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Modeling and Simulation of Switched Reluctance Motor Double Closed Loop Control System

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Abstract:

This paper presents the modeling, simulation, and speed control aspects of a 3-phase 6/4 switched reluctance motor (SRM) drives. Using hybrid combination of conventional PI & expert fuzzy system. Fourier series expression of phase self-inductance under the assumption of negligible mutual effect and various losses is introduced to describe the nonlinear dynamic model of SRM. In addition, to improve the adjustable speed performance of SRM drives, the double closed loop control strategy based on a chopping controller in the current loop and a Fuzzy PI controller in the speed loop is proposed. Simulation results have shown the rationality of model and validity of control strategy. By virtue of MATLAB/SIMULINK, the models of various subsystems are achieved and the modeling procedure is described in detail. By the organic combination of subsystems, the whole simulation model of SRM drives is established. The model developed here can be widely used and is easy to modify, which offers a good platform for choosing the best control strategy

Key words: *switched reluctance drives, modeling and simulation, double closed loop compound control, chopping control.*

1. Introduction

The concept of the switched reluctance machine is actually very old, going back to the 19th century inventions called electromagnetic engines" [2], which were the forerunners of modern stepper motors. The switched reluctance motor is basically a stepper motor and has had many applications in

both rotary and linear stepping. In the 1960's only thyristor power semiconductors were available for the relatively high-current, high-voltage type of control needed for SRM type machines. These years, power transistors, GTOs, IGBTs, and power MOSFETs have been developed in the power ranges required for SRM control. Switched reluctance Motor (SRM) have been found to offer important advantages over conventional AC machines in generating/breaking as well as motoring operations and has proved to be the potential candidate for many industrial applications. The researches on this machine had been focused on the motoring operation over a long period of time. Since the machine has the good reversibility characteristics and the SRG can run as good as SRM, fewer scholars took notice on the generating mode of SRM. This led to the increased interest in researchers of electrical community as this machine is an attractive solution for worldwide increasing demand of electrical energy. The shortcomings of the conventionally used generators have turned research attention to a more simple and robust variable speed switched reluctance generator (SRG) which exhibits the most desirable features of a generator. The switched reluctance motor (SRM) has a simple design with a rotor without windings and stator with windings located at the poles [1,2,3]. The inherent simplicity, ruggedness, and low cost of SRM make it possess strong competition in many adjustable speed and servo-type applications. Switched Reluctance Drive (SRD) is a steeples speed regulation system, which is composed of SRM, converter and controller. However, control strategy, converter’s topology and optimization design of SRM have crucial influence on performance of SRD. Thus, dynamic simulation of the whole SRD has become very important In this paper, a whole simulation model for SRM double closed loop compound control system is presented. In order to describe the characteristic of SRM exactly, a nonlinear model of SRM is adopted. With the help of MATLAB/SIMULINK, various subsystems, such as motor model block, speed controller block, current control block etc, have been modeled and the actual implementation of the models are explained in detail. Simulation results are presented to verify the effectiveness of the model, which lays the foundation for the study of the dynamic performance of switched reluctance motor drives with different control methods and shows that it can be easily generalized to the modeling and simulation research of SRD with arbitrary phase numbers.

2.History, Design And Application Developments Of Switched Reluctance Generator

The switched reluctance machine as a motor has been known for over 150 years. The generating mode of this machine SRG has created considerable interest during past few years in machine systems which either generate or regenerate. Although it is one of the earliest discovered machines, special power requirements limited the earlier investigation and application. Development of power electronic components and the advent of cheap microcomputers renewed the research interest in SRG.

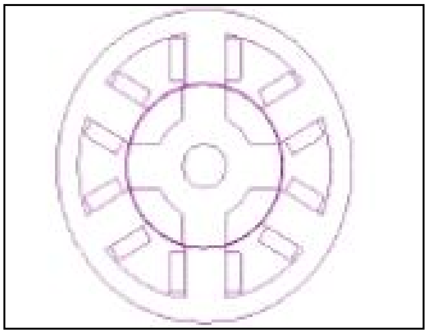

Figure 1:Cross section of the Switched Reluctance Machine

The inherent simple construction, ruggedness, wide speed range of operation, low cost, fault tolerant capability, easy cooling simple excitation, requirement of simple converter circuit, high torque volume ratio, high efficiency and suitability under harsh environments are some of the important advantageous features of switched reluctance machine. The simple construction of the doubly salient, singly excited switched reluctance machine is shown in fig1

