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Sensor-less field orientation control for brushless direct current motor controller for electric vehicles

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ABSTRACT

The electric vehicle traction of Brushless Direct Current Motor (BLDCM) is better from other electric machines due to its magnetic flux linkage, power to weight ratio and so on. The conventional Field Orientation Control (FOC) scheme with sensor for BLDCM has few shortcomings like deviation of current and thrust characteristics. In this paper, we have proposed a sensor less FOC for BLDCM. The back emf and speed of machine are estimated using slide mode controller which is given as a feedback to the motor controller part. The results are observed by varying reference speed which results in controlling the speed of machine accordingly. The results are verified by simulation and experimental evaluation. Simulation is done through MATLAB 2020a software and the experimental evaluation is done through Altair Embed Emulator which controls the BLDCM.

1. Introduction

The BLDCM is known to have high efficiency, reduced size and high torque which are essentially the most important factor to start the motor. Hence the Brushless Direct current motor is seen to have wide application in industrial products and automobiles [1]. The BLDCM is also known as electronically commutated motor as these motors are run on Direct current through an inverter source to feed the motor with an Alternating Current (AC) supply [2–3]. Every stator phase of the BLDCM is driven via a closed loop controller. The main usage of a closed loop feedback controller is to provide current pulse to the motor stator windings so as to have a control over the speed and torque and as both are complimentary phenomena in a motor. The Permanent Magnet Synchronous Motor sees a very similar construction to that of the BLDCM [4–5]. The main switching of industries from brushed motors to brushless motors is because of high power to weight ratio, low maintenance, and high speed [6–7]. In the late 20th century there was a significant boom in the field of solid state devices and semiconductor electronics, which allowed the shift of motors with commutators and brushes to brushless [8–9]. The Hall Effect sensor detects the rotor angle of the rotating part, and converters control the IGBT switches, it helps in maintaining the alternations of current in the trapezoidal windings, the back electromagnetic field (EMF) current reverse direction, or every 180-degree conduction mode the switches will be OFF and electromagnetic torque flows unidirectional. The brushes are not available in the BLDC motor which reduces the friction and avoids frequent maintenance, thus the life time has been increased. [10–11]. BLDCM converter commutation process is deploying from computer software tools, or other techniques to deployed from hardware like microprocessors, or digital signal processing (DSP), or field programmable gate array (FPGA) or dspace [12–13].

Commutation with brushless motor based electronic circuits rather than conventional brushes in dc motor allows for larger capability which cannot be derived from brushed motors, including speed limiting, small stepped working for slow and smooth control of rotational force, and a reverse torque that holds the rotor when not in motion. The program used for the microcontroller can be changed according to the needs and wants of the motor based on the application [14]. The microcontroller uses the regular brushes functionality needed for the rotor's orientation. The rotor position can be detected and measured by Hall Effect sensors. This is triggered automatically in brushed motors due to the fixed

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geometry of the brushes in front of the rotor. Some measure the back-EMF within the non-driven coils to gather the position of the rotor, rejecting the need for a separate sensor based on the principle of Hall Effect, and it is called sensor less controllers.

A general controller contains 3 dual directional outputs which are controlled by a circuit based on digital logic. Basic controllers make use of IC based comparator circuits to work out when the phase in the output should be higher, while more even better and higher configuration controllers use a microcontroller to keep track of acceleration, control speed and efficiency [15]. The rotor position can be sensed by back-EMF and send the signal to controllers are more complex when rotor at stationary. Based on the rotor rotation start to begin, stator phase winding is energised properly, otherwise phase energise wrongly. The converter switching sequence at initial position are more complex, when the motor runs backwards. The sensor-less controllers are made for measuring stator winding current flow caused by the direction of magnets to get the position of rotor [16–18]. BLDCM has numerous advantages but has the biggest disadvantage of having high cost in comparison to the regular DC motor that uses brushes for commutation, because of the use of an inverter and microcontrollers to get rid of the brushes used in regular DC motor. The most common comparison of the BLDCM is with PMSM, the speed adjusting performance and power density of the BLDCM is high compared to PMSM. The BLDCM is mainly powered with the help of either a Current Source Inverter (CSI) or a Voltage Source Inverter (VSI) [19–20]. The rotor position is obtained using sensors like hall sensors and optical encoders and using this information, the power electronic switches are commutated.

