Experimental Implementation of Fuzzy Controller of Switched Reluctance Motor on FPGA

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***Abstract* – This paper presents modeling, simulation and analysis of switched reluctance motor (SRM). Switched reluctance motors are used in applications such as electric vehicles, washers, dryers and aerospace applications as the machine is brushless, maintenance free and has rugged and simple construction. MATLAB/SIMULINK is used to simulate linear model of SRM. A 1HP machine is designed for possible applications such as direct drive in washing machines and electric vehicles. Conventional PI and fuzzy logic controllers are used to control the speed of SRM. Simulation results verify considerable reduction in torque ripple and speed settling time when fuzzy controller is employed compared to PI controller. Field programmed gate array (FPGA) control fabricated with Xilinx Spartan 3E developed board for SRM is presented. The experimental results of SRM with PI and fuzzy control verify the simulation results.**

Keywords: Field programmed gate array, Fuzzy controller, PI control, Switched Reluctance motor.

I. INTRODUCTION

The electrical drive plays an important role on productivity to any industry. The drive requirement is based on available mains and load characteristics. Switched reluctance motor (SRM) is a singly excited, doubly salient machine in which electromagnetic torque is developed due to variable reluctance principle. SRM have advantages of low manufacturing cost compare to other motors, rugged & simple construction, lesser switches in drive circuit, no windings or permanent magnets on rotor side and high efficiency [1] - [2]. The advent of modern control technology and power electronics has enabled SRM drive to becoming increasingly popular. Switched reluctance machines are used in electric vehicles, washers, dryers and aerospace applications. However, some of the limitations are noise, torque ripple and low torque to volume ratio [1] – [2]. Noise and low torque to volume ratio can be rectified by changing the geometry of SRM [3] – [4].Segmented switched reluctance motor proposed in [4] shows mitigation of noise and low torque to volume ratio.

Research is being done in various subjects such as different motor shapes [3]-[4], control strategies and converter types [5] - [6], but the studies are not completed. On the other hand, considering simulation of SRM, the electrical and mechanical circuit equations are realized by using the MATLAB/Simulink program [7],[8]. The hardware implementation can be done after analyzing the dynamic behaviour of SRM using Simulink model [7] - [9].

This paper presents a simplified linear model for closed loop control of SRM for simulation studies, which uses the fundamental mathematical functions to describe the saturation of the flux linkage depending on the winding current and rotor position. The theme of the paper is to reduce torque ripples using fuzzy controller. SRM is modeled using PI and fuzzy controllers and simulated using MATLAB/SIMULINK. Hardware implementation of SRM is done using FPGA. The simulation results verify that there is a considerable reduction in torque ripple and speed settling time when fuzzy controller is employed when compared to PI controller. The experimental results verify that speed response is very smooth and ripple is reduced to small amount by using fuzzy logic controller in comparison with conventional PI controller.

In section 2, modeling of SRM with PI and fuzzy controllers is given using MATLAB/Simulink. Simulation results are presented in section 3. Hardware implementation is explained in section 4; experimental results are presented and analyzed in section 5. In section 6, the paper is concluded.

II. MODELING OF SRM WITH PI AND FUZZY CONTROLLERS

The model for simulation is developed by assuming a linear model for SRM [7]. Fig.1 shows the MATLAB/Simulink model of SRM with PI controller. It consists of four phase blocks. Fig.2 shows the construction of one phase block. To be more complete, the block named phase1 is described with details that follow. It contains four other blocks, each one associated with a specific MATLAB function. They are the following.

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II.1. Switch

Switch block permits to assure the power converter commutations at angles theta on, theta off.

