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Control of SRM using 3-level Neutral point diode clamped converter with PI and Fuzzy controller

S.N.V. Akhila[1], K. Rajani[2]

M-tech Student, Department of Electrical & Electronics Engineering, Vignan's Lara Institute of Technology & Science, Vadlamudi, Guntur dist, A.P, India[1]

Assistant Professor, Department of Electrical & Electronics Engineering, Vignan's Lara Institute of Technology & Science, Vadlamudi, Guntur dist, A.P, India[2]

Abstract: In this paper 3-level neutral point diode clamped converter is used to control the SRM instead of generally used asymmetric half bridge converter. The modulation method and current control method of the diode clamped converter are also presented. By comparing both the converters it will prove that 3-level neutral point diode clamped converter has higher efficiency and lower current ripple than the half bridge converter with the same switching frequency. Both conventional PI and Fuzzy logic controllers are used as speed controllers and their results are compared which shows that Fuzzy Logic controller is best than conventional PI controller in obtaining steady state speed. Both the controllers are compared at constant speed and also at the variation of speed and their simulation/MATLAB results are shown.

Key words: Switched Reluctance Motor, clamped converter, NPC converter, fuzzy logic controller.

I. INTRODUCTION

With the advancement of variable-speed motors in home appliances and power tools the searching for a lower cost and higher efficient brushless motor drive has increased. Due to the reasons of safety, reliability, longevity, and acoustic noise the industry significantly moves away from brush and commutator - based machines [1], although a variable-speed motor drive can be acceptable in some appliances. So, the search for a simple and low cost brushless motor drive has increased with the advancement in variable-speed applications. Switched reluctance motor (SRM) is one of the electrical machines available in low cost and variable-speed. The Switched Reluctance Motor is a doubly salient machine where torque is produced by the propensity of the rotor to move to a position where there is a maximum inductance for the excited [1]-[2]. The SRMs are considered to be attractive solutions for variable speed applications with high power density. The main advantages of SRM drive system are robustness, low manufacturing cost, high starting torque, high speed, ,high efficiency, simple construction of the machine, brushless operation, absence of magnets and windings on the rotor and still maintaining a relatively high torque density. This makes it potentially a very cost-effective and high-performance drive suitable for many applications. Another advantage for choosing such low-cost motor drive is requiring the minimum number of switching devices and using a single-switch-per-phase are also the cost-effective solutions [3-5]. On the other hand, the stator windings are concentrated and no windings, no brushes on the rotor. In addition to this, only simple converter circuit with reduced number of switches due to unidirectional current requirements are needed [5]-[6]. These advantages make this type of motors, a competitive choice to both the dc series motor and the squirrel cage induction motor [7]. The SRM can be used for general purpose industrial drives. The motor ability to operate in the four quadrants and its suitability for hazardous areas open a wide range of applications for switched reluctance motor drives including mining, explosion proof machinery, traction and domestic applications.

Power converters are used for controlling the SRM drive. Many cost-reducing solutions for converters have been proposed, and almost all have concentrated on minimizing the number of power switches. Single-switch-per-phase converters are most suitable for inexpensive applications due to their relatively low component count and simplicity of the drive system as compared to other well-known converters [6].The single-switch-per-phase configuration [9] is highly cost effective because it contains only one switch per phase. Several topologies in this category have been developed such as bifilar, R-dump, C-dump, and split dc link. Bifilar and R-dump have the drawback of lower system efficiency under high-voltage operation. The split dc-link converter [10] has two equally split capacitors and also requires one switch per phase. This converter, however, has drawbacks of having half the dc supply voltage per phase and voltage asymmetry between the two dc-link capacitors. In [11], a low-cost four-quadrant brushless motor drive using a single controllable switch is presented. The cost of this converter is significantly lower due to the reduction of attendant circuits such as gate drives, logic power supplies, and heat sinks. However, it has the disadvantage of low-performance since the main

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phase winding is controlled using the single controllable switch, and the auxiliary winding [12].
Generally the asymmetric half bridge converter is used to drive an SRM along with current hysteresis control .The asymmetric converter [7], shown in Fig. 1, is a well known converter that has two power switches and two diodes per phase, resembling the conventional ac motor drives, and the minimum voltage rating of each switch is the dc-link supply voltage. The motor phases are independently controlled. The main disadvantage is the total number of the switches and the diodes which reduces its cost competitiveness, and it is only embraced in high-performance applications [8].Under the same voltage rating, the winding inductance decreases when the power rating of SRM increases. With lower inductance, either the current hysteresis band increases to maintain the similar switching frequency or the switching frequency increases to keep the same current ripple. Increasing of current ripple or switching frequency introduces higher switching loss of power devices, iron loss, and also higher winding loss because of skin and proximity effects. It also brings challenges for designing the winding insulation and electromagnetic interference (EMI) issues. Therefore half bridge converter is not a promising topology for SRM with low inductance.

