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Torque Ripple Minimization of a Switched Reluctance Motor using Fuzzy Logic Control

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Abstract: Switched Reluctance Motors (SRMs) are attractive for industrial applications because of their simple construction and low cost, ruggedness, the capability to cover a wide speed range and relatively high torque-to-mass ratio. The primary disadvantage of an SRM is the higher torque ripple compared with conventional machines, which contributes to acoustic noise & vibration. The origin of torque pulsations in an SRM is due to the highly nonlinear & discrete nature of torque production mechanism. The total torque in an SRM is the sum of torques generated by each of the stator phases, which are controlled independently. Torque-ripple reduction in switched reluctance motors (SRM) has become a major research theme. In servo control applications or when smooth control is required at low speeds, reduction of the torque ripple becomes the main issue in an acceptable control strategy. In this paper intelligent controller such as Fuzzy Logic Controller current compensating technique is employed for minimizing the torque ripples in switched reluctance motor. For the purpose of comparison, the performance of conventional Proportional- Integral (PI) controller and PID controller are also considered. The statistical parameters like minimum, maximum, mean of total torque and torque ripple coefficient are reported.

Keywords: *PMSM, sensorless, position estimation, FOC, flux linkage.*

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I. INTRODUCTION

Switched reluctance motors (SRM) have many advantageous characteristics comparing to those of the conventional AC and DC machines [1]. The mechanical simplicity in construction of the SRM can be seen through their purely laminated-steel structure without permanent magnets, rotor windings and squirrel-cage bars. Thus, SR machines offer high reliability and robustness in operation. Due to their ruggedness, the SR motors are inherently suitable for high-speed drives and applications in high-temperature and hazardous environments. In addition, the SRM are efficient and suitable for some applications which required high torque and high dynamics. Consequently, the switched reluctance motors have recently gained a considerable attention from industries and researchers in the specific areas of high-performance and adjustable speed drives. Nevertheless, SRM are very nonlinear in nature due to their operations in high-saturation conditions. The highly non-uniform reluctance torque is produced from magnetic saliency between stator poles and rotor poles [2]. Phase flux linkages and instantaneous phase torque are nonlinear functions of phase currents and rotor positions. Therefore, without proper control, the inherent torque ripples, vibrations and acoustic noise can become major problems of the SRM drives. For a century, such drawbacks have prevented the SR motors from being widely used in applications of high-quality and variable speed drives.

The minimization of torque ripples is essential in high performance servo applications which require smooth operation with minimum torque pulsations [3]. The excellent positive features of an SRM may be utilized in a servo system by developing techniques for reducing the torque ripples. There are essentially two primary approaches for reducing the torque pulsations: one method is to improve the magnetic design of the motor, while the other method is to uses ophisticated electronic control. Machine designers are able to reduce the torque pulsations by changing the stator and rotor pole structures, but only at the expense of motor performance.

The electronic approach is based on selecting an optimum combination of the operating parameters, which include supply voltage, turn on and turn off angles, current level and the shaft load [4]. Among these, a simple current modulation technique is widely used for the minimization of torque ripples in SRM. The simple and popular current compensating techniques can be implemented using both classical and intelligent controllers. The classical controllers require exact mathematical model of the systems and are very sensitive to parameter variations As SRM presents strong non linear characteristics, the dynamic control of SRM drive can be obtained by using intelligent controllers based on artificial intelligent techniques such as fuzzy logic controller. However, in the case of servo control applications or when smooth control is required at low speeds, the elimination of the torque ripples becomes the main issue [5]. In this case, the fuzzy logic controller is very useful. The application of a fuzzy logic based on adding a compensating current signal to the switched reluctance motor to minimize the torque ripples is investigated. The dynamic response of the SRM with proposed controllers like PI, PID, Fuzzy and combination of these are analyzed. For the purpose of comparison, the performance of the drive without controller is considered.

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II. CHARACTERISTICS of SRM

The SRM is an electric machine that converts the reluctance torque into mechanical power [6]. In the SRM, both the stator and rotor have a structure of salient-pole, which contributes to produce a high output torque. The torque is produced by the alignment tendency of poles. The rotor will shift to a position where reluctance is to be minimized and thus the inductance of the excited winding is maximized. The SRM has a doubly salient structure, but there are no windings or permanent magnets on the rotor.The rotor is basically a piece of steel (and laminations) shaped to form salient poles. So it is the only motor type with salient poles in both the rotor and stator [7]. As a result of its inherent simplicity, the SRM promises a reliable and a low-cost variable-speed drive and will undoubtedly take the place of many drives now using the cage induction, PM and DC machines in the short future. The number of poles on the SRM's stator is usually unequal to the number of the rotor to avoid the possibility of the rotor being in a state where it cannot produce initial torque, which occurs when all the rotor poles are aligned with the stator poles. Fig.1 shows a 8/6 SRM with one phase Asymmetric converter. This 4-phase SRM has 8 stator and 6 rotor poles, each phase comprises two coils wound on opposite poles and connected in series or parallel consisting of a number of electrically separated circuit or phases. These phase windings can be excited separately or together depending on the control scheme or converter. Due to the simple motor construction, an SRM requires a simple converter and it is simple to control.