The physical appearance of a Switched Reluctance motor is similar to that of other rotating motors (AC and DC) Induction Motor, DC motor etc. The construction of SRM is shown in figure. It has doubly salient construction. Usually the number of stator and rotor poles is even. The windings of Switched Reluctance Motor are simpler than those of other types of motor. There is winding only on stator poles, simply wound on it and no winding on rotor poles. The winding of opposite poles is connected in series or in parallel forming no of phases exactly half of the number of stator poles. Therefore excitation of single phase excites two stator poles. The rotor has simple laminated salient pole structure without winding. This is the advantage of this motor as it reduces copper loss in rotor winding. The stampings are made preferably of silicon steel, especially in higher efficiency applications. For aerospace application the rotor is operating at very high speed, for that cobalt, iron and variants are used. The air gap is kept as minimum as possible, especially 0.1 to 0.3mm. The rotor and stator pole arc should be approximately the same. If the rotor pole arc is larger than the stator pole arc it is more advantageous.

2.1.Excitation Methods

The recent research shows that the SRG is inherently completely passive and has no self excitation capability. To overcome this problem some researchers used a slot of permanent magnet on the edge of the stator pole to create a magnetic field that run through the rotor to both sides of the stator; the rotation of the rotor will change the permanent magnetic flux which induces alternating voltage in the stator winding. The others have chosen an external power source to help in self excitation for this SRG like using a battery or capacitor to create a magnetic field around the stator winding for a set time and then this magnetic field will be used to create electricity when the rotor moves [1]. The concept of attaching rectangular pieces to each pole of the machine phase for self excitation has been presented and implemented the same in three different means in [13]. The Permanent magnet material used is Samarium Cobalt. In the first option of magnet placement, the stator core was cut around the teeth of one phase from top surface towards bottom of the core. Several lamination layers of each tooth were removed and room for the permanent magnets was provided. The second option that has been implemented comprises only permanent magnets fastened to the stator poles without cutting the stator core. The last option for a self excited SR Generator design was the same as the first case except that only two instead of four permanent magnet pieces were fastened on each phase tooth on only one side of the stator core.

3.Mathematical Model Theory

SRM is very non-linear system, therefore the torque generation process can be described accurately only while using the non-linear mathematical model. The model is based on the electrical diagram of one phase (Fig. 2) and following simplifications:

The functions Ψ (i, Θ), M (i, Θ) and R for one phase are known.

Magnetic material hysteresis is negligible.

The mutual phase inductance is neglected.

In time t = 0s is valid W_{el}= 0 J, W_{mag} = 0 J and W_{mech} = 0 J.

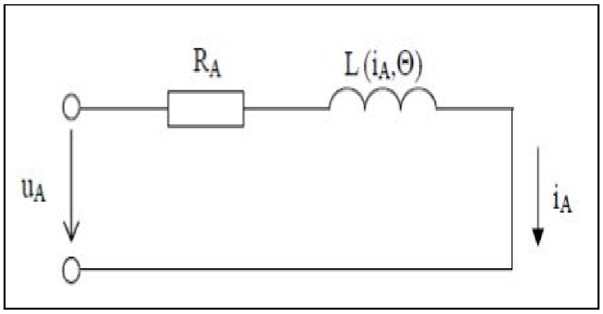

Figure 2: Electrical diagram for phase A.

According the diagram, any phase of the SRM can be described as

$$u_a(t) = R_a . i_a(t) + \frac{\partial \Psi_a(t)}{\partial i_a(t)} \frac{di_a(t)}{dt} + \frac{\partial \Psi_a(t)}{\partial \Theta(t)} \omega \qquad (1)$$

The mathematical model of SRM is based on the following system of differential equations and described the electromechanical conversion of energy.

Where Θ – rotor position angel, ω – angular velocity, T_{ix} – phase x torque, T_L – loading torque, T_d – dynamic torque, m – number of phases and u_x – phase x voltage.