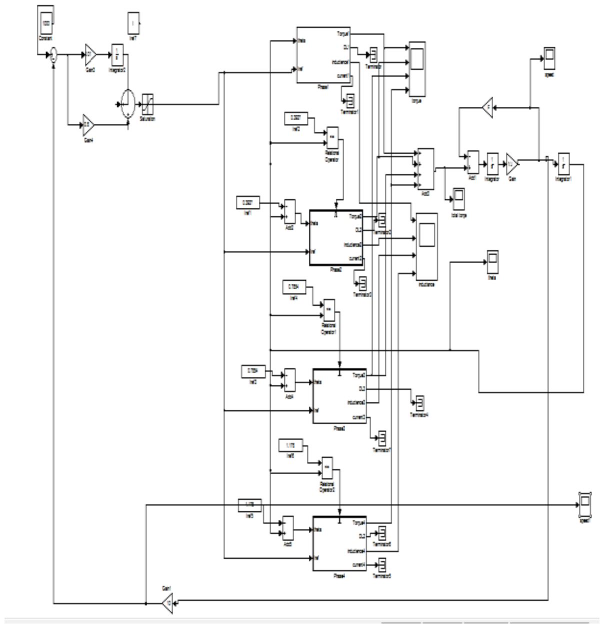

Fig. 1 Simulink model for 8/6 SRM Motor with PI controller

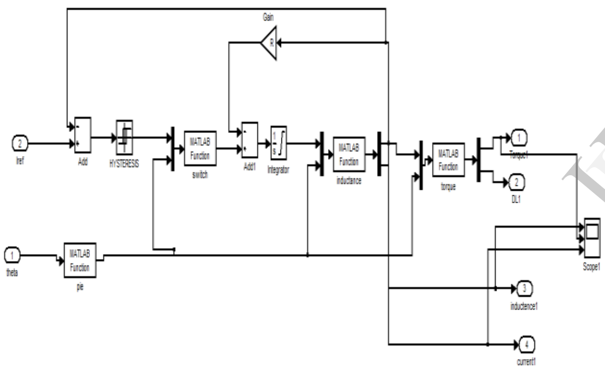

Fig. 2 Expansion of one of the phase

II.2 Inductance

Inductance block computes the current on the respective phase inductance according to rotor Position theta and phase flux. Therefore, one gets phase current I as its output signal, by output block 3 named current1.

II.3 Torque

Torque block computes the torque produced in this phase according to the rotor position theta and the current value I.

II.4 Modulo pi/2

Each phase inductance has a periodicity of $2\pi/N_r$ degrees. Therefore, it is appropriate to transform the rotor position angle coming from the mechanical equation to modulo $2\pi/N_r$.

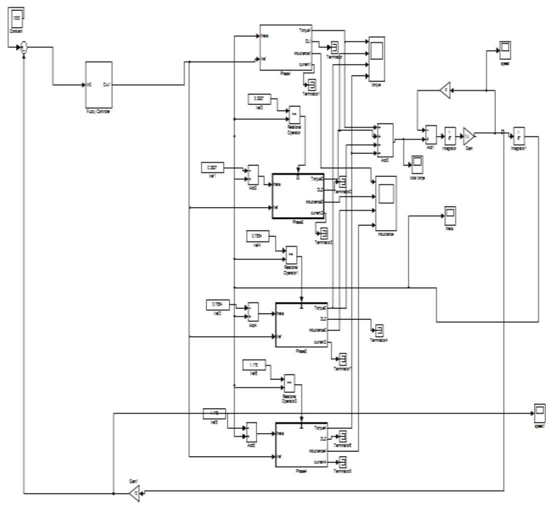

Fig. 3 Simulink model for 8/6 SRM Motor with fuzzy controller.

