DESIGN AND ANALYSIS OF AN FPGA BASED SIMPLE CONTROLLER FOR SWITCHED RELUCTANCE DRIVE

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Abstract: This paper proposes a new simple control technique using FPGA for controlling the variable speed switched reluctance drive. The phase currents in the low speed zones are controlled by hysteresis chopping method for which the reference current is generated by PI controller. The turn-on angle is kept fixed in current control. Angle control method is used in the high speeds zones, in which, turn-on angles are obtained by using a separate PI controller rather than generally used lookup table method. The turn-off angles are made to decrease with increase in speed using a generalized equation for both low and high speeds. Boundary issues are discussed in detail to find the suitable border line between chopping and angle control. This new control strategy is not only easy to implement but it reduces complexity, solves boundary problems and reduces time and efforts required for computation of angles as compared to look up table approach. Simulation and experimental results are presented for a 2.2 KW machine to validate the proposed control strategy. FPGA based controller is used for implementing the control technique.

Key words: *angle control, current control, FPGA, PI controller, speed control, switched reluctance drive.*

1. Introduction

The Switched Reluctance Motor (SRM) became popular in early 1980's when the development of control techniques using power electronics gained the attention of researchers. The operating principle of SRM is widely known and is simple to understand. The torque production mechanism in SRM depends on the tendency of its rotor to move to a position where the reluctance is minimum [1, 2]. It is a doubly salient, singly excited, variable reluctance machine which has many advantages like absence of permanent magnets, rugged and simple construction, thermal robustness, high torque to inertia ratio, etc. It is widely used for variable speed drives.

In conventional control methods, SRM is controlled with current chopping in low speed zone and angle control in high speed zone [1-3]. Implementation of current control is generally done by controlling the phase currents by gain scheduling and implementation of angle control is performed either by changing turn-on (T_{on}) angle with fixed turn-off (T_{off}) angle or by changing both T_{on} and T_{off} angles [3,4]. In the conventional angle control method, T_{off} angles are varied as a function of speed only, whereas, T_{on} angles are varied as the function of both speed and developed torque [5]. This information can be obtained by running the simulated model in open loop with various speeds and torque levels. The data collected for T_{on} and T_{off} angles are stored in the lookup tables for closed loop control. The criterion for selection of angles can be minimum r.m.s. phase current or low torque ripple [6]. This method is tedious and takes appreciable computation time.

Authors in [7], select the control parameters based on requirement of torque-per-ampere maximization. PID controllers with their limitations are discussed by [8] for dynamic operation of motor. Voltage control of SRM is implemented in [9] using DSP processors. Nashed [10] describes an automatic T_{off} control, using a look-up table and implements the SRM torque operation over its entire speed range. In paper [11], the authors have simulated an FPGA based SRM drive with a torque distribution function, which results in lower torque ripple, for high-speed drives. A self-tuning method has been implemented using FPGA in [12] for various speeds by varying the excitation parameters but without the use of position encoder.

In paper [13], the closed loop system with two feedback paths to control phase current speed of SRM are practically implemented. Authors in [14] utilize a linearized model to propose a fixed PI current controller and then evaluate back-electromotive force for disturbance rejection in current control. A direct torque control algorithm SRM using sliding mode control is implemented in [15] where a new shape of SRM is constructed by choosing the parameters.

The aim of this paper is to find an easy implementable control law by simulating a simple non-linear model to control its parameters. In order to find a suitable boundary between current control and angle control, a narrow band is defined so that the oscillations at the border line are minimum. The phase currents are controlled by hysteresis chopping in the low speed zones. The reference current is generated by PI controller which is used for chopping control. A generalized equation is used for controlling T_{off} angles in both low and high-speed zones.

The results obtained through extensive simulations are analyzed and verified with the experimental implementation using Xilinx FPGA based controller. A four phase, 2.2 KW, 8/6, SRM is used for this work, which is coupled to a separately excited DC machine and the performance analysis of the drive is discussed in detail in the following sections of the paper.

2. Non-Linear Mathematical Modelling of SRM

Fig.1 shows the cross-section of a 8/6 pole SRM in which it can be observed that if windings on phase poles Ph2-Ph2' is excited, the rotor will move in clockwise direction in line with the magnetic field axis. Then, if the windings on poles Ph1-Ph1' is excited, the rotor will continue to move in the same direction. Thus, due to the double saliency in poles construction, the rotor tries to move to the position where inductance is maximum, or reluctance is minimum. The developed torque is a non-linear function of current [1,2]. Therefore, a non-linear model is required to analyze the machine. The SRM specifications used for simulation model are given in Appendix I.

