International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-9 Issue-2, December 2019

FPGA Implementation for Speed Controlling of 8/6 Switched Reluctance Motor using PI Controller

Hadapad Basavaraju, Naik R. L.

Abstract: This paper presents the field programmable gate array (FPGA) implementation for the speed controlling of 8/6 switched reluctance motor (SRM) using conventional proportional integral (PI) controller. PI controller is tuned by trial and error method such that the actual speed of motor follows reference speed under different loading conditions. The main focus of the paper is to construct and implement the commutation table for consecutive excitation of the successive phases of SRM. In order to implement it, an inductance profile of SRM is stored into the ROM indicating the direction of the rotor. Four hall sensors are used to obtain the pulses from the respective phases and compared with inductance profile to excite the appropriate phases. The entire algorithm is modeled using Xilinx tool box and wavect controller to integrate SRM with asymmetric converter. The developed Xilinx model is validated for load and no-load condition and the experimental results are presented.

Keywords: FPGA, PI Controller, Switched Reluctance Motor, Xilinx

I. INTRODUCTION

Recently, adoption of SRM in industries is growing due to its advantages over conventional motors such as simple and rugged construction, capable of high speed operation, comparatively smaller in size, fault tolerant operation, high starting torque and economical. The quantity and quality of products in industries depends on variable speed output of the motor. Therefore, effective speed control is of great importance.

A simple adoptive speed control technique is presented and implemented with conventional PID controller for 12/8 SRM using digital signal processor (TMS320F2812) [1]. Speed of the SRM was controlled by controlling its phase currents through PWM control scheme. This strategy using DSP showed that, it is highly reliable and efficient drive without considering the delay of digital control system. However, the conventional PID controller in the speed loop causes small oscillations in the steady state due to the position sensor error.

Revised Manuscript Received on December 30, 2019.
* Correspondence Author

Hadapad Basavaraju*, Research Scholar, Electrical and Electronics department, Basaveshwar Engineering College (Autonomous), Bagalkot, Karnataka, India. Email: basavarajuhadapad@yahoo.in

Naik R. L, Associate Professor, Electrical and Electronics department, Basaveshwar Engineering College (Autonomous), Bagalkot, Karnataka, India. Email: r_l_naik@yahoo.co.in

An intelligent controller is designed to control the speed and current of 7.5 KW, 4 phase, 8/6 SRM based on powerful digital signal processor (TMS320F240), which has the potential to perform distinct real time applications [2]. By employing DSP, the proposed controller regulates the speed and current of SRM at various loading conditions by considering present status of current and speed of the motor.Various sped controlling schemes like current chopping control or voltage chopping control for low speed and angular position control for high speed 3 phase, 6/4 pole SRM based on STM32 micro controller was described [3]. Further, a PI controller was added to enhance the reliability, dynamic behavior and steady state response of SRM. Designing PWM current and speed controller for 3 phase, 2 kw, 12/8 pole SRM using ac small signal modeling technique was depicted in [4]. PI controller is designed and applied in the current and speed loop to enhance the effectiveness of the current and speed control of SRM. Further, a control algorithm is developed in assembly language of digital signal processor- TMS320F288335 to integrate SRM with power converter. The current and speed control of the SRM based on 16 bit micro controller dsPIC30F6010 is illustrated in [5]. In order to obtain stable output, appropriate control techniques such as chopped current control, chopped voltage control and angle position control is preferred based on inner current and outer speed loop of motor by employing said microcontroller. Another speed control approach for SRM using FPGA processor is presented in [6]. Firstly, the control system was simulated using LabView FPGA and validated same with hardware implementation through Kintex-7 FPGA processor chip. FPGA processors have some advantages over conventional processors like reduced cost, capability of parallel operation, contains 32-bit RISC microprocessor cores and hardwired DSP units for fast computation etc. [7].

Various static characteristics such as torque-current-rotor position and flux linkage- current-rotor position are required in developing the speed control strategies for SRM. Conventional methods employ popular technique like finite element method to determine motor characteristics [8]. However, it increases the complexity in designing speed control strategies. Therefore, a simple speed control approach is required without much complexity.

