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Labview Based Indirect Position Control of Four Switch Three-Phase Brushless Dc Motor Using FPGA

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Abstract

This paper presents a novel LABVIEW based indirect position control of four switch three phase inverter (FSTPI) fed brushless DC (BLDC) motor drives using a field programmable gate array (FPGA). In this proposed experimental technique the Sensorless position detection based on zero crossing points of the line voltage difference measured at the terminals of the motor using Virtual Instrumentation. The controlled PWM pulses for FSTPI are generated using Xilinx FPGA program. The low cost BLDC drive is achieved by the reduction of switch device count, cost down of control, and saving of hall sensors. The feasibility of proposed LABVIEW based sensorless control for FSTP BLDC motor drives is demonstrated by analysis and experimental results.

Keywords: Brushless dc (BLDC) motor, four-switch three-phase (FSTP) Inverter, field programmable gate array (FPGA), Virtual Instrumentation-LABVIEW, Sensorless control.

Introduction

Recently, the brushless dc (BLDC) motor is becoming popular in various applications because of its simple construction, high reliability, high efficiency, light electromagnetic pollution, high power factor, high torque, simple control, lower maintenance, Hence Permanent magnet (PM) motors have been widely used in variety of applications in industrial automation and consumer appliances and extensively used in Servo systems and low-power drive systems. The performance of such motors has been significantly improved due to great development of power electronics, magnetic performance of magnets, and motion control technology in recent years. As shown in fig.1, BLDC motors are conventionally excited by six switch inverters and for position detection hall sensors are used. However the cost effective design is becoming one of the most important concerns for the modern control research. Some researchers developed new power inverters with reduced costs. Among these developments, three – phase voltage source inverters with only four switches without hall sensors as shown in fig. 2 is an attractive solution.