The compulsory prerequisite to obtain the model of the machine is to find the flux-linkage characteristics which is dependent on rotor position and phase current. The equation governing the operation of SRM is given by [4]:

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$$v = i * r + (d\Psi/d\theta) \quad (1)$$

Where, v, i, r, Ψ and θ are voltage applied, phase current, resistance, flux linkage and rotor angle respectively. The typical flux linkage characteristics of SRM are shown in Fig. 2.

The developed torque of the motor can be expressed as:

$$T_d = \frac{dW'}{d\theta}\Big|_{i=constant} \quad (2)$$

Where W' is the co-energy and is given by

$$W' = \int_0^i \Psi \, di\Big|_{\theta=constant} \quad (3)$$

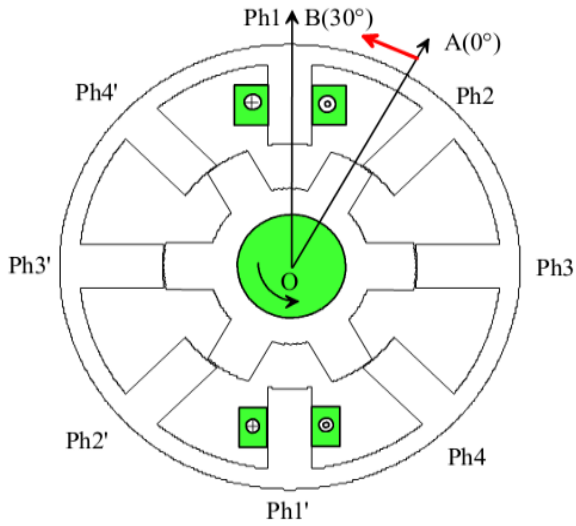

Fig. 1. Cross section of an 8/6 SRM [3]

Using (2) and (3), the static torque characteristics of the machine can be obtained. Fig. 3 shows the typical static torque characteristics of SRM. The equation governing the speed of the machine is given by[4]:

$$T_d = T_L + B*\omega + J*(d\omega/dt) \quad (4)$$

Where, Td is the total torque developed in all the phases, TL is the load torque, B is the Coefficient of friction, J is the momemt of inertia, ω is the speed of SRM.

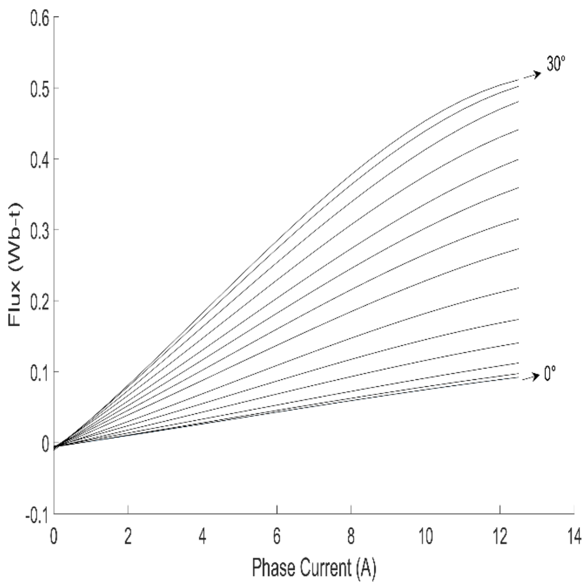

Fig .2. Measured Flux linkage characteristics of SRM

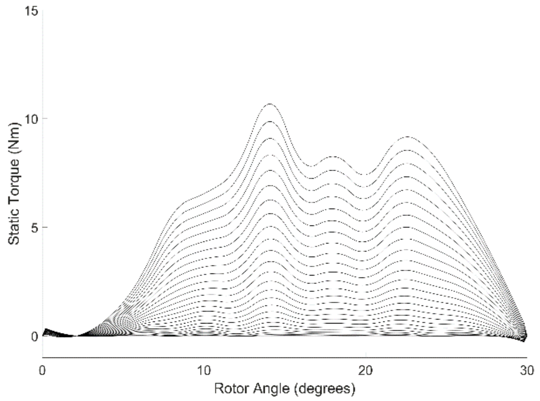

Fig. 3. Static torque characteristics of SRM obtained from Flux linkage characteristics

3. Proposed Control Technique

In this paper, a simple control technique is proposed for controlling the speed of the SRM. Fig. 4 presents the basic block diagram for the proposed control scheme for SRM. According to the given reference speed ($\omega_{reference}$) and the computed speed (ω_{actual}), the mode of operation of SRM is selected as either current control or angle control. Current control mode is used for low speed zone whereas angle control mode is used for high speed zone. In current control mode, the phase currents are controlled by chopping using hysteresis controller and T_{on} angle is kept fixed. The reference current (I_{ref}) is obtained from a PI controller which takes speed error as the input ($\omega_{reference} - \omega_{actual}$).