In this connection, a simple speed control strategy is realized in the paper through FPGA based PI controller and is validated by experimental set up at both load and no-load condition.

In the proposed method, the control algorithm is developed using Xilinx toolbox and is implemented using FPGA based WAVECT controller.

II. SWITCHED RELUCTANCE MOTOR

SRM is a doubly salient and singly excited machine. Both stator and rotor have salient poles however windings are wounded only on stator poles whereas rotor poles does not have any windings. In this paper 4 phase, 8/6 poles SRM (which means stator has 8 salient poles and rotor has 6 salient poles) is considered for study. To avoid magnetic locking and provide sufficient torque, stator poles are more in number than rotor poles. It is as shown in Fig-1. Stator windings needs to be excited sequentially to provide torque for the continuous rotation of rotor with respect to stator.

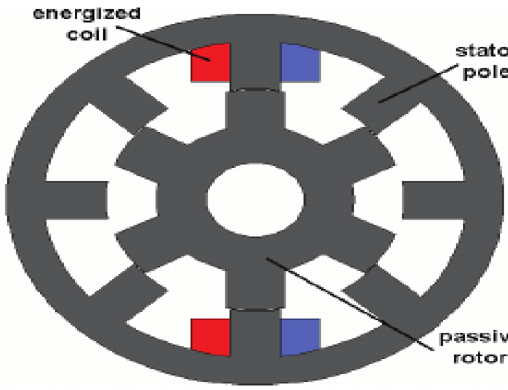

Fig. 1.Stator and Rotor part of SRM

The SRM works on the principle of reluctance torque. The electromagnetic torque equation of SRM is obtained as below [9].

The per phase voltage of stator of the SRM is given by,

$$V = IR + \frac{d\varphi}{dt} \quad (1)$$

Where, IR is the voltage drop in stator phase windings and Ψ is the flux linkage.

As both stator and rotor have salient poles, hence flux linked with SRM phase changes as a function of motor phase current and rotor position angle. Hence, equation (1) can be further written as,

$$V = IR + \frac{\partial\varphi}{\partial I}\cdot\frac{dI}{dt} + \frac{\partial\varphi}{\partial\theta}\cdot\frac{d\theta}{dt} \quad (2)$$

The torque of any phase A is given by equation (3),

$$T_A = \frac{1}{2} I_A^2 \frac{dL_A(\theta, I)}{d\theta} \quad (3)$$

Thus, total torque of 4 phase SRM is given by algebraic sum of torques developed by the individual 4 phases of the motor.

$$T_{total} = T_A + T_B + T_C + T_D$$

III. FPGA IMPLEMENTATION FOR SPEED CONTROLLING OF SRM

Microcontrollers and digital signal processors are the conventional methods employed for the implementation of speed control strategies of SRM drives [1-5]. However, the conventional methods often suffer from the limitations such as limited sampling time, precise number of execution and high development cost. In order to overcome the limitations due to conventional method, a Field Programmable Gate Array (FPGA) is adopted.

The block diagram of FPGA implementation for speed controlling of SRM drive is as shown in Fig-2. It consists of hall sensors to find the rotor position with respect to stator poles, commutation table for the sequential excitation of phases, PI controller for producing duty cycles and PWM generator to generate required PWM signals to the asymmetric bridge converter.

