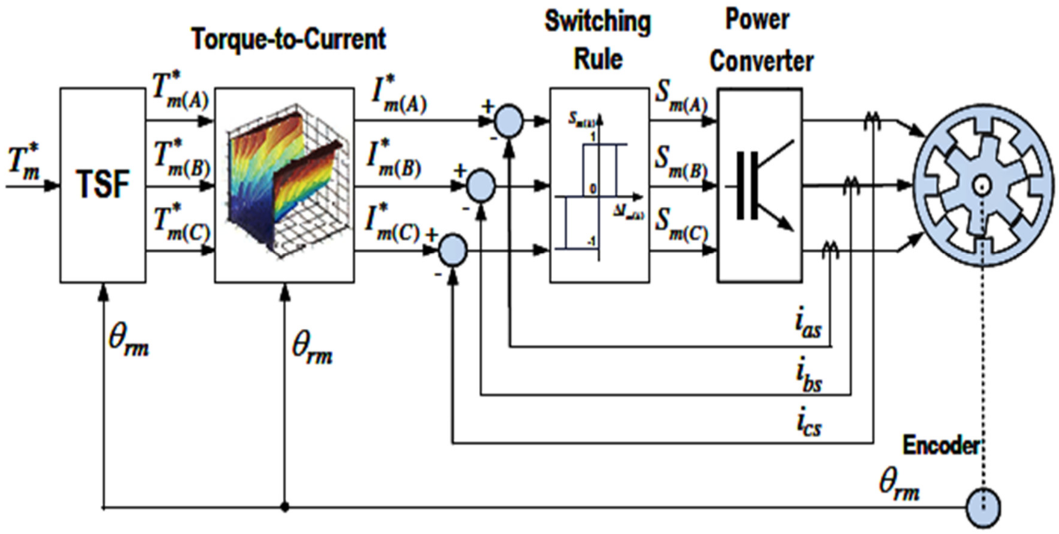

Fig. 3.2. The torque sharing function block diagram [7]

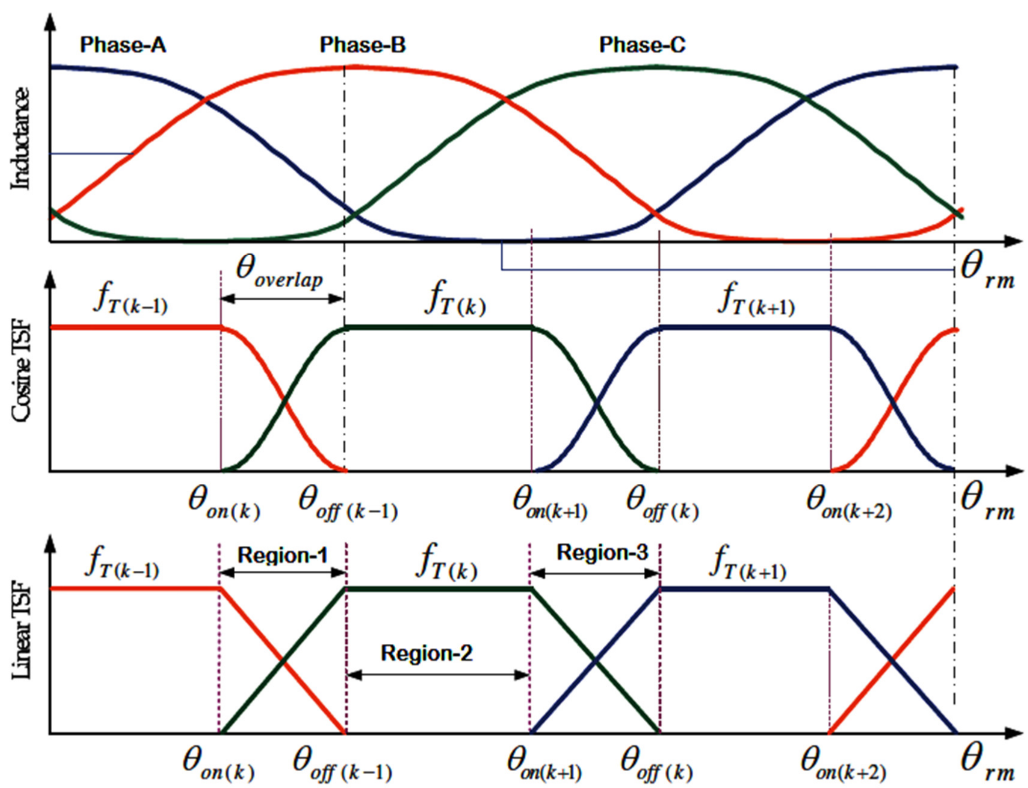

Fig. 3.3. Phase inductances, cosine and linear TSF curve [7]

In the article M. Illic-Spong, et.al, a rising and falling exponential TSF, referred as *m* function relating to rotor position θ has been used. The torque per phase (T_{ph}) is defined as:

$$T_{Ph}(\theta) = T_{ref} * m(\theta) \tag{3.06}$$

Where

$$\sum_{p=1}^{q} m(\theta - \theta_p) = 1 \tag{3.07}$$

The major limitation in this technique is that it needs the spiky voltage. To obtain the reference phase voltage, the theory of floquet transformation is used.

Schramm et.al proposed a linear TSF in which the torque varies linearly during the commutation and the value of current in both incoming and outgoing phases are equal at the central commutation point as shown in Fig. 3.4 [36].

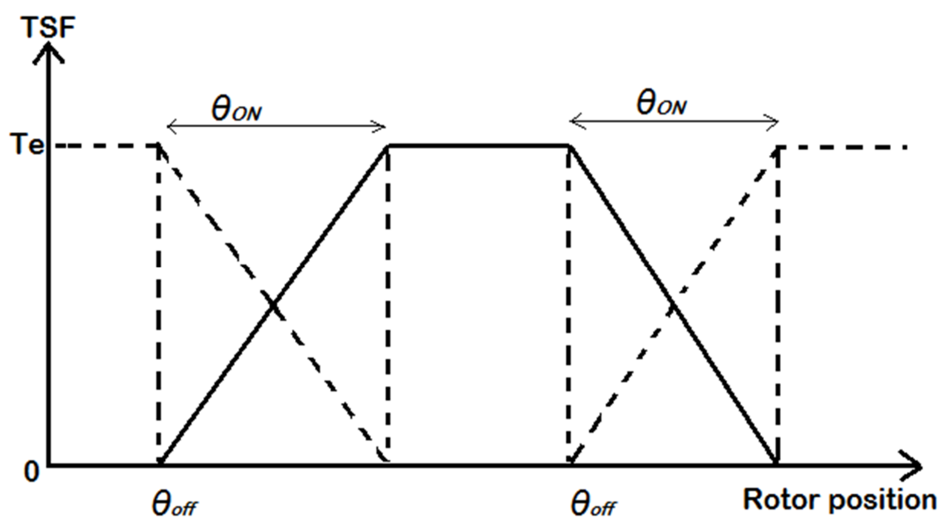

Fig. 3.4. Typical Profile of linear TSF [7]

Iqbal Husain et.al proposed a sinusoidal TSF, shown in Fig. 3.5 where the torque is produced by phases changes with rotor position as a sinusoidal function during the phase commutation.

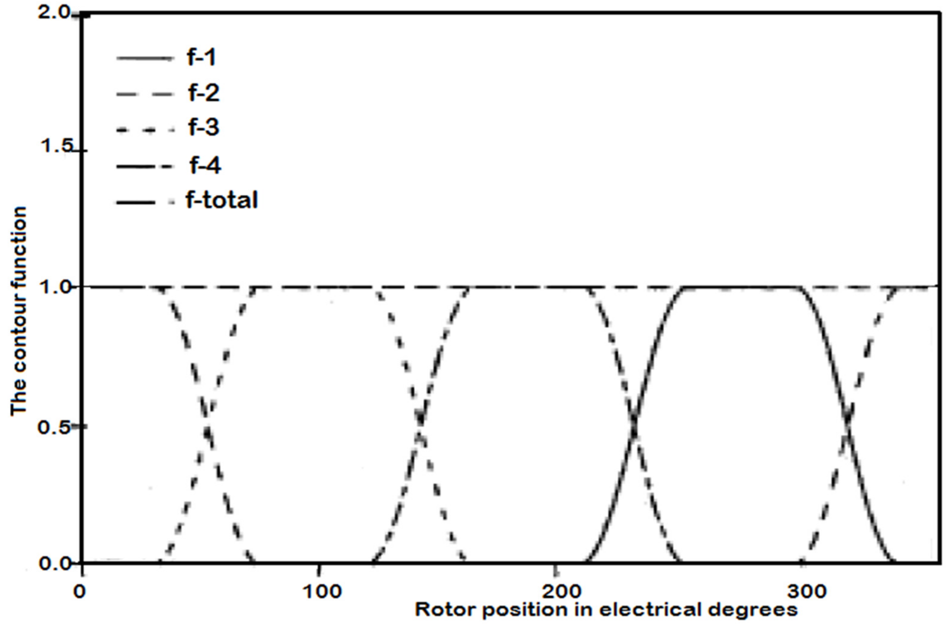

Fig. 3.5. Sinusoidal TSF [7]

Sanjib et.al proposed the cubic TSF, shown in Fig. 3.6 in which the torque produced in each phase changes nonlinearly with the rotor position. The nonlinearity is expressed in the form of cubic polynomial.

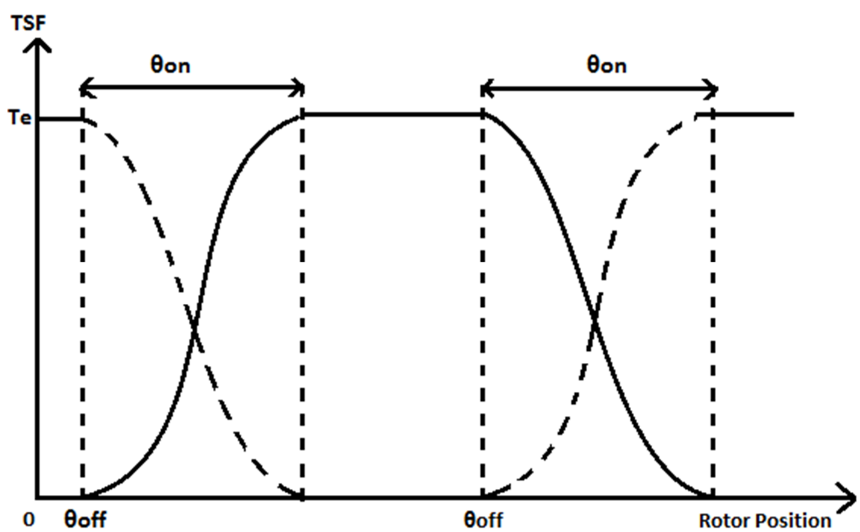

Fig. 3.6. Cubic TSF [7]

Xue et al has carried out a critical evaluation of all four TSFs for torque ripple minimization with speed range, copper loss, overlap angle and turn on angle, to prove the importance of TSF for improving performance indicators of SRM drive. They further proposed the torque ripple factor (TRF), a performance index to evaluate the effectiveness of TSF for ripple reduction, also depends on the dependents of TSF. Genetic algorithm is used to optimize the all four TSF for minimum TRF. The optimal turn on and overlap angles are found using least square polynomial in this method. The author compared the TRF value of all the TSFs and had concluded that the cubic TSF yielded less in both TRF and computation time. Thus, it can be inferred that nature of function and its independency on rotor position decides the smoother and ripple-less torque production.

3.6. Direct Torque Control Method

In advanced control systems, high performance frequency control system is used which is known as Direct Torque Control System (DTC). In this method the torque of the Switched Reluctance Motor is directly controlled by controlling the magnitude of flux linkage and the change in speed of the stator flux vector. The details of this method are given in Chapter 4.

3.7. Summary of Recent Research Work Done on Torque Ripple Reduction of SRM

There is a lot of research work on this topic and many controlling systems used to minimize the torque ripple and to control the speed of switched reluctance motor. It is a big challenging work. Several control strategies have been proposed in recent years, typically including current chopping control (CCC), torque sharing function (TSF), voltage space vector control (VSVC) etc.

In current chopping control the current amplitude is controlled to a certain range to control the output torque. This method is easy but also results in obvious ripples because the phase current is too small to provide enough torque at the beginning of the phase inductance rising.

L. Kalaivani et.all proposed intelligent control for torque ripple minimization in switched reluctance motor. They presented fuzzy control and adaptive neuro fuzzy inference system.

This method is based on injection of compensation current in each phase by using fuzzy logic current compensation (FLCC). This method used to control the switched reluctance drive consists of the use of a fuzzy logic current controller with the supervision of an adaptive neuro fuzzy inference system responsible for torque ripple reduction. First compensation current is injected in to each phase by using FLCC. Then by learning capabilities of the compensator, the control shows large operation flexibility. If the system has some load modification and/or change of speed, the compensator will have the ability to adopt itself to this new operating point, searching for the required torque ripple minimization. The results for this method they obtained are shown in Fig 3.7. In this method the torque ripples are minimized but still it has a large value of peak to peak torque ripple that is 8Nm to 28Nm [38].

