International Journal of Reconfigurable and Embedded Systems (IJRES)
Vol. 4, No. 1, March 2015, pp. 42~54
ISSN: 2089-4864 ❒ 42

Implementation of PI Controller for 3ф BLDCM Drive Using FPGA

S.M. Ramesh Balaji*, C. Muniraj*
*Electrical Drives and Control Laboratary, Department of Electrical and Electronics Engineering, K.S. Rangasamy College of Technology, India

Article Info

Article history:

Received Sep 2, 2014
Revised Jan 27, 2015
Accepted Feb 10, 2015

Keyword:

Brushless DC (BLDC)
Motor drive
Converters
Field-programmable gate arrays
Pulse width modulation

ABSTRACT

Despite the need of a complex motor controller, the simple construction of BLDC motors offers several inherent advantages not provided with brushed DC motors in terms of low inertia, high torque and a very wide speed range. The BLDC motors include, Longer service life due to a lack of electrical and friction losses and also free maintenance due to a lack of brushes and mechanical commutators. The EMI and noise are reduced because of the elimination of ionizing spikes from brushes. The control system of BLDCM is highly complex drive due to nonlinear nature. In such a system for implementing control algorithm needs high speed processor. In this work the controller Xilinx Spartan-6 FPGA is a demonstration platform intended to become familiar with the new features and availability of the Spartan-6 FPGA. The various experimental tests are carried out in 3Φ BLDCM .The experimental results are reported in order to verify the steady state, transient and robustness performance of the controller.

Corresponding Author:

S.M. Ramesh Balaji,
Department of Electrical and Electronics Engineering,
K.S. Rangasamy College of Technology, K.S.R. Kalvi Nagar, Tiruchengode, Namakkal – 637215
Email: rameshbalaji13@gmail.com

1. INTRODUCTION

Environments and requirements in which manufacturers use brushless-type DC motors include low maintenance operation, higher speed, and no sparking operation. When converting electricity into mechanical power, brushless motors are more efficiency than brushed motors. Brushless DC motor (BLDC) is a brushless motor because there are no brushes and commutator. In BLDC Motor the commutation is act with the help of electronic circuits, which decreases the mechanic losses and improves the efficiency. A Brushless DC motor has a rotor with permanent magnets and a stator with windings. BLDC motors have long been used in industrial applications such as actuators, CNC machines, industrial robots, extruder drives, among others. Small cooling fans in electronic equipment are powered exclusively by brushless motors. Low speed, low power brushless motors are used in direct-drive turntables for gramophone records. Therefore, BLDC motors may be used in fans, washing machines, high-end pumps, and in other appliances which require high reliability and efficiency.

The controller must direct the rotor rotation; the controller requires some means of determining the rotor's orientation/position (relative to the stator coils). Several designs use Hall Effect sensors or a rotary encoder to directly measure the rotor's position. A typical controller contains 3 bi-directional outputs (i.e. frequency controlled three phase output), which are controlled by a logic circuits. Different methods are accessible for control the speed of BLDC motor, like Pulse Width Modulation (PWM), DC link variable voltage. The BLDC motor control based on rotor position sensing scheme and phase currents that the modified PWM signals to reduce the current and hence resulting lower torque ripples in [4]. In [1], BLDCM drive trapezoidal signal has been implemented by Simple digital PWM control and FPGA is used to verification of experimental results. Due to the simple control it has been implemented specific low cost application. Under varies condition of load disturbance, reduction in processor capability, potential stability issues due to the simplicity of this control to be investigated. The closed loop system of stability to be analyzed by using Lyapunov stability criteria [9]. To implemented current and position controllers in a single FPGA chip in this system to develop a flexible, configurable, compact and high-performance of BLDCM control system [13].

In this work the PI controller is used for control the speed of the motor. The control algorithm have been developed and tested by FPGA processor. The experimental analysis is performed to test the controller with respect to steady state, transient. The robustness of the controller also tested by varying the load torque. This paper organized as follows, brief about BLDCM and converter in section 2. The implementation of FPGA processor discussed in section 3. Section 4 discusses the control structure of BLDCM. Section 5 discusses the experimental setup. Experimental results discussed in section 6 and concluding the remarks in section 7.

2. BLDC MOTOR DRIVE

Brushless DC motor (BLDC) is a brushless motor because there are no brushes and commutator. In BLDC Motor the commutation is act with the help of electronic circuit, which decreases the mechanic losses and improves the efficiency. A Brushless DC motor has a rotor with permanent magnets and a stator with windings. In the 1970s, a magnet sensing diode, whose sensitivity is almost thousands of times greater than that of the Hall element, was used successfully for the control of BLDC motor. Presently the electrical and electronics industry was developing, a large number of high-performance power semiconductors and permanent magnet materials like samarium cobalt and Neodymium-Iron-Boron (NdFeB) emerged, which conventionally a solid ground for widespread use of BLDC motors. The closed loop control of BLDCM is shown in Figure 1.