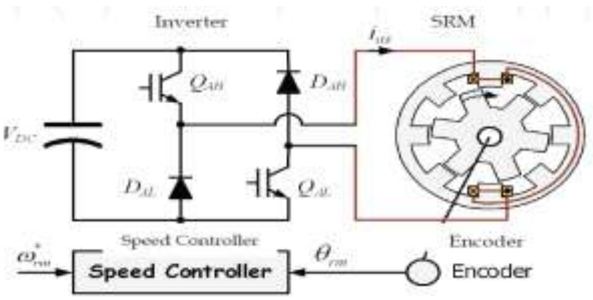

Fig.1 SRM with one phase asymmetric converter

The aligned position of a phase is defined to be the situation when the stator and rotor poles of the phase are perfectly aligned with each other , attaining the minimum reluctance position and at this position phase inductance is maximum .

The phase inductance decreases gradually as the rotor poles move away from the aligned position in either direction. When the rotor poles are symmetrically misaligned with the stator poles of a phase, the position is said to be the unaligned position and at this position the phase has minimum inductance. Although the concept of inductance is not valid for a highly saturated machine like SR motor, the unsaturated aligned and unaligned incremental inductances are the two key reference positions for the controller. The relationship between inductance and torque production according to rotor position is shown in Fig. 2.

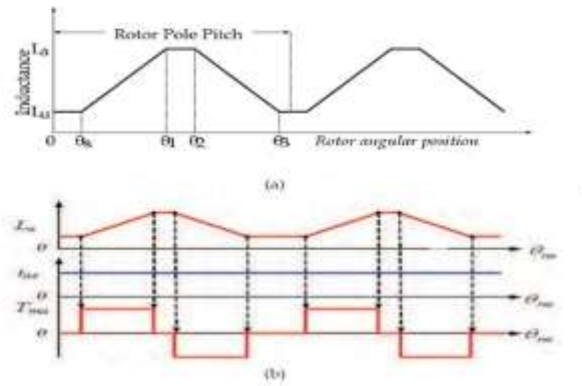

Fig. 2 (a) Inductance and (b) torque in SRM

Constructions of SRM with no magnets or windings on the rotor also bring some disadvantage in SRM. Since there is only a single excitation source and because of magnetic saturation, the power density of reluctance motor is lower than PM motor.

The construction of SRM is shown in Fig. 3. The dependence on magnetic saturation for torque production, coupled with the effects of fringing fields, and the classical fundamental square wave excitation result in nonlinear control characteristics for the reluctance motor [8]. The double saliency construction and the discrete nature of torque production by the independent phases lead to higher torque ripple compared with other machines. The higher torque ripple, and the need to recover some energy from the magnetic flux, also cause the ripple current in the DC supply to be quite large, necessitating a large filter capacitor [9].

The doubly salient structure of the SRM also causes higher acoustic noise compared with other machines. The main source of acoustic noise is the radial magnetic force induced. So higher torque ripple and acoustic noise are the most critical disadvantages of the SRM. The absence of permanent magnets imposes the burden of excitation on the stator windings and converter, which increases the converter kVA requirement. Compared with PM brushless machines, the per unit stator copper losses will be higher, reducing the efficiency and torque per ampere. However, the maximum speed at constant power is not limited by the fixed magnet flux as in the PM machine, and, hence, an extended constant power region of operation is possible in SRM [10].

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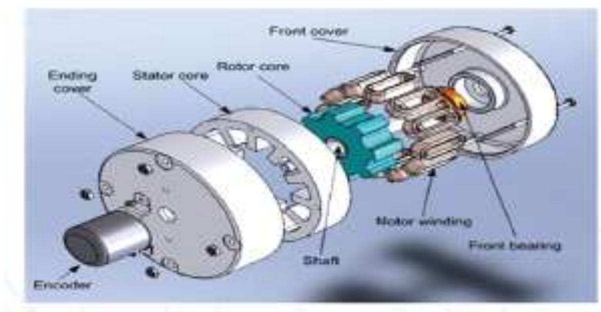

Fig.3. Construction diagram of SRM

Switched reluctance motor has salient poles on stator and rotor with concentrated windings on the stator and no windings on the rotor. Thus, it is mechanically robust and naturally suited for high speed operation. The SRM achieves high torque levels at low peak currents by using small air gaps. The rotor losses are smaller compared to the stator, unlike motors like DC motor and Induction motor. The phase winding of SRM is excited through the positive increasing region of the phase inductance region, which is performed through a converter. The popularly used converter is Asymmetrical converter, as it has fault tolerant capability, independent excitation of all phases and possibility of soft and hard switching. At lower speeds, the motor back-EMF is small compared to the supply voltage and the current flowing through the stator winding can be regulated by PWM Control. In PWM Control strategy, the current is regulated below the reference value by applying voltage pulses of fixed frequency and variable duty ratio.