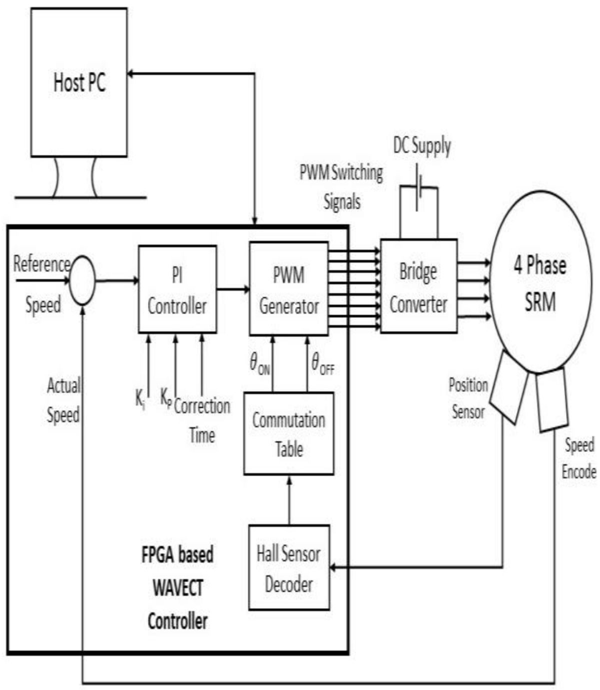

Fig. 2.FPGA based Implementation for Speed Controlling of SRM

A. Commutation Table:

The commutation table is obtained based on output of Hall sensors. In the proposed work, four hall sensors have been used as position sensors to determine the position of rotor with respect to stator. Table-I gives all possible position of Hall sensors for rotor and its concated output is expressed in terms of decimal values.

Table- I: All possible position of Hall Sensors

Ha	Hb	Hc	Hd	Concated output in Decimal values
1	0	0	1	9
1	0	0	0	8
1	1	0	0	12
0	1	0	0	4
0	1	1	0	6
0	0	1	0	2
0	0	1	1	3
0	0	0	1	1

For the sequential excitation of stator phases, their inductance values are essetial.

Hence, stator phase inductances are measured using LCR meter and values are recorded in Table-II. These inductance profiles are stored in memory element or ROM. The ideal inductance profile of the SRM is as shown in Fig-3.

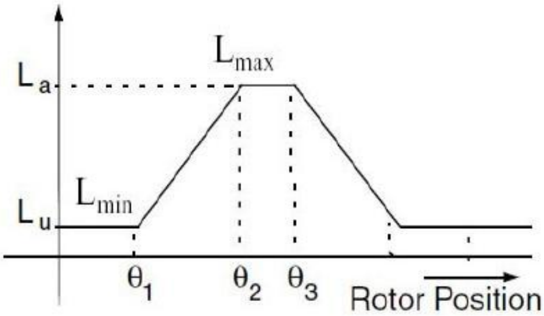

Fig. 3.Ideal inductance profile of any stator phase

Now stator phases are excited at increasing inductance values. During this period, rotor pole pair will be pulled by the nearest stator phase. Once the rotor aligned completely with stator phase, its inductance value will be maximum and hence respective stator phase is turned off. Then, next immediate stator phase is excited and pulls its nearest rotor pole pair. This process repeats and hence rotor makes continuous rotation. This algorithm for the sequential excitation of successive stator phases is designed based on commutation table, as shown in Table-III.

Table- II: Measured phase inductance values

Hall Sensor position	R	Y	B	G
1	13.2 2	11.3 4	3.92	6.71
9	13.7	10.4	4.14	7.96
8	11.5 1	4.31	6	10.9 9
8	11.5 1	4.31	6	12.2 2
12	4.21	6.47	7.28	12.7 9
4	3.98	7.69	12.1 6	10.3 4
4	3.98	7.69	12.1 6	10.3 4
6	3.83	9.01	12.6	9.54
6	3.97	12.7 7	11.3 4	9.54
2	4.55	13.6 8	10.3 8	4.02
3	7.8	14.2 6	9.47	3.79
3	12.3 2	12.4 5	4.24	5.45
1	12.6 5	11.4 2	3.85	7.11

Table- III: Commutation table

Hall Sensor position	R	Y	B	G
1	13.2 2	11.3 4	3.92	6.71
9	13.7	10.4	4.14	7.96
8	11.5 1	4.31	6	10.9 9
8	11.5 1	4.31	6	12.2 2
12	4.21	6.47	7.28	12.7 9
4	3.98	7.69	12.1 6	10.3 4
4	3.98	7.69	12.1 6	10.3 4
6	3.83	9.01	12.6	9.54
6	3.97	12.7 7	11.3 4	9.54
2	4.55	13.6 8	10.3 8	4.02
3	7.8	14.2 6	9.47	3.79
3	12.3 2	12.4 5	4.24	5.45
1	12.6 5	11.4 2	3.85	7.11

It depicts the sequential excitation SRM phases. The slice of 1st bit represents excitation of R-phase, slice of 2nd bit represents Y-phase excitation, slice of 3rd bit represents B-phase excitation and slice of 4th bit represents G-phase excitation based on Lower bit Location. The implementation of commutation table using FPGA controller is as shown in Fig-4.