A dynamic model of a SRM is composed of a set of electrical equations for each phase and equations of mechanical system. In a typical p-phase SRM, if negligible phase interaction is assumed, the machine’s voltage equation can be expressed as [1, 2, 3, 4]

$$U_K = R_k i_k + \frac{d\psi_k(\theta, i_k)}{dt} \qquad \text{k=1,2,…..p,} \qquad (2)$$

where U_k is the terminal voltage of phase *k* , i_k is phase current, Ψ_k is the flux linkage. R_k is the phase winding resistance and θ is rotor position. Flux linkage is related to the inductance and current in the electromagnetic circuit of a

SRM phase and expressed by (2).

$$\psi_k = \psi_k(\theta, i_k) = L_k(\theta, i_k) i_k \qquad \text{k=1,2,….p} \qquad (3)$$

In (2), L_k is the inductance of *k* phase. Just as literatures Mentioned, $Lk\,(\theta, i_k)i_k$ can be fit by (3).

$$L_k(\theta,i_k)=L_0(i_k)+\cos(N_r\theta+\pi)+\sum_{n=2,3\ldots}^{N}L_n(i_k)\cos(nN_r\theta+n\pi) \quad (4)$$

where *Nr* is the number of rotor poles, if only the first two terms are considered, then $Lk\,(\theta, i_k)i_k$ can be expressed as

$$L_k(\theta,i_k)=L_0(i_k)+L_1(i_k)\cos(N_r\theta+\pi) \quad ,(5)$$

where

$$L_0(i_k)=\frac{L_{k\max}(i_k)+L_{k\min}(i_k)}{2} \quad (6)$$

$$L_1(i_k)=\frac{L_{k\max}(i_k)-L_{k\min}(i_k)}{2} \quad (7)$$

$$L_{k\max}(i_k)=\sum_{n=0}^{3}a_n i_k^n \quad (8)$$

is the aligned position inductance[2,3,4,5], $L_{k\min}(i_k)$ is the unaligned position inductance and is assumed to be a constant. The phase torque is given as literature [3,4,8] derived:

$$T_k=\frac{-N_r i_k^2}{4}\left[\left(\sum_{n=0}^{3}\frac{2a_n}{n+2}i_k^n-L_{k\min}(i_k)\right)\sin(N_r\theta)\right] \quad (9)$$

On the mechanical side, the dynamic equation can beexpressed as: $\omega=\dfrac{d\theta}{dt}$ and

$$T_e=\sum_{k=1}^{p}T_k=J\frac{d^2\theta}{dt^2}+D\frac{d\theta}{dt}+T_L \quad (10)$$

In (8), T_e is electromagnetic torque, T_L is load torque, ω is angle velocity, *J* and *D* represent moment of inertia and coefficient of friction respectively. In this paper, a 3-phase 6/4 SRM is chosen as the object of study, detailed specification of the motor used in this investigation is given in the following text.

4.Dynamic Model Foundation Of The Srm Control System Based On Matlab/Simulink

On the basis of analyzing nonlinear model of SRM, dynamic model of SRM with improved transient response to make drive run with higher speed. Thus adjustable speed syste is established with the help of MATLAB/SIMULINK in this part. A general schematic of a drive system shown in Fig.1 is considered. It consists of outer speed loop controller. and the inner current loop. The working of the system is briefly discussed here so as to with PI+Fuzzy controller develop the control algorithm.

Rotor position is sensed by position sensor, the derivative of which gives the rotor speed in rad/sec. The reference speed compared with the rotor speed is the speed error. The speed error signal is processed through a proportional plus integral and fuzzy logic hybrid or Add on speed controller to yield the reference current I_{ref}. The reference current *Iref* is compared with the motor currents and the errors are used to determine the switching of the phase and main switches of any converter by current chopping controller. Then the voltages are applied to respective windings based on their position information obtained from position sensor.

In order to make the model of SRM drive system be generalized to other phase numbers and be convenient for using various control methods, blocking idea is introduced here[6,9].The whole model is divided into several independent blocks, such as motor phase winding block, speed controller block, current control block etc. Motor phase winding block is composed of modulo block, switch logic and converter block, current calculation block and torque calculation block etc[6,9]. The whole simulation of SRM drive system is shown in Fig.2. Detailed implementation of various subsystems blocks are introduced as follows.

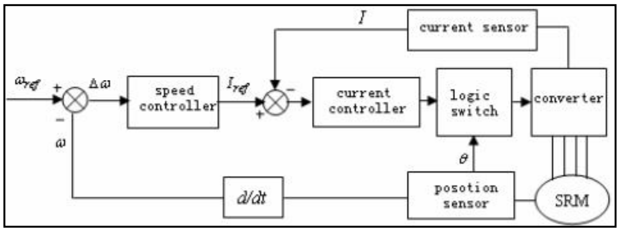

Figure 2: Double closed loop compound controlled SRM drive system

The below figure shows the Full MATLAB /Simulink model of the SRM drive system.