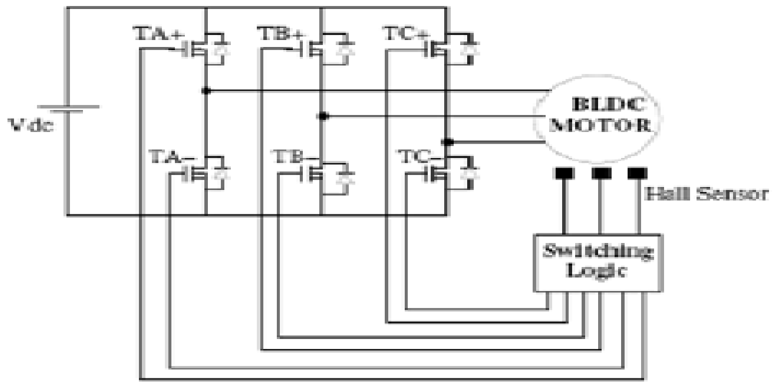

Figure 1: Conventional BLDC motor control

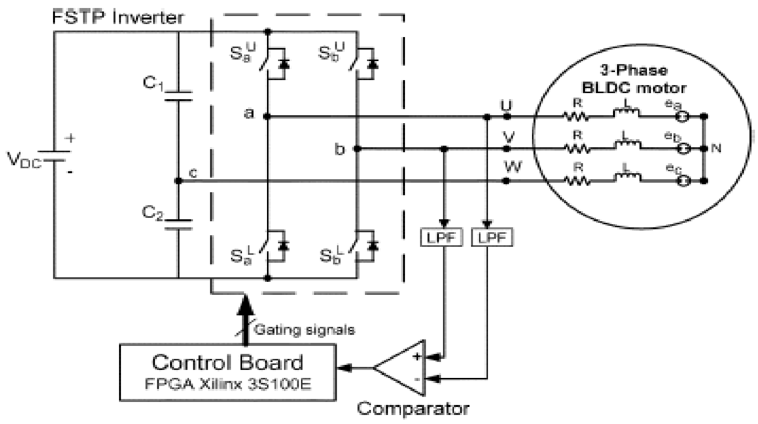

Figure 2: FPGA-based sensorless FSTP BLDC motor control

Indirect position detection is achieved by so many methods. These methods are based on using back-EMF of the motor [1]-[3], detection of the conducting state of freewheeling diode in the unexcited phase [4], back-EMF integration method [5],[6], Detection of stator third harmonic voltage components[7],[8].Back-EMF estimation methods typically rely on the zero crossing detection of the EMF waveform. The technique of estimating back-EMF by sensing the terminal voltages with respect to a virtual neutral point is proposed in [1]. The neutral point will not be stable during PWM switching. Low pass filters have been used to eliminate the higher harmonics and to convert the terminal voltages into triangular waveform signals. Delay is introduced in the sensed signal due to heavy filtering,which also varies with the operating speed. Therefore this method is well suited only for a narrow speed range. Indirect back-EMF sensing technique is proposed by [2] without the need of neutral or virtual neutral potential. The back-EMF zero crossing is sensed with respect to the negative dc bus potential. In [3], the authors define a function depending on the measured voltages, currents and the derivative of the currents which indicates the switching instants. After pre- positioning, the authors in [3] advance the switching pattern by 60 electrical degrees and let their sensor less algorithm take over. Since their functions are dependent on the computation of derivatives of currents, the method requires digital implementation and could be affected by sensor noise.

Detecting the free-wheeling diode conduction in the open phase gives the zero crossing point of the back-EMF waveform [4].This approach of rotor position sensing works over a wide speed range, especially at lower speed. The main drawback of this scheme is the requirement of six additional power supplies for the comparator circuits to detect current flowing through the free- wheeling diode. Integrating the back-EMF waveform of the unexcited phase is another method to extract the position information for the phase commutation [5].Integration starts when zero crossing of the back-EMF occurs and the integration stops when the threshold set value is reached which gives the commutation instant. This approach is less sensitive to switching noise but low speed operation is poor. Further, this scheme needs the neutral potential and suffers from the offset error due to integration. Based on this technique a low cost sensorless scheme has been proposed [6]. Only one terminal voltage is sensed to detect the switching instant of a phase. Due to interpolation of the switching instants for other two phases from the sensed phase switching instants, frequent, rapid acceleration or deceleration is not possible.

Switching instants of star connected BLDC motors have also been estimated from the third harmonic of the back-EMF waveform [7],[8]. Summation of the terminal voltages gives the third harmonic voltage. The third harmonic voltage component is then integrated to find the third harmonic flux linkage whose zero crossing corresponds to the commutation instants [7].The approach based on the inherent third harmonic voltage components [7] has the limitation that the amplitude and phase of harmonic components vary with magnetic saturation, and it is not suited to the low speed range owing to the relatively low amplitude of harmonic component voltages. Authors in[8] proposes integration of third harmonic of back-EMF instead of terminal voltages using ASIC for ultrahigh speed operation, however access to motor winding neutral potential is required. A detailed review of the recent literature on sensorless methods is given by authors in [9].Direct commutation instant detection from line voltages is proposed by authors in[10] along with a fine tuning technique to further improve the accuracy of the detected commutation instant. In [11], the authors implement sensorless operation by using the average line to line voltage, which is obtained by filtering the PWM waveforms. Filtering introduces a delay, which to be minimized, requires a high switching frequency. Further, [11] does not discuss the details of sensorless starting of the motor. Authors in [12] designed and implemented an integrated circuit for the sensorless operation of BLDC motor by sensing the motor terminal voltages. Frequency independent phase shifter is proposed by authors in [13] for sensorless control of BLDC motor which can shift the zero crossing point of input signal with a specified phase delay. However direct commutation instant detection technique proposed by [10],[11] lacks this flexibility to advance the commutation instant, which is possible to implement using the back- EMF zero crossing detection techniques.

This paper proposes a novel method of detecting the back- EMF zero crossings, by making use of line voltage differences. It is shown that the difference of line voltages provides an amplified version of the back-EMF in appropriate phase near the zero crossing. The line voltage difference is fed to the virtual instrument developed in LABVIEW through serial communication and the zero crossing points are detected. These details are given through serial port to the FPGA controller. The pulses generated and the pulse width modulation is done according to the set speed in the FPGA controller. Further to reduce cost two MOSFET switches are replaced by capacitors without affecting the characteristics. The method is simple, reliable and does not involve any integration. Further, since line voltages are used, the requirement of neutral potential has been eliminated. The Zero crossing instants are done using virtual circuits developed in LABVIEW. This also eliminates the common mode noise. Device drops and their variations would also not play a part since line voltages are used. Unlike the method of [3] this scheme is easy to implement. No derivative operations are involved.