III. MOTOR MODEL EQUATIONS

The physical behavior of the switched reluctance motor can be described by a set of dynamic equations as shown in Table 1 that incorporate the rotor inertia (*J*), rotating friction, and the load torque (*Tload*). The rotating friction is represented by *Bm*, the viscous coefficient of friction (with units of N-m/rad/s), and depends on the rotor's angular velocity (*ωrotor*). Sum of these forces provide the dynamic model for the SRM.

IV. SRM CONTROLLERS DESIGN

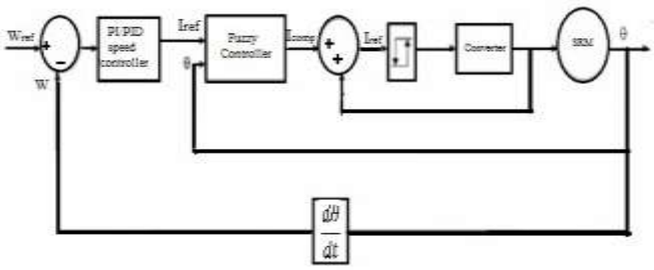

Fig. 4 Block diagram of SRM with Controller

Table 1Model Equations for a Switched Reluctance Motor

Description	Equation
Fundamental Phase frequency of current	$f_1 = \omega_{rotor}\frac{N_r}{2\pi} = \frac{rpm}{60}N_r$ (2.2)
Mechaniacal frequency	$f_{mech} = mf_1$ (2.3)
Instantaneous phase torque	$T_{\phi k} = \frac{d}{d\theta}\int_0^{i_k} \lambda(\theta, i)di$ (2.4)
Instantaneous motor torque	$T_{net}^{inst} = \sum_{k=1}^{k=m} T_{\phi k}$ (2.5)
Average motor torque	$T_{avg}^{motor} = \frac{1}{T_{rev}}\int_0^{T_{rev}} T_{net}^{inst}\, dt$ (2.6)
Voltage equation for SRM single phase equivalent circuit	$V_s = R_{cond}i + L(\theta, i)\frac{di}{dt} + \frac{dL(\theta, i)}{d\theta}\omega_{rotor}i$ (2.7)
Mechanical dynamic equation for SRM	$J\frac{dw_{rotor}}{dt} = T_{avg}^{motor} - B_m w_{rotor} - T_{load}$ (2.8)
Rotor Position relative to phase k)	$\theta_k = N_r\theta - \frac{2\Pi(k-1)}{m}$ (2.9)

Because of the saliency of the stator and rotor, the torque ripple is produced when the former phase is being excited opposite voltage and the latter phase has been excited. The point of intersection between the two excited phases must be advanced to a higher value to minimize the torque ripple. To attenuate the torque ripple, the addition of a compensating current signal is proposed, as shown in Figure 4.1.This signal is dependent of the rotor position and the reference current which in turn depends on the motor speed and the torque load value. The output compensating current signal produced by the controllers, Icomp is added to the reference current signal, which ideally, should be constant in steady state, but producing significant ripple. The compensating signal should then be adjusted in order to produce a ripple free output torque. In fact, it is a function that possesses high mathematical complexity and therefore the production of this signal is quite complicated.
In this chapter, intelligent controller such as fuzzy logic controller (FLC) is used to provide compensating current *Icomp* to minimize the torque ripples in SRM drives. The intelligent controller has two inputs, reference current (*Iref*), rotor position (θ) and one output, compensating current (*Icomp*), by means of a relation such as *Icomp* = *f* (θ, *Iref*). Consequently new reference current (*I'ref*) is obtained by the addition of a phase current (*Ipha*) and compensating current (*Icomp*) as shown in Fig. 4
Fuzzy controllers are easy to implement and, with adaptive schemes, these controllers may be made robust. First, compensating current is injected in each phase by using FLC

[11]. The motor model is designed and membership functions are chosen according to the parameters of the motor model. Fuzzy control is one of the appropriate control schemes for torque control of SRM drives [12]. The mamdani fuzzy controller uses the rotor position and reference current as inputs and produces the compensating current as the output. The inputs are divided into membership functions which are designed to give an optimum number of rules and allow the SRM to conduct over the entire positive torque producing region. Max-product rule of inference scheme is used and the output is determined using the centre of average for defuzzification.

