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Real Time Implementation of Fuzzy Controller to Minimize Torque Ripple in Switched Reluctance Motor

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Abstract: Switched reluctance motors are widely utilized in a variety of industrial applications due to their simple construction, high torque-to-inertia ratio, and cost-effectiveness. However, they suffer from torque ripple, which refers to a fluctuation in torque output during operation. This ripple can cause in vibrations, noise, and decreased efficiency. Torque ripple is a typical issue in switched reluctance motors (SRMs) that can lead to decreased performance and increased energy consumption. To address this problem, researchers have been investigating several control strategies, with fuzzy control emerging as a promising solution. Fuzzy control is a type of intelligent control that utilizes linguistic variables and rules to handles complicated and uncertain systems. It has been shown to be effective in reducing torque ripple in SRMs by adjusting the current profiles based on real-time feedback. The implementation of a fuzzy controller requires a reliable and efficient platform, such as RTLAB are presented in this paper. To generate gating pulses for the Insulated-Gate Bipolar Transistor (IGBT) Converter driving the switched reluctance motor, a fuzzy logic controller is used. The model developed compares the real time results of the simulator with results obtained using Simulink software. The real time simulator implementation of the intelligent controller signifies that such a controller can be modelled and can significantly reduce the cost. The results obtained by the Software and the simulator are found to be closer. The simulator OP4200 is used to carry out the implementation.

Keywords: *Torque Ripple, Fuzzy Controller, RTLAB, Sensorless, OPComm blocks*

1. Introduction

Past two decades Switched reluctance motors (SRM) are rapidly becoming dominant machines due to their cost-effectiveness and increased efficiency. It has characteristics such as structural simplicity and high reliability [1]. Furthermore, it is a single-excited, doubly salient mechanism. Excitation occurs only to stator windings. There are no permanent magnets and or windings on the rotor resulting in design flexibility and a high power to weight ratio resulting in less core material [2]. This feature of the rotor makes the SRM more advantageous over the other synchronous machines. Rotors without a permanent magnet result in very less low losses, reduced weight, and high power to weight ratio. Moreover, the stator and rotor have saliency, giving rise to different configurations like 6/4, 8/6, 8/12, etc. The rotor tries to rotate from an unaligned position to an aligned position when the stator windings are excited, and the reluctance in the air gap is varied, hence the name Switched Reluctance Motor.

In general, noise, vibration, and torque ripple affect the efficiency of the SRM. The primary cause of harmonics in air gap flux is torque ripples. Either the stator and pole structure can be changed or a better electronic circuit can be used to lower it [3]. Through indirect rotor position estimation for sensor-less control methods, SRM speed can be managed. One such method is the Vector Control method [4-5]. There are various types of sensorless techniques, and rotor position estimation in switching reluctance motors greatly benefits from these techniques. Different types of position sensor-less methods are magnetic model-based, magnetic model-free and hybrid detection methods. While dealing with nonlinearities in SRM, intelligent control algorithms have commendable performance. Intelligent control methods have difficult algorithm to design but provide good real time performance.

In this article, a fuzzy logic controller is applied to generate gating pulses for the IGBT to drive the Switched reluctance motor. The fuzzy based model developed using RTLAB is compared with the results obtained using Simulink software.

2. Literature Review

Torque ripple is a common issue in Switched Reluctance Motors (SRMs) that can affect their performance and

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efficiency. The torque ripple in SRMs is primarily caused by the nonlinear magnetic characteristics of the motor, including the flux linkage and inductance profiles. Various factors contribute to torque ripple, such as magnetic saturation, mutual inductance, and hysteresis. The literature survey carried out provides an insight into various sensor-less controllers designed for SRM.

A sensor-free, field-based control system based on the ANFIS technique, where the runtime voltage is simulated, and to determine the rotor position the phase current is used. A mathematical model [1] is provided that transforms the stator phase voltage into a d-q reference. A numerical approach is discussed in order to determine the flux linkage-based rotor position, location, and phase current characteristics. To assess the effects of sampling noise and residual numerical error position, a PLL of third order is taken into consideration. It describes the current pulse injection technique [4]. EMF and BEMF are utilised to estimate the location of the rotor using the sensor-less technique. The cross point position is calculated using the SRM's inductance model and is utilised as the base location. Each electrical cycle contains a special point that is sensed. PID controllers are not a good choice for SRM's dynamic performance since this motor has nonlinear characteristics and torque is inversely proportional to phase current and a derivative of rotor angle. To manage speed in a nonlinear system using human problem-solving techniques, fuzzy logic is applied [7]. Fuzzy logic is a nonlinear technique for difficult-to-model complex systems. To create a fuzzy PI controller, a current sensor gradient approach is combined with a PI controller. It is a nonlinear controller with controllable gain [5]. The difference between the observed speed and the reference speed is adjusted by the fuzzy PI controller [6]. The fuzzy sliding mode controller (SMC) combines the sliding mode controller and the FIS intelligence. The Fixed nature of the controller parameter of PI results in significant overshoot and a long settling time. For 6/4 SRM, a mathematical model is developed [11]. The fuzzy SMC improves speed response and removes overshoot. A Matlab/Simulink model is used for modelling [8]. ANFIS and GA-based optimization techniques are used. These techniques are used to optimize speed controller for SRM [14]. It is advised a sensor-less approach is used for estimation of rotor position in a real-time controller for a four phase SRM drive system. Inputs used to evaluate flux include phase voltage and current [10]. By utilizing fuzzy rules to calculate angles, fuzzy decision makers map these objects. In terms of freedom and control, fuzzy is more empowering [15]. SRM is controlled without sensors using a Binary Observer-based algorithm. The linear flux linkage parameter is calculated using an adaptive identification approach. With this technique, rotor location and speed may be accurately estimated. [16].