The organization of this paper is as follows. Section II presents four switch three –phase BLDC motor drive. Section III describes the proposed back-EMF zero crossing estimation method. Section IV presents hardware implementation of the proposed method. Section V presents the virtual instrument and results that validate the proposal and section VI presents the conclusion.

Four Switch, Three Phase BLDC Motor Drive

Fig.3 shows the configuration of a four-switch inverter along with the equivalent circuit of a three phase BLDC motor. The typical mathematical model of the BLDC motor is represented as follows

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} + \begin{bmatrix} L_a & 0 & 0 \\ 0 & L_b & 0 \\ 0 & 0 & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

where *v*an, *e*a, *i*a, *L*s and *L*m represent the phase voltage, back-EMF voltage, phase current, self inductance and mutual inductance of phase A, respectively. The electromagnetic torque is expressed as

$$T_e = \frac{Z_p}{2\omega_m}(e_a i_a + e_b i_b + e_c i_c)$$

Where ω_m is the rotor speed and Z_p is the number of magnetic poles.

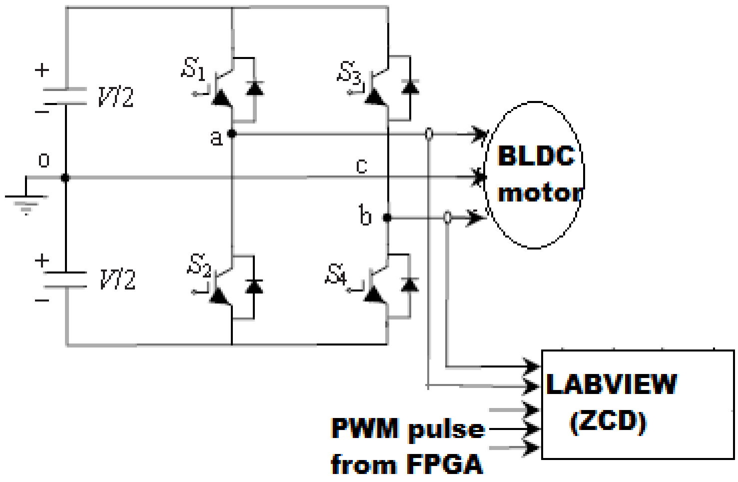

Figure 3: Four-switch brushless DC motor drive

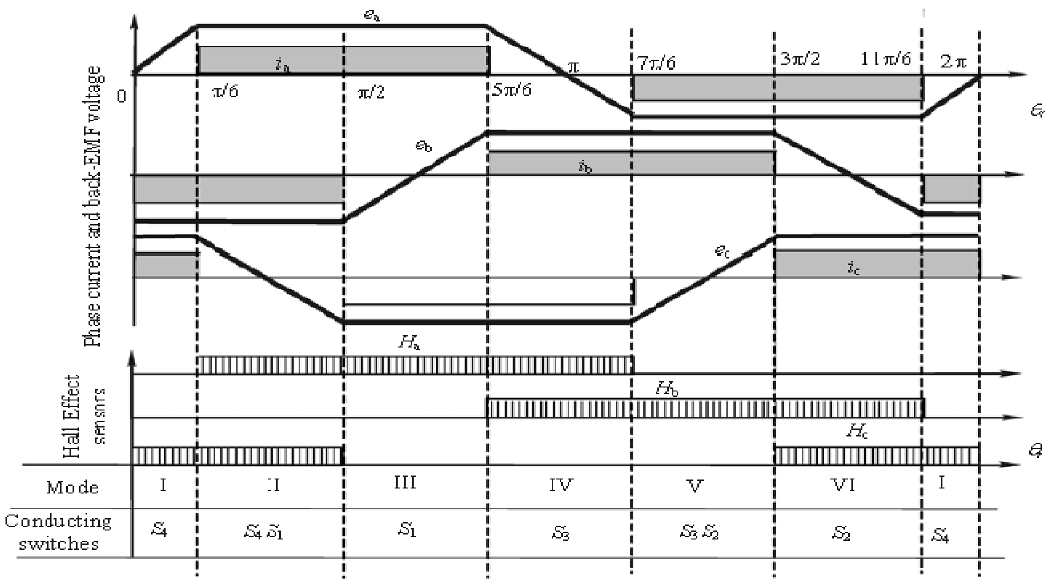

Figure 4: Signal waveforms of BLDC motor

Fig.4 shows the phase back-EMF and current waveforms, and Hall Effect sensor signals of a three phase BLDC motor drive in the ideal case. In each operation mode, only two phases are conducting and the third phase is inactive. To drive the motor with maximum and constant torque, the phase currents should be square waves. However, in a four-switch inverter, the generation of 120° conducting current profiles is inherently difficult. Hence, in order to use the four-switch inverter topology for a three-phase BLDC motor, the direct phase current (DPC) control approach is used. By this way, the currents of phases A and B in two modes II and V are controlled via independent current regulators. Therefore, the back-EMF voltage of phase C cannot cause current distortion in the phases A and B.

The Proposed Back-EMF Estimation Method