A three-phase, 6/4 pole SRM is modelled, with 120 A maximum current, 240V source, and maximum speed of 12000 rpm. In order to achieve the high motor speed, while providing relatively short simulation times, the motor inertia has been selected as *Jmotor* = 0.01 kg-m2 and the viscous coefficient of friction kept very low at *Bm*=0.001 Nm/rad/s. Otherwise, the motor is unable to attain such a high operating speed. An unaligned inductance of *LUA*=0.67 mH, aligned inductance of *LA* =23.6 mH, and saturated aligned inductance of *LA,sat*=0.15 mH are assumed, which produce the magnetization curve shown in Fig 4.5 A hysteresis band of 2% is assumed.

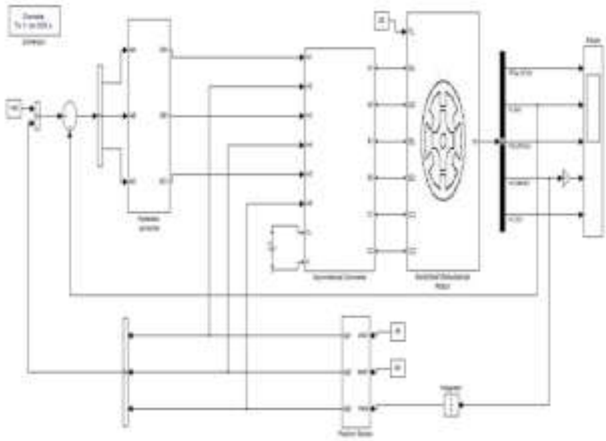

Fig. 5 Simulink model of SRM drive without any controller

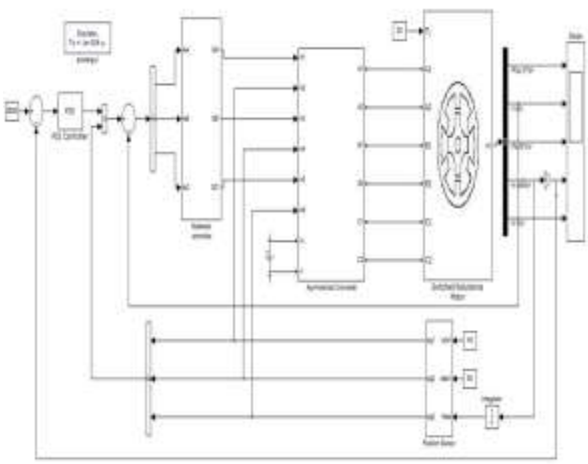

Fig. 6 Simulink model of SRM drive with PID control

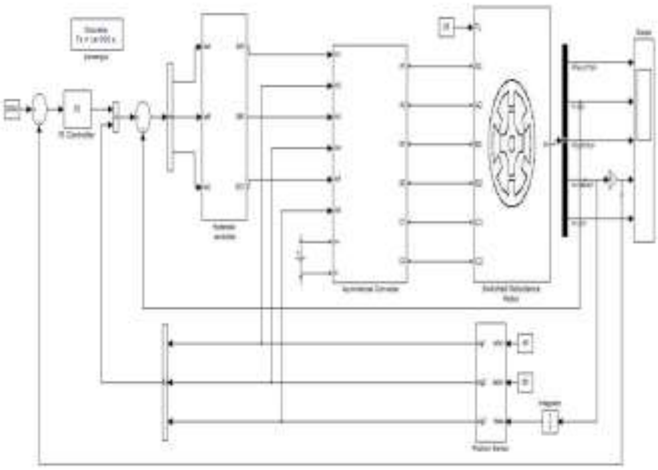

Fig. 7 Simulink model of SRM drive with PI control

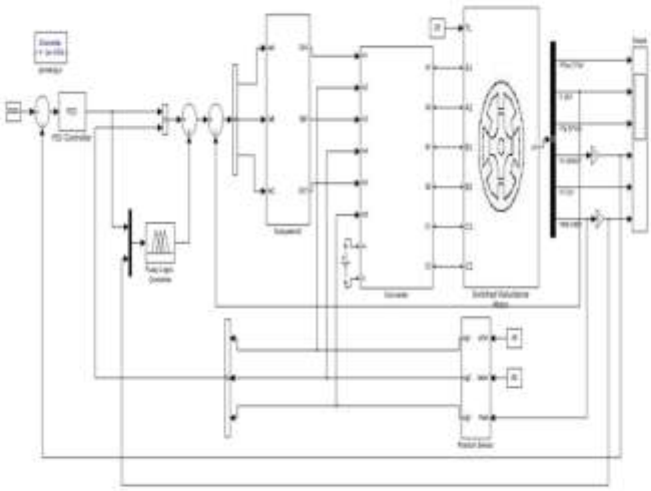

Fig. 8 Simulink model of SRM drive with FLC-PID control

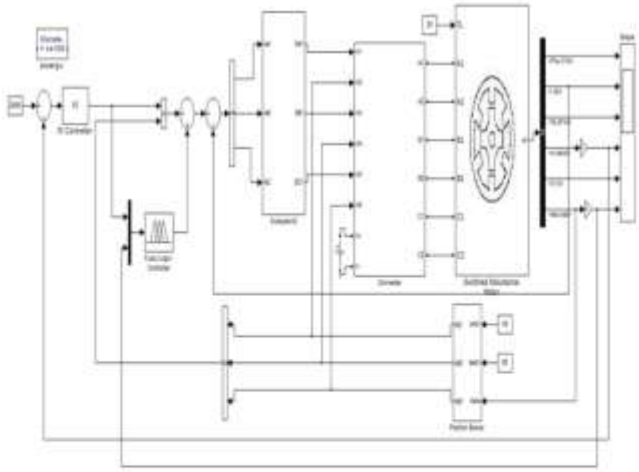

Fig. 9 Simulink model of SRM drive with FLC-PI control

