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Control of Four Switch Inverter Fed BLDC Motor Using FPGA

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ABSTRACT: Researches and development of Advanced motor drives has yielded increase in efficiency and reliability. Commercial appliances and residential appliances such as air conditioners and refrigeration systems use conventional motor drive technology. Brushless DC motor is a completely new and reliable motor, since it has high torque to power ratio, high efficiency, compact size and lower maintenance due to brushless architecture etc. This paper presents FPGA based digital control strategy of BLDC motor. It has the potential to be implemented in a low-cost application specific integrated circuit due to the simplistic nature of this control. The proposed method is verified using simulations. According to simulation results, the current ripple associated with the stator is low, hence the switching and conduction loss will be reduced and as a result, the over all efficiency will be improved which further reduces the cost. The proposed strategy shows good self adapted track ability.

KEYWORDS: Brushless direct current (BLDC) motor drives, converters, field-programmable gate arrays (FPGA) and pulse width modulation (PWM),four switch inverter.

I. INTRODUCTION

An electric motor is considered as a transducer that converts electrical energy that is given as input into mechanical energy which will be available as output. Electrical motors are an inevitable part of industrial applications with no less than 5 billion motors built worldwide every year. Conventional motor drive technologies were mostly adopted in commercial and residential applications.

In these kinds of application Brushed dc machines or single-phase induction motors were used which has low efficiency and high maintenance, respectively . Single-phase induction motors are less efficient because of the ohmic loss in the rotor and which is due to the displacement of phase angles between back electromotive force (EMF) and stator current, because of the presence of brushes dc machines require more maintenance. Replacing these inefficient motors with more efficient brushless dc (BLDC) motors will result in substantial energy savings. They require lower maintenance due to the elimination of the mechanical commutators considered as the major advantage of brushless dc motor over other machines.[1]

They have high power density. Compared to induction machines BLDC motors have lower inertia, which allows them for faster dynamic response to reference commands provided through the controller. Since rotor is a permanent magnet they are found to be more efficient due to significantly . Also the absence of brushes will lead to reduced maintenance and low noise production.[2] Lower rotor losses, higher cost is one of the major disadvantage of BLDC motor, along with that relatively greater degree of complexity introduced by the power electronic converter used to drive them is another major disadvantage.[3][4]
In this paper we proposes a low cost four switch inverter instead of conventional six switch inverter which provides Some advantages over the traditional SSTP inverters. They were minimized switching losses, reduction in cost of number of switches, number of interface circuit required is minimum, control schemes to produce logic pulses will be simpler, low computational burden, and more reliability because of lesser interaction between switches.[5]
Due to fast progress of very large scale integration technology and electronic design automation techniques the applications with speed control of motors were widely done using electronic devices, such as microcontrollers and DSP . These devices are usually have fixed hardware, leaving software as the only method for designers to update designs and limiting the development of application specific functions . Field programmable gate arrays (FPGAs) allows designers to create custom functions completely adapted to their specific application requirements by enabling both hardware and software customization. It provides the ability to introduce functions in hardware results in improved

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performance . These additional freedom provide enhanced system performance, especially for motor speed control and energy efficiency.

Paper is organised as follows. Section II describes the mathematical modelling of BLDC motor and its transfer Function represents basic design of BLDC motor. Section III presents the four switch control of BLDC motor. Section IV represents drive strategies of BLDC motor and the working of a four switch inverter with different modes and schematic diagram. Section V represents the matlab/ simulink model and results of the proposed system. Finally section VI represents the conclusion.

II.MATHEMATICAL MODELLING OF BLDC MOTOR

This section presents the mathematical modelling and design of a BLDC motor. The controller will consider the BLDC motor as a digital system. The method used in this digital controller strategy is very simple. Change in speed is obtained by having variation in the duty ratio of the switches. Hysteresis current controller has inherent current control capability, whereas a PWM control does not have that property, and that incapability is compensated with the help of a current limiter.[7]

Basic circuit analysis is used to obtain the equations associated with the BLDC motor. The mathematical model of the machine are defined by a set of differential equations . These are per phase modelled equations. A per phase model is shown in figure 1 [7][8].