For an efficient control the speed of the motor the commutation logics are being controlled in the drive by collecting inputs from both drive and motors such as position of the rotor or rotor angle, stator currents, hysteresis band current, etc., [21]. Proper control of switching of various switches in motor drives confirms correct rotation of motor. Even though there are various methods for controlling the harmonic content in the supply in drives we prefer it to control through PWM technique in that specifically every one prefer to use space vector PWM control [22]. The back EMF generated in a BLDCM is a trapezoidal type back EMF and the stator field coils are fed by means of quasi square wave input current. These both Back EMF and input stator currents should be in phase with each other. Torque ripple is concerned with variation of speed during commutation of power switches in voltage source inverter. Several researches are done in torque ripple mitigation of BLDCM. Torque ripple mitigation include technique such as Field Orientation Control, Direct torque control, Current shaping technique, Voltage control technique, Intelligent control and Drive inverter Topology [23–24].

This paper represents a sensor less FOC for BLDCM. The back emf and speed of the machine are estimated using sliding mode controller. We have compared the results by varying the speed of the machine.

2. BLDC motor modelling

The rotor position of the BLDCM can be predictable by designing the model of a conventional DC Motor, which can be represented by stator winding resistance, inductance coil winding and the back EMF. Three phase BLDCM has three individual phase winding and a different rotor high-cost permanent magnet. While modelling rotor induced currents are neglected due to high resistivity of magnets and silicon core.

The three phase voltage equations for windings are modelled as follows,

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

where V_x, V_y and V_z are phase voltages of the BLDC motor, R is the stator resistance of the BLDCM, i_a,i_b and i_c are the stator currents of the BLDCM, L_{aa}, L_{bb} and L_{cc} represent the stator inductance of the BLDCM, e_a, e_b, and e_c represent the back EMF of the BLDCM. The resistance of the machine is assumed to be equal. The reluctance between the stator and rotor are assumed to be null (i.e there is no change in the stator and rotor reluctance angle.) then.

$$L_{aa} = L_{bb} = L_{cc} = L \tag{2}$$

$$L_{ab} = L_{ac} = L_{ba} = L_{bc} = L_{ca} = L_{cb} = M \tag{3}$$

Substituting the above equations in Eq. (1),

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{4}$$

Since the motor is star connected. And the stator currents are considered to be balanced.

$$i_a + i_b + i_c = 0 \tag{5}$$

This used to simplify the inductance matrix,

$$Mi_b + Mi_c = -Mi_a \tag{6}$$

Therefore the main equation becomes as,

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{7}$$

Since the back EMF of brush less direct current motor is trapezoidal. The back EMF equation are given as,

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \omega_m \lambda_m \begin{bmatrix} f_{as}(\theta_r) \\ f_{bs}(\theta_r) \\ f_{cs}(\theta_r) \end{bmatrix} \tag{8}$$

where ω_m is the rotating speed of the motor, λ_m is the flux linkage of the motor, $f_{as}(\theta_r)$, $f_{bs}(\theta_r)$ and $f_{cs}(\theta_r)$ represent the functions of back EMF for various magnitude instants. The flux linkages between the stator and rotor are made smooth. Hence the electromagnetic torque developed by the BLDC motor is given by the following expression-.

$$T_e = \frac{1}{\omega_m} * (e_a i_a + e_b i_b + e_c i_c) \tag{9}$$

The obtained phase voltage equation looks similar to the armature voltage equation of the direct current machine. The equation of motion of motor drive,

$$T_e - T_m = J\frac{d\omega}{dt} + F\omega(t) \tag{10}$$

where J is the combined inertia, F is the mechanical friction coefficient.

Electrical and mechanical speed of the motor are related by,

$$P\omega_m = \frac{d\theta_r}{dt} \tag{11}$$

where P is the number of poles of the motor.

Combining all the relevant equations, the system in state space equation becomes as,

$$x = Ax + Bu + Ce \quad (12)$$

where

$$x = [i_a \quad i_b \quad i_c \; \omega_m \quad \theta_r] \quad (13)$$

$$A = \begin{bmatrix} -\frac{R}{L-M} & 0 & 0 & -\lambda_m f_{as}(\theta_r) & 0 \\ 0 & -\frac{R}{L-M} & 0 & -\lambda_m f_{bs}(\theta_r) & 0 \\ 0 & 0 & -\frac{R}{L-M} & -\lambda_m f_{cs}(\theta_r) & 0 \\ \lambda_m f_{as}(\theta_r) & \lambda_m f_{bs}(\theta_r) & \lambda_m f_{cs}(\theta_r) & -\frac{B}{J} & 0 \\ 0 & 0 & 0 & \frac{P}{2} & 0 \end{bmatrix} \quad (14)$$

$$B = \begin{bmatrix} \frac{1}{L-M} & 0 & 0 & 0 \\ 0 & \frac{1}{L-M} & 0 & 0 \\ 0 & 0 & \frac{1}{L-M} & 0 \\ 0 & 0 & 0 & \frac{1}{L-M} \end{bmatrix} \quad (15)$$

$$C = \begin{bmatrix} -\frac{1}{L-M} & 0 & 0 \\ 0 & -\frac{1}{L-M} & 0 \\ 0 & 0 & -\frac{1}{L-M} \end{bmatrix} \quad (16)$$