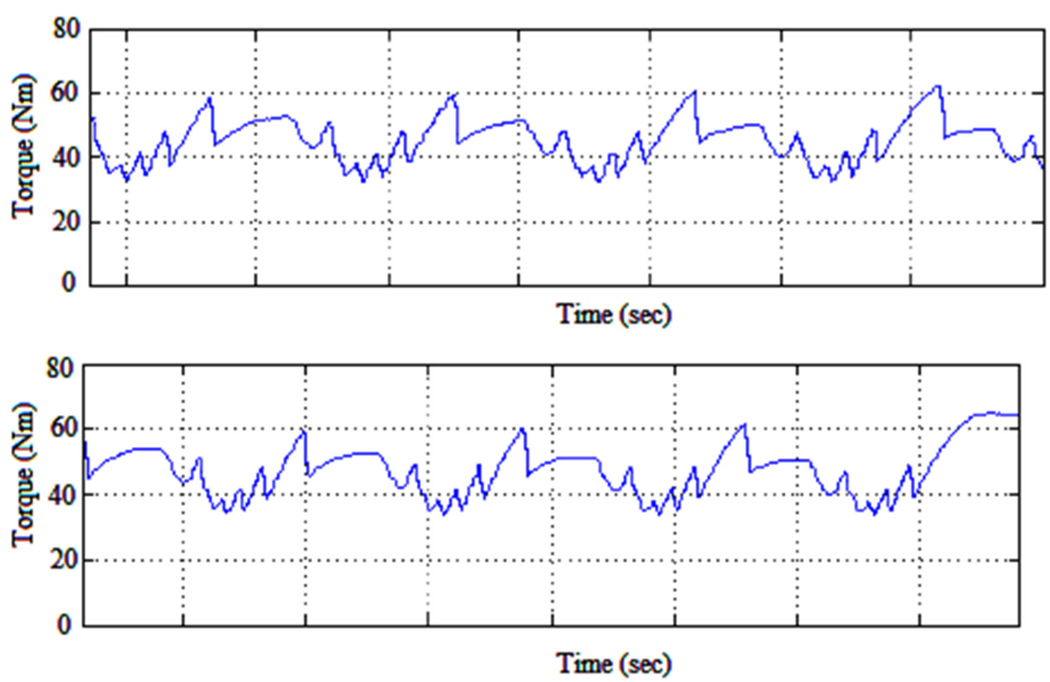

Fig. 3.7. Torque output of fuzzy logic current compensation method [38]

M. M. Borujeni et.all proposed particle swarm optimization method in their paper. Their control mechanism is composed of a proportional-integral controller and a hysteresis current controller. The proportional and integral gain, the turn ON and turn OFF angles along with the maximum value of the phase current have been optimized by using particle swarm optimization by considering the magnetic saturation of Switched Reluctance motor. The output of PI speed controller is reference current that is restricted by limiter with maximum value of the phase current. By passing the current through hysteresis controller and according to the turn ON and turn OFF angle, the gate pulses are generated and the voltage applied to the phase winding. Thus the optimal choice of turn ON and turn OFF angle can reduce torque ripples. The output torque of this method is shown in Fig. 3.8. In this method the torque ripples are minimized but not so well, it has peak to peak value of 2Nm to 8Nm [35].

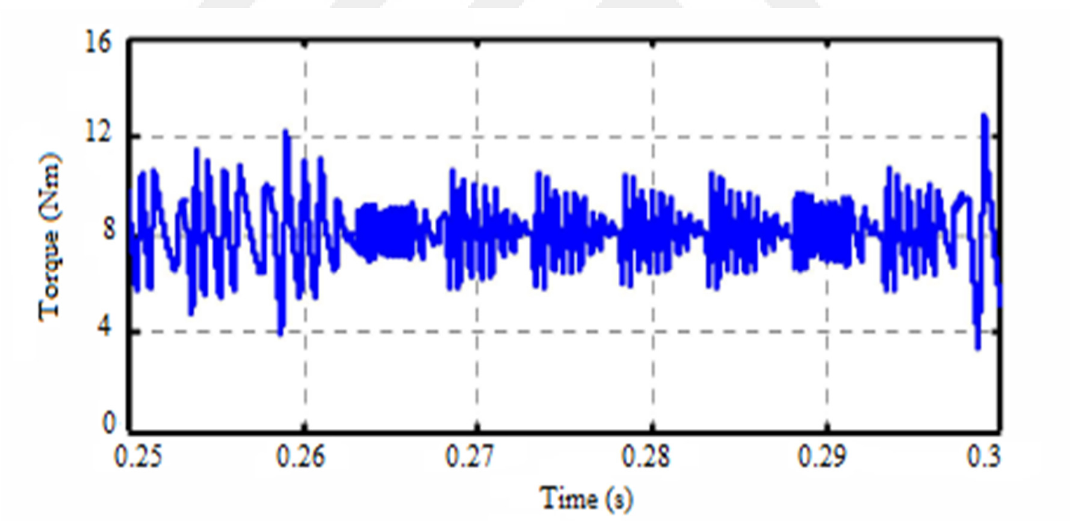

Fig. 3.8. Torque output of particle swarm optimization method [35]

Weiye et.all presents minimization of torque ripples through controlling of the phase currents during commutation. According to them, by changing the slops of the supplied currents appropriately, the torque ripple can be reduced significantly. The shaping of the current is applied in the commutation region because the high ripple occurs during this period. By this method the torque ripples are reduced but no so well. It has peak to peak value of 6Nm to 29Nm, it is a very large value. The output of this method is shown in Fig 3.9 [36].

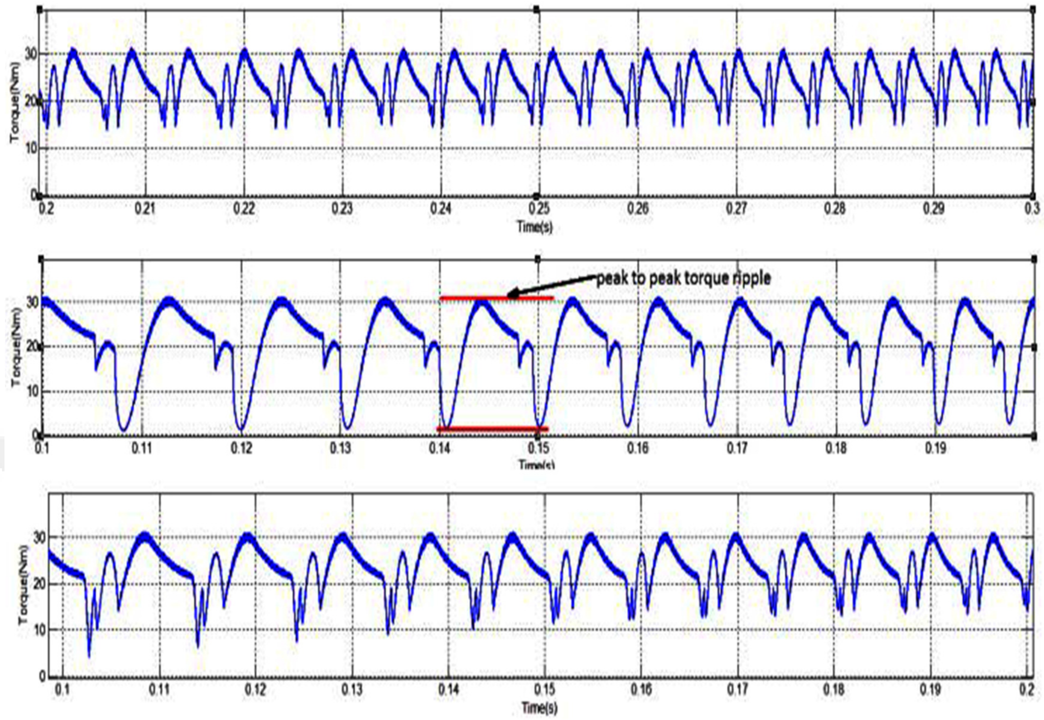

Fig. 3.9. Torque output of controlling of the phase currents during commutation method [36]

E.Daryabeigi et.all presented a modern intelligent control system based on computational model of mammalian limbic system and emotional process, Brain emotional learning based on intelligent control (BELBIC) for torque reduction. In this method, the emotional control system (BELBIC) receives the error signal between the command speed and the actual motor speed as the part of inputs and generates the output signal. The BELBIC receives the speed error as input and generates reference current of stator winding. The reference current is compared to actual stator current and then generated current error is entered to hysteresis inverter for generating pulse command to thyristors. The output result of this method is shown in Fig 3.10. It also has a lot of pulses and have a large peak to peak value of torque ripple that is of 5Nm to 15Nm [37].

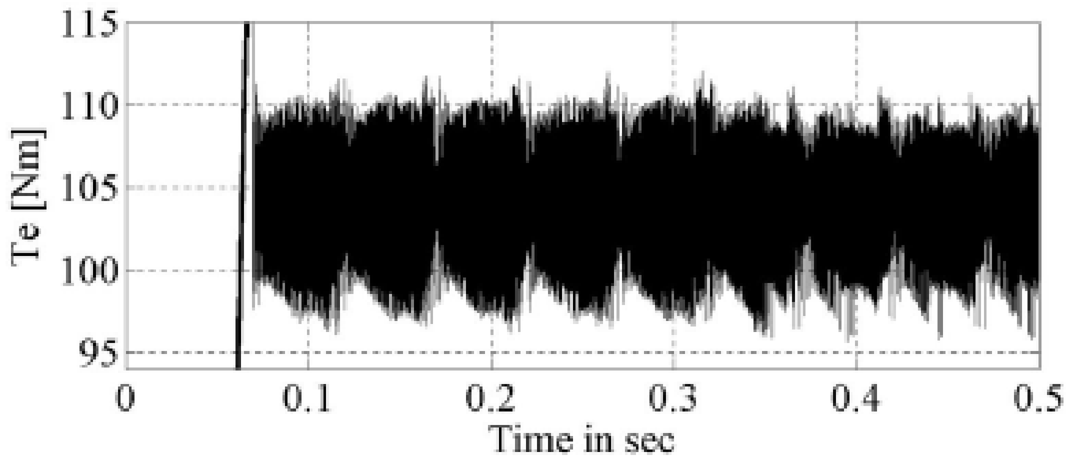

Fig. 3.10. Torque output of Brain emotional learning based on intelligent control (BELBIC) method [37]

4. DIRECT TORQUE CONTROL (DTC) OF SWITCHED RELUCTANCE MOTOR WITH FUZZY LOGIC CONTROLLER

4.1. Introduction

In the last decade the frequency control of asynchronous motor is widely used. When we discuss it for the switched reluctance motor then it has more advantageous in respect of efficiency, cost, reliability, heat dissipation and speed control performance. Because of the large amount of torque ripples, the switched reluctance motor has limited applications. The Switched Reluctance Motor produces a high acoustic noise and vibration. To control or minimize the torque ripples in Switched Reluctance Motor drive various methods have been proposed. These control methods are mainly classified as the design of motor shape and optimization of control technique.

There are some mechanical techniques like skewing the rotor and pole shaping technique. By increasing air gap between stator and rotor we are able to minimize the torque ripple but the main limitation in these techniques is that it reduces the maximum available torque due to an increase in effective air gap.

We can also reduce the torque ripples by using electronic control techniques, which include controlling the supply voltage, controlling the turn-on and turn-off angles of the converter and controlling the current levels. But these methods also have some limitations such as reducing the overall torque. So in order to improve the performance of Switched Reluctance Motor and to control the torque ripples it is required to apply the advanced control strategy.

In advanced control systems, a high performance frequency control system is used which is known as Direct Torque Control system (DTC). In this method the torque of the Switched Reluctance Motor is directly controlled by controlling the magnitude of flux linkage and the change in speed of the stator flux vector.

The mathematical equations of DTC applied to SRM are described below. The motor torque output can be found using the electromagnetic equation.

$$v = Ri + \frac{d\psi(\theta, i)}{dt} \tag{4.01}$$

Where ψ(θ,i) is the nonlinear function of phase flux linkage as a function of rotor position θ and current i. Expanding the above equation:

$$v = Ri + \frac{\partial\psi(\theta, i)}{\partial i}\frac{di}{dt} + \frac{\partial\psi(\theta, i)}{\partial\theta}\frac{d\theta}{dt} \tag{4.02}$$

Thus the equation for the power flow can be written as:

$$vi = Ri^2 + i\frac{\partial\psi(\theta, i)}{\partial i}\frac{di}{dt} + i\frac{\partial\psi(\theta, i)}{\partial\theta}\frac{d\theta}{dt} \tag{4.03}$$

The effective power flow from the source can be defined as:

$$P_{eff} = ei \tag{4.04}$$

Where e=(v-Ri).

Thus in a differential time dt, the differential electrical energy dWe transferred from the source is given by.

$$dW_e = eidt \tag{4.05}$$

This equation can be written as following to find the expression for the motor torque production,

$$dW_e = dW_m + dW_f \tag{4.06}$$

Where dW_m and dW_f are the differential mechanical energy and field energy respectively. The field energy dW_f can be separated into its constituent components as shown below,

$$dW_f = \frac{\partial W_f}{\partial i} di|_{\theta=constant} + \frac{\partial W_f}{\partial \theta} d\theta|_{i=constant} \tag{4.07}$$

From the consideration of the stored energy it can be shown,

$$dW_e = i\frac{\partial \psi(\theta,i)}{\partial i} di|_{\theta=constant} + \frac{\partial \psi(\theta,i)}{\partial \theta} d\theta|_{i=constant} \tag{4.08}$$

$$dW_{f|\theta=constant} = i\frac{\partial \psi(\theta,i)}{\partial i} di|_{\theta=constant} \tag{4.09}$$

By solving these equations we can get,

$$dW_m = i\frac{\partial \psi(\theta,i)}{\partial \theta} d\theta - \frac{\partial W_f}{\partial \theta} d\theta \tag{4.10}$$

The instantaneous torque is defined by,

$$T = \frac{dW_m}{d\theta} \tag{4.11}$$

Solving the previous two equations, the expression for the instantaneous torque production of a Switched Reluctance motor phase can be written as,

$$T = i\frac{\partial \psi(\theta,i)}{\partial \theta} - \frac{\partial W_f}{\partial \theta} \tag{4.12}$$

This is a rarely used variant of conventional torque equation. The influence of the second term in above equation is negligible due to saturation in the switched reluctance motor. Thus by using the approximation, the following equation for torque production may be derived,

$$T \approx i\frac{\partial \psi(\theta,i)}{\partial \theta} \tag{4.13}$$

In SRM, unipolar drives are normally used and thus the current in a motor phase is always positive. Hence from above equation the sign of the torque is directly related to the sign of $\partial\psi/\partial\theta$. So to produce a positive torque, the stator flux amplitude must increase relative to the rotor position, whereas to produce a negative torque the change in stator flux must decrease with respect to the rotor movement. A positive value of $\partial\psi/\partial\theta$ is defined as "flux acceleration", whereas a negative value of $\partial\psi/\partial\theta$ is defined as "flux deceleration". Hence the DTC of SRM is defined as:

i. The stator flux linkage vector of the motor is kept at constant amplitude.
ii. Torque is controlled by accelerating or decelerating the stator flux vector [41].