This literature survey mainly focuses on speed estimation, a torque estimator using controller was less in discussion. So an Intelligent Controller is designed in order to reduce torque ripples. As the torque ripples were one of the major issues in the Switched Reluctance motor, this problem is addressed in this paper.

This study also demonstrates the implementation of a fuzzy controller to reduce torque ripple in an 8/6 switched reluctance motor drive. The creation of gating signals takes place using a vector control approach. It is considered as one of the most effective techniques for torque ripple minimization. Implementation of the controller on a real-time simulator is to verify the performance parameters such as speed, Torque and current obtained from the Simulink Model. The Steps involved in Converting the Simulink Model to Real Time Compatible model are also discussed. The controllers designed do not require an external position sensor to sense the rotor position, hence, the controllers designed are sensor-less. An indirect Rotor Position estimation method is used.

3. Proposed Work

3.1. Sensorless SRM Drives:

Sensorless SRM drives can be either open loop or closed loop in terms of speed (or position) control. Sensorless Open loop SRM Drives suffer from stability problems, low dynamic speed and limited speed control range. Sensorless closed loop sensorless SRM drives are of the highest calibre, able to produce rotor position and speed through estimate with good accuracy and robustness, as well as on time [16]. Voltage-Current Model Based: Utilising frequency sensors, the phase voltages and currents are detected. Stator phase Eq. 1 are used to represent the voltage model.

$$\frac{d\lambda i}{dt} = V_s - r_s i_i \qquad (1)$$

A position correction is $\Delta\theta_r(k)$ is operated to drive current error to zero.

The average of the three position corrections (from all three stages) can be calculated using Eq. 2.

$$\Delta\theta_r = \left(\frac{\Delta\theta_r + \Delta\theta_r + \Delta\theta_r}{m}\right) \qquad (2)$$

The estimated position is

$$\theta^e(k) = \theta_p\ (k) + \Delta\theta_r \qquad (3)$$

$\theta_p\ (k)$ is the value calculated in the previous step. The $\lambda(\theta_r, i)$ curve is approximated using fuzzy logic approach.

3.2. Speed Controller for SRM

Switched reluctance motor control is a herculean task and not as easy as compared to traditional machines. The controllers are designed are mainly to attenuate torque ripple. This section provides an insight to into different intelligent controllers that will be able to decrease torque ripple in SRM. A simple control technique is to magnetize and demagnetize each phase of the motor (similar to a stepper motor) at the right movements (estimating position of rotor) to obtain less torque ripples. The Non Linear nature of motors poses a challenge to this task; hence Linear Controllers are complicated and tricky to design [12].

A Constant torque with the lowest possible torque ripple is the main objective of a speed controller. Sensor usage for instantaneous torque measurement increases cost. Indirect Torque estimation method is an affordable alternative method which uses voltage and current values to estimate flux and look up table method for rotor position estimation [18]. The Proposed Controller receives speed error as input, and the reference torque is estimated using Fuzzy Controller, the initial rotor angle is taken as 22.5 as the stator pole pitch is 45 degrees, (8/6). Figure 1 depicts the proposed model diagram for a sensorless fuzzy Controller.

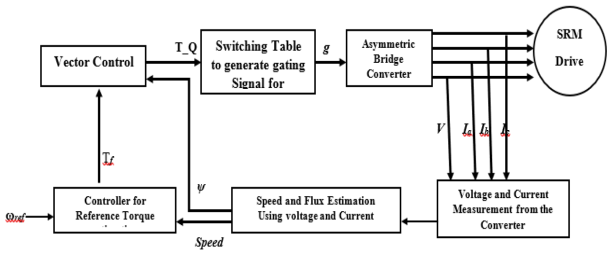

Fig. 1. Proposed Fuzzy controller Model

Step 1: The speed and flux are estimated using a converter with phase voltages and currents. This data (flux) is used to calculate the rotor angle. The speed is estimated from the angle using a maths function available. The modulus is performed after division, which uses (t, θ), for calculating "‘ ω’.".