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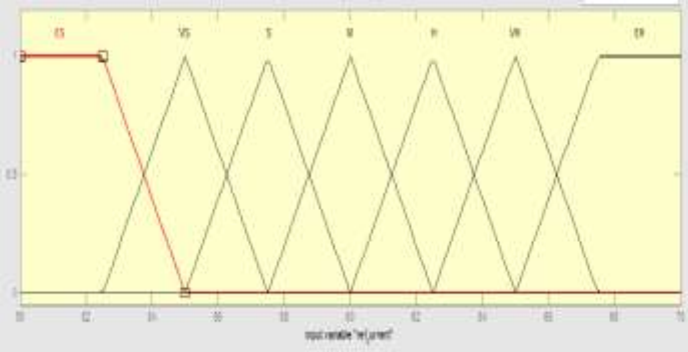

Fig. 10 Membership functions of reference current

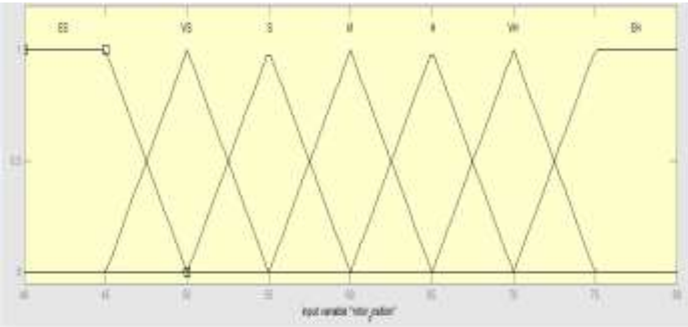

Fig. 11 Membership functions of Rotor Position

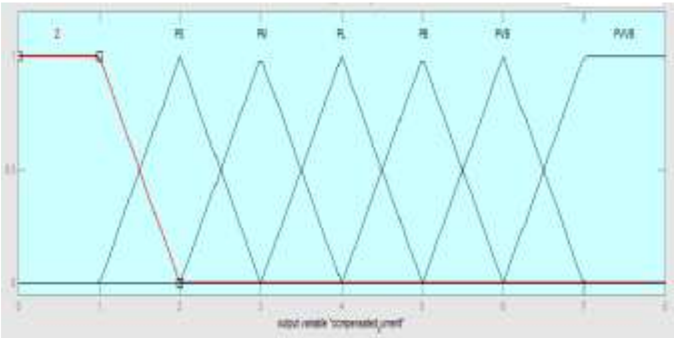

Fig. 12 Membership functions of Compensated Current

Linguistic Variables for Inputs: ES-Extremely Small; VS-Very Small; S-Small; M-Medium; H-High; VH-Very High;

EH-Extremely High. Linguistic Variables for Output: Z-Zero; PS-Positive Small; PM-Positive Medium; PL-Positive Large; PB-Positive Big; PVB-Positive Very Big; PVVB-Positive Very Very Big. The rule base developed for the control of SRM drive is given in Table 2. In the regions of ES, VS and S of both inputs, ripples are more and for torque ripple minimization, fuzzy rules PVB or PVVB are developed. However, in the VH and EH regions, torque reduces by far slowly; consequently, fuzzy rules PB and PM have been determined. In addition, fuzzy logic rules for maximum compensation in near zero speeds up to rated speed has been used. Even in higher speed, fuzzy logic rules for compensating current is limited to PB because high ripple in high current will damage the SRM.