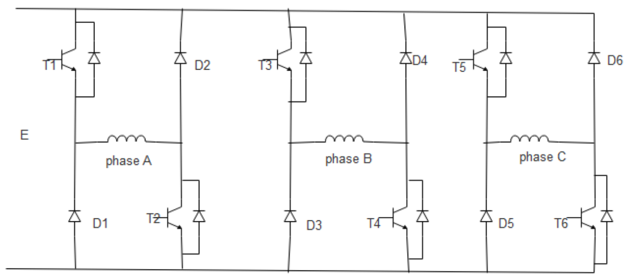

Fig 1: Asymmetry half bridge for three-phase SRM drives

Therefore research has been done to find an attractive solution for overcoming these disadvantages. It is known that multilevel converters are more advantageous than conventional two-level converters because of lower magnitude of current ripple, lower common mode voltage, low power loss at higher switching frequency and lower EMI. These advantages gained popularity for multilevel converters in medium voltage applications.

There are many multilevel converters such as flying capacitor multilevel converters, neutral point diode clamped converter, cascaded H-Bridge converter, generalized multilevel converters and mixed level hybrid multilevel converters. Recently, a good deal of the research work is done focusing on SRM control and torque smoothness in order to make it a competitor to both fully controlled dc and ac drives [8]. This paper considers an improved controller i.e three-level neutral point diode clamped converter, shown in Fig 2 based on fuzzy logic technique. The controller effects on the motor dynamic response are evaluated. The speed control of switched reluctance motor is carried out using different speed controllers. The speed controllers applied here are based on conventional PI Controller and the other one is AI based Fuzzy Logic Controller. The PI Controller (proportional integral controller) is a special case of the PID controller in which the derivative of the error is not used. Fuzzy logic controller is an intelligent controller which uses fuzzy logic to process the input. Fuzzy logic is a many valued logic which is much like human reasoning. In industrial control FLC has various applications, particularly where conventional control design techniques are difficult to apply. The Simulink models are designed for PI & Fuzzy logic controller separately and their performance result is compared. The Switched Reluctance Motor is an electric motor which runs by reluctance torque. For industrial application very high speed of 50,000 rpm motor is used.

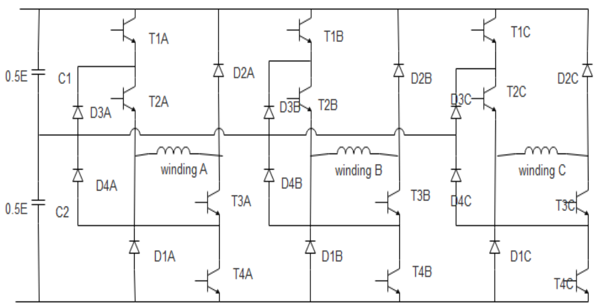

Fig 2: Three-level neutral point diode clamped converter

II. OPERATIONAL PRINCIPLE OF THE PROPOSED ASYMMETRIC THREE-LEVEL NPC CONVERTER

The considered three-level NPC converter for three-phase SRM is shown in Fig. 2. Half of the DC-link voltage (E/2) is required as the blocking voltages for the main switches (T_{1Z}, T_{2Z}, T_{3Z}, and T_{4Z}, Z=A, B or C) and clamping diodes (D_{3Z}, D_{4Z}). Full DC-link voltage (E) is the required blocking voltages for D_{1Z} and D_{2Z}. For each phase there are nine operational modes and are exemplified in Fig. 3. For simplicity, all the power devices of the topology are assumed to be ideal devices. The detailed operational modes are as follows.

Mode 1 (Fig. 3a): All the switches are turned on. To the phase winding DC link voltage E is applied and through T_1, T_2, T_3 and T_4 the load current flows. The diodes D_1, D_2, D_3, and D_4 are blocked. Into the neutral point no current flows and therefore, the potential of the neutral point is unchanged in this mode. E is the phase voltage.
Mode 2 (Fig. 3b): T_1, T_2, and T_3 are turned on and T_4 is turned off. Diode D_2 and D_3 are blocked. Through T_1, T_2, T_3, and D_4 load current flows. Into the neutral point Current flows and therefore, there is increase in neutral point potential in this mode. Around 0.5E is the phase voltage.