4.2. Direct Torque and Flux Control

In switched reluctance motor, the torque produced depends on the reluctance principle. Due to nonlinear characteristics of the magnetic circuit the expression for the phase torque is given by:

$$T(\theta, i) = i\frac{\partial\psi(\theta, i)}{\partial\theta} \tag{4.14}$$

Where θ is the rotor angular position and i is the phase current. From the equation 4.14 it is clear that the T (θ,i) is directly proportional to $(\partial\psi(\theta,i))/\partial\theta$. So for the production of positive torque the change in the stator flux amplitude must increase with respect to rotor position and for the negative torque to produced the change in the stator flux amplitude must be decreasing with respect to rotor position.

The block diagram of the direct torque control is shown in Fig 4.1. The direct torque control technique consists of three important functions, hysteresis control of torque and flux, an optimal switching vector look- up table and a motor model. In Direct Torque Control method, the actual or estimated speed is compared with the reference speed. The output of the comparison is known as error signal. This error signal is applied to controller which is a Fuzzy Logic Controller. The output of Fuzzy Logic Controller gives the reference value of electromagnetic torque which is known as torque reference T_{ref}. The reference value of torque and flux is compared with the actual value and the control signal is produced by using a torque and flux hysteresis control method. The output of hysteresis controller give an input signal for the vector look-up table. The angle of the calculated flux which determines the region where the flux vector is excited and then the output signal also passes through the switching table.

The pulses for invertor circuit are provided by the signals of switching table. So it is concluded that the space vector invertor mostly depends upon three factors,

i. Flux hysteresis control signal
ii. The angle of flux vector and the direction of the flux vector rotation
iii. Torque hysteresis control signal

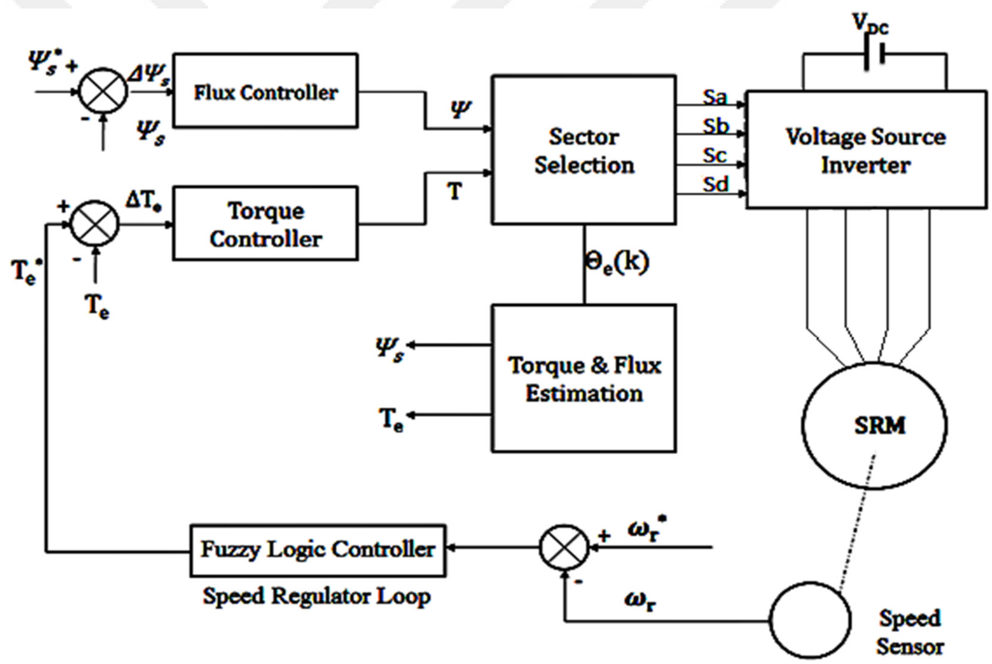

Fig. 4.1. Block diagram of direct torque and flux control

4.3. Direct Torque Control Technique and its Control Objectives

We can analyze the direct torque control system by using the space vector. With the help of stator co-ordinate system we can directly calculate and control the torque of the motor. The control method of the switched reluctance motor has two main control objectives:

i. The amplitude of the motor's stator flux vector should be constant in order to make the trajectory of the stator flux linkage circular.

ii. By accelerating and decelerating the stator flux linkage vector, we can control the torque.

Our main aim in Direct Torque Control of Switched Reluctance Motor is to control the electromagnetic torque by selecting the proper switching state of inverter. By doing this, we can reduce the loss due to switches and harmonic distortion in the stator currents. In order to control the torque and flux of the Switched Reluctance Motor independently, we use two hysteresis controlling loops which are torque hysteresis control loop and flux hysteresis control loop.

4.3.1. Torque Hysteresis Control Loop

For torque hysteresis controller, the control loop consist of a three levels for controlling the torque error. The difference between the reference torque and estimated torque gives rise to torque error. The torque hysteresis control loop gives three kinds of output which are shown in Fig. 4.2, relations of which is shown in Table 4.1. When the torque hysteresis band is T_n=1, the torque starts to increase; when T_n=0, no need to change, and when T_n=-1 the torque starts to decrease.

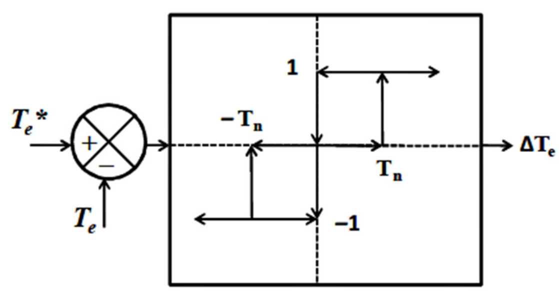

Fig. 4.2. Three level hysteresis controller for the control of torque error

Table 4.1. Switching states for torque error

State	Torque hysteresis (T)
$(T_e^*-T_e) > \Delta T_e$	1 ↑
$-\Delta T_e < (T_e^*-T_e) < \Delta T_e$	0 =
$(T_e^*-T_e) < -\Delta T_e$	-1 ↓

The change in input to the flux hysteresis controller can be written as,

$$\Delta T_e = T_e^* - T_e \tag{4.14}$$

The electromagnetic torque T_e can be expressed as,

$$T_e = \frac{3}{2} p \frac{L_m}{\sigma L_s L_r} \psi_s \times \psi_r \tag{4.15}$$

Where

L_m= mutual inductance

L_s= stator self-inductance

L_r= rotor self-inductance

σ = leakage co-efficient of the motor

ψ_s= stator flux linkage vector

ψ_r= rotor flux linkage vector in the stationary reference frame

From the above equation, it is clear that the torque of switched reluctance motor is directly proportional to the scalar product between the stator and rotor fluxes in the stationary reference frame.

The control scheme assumes that during changes in the control of the stator flux, the rotor flux will remain constant. The control scheme can be operated by keeping the magnitude of the stator flux within the hysteresis band. The torque is thus controlled by varying the relative angle between the stator flux and the rotor flux.

For resolving the individual phase flux vectors into a single stator flux linkage vector, the flux vector for the four phase switched reluctance motor is transformed into a stationary orthogonal two axis α-β reference frame. The orthogonal flux vector components can be defined as,

$$\psi_\alpha = \psi_1 cos45^o - \psi_2 cos45^o - \psi_3 cos45^o + \psi_4 cos45^o \tag{4.16}$$

$$\psi_\beta = \psi_1 sin45^o + \psi_2 sin45^o - \psi_3 sin45^o - \psi_4 sin45^o \quad (4.17)$$

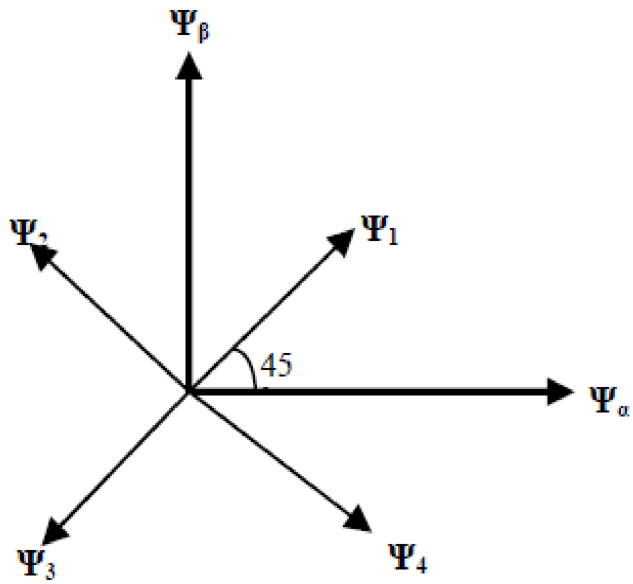

Fig. 4.3. α-β axis of motor voltage

The magnitude of ψ_s and angle θ_e of an equivalent flux vector are then given by,

$$\psi_s = \sqrt{\psi_\alpha^2 + \psi_\beta^2} \quad (4.18)$$

$$\theta_e = arctan\left[\frac{\psi_\beta}{\psi_\alpha}\right] \quad (4.19)$$

The instantaneous torque equation for switched reluctance motor is given by,

$$T = p\left(\psi_\alpha i_\beta - \psi_\beta i_\alpha\right) \quad (4.20)$$

Where p is the number of pole pairs, ψ is the stator flux component, i is the stator current component, and α & β is the transformation components in the stationary reference frame.

4.3.2. Flux Hysteresis Control Loop

The flux hysteresis control loop has two levels of output as shown in Fig. 4.4, relations of which is shown in Table 4.2. Here the main aim is to control the flux error. Flux error is the difference between reference flux and actual flux. By using a two level hysteresis comparator the stator flux will follow the reference value of flux within the hysteresis band. The stator flux in the stationary reference frame ($\alpha_s - \beta_s$) can be expressed as,

$$\psi_{\alpha s}^{s} = \int (V_{\alpha s}^{s} - i_{\alpha s}^{s} R_s) dt \tag{4.21}$$

$$\psi_{\beta s}^{s} = \int \left(V_{\beta s}^{s} - i_{\beta s}^{s} R_s\right) dt \tag{4.22}$$

Generally the stator flux linkage is obtained from the stator voltage vector. By neglecting stator resistance, R_s can be described as,

$$V_s = \frac{d}{dt}(\psi_s) \qquad or \qquad \Delta\psi_s = V_s \Delta t \tag{4.23}$$

The change in input to the flux hysteresis controller can be written as,

$$\Delta\psi_s = \psi_s^* - \psi_s \tag{4.24}$$

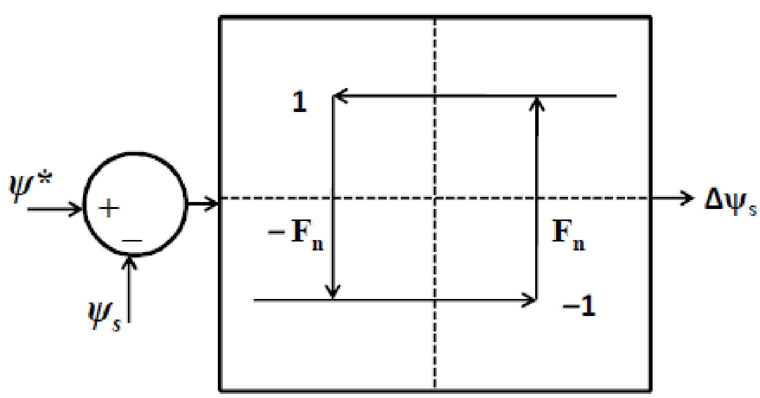

Fig. 4.4. Two level hysteresis controller for controlling the flux error

The Fig.4.4 shows the two level flux hysteresis controller for controlling the error in flux. The two level output states of the hysteresis controller is shown in Table 4.2.

Table 4.2. Switching states for flux error

State	Flux Hysteresis (ψ)
$(\psi_s^*-\psi_s)>\Delta\psi_s$	1 ↑
$(\psi_s^*-\psi_s)<-\Delta\psi_s$	-1 ↓

4.4. Voltage Vector Switching Selection

Direct Torque algorithm for the four phase switched reluctance motor has eight possible voltage vector states which are shown in Fig. 4.5.