Step 2: angle estimation is done from flux using Eq. 4.

$$u(1)*cos(pi/4)-u(2)*cos(pi/4)-u(3)*cos(pi/4)+u(4)*cos(pi/4) \quad (4)$$

$$u(1)*sin(pi/4)+u(2)*sin(pi/4)-u(3)*sin(pi/4)-u(4)*sin(pi/4) \quad (5)$$

Step 3: From the estimated angle with a decimation interval and a PI Controller with Kp and Ki values 30000 and 50000 respectively used in support of a low pass filter for estimation of speed.

Step 4: The estimated speed and flux are noted, reference speed is set for tracking the analysing the response of motor with respect to various parameters such as torque, speed and flux.

Step 5: A reference speed (set at 1500 rpm) and the estimated speed from the feedback are compared and the difference input is used as the input to the fuzzy controller.

Step 6: The Fuzzy Controller estimates the reference Torque as shown in Fig 3. This reference torque along with the one generated from by the motor are compared. A reverse estimation of angle (using flux) is done to generate switching vectors, keeping torque ripples to a minimum at the settling speed. The position of the rotor is calculated from flux. The initial rotor angle is set to 22.5º.

Step 7: The switching tables generates the gating signals required for the IGBT switching in the Converter.

Vector control method is as a witching table method to provide excitation to the stator winding, using vector modulation thus generating gate pulses as in Figure 2 is required for the converter. The above steps describe how the model is designed in detailed way.

3.3. Fuzzy Controller

A Fuzzy system is used as controller where, a clear output is required, then it is necessary to defuzzify to extract a crisp value. The controller uses the following fuzzy rules [4]. If x=A and y = B then z = C, where x, y,z are fuzzy variables in the universe of discourse A, B,C. For Torque estimation, speed error 'E' and its derivative CE are fuzzy variables. A mamdani fuzzy model using max min method with centroid defuzzification is used. A 3 Membership Function is Used (as it is best suited for torque ripple minimization). Figure 3 depicts the fuzzy controller.

3.4. Simulink Model:

This Section depicts the model developed in the Simulink and also discuss the results obtained The Simulink model developed is as depicted in Figure 4.

3.5. Real Time Simulators:

Electrical system design and improvement are aided by simulation technologies. Previously expensive and only available to large firms, simulation tools are now affordable for researchers and engineers. The optimisation of transportation in motor drives and gearbox lines depends heavily on simulation designs for massive power systems, as well as the successful development of many applications [17]. Simulators speed up the resolution of challenging issues. In a fixed step simulation, time advances in steps of identical length.

Simulators carry out a number of tasks for each time step, like:

1) Reading inputs and producing outputs

2) Resolve model problems

(3) Exchange outcomes with other simulation nodes

(4) Watch for the beginning of the subsequent stage.

If timing conditions are not met, overruns occur. Real time simulators are classified into three categories.

- Rapid Control Prototyping (RCP)
- Hardware in the loop (HIL)
- Software in the loop (SIL)

The RCP programme connects the controller to the physical plant through a real-time simulator. In HIL, a computer model that is exactly identical to the physical plant is used in place of it, and it runs in real-time on a simulator that is adequately furnished with inputs and outputs (I/Os) capable of interacting with machinery and other control systems. Without the requirement for testing on actual systems, the HIL simulator faithfully recreates the plant and its dynamics, along with sensors and actuators, to provide thorough closed-loop testing [19].

On the same simulator, the controller and plant are simulated in SIL in real time. The advantage of software-in-loop (SIL) is that it has no inputs or outputs and thereby preserves signal integrity.