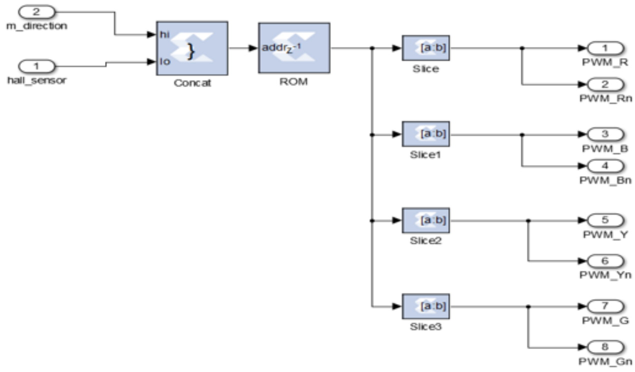

Fig. 4.mplementation of commutation table using FPGA

B. PI Controller:

PI controller is the combination of P controller and I controller. The output of the PI controller must be proportional to the error signal and integral of error signal. It is given in equation (4) [10].

$$u(t)\ \alpha\ e(t) + \int e(t)\, dt$$

(4)

$$u(t) = K_P\, e(t) + K_I \int e(t)\, dt$$

where, u(t) is the output of controller,

e(t) is the error signal,

$\int e\ (t)$ is the integral of error signal and

K_p and K_i are the proportionality constants known as proportional gain and integral gain respectively.

The values of K_p and K_i are tuned by trial and error method to maintain the rated speed under different loading conditions. For the proposed study, tuned values of K_p and K_i are 16 and 6400 respectively. The PI controller generates the duty cycles to the PWM generator. The FPGA based implementation of PI controller is as shown in Fig-5.

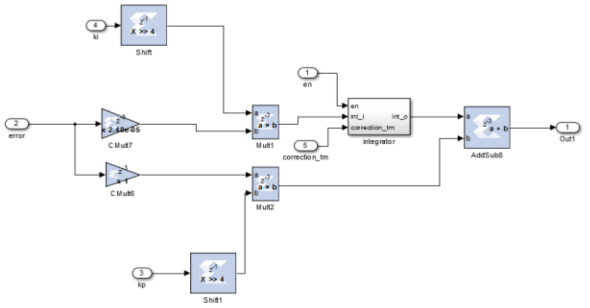

Fig. 5.Implementation of PI Controller using FPGA

C. PWM Generator:

It compares the duty ratio of PI Controller with the reference signal and provides the necessary PWM switching signals to the bridge converter for sequential excitation of stator phases.

IV. EXPERIMENTAL SET UP

The experimental test bench for speed controlling of SRM is as shown in Fig-6. It consist of 8/6 SRM powered through asymmetric half bridge converter. A customized FPGA based WAVECT controller is employed to integrate SRM with bridge converter.

Fig. 6.Experimental test bench for Speed Controlling of 8/6 SRM

The detailed specifications of the SRM employed in the experiment is as mentioned in Table-IV.

Table- IV: Specifications of SRM

Sl No.	Parameter	Rating
1	Type	8/6
2	Speed	3000 RPM
3	KW	2.2
4	Voltage	230 V DC
5	Current	11 A

The entire control algorithm is developed using Xilinx software toolbox. Xilinx develops extremely adjustable processing platform that facilitate accelerated innovation across a various technologies. Xilinx is the innovator of FPGA, hardware programmable System on a Chip (SoCs) to provide the most dynamic processor technology in industry [10].

FPGA is considered as a powerful processor as it comprise millions of logic blocks, huge interconnected network, effective parallel operation and contains 32-bit microprocessor cores with memory blocks and hardwired DSP units [11]. The experimental test bench consists of FPGA based WAVECT controller. It is a compact, versatile, real time control prototyping system consists of FPGA, dual core processor, voltage and current sensors, large number of PWM outputs. It integrates hardware with software [12].