Consider a BLDC motor having three stator phase windings connected in star. PMs are mounted on the rotor. The BLDC motor is driven by a three phase inverter in which the devices are triggered with respect to the rotor position as shown in Fig.4. The phase A terminal voltage with respect to the star point of the stator V_{an}, is given in (1)

$$V_{an} = R_a i_a + L_a (di_a/dt) + e_a \quad (1)$$

Similar equations for the other two phases are,

$$V_{bn} = R_b i_b + L_b (di_b/dt) + e_b \quad (2)$$

$$V_{cn} = R_c i_c + Lc (di_c/dt) + e_c \quad (3)$$

From equation (1),(2),(3) the line voltage V_{ab} and

V_{bc} may be determined.

Assuming

$R_a = R_b = R_c = R$

$L_a = L_b = L_c = L$

$$V_{ab} = V_{an} - V_{bn} = R (i_a - i_b) + L(d (i_a - i_b) /dt) + e_a - e_b \quad (4)$$

$$V_{bc} = V_{bn} - V_{cn} = R(i_b - i_c) + L(d(i_b - i_c) /dt) + e_b - e_c \quad (5)$$

A similar expression can be written for V_{ca} also. These line voltages can however be estimated without the need for STAR point by taking the difference of terminal voltages measured with respect to the negative DC bus.

Subtracting (5) from (4) gives

$$V_{abbc} = R(i_a - 2i_b + i_c) + Ld(i_a - 2i_b + i_c)/dt + e_a - 2e_b + e_c \quad (6)$$

In the interval when phases A and C are conducting and phase B is open, phase A winding is connected to the positiveof the DC supply, phase C to the negative of the DC supply and phase B is open.

Therefore $i_a = -i_c$ and $i_b = 0$.

Therefore in this interval the equation is simplified as,

$$V_{abbc} = V_{ab} - V_{bc} = -2 e_b \quad (7)$$

The line voltage difference waveform thus is an inverted representation of the back-EMF waveform. The error between the line voltage difference and back EMF, also shown in Fig. 5 is negligible at the zero crossing instant. Therefore the operation V_{ab}-V_{bc} (V_{abbc}) enables detection of the zero crossing of the phase Back EMF. Similarly the line voltage difference V_{bcca} enables the detection of zero crossing of phase C back-EMF. The line voltage difference V_{caab} waveform gives the zero crossing of phase A back-EMF.