Mode 3 (Fig. 3c): T_1 and T_2 are turned on. T_3 and T_4 are turned off. Through T_1, T_2 and the freewheeling diode D_2 Load current flows. Diode D_1, D_3, and D_4 are blocked. Into the neutral point no current is injected. Therefore, there

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will be no change in the neutral point potential in this mode. The phase voltage is 0.

Mode 4 (Fig 3d): T1 is turned off and T2, T3, T4 are turned on. D1, D2 and D4 are blocked. Through D3, T2, T3 and T4 the current flows. In this mode there is a decrease in neutral point potential because from the neutral point the current flows out. Around 0.5E is the phase voltage.

Mode 5 (Fig 3e): T2, T3 are turned on while T1, T4 are turned off. Through T2, T3, D3 and D4 the current flows. Diodes D1 and D2 are blocked. Into the neutral point no current is injected therefore there is no change in neutral point potential. 0 is the phase voltage.

Mode 6 (Fig 3f): T2 is turned on while T1, T3 and T4 are turned off. Through D2, D3 and T2 the current flows. Diodes D1 and D4 are blocked. From the neutral point the current flows out and therefore in this mode there is decrease in neutral point potential. Around -0.5E is the phase voltage.

Mode 7(Fig 3g): T3, T4 are turned on while T1, T2 are turned off. Through the freewheeling diode D1, T3 and T4 the current flows. Diodes D2, D3 and D4 are blocked. Into the neutral point no current is injected therefore there is no change in neutral point potential. 0 is the phase voltage.

Mode 8(Fig 3h): T3 is turned on while T1, T2 and T4 are turned off. Through D1, T3, and D4 the current flows. Diodes D2 and D3 are blocked. Into the neutral point current is injected therefore in this mode there is increase in neutral point potential. Around -0.5E is the phase voltage.

Mode 9 (Fig 3i): All switches are turned off. Through freewheeling diodes D1 and D2 the current flows. Diode D3 and D4 are blocked. Into the neutral point no current is injected therefore there is no change in neutral point potential. 0 is the phase voltage.

The neutral point potential (u_n) and the phase voltage (u_w) under different modes are listed in Table 1. "1" and "0" are denoted as on and off state of the switches, respectively. "↑" represents the increase of voltage potential, "↓" represents the decrease of voltage potential, and "×" represents no change of voltage potential. For each phase there are five voltages.

TABLEL.1 POSSIBLE STATES OF THE FOUR SWITCHES IN ONE PHASE

MODE	T1	T2	T3	T4	u_w	u_n
1	1	1	1	1	E	×
2	1	1	1	0	0.5E	↑
3	1	1	0	0	0	×
4	0	1	1	1	0.5E	↓
5	0	1	1	0	0	×
6	0	1	0	0	-0.5E	↓
7	0	0	1	1	0	×
8	0	0	1	0	-0.5E	↑
9	0	0	0	0	-E	×

Different modes can produce the same voltage with different behaviors of the neutral point potential. In order to figure out which mode should be applied, the modulation scheme has to be developed.

III. THE MODULANON SCHEME AND CONTROL OF THE NPC CONVERTER

For the conventional current hysteresis control for SRM two voltages are applied. But, there are five voltages in the considered three-level NPC converter: -E, -0.5E, OV, 0.5E, and E. Therefore, for three-level NPC converters current hysteresis control is not applicable, so PWM method should be applied. The modulation method of the three-level NPC converter is shown in Fig. 4. Space sections are separated by five voltages, and for each space section a triangle carrier waveform is applied. The reference voltage (u_{ref}) provided by the current controller is located in one of the sections. If u_{ref} is higher than the carrier waveform, top voltage of this section should be applied and if u_{ref} is smaller than the carrier waveform, the bottom voltage of this section should be applied. After selecting the output voltage, the corresponding switching mode has to be determined. As shown in TABLE II there are two modes (mode 6 and mode 8) can produce -0.5E and two modes (mode 2 and mode 4) can produce 0.5E. Mode 8 and mode 2 increase the neutral point voltage. Mode 6 and mode 4 decrease the neutral point voltage. There are three modes (mode3, mode 5 and mode 7) can produce 0V, and these three modes all don't influence the neutral point voltage. In this case, to produce voltage 0 mode 5 should be selected as it needs least switching actions compared to other modes to switch to other non-zero voltages.