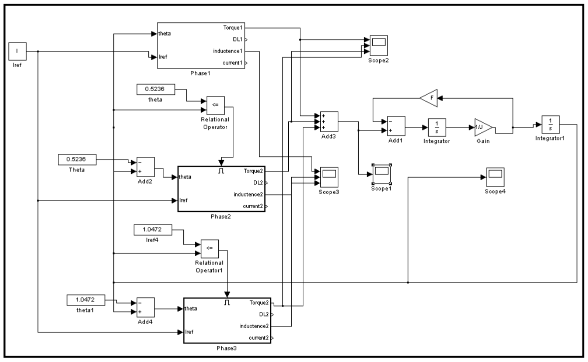

Figure 3: MATLAB /Simulink model of the SRM drive system.

4.1.Motor phase winding block

Motor phase winding block is the most important part of

the whole system simulation. It shows the inherent properties of SRM. Here, all three phases are assumed to be identical, then modeling procedure of them are almost samely, just have a little difference in modulo block. Detailed implementation is presented by illustrating the modeling procedure of A-phase windings. The model of A phase winding is shown in Fig.4

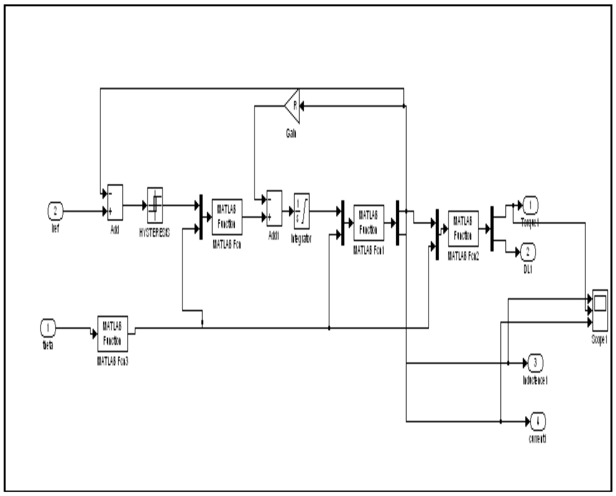

Figure 4: A-phase simulation model of SRM

4.2.Modulo block

The function of modulo block is to work out the angle of rotor position angle relative to reference zero angles in a electric cycle. For a 3-phase 6/4 SRM, each phase inductance has a periodicity of π / 2 degrees. Therefore, it is appropriate to transform the rotor

position angle coming from the mechanical equation so that it is modulo $\pi / 2$. Here, modulo $\pi / 2$ is realized by virtue of rem function in
MATLAB/SIMULINK.

4.3.Switch logic and converter block

A symmetric half-bridge converter is adopted here, it’s function is implemented by programming MATLAB function.The simulation model of switch logic and converter is shownas Fig.5, where In1 is the output of current choppingcontroller, In2 is position angle, and the output(Out1) is the phase voltage. Step motion of Switched Reluctance Motor is realized by switching on or off phase windings. The choosing of conduction angle is crucial to the power and torque ripple of SRM. However, it is not easy to choose appropriate conduction angle. And then in order to reduce torque ripple and acoustic noise, micro-step control strategy[10] is used. Micro-step control strategy substitutes conduction section for conduction angle and makes switching on or off phase current steeply. Then step magnetic field of current produced is close to roundish magnetic field and the motor's step angle is reduced. Thus, a smooth torque can be achieved. Switch relations of 3-phase windings are listed as Table I.

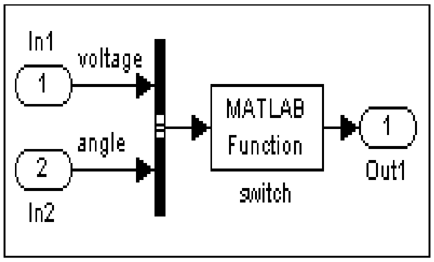

Figure 5: The model of switch logic and converter

4.4.Current calculation block

The simulation model of current calculation block is shown as Fig.6. Inputs of it are voltage of phase winding, rotor position angle and phase current. The output of it is phase current. The integral limited upper saturation of the difference of phase voltage and resistance voltage is phase magnetic linkage