3. Sensor-less field orientation control

One of the most conventional techniques for torque ripple mitigation is FOC. In a permanent magnet motor the desirable output is obtained when the rotor and stator flux linkages is 90°. In FOC, the feedbacks are obtained as voltage and current vectors. After the development of space vector pulse width modulation schemes led many researchers in the development of latest inventions in FOC. The stator currents are mostly characterized as Torque and Flux. The FOC topology is shown in Fig. 1.

The FOC starts with stator current measurement. The current relation is obtained as the formula shown below:

$$i_a + i_b + i_c = 0 \quad (17)$$

After the measurement of current. The abc currents are fed to Clarke transform block for converting reference frame currents into two co-ordinate orthogonal frames by the formula given below:

$$i_\alpha = i_a \quad (18)$$

$$i_\beta = \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b \quad (19)$$

Using park transform, the two axis time variant system is transformed to direct and quadrature axis.

$$i_d = i_\alpha \cos\theta + i_\beta \sin\theta \quad (20)$$

$$i_q = -i_\alpha \sin\theta + i_\beta \cos\theta \quad (21)$$

where θ is the rotor position angle. The d-q components represent the time invariant systems. The i_d reference is kept as zero and the i_q reference the speed reference with respect to the motor parameters. The PI controllers are used to process the error signals for controlling the output v_d and v_q vector signals.

The obtained d-q frameworks are again transformed into α and β frame works using inverse park's transform.

$$v_\alpha = v_d \cos\theta - v_q \sin\theta \quad (22)$$

$$v_\beta = v_d \sin\theta + v_q \cos\theta \quad (23)$$

The obtained α and β frame works are again transformed to abc frame works using inverse park transform in order to use generated voltage vectors to generate switching pulses using sinusoidal pulse width modulation.

$$v_a = v_\alpha \quad (24)$$

$$v_b = -\frac{1}{2} v_a + \frac{\sqrt{3}}{2} v_\beta \quad (25)$$

$$v_c = -\frac{1}{2} v_a - \frac{\sqrt{3}}{2} v_\beta \quad (26)$$

4. Estimation of back-EMF

Sensorless FOC mainly consists of the calculation of the angle at which the motor commutation happens. The main aim of Sensorless FOC is to estimate the rotor position and angle without using position sensors and by using estimation algorithms and control tools. Figure below shows a general working model of the position estimator. Speed and position of the motor are determined and estimated based on pre calculated V and I values. The Sensor used for positioning in the Sensorless algorithm is required not for getting the flux position, but instead the I_α and I_β are derived from current measurements, V_α and V_β are calculated during the FOC process. These 4 variables are given as an input to the position and speed estimator to find the rotor flux position, so that the sen-