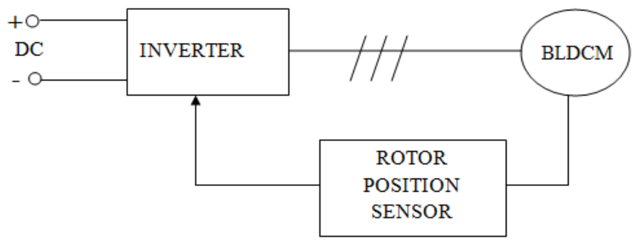

Figure 1. Basic Block Diagram of BLDC Motor

A BLDC has several advantages over other machines types. BLDCM is a potentially cleaner, more efficient, less noise, faster and more reliable. Most especially they require lower maintenance due to the elimination of the mechanical commutator. It also has high power density. The specification of the BLDC Motor is shown in the Table 1.

Table 1. BLDC Motor Specifications

Type	Trapezoidal Motor
Motor Power Rating	1 HP
Voltage	310V DC
No. of Poles	4.00
Continuous Stall Current	4.52 A
Continuous Stall Torque	2.20Nm
Voltage constant (Ke)	5volts
Torque constant (Kt)	0.49Nm
Max. speed	4600 rpm
Moment of inertia (Jm)	1.8/1.4kg cm2
Phase / Phase Resistance ±10% at 25°C	3.07 ohm
Phase / Phase inductance	6.57Mh
Electrical time constant	2.14 ms

2.1. Intelligent Power Module (IPM)

IPM based power module work as DC-DC Converter (Chopper) or DC-AC Converter (Inverter). It works using an IGBT based IPM and works on basis of software from SPARTAN-6 Processor. The power module can be used for studying the operation of chopper, three phase inverter, single phase inverter and speed control of three phase induction motor, single phase induction motor. Intelligent Power Modules (IPMs) are advanced hybrid power devices that combine higher speed, lower loss IGBTs with optimized gate drive and protection circuitry. Highly effective short-circuit and over-current protection is realized through the use of advanced current sense IGBT chips that allow continuous monitoring of power device current. IPM has been optimized for minimum switching losses in order to meet industry demands for acoustically noiseless inverters with carrier frequencies up to 20 KHz.

2.2. Power Converter

The Voltage Source Inverter (VSI) is used to create single or polyphase AC voltages from a DC supply. It consists of IGBT switches and diodes. If single-phase VSIs, the switches of any leg of the inverter (SW1 and SW4, SW3 and SW6, or SW5 and SW2) cannot be switched on simultaneously because this would result in a short circuit across the dc link voltage supply. The standard three-phase VSI topology is shown in Figure 2.

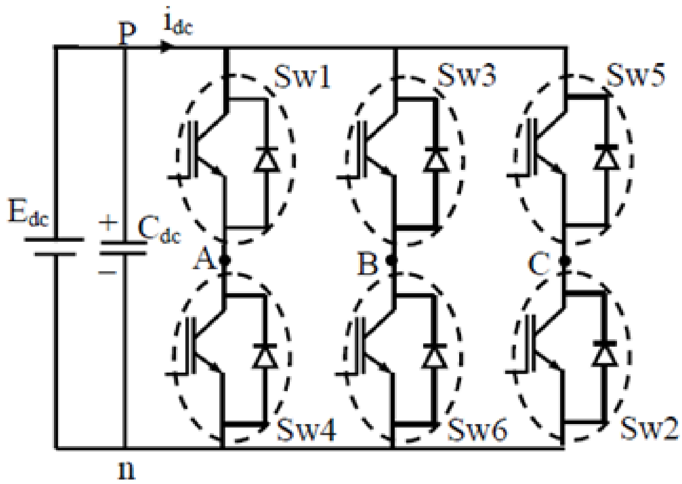

Figure 2. 3ΦPhaseVoltage Source Inverter Circuit

Similarly, in order to avoid indeterminate states in the VSI, and thus indeterminate ac output line voltages, the switches of any leg of the inverter cannot be switch off simultaneously as this will result in voltages that will depend upon the respective line current polarity. In this case, the ac line currents freewheel through either the upper or lower components.

3. SPARTAN-6 FPGA PROCESSOR

The Xilinx Spartan-6 FPGA processor is a demonstration platform intended for you to become familiar with the new features and availability of the Spartan-6 FPGA family. The Spartan-6 family provides leading system integration capabilities with the lowest total cost for high-volume applications. Built on a mature 45 nm low-power copper process technology that delivers the optimal, power, balance of cost and performance, the Spartan-6 family offers a new, more efficient, dual-register 6-input lookup table (LUT) logic and a rich selection of built-in system-level blocks.

The architecture of Xilinx Spartan-6 FPGA processor is shown in Figure 3. These features provide a low cost programmable alternative to custom ASIC products with unprecedented easy to use. Spartan-6 FPGAs offer the best solution for high-volume logic designs, cost-sensitive embedded applications, consumer-oriented DSP designs. Spartan-6 FPGAs are the programmable silicon foundation for Targeted Design Platforms that deliver integrated software and hardware components that enable designers to focus on innovation as soon as their development cycle begins.