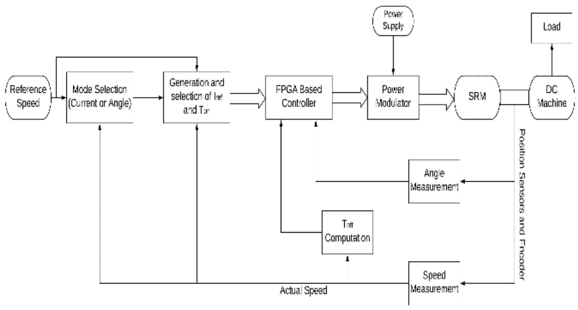

Fig. 4. Block diagram of the proposed control technique.

In angle control, T_{on} angles are controlled using another PI controller within a pre-computed band. The input for this controller is opposite to the first PI controller ($\omega_{actual} - \omega_{reference}$). The minimum limit of T_{on} angle band is computed at rated speed (ω_{rated}) with full load whereas the maximum limit is computed at minimum speed (ω_{min}) at no load condition. Here ω_{min} is the minimum operating speed at which motor is expected to run and ω_{rated} is the rated speed of the motor. In angle control, I_{ref} is fixed to a peak allowable current of the motor to avoid the current overshoot during dynamics.

T_{off} angles are controlled as a function of speed for whole speed range. They are varied from ω_{min} to ω_{rated} and are held constant below ω_{min} and above ω_{rated} as given in (5). They are continuously decreased with increase in speed [16].

$$T_{off}(\omega)=\begin{cases} T_{off}(\omega_{min}) & ;0\leq\omega<\omega_{min} \\ \dfrac{(T_{off}(\omega_{min})-T_{off}(\omega_{rated}))*(\omega-\omega_{min})}{(\omega_{min}-\omega_{rated})}+T_{off}(\omega_{min}) & ;\omega_{min}\leq\omega<\omega_{rated} \\ T_{off}(\omega_{rated}) & ;\omega_{rated}\leq\omega \end{cases} \quad (5)$$

Where, $T_{off}(\omega_{min})$ is computed T_{off} angle at ω_{min} speed and $T_{off}(\omega_{rated})$ is computed T_{off} angle at ω_{rated} speed. T_{off} angles are selected based on minimum rms phase current as the criterion.

The boundary speed between current control and angle control can be obtained using a band of cross-over speeds. This reduces the jitter at the boundary speed and operates well within the specified current or angle control. Depending upon the output of mode selection block, suitable I_{ref} and T_{on} are obtained. T_{off} are obtained from (5) irrespective of the mode. The parameters are fed to a FPGA based controller which generates the pulses for IGBT switches of the modulator. This drives the SRM coupled to a separately excited DC machine with load.

4. Simulation Results

The mathematical modelling of the system is performed. SRM is coupled to a separately excited DC motor of matching specifications, i.e. 2.2 KW, 230V, 3000rpm. Extensive simulation studies are performed using MATLAB for various reference speeds and results are shown for few speeds. Boundary speed between current and angle control is set as 1500 rpm.

Fig. 5 shows the torque, speed and phase current for 500 rpm. In this case, current control is implemented. Chopping of phase current is observed here. Fig. 6 shows the waveforms for 1600 rpm. The torque, speed and phase current waveforms are shown. The chopping of current is not observed here because as speed increases, back-emf increases and applied voltage may be insufficient for chopping. Therefore, angle control is implemented for high speeds.

Fig. 7 shows the angle control for 2200 rpm where back-emf becomes equal to applied voltage and a flat-top current profile is obtained. Fig. 8 shows the results for high speed angle control speed i.e. at 2900 rpm.

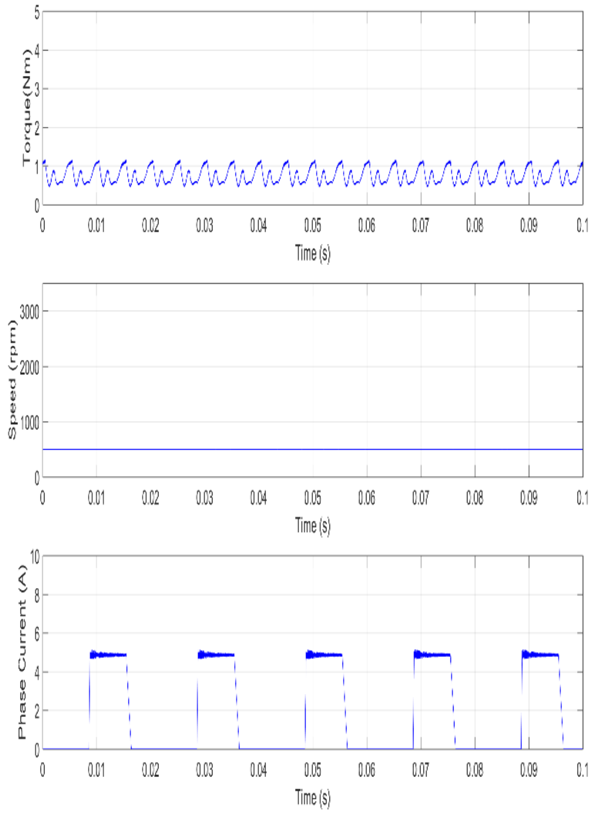

Fig. 5. Simulation results for torque, speed and phase current for 500 rpm in current control mode