TABLE II METHOD OF SELECTING SWITCHING MODE

Mode		Voltage				
		-E	**-0.5E**	**0**	**0.5E**	**E**
Neutral point voltage	>0.5E	9	6	5	4	1
	<0.5E	9	8	5	2	1

TABLE II Describes the method of selecting the switching mode. To control the phase current of SRM precisely, a current controller is needed to generate the reference voltage for the modulator. Neglecting the magnetic mutual coupling between the phases, the phase voltage equation of SRM can be obtained as

$$u = Ri + \frac{d\Psi(\theta, i)}{dt}$$

Where u is the phase voltage, R is the winding resistance, i is the phase current, θ is the rotor position, and Ψ is the flux linkage profile, which is a function of i and θ.

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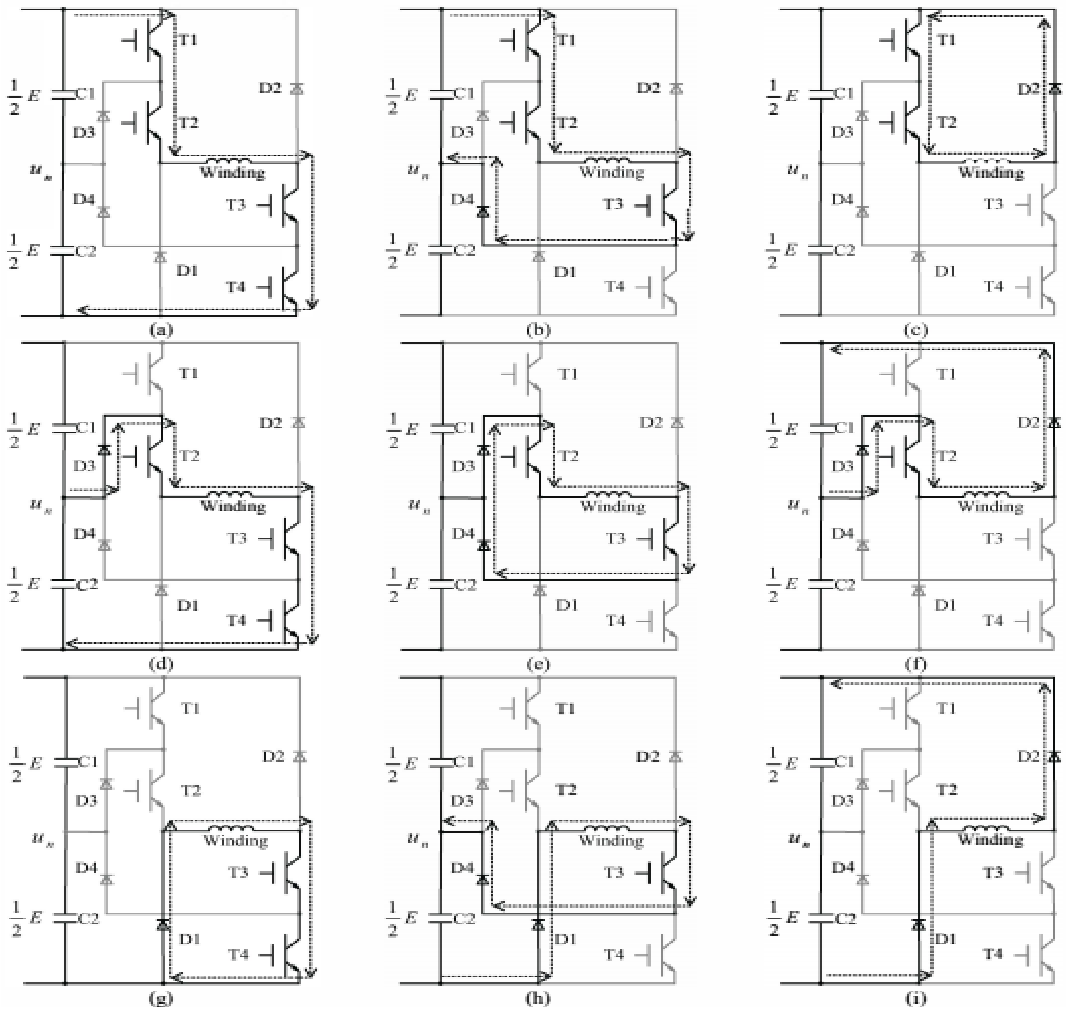

Fig.3. Current flow of each state

When the SRM is controlled digitally, and considering the one sample time delay of the digital PWM generator, a predictive current controller could be written as [9]:

$$\mathrm{uref} = \frac{\Psi(\theta(k+2), \mathrm{iref}) - \Psi(\theta(k), i(k))}{T} - \mathrm{uref}(k-1)$$

where T is the sample time, i_{ref} is the reference current, $\theta(k+2)=\theta(k)+2\omega T$ and ω is the electrical angular speed.