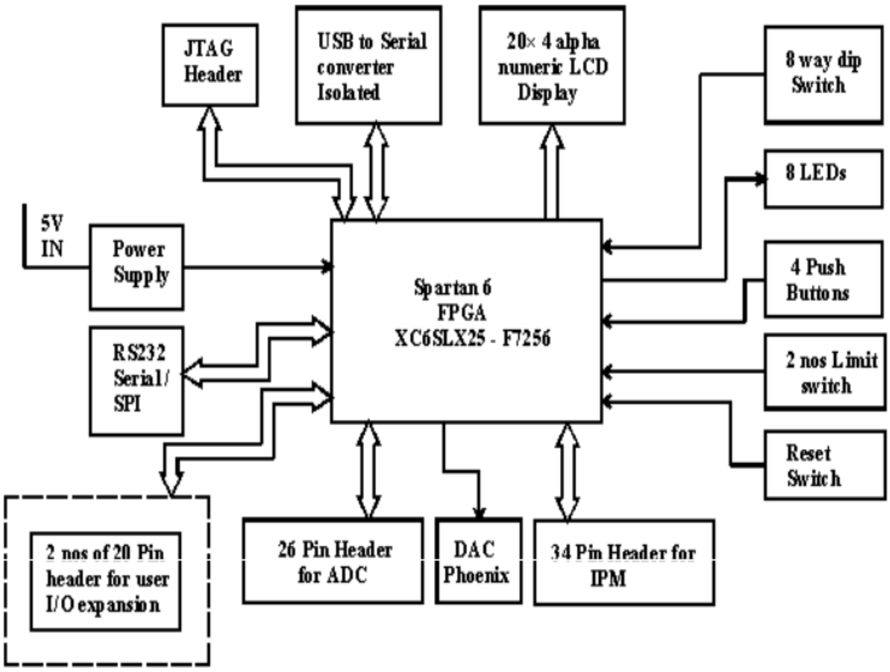

Figure 3. Architecture of Xilinx Spartan-6 FPGA Processor

4. BLDC MOTOR CONTROL STRUCTURE

The amplitude of the applied voltage is adjusted by using the PWM techniques. The required speed is controlled by a speed controller. The speed control is implemented as a conventional PI controller. The difference between the actual and reference speed is input to the PI controller based on this difference, the PI controller controls the duty cycle of PWM pulses fed to the variable DC link 3Φ inverter, which corresponds to the voltage amplitude required to keep the required speed. The control structure of BLDC motor is shown in Figure 4.

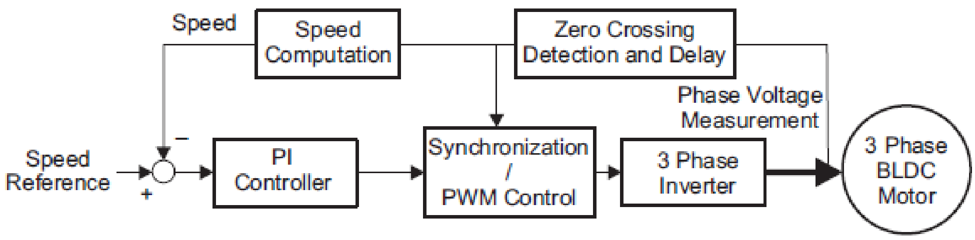

Figure 4. BLDCM PI control structure

4.1. Design of Speed Controller

The reference speed (ω*) is compared to the speed signal (ω) to produce a speed error signal (e). Then I* is achieved by integral gain (KI), proportional gain (Kp) and speed error(e). The PI based speed controller is shown in Figure 5.

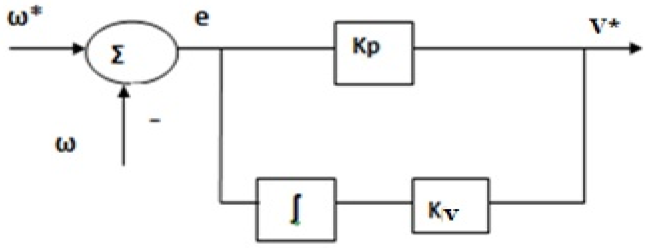

Figure 5. PI Based Speed Controller

Where,

Kv : Integral gain
Kp : Proportional gain
e: Error

$$e = \omega^* - \omega \tag{1}$$

The proportional and integral terms is given by

$$V^* = ek_p + \int ek_v \tag{2}$$

4.2 PWM Control Strategy

In this system have been used Pulse Width Modulation techniques. These techniques are most efficient and they control the drives of the switching devices. Different PWM techniques are accessible, like single, multiple, sinusoidal and modified sinusoidal PWM. Out of the above technique, sinusoidal PWM techniques are most widely used. They control the output voltage as well as reduce the harmonics. The sinusoidal pulse width modulation (PWM) is most widely used method of voltage control in inverters. The width of each pulse is weighted by the amplitude sine wave at the instant [8]. The carrier signal is a trapezoidal wave of frequency 'fc' and amplitude 'Vc'. The control signal is a sine wave of frequency 'f' and amplitude 'Vr'. Here f becomes the frequency of the output inverter. The sine wave and trapezoidal waves are compared and the PWM signal is prepared shown in Figure 6.