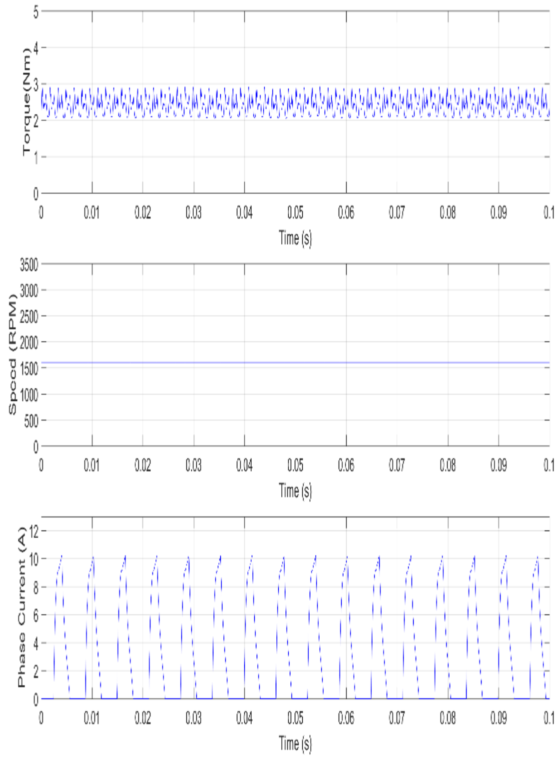

Fig. 6. Simulation results for torque, speed and phase current for 1600 rpm in angle control mode.

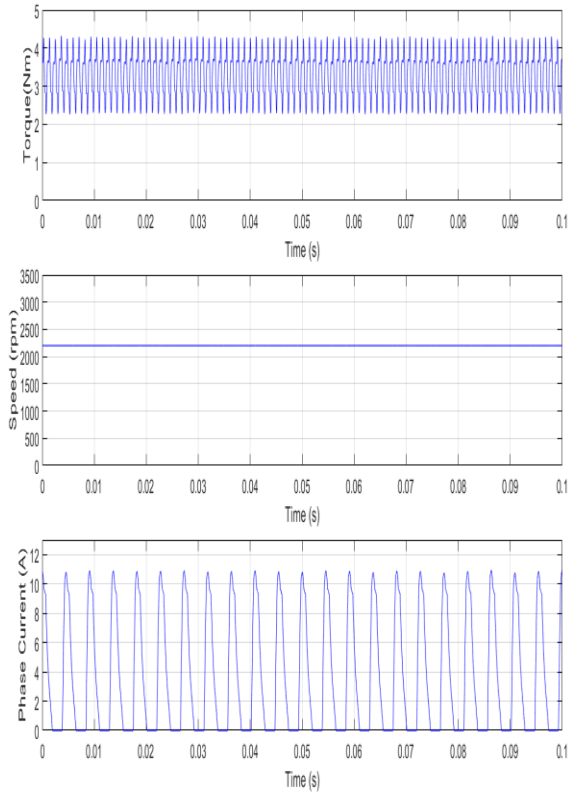

Fig. 7. Simulation results for torque, speed and phase current for 2200 rpm in angle control mode

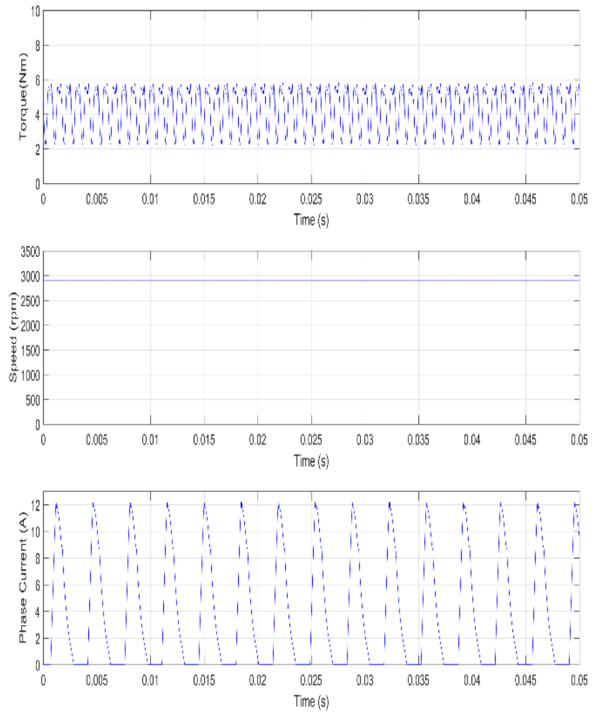

Fig. 8. Simulation results for torque, speed and phase current for 2900 rpm in angle control mode