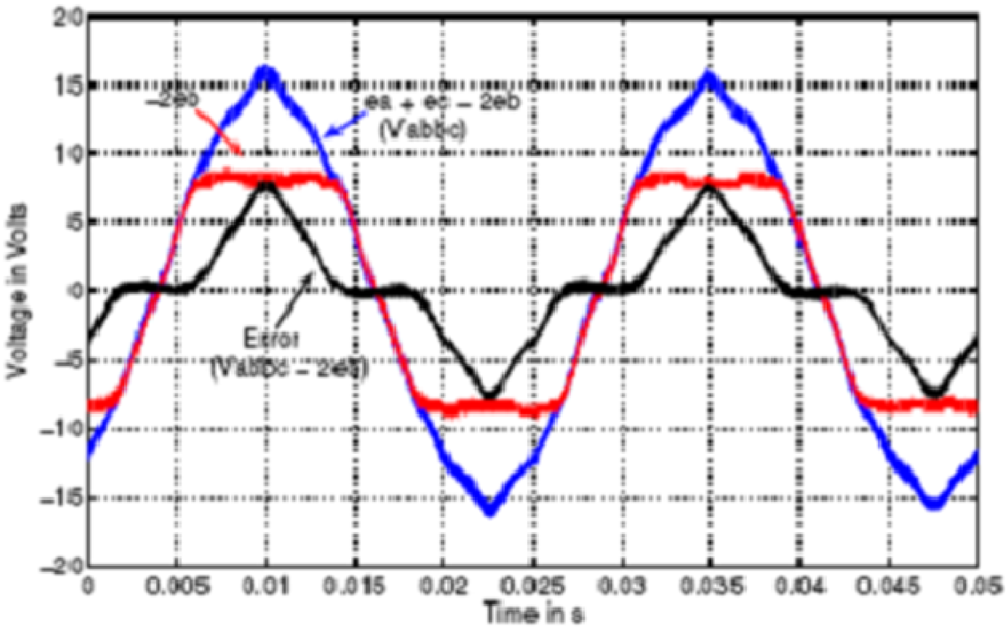

Figure 5: Line Voltage Difference and Back –EMF

Therefore the zero crossing instants of the back-EMF waveforms may be estimated indirectly from the line voltage differences. While the discussion above used an ideal trapezoidal waveform, the practical induced emf deviates from this wave shape due to slot ripples. The validity of (7) for a practical machine is verified from experimental waveforms. Real back- EMF waveforms are measured and the line voltage difference V_{abbc} is evaluated from the expression e_a+e_c-2e_b using the measured back-EMF waveforms in order to verify the ZCP match. Fig. 5 shows the V_{abbc} waveform along with the back- EMF waveform (multiplied by gain two, 2e_b) and the error between the two. It is evident from the Fig. 5 that the V_{abbc} waveform matches well with the back-EMF waveform -2e_b in the zero crossing regions. The error between the two, also shown in Fig. 5 is negligible at the zero crossing instant. The line voltage difference waveform is fed in to the virtual instrument developed in using RS232 serial communication. Using the LABVIEW the zero crossing of Line voltage difference is determined and the switching signals are generated. The switching signals are further fed to the FPGA controller through the same Serial port. In the micro controller the pulse width modulation of the particular signals are performed and fed to the MOSFET inverter circuit. The set speed is given by the user in the VI developed in LABVIEW and it fed to the FPGA controller using serial communication.

Hardware Implementation of the Proposed Method

Fig. 6 shows the block diagram of the proposed sensorless BLDC motor drive. Three phase bridge inverter fabricated using n – channel MOSFET is operated in 120 degree mode to provide square wave current excitation to the stator windings. The FSTP BLDC motor drives using the novel voltage PWM scheme have two phases to detect the back EMF, but the split capacitors cause the voltage waveform of back EMF to be triangular like. The voltages detected from phases A and B become two triangular like waveforms, and the voltage of the uncontrolled phase (phase C) becomes $V_{DC}/2$. PWM techniques use to produces the switching pulses for the 120 degree inverter. Inverter switches are triggered in a sequence provided by the high performance FPGA controller.

The output of driver circuit is ideally suited for driving power MOSFET's of low ratings. For isolation 4N35 opto coupler are used. The regulators 7812, 7912 and 7805 in the control circuit give the DC supply required by the driver and operational amplifier respectively. The driver chip amplifies 5V pulse to 10V level. DC output from the rectifier is ripple free due to the filter. The FPGA controller is used to generate the pulses.