Table 2 Fuzzy Rules for SRM drive control

[illegible]	ES	VS	S	M	H	VH	EH
ES	PVVB	PVB	PL	PM	PB	PVB	PVVB
VS	PVVB	PVB	PL	PS	PB	PL	PVB
S	PVVB	PVB	PB	Z	PM	PB	PVB
M	PVVB	PB	PM	PB	PVB	PB	PM
H	PVB	PB	PM	Z	PM	PB	PL
VH	PB	PS	PS	Z	PS	PM	PB
EH	PM	PS	PS	Z	PS	PM	PB

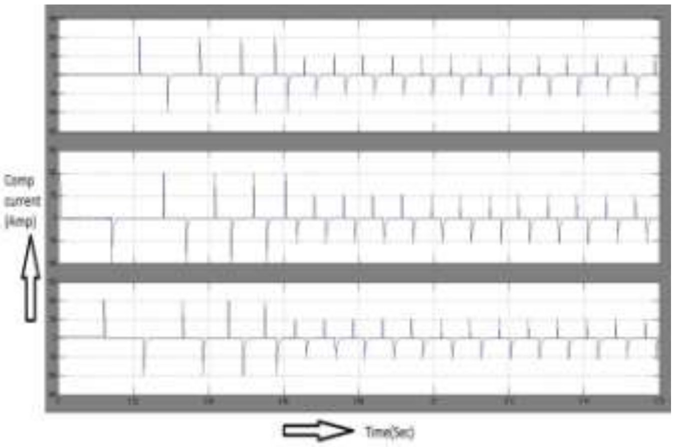

Fig. 13 Input to Hysteresis controller

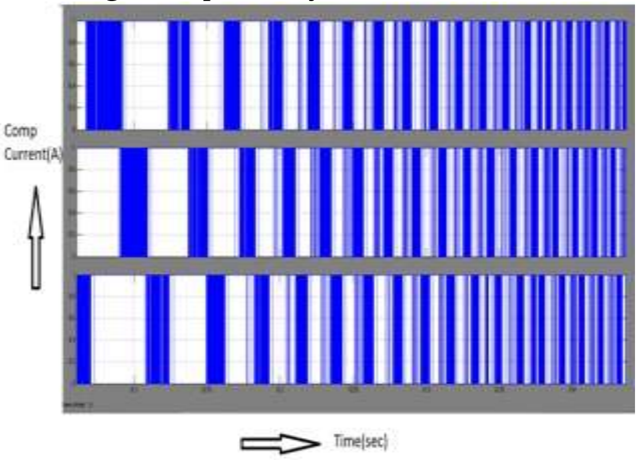

Fig. 14 Output of Hysteresis controller

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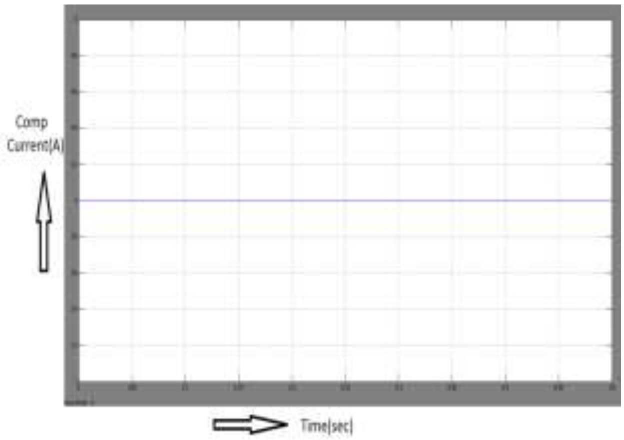