To explore the dynamic behavior of the drive, the reference speed and load torque are changed. For fixed load, the transition of speed from 1000 rpm to 2000 rpm is observed in Fig. 9. It can be observed that during dynamic conditions, the jitter in speed near boundary speed is avoided and there is a smooth transition between current to angle control and vice-versa under changing load conditions. For fixed speed 900 rpm, the transition of load torque is shown in Fig. 10.

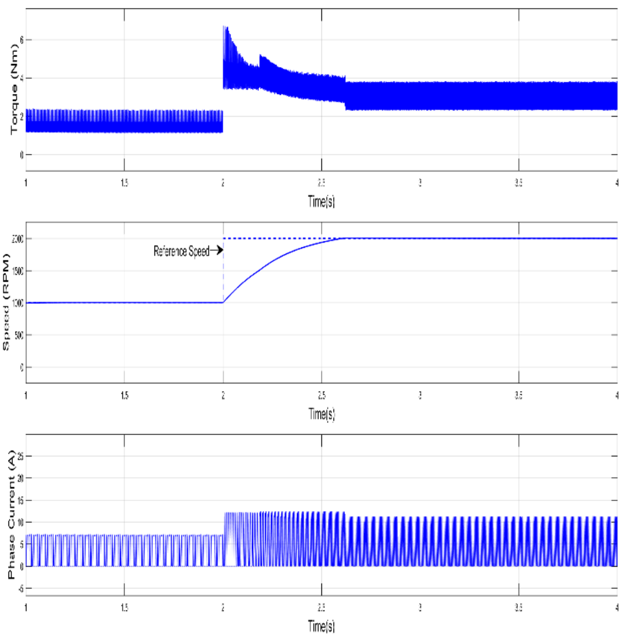

Fig. 9. Dynamic performance of machine showing Torque, Speed, Current, for change in speed from 1000 rpm to 2000 rpm

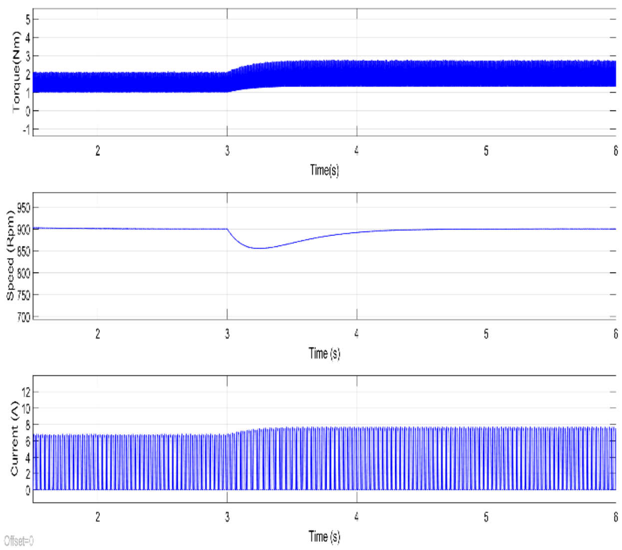

Fig. 10. Dynamic performance of machine showing Torque, Speed, Current, for change in load torque at 900 rpm

5. Experimental Implementation and Results

The proposed model is implemented practically using FPGA based controller which is programed using Xilinx Vivado System Generator. Fig.11 shows the Xilinx model used for implementation. Fig. 12 shows the experimental-set up for the same. A 4 Phase, 2.2 KW, 3000 rpm, 8/6 SRM is coupled with a seperately excited DC machine which acts as a generator. SRM is indirectly loaded by loading the DC machine with similar specifications.

The DC bus voltage for running SRM is derived from a three phase supply. The power modulator used for control is an asymmetric bridge converter. Four current sensors are used for sensing phase currents and speed encoder is connected for speed and angle measurement. The required angles for controlling SRM are derived from the position sensor signals and the encoder pulses. The program used for running the experiment is built using Xilinx Vivado Library in MATLAB and controller is programmed. The FPGA controller used in this work communicates with the computer and results obtained are directly saved in MATLAB.