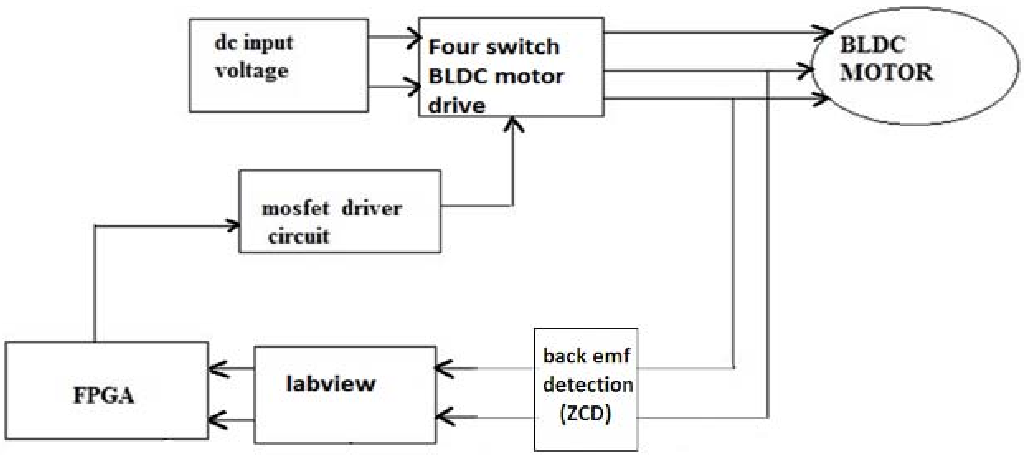

Figure 6: Block diagram of proposed method

Experimental Results

Specifications of BLDC motor drive is shown in Table-1. The crossings of the two controlled voltages which are filtered by low pass filters (LPF) , are detected by a comparator. The proposed algorithm is implemented with the Xilinx 3S100E that is built in the Xilinx Spartan-3E sample pack. Fig. 7 shows the whole experimental system configuration and Fig. 8 shows the line voltage difference waveform.

Table 1: Motor Specifications

PARAMETRS	SPECFICATIONS
Number of Poles	4 poles
Line to Line Resistance	0.2 Ohms
Line to line Inductance	0.45 mh
Nominal Voltage	48V
No load Speed	11500 RPM
No load Current	0.8 A
Rated Torque	0.05N-m
Rated Speed	10000RPM
Back EMF Constant	2V/KRPM
Torque Constant	0.02N-m/A
Weight	0.5 Kg

Figure 7: Configuration of four switch BLDC motor drive

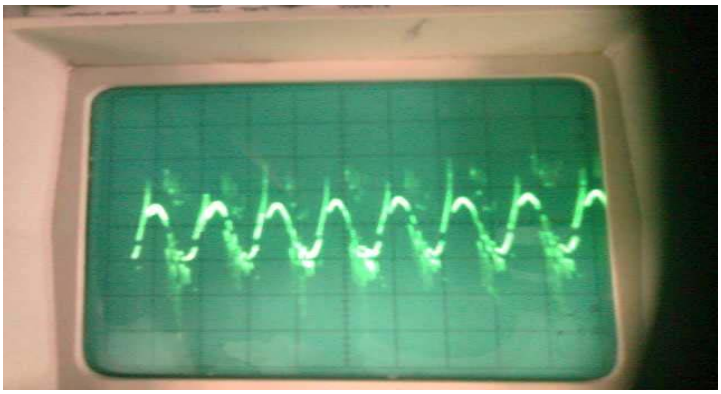

Figure 8: Line voltage difference waveform

The split capacitor bank must be large enough that it can be treated as a voltage source. The voltage across capacitors and the voltage ripple are applied across the switch. It is reasonable to allow 5% voltage ripple in the voltages across C1 and C2 [17], [18]. The relationship between the capacitors' ripple voltage and the current in the capacitors is

$$i_c = C\frac{\Delta V_c}{\Delta t}$$

$$C = \frac{i_c \Delta t}{\Delta Vc}$$

Using this, capacitor value is calculated.

Virtual Instrumentation and Its Results

LABVIEW is a graphical programming language that uses icons instead of lines of text to create applications. LABVIEW program facilitates Virtual Instrumentation (VI), which imitates the appearance and operation of physical instruments.

VI is defined as a process of combining hardware and software with industry standard computer technology to create a user-defined instrumentation solution. Several other add-on toolsets can be incorporated for developing the specialized applications. The voltage is measured and actual speed is determined. Serial VISA in stacked sequence of LABVIEW program is set with 9600bps and speed in the form of 8 bit data with start and stop bit is given as input. The first and fifth stacked sequence structure is shown in Fig.11 and Fig.12 The fifth stacked sequence contains the square wave generator block to produce PWM pulses. Using this data and according to set speed the gating signals are produced using LABVIEW software.