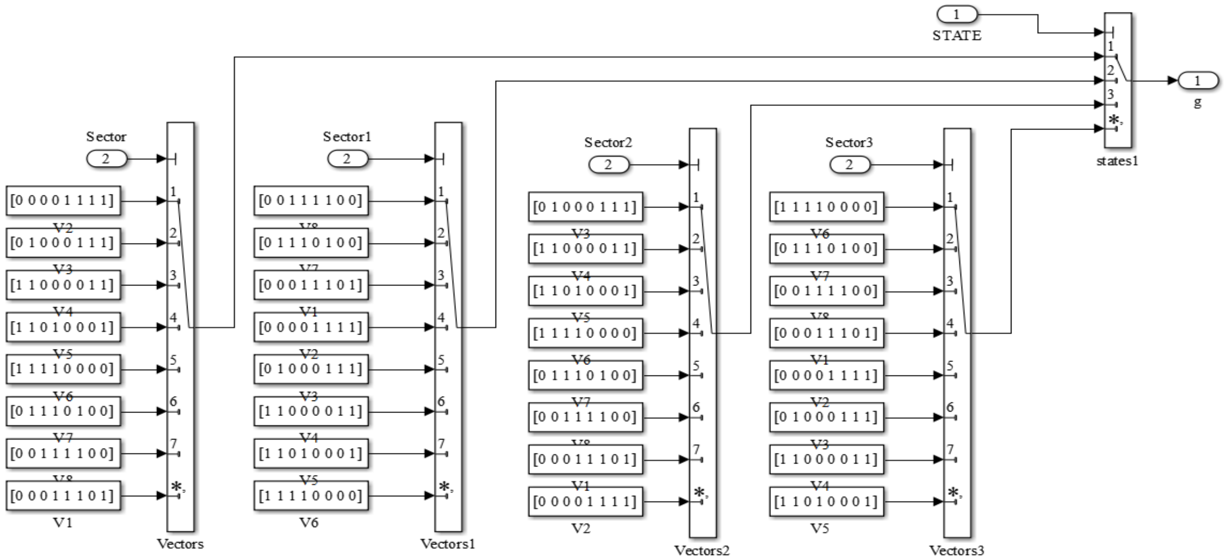

Fig. 2. Vector Control Method

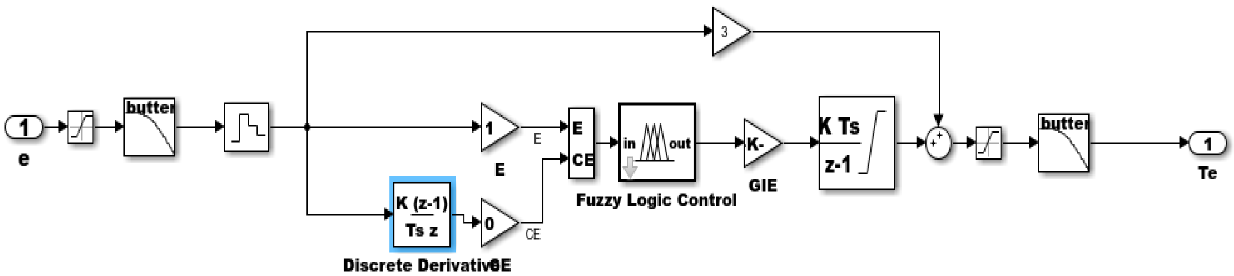

Fig. 3. Fuzzy Logic Controller to estimate reference torque.

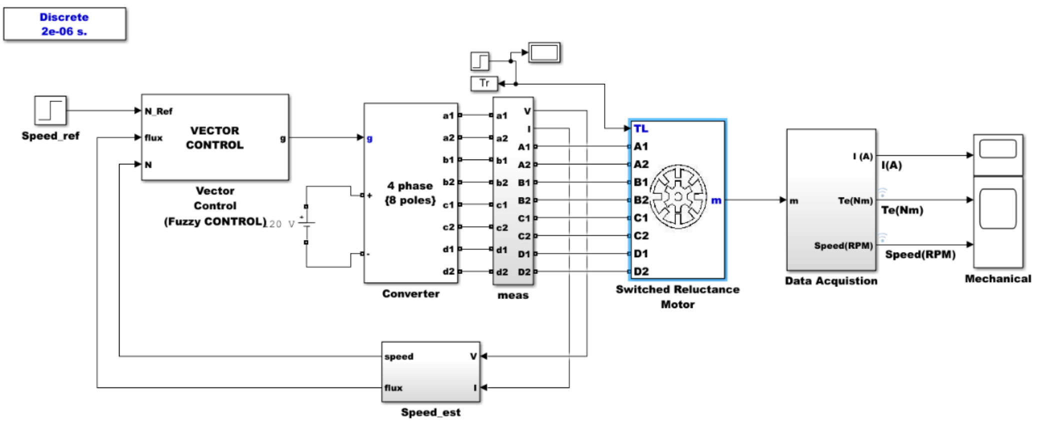

Fig. 4. MATLAB/Simulink Model developed for torque ripple minimization.

This article describes the RT-Lab simulator platform for simulating switched reluctance motors. Using RT-Lab, semi physical simulation experiments is are carried out. Phase current waveforms and the rotor speed response curve are measured. Vector Control stratergy is used in this paper for generation of gating pulses. Synchronized Hardware simulation including modelling, making of hardware required is demonstrated. The Model converted from the Simulink Model to RTLAB is found to be satisfactorily implemented on Simulator. Using hardware synchronized simulation will help to verify the controller in real time, make it Simple to change command parameters and check the controller output [20].

3.6 Converting MATLAB/Simulink Model compatible to RTLAB:

Before running a MATLAB/Simulink model on the RT-LAB platform, the Simulink model need needs to be converted to a compatible loadable model by adding additional interfacing blocks available in through RT- SIM platform of Simulink.