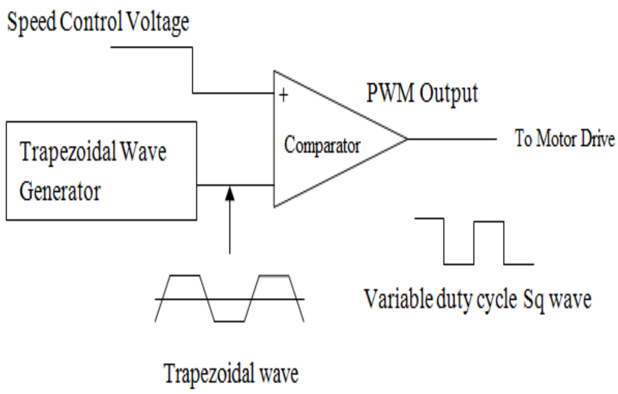

Figure 6. PWM Generation Logic

From this PWM, the drives for the IGBT in the inverter prepared the output waveform of the bridge inverter when sine PWM drives are applied. Average output voltage is controlled through duty cycle of PWM. The relationship between average output voltage, duty cycle and input voltage is,

$$V_{avg} = D\ V_{input} \tag{3}$$

Where,

D = Duty cycle
Vavg = Average output voltage

Vinput = Input DC voltage

5. EXPERIMENTAL SETUP

The development control system is tested on a FPGA based BLDC Motor drive setup in Electrical Drives and Control laboratory at K.S.Rangasamy college of technology. The BLDCM is a 3Φ 310V, 1Hp, Trapezoidal type machine. A diode rectifier with VSI is assembled in a BLDCM intelligent power module. A Hall Effect voltage and current sensor was used to provide accurate information for the angle control as in the form of voltage pulses. A shunt DC motor was coupled in the BLDCM shaft. It excitation is controlled by 30V DC power supply and generator, resistor to a load. Hall-effect current sensors are used for measuring the current. A load cell is used to measure the torque and its values are indicated in torque indicator. The total drive system is controlled by SPARTAN-6 FPGA processor. The block diagram of Experimental setup and FPGA controlled BLDCM drive is shown in Figure 7.

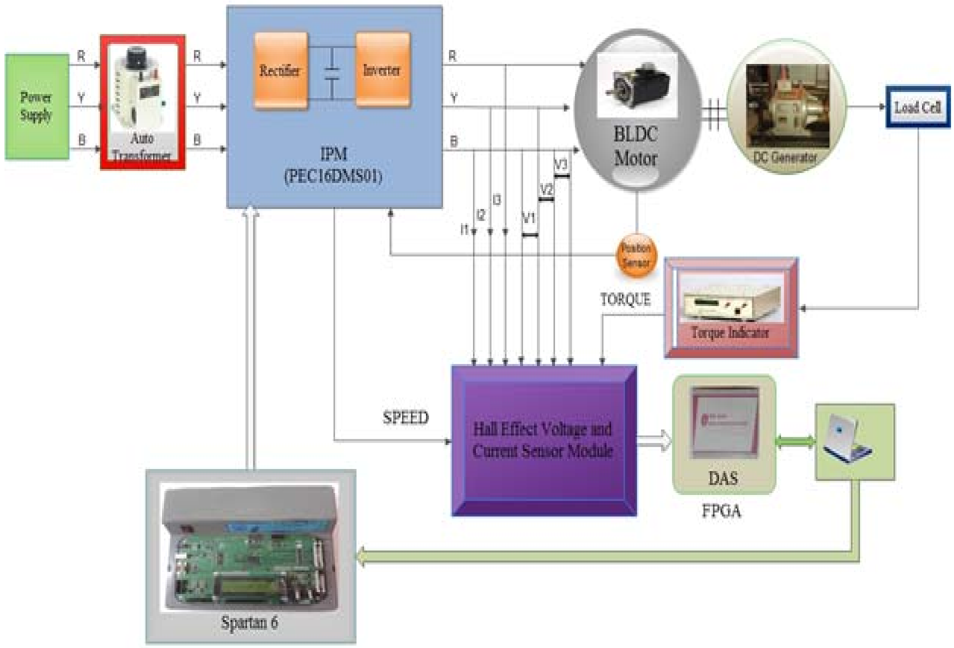

Figure 7. Block Diagram of BLDC Motor Drive

The Spartan-6 FPGA enhancements, combine with advanced process technology, deliver more functionality and bandwidth per dollar than was previously possible. The clockwise direction of the sensor and drive is shown in Table 1.