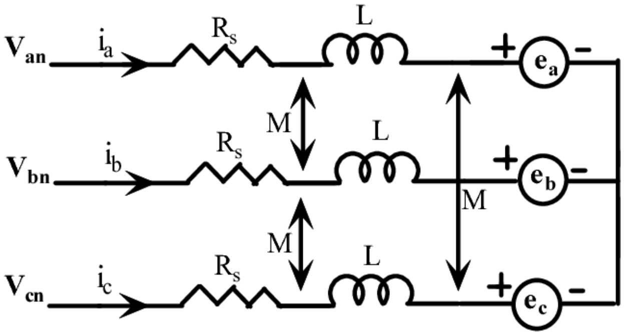

Fig. 1 Equivalent circuit of BLDC motor

$$Va = ia\,(t)\,Ra + La\frac{di_a}{dt} + e_a\,(t) \qquad (1)$$

$$Vb = ib\,(t)Rb + Lb\frac{di_b}{dt} + e_b\,(t) \qquad (2)$$

$$Vc = ic\,(t)Rc + La\frac{di_c}{dt} + e_c\,(t) \qquad (3)$$

$$T_e(t) - T_l(t) = j\,\frac{d\omega(t)}{dt} + B\omega(t) \qquad (4)$$

Where V, I and e are the voltage, current and back-emf's of three phases *a,b* and *c*. R and L are the resistance and inductance of each phase respectively.

The electrical and mechanical equations were used to obtain the value of duty ratio D . The value of D can be defined as a function of the motor parameters. From the torque equation,

$$T_{em} = j\frac{d\omega}{dt} + B\omega + T_L \qquad (5)$$

where T_{em}, $\omega(t)$, b, J, and T_L were developed electromagnetic torque, rotor angular velocity, viscous friction constant, rotor moment of inertia, and load torque, respectively

$$K_t I = J\frac{d\omega}{dt} + B\omega + T_l \qquad (6)$$

where K_t = torque constant and I = average current.

At steady state, the time phase voltage equations can be written in terms of phase voltage Van, phase current I, winding resistance, and velocity constant K_e as

$$V_{an} = IR_a + K_e w_{ss} \quad (7)$$

Substituting the value of the steady-state current and defining the phase voltage in terms of dc-link voltage V_{DC} and duty D, we get

$$DV_{DC} = \frac{(T_L + W_{SS})}{K_t} R + K_e\, \omega_{ss} \quad (8)$$

where ω_{ss} denotes the steady-state angular velocity. Therefore, the duty ratio can be expressed in terms of the motor parameters as

$$D = \frac{1}{V_{DC}} [\frac{(T_L + W_{SS})}{K_t} R + K_e] \quad (9)$$

The expression of back-EMF can be modified as denoted in;

$$E_a = K_e * (\theta) * \omega(t) \quad (10)$$
$$E_b = K_e * (\theta - 2\pi/3) * \omega(t) \quad (11)$$
$$E_c = K_e * (\theta + 2\pi/3) * \omega(t) \quad (12)$$

Where K_e is the back-EMF constant in volts, $F(\theta)$ is back- EMF function and ω is the rotor speed. The permanent magnet (PM) also made torques due to the trapezoidal flux linkage. The produced torques;

$$T_e = \frac{E_a i_a + E_b I_b + E_C I_C}{W} \quad (13)$$

The resultant torque T, , can be obtained by the following expressions;

$$T_a(t) = K_t * \varphi\ (\theta) * Ia(t) \quad (14)$$
$$T_b(t) = K_t * \varphi\ (\theta - 2\pi 3) * Ib(t) \quad (15)$$
$$T_c(t) = K_t * \varphi\ (\theta + 2\pi 3) * Ic(t) \quad (16)$$
$$T(t) = T_a(t) + T_b(t) + T_c(t) \quad (17)$$

With the Newton's second law of motion, the angular motion of the rotor can be written as follows;

$$T_e(t) - T_l(t) = j \frac{d\omega(t)}{dt} + B\omega(t) \quad (18)$$

This is one kind of mathematical equation that represents a BLDC motor.

Consider T_e and T_L where T_e is electrical torque and T_L load torque, j is the rotor inertia and ω_m is the rotor speed. But we know that Electromagnetic torque(T_{em}) and back emf are given by equations (19)and (20).

$$T_{em} = K_t ia\ (t) \quad (19)$$
$$e_a\ (t) = K_e\ \ \omega(t) \quad (20)$$

Where K_t is torque constant and K_e motor constant.