When half bridge asymmetric converter is connected to 150 V DC supply, it excites the SRM stator phases sequentially by means of PWM signals provided by signal generator located in FPGA based WAVECT controller. PWM signals determines the turning ON/OFF of successive phases sequentially.

As stator phases excited sequentially, current flows into phases one after the other. This sequential flow of stator phase current is as shown in Fig-7 and Fig-8 illustrates the stator phase voltages.

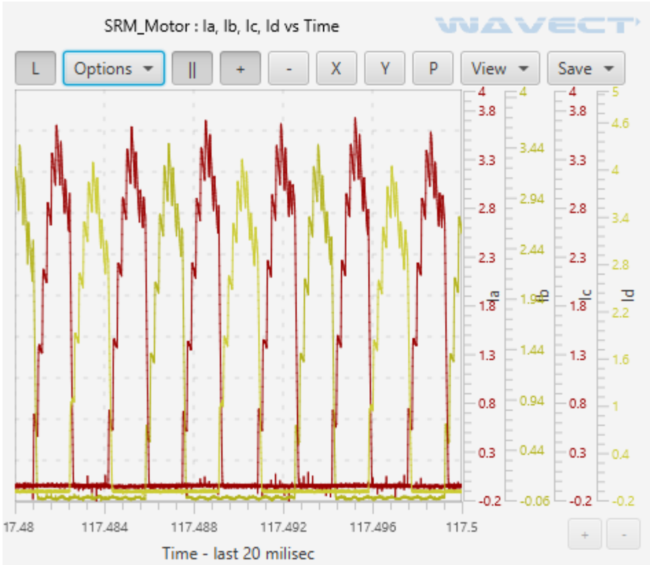

Fig. 7. Stator **Phase** Currents

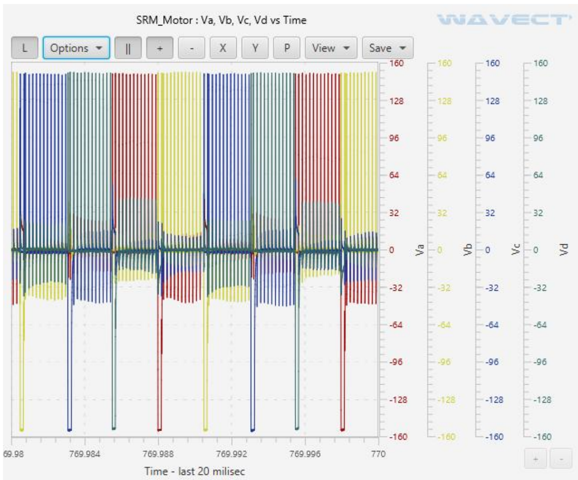

Fig. 8.Stator Phase Voltages

For any rotor pole to be in continuous operation, its nearest stator pole needs to be excited. In this case, Hall sensors plays a major role in providing position of rotor with respect to stator and hence appropriate stator pole can be excited. The sequential excitation of stator poles is depicted in Fig-9.

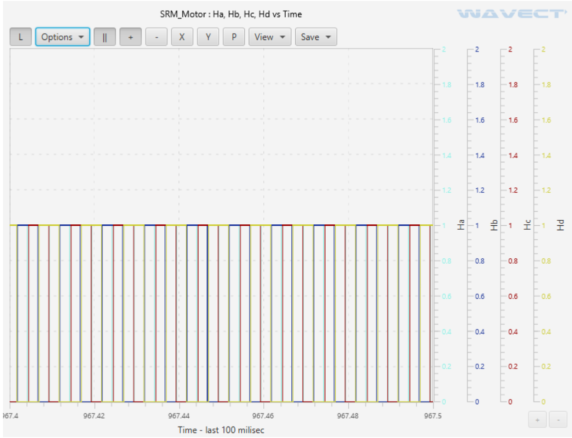

Fig. 9.Sequential excitation of stator phases

V. RESULTS AND DISCUSSIONS

In the proposed system, a conventional PI controller is employed in speed controlling of 8/6 SRM based on FPGA implementation. The controller gains such as K_P and K_i values are properly tuned by trial and error method to maintain the rated speed under different loading condition. In the proposed system, K_P and K_i values are taken as 16 and 6400 respectively. Initially, PI controller was validated by running the motor under no-load condition at various reference speeds. It is as shown in Fig-10. In the beginning, the reference speed was set at 1000 rpm, later it is changed in terms of 1200 rpm, 1500 rpm, 2000 rpm and 2500 rpm. Actual speed of the motor quickly attains the reference speed and almost zero steady state error was spotted in result.