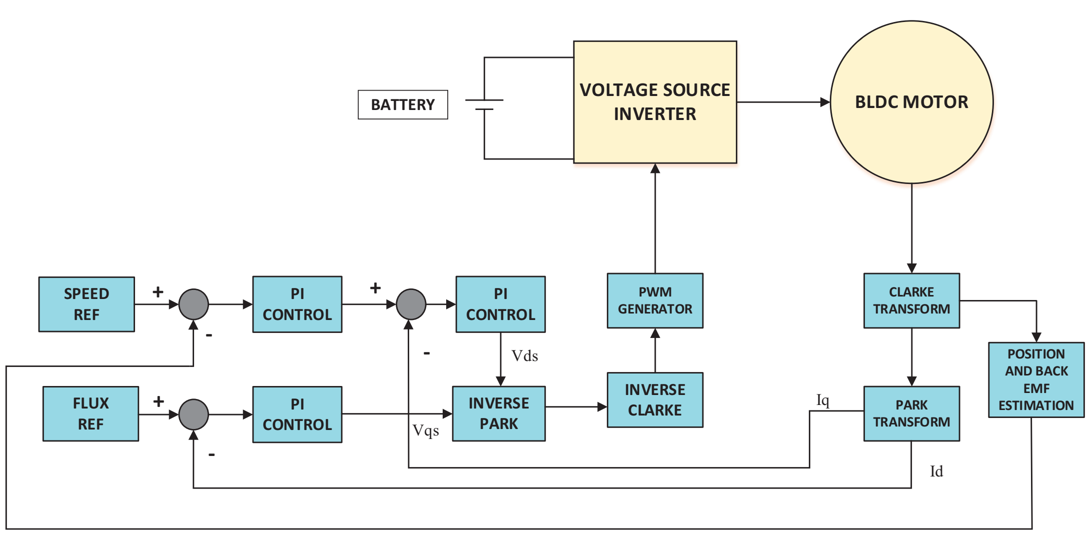


Fig. 1. Field orientation control Block diagram.

sor is not required. The motor model has two parameters that need to be modified for a particular motor. These two parameters are F and G gains, where.

$$F = 1 - T_S * \frac{R}{L} \quad (27)$$

$$G = \frac{T_S}{L} \quad (28)$$

Resistive and Inductance constants are found using a simple digital meter used for general measurements. For instance, if a L-L Resistance is found, the R used to find the gains F and G are the measured values divided by 2, this is done because the phase resistance is needed to be found. The exact same process is applicable for calculation of the inductance L.

The speed estimator and positioning sensors are based on digitized model of the motor made in the form of a current observer. These are derived in the equations given in previous sections. A SMC or Slide mode controller is a controller that is used control the digitized model of the motor. It is used to integrate the hardware motor eith the digitized motor model. The summation block in SMC sums the measured current with the estimated current of the digitized model. The SMC also estimates the sign of the summed value. The sign and the value is multiplied with the SMC gain factor and the output of the SMC is known as factor of correction or correction factor. This process repeats for n number of cycles until the error value becomes zero and is added to the input voltage of the digitized motor.

A digitized motor is calibrated and modelled with the same voltage and current values. The back EMF is estimated by filtering the correction factor and the new back emf values are fed back to the input. The values are updated after every control cycle. The current value and previous value of back emf are used as vector component for the back emf in the supply of the motor and is used in estimation of the rotor angle in the motor. The maximum value of frequency is made to be equal to the value of frequency that drives the motor. The presence of the Low pass filter causes a phase delay of forty-five degrees in every cycle of angular compensation in al ranges of speed. The motor gathers higher speed for changes in frequency at the same time. The LPF output is used in 2 block and the first block is a digitized motor model where the calculation of the current of the future steps (estimated steps), and is also used to calculate the estimated value of the angular rotation theta. The second is for the low pass digital filter and it is used for the calculation of a smoother modulated as an output of the digitized motor model.

$$\theta = arc\ \tan\left(e_\alpha, e_\beta\right) \quad (29)$$

Table 1
Motor controller parameters.

S.no	Parameters	Values
1	Supply voltage (V_{dc})	48 V
2	Motor voltage	48 V
3	poles	4
4	Stator inductance	10.5 mH
5	Mutual inductance	1H
6	Stator Resistance	1.12 Ω
7	Power ratings	250 W
8	Current reference	0.7

5. Simulation and experimentation of proposed sensor-less field orientation control

The overall analysis, performance and designing of electronic differential is done and the results are verified through MATLAB simulations. The parameter used for FOC simulation is shown in Table 1. The results are evident that vector control of brushless direct current motor provides less torque ripples and good response over dynamic conditions. Fig. 2(a) and (b) represent the vector control output.

5.1. Altair embed code generation

Altair embed is visual simulator which is used to generate embedded codes for various micro controllers such as C2000 series, TSP series and STM series micro controllers. Flow paradigm of Altair embed depends on graphical data and differential equations. In order to implement vector control of motor drives in controller Altair embed uses dynamic diagnosation of various instants. These can be classified into various phases. Phase A refers to open loop diagnosation and code generation. Phase B refers to variable frequency control and phase C refers to closed loop speed control. In this proposed system we are dealing with phase C closed loop emulation. The compilation of phase c refers to run a file visual simulator file with dynamic diagnosation. We can categorise the code generation in following ways dynamic variable designing, main motor control designing, output code fetching and code compilation. Since the main used topology is FOC, the motor control used needs to be coded with various equation of FOC. Fig. 3 shows the main block diagram in Altair embed visual simulator.

This blocks represent phase c control of visual simulation of motor controller. These blocks are used to control brushless direct control motor. The motor output is computed in the post scaling block while the feedback of motor is given back to the motor controller through pre scaling block.