IV. FUZZY LOGIC CONTROL

The first paper on fuzzy set theory was presented by L. A. Zadeh in 1965. Since then, a new language was developed to describe the fuzzy properties of reality, which are very difficult and sometime even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to power system [5]. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of converter. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of compensator.

The basic scheme of a fuzzy logic controller is shown in Fig .4 and consists of four principal components such as: a fuzzification interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a de-fuzzification interface which yields non fuzzy control action from an inferred fuzzy control action [10].

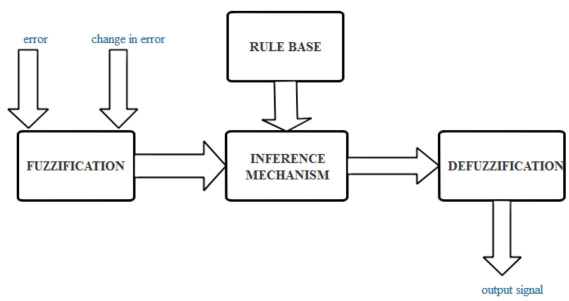

Fig 4 Structure of fuzzy logic controller

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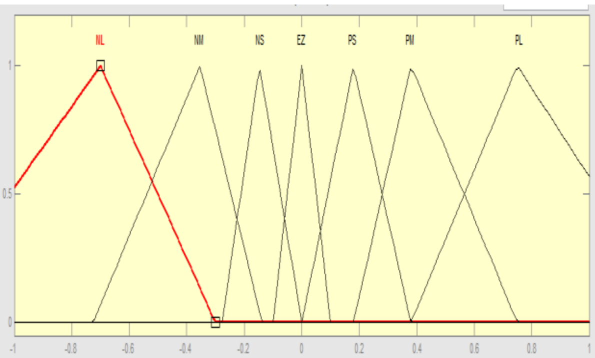


Fig.5. Membership functions for error, change in error, Output signal.

Rule Base: the elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse input/output variables; in the steady state, small errors need fine control, which requires fine input/output variables. Based on this the elements of the rule table are obtained as shown in Table III.

TABLE III. FLC RULE TABLE

Δe \ e	NL	NM	NS	EZ	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	EZ
NM	NL	NL	NL	NM	NS	EZ	PS
NS	NL	NL	NM	NS	EZ	PS	PM
EZ	NL	NM	NS	EZ	PS	PM	PL
PS	NM	NS	EZ	PS	PM	PL	PL
PM	NS	EZ	PS	PM	PL	PL	PL
PL	NL	NM	NS	EZ	PS	PM	PL

V. COMPARISON OF CONVENTIONAL TWO LEVEL CONVERTER AND THREE LEVEL NPC CONVERTER USING SIMULINK

The conventional two level converter and the considered converter are simulated in MATLAB/SIMULINK and their results are compared.

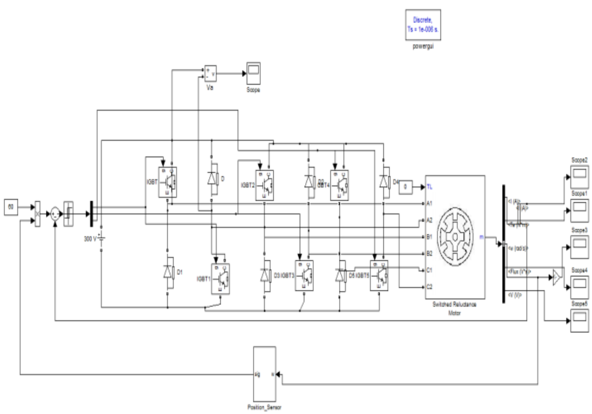


Fig.6. Simulation Model of Conventional Two-Level Current Hysteresis Converter.