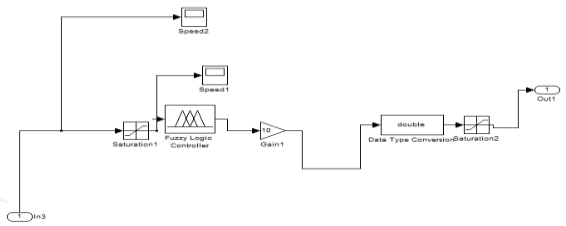

Fig. 4 Fuzzy controller sub block

Fig.3 shows the MATLAB/Simulink model of SRM with Fuzzy controller. The fuzzy logic controller block has error and change in error (del) as inputs and one output. Fuzzy controller sub block is shown in Fig. 4. The rules developed are based on IF-THEN methodology. The membership functions of fuzzy logic controller for error, change in error and output are shown in Fig.5

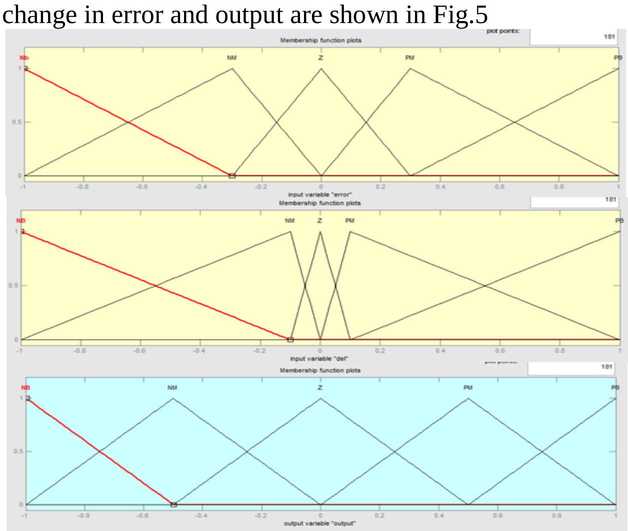

Fig.5 Membership functions of Fuzzy controller.

The membership functions are triangle ones having labels of NB(Negative Big), NM(Negative Medium), Z(Zero), PM(Positive Medium), PB(Positive Big). Table 1 shows the rule base of fuzzy controller. The rule base consists of

25 IF-THEN rules. The ANN used for self-tuning is feed forward with four layers.

TABLE 1: RULE BASE OF FUZZY LOGIC CONTROLLER

	Change in error(del)					
Error(e)		NB	NM	Z	PM	PB
	NB	NB	NB	NB	NM	Z
	NM	NB	NB	NM	Z	PM
	Z	NB	NM	Z	PM	PB
	PM	NM	Z	PM	PB	PB
	PB	Z	PM	PB	PB	PB

III. SIMULATION RESULTS

The performance of switched reluctance motor and SSRM was analyzed by using PI and Fuzzy controllers with the help of simulation.

The system was operated at a reference speed of 1000 rpm when motor shaft is under no load are observed from the wave forms.

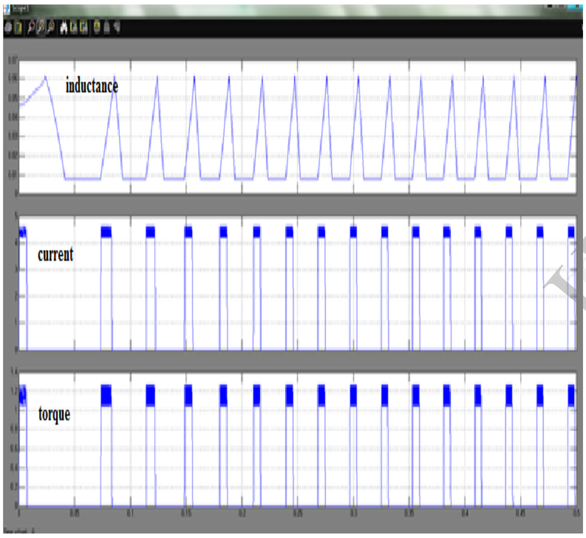

Fig. 6 Phase A inductance, current and torque in SRM.

Fig. 6 shows the one phase inductance, current and torque of SRM.

Fig.7 shows the speed responses of SRM with PI and Fuzzy controllers respectively. Comparison of proposed controllers with PI and Fuzzy for SRM shows great reduction in torque ripples and settling speed. To reach the desired speed (1000 rpm) it takes 0.15sec and the ripple contact in speed was compared to PI controller shown reduced with this method.