Table 1. Sensor Clockwise Direction of Drive

Sensor			Clockwise Direction					
A	B	C	1	2	3	4	5	6
0	0	1	0	0	0	1	1	0
0	1	0	1	0	0	0	0	1
0	1	1	1	0	0	1	0	0
1	0	0	0	1	1	0	0	0
1	1	0	0	0	1	0	1	0
1	1	1	0	0	1	0	0	1

5.1. Implementation of PI Controller

The PI speed control algorithm source code has been developed using Spartan-6 FPGA processor through to the VHDL program and downloaded in to the target FPGA processor. The PC machine and the target processor were interfaced using USB cable.

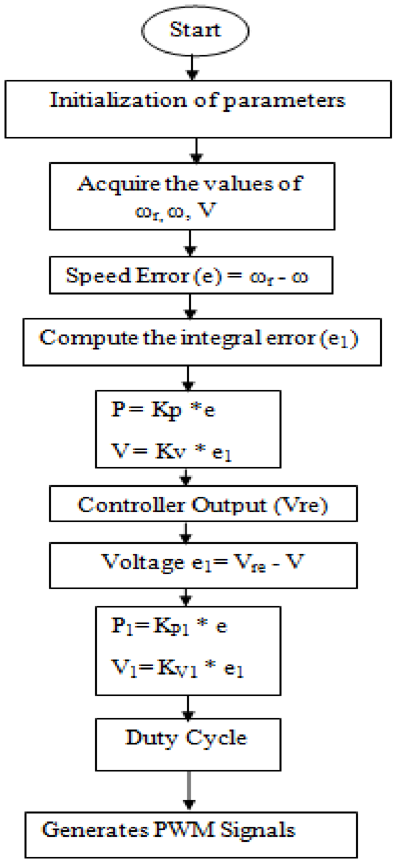

Figure 8. Implementation of PI Control Algorithm

The photograph of the experimental setup is shown in Figure 9. Flow chart for the various steps involved in the design of PI control algorithm is shown in Figure 8.

6. EXPERIMENTAL RESULT AND DISCUSSION

The photograph of experiment setup for speed control of BLDC motor through SPARTAN-6 FPGA kit and data acquisition system is shown in the Figure 9.

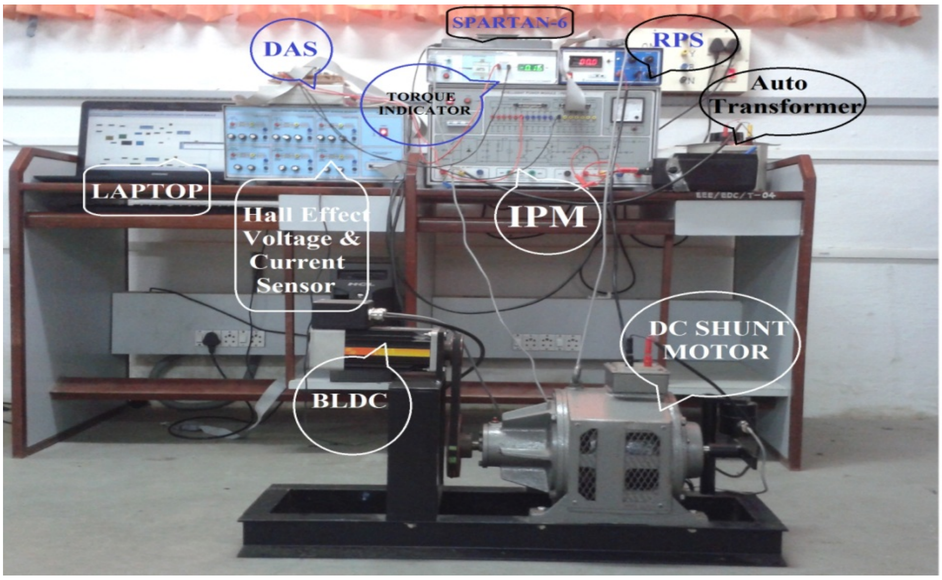

Figure 9. Pictorial view of experiment setup of BLDC Motor

6.1. Open Loop Speed Control Analysis

The Open-loop system also referred to as non-feedback system and it is a type of continuous control system in which the output has no influence or effect on the control action of the input signal. The electrical characteristics of BLDCM obtained results is shown in the Figures 10 – 13.

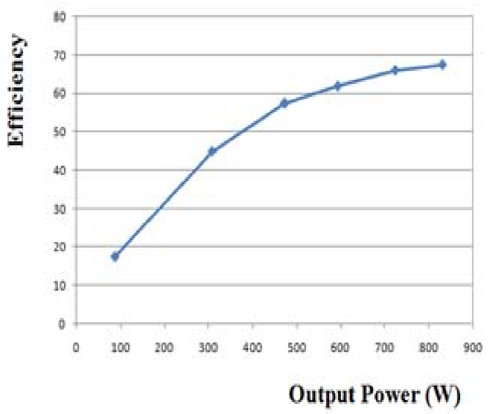

Figure 10. Efficiency Vs Output Power (W)