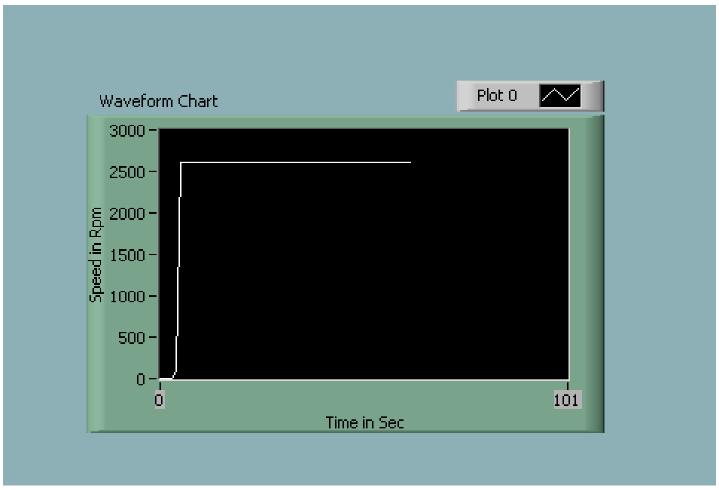

Figure 9: Speed wave form in LABVIEW Front panel for 2600 RPM

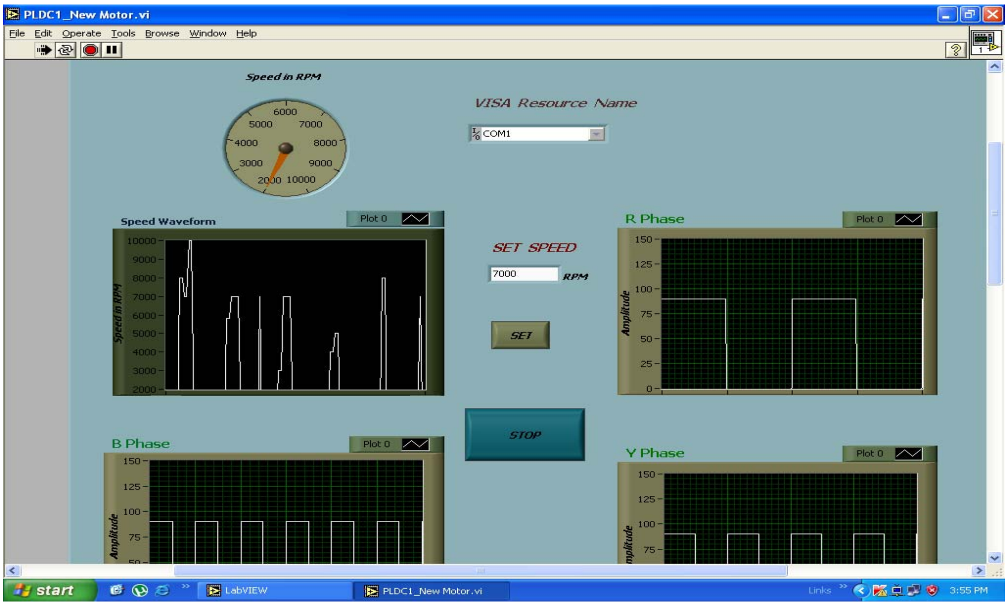

Figure 10: PWM pulses and speed waveform for 2000r.p.m

The Speed wave form for 2600 rpm is shown in Fig.9. From the wave form we observed that there is no peak overshoot and the settling time is also very less and the motor will run at constant speed. The PWM pulses and speed waveform is also displayed using LABVIEW as shown in Fig 10 The frequency of this pulses are measured and send that to FPGA using RS232, The PWM pulses are produced by the FPGA.