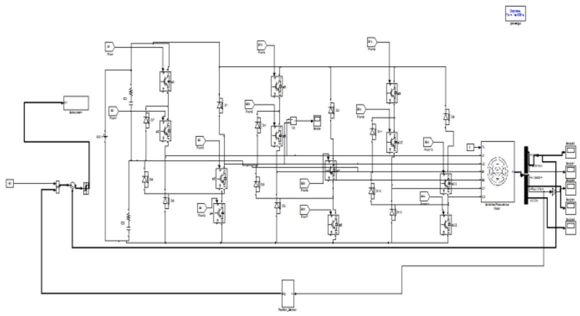


Fig 7: Simulink model of three level neutral point diode clamped converter using current control

The considered current control algorithm and PWM method are applied for the three level NPC diode clamped converter. The output of modulation block using simulink is shown in fig 8. A 6/4 60kW three phase SRM is applied for simulation. The DC supply voltage is 300V. The phase current waveforms obtained by using both the converters are shown in Fig 9.

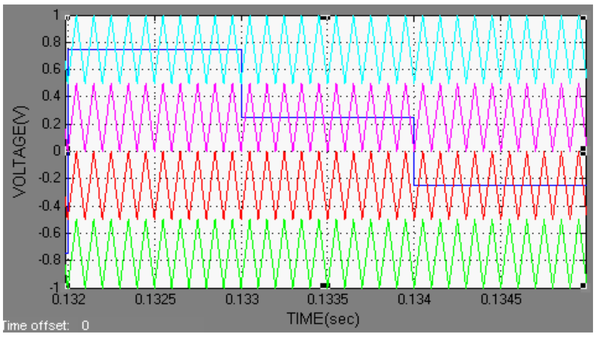
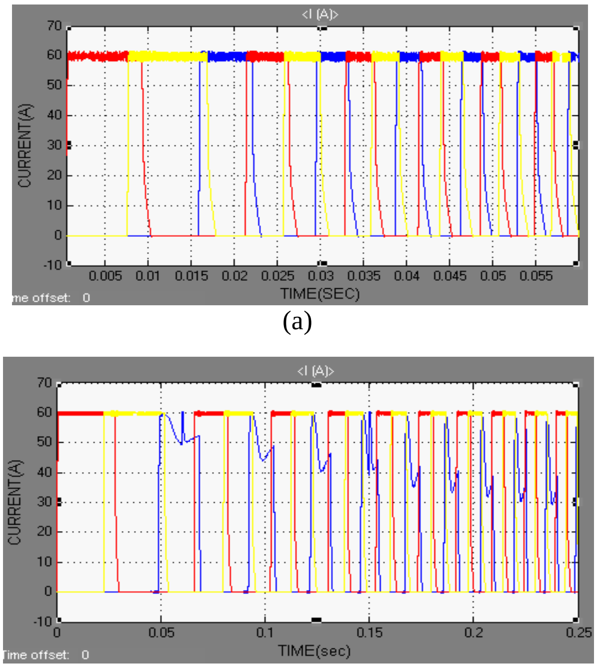


Fig 8: Modulation method of the three level NPC converter



(a)

(b)

Fig 9: phase current of conventional two level converter (a) and three level NPC converter (b)

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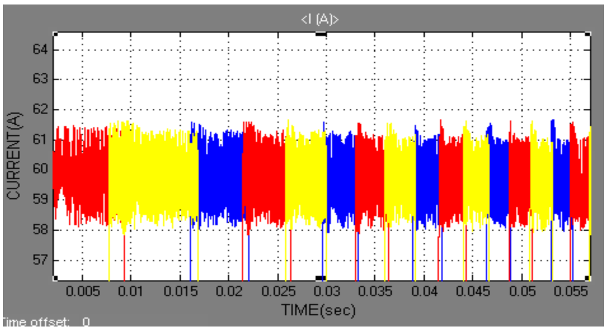
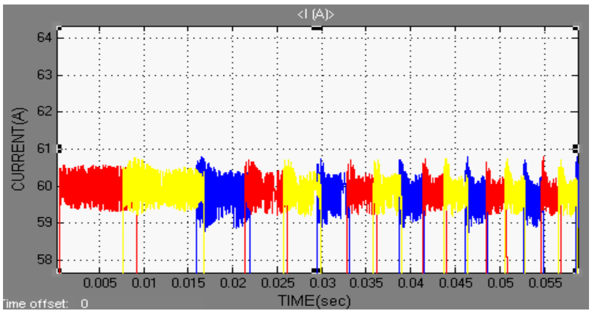
The current of both the converters are controlled at 60A. By using simulink it is shown that the conventional two level converter has the ripple current of around 4A peak-peak ripple which is more than the ripple current of considered three level NPC converter which is only around 1.5A peak-peak ripple. This shows that the considered three level NPC diode clamped converter is better than the conventional two level asymmetry converter.