Taking Laplace transformation of the equations and rearranging the terms equations (21) and (22) are obtained

$$\omega\ (s) = \frac{T_{em}(s) - T_l}{B + sJ} \quad (21)$$

$$ia\ (s) = \frac{Van(s) - Ke\ \omega\ (s)}{Ra + sLa} \quad (22)$$

From the above equation it is possible to draw the model of the BLDC motor as shown in Fig. 2. From the Fig.2 transfer function of the system is presented in equation (23).

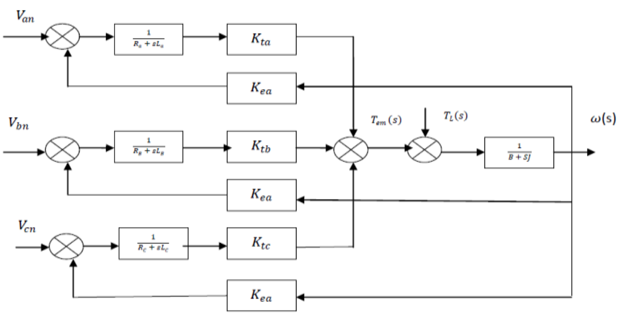

Fig . 2 Transfer function model of BLDC motor

$$\frac{\omega(s)}{V(s)} = \frac{\frac{K_t}{JL_a}}{s^2 + \frac{(JR_a + BL_a)}{JL_a}s + \frac{BR_a + K_t K_e}{JL_a}} \qquad (23)$$

III.FPGA CONTROL OF BLDC MOTOR

Hysteresis current control and pulse width modulation (PWM) control combined with continuous control theory have produced the most widely used BLDC motor control techniques. Hysteresis current control is necessary toward achieving adequate servo performance, namely, instantaneous torque control, yielding faster speed response compared to PWM control. For most applications, proportional-integral (PI) current and speed compensators were enough to establish a well-regulated speed/torque controller. Linear system theory and conventional control theory are very well understood but they are highly complex and require extensive control systems knowledge to develop a well-designed controller. Discrete control theory allows these controllers to be digitally implemented with microcontrollers, microprocessors, or digital signal processors (dsps).

Digitizing analog control strategy will increases the complexity to the overall design procedure . In this project, digital PWM controller has been proposed for the control of bldc motor BLDC motor. This controller consider the BLDC motor as a digitalized system. Speed regulation is obtained by having variation in duty ratio, which makes the concept of the controller extremely simple for design and implementation.[9]

FPGAs technology is widely adopted in many applications such as wired & wireless telecommunications, image processing, etc. Speed control of motor is another area were lots of researches were going on since, it can results in increases the expected performance along with reduced cost of control system .Nowadays fpgas is widely used in many different electric system applications such as PWM control of inverters , soft switching, STATCOM and electrical machines control).New generations of equipment must have higher performance parameters such as better efficiency and reduced electromagnetic interference also system flexibility so that the development and modification can be done with in a short span of time. All these improvements must be achieved along with decreasing the system cost. Brushless DC motor technology makes it possible to achieve these specifications. Such motor combine high reliability with high efficiency.[10][11]

IV. PROPOSED TOPOLOGY

Four switch inverter fed BLDC motor

The topology that generally used for bldc motor is a three-phase buck-derived converter or a three-phase inverter bridge. the input side constitutes of a three phase inverter with four switches that could be MOSFETs or insulated-gate bipolar transistors (IGBTs). anti-parallel diodes need to be connected if IGBTs were used as switches for carrying reverse currents, whereas MOSFETs use body diodes. MOSFETs give lower turn-off switching loss and usually lower diode forward drop, but that advantage can be compensated by higher voltage drop during turn on . Waveforms trapezoidal flux distribution for three phase BLDC motor are shown in Fig.3 . Approximately, the back EMF induced per phase of the motor winding is constant for 120◦, before and after which it changes linearly with rotor angle.