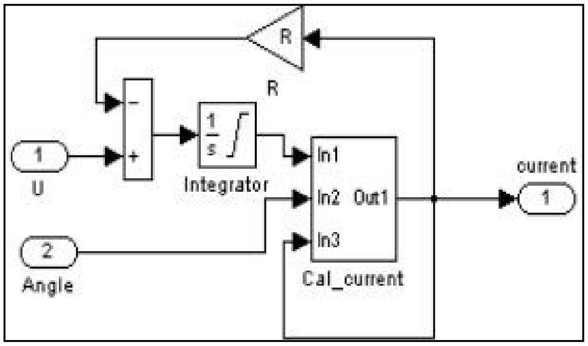

Figure 6: The model of current calculation block.

4.5.Torque calculation block

The simulation model of torque calculation block is shown as Fig.7, where In1 is the A-phase current (the output of current calculation block) and In2 is the rotor position angle. Then we can get the torque. Besides, just as Fig.2 mentioned, according to, we can get total torque of switched reluctance motor with sum module of MATLAB/SIMULINK. Angle velocity may be obtained from (7) and rotor position angle can be easily gained by integrating angle velocity. As a result, the complete model of SRM may be established.

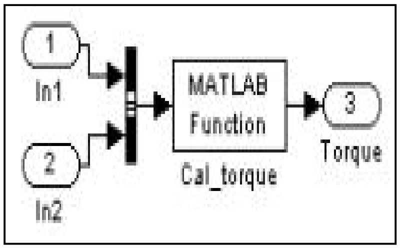

Figure 7: The model of torque calculation block

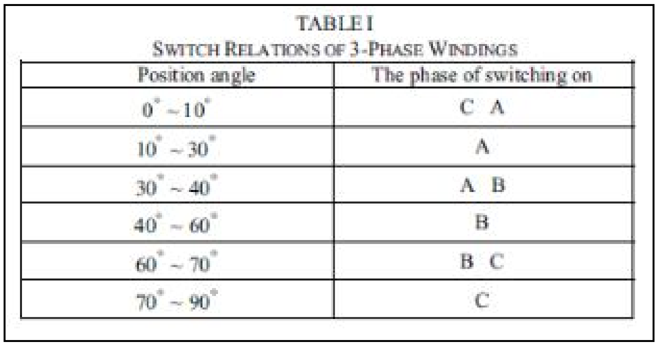

TABLE I
SWITCH RELATIONS OF 3-PHASE WINDINGS

Position angle	The phase of switching on
$0^{\circ} \sim 10^{\circ}$	C A
$10^{\circ} \sim 30^{\circ}$	A
$30^{\circ} \sim 40^{\circ}$	A B
$40^{\circ} \sim 60^{\circ}$	B
$60^{\circ} \sim 70^{\circ}$	B C
$70^{\circ} \sim 90^{\circ}$	C

Table 1: Switch relations of 3-phase Windings

4.6.Current control block

Current control is achieved with current switching closed loop chopping control of the converter. In chopping current controller[1,5,6,7,9], the current error is computed from which the switching is generated depending on its relationship to the chopping current breadth. The reference current *I ref* will be compared to the motor phase current I. The switching logic of current chopping controller is summarized as[7]:

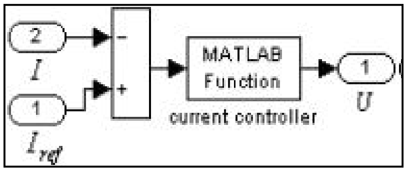

Figure 8: The model of current controller

4.7.Speed control block

It is well known that the Fuzzy Logic Controller is robust to load disturbances or sudden changes in reference speed, but it has significant steady state error compared with the conventional proportional integral controller [11]. Hence, a Fuzzy+PI compound controller is necessary to overcome the

drawbacks existing in the fuzzy logic controller and proportional integral controller. The fuzzy logic controller takes the action during transient states to get fast response [11,12]. By all appearances, speed error $\Delta\omega$ and change of speed error $\Delta\omega$ ′ $\Delta\omega$ become smaller and smaller when the actual speed of SRM is close to the reference speed. While the speed error $\Delta\omega$ is less than 15rpm, we consider that the actual speed of SRM is in the steady state. Then, the PI controller is used during steady state to reduce the steady state error of the system. Here, the switch of the fuzzy logic controller and the PI controller is realized by a switching function.