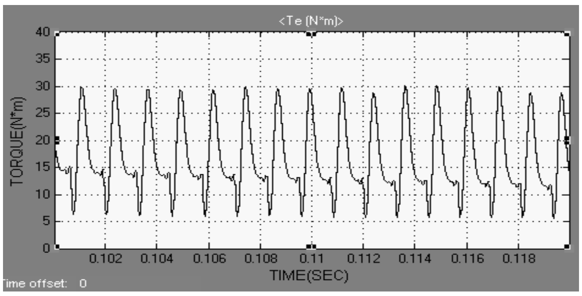


(a)

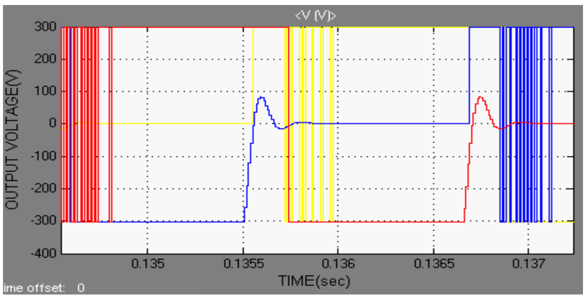


(b)

Fig 10: Magnified view of phase current of two level converter (a) and three level np diode clamped converter



(a)



(b)

Fig 11: Torque (a) and output voltage (b) of SRM driven by asymmetry half bridge converter

VI. COMPARISON OF PI AND FUZZY LOGIC CONTROLLER AS THE SPEED CONTROLLER FOR NPC CONVERTER

As from the above results it is shown that three level NPC diode clamped converter is a better converter now speed controller is also used to control the SRM. Here, different speed controllers are used and their performance is compared. The simulink models are designed for PI and Fuzzy logic controller separately. The speed of the SRM is controlled at 5000 RPM.

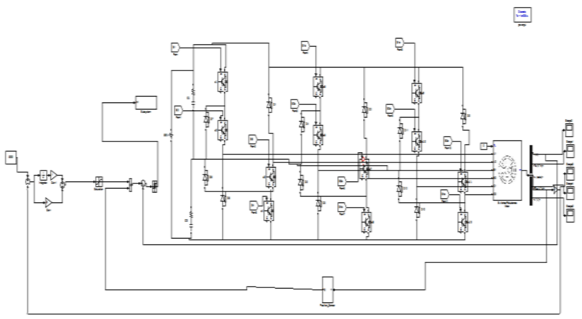


Fig 12: Simulink model of PI controller used as speed controller for SRM

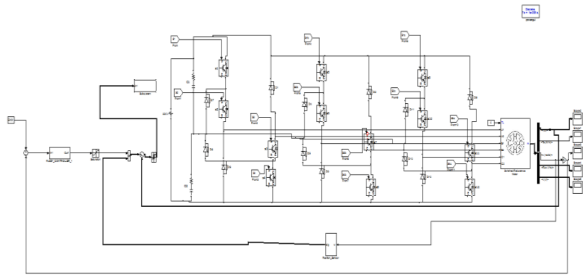
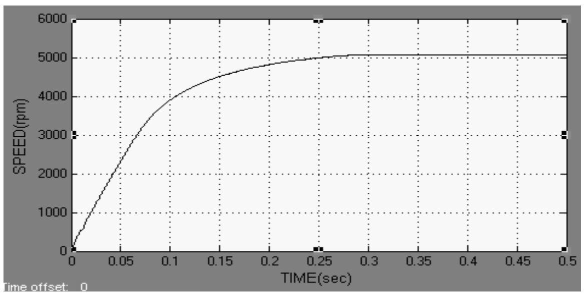
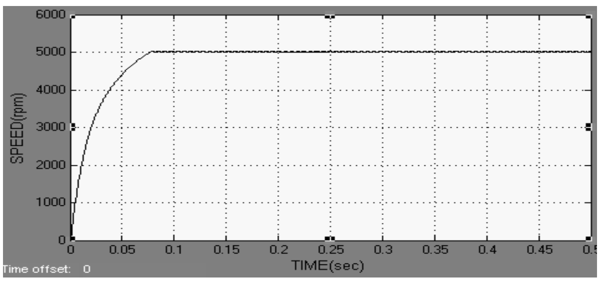


Fig 13: Simulink model of Fuzzy logic Controller used as speed controller for SRM