PI controller again validated by applying load in steps. The reference speed was set at 1000 rpm and motor was loaded in terms 1.1 kg, 2 kg and 3 kg.

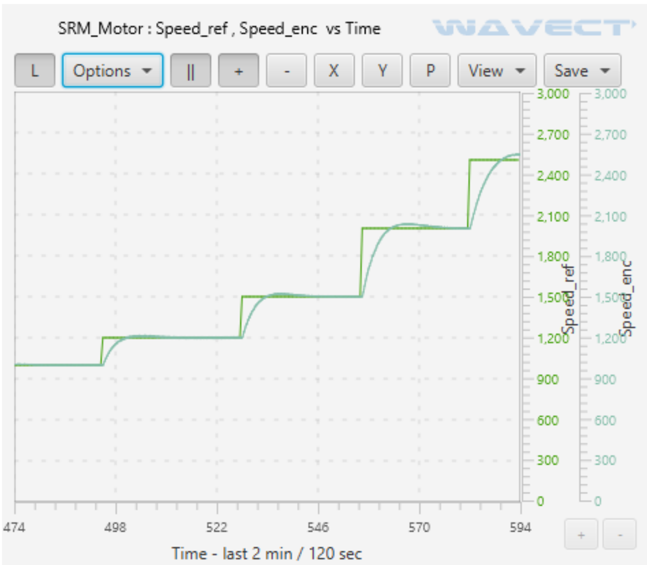

Fig. 10. Speed variation at no-load

It is observed that when load is applied, speed of the motor drops. However, PI controller brings speed back to reference speed quickly. Similarly, when load is removed speed increases beyond reference value for a short period of time and finally reaches reference value. It is as shown in Fig-11.

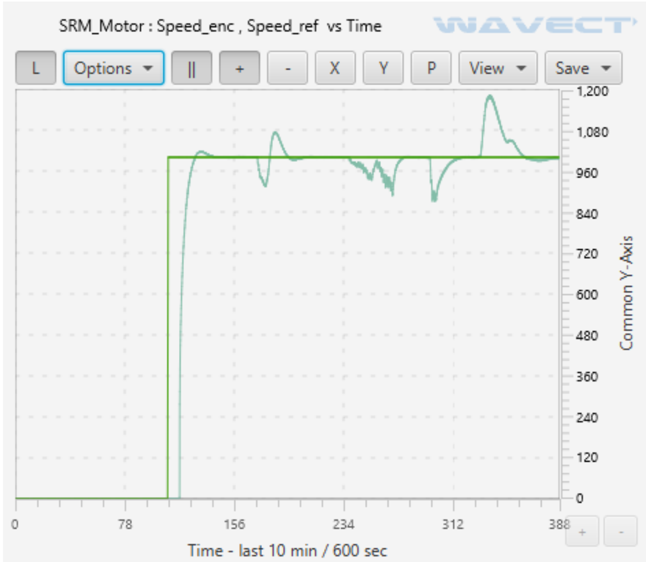

Fig. 11. Speed variation at different loading condition

VI. CONCLUSION

FPGA implementation for speed controlling of 8/6 SRM using conventional PI controller is presented in this paper. Controller gains are tuned by trial and error method to make actual speed to follow reference speed quickly. In the proposed work, a commutation table is constructed using inductance profile of stator phases and is implemented through FPGA for the sequential excitation of the stator phases continuously. The experiment is conducted in the laboratory at both load and no-load condition and results are recorded. It is observed from results that, change in actual speed of the motor with reference speed is instantaneous irrespective of loading conditions. Therefore, speed can be easily controlled by employing proposed strategy at various load levels compared to conventional methods.