The experimental results for current control mode at 500 rpm are shown in Fig. 13 and angle control mode at 1600 rpm are shown in Fig. 14. Fig 15 and Fig. 16 show the results for 2200 rpm and 2900 rpm respectively. All the figures show the speed, phase current with respect to time and phase current with respect to rotor angle .

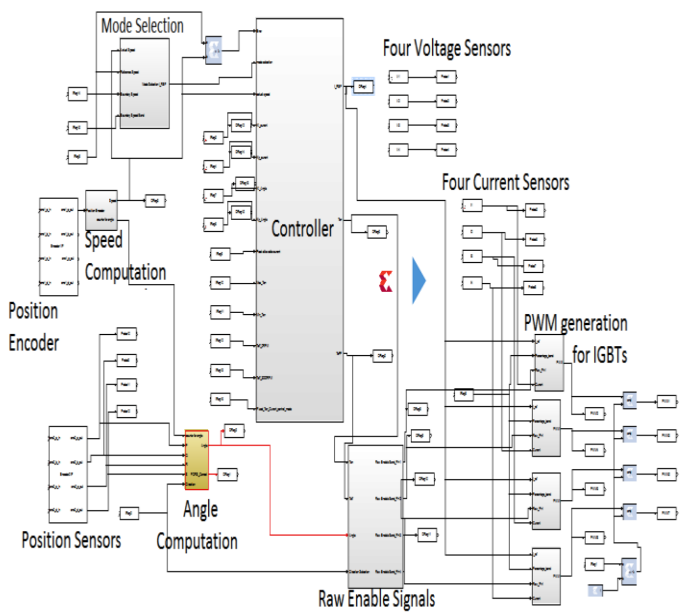

Fig. 11. Xilinx model used for experimental implementation

Fig. 12. Experimental Set-up for control of SRM.

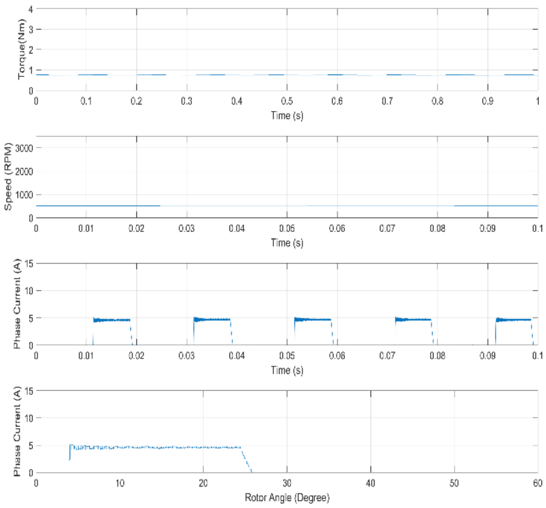

Fig.13. Experimental results showing torque, speed, phase current with time and phase current with rotor angle for 500 rpm in current control mode

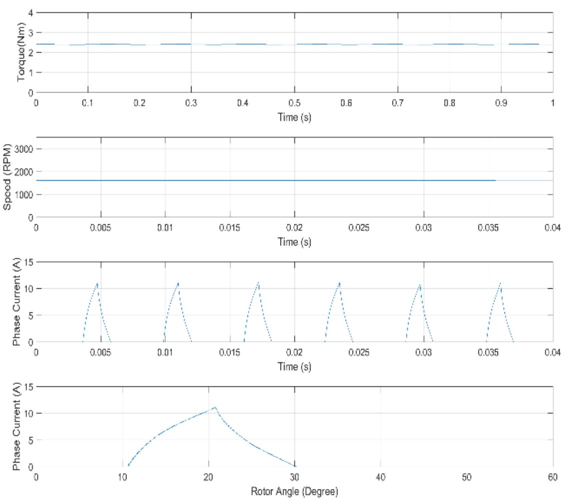

Fig.14. Experimental results showing torque, speed, phase current with time and phase current with rotor angle for 1600 rpm in angle control mode

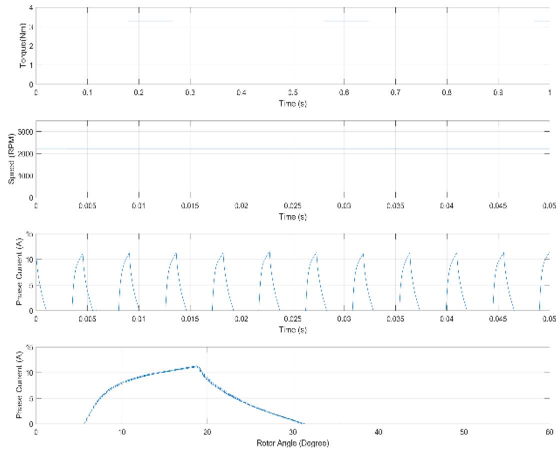

Fig. 15. Experimental results showing torque, speed, phase current with time and phase current with rotor angle for 2200 rpm in angle control mode