The model has to run perfectly in the Simulink software. The model needs to be grouped into two subsystems,

i) Master

ii) Console

i. Master–SM_[name] is subsystem block master. This subsystem block responsible controlling and monitoring of real- time simulation. This subsystem contains Input and output blocks.

ii. Console-SC_Console_SC_[name] is a subsystem console. This subsystem is asynchronous in nature and acts as a user interface to provide the necessary inputs. In this subsystem, Mathematical logic is not included. The Converted RTLAB Model from Simulink is shown in Figure 5. A Data Converter and Opwrite file need to be added at the output of Data Acquisition block from the RTSIM Library. The Opcomm output blocks are also added for verifying output on Oscilloscope.

The computational blocks are enclosed in the SM_Subsytems. The scope and outputs are enclosed in SC_subsytem as shown in Figure 6.

3.7 OP COMM blocks

Once the model is connected to the Computation subsystems, specialized blocks called OpComm need to be inserted into the subsystems. The model is divided into Console and Computation subsystems before adding OpComm, as shown in Figure 5. The incoming signals are all intercepted by these straight forward feed-through blocks before being sent to the computing blocks in the supplied subsystem. OpComm blocks are used for three things:

1. Hardware communication links are used in connecting between the subsystems blocks (SC_, SM) when the model simulation carried out in RT-LAB environment.

2. OpComm blocks convey RT-LAB about kind and magnitude of the signals that are transmitted from one block to other block.

3. By inserting OpComm blocks in block of the Subsystem, the user can choose the data acquisition block according to the wish of the user to collect the data and to specify the data acquisition parameters.

Figure 7 is the automatically generated RT-LAB model obtained after downloading the Sensorless Fuzzy Controller on to the real time Simulator [21].