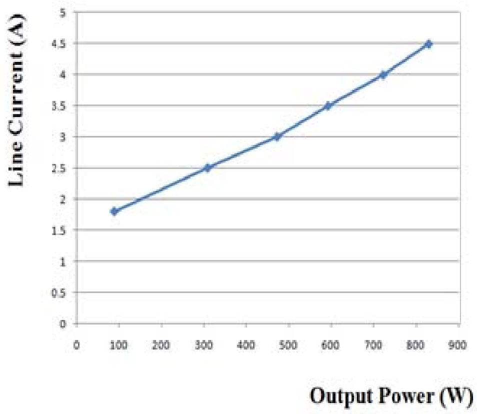

Figure 11. Line Current (A) Vs Output Power (W)

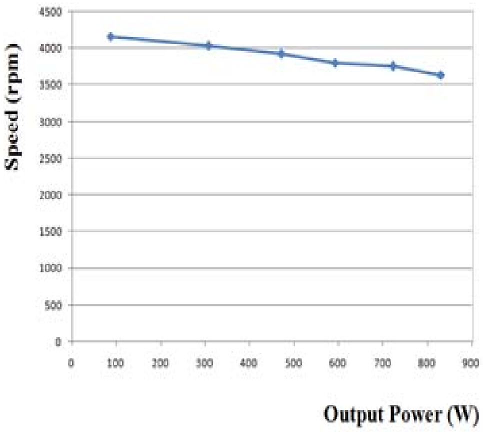

Figure 12. Speed (rpm) Vs Output Power (W)

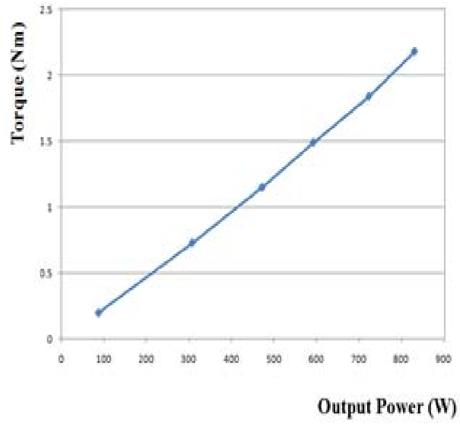

Figure 13. Torque (Nm) Vs Output Power (W)

Mechanical characteristics of the proposed system open loop speed control system obtained result are shown in Figure 14. Here, speed of the system is reduced and torque will be attained constant stall torque.

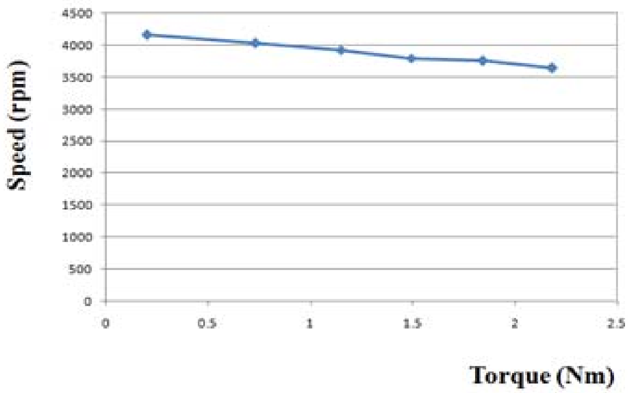

Figure 14. Speed (rpm) Vs Torque (Nm)

6.2. Steady State Analysis

It is the ability of electrical machine or power system to regain its original/previous state is called Steady state stability. The stability of a system refers to the ability of a system to return to its steady state when subjected to a disturbance. In this system have analysis under no load, different torque and variable torque with the constant speed.