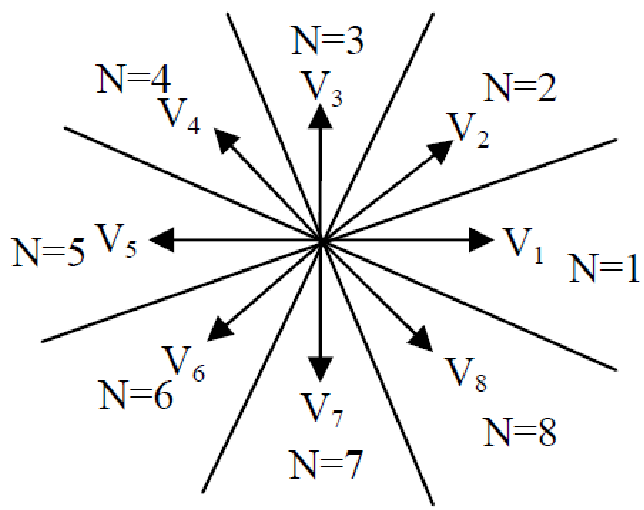

Fig. 4.5. Sectors and voltage vectors for DTC of four phase SRM

These voltage state vectors are defined to lie in the center of eight zones. Only one of the eight possible states has been chosen in order to keep the stator flux linkage and the torque of the motor within the hysteresis band. If the stator flux linkage lies in the kth zone then by using the switching vector V_{k+1} and V_{k-1} the magnitude of the flux can be increased and by using the voltage vector V_{k+2} and V_{k-2} the magnitude of the flux can be decreased. Whenever the stator flux linkage reaches its lower limit in the hysteresis band, it is improved by applying voltage vectors which are directed away from the center of the flux vector space and vice-versa.

By acceleration or deceleration of the stator flux relative to the rotor movement the torque is controlled. So for an increasing the torque, voltage vectors that advances the stator flux linkage in the direction of rotation are selected. This correspond to the selection of vector V_{K+1} and V_{K+2} for a stator flux linkage in the k_{th} zone. If a decrease in the torque is required, voltage vectors are selected which decelerate the stator flux linkage vector. This result to the selection of vectors V_{K-1} and V_{K-2} in the K_{th} zone. Hence a switching table for controlling the stator flux linkage and the motor torque can be defined in Table 4.3 where Ψ_Q=1 & Ψ_Q=0 indicate the increase and decrease in the flux linkages respectively and T_Q=1 and T_Q=-1 show the increase and decrease in torque, respectively.

Table 4.3. Switching Table of Space voltage vectors

N		1	2	3	4	5	6	7	8
Ψ_Q=1	T_Q= 1	V2	V3	V4	V5	V6	V7	V8	V1
	T_Q= 0	V9	V0	V9	V0	V9	V0	V9	V0
	T_Q= -1	V7	V8	V1	V2	V3	V4	V5	V6
Ψ_Q=0	T_Q= 1	V3	V4	V5	V6	V7	V8	V1	V2
	T_Q= 0	V0	V9	V0	V9	V0	V9	V0	V9
	T_Q= -1	V6	V7	V8	V1	V2	V3	V4	V5

In order to resolve the individual phase flux vectors into a single stator flux linkage vector, the flux vectors for the four phase SRM are transformed to a stationary orthogonal two axis reference frame as shown in Fig.4.6.

$$\psi_{\alpha=}\psi_1 cos45^o - \psi_2 cos45^o - \psi_3 cos45^o + \psi_4 cos45^o \quad (4.25)$$

$$\psi_\beta = \psi_1 sin45^o + \psi_2 sin45^o - \psi_3 sin45^o - \psi_4 sin45^o \quad (4.26)$$

$$\psi_s = \sqrt{(\psi_\alpha^2 + \psi_\beta^2)}, \quad \& \quad \delta = arctan\left[\frac{\psi_\beta}{\psi_\alpha}\right] \quad (4.27)$$

Where ψ_s is the flux vector, δ is the angle of the flux vector and ψ_1, ψ_2, ψ_3, ψ_4 are the flux linkages of the four phases.

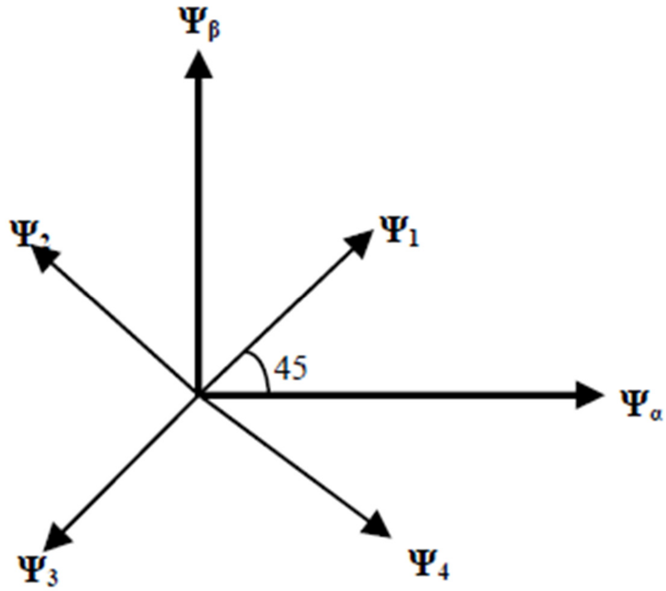

Fig. 4.6. Definition of axis for motor voltage

4.5. Fuzzy Logic Controller

Fuzzy logic controller uses fuzzy logic which is based on fuzzy set theory. This fuzzy set theory and controller represent the experience and knowledge of a human in terms of some linguistic variables. These variables are called fuzzy rules. As an experienced human operator by looking at the system output without having any knowledge of the system's dynamics and parameter variations can adjust the inputs for the system to get the desired output. The implementation of linguistic fuzzy rules based on the method done by human operator also does not require a mathematical model of the system. Because of having a robust performance under parameter variations with the ability to get desired control actions for uncertain, complex and nonlinear systems without the requirement of their mathematical models and parameter estimation, the fuzzy logic controller becomes nonlinear and adaptive. Fuzzy logic controller provides a mathematical foundation for approximate reasoning, which has been proven to be very successful in a variety of applications. In modern control techniques, uncertainty and vagueness have a great importance to deal with. The use of membership functions quantified from ambiguous terms in fuzzy logic control rules has given a pulse to speed up the systems with uncertainty and vagueness. The fuzzy logic controller has become an important and useful tool for controlling nonlinear systems [9].

The fuzzy logic controller studies increased tremendously after its development by Zadeh. After that the Mamdani and his colleges provided a base for its usage in control applications in the real world. The Fuzzy logic controller performs the same operation as a human operator by adjusting the input signal by looking only at the system output. A fuzzy logic controller consists of three sections, fuzzifier, rule base and defuzzifier as shown in Fig.4.7 [9].

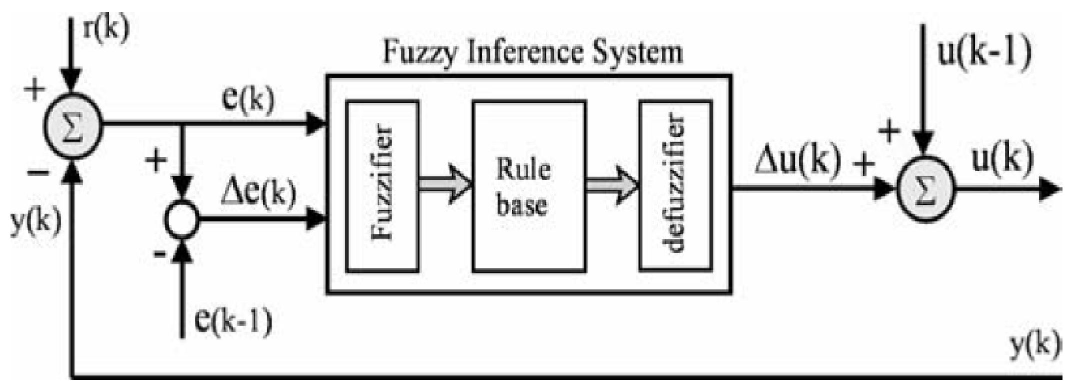

Fig. 4.7. Basic structure of Fuzzy logic controller [9]

The fuzzy logic controller has two main input signals, the error signal and the change in error signal. These inputs are applied to fuzzifier. Fuzzifier converts these inputs to fuzzy numbers. Then the output is generated according to these inputs, based on rules of rule table. And then, lastly the generated output fuzzy data is converted to crisp values in the defuzzifier section. The fuzzy logic controller is designed to act as an integrator controller, such that the resultant incremental output Δu(k) is added to the previous value u(k-1) to yield the current output u(k). Recalling the digital solution of an integrator using Euler's integration as,

$$u(k) = u(k-1) + \Delta u(k) \quad (4.28)$$

In a digital integration the term Δu(k) is expressed as,

$$\Delta u(k) = K_I T_s e(k) \quad (4.29)$$

Where K_I is the integral constant, T_s is the sampling period, and e(k) is the integral signal. The change Δu(k) on the output of an integrator becomes zero when the input e(k) is zero. Therefore output of an integrator retains the previous value. The difference between an integrator and fuzzy logic controller is the method that is used to obtain Δu(k), which is obtained using equation 4.29 for an integrator, and using fuzzy inference system shown in Fig.4.7 for fuzzy logic controller.

4.5.1. Fuzzy Inference System

There are two inputs to the fuzzy inference system as shown in Fig.4.7. One is the control error e(k), which is the difference between the reference signal r(k) and the output signal y(k), the other one is the change in this error Δe(k). These two inputs are described in equation form as Eq.4.30 and Eq.4.31. These inputs are first fuzzified and converted to fuzzy membership values that are used in the rule base in order to execute the related rules so that an output can be generated.

$$e(k) = r(k) - y(k) \quad (4.30)$$

$$\Delta e(k) = e(k) - e(k-1) \quad (4.31)$$

The fuzzy rule base table also called the fuzzy decision table, is the section mapping of two crisp inputs, e(k) and Δe(k) to the fuzzy output space defined on the universe of Δu(k). the tıme response of the control error *e* for a step input can be represented by the generalized step response error of a second order system as shown in Fig. 4.8 where the crisp *e* and Δe axis are divided into seven fuzzy subset as negative big (NB), negative medium (NM), negative small (NS), zero (ZZ), positive small (PS), positive medium (PM), and positive big (PB). This error signal has an oscillatory or a damp response with a decaying exponential component [9].

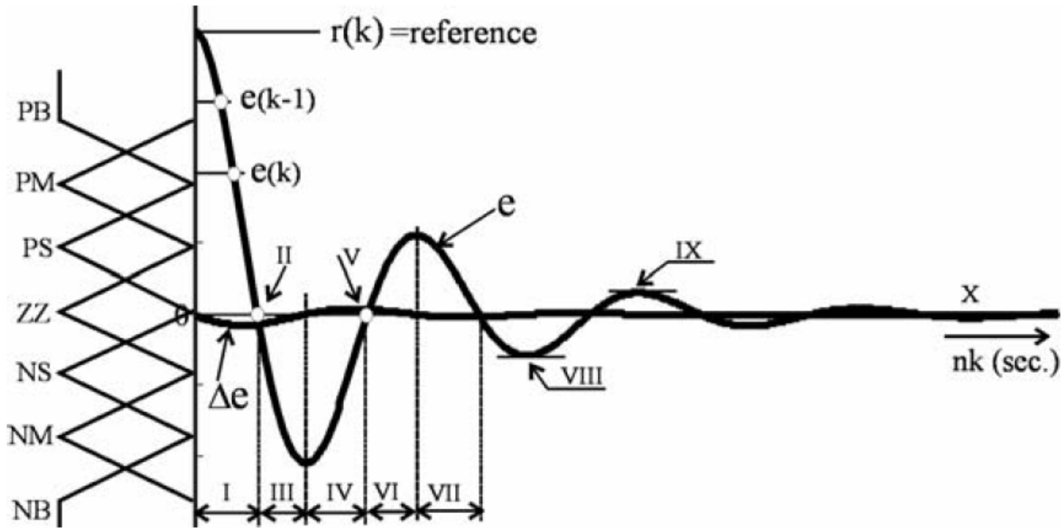

Fig. 4.8 Fuzzy division of the time responses of error and error change for a generalized second order system

The fuzzy rules are defined by a human operator who makes necessary adjustment to operate the system with minimum error and fast response. In order to model the actions that a human operator would decide whether the change, Δu, in the controller output is to be increased or decreased according to the error, e and its change Δe, it is necessary to observe the behavior of the error signal e and its change Δe on various operating regions, as shown in Fig.4.8 by roman numbers. The output Δu from the fuzzy logic controller is the change that is required to increase or decrease the overall control action to the controlled system. Therefore the signs of e and Δe are used to determine the sign s of Δu, which determine whether the overall control signal is to be increased. The sign of Δu should be positive if u is required to increase and it should be negative otherwise.

The rules applied are as follows to determine the sign of Δu.

For region I: e=+ and Δe=-, the error is decreasing from positive value to zero. Therefore Δu is set to positive to reduce error.

For region II: e=0 and Δe=-, the error is zero and going towards negative therefore a negative Δu is used to reduce the error.

For region III: e=- and Δe=-, the error is negative and increasing so Δu will be negative to reduce the error.

For region IV: e=- and Δe=+, the error is negative and decreasing so negative Δu is applied to reduce the error.

For region V: e=0 and Δe=+, the error is zero but increasing in positive direction therefore a positive Δu is applied to increase the output and to reduce the error.

For region VI: e=+ and Δe=+, the error is positive and increasing. So a positive Δu will be used to reduce the error.

For region VII: same to region I.

For region VIII: e=- and Δe=0, the error is negative and constant, so a negative value of Δu should be used to decrease the error.

For region IX: e=+ and Δe=0, the error is positive and constant, therefore a positive value of Δu is needed to decrease the error.

For region X: e=0 and Δe=0, the error is zero and constant, so Δu is set to zero because no change is required for control signal.

These rules and states of Δu described above are listed in Table 4.4.

Table 4.4. The states of e, Δe and Δu

	Operating regions									
	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**
e	+	0	-	-	0	+	+	-	+	0
Δe	-	-	-	+	+	+	-	0	0	0
Δu	+	-	-	-	+	+	+	-	+	0

Table 4.4 shows that each one of e, Δe and Δu has three different signs; positive, negative or zero.