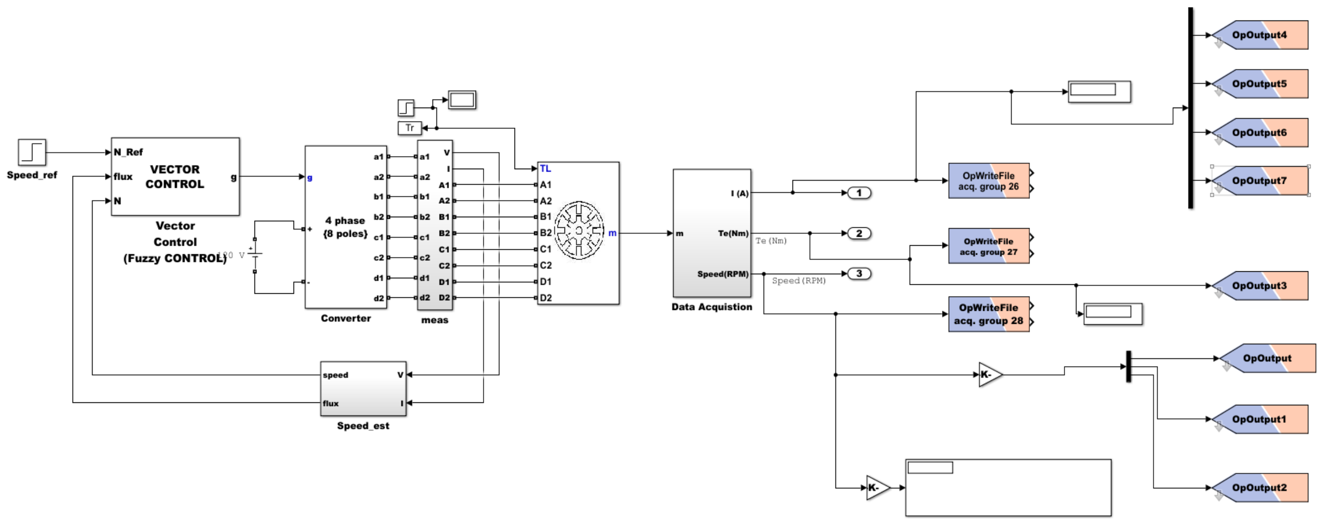

Fig. 5. RTLAB compatible model from Simulink

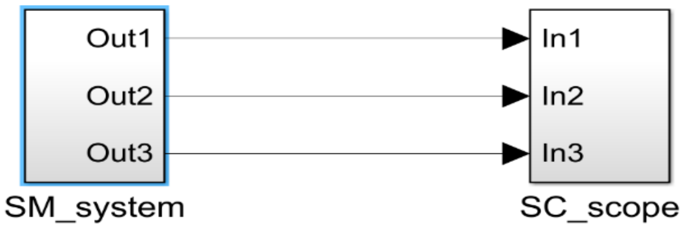

Fig. 6. Master and Console Blocks of the Fuzzy Contorller

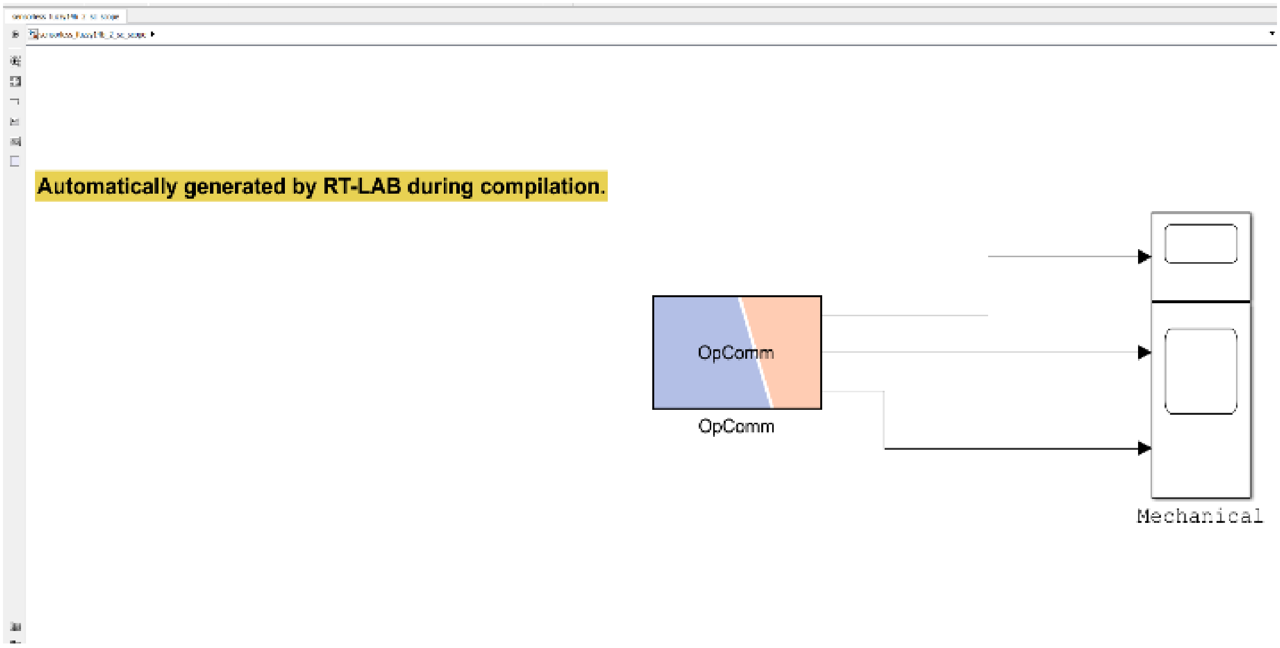

Fig. 7. Compiled model ready for downloading

4. Results and Discussion

4.1. Simulink Results

The response plot of various parameters such as speed, Current, Torque are noted. The speed settles finally at 0.7 sec and at 1584 rpm (set speed is 1500 rpm), as shown Figure 8. Initial Torque is 8 Nm (Figure 9). Initially the motor Torque is high. As the speed settles, the final torque is 2 Nm at settling speed. Torque ripples

are less at the settling time, i.e. 0.7 sec. Initial current is 28A (Figure 10). At settling, the current is around 6 A.

The current response in Figure 10 implies that as one phase of the converter triggers one stator winding, during the falling slope of this the second converter is triggered. The vector control table is the one that generates the stator driving pattern as stated by the switching table. Estimates of the rotor location are made prior with the help of AND-OR logic from the flux estimated.