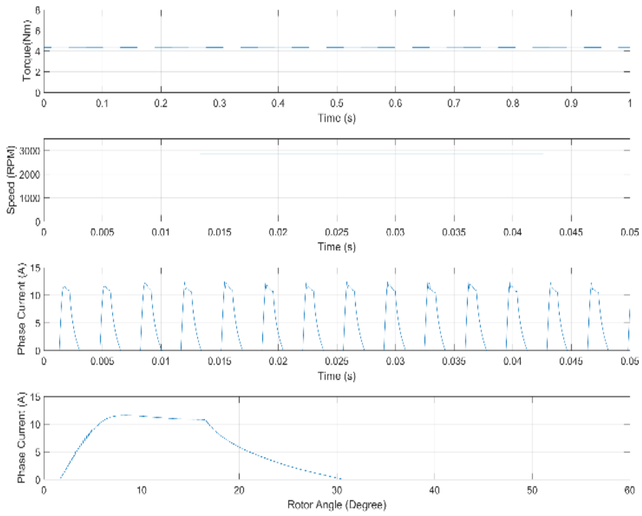

Fig. 16. Experimental results showing torque, speed, phase current with time and phase current with rotor angle for 2900 rpm in angle control mode

Fig 17 shows the dynamic behavior of the machine with change in speed from 1000 to 2000 rpm whereas Fig. 18 shows the change in load torque at 900 rpm. It can be inferred from the figures that experimented results closely follow the simulated results. The mean value of torque, speed and the rms phase currents varies negligibly for simulation and experiment both. The experimental loading conditions are made to closely match with the simulated loading conditions. It can be observed that the actual speed closely follows the reference speed. The response time is less and it settles to the reference speed very fast. Also, the experimental response time closely follows the simulated response time during dynamics.

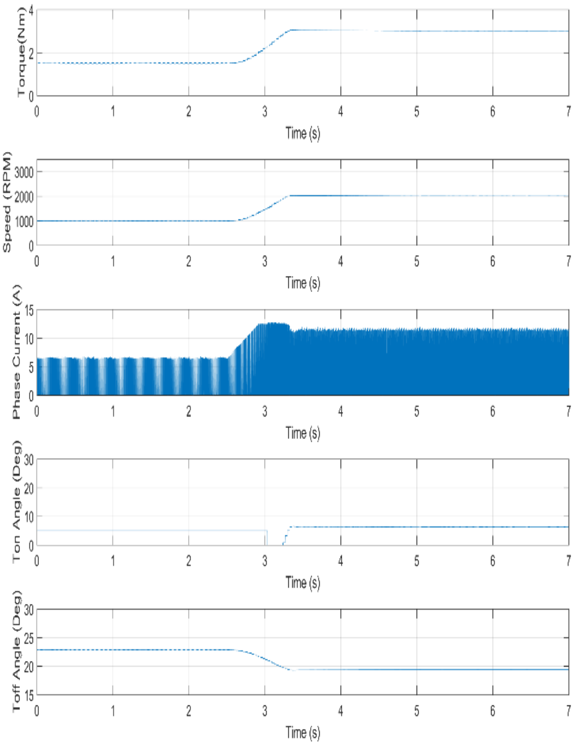

Fig. 17. Dynamic performance of machine showing Torque, Speed, Phase Current, T_{on}, T_{off} for change in speed from 1000 rpm to 2000 rpm

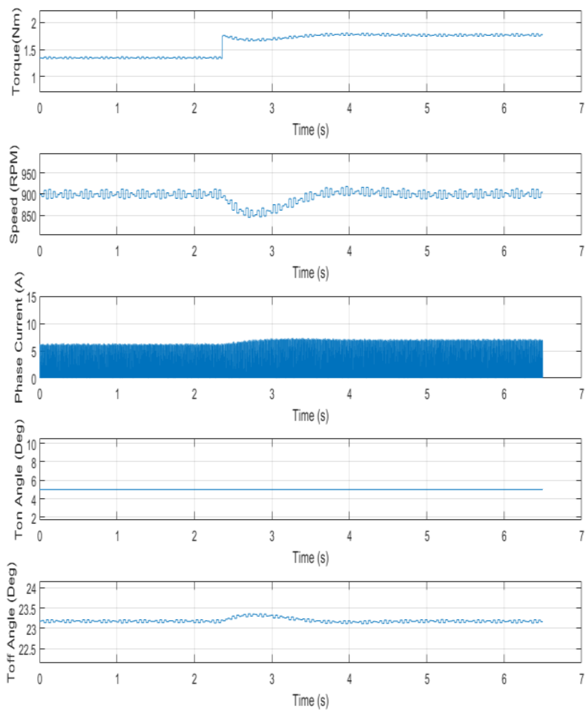

Fig. 18. Dynamic performance of machine showing Torque, Speed, Phase Current, T_{on}, T_{off} for change in load torque at 900 rpm