In view of the range of speed error and precision of regulating speed, it is necessary to deal with the input variables and the Madani method is used here. The domains of the input variables are switched to -7 to 7 and are divided into 7 fuzzy regions, that is [-7,-4,-2,0,2,4,7]. The domain of the output variable is 0 to 15 and is also divided into 7 fuzzy regions, that is [0,2.5,5,7.5,10,12.5,15].The corresponding linguistic variables of the input fuzzy regions are negative big(NB), Negative medium(NM), negative small(NS), zero(ZE), positive small(PS), positive medium(PM) and positive big(PB).The corresponding linguistic variables of the output fuzzy regions are zero(ZE), very small(VS), small(S), medium(M),big(B), very big(VB), extreme big(EB). Each region is assigned a fuzzy membership function. In this work, the fuzzy sets are chosen to be triangular shapes and the center of area (COA) method of defuzzification is used. The rules of fuzzy logic controller are formed by experience gained during practical experiments on SRM and are shown in Table II. There are three rules invoked as shown, these three rules and inference of results are

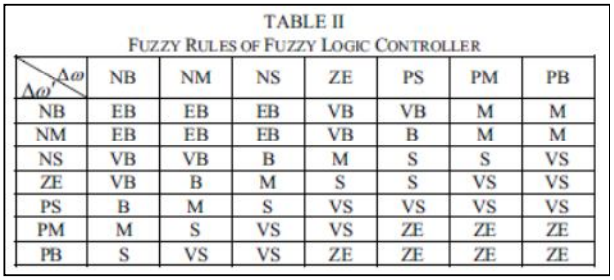

TABLE II

FUZZY RULES OF FUZZY LOGIC CONTROLLER

$\Delta\omega$ \ $\Delta\omega'$	NB	NM	NS	ZE	PS	PM	PB
NB	EB	EB	EB	VB	VB	M	M
NM	EB	EB	EB	VB	B	M	M
NS	VB	VB	B	M	S	S	VS
ZE	VB	B	M	S	S	VS	VS
PS	B	M	S	VS	VS	VS	VS
PM	M	S	VS	VS	ZE	ZE	ZE
PB	S	VS	VS	ZE	ZE	ZE	ZE

Table 2: Fuzzy Rules of Fuzzy Logic Controler

Just as above expressed, the fuzzy logic controller for the SRM drive can be designed by use of fuzzy logic toolbox of MATLAB. Besides, conventional proportional integral controller also can be designed easily in MATLAB/SIMULINK. Thereby, the design of speed controller is accomplished. A block diagram of the speed controller is shown in Fig.9

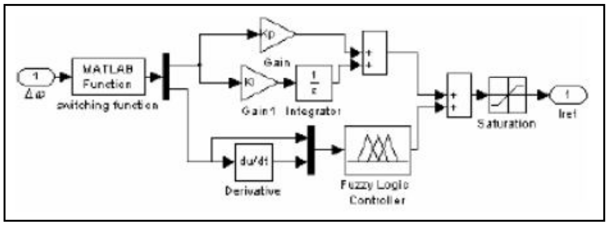

Figure 9:The model of speed controller

5.Simulation Results

5.1.Case :1 Using Pi Controller

The below figure shows the Torque waveforms in three phases a, b, c respectively.

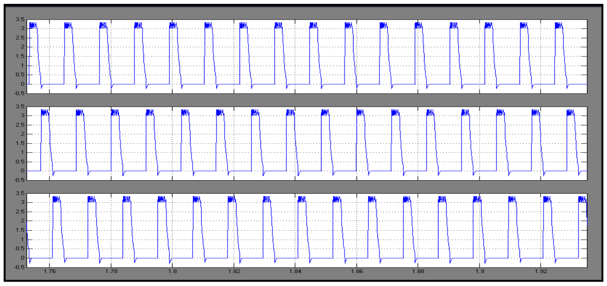

Figure 10: Torque characteristics

The below figure shows the Inductance waveforms in three phases a, b, c respectively

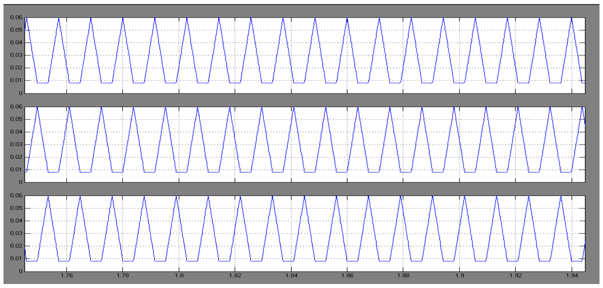

Figure 11: Inductance characteristics

The below figure shows the speed response of the SRM drive.