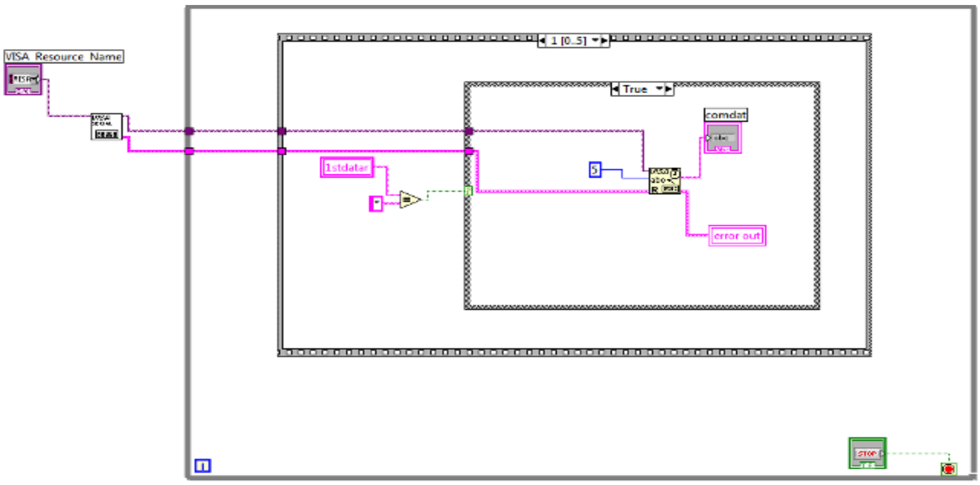

Figure 11: Stacked sequence-1

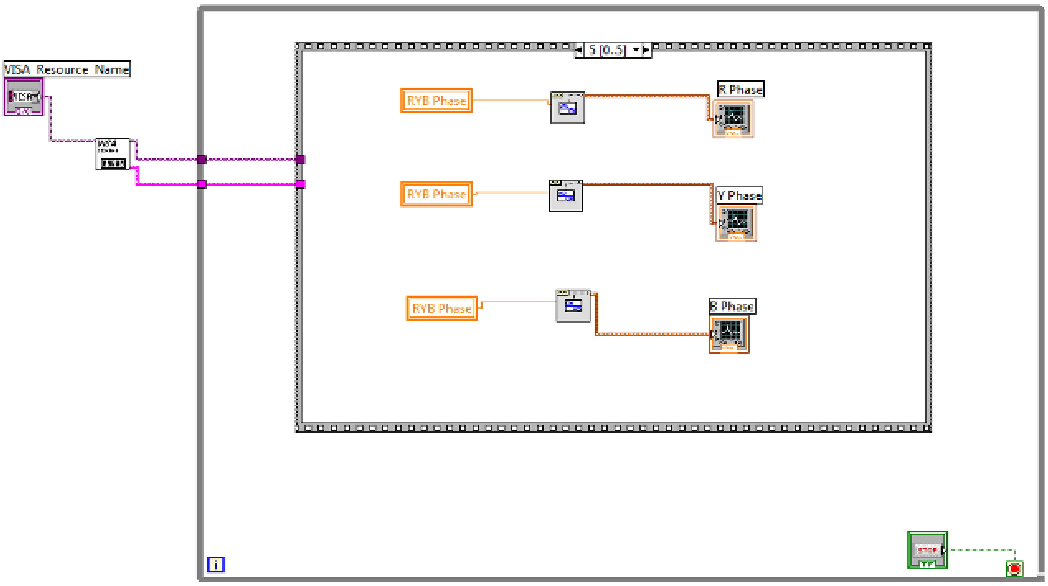

Figure 12: Stacked sequence-5

The results are also displayed in LABVIEW Front panel diagram easily. Fig 9 shows the results for the speed control of brushless dc motor using LABVIEW. The set speed and the actual speed of the motor is also displayed in front panel of LABVIEW.

Conclusion

This paper has presented a novel FPGA-based sensorless control scheme for four-switch three-phase brushless dc motor drives. The position information is estimated from the crossings of voltage waveforms in floating phases, and a low cost FPGA is utilized to implement the algorithm. Speed control of PMBLDC motor is achieved using virtual instrumentation. This proposed method controls the speed for various ranges. When Compared with the conventional back EMF zero crossing sensorless control, the proposed new sensorless control methods for brushless DC technique is more robust, easier to implement, and cost Effective because of virtual instrumentation and FPGA

The cost is reduced by reducing the hall sensors and two MOSFET switches and by using virtual zero crossing detection in LABVIEW. The speed control is achieved for different speed using this method is tabulated in TABLE- I for the motor having specifications given in TABLE- II.

Table-2

SET SPEED in RPM	ACTUAL SPEED in RPM
1500	1500
2600	2605
4000	4000
5000	5000
6000	6000
7800	7800

When Compared with the conventional back EMF zero crossing sensorless control, the proposed new sensorless control methods for brushless DC technique is more robust, easier to implement, and cost Effective because of virtual instrumentation and FPGA.

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