For these signs to be assigned, a table with 49 rules is formed. This table represents the input crisp variables e and Δe by seven fuzzy sets, Negative big (NB), Negative medium (NM), Negative small (NS), Zero (Z), Positive small (PS), Positive medium (PM) and Positive big (PB) and this yields a fuzzy output space with maximum of 49 rules as given in Table 4.5.

Table 4.5. Fuzzy rule's table

Δu		Δe						
		NB	NM	NS	Z	PS	PM	PB
e	NB	NB	NB	NB	NB	NM	NS	Z
	NM	NB	NB	NB	NM	NS	Z	PS
	NS	NB	NB	NM	NS	Z	PS	PM
	Z	NB	NM	NS	Z	PS	PM	PB
	PS	NM	NS	Z	PS	PM	PB	PB
	PM	NS	Z	PS	PM	PB	PB	PB
	PB	Z	PS	PM	PB	PB	PB	PB

For some applications, the nine rules or 25 rules are also sufficient. For Switched Reluctance Motor, the 49 rules give good results so here we used 49 rule's table.

In this study, triangular type membership functions are used for converting the crisps universe into fuzzy subsets. Different membership functions such as Gaussian, trapezoidal etc. can also be used. Each one of them has its own effects on FLC output. However triangular membership function is more convenient and more suitable to use. The following function is used to represent the fuzzy triangular membership functions.

$$\mu(x) = max\left[min\left(\frac{x - x_1}{x_2 - x_1}, \frac{x_3 - x}{x_3 - x_2}\right), 0\right] \tag{4.32}$$

Where x is the crisp values from one of the three universes e, Δe, and Δu. x_1 is the left end point on the corresponding crisp universe as the x_2 and x_3 are the crisp points corresponding peak and right end points respectively.

4.5.2. The Inference and Fuzzy Reasoning

The final control action is the crisp output that is defuzzified from the resultant fuzzy values of the fuzzy rule base. The fuzzy output of the rule base is obtained by triggering the active rules for the K_{th} sampling instant corresponding to the values e(k) and Δe(k). For any point (e(k), Δe(k)) on the trajectory plot of e(k) vs Δe(k), there are maximum of two intercepting fuzzy sets on each one of the universes e(k) and Δe(k). Therefore for any instant the value of e(k) activates only one or two fuzzy sets in the universe of e. Similarly for the value of Δe(k) for any sampling instant also activates only one or two fuzzy sets in the universe of Δe(k) as shown in Fig 4.9.

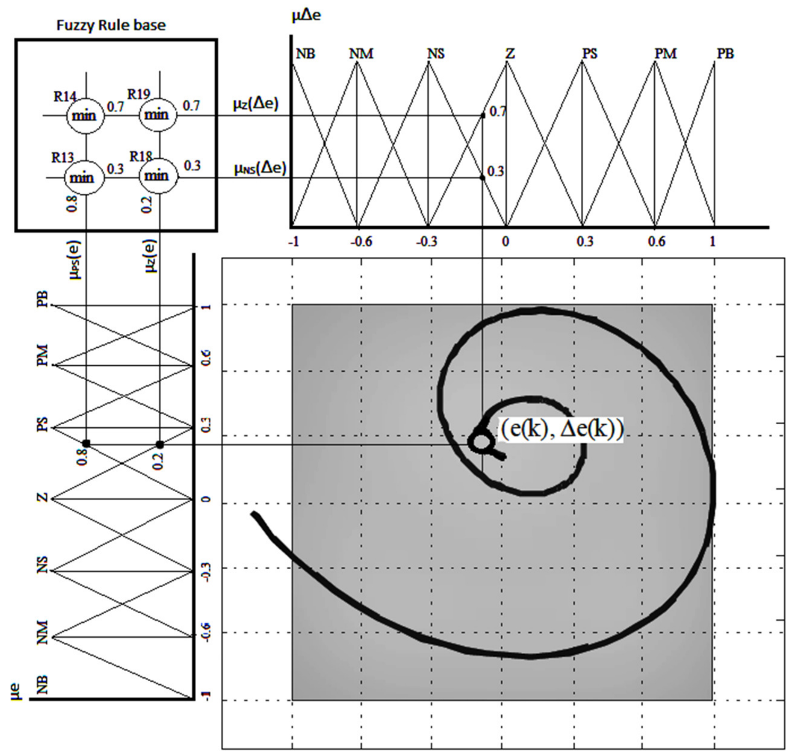

Fig. 4.9. Fuzzy reasoning

In the Figure the plot intercepts with the fuzzy sets of Z and PS for the universe of e and fuzzy sets of Z and NS for the universe of Δe. Therefore the following rules are activated for the given points.

Rule 13 (R13): if e is PS and Δe is NS then Δu will be Z.

Rule 14 (R14): If e is PS and Δe is Z then Δu will be PS.

Rule 18 (R18): If e is Z and Δe is NS then Δu will be NS.

Rule 19 (R19): If e is Z and Δe is Z then Δu will be Z.

The membership degrees for e in the fuzzy sets PS and Z is μPS=0.7 and μZ=0.3. And the membership degrees for Δe in fuzzy sets NS and Z are μNS=0.2 and μZ=0.8, respectively. Then the resultant membership values from each active rule to be used in the output space Δu are of following.

μR13(Δu)=min(μPS(e), μNS(Δe))= min(0.7, 0.2)= 0.2

μR14(Δu)=min(μPS(e), μZ(Δe))= min(0.7, 0.8)= 0.7

μR18(Δu)=min(μZ(e), μNS(Δe))= min(0.3, 0.2)= 0.2

μR19(Δu)=min(μZ(e), μZ(Δe))= min(0.3, 0.8)= 0.3

The resultant fuzzy outputs in the universe of Δu for these four active rules are depicted in Fig 4.10 with membership degrees.

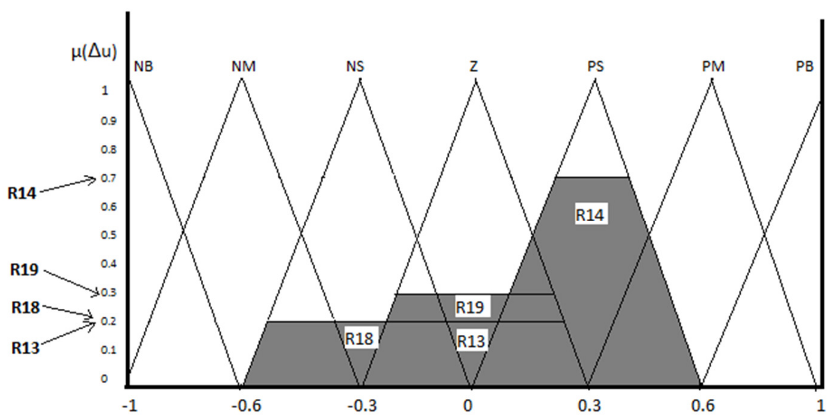

Fig. 4.10. Membership functions used in the universe of Δu

4.5.3. Defuzzification

The resultant membership values of the active rules determine the values of fuzzy sets for Δu as shown in Fig 4.10 with the shaded parts of the fuzzy sets. The average value of the union of these shaded fuzzy sets is used to calculate final crisp output as Δu(k). This process is called defuzzification. There are several methods for defuzzification but in this study the center of area is used. The center of area method is given by.

$$\Delta U_R(k) = \frac{\sum_{i=13,14,18,19} \mu_{Ri}(\Delta u_R)\Delta u_R(Ri)}{\sum_{i=1}^{4} \mu_i(uV_R)} \tag{4.33}$$

$$\Delta U_R(k) = \frac{0.2(0.0) + 0.7(0.3) + 0.2(-0.3) + 0.3(0.0)}{0.2 + 0.7 + 0.2 + 0.3} \quad (4.34)$$

$$\Delta U_R(k) = \frac{0.15}{1.4} = 0.10714 \quad (4.35)$$

Where Δu(Ri) is the crisp Δu value corresponding to the maximum membership degree of the fuzzy set that is an output from the rule decision table for the R_i. For example for rule 19, the output fuzzy set is Z and the crisp value Δu for rule 19 is 0.3.

4.5.4. Formation of FIS (Fuzzy inference system) file in Matlab Using Fuzzy Toolbox

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. This mapping then provides a base according to which decisions can be made. The fuzzy inference process involves all of the membership functions, fuzzy logic operator, and if-then rules. In Matlab Fuzzy Logic Toolbox, there are two types of fuzzy inference systems that can be implemented, Mamdani type and Sugeno type. Here in this study we will use Mamdani type of fuzzy inference system. Mamdani's fuzzy inference method is the most commonly used method. It was proposed in 1975 by Ebrahim Mamdani as an attempt to control a steam engine and boiler combination by synthesizing a set of linguistic control rules obtained from experienced human operators.

In the fuzzy logic toolbox, there are five sections of the fuzzy inference process, fuzzification of the inputs, application of the fuzzy operator (AND or OR), implication from the antecedent to the consequent, aggregation of the consequents across the rules, and defuzzification.

4.5.4.1. Fuzzification of Inputs

The first step is to determine the inputs and the degree to which they belong to for each of the appropriate fuzzy sets via membership functions. The input is always a crisp numerical value limited to the universe of discourse of the input variable and the output is a fuzzy degree of membership in the qualifying linguistic set (the interval between 0 and 1).

4.5.4.2. Applying Fuzzy Operator

After fuzzification of the inputs, we know the degree to which each part of the antecedent has been satisfied for each rule. If the antecedent of a given rule has more than one part, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. This number will then be applied to the output function. The input applied to the fuzzy operator has two or more membership value from fuzzified input variables. The output is a single truth value. In Fuzzy Logic Toolbox, two methods for the AND operator are used min (minimum) and prod (product) and two methods are used for OR operator, max (maximum) and prob (probabilistic OR) method.

4.5.4.3. Applying Implementation Method

According to the rule weight we will apply the implication method. Every rule has a weight (a number between 0 and 1) which is applied to the number given by the antecedent.

4.5.4.4. Aggregation of all Outputs

As decisions are based on the testing of all the rules in an FIS, the rules must be combined in some manner in order to come to a decision. Aggregation is the process by which the fuzzy sets representing the output of each rule are combined into a single fuzzy set. The input of the aggregation process is the list of truncated output functions returned by the implication process for each rule. The output of the aggregation process is one fuzzy set for each output variable.

4.5.4.5. Defuzzification

The input for the defuzzification process is a fuzzy set and the output is a single number. The aggregation of a fuzzy set encompasses a range of output values, and so must be defuzzified in order to resolve a single output value from the set. For defuzzification the most popular method is centroid method. There are five built-in methods, centroid, bisector, middle of maximum, largest of maximum and smallest of maximum.

The fuzzy inference file will be built using the graphical user interface (GUI) tools provided by fuzzy logic box. There are five primary GUI tools, FIS editor, the membership function editor, the rule editor, the rule viewer, and the surface viewer.

Firstly we have to define our input variables. Here, we have two inputs Error (e) and change in error (de) and one output. We have the same seven membership functions for each input and output. The membership functions and their ranges are defined below.

a)	Negative Big	NB	-1	-1	-0.7
b)	Negative Medium	NM	-0.7	-0.4	-0.1
c)	Negative Small	NS	-0.4	-0.2	0
d)	Zero	Z	-0.1	0	+0.1
e)	Positive Small	PS	0	+0.15	+0.3
f)	Positive Medium	PM	+0.15	+0.4	+0.7
g)	Positive Big	PB	+0.3	+0.7	+1

Now in FIS editor we have to introduce our inputs and output variables. Here the Mamdani type fuzzy system will be used. For these variables we will use the triangular and trapezoidal membership functions. These inputs and output are shown in Fig. 4.11.

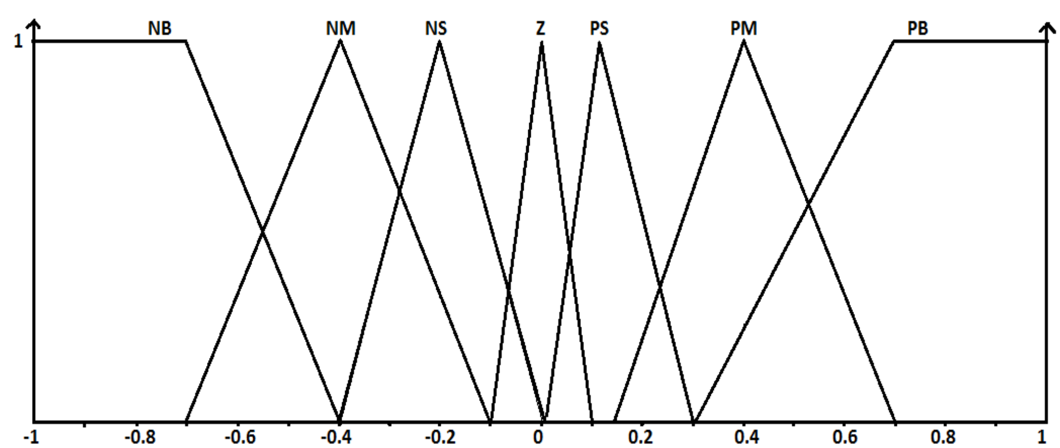

Fig. 4.11. Membership functions of input error (e), input change in error (de) and of the output (du)

After, the rules will be defined in rule editor. These rules will be defined according to the Table 4.5. In if-then statement these rules are as following.