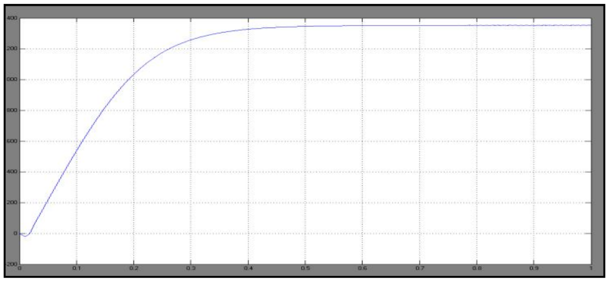

Figure 12: Speed Response of SRM drive

5.2.Case: 2using Fuzzy Controller

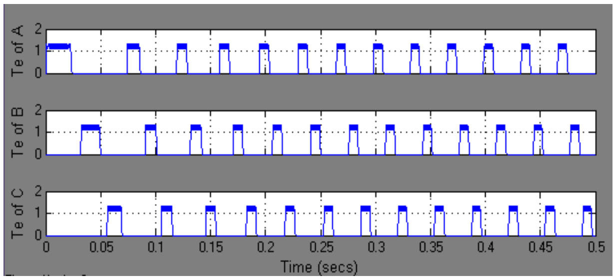

Figure 13: Torque waveforms

The above figure shows the Torque waveforms in three phases a, b, c respectively.

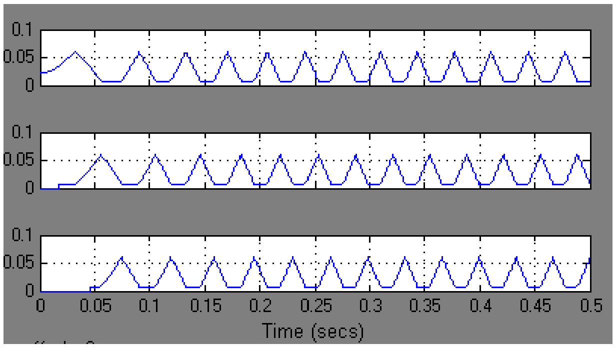

Figure 14: Inductance waveforms

The above figure shows the Inductance waveforms in three phases a, b, c respectively

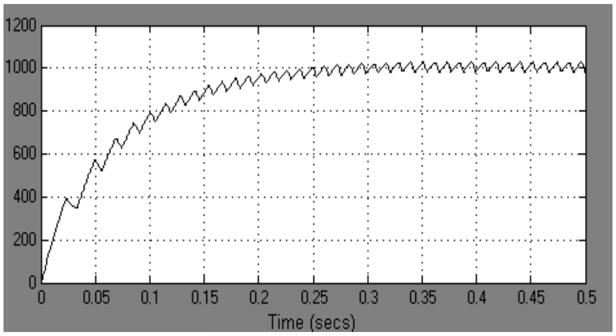

Figure 15: Speed Response of SRM drive

The above figure shows the speed response of the SRM drive.

5.3.Case: 3 Using Hybrid Fuzzy Controller

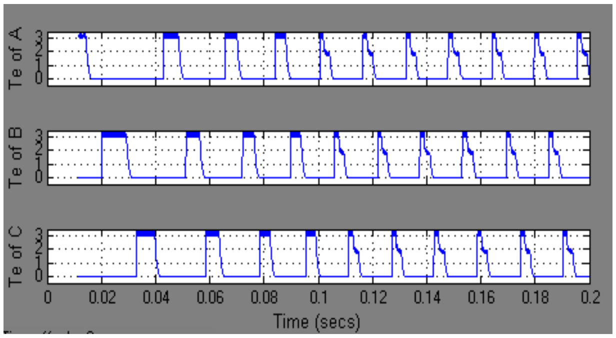

Figure 16: Torque waveforms

The above figure shows the Torque waveforms in three phases a, b, c respectively

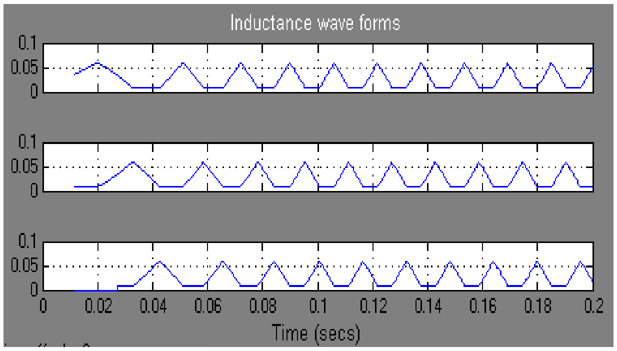

Figure17: Inductance waveforms

The above figure shows the Inductance waveforms in three phases a, b, c respectively