REFERENCES

1. L. L. N. Dos Reis, F. Sobreira, A. R. R. Coelhoa, O. M. Almeida, J. C. T. Campos, and S. Daher, “Identification and adaptive speed control for switched reluctance motor using DSP,” 2009 Brazilian Power Electron. Conf. COBEP2009, pp. 836–841, 2009.
2. J. L. Yang, R. C. Han, and Y. J. Zhang, “Design the controller of switched reluctance motor based on DSP,” Proc. - 1st Int. Conf. Robot. Vis. Signal Process. RVSP 2011, vol. 2, pp. 182–185, 2011.
3. Y. Xu and Y. Zhang, “The design of controller for SRM based on STM32,” Proc. 2019 IEEE 3rd Inf. Technol. Networking, Electron. Autom. Control Conf. ITNEC 2019, no. Itnec, pp. 1692–1696, 2019.
4. Q. Ma, A. El-Refaie, and J. S. Lai, “Small-Signal Modeling and Speed Controller Design for Switched Reluctance Motor Drives,” 2018 IEEE Energy Convers. Congr. Expo. ECCE 2018, pp. 4497–4504, 2018.
5. Z. Yang, Y. Huo, and X. Wang, “DsPIC30F6010A for 12 / 8 Switched Reluctance Motor,” pp. 296–300.
6. H. Nagy, M. Ruba, H. Hedesiu, and C. Martis, “Rapid control prototyping of a speed control strategy for a switched reluctance machine,” Proc. 2016 Int. Conf. Expo. Electr. Power Eng. EPE 2016, no. Epe, pp. 664–668, 2016.
7. H. Nagy, M. Ruba, H. Hedesiu, and C. Martis, “FPGA based real-Time simulation of a Switched Reluctance machine drive unit,” 2016 20th IEEE Int. Conf. Autom. Qual. Testing, Robot. AQTR 2016 - Proc., 2016.

8. T. Jahan, M. B. B. Sharifian, and M. R. Feyzi, "Static characteristics of switched reluctance motor 6/4 by finite element analysis," Aust. J. Basic Appl. Sci., vol. 5, no. 9, pp. 1403–1411, 2011.
9. T. J. E. Miller, "Switched Reluctance Motors and Their Control," Monogr. Electr. Electron. Eng., vol. 31, no. 1, p. 216, 1993.
10. "index @ www.xilinx.com." .
11. E. Monmasson, I. Bahri, L. Idkhajine, A. Maalouf, and W. M. Naouar, "Recent advancements in FPGA-based controllers for AC drives applications," Proc. Int. Conf. Optim. Electr. Electron. Equipment, OPTIM, vol. 33, no. 0, pp. 8–15, 2012.
12. "index @ www.entuple.com." .

AUTHORS PROFILE

Mr. Hadapad Basavaraju was born in Vijayapura district, Karnataka, India on 29th November 1991. He has obtained B.E. degree from Shridevi Institute of Engineering and Technology, Tumkur in 2013 and M.Tech degree (Power and Energy System) from Basaveshwar Engineering College (Autonomous), Bagalkot in 2015. Then he worked as an Assistant Professor at Tontadarya College of Engineering, Gadag for four years. Currently, he is a research scholar at Basaveshwar Engineering College (Autonomous), Bagalkot, Karnataka, India. His main research interests are power electronics and drives.

Dr. Naik R. L. was born in Vijayapura, Karnataka, India on 1st July 1974. He obtained B.E. degree (Electrical and Electronics) from Basaveshwar Engineering College, Bagalkot under Karnataka University, Dharwad, India, in the year 1996 and M.Tech (Power and Energy Systems) from NITK, Suratkal Karnataka, India in 2005. He obtained his Ph.D from VTU Belagavi in the year 2015. He is presently working as Associate Professor in the department of E&EE, Basaveshwar Engineering College (Autonomous), Bagalkot. His main research interests are Power electronics, Drives and Renewable energy sources. He is a member of IEEE; he is co- principal investigator for RPS (Research Promotion Scheme), AICTE project.

.