Fig. 15 Output of FLC

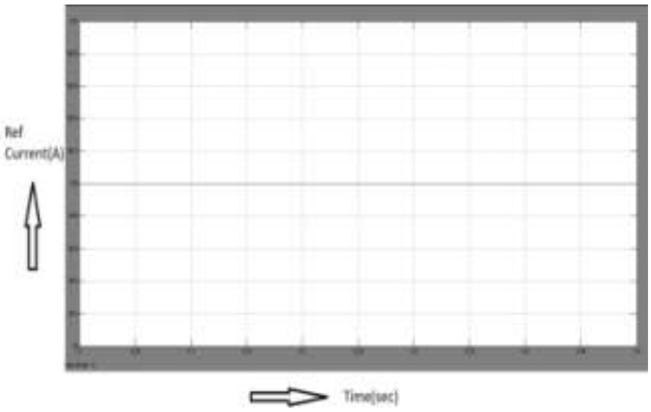

Fig. 16 Output of PID

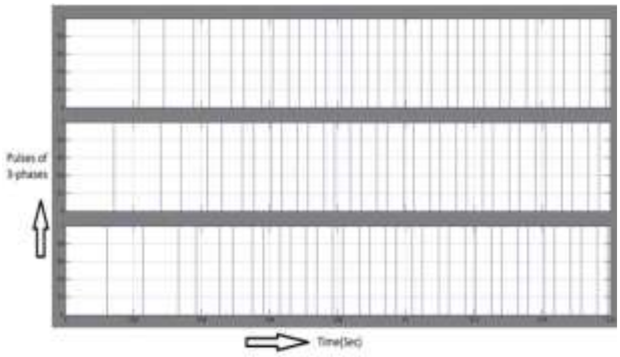

Fig. 17 Output of Position Sensor

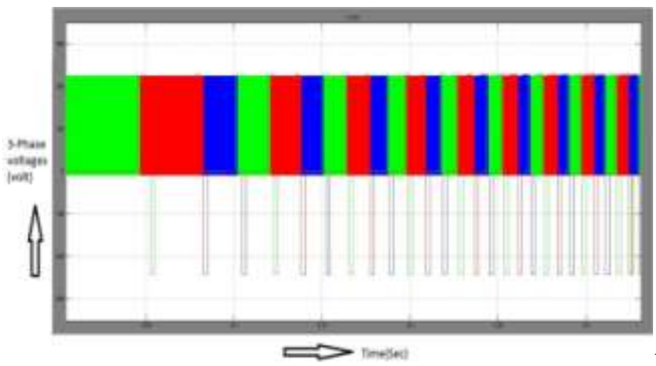

Fig. 18 Voltages of 3-Phases

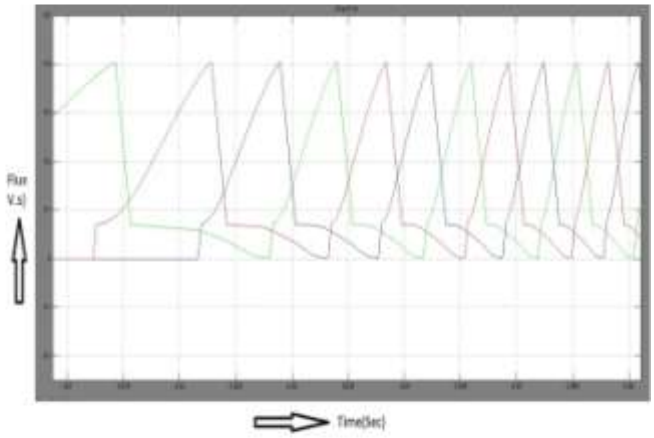

Fig. 18 Flux waveforms of 3- phases

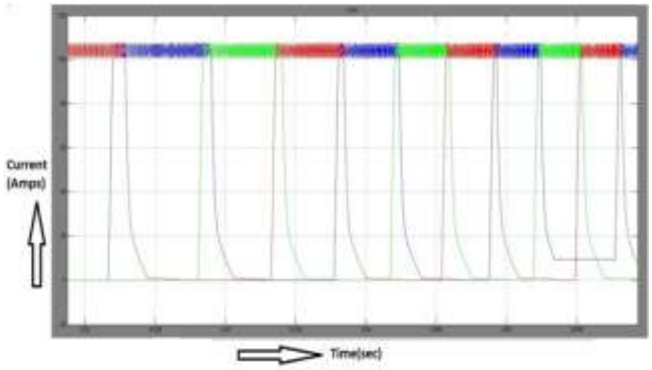

Fig. 19 Current waveforms of 3- phases

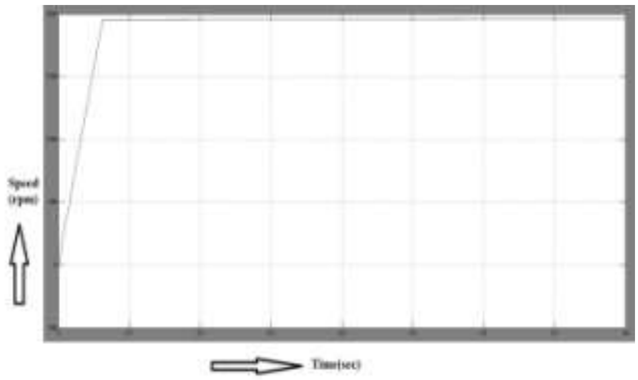

Fig. 20 Speed response of SRM Drive

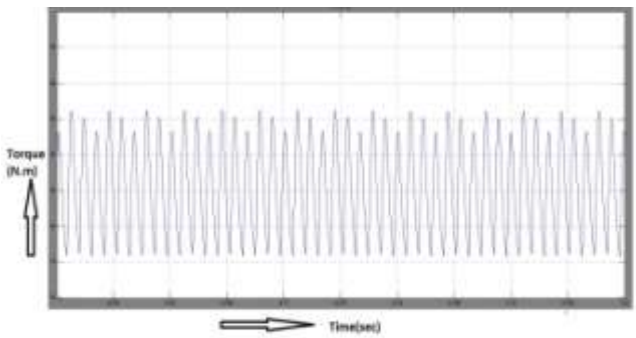

Fig. 21 Toque waveform without any control

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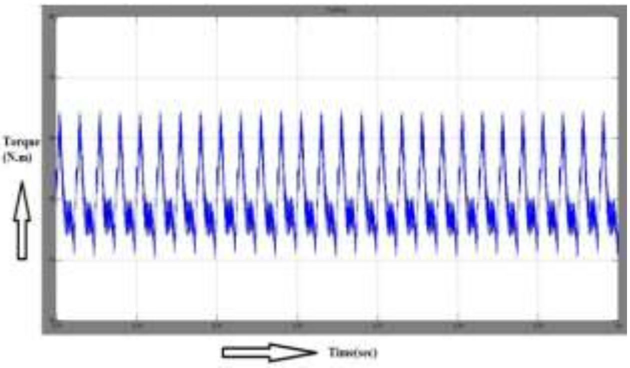