The detailed comparison for torque ripple and settling time at steady state are presented in Table 2.

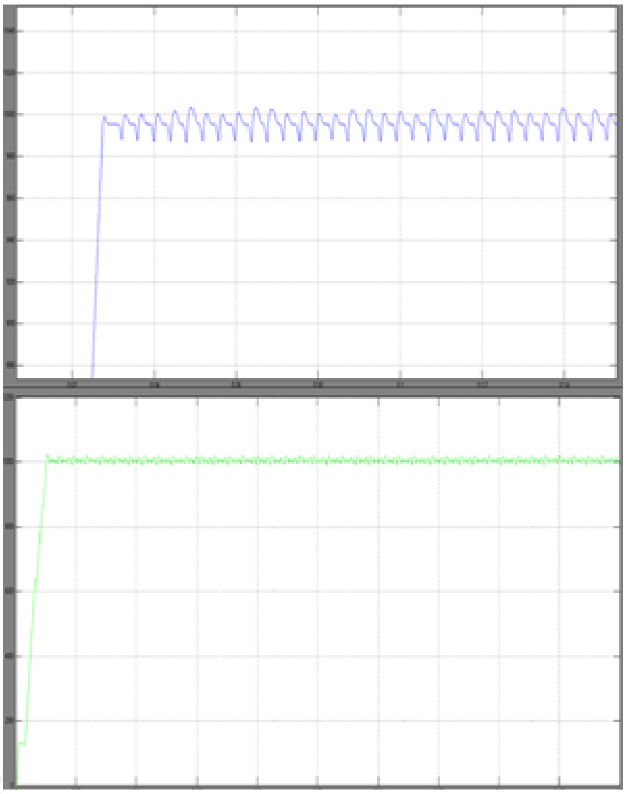

Fig. 7 Speed response of SRM with PI & fuzzy controllers with 1000 rpm as reference speed

TABLE 2 COMPARISON RESULTS BETWEEN PI AND FUZZY CONTROLLERS

Controller	Torque Ripple	Speed Settling time (sec)
Classical PI controller	1.06	0.23
Fuzzy controller	0.36	0.15

It is obvious that fuzzy controller has better results than PI controller.

IV. HARDWARE IMPLEMENTATION

The controllers for SRM can be implemented using Field Programmed Gate Array (FPGA) as it has key components in implementing high performance processors [10], [11]. The speed, size and the number of inputs and outputs of a modern FPGA far exceeds that of a microprocessor or DSP processor. The drive system of SRM consists of SRM motor, FPGA controller, power circuit, driver circuit, converter circuit and starter kit. Fig. 8 presents the structure of SRM drive system. The modules of drive system are: a 1 hp 4-∅, 8/6 SRM, FPGA Spartan-3E Starter kit, a driver circuit, power circuit and multi output transformer. The rated current is 2.2 A per phase, rated speed is 4000 rpm, Supply voltage 110 to 350 volts DC, Air Gap is 0.3 mm, No. of turns per phase is

100, Cross sectional area of conductor 0.4 mm^2 and Stack length is 130 mm. Here power supply is single phase ac 230V, power circuit with four IGBT's is used to convert ac to dc at ±100-300V.Power circuit is used to energize the each phase of motor by receiving the switching pulses from Field Programmable Gate Array(FPGA)Controller. The FPGA Controller generates PWM pluses based on motor rotor position angle and speed signals. For these signals position sensor is used.