Rule 01. *If* e is NB and Δe is NB *then* the Δu will be NB
Rule 02. *If* e is NB and Δe is NM *then* the Δu will be NB
Rule 03. *If* e is NB and Δe is NS *then* the Δu will be NB
Rule 04. *If* e is NB and Δe is Z *then* the Δu will be NB
Rule 05. *If* e is NB and Δe is PS *then* the Δu will be NM
Rule 06. *If* e is NB and Δe is PM *then* the Δu will be NS
Rule 07. *If* e is NB and Δe is PB *then* the Δu will be Z
Rule 08. *If* e is NM and Δe is NB *then* the Δu will be NB
Rule 09. *If* e is NM and Δe is NM *then* the Δu will be NB
Rule 10. *If* e is NM and Δe is NS *then* the Δu will be NB
Rule 11. *If* e is NM and Δe is Z *then* the Δu will be NM
Rule 12. *If* e is NM and Δe is PS *then* the Δu will be NS
Rule 13. *If* e is NM and Δe is PM *then* the Δu will be Z
Rule 14. *If* e is NM and Δe is PB *then* the Δu will be PS
Rule 15. *If* e is NS and Δe is NB *then* the Δu will be NB
Rule 16. *If* e is NS and Δe is NM *then* the Δu will be NB
Rule 17. *If* e is NS and Δe is NS *then* the Δu will be NM
Rule 18. *If* e is NS and Δe is Z *then* the Δu will be NS
Rule 19. *If* e is NS and Δe is PS *then* the Δu will be Z
Rule 20. *If* e is NS and Δe is PM *then* the Δu will be PS
Rule 21. *If* e is NS and Δe is PB *then* the Δu will be PM
Rule 22. *If* e is Z and Δe is NB *then* the Δu will be NB
Rule 23. *If* e is Z and Δe is NM *then* the Δu will be NM
Rule 24. *If* e is Z and Δe is NS *then* the Δu will be NS
Rule 25. *If* e is Z and Δe is Z *then* the Δu will be Z
Rule 26. *If* e is Z and Δe is PS *then* the Δu will be PS
Rule 27. *If* e is Z and Δe is PM *then* the Δu will be PM
Rule 28. *If* e is Z and Δe is PB *then* the Δu will be PB
Rule 29. *If* e is PS and Δe is NB *then* the Δu will be NM
Rule 30. *If* e is PS and Δe is NM *then* the Δu will be NS

Rule 31. *If* e is PS and Δe is NS *then* the Δu will be Z

Rule 32. *If* e is PS and Δe is Z *then* the Δu will be PS

Rule 33. *If* e is PS and Δe is PS *then* the Δu will be PM

Rule 34. *If* e is PS and Δe is PM *then* the Δu will be PB

Rule 35. *If* e is PS and Δe is PB *then* the Δu will be PB

Rule 36. *If* e is PM and Δe is NB *then* the Δu will be NS

Rule 37. *If* e is PM and Δe is NM *then* the Δu will be Z

Rule 38. *If* e is PM and Δe is NS *then* the Δu will be PS

Rule 39. *If* e is PM and Δe is Z *then* the Δu will be PM

Rule 40. *If* e is PM and Δe is PS *then* the Δu will be PB

Rule 41. *If* e is PM and Δe is PM *then* the Δu will be PB

Rule 42. *If* e is PM and Δe is PB *then* the Δu will be PB

Rule 43. *If* e is PB and Δe is NB *then* the Δu will be Z

Rule 44. *If* e is PB and Δe is NM *then* the Δu will be PS

Rule 45. *If* e is PB and Δe is NS *then* the Δu will be PM

Rule 46. *If* e is PB and Δe is Z *then* the Δu will be PB

Rule 47. *If* e is PB and Δe is PS *then* the Δu will be PB

Rule 48. *If* e is PB and Δe is PM *then* the Δu will be PB

Rule 49. *If* e is PB and Δe is PB *then* the Δu will be PB

These rules are defined in the rule viewer, and in graphics it is shown in Fig.4.12.

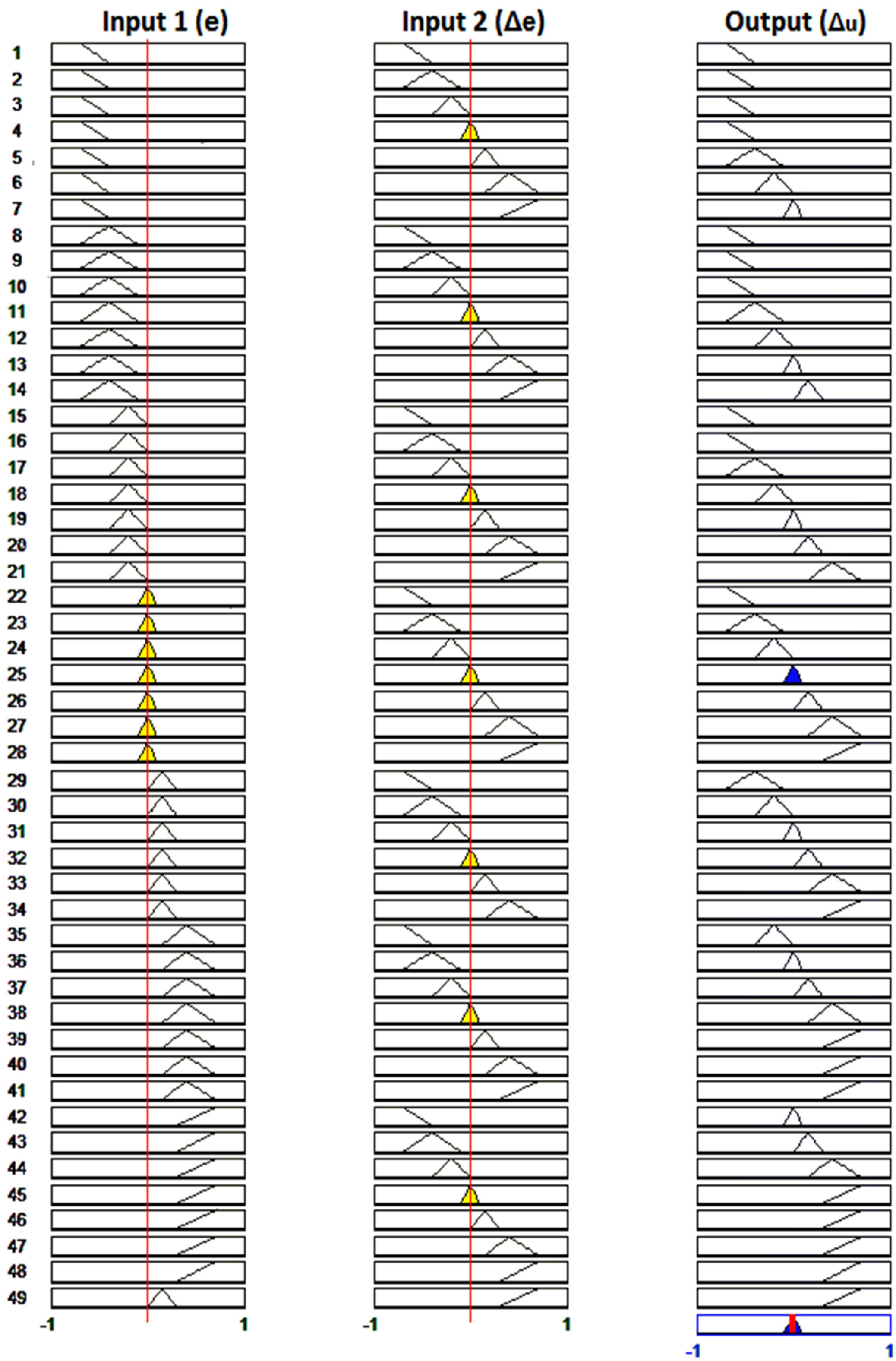

Fig. 4.12. Fuzzy Rules

The surface view of these rules is given in Fig.4.13.

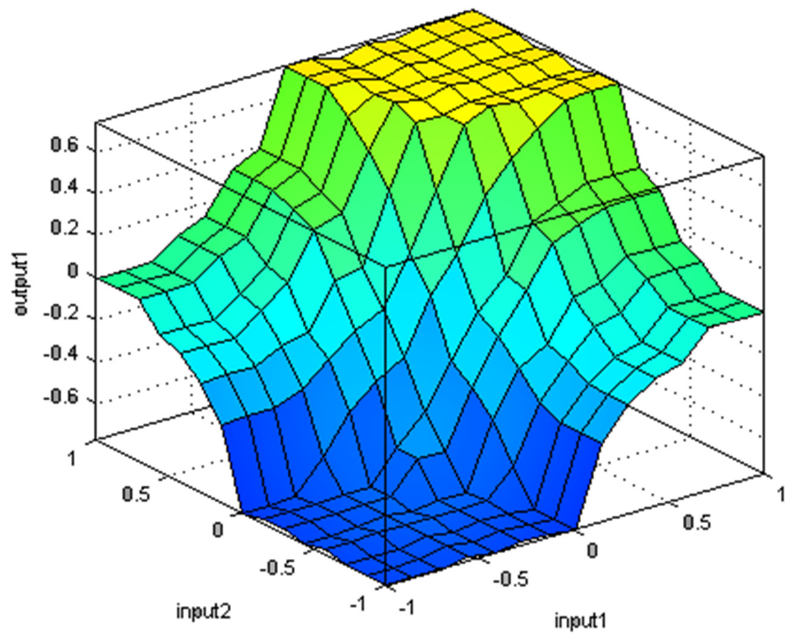

Fig. 4.13. Surface view of rules

Now the FIS file according to our rules is ready and is coded as below,

```
[System]
Name='fuzzy_controller'
Type='mamdani'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=49
AndMethod='prod'
OrMethod='max'
ImpMethod='prod'
AggMethod='sum'
DefuzzMethod='centroid'

[Input1]
Name='input1'
Range=[-1 1]
NumMFs=7
MF1='NB':'trapmf',[-1 -1 -0.7 -0.4]
MF2='NM':'trimf',[-0.7 -0.4 -0.1]
MF3='NS':'trimf',[-0.4 -0.2 0]
MF4='Z':'trimf',[-0.1 0 0.1]
MF5='PS':'trimf',[0 0.15 0.3]
```

```
MF6='PM':'trimf',[0.15 0.4 0.7]
MF7='PB':'trapmf',[0.3 0.7 1 1]

[Input2]
Name='input2'
Range=[-1 1]
NumMFs=7
MF1='NB':'trapmf',[-1 -1 -0.7 -0.4]
MF2='NM':'trimf',[-0.7 -0.4 -0.1]
MF3='NS':'trimf',[-0.4 -0.2 0]
MF4='Z':'trimf',[-0.1 0 0.1]
MF5='PS':'trimf',[0 0.15 0.3]
MF6='PB':'trapmf',[0.3 0.7 1 1]
MF7='PM':'trimf',[0.15 0.4 0.7]

[Output1]
Name='output1'
Range=[-1 1]
NumMFs=7
MF1='NB':'trapmf',[-1 -1 -0.7 -0.4]
MF2='NM':'trimf',[-0.7 -0.4 -0.1]
MF3='NS':'trimf',[-0.4 -0.2 0]
MF4='Z':'trimf',[-0.1 0 0.1]
MF5='PS':'trimf',[0 0.15 0.3]
MF6='PM':'trimf',[0.15 0.4 0.7]
MF7='PB':'trapmf',[0.3 0.7 1 1]

[Rules]
1 1, 1 (1) : 1
1 2, 1 (1) : 1
1 3, 1 (1) : 1
1 4, 1 (1) : 1
1 5, 2 (1) : 1
1 7, 3 (1) : 1
1 6, 4 (1) : 1
2 1, 1 (1) : 1
2 2, 1 (1) : 1
2 3, 1 (1) : 1
2 4, 2 (1) : 1
2 5, 3 (1) : 1
2 7, 4 (1) : 1
2 6, 5 (1) : 1
3 1, 1 (1) : 1
3 2, 1 (1) : 1
3 3, 2 (1) : 1
3 4, 3 (1) : 1
3 5, 4 (1) : 1
3 7, 5 (1) : 1
3 6, 6 (1) : 1
4 1, 1 (1) : 1
4 2, 2 (1) : 1
4 3, 3 (1) : 1
4 4, 4 (1) : 1
4 5, 5 (1) : 1
4 7, 6 (1) : 1
4 6, 7 (1) : 1
5 1, 2 (1) : 1
5 2, 3 (1) : 1
5 3, 4 (1) : 1
5 4, 5 (1) : 1
```

```
83 5 5, 6 (1) : 1
84 5 6, 7 (1) : 1
85 6 1, 3 (1) : 1
86 6 2, 4 (1) : 1
87 6 3, 5 (1) : 1
88 6 4, 6 (1) : 1
89 6 5, 7 (1) : 1
90 6 6, 7 (1) : 1
91 6 7, 7 (1) : 1
92 7 1, 4 (1) : 1
93 7 2, 5 (1) : 1
94 7 3, 6 (1) : 1
95 7 4, 7 (1) : 1
96 7 5, 7 (1) : 1
97 7 7, 7 (1) : 1
98 7 6, 7 (1) : 1
99 5 7, 7 (1) : 1
```

4.5.5. Direct Torque Control of Switched Reluctance Motor in Simulink Environment

In this section, Switched Reluctance Motor is simulated with Fuzzy Logic Controller and the result is observed for its torque ripples minimization and its speed control. The Switched Reluctance Motor here has the following parameters.

Table 4.6. Switched Reluctance Motor parameters

Motor type	8/6, Four phase
Stator Resistance	3.1 ohm
Inertia	0.0089 kg.m^2
Friction	0.01N.m.s
Unaligned inductance	5.9 mH
Aligned inductance	23.6 mH
Maximum current	10A
Maximum Flux linkages	0.486 V.s

In this study the single phase 120V is used for the circuit. This 120V is converted to four phase eight pole by a converter according to pulses generated by fuzzy direct torque control circuit. The converter circuit is shown in Fig. 4.14.