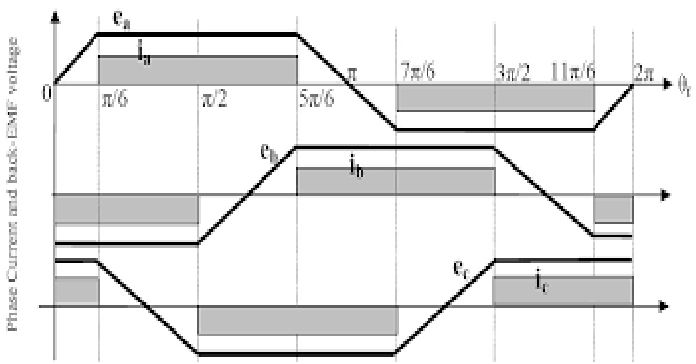

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Fig. 3 Back Emf and sensor waveforms

In this project instead of conventional six switch inverter we will be using a four switch inverter to drive the bldc motor.

Four-switch converter for BLDC motor drives.

In the four-switch configuration of the inverter is shown in the Fig. 4. Let "0"means the lower switch is turned on and "1" means the upper switch is turned on. In the case of six-switch converter, the switching status (0,0) and (1,1) cannot supply the DC –link voltage to the load. So the current cannot flow through the load at these instants and hence they are regarded as zero vectors.[12]

However, one of the phase will be always connected to the midpoint of the dc-link capacitors in the four-switch converter, and hence current flows even at the zero-vector . Moreover, the phase which is connected to the midpoint of dc-link capacitors is uncontrolled and only the resultant current flowing through the other two phases flow through this phase during the switching status (0, 1) and (1, 0).

For a BLDC motor to generate maximum and constant output torque, their phase currents should be rectangular with 120° conducting and 60° non-conducting intervals. Also at each operating mode, only two phases are conducting and the other phase remains silent. However, in the four-switch converter based on the four switching vectors, the generation of 120°conducting and a 60° non-conducting current profiles is inherently difficult. That means the conventional PWM schemes employed for four switch induction motor drives cannot be directly applied to BLDC motor drives. [13]

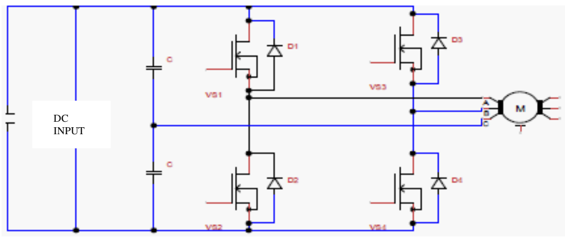

Fig. 4 Four switch three phase inverter

Here the switching pulses will be generated on the basis of analysing the hall sensor feedback, since we are using sensor based control of BLDC motor. The truth table associated with hall sensor and corresponding switching pulse has shown below.

Mode 1:

Switch S1 is turned ON

Phase A and Phase C is conducting

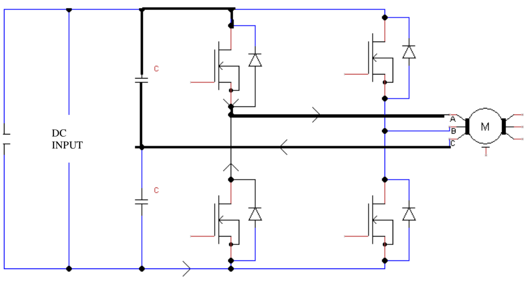

Fig. 5. Four switch inverter mode-1

Mode 2:

Switch S1 is S4 turned ON

Phase A and Phase B is conducting

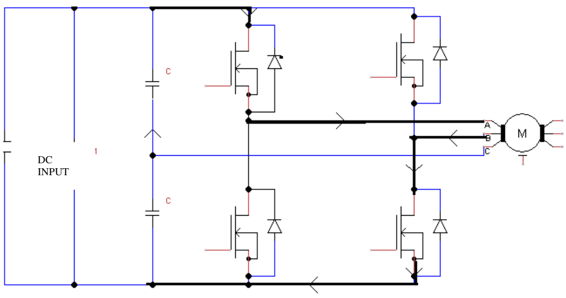

Fig. 6 Four switch inverter mode-2

Mode 3:
Switch S4 turned ON
Phase C and Phase B is conducting

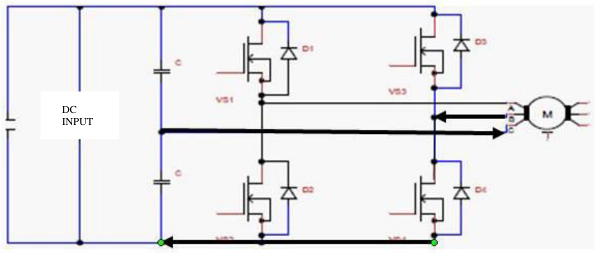

Fig. 7 Four switch inverter mode-3

Mode 4:

Switch S2 turned ON

Phase C and Phase A is conducting

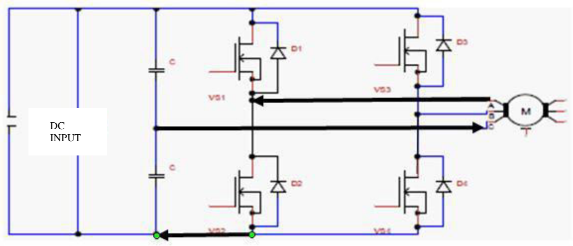

Fig. 8 Four switch inverter mode-4

Mode 5:
Switch S2 and S3 and turned ON
Phase B and Phase A is conducting

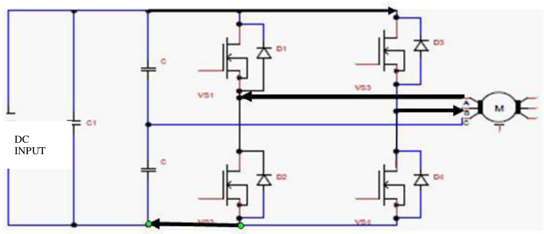

Fig. 9 Four switch inverter mode-5

Mode 6:

Switch S3 turned ON

Phase B and Phase C is conducting

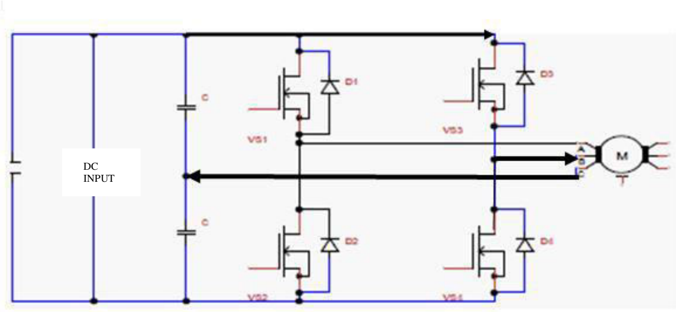

Fig. 10 Four switch inverter mode-6

MODES	HALL A	HALL B	HALL C	s_1	s_2	s_3	s_4
Mode 1	HIGH	HIGH	LOW	ON	OFF	OFF	OFF
Mode 2	LOW	HIGH	LOW	ON	OFF	OFF	ON
Mode 3	LOW	HIGH	HIGH	OFF	OFF	OFF	ON
Mode 4	LOW	LOW	HIGH	OFF	ON	OFF	OFF
Mode 5	HIGH	LOW	HIGH	OFF	ON	ON	OFF
Mode 6	HIGH	LOW	LOW	OFF	OFF	ON	OFF

Table 1 Switching sequences for four switch converter

Modes	Active Phases	Current restrains	Switching devices
Mode 1	+A,-C	$+I_A, -I_C$	s_1
Mode 2	+A,+B	$+I_A, -I_B$	s_1, s_4
Mode 3	+C,-B	$+I_C, -I_B$	s_4
Mode 4	+C,-A	$+I_C, -I_A$	s_2
Mode 5	+B,-A	$+I_B, -I_A$	s_2, s_3
Mode 6	+B,-C	$+I_B, -I_C$	s_3

Table 2 Working modes of four switch BLDC inverter

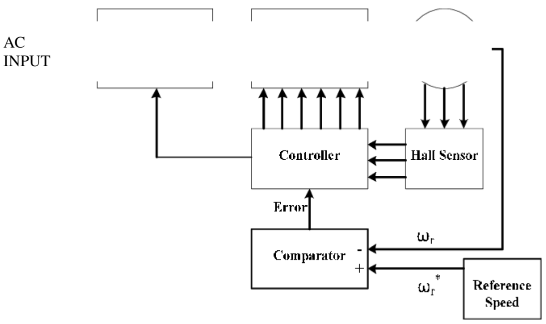

Fig. 12 Block diagram of proposed system

V. SIMULATION RESULTS

The proposed BLDC motor control strategy is modeled in matlab/Simulink using Simscape library. Data of the experimental BLDC motor is given in the Table I is used in the motor drive model. BLDC motor commutation is done with the help of inbuilt Hall Effect position sensors signals

A three phase four switch VSI is modeled using Metal Oxide Semiconductor Field Effect Transistor (MOSFET) switches based on experimental inverter drive. Six-step switching algorithm is used to drive the four switch inverter drive of BLDC motor.