6. Conlusion

A simple control strategy for operation of SRM in entire speed range is proposed. It uses one PI controller to generate I_{ref} in current control and another PI control for generating T_{on} angle in angle control. T_{off} angle is varied as a function of speed in both current and angle control using a simplified equation. This proposed control is less complex, easily implementable and reduces the computation time as compared to conventional look-up table approach. Simulation results are provided and the same is validated using experimental results with a FPGA based controller. It can be inferred that using this simple control technique avoids jitter at the boundary speeds between current and angle control and a satisfactory performance of machine is observed during dynamics and steady-state conditions.

References

[1] Miller, T.J.E., (*Switched Reluctance Motor and Their Controls*), Magna Physics Publishing And Clarendon Press Oxford, 1993.

[2] Krishnan, R., (*Switched Reluctance Motor Drives, Modeling, Simulation, Analysis, Design and Applications*), CRC Press, 2001.

[3] Boldea I., (*Variable Speed Generators*), CRC Press,Taylor and Francis Group, Boca Raton, FL. 2006.

[4] Wang Shun-Chung and Lan Wen-Han (*Turn-On Angle Searching Strategy for Optimized Effeciency Drive of Switched ReluctanceMotors*) In: Proceedings of The 313th Annual Conference of the IEEE Industrial Electronics Society, November 2004, Busan, Korea.

[5] Hannoun, H., Hilairet, M., and Marchand, C., (*High Performance Current Control of a Switched Reluctance Machine based on a Gain-Scheduling PI Controller*) Control Eng. Practice, 2011, Vol. 19, No. 11, pp. 1377–1386.

[6] Venkatesha, L., (*Determination of Flux-linkage Characteristics and Torque Ripple Minimization with Pre-computed Currents in Switched Reluctance Motor)* PhD Thesis, 1999, IISc, Bangalore, India.

[7] Panda, D.B., (*Control Strategies Sensorless and Low Noise Operation of Switched Reluctance motor*) PhD Thesis, 1999, IISc, Bangalore, India.

[8] Husain I., Hossain Syed A., (*Modeling, Simulation, and Control of Switched Reluctance Motor Drives*), IEEE Transactions on Industrial Electronics, Dec. 2005, Vol. 52, NO. 6.

[9] Singh Bhim, Sharma Virendra Kumar, Murthy S.S., (*Dynamic Control of Switched Reluctance Motor using PID Speed Controller*),In: Proceedings of NPSC 1988, pp88.

[10] Wadnekar V., TulasiRam Das G., Rajkumar A.D.. (*Performance Analysis of Switched Reluctance Motor; Design, Modeling and Simulation of 8/6 Switched Reluctance motor)*, Journal of Theoritical Applied Information Technology, Nov. 2008, Vol.4 No.11.

[11] Maged N. F. Nashed, (*Variable Angle Adjustable-High Speed Control with PI for SRM)*, World Automation Congress , Dec 2010.

[12] Khaldoon Asghar, (*Analysis of Switched Reluctance Motor Drives for Reduced Torque Ripple using FPGA based Simulation Technique),* American Journal of Information Sciences, 2013,Vol.6 No.2

[13] Saravanan, P., Arumugam, R. and Kumaran, M.S. (2016) (*FPGA Based Speed Control of SRM with Optimized Switching Angles by Self Tuning*), Circuits and Systems, 2016, 7, pp. 1530-1545,. http://dx.doi.org/10.4236/cs.2016.78134

[14] Rajdeep Banerjee, Mainak Sengupta, Suvarun Dalapati, (*Design and Implementation of Current Mode Control in a Switched Reluctance Motor*), 2014 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), February 2015,Issue 16.

[15] Ahmad S. S., and Narayanan, G.,(*Linearized Modeling of Switched Reluctance Motor for Closed-Loop Current Control*) IEEE Transactions on Industry Applications, July-Aug,2016, Vol. 52.

[16] Ivanov, A.S., Nusratov P. R., (*Direct torque control of the switched-reluctance motor drives)* In: proceedings of 2017 IEEE Dynamics of Systems, Mechanisms and Machines Dynamics, 2017, Omsk, Russia.

[17] Sah Gyanendra Kumar, Jagwani Shefali, Venkatesha L., (*A New Simplified Control Strategy for Switched Reluctance Motor)*, In: Proceedings of IEEE conference on Recent Developments in Control and Automation Engineering (RDCAPE), 2017,Noida, India.