A. Constant Speed at No Load

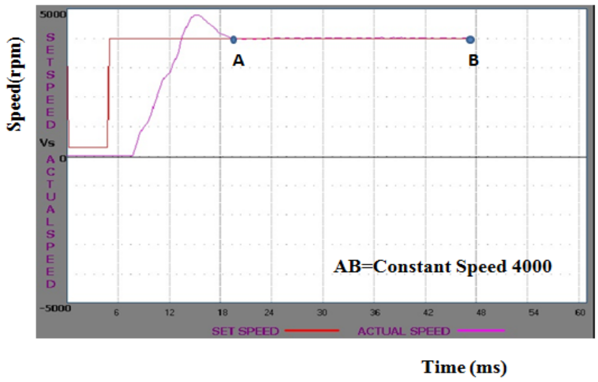

Figure 15. Speed Response at No Load

B. Constant Speed with Constant Torque

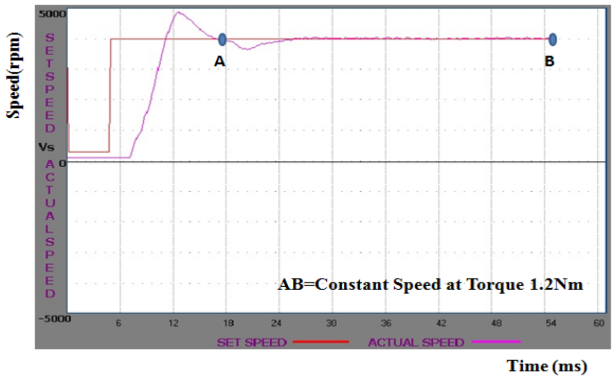

Figure 16. Speed Response with Constant Torque

C. Constant Speed with Variable Torque

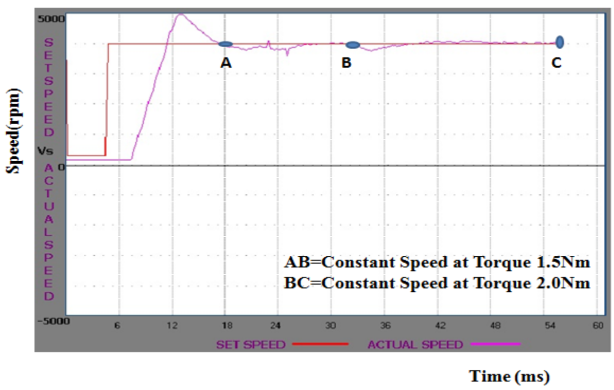

Figure 17. Speed Response with Variable Torque

To analysis the stability of the proposed system under different load condition with constant speed. Speed of the motor has been occurred some changes in under these conditions shown in the Figures 18 - 20.

6.3. Transient Analysis

Starting, braking, reversing, speed changing and load changing are the transient operations which commonly occur in an industrial drive. One is interested in knowing how current, torque and speed of the driving motor change with time when under these transient operations. One is also interested in knowing energy losses, particularly those responsible for heating of the motor, and time taken for the completion of the transient process shown in Figures 18 - 20.

A. Speed Changes at No Load

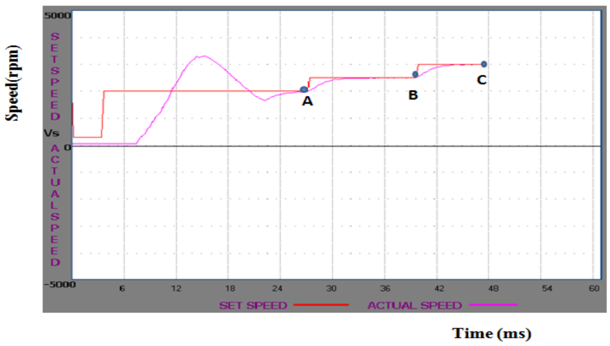

Figure 18. Transient Response at No Load

B. Speed Changes at Constant Torque

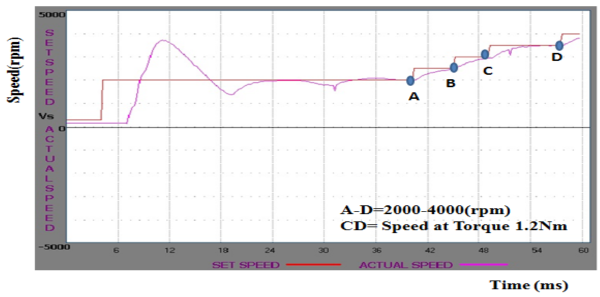

Figure 19. Transient Response with Constant Torque

C. Speed Changes at Variable Torque

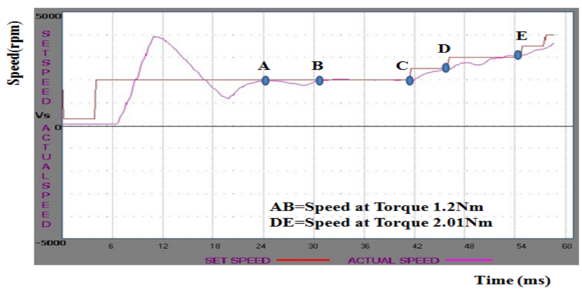

Figure 20. Transient Response with Variable Torque

6.4. Robustness Analysis

The bottom plot shows that the closed-loop system is reasonably robust despite significant fluctuations in the plant DC gain. This is a desirable and most common characteristic of a properly designed feedback system.

A. Sudden Load Injection

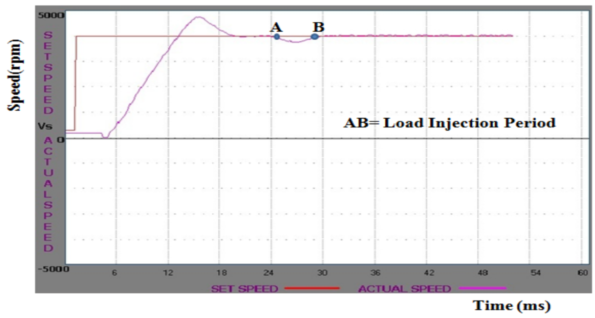

Figure 21. Robustness Response at Sudden Load Injection

B. Sudden Load Rejection

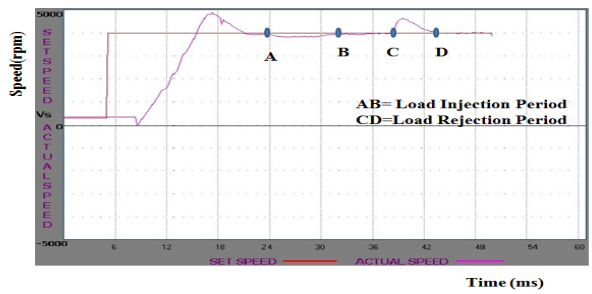

Figure 22. Robustness Response at Sudden Load Rejection

The analysis to be performed under load injection and rejection in the BLDC motor here the speed should be increased when load rejection and speed will be decreased when load injection are shown in the Figures 21 – 22.