Number of phases	3
Number of poles(P)	3
Rated voltage	48V
Per phase resistance(R)	2.18ohm
Inductance(L)	2.3mh
Rated Torque(T)	.00269Nm/A
Rated speed	3000rpm

Table 3 Specifications of experimental BLDC motor

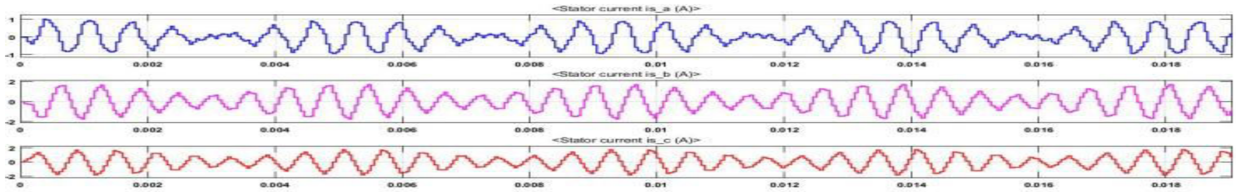

Fig.13 Stator current waveform

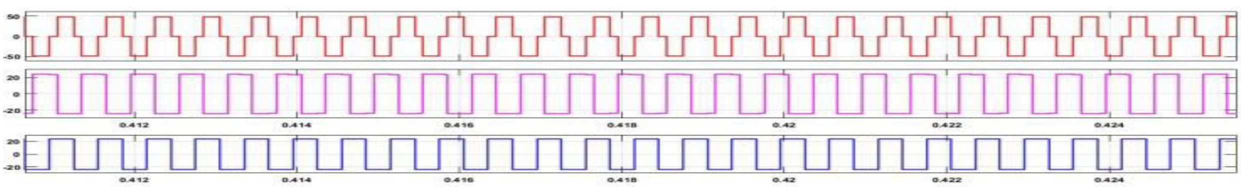

Fig.14 Three phase current output of four switch inverter

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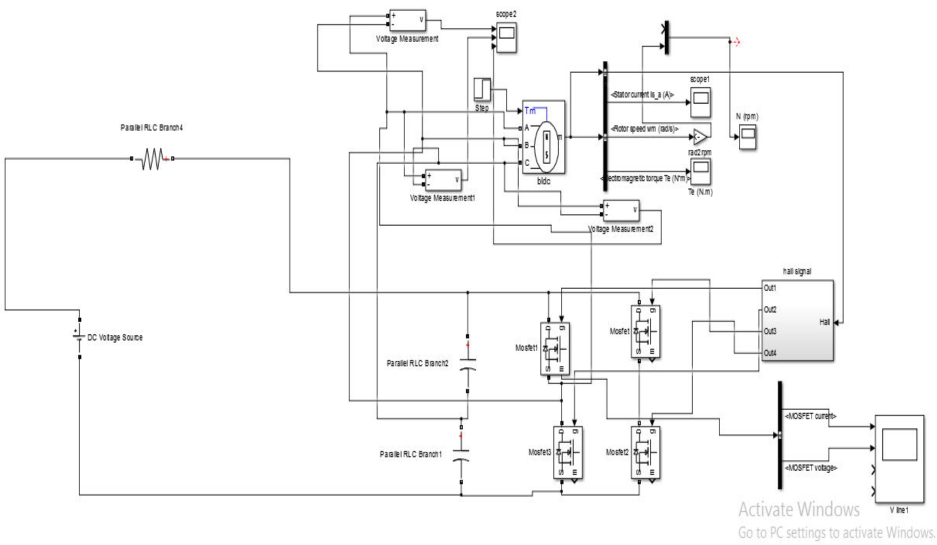