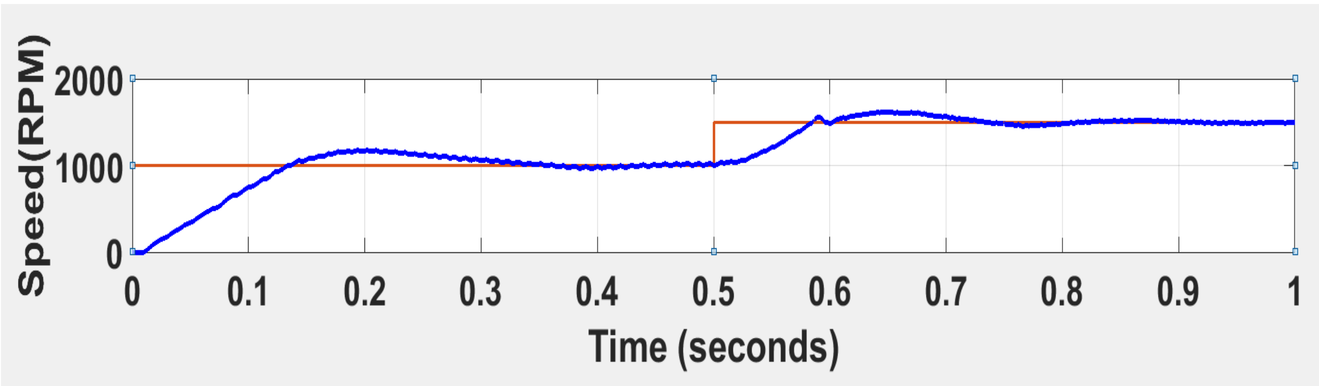

Fig. 8. Speed response

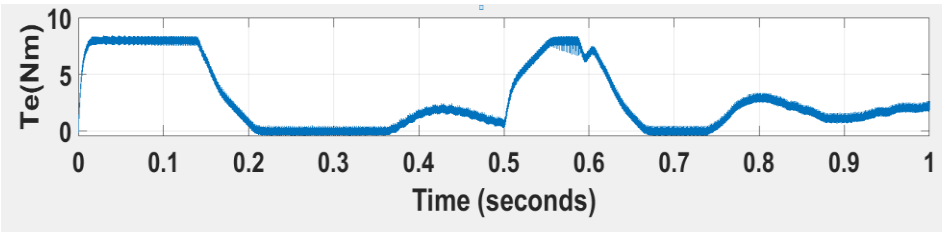

Fig. 9. Torque response

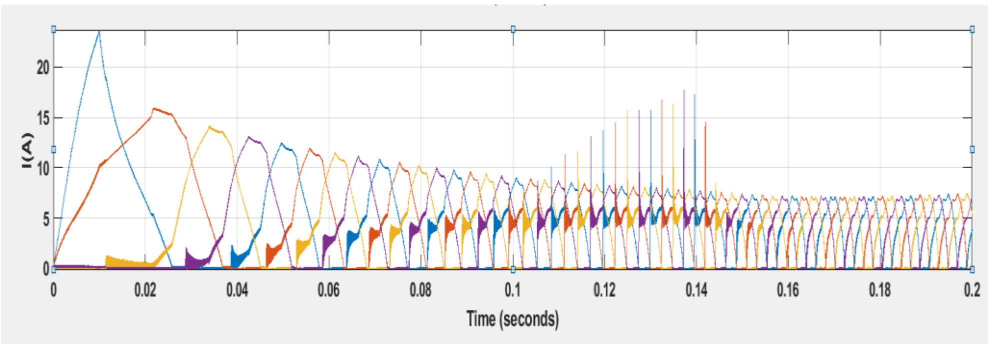

Fig. 10. Current response of 4 different phases

This section explains the real time simulator results obtained from the Model in Loop Simulation carried out on the Simulator OP4200. Fig 11-13 is the response obtained from the real time simulator.