(a)



(b)

Fig 14: speed waveform of PI controller (a) and Fuzzy Logic Controller (b) used as speed controller

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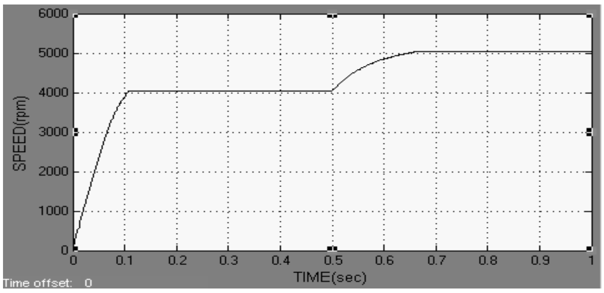
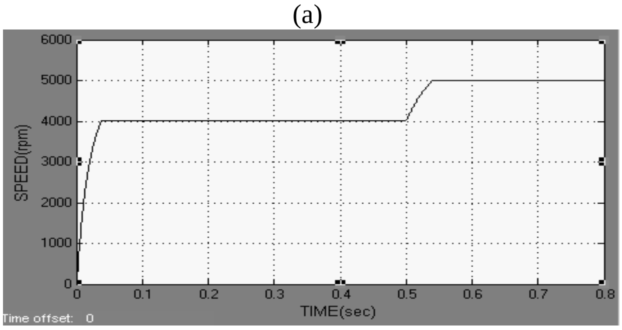
From the above graph it is shown that for the PI controller when used as speed controller steady state speed is obtained at 0.28 sec while the steady state speed obtained for Fuzzy logic controller is at only 0.075 sec. This shows that AI based Fuzzy controller is better than PI controller.
In the above model only constant speed is taken now the controllers are compared using variation of speed set points. At initial level speed is controlled at 4000rpm and it is been varied at 0.5sec to 5000rpm.

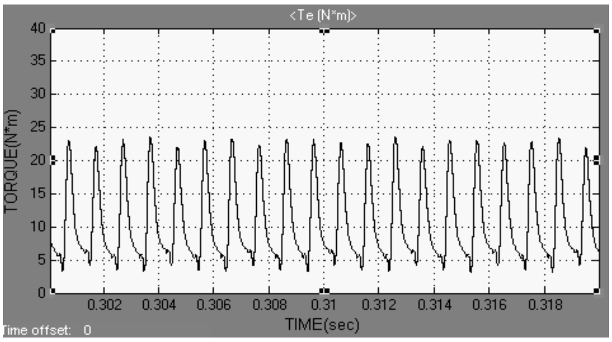


(a)

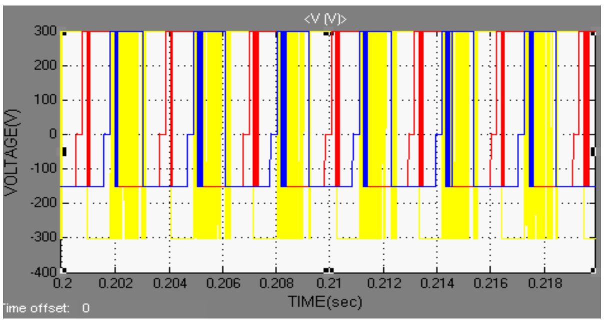


(b)

Fig 15: Speed variation waveforms for PI controller (a) and Fuzzy Logic controller(b)



(a)



(b)

Fig 16: Torque (a) and output voltage (b) of SRM driven by 3-level NPC converter using PI controller

From Fig 15 it is observed that after the sudden variation in speed, conventional PI controller gained steady state speed at 0.66 sec while the Fuzzy Logic controller gained steady state speed at 0.54sec. Therefore, from the above graph it is shown that when there is a sudden variation in speed Fuzzy Logic controller obtains steady state speed faster than the conventional PI controller. For both constant speed and variation in speed it is proven that the performance of Fuzzy logic controller is better than conventional PI controller.

VII. CONCLUSION

This paper presented An Asymmetric Three-Level Neutral Point Diode Clamped Converter for Switched Reluctance Motor Drives and to use the fuzzy logic controller to ensure excellent reference tracking of switched reluctance motor drives. The fuzzy logic controller enhanced the speed regulation of this type of drives over both constant speed and speed variation periods. Simulation results have verified the validity and effectiveness of the considered control scheme. The fuzzy logic controller gives a perfect speed tracking without overshoot and enhances the speed regulation.

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