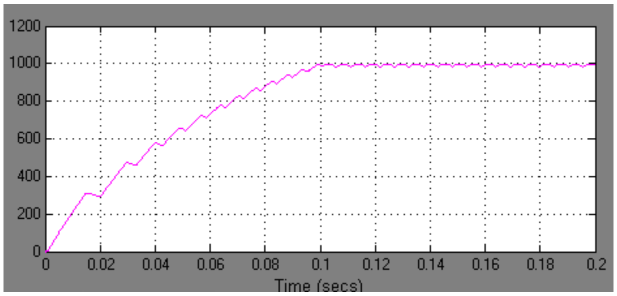

Figure 18: Speed Response of SRM drive

The above figure shows the speed response of the srm drive.

6.Conclusion

In this paper, an effective Non-linear dynamic model for simulating adjustable speed performance of a SRM drive has been described in detail.The proposed strategy uses the advantages of both conventional& expert fuzzy system to have better performance.The model is a general one with simple representation in matlab functions. This model is an ideal tool to validate the performance of the different control algorithms during steady state and transient state of an SRM drive for any kind of applications. The simulation results show that the double closed loop compound control methods designed are suitable for both transient and steady state.

7.Reference

1. Wang Honghua, The speed regulation control system of SwitchedReluctance Motor , Machine Industry Publishing Company,1995.
2. SUN Dan and HE Yikang, “A Model of the Nonlinear Inductance for aSwitched Reluctance Motor Suitable for Analysis of ControlAlgorithmic,” Small and Special Electrical Machines of China, no.3 of2001, pp. 3-5.
3. J.Mahdavi, G.Suresh, B.Fahimi and M.Ehsani, “Dynamic Modeling ofNonlinear SRM drive with pspice,” IEEE Proceedings of IndustryApplications Society 1997, pp. 661-667.
4. Chen Xin, ZHeng Hongtao and Jiang Jingping, “Non-linear DynamicModeling of SRM Based On Matlab,” Electric Drive of China, no.6 of2002 , pp. 52-56.
5. Soares, F and Costa Branco, “Simulation of a 6/4 switched reluctancemotor based on Matlab/Simulink environment,” IEEE Transactions onAerospace and Electronic Systems, volume 37, issue 3, July 2001, pp. 989-1009.
6. JI Zhi-cheng and XUE Hua, “Study on Modeling and Simulation ofSwitched Reluctance Motor Control System Based on Matlab,” Journal ofSystem Simulation of China, April 2005, vol.17, no.4, pp.1015-1021.
7. R. Krishnan, Switched Reluctance Motor Drives Modeling, Simulation,Analysis, Design, and Applications, CRC Press Boca Raton London NewYork Washington, D.C.
8. Ye, Z.Z, Martin, T.W and Balda, J.C, “Modeling and nonlinear control ofa switched reluctance motor to minimize torque ripple,” 2000 IEEEInternational Conference on Systems, Man, and Cybernetics, volume5, 8-11 October 2000, pp. 3471-3478.
9. Ji Lili and Chen Hao, “Nonlinear modeling and simulation of switchedreluctance motor drive system based on Matlab,” Journal of SoutheastUniversity of China(Natural Science Edition), November 2004, vol.34 sup, pp. 149-154.
10. Zheng Hongtao, A Study on Micro-step Position Servo Control System of Switched Reluctance Motor , Master thesis of Hebei University oftechnology of China, January 2000, pp.14-18.
11. S. Paramasivam and R. Arumugam, “Hybrid fuzzy controller for speedcontrol of switched reluctance motor drives,” Energy Conversion andManagement, volume 46, issues 9-10, June 2005, pp. 1365-1378.

12. Zhang zhi-yuan, “The switched reluctance motor adjustable speed systemusing fuzzy control technology,” Small and Special Electrical Machinesof China, no.1 of 2004, pp.21-23.