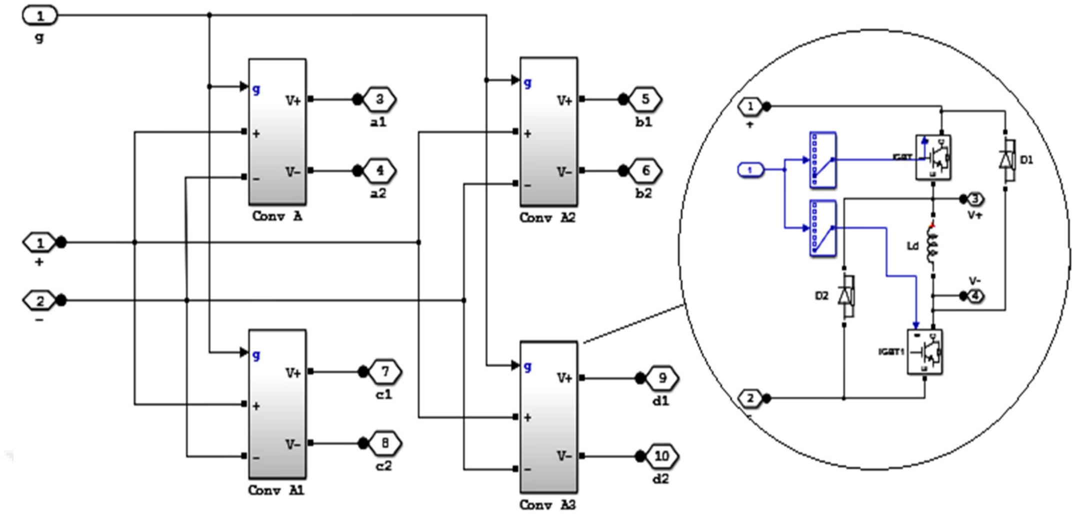

Fig. 4.14. Converter circuit

This 4 phase 8 pole voltage is applied to Switched Reluctance Motor and it is also applied to speed and flux estimation block. The speed and flux are estimated from the voltage and current applied to controller block as a reference. The flux and speed estimation circuit are shown in Fig. 4.15.

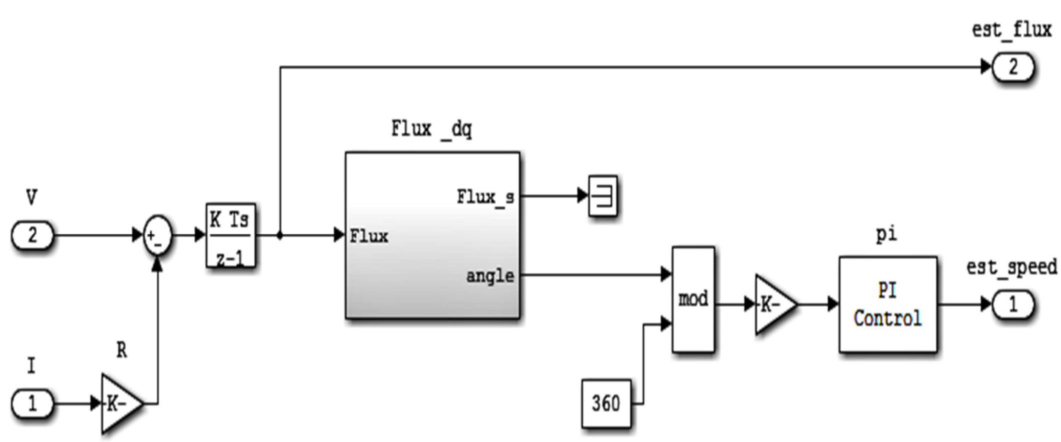

Fig. 4.15. Flux and speed estimation block

The estimated flux and speed are applied to fuzzy based direct torque control circuit, where the gate pulses are generated for converter. The FLC based DTC block is shown in Fig.4.16.

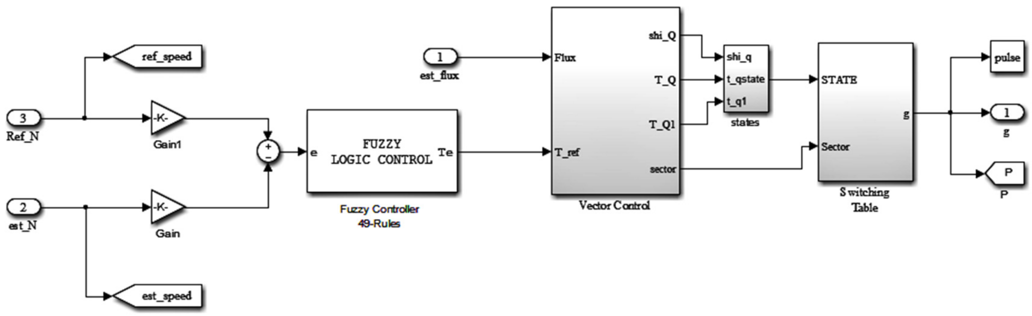

Fig. 4.16. FLC-DTC Block diagram

The switching table in section FLC-DTC block has 6 states and 8 vectors. The states are selected according to the condition of flux and torque vector. These states and conditions are given in Table 4.3 and from these 8 vector the selection of vector is done according to the states of flux and torque vector. The switching table in Simulink environment is shown in Fig. 4.17.

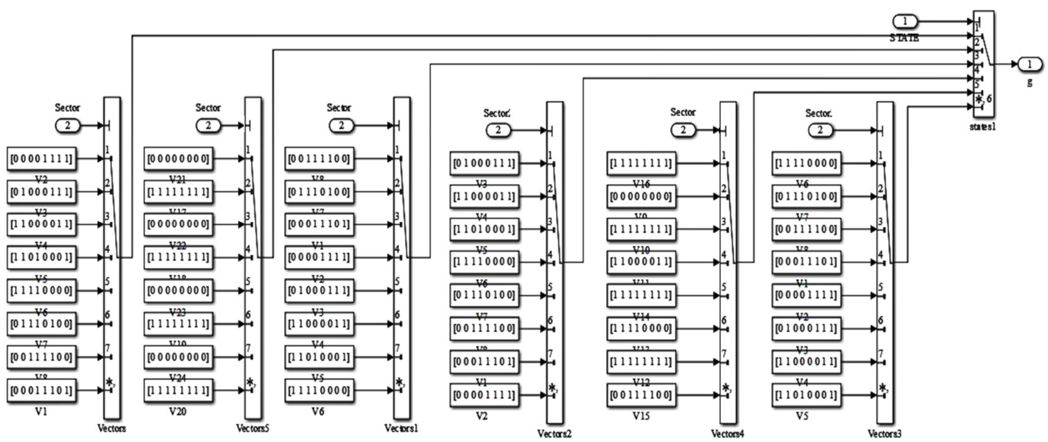

Fig. 4.17. Switching table in Simulink

The complete block diagram of the Fuzzy Logic based Direct Torque Control for torque ripple minimization and for speed control of Switched Reluctance Motor is shown in Fig.4.18.

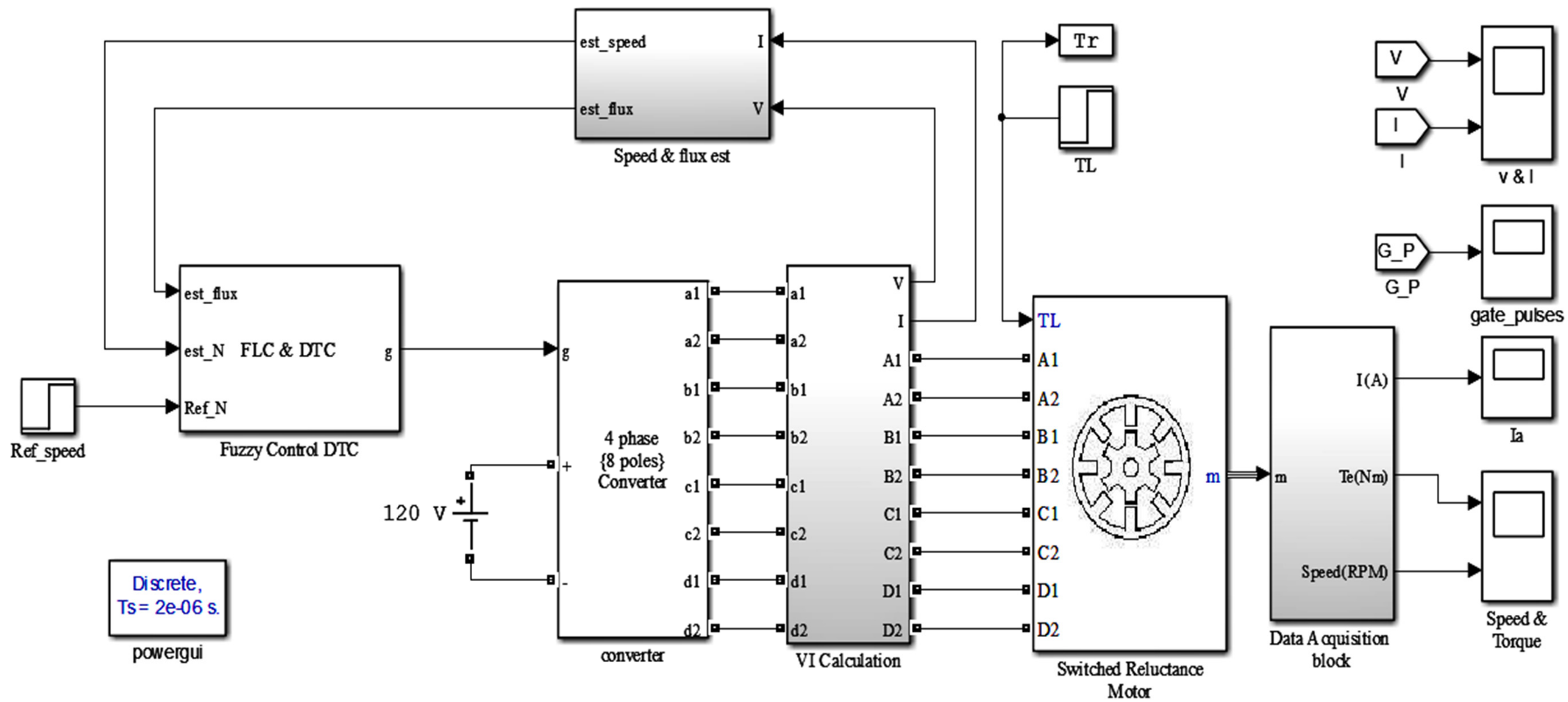

Fig. 4.18. FLC-DTC block diagram

4.5.6. Simulation and Results

The Switched Reluctance Motor specifications are given in Table 5.6. First the Switched Reluctance drive is simulated for 2sec and for a reference input of 750 rpm. The load torque is zero at starting point and after 1 sec, the load torque is increased to 3Nm. The simulation result is shown in Fig. 4.19.

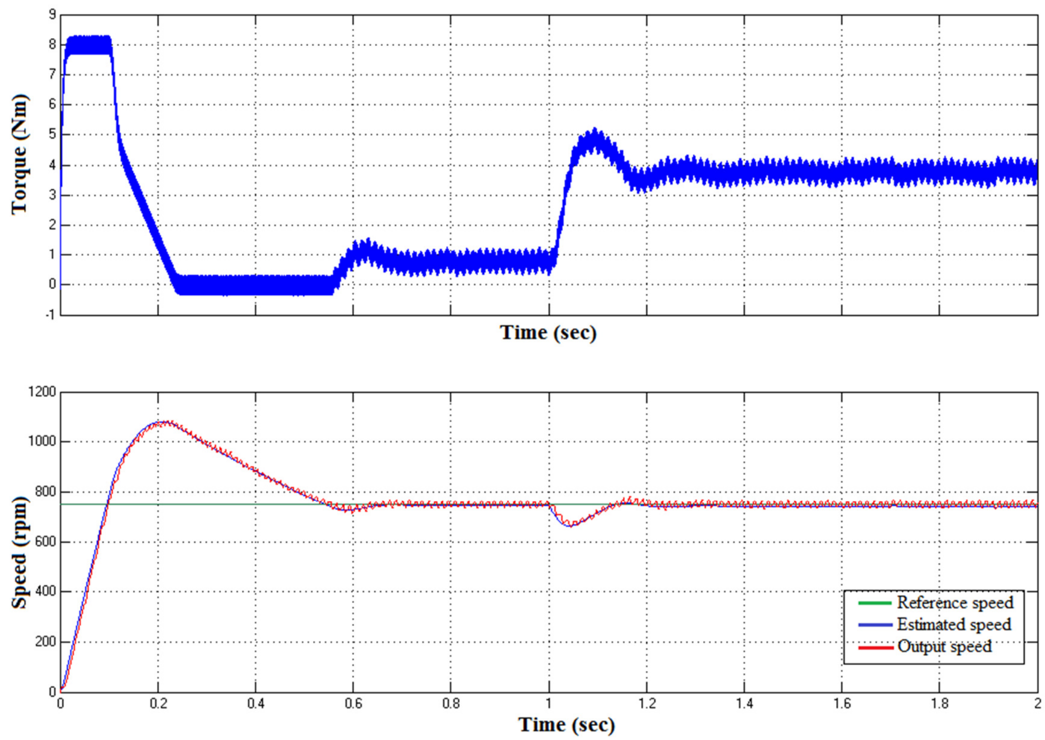

Fig. 4.19. Simulation result for a constant reference speed

The torque ripples are minimized to a very low value. The estimated speed is the same as the reference speed applied and the output speed is following the estimated speed very closely. And at starting it takes only 0.4sec to reach the exact reference speed, it is a good value. After 0.4sec it remains constant as the reference is applied. At 1 sec the torque increased from zero to 3Nm so it affects the speed a little, after that the speed again takes the reference value. For the constant input the motor current and the gate pulses are also shown in Fig.4.20.