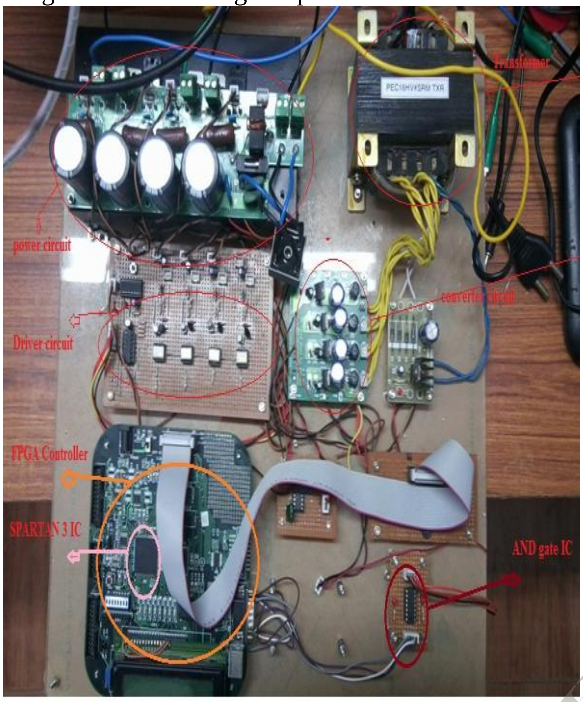

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Fig. 8 Snapshot of SRM drive system

V. EXPERIMENTAL RESULTS

The proposed control techniques were performed in laboratory when the motor was operated under different load conditions.

Figures 9 and 10 shows the speed response of the motor with PI controller and fuzzy logic controller respectively. It is observed that speed response is very smooth and ripple is reduced to a small value with fuzzy logic controller in comparison with conventional PI controller.

The practical results agree with the simulation results.

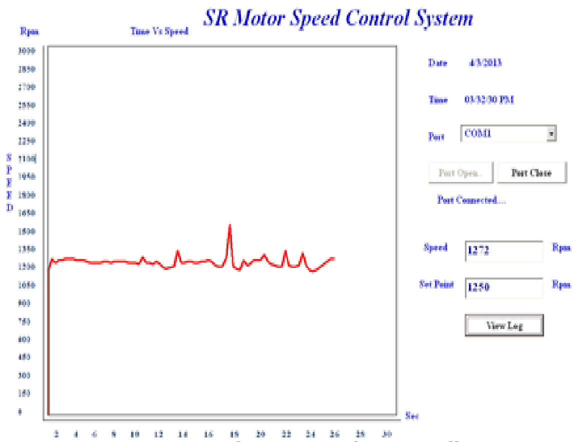

Fig. 9 Speed response with PI controller

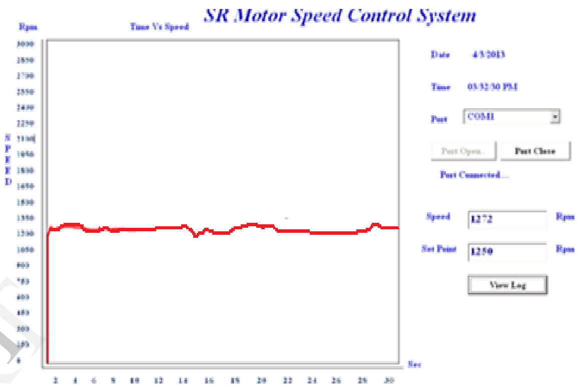

Fig. 10 Speed response with fuzzy controller

VI. CONCLUSION

Modeling, simulation and analysis of switched reluctance machine (SRM) is done. Simulation results of SRM with PI and fuzzy control shows considerable reduction in torque ripple and speed settling time when fuzzy controller is employed in comparison with PI controller.

Simulation helps to get exact switching angles. The speed of the motor increases with decrease in switching 'ON' time i.e. as switching frequency increases, the speed of the motor increases.SRM control was fabricated by using FPGA (field-programmable gate array). By comparison of simulation results and hardware results, the time response for fuzzy controller to reach desired speed is improved and ripple contents are lesser than the PI controller.

More accurate results can be obtained by linearization of SRM machine model. Research work is already done in this field by the authors. The linearization method proposed in [12], [13] can be extended to SRM model as well.

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