7. CONCLUSION

In this paper reviewed simple speed control method and it has the potential to be in a low cost application. FPGAs based on speed control of this system reveal the use of reliable and lower cost controller. Using FPGAs gives us flexibility of implementing different algorithms quickly and without complications. The speed of BLDCM is controlled by duty cycle and frequency of the simple Pulse Width Modulation (PWM) techniques. The proposed system is achieved better operating characteristics and experimentally analyzed the transient, steady state and robustness of this system.

REFERENCES

[1] Anand Sathyan, et al, "An FPGA-Based Novel Digital PWM Control Scheme for BLDC Motor Drives", *IEEE Transactions On Industrial Electronics,* Vol. 56, No. 8, pp. 3040-3049, August 2009.

[2] Alfoni Jose, et al, "Implementation of FPGA based 3-Phase Inverter FED BLDC Motor", *International Journal of Applied Sciences, Engineering and Technology*, Vol. 01, No. 01, pp. 26-30, Dec 2012.

[3] Byoung-Gun Park, et al, "Fault Tolerant Strategies for BLDC Motor Drives under Switch Faults, *IEEE Transaction*, pp. 1637-1641, 2006.
[4] Dahaman Ishak, et al, "PWM Switching Strategy for Torque Ripple Minimization in BLDC Motor" *Journal of Electrical Engineering*, Vol. 62, No. 3, Nov 2011.
[5] Eric Monmasson, et al, "FPGA Design Methodology for Industrial Control Systems"*, IEEE Transactions on Industrial Electronics,* Vol. 54, No. 4, pp.1824-1842, August 2007.
[6] Gautham R, et al, "FPGA Based Digital Controllers for BLDC Motors", *International Journal of Engineering Research and Applications*", Vol. 3, Issue 2, pp.1615-1619, March 2013.
[7] Kirti B. Satale, et al, "Analysis of Different Speed Controllers and Implementation of Novel Speed Controller using FPGA for BLDC Motor", *International Journal of Soft Computing and Engineering*, Volume 4, Issue 2, pp.131-134, May 2014.
[8] Muhammad H. Rashid, "*Power Electronics Handbook*", by ACADEMIC PRESS, 2001.
[9] Nikola Milivojevic, et al, "Stability Analysis of FPGA-Based Control of Brushless DC Motors and Generators Using Digital PWM Technique", *IEEE Transactions On Industrial Electronics,* Vol. 59, No. 1, pp. 343-352, January 2012.
[10] Pindoriya, et al, "Speed Control of BLDC Motor using Sinusoidal PWM Technique", *National Conference on Emerging Trends in Computer & Electrical Engineering*, pp. 151-155, 2014.
[11] Robert Horvat, et al, "An Event-Driven Approach to the Current Control of a BLDC Motor Using FPGA", *IEEE Transactions On Industrial Electronics,* Vol. 61, No. 7, pp. 1319-1327, July 2014.
[12] Satish Rajagopalan, et al, "Analytic-Wavelet-Ridge-Based Detection of Dynamic Eccentricity in Brushless Direct Current (BLDC) Motors Functioning Under Dynamic Operating Conditions", *IEEE Transactions on Industrial Electronics*, Vol. 54, No. 3, pp. 1410-1419, June 2007.
[13] Serdar Uygur, et al, "An FPGA Based BLDC Motor Control System", Thesis of the Graduate School of Natural and Applied Sciences of Middle East Technical University, February 2012.
[14] Shyu, and Y. Chang, et al, "Novel Loss Reduction Pulse Width Modulation Technique for Brushless DC Motor Drives fed by MOSFET Inverter", *IEEE Trans. Power Electron*., vol. 19, no. 6, pp. 1646–1652, Nov. 2004.

BIOGRAPHIES OF AUTHORS

S.M. Ramesh Balaji was born in Salem, Tamilnadu. He received diploma in electrical and electronics engineering from Muthayammal Polytechnic College, Rasipuram, Tamilnadu, in 2007, and B.E. degree from Vidyaa Vikas College of Engineering and Technology, Tiruchengode, Tamilnadu, in 2010 and pursuing M.E in power electronics and drives in K.S. Rangasamy College of Technology, Tiruchengode. Tamilnadu.

Muniraj C was born in India, in 1980. He received B.E., M.E and Ph.D, degrees in Electrical Engineering at Bharathiyar University and Anna University in 2003, 2006 and 2012 respectively. He has been working as Associate professor in K.S. Rangasamy college of Technology in the Department of Electrical and Electronics Engineering. His researches interests include condition monitoring of power apparatus and systems, power electronics and drives, signal processing and intelligence controller application in electrical drives.