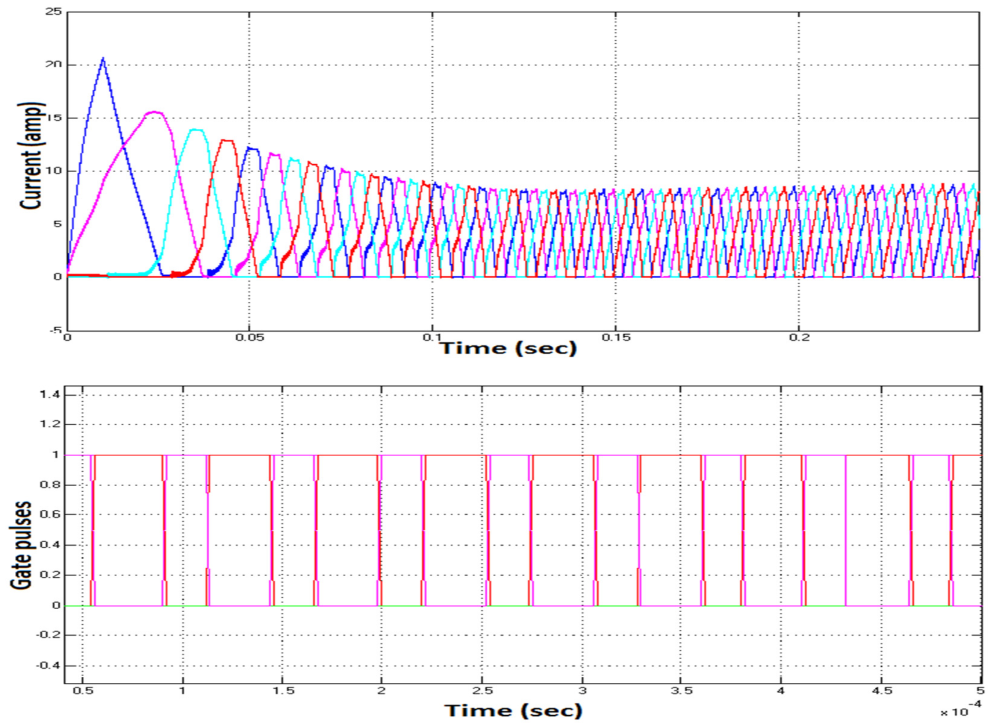

Fig. 4.20. Motor current and gate pulses for a constant reference

Now the switched reluctance motor is simulated for 3 sec and the reference applied has varying speed. The input reference speed of 500 rpm is applied for up to 1.5sec. After 1.5sec the reference speed is changed to -500 rpm for up to 3sec. The load torque is set to zero. The torque and speed simulation results are shown in Fig.4.21. From simulation results it is clear that the system is also worked well for a negative reference speed, means for reverse direction. For the forward direction it has a low value of peak to peak torque ripple as well as for reverse direction.

Here the torque ripples are reduced to a very low value. If we compare it with the simulation results of uncontrolled switched reluctance drive as shown in Fig. 2.14(c), it has negligible ripples. In uncontrolled system, the torque ripples swing up to a minimum of 100 Nm and here in FLC-DTC controlled system the torque ripples swings up to a maximum value of 1 Nm. There is a big difference. For this configuration, the motor current and the gate pulses are shown in Fig.4.22.

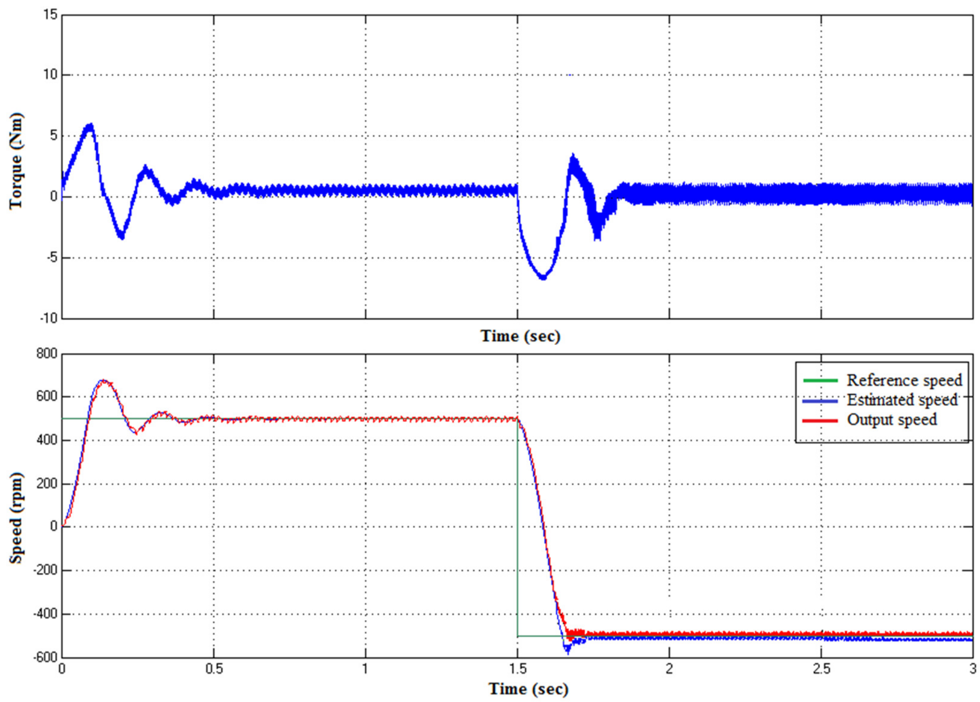

Fig. 4.21. Torque and Speed simulation results for a varying reference

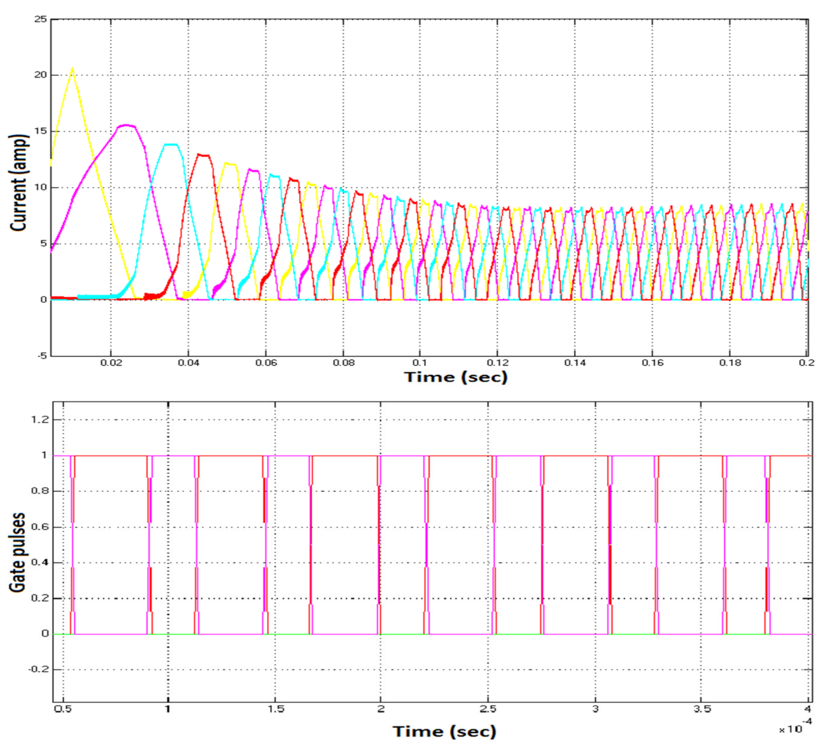

Fig. 4.22. Motor current and gate pulses for a varying reference

4.5.7. Comparison of FLC-DTC Method With Some Other Recent Proposed Methods

If we compare the simulation results of the fuzzy logic based direct torque control, (FLC-DTC method) to other recent proposed methods, the FLC-DTC method has much better results than the other methods. The fuzzy logic based direct torque control method has a minimum number of torque ripples and has a very small value of peak to peak torque ripple as compared to other methods.

The FLC-DTC method is compared to Fuzzy logic control compensation method, particle swarm optimization method, controlling of phase current during commutation method and brain emotional learning based on intelligent control method. By comparing all these methods the FLC-DTC method has a small value of peak to peak torque ripple of 1Nm and it has also less amount of the torque ripples.

These methods are compared for a speed reference of 800-1000 rpm and a load toque of 3-5 Nm. The peak to peak torque ripples are observed as given in Table 4.7.

Table 4.7. Comparison of different methods

Control strategy	**Speed (RPM)**	**Load torque (Nm)**	**Peak-Peak Torque ripple (Nm)**
Fuzzy logic control compensation method	800-1000	3-5	28
Particle swarm optimization method	800-1000	3-5	8
Controlling of phase current during commutation method	800-1000	3-5	29
Brain emotional learning based on intelligent control	800-1000	3-5	15
FLC based Direct torque control method	800-1000	3-5	**1.5**

The torque simulation results for each method is shown in Fig.4.23. The Fuzzy logic controller based direct torque control method has a minimum peak to peak value for torque ripples among all methods.

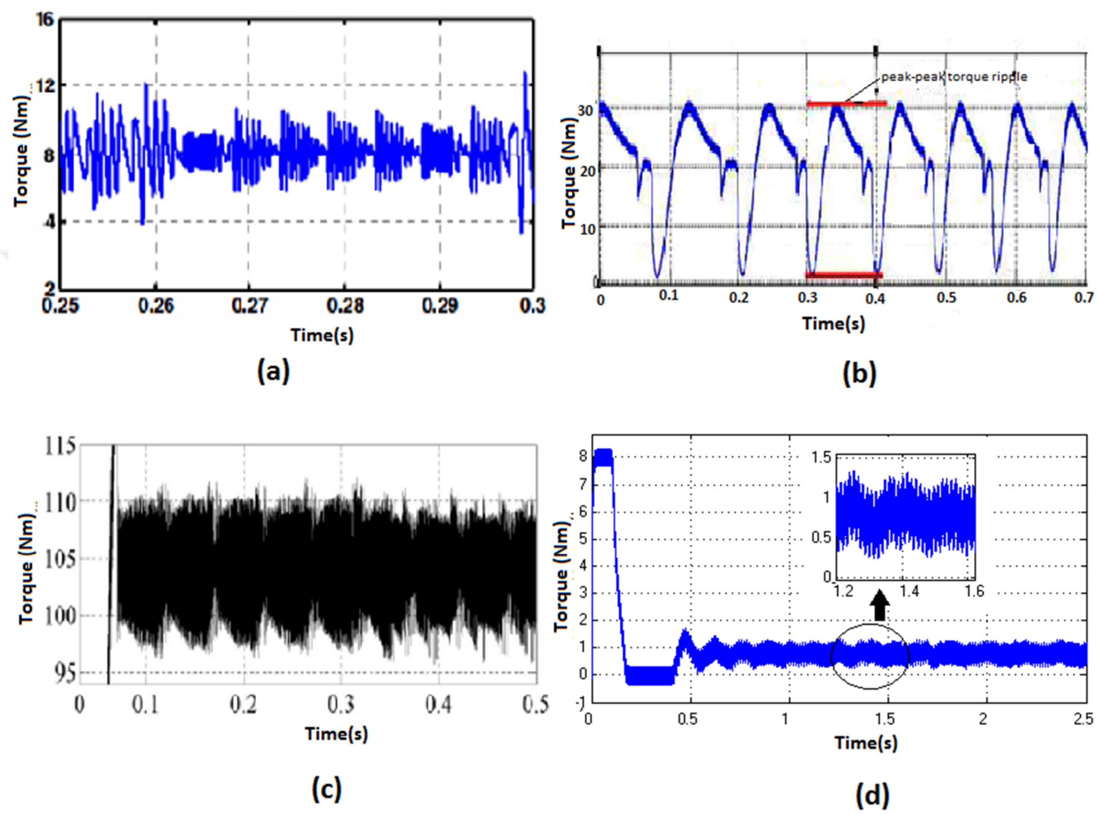

Fig. 4.23. Comparison of various methods (a) Particle swarm optimization method (b) Controlling of the phase currents during commutation method (c) Brain emotional learning based on intelligent control (BELBIC) method (d) FLC-DTC method

If we observe peak to peak torque ripples, the proposed Fuzzy logic based direct torque control method has the smallest value of only 1-1.5Nm. So the proposed method gives much better results than the other methods.

5. CONCLUSION

This thesis describes the structure of Switched Reluctance Motor and its operation principle with a control algorithm. A linear mathematical model of the 8/6 switched reluctance motor is designed in Simulink. The thesis focused on the minimization of the torque ripples produced by switched reluctance motor due to its doubly silent structure. It also focused on the speed control of the switched reluctance motor. It is observed from simulation that the torque is improved when the inductance has changed. At constant inductance i.e. unaligned position the developed torque is zero. To produce positive torque, voltage should be applied during $+dL/d\theta$ region, whereas negative torque is produced at $-dL/d\theta$ region. Therefore the exact switching (turn-on and turn-off angle) is needed. To get these exact angles for converters to improve the torque of the motor, a fuzzy logic controller is developed. And the developed fuzzy logic controller is used with direct torque control method to control the ripples in torque and also to control the speed of the motor. The direct torque control method with fuzzy logic controller controls the speed of the switched reluctance motor according to the required reference applied. It also reduces the torque ripples to a very low value. Here in this study the "fis" file is used for fuzzy logic controller. The proposed fuzzy logic based direct torque control method reduces the torque ripples to a very low value. In this method the produced torque ripple are only of 1Nm. By comparing this value of torque ripple to other methods it is concluded that the fuzzy logic based direct torque control method has much better torque ripple reduction than the other methods.

6. FUTURE WORK

As discussed before, the control of Switched Reluctance Motor is a very big issue which contains a lot of challenges. From the view of this thesis, further research can be performed, the motor dynamic performance can be investigated and new control methods can be implemented to further decrease the torque ripples and to get more accurate reference speed. The new methods can be artificial neural network etc.

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