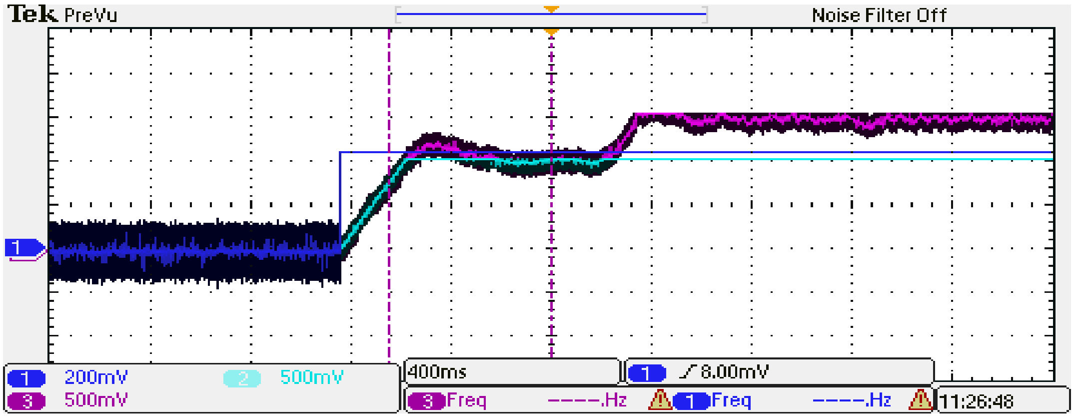

Fig. 11. Speed Response on Simulator

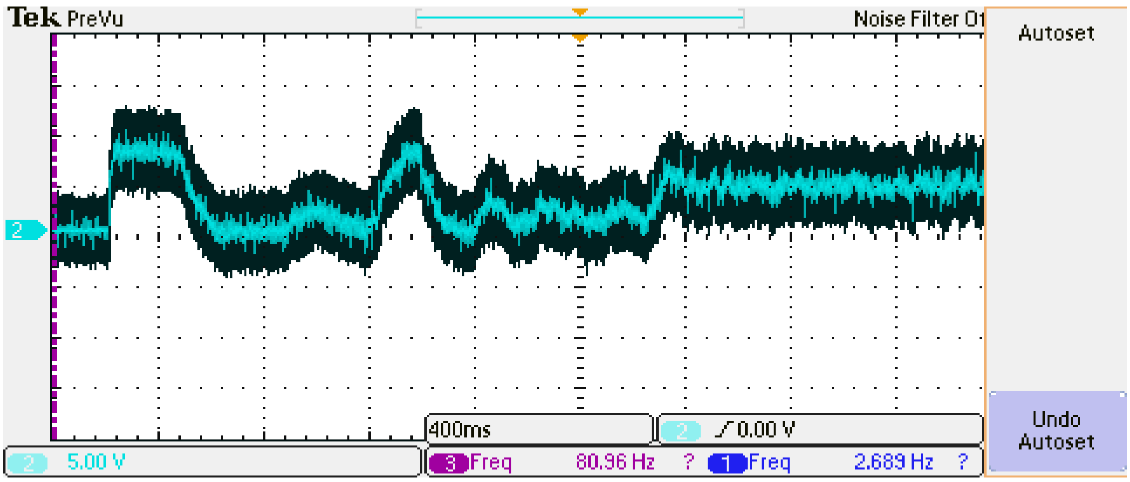

Fig. 12. Torque response on Simulator

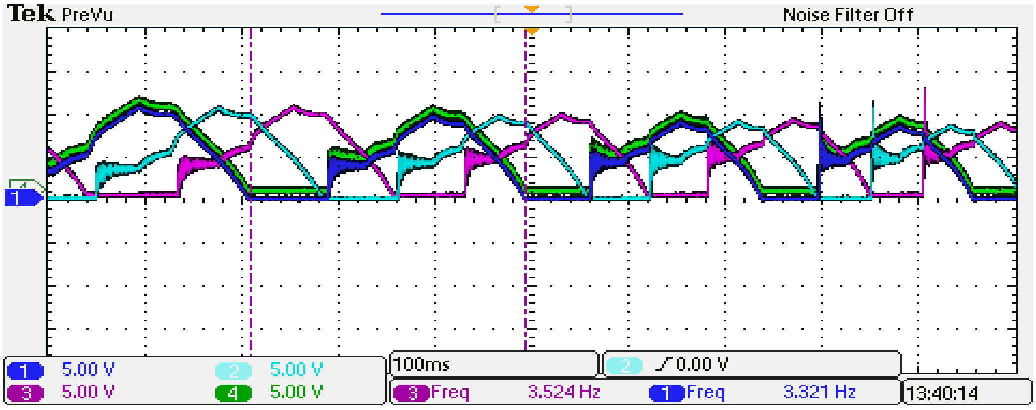

Fig. 13. Current Response of simulator

The plots obtained for speed, Current a Torque of the Fuzzy Controller are closer to the Simulink Results obtained. As it can be seen from the Current plot, the Switching of Current to the stator happens at the Crossover so that the air gap flux is at its minimum resulting in fewer torque ripples.

Table 1. Comparison of Controllers

Sl no	Name Of Controller	Speed(in rpm)	Current(in A)	Torque ripple (in %)
1	PI	1504	11.79	>90
2	FUZZY	1581	6.004	2.5

From the table 1, it's clear that a fuzzy controller is a better option if torque ripple is one of the main criteria for switched reluctance motor implementation. Provides a comparison of Fuzzy and PI Controller for Speed, Current and Torque Ripple. As it can be inferred from the table the Fuzzy controller implemented has reduced Torque Ripples and less Current cosumption when compared to a PI.

The SRM chosen for the implementation is 8/6 having the following features mentioned in table 2.

Table 2. SRM Parameters

Sl no	Parameter	Value
1	Type	8/6
2	Stator resistance (Ohm)	3.1
3	Inertia (kg.m.m)	0.0089
4	Friction (N.m.s)	0.01
5	Unaligned inductance (H)	0.67e-3
6	Aligned inductance (H)	23.6e-3
7	Saturated aligned inductance (H)	0.15e-3
8	Maximum flux linkage (V.s)	0.486

5. Conclusions

This paper presents a novel implementation of Fuzzy Controller on a Real Time Simulator. The work carried out outlines the various steps involved in implementing the Fuzzy Controller and also the steps involved in converting as Simulink Model to be Compatible to RTLAB for its realization on Simulator. The speed, Torque and Current responses are noted both in SIMULNIK and also On the RTLAB Simulator. The results obtained are appreciable, and the model is found to be working on the real time simulator.

Conflicts of Interest

All authors declare that they have no conflicts of interest.

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Author Contributions

Mrs. Babitha S has identified Initial problem identification, algorithm write-up, analysis, drafting of the manuscript, and simulation. **Dr. H. V. Govindaraju** was responsible for the Literature survey and helped in the initial review process. **Mrs. Padmashree V. Kulkarni, Dr. Rohith S** were responsible for the Complexity analysis of the research, evaluation of the research work. **Dr. Jyoti P. Koujalagi** was responsible for the final formatting and applied for the journal. All authors worked together to implement and evaluate the integrated system, and approved the final version of the paper.

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