Fig. 12 Simulation model of BLDC motor drive

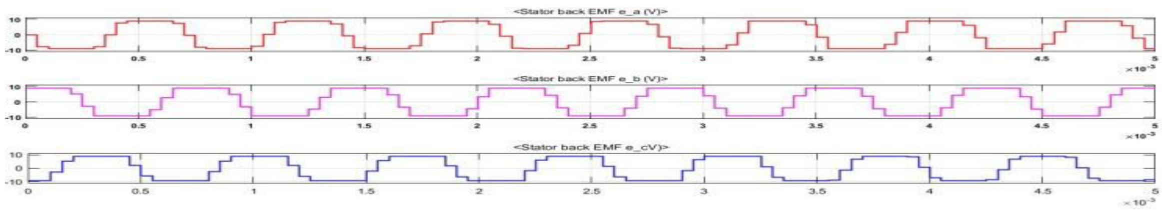

Fig. 15 Back EMF wave form

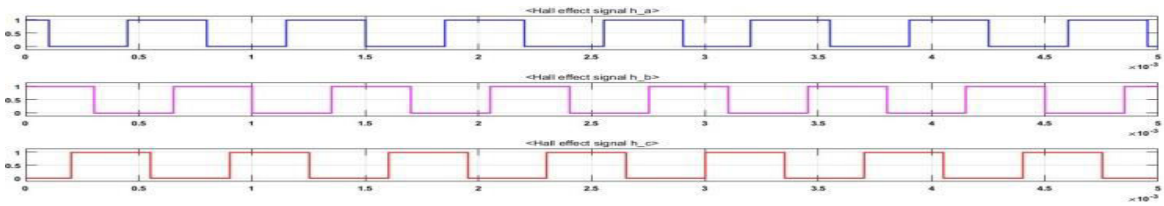

Fig. 16 Hall sensor Waveform

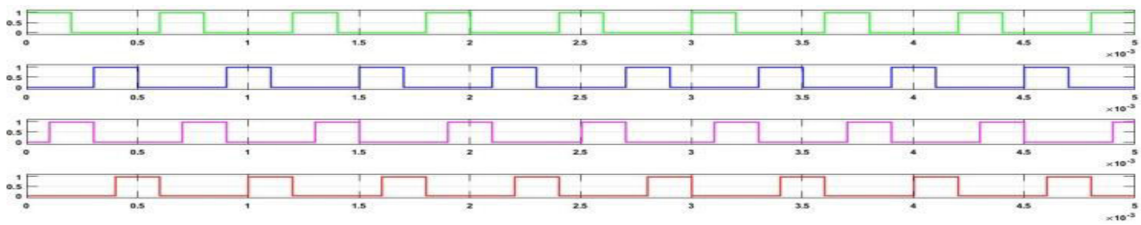

Fig. 17 Switching Pulse

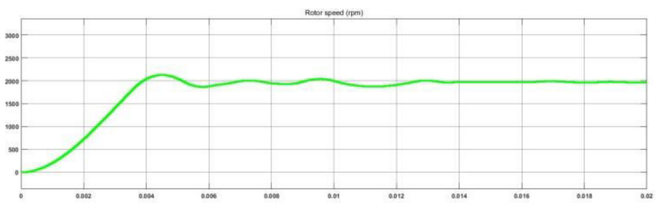

Fig. 18 Rotor speed in RPM

MATLAB codes have been written and embedded into the model to generate a duty cycle controlled PWM signal, detect motor speed from position sensors signals and implement the proposed control algorithm.

VI. CONCLUSION

This work demonstrates the use of an efficient and lower cost FPGAs based speed control of BLDC motor. The advantages of digital hardware is that controlling and adjustments can be done in faster manner. The FPGAs is very much flexible so that the digital control can be easily adapted to analog control. The effectiveness of PWM technique for speed control of BLDC motor and its practical applications has been demonstrated in this project. Using FPGAs platform drives are easily controlled, least time consuming, real time control action, parallel processing and transient response is fast compared to microcontroller based approach. Four-switch converter topology is introduced in this paper where cost saving is achieved by reducing the number of inverter power switches. The advantages of proposed method are Simplification of power conversion circuit, Using four switch inverter, all the six commutation instants can be detected, also this method can be applied to permanent magnet synchronous motors as it is independent of back emf waveforms. Therefore, the implementation of the proposed technique is easier and less expensive.

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