Fig. 22 Toque waveform with PI controller

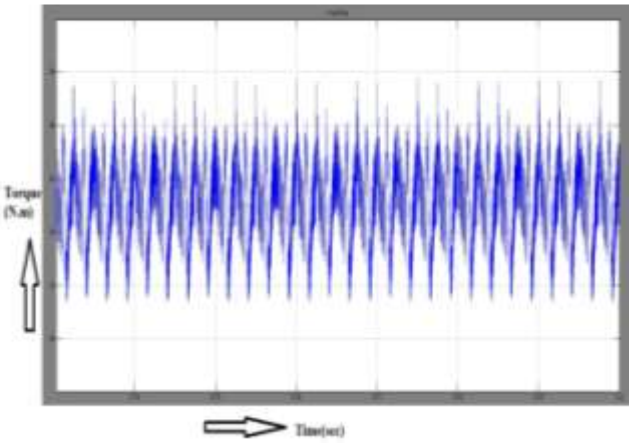

Fig. 23 Toque waveform with FLC-PI controller

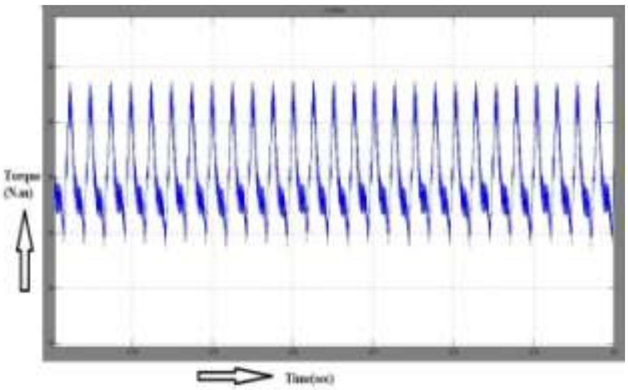

Fig. 24 Toque waveform with PID controller

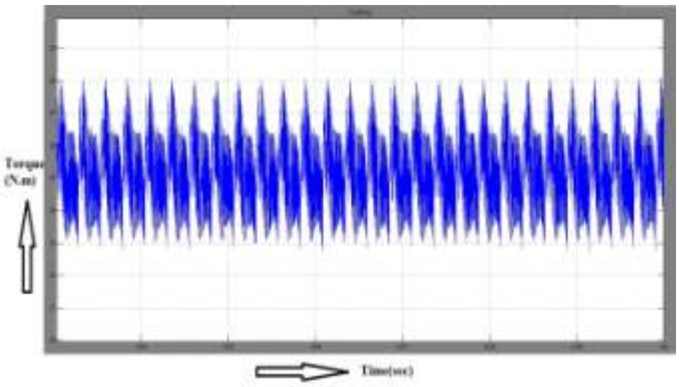

Fig. 25 Toque waveform with FLC-PID controller

Table 3 Simulation Output results

Controller used	**Max Torque (N.m)**	**Min Torque (N.m)**	**Avg Torque (N.m)**	**Torque Ripple (%)**
Without any controller	36.1	15.9	26	77.69
With PID	33.8	19	26.4	56.06
With PI	32.4	20.4	26.4	45.45
With FLC-PI	29.6	21.4	25.5	32.15
With FLC-PID	28.1	22.7	25.4	21.25

V. CONCLUSIONS

This project analyzed the performance of SRM drive without & with PID, PI, FLC-PID, FLC-PI controllers. Fuzzy Logic Controller (FLC) current compensating technique is employed for minimizing the torque ripples in Switched Reluctance Motor. The statistical parameters of torque ripple are reported. Simulation results shows that FLC-PID, FLC-PI controllers give better performance than conventional controllers. FLC improves the dynamic performance of SRM drives, due to its good learning and generalization capabilities. Without using any controller the Torque ripple is very high and is 77.69%. By using only PID controller Torque ripple is reduced to 56.06% , by using only PI controller Torque ripple is reduced to 45.45%, with FLC-PIcontroller Torque ripple is reduced to 32.15% & by using FLC-PID controller the Torque ripple is further reduced to 21.25%.

Future scope of the work is reduction of torque ripple by Artificial Neural Networks, direct instantaneous Torque control & Torque sharing function methods

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