5.2. Main motor controller designing

The Main Motor Controller Used Works On FOC Topology. FOC Can Be Divided Into Following Division Park And Clarke Transformation Designing, I_d And I_q Designing, K_p And K_i Designing And Pulse Width Modulation Designing. The Corresponding Pic-

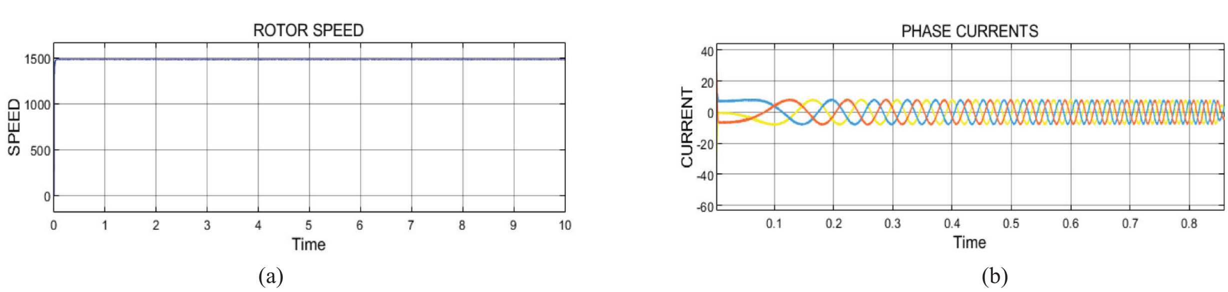


Fig. 2. (a) Rotor speed, (b) Phase currents of BLDC motor using field orientation control.

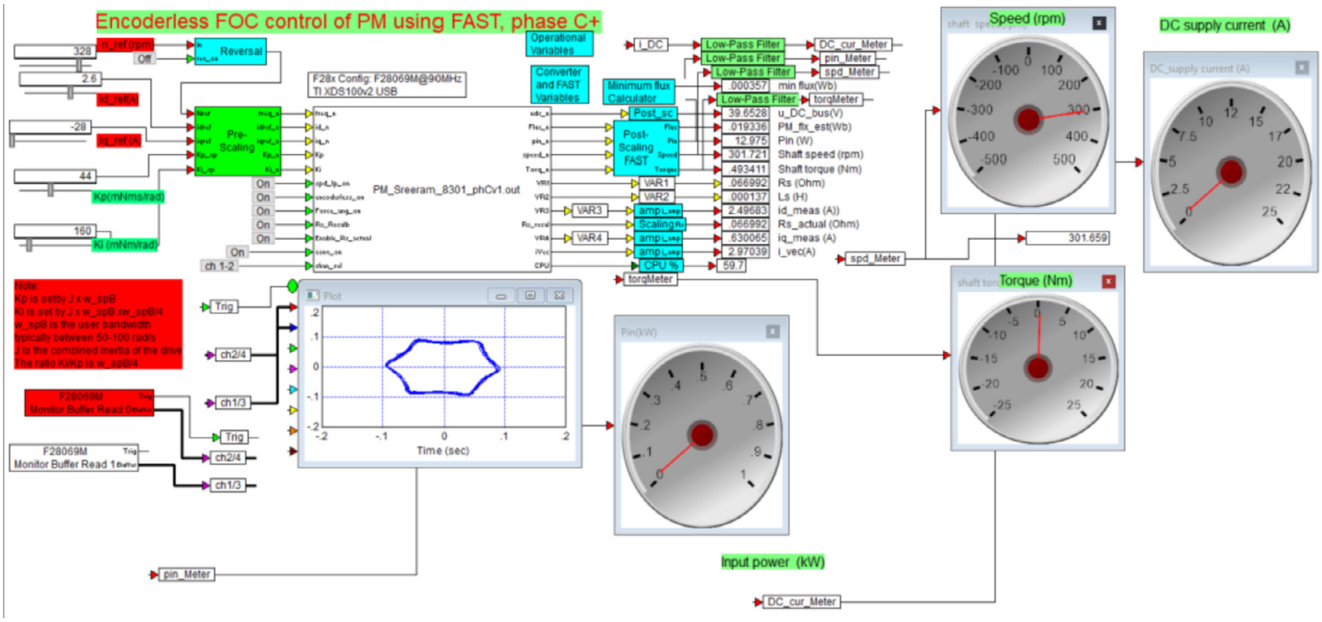


Fig. 3. Altair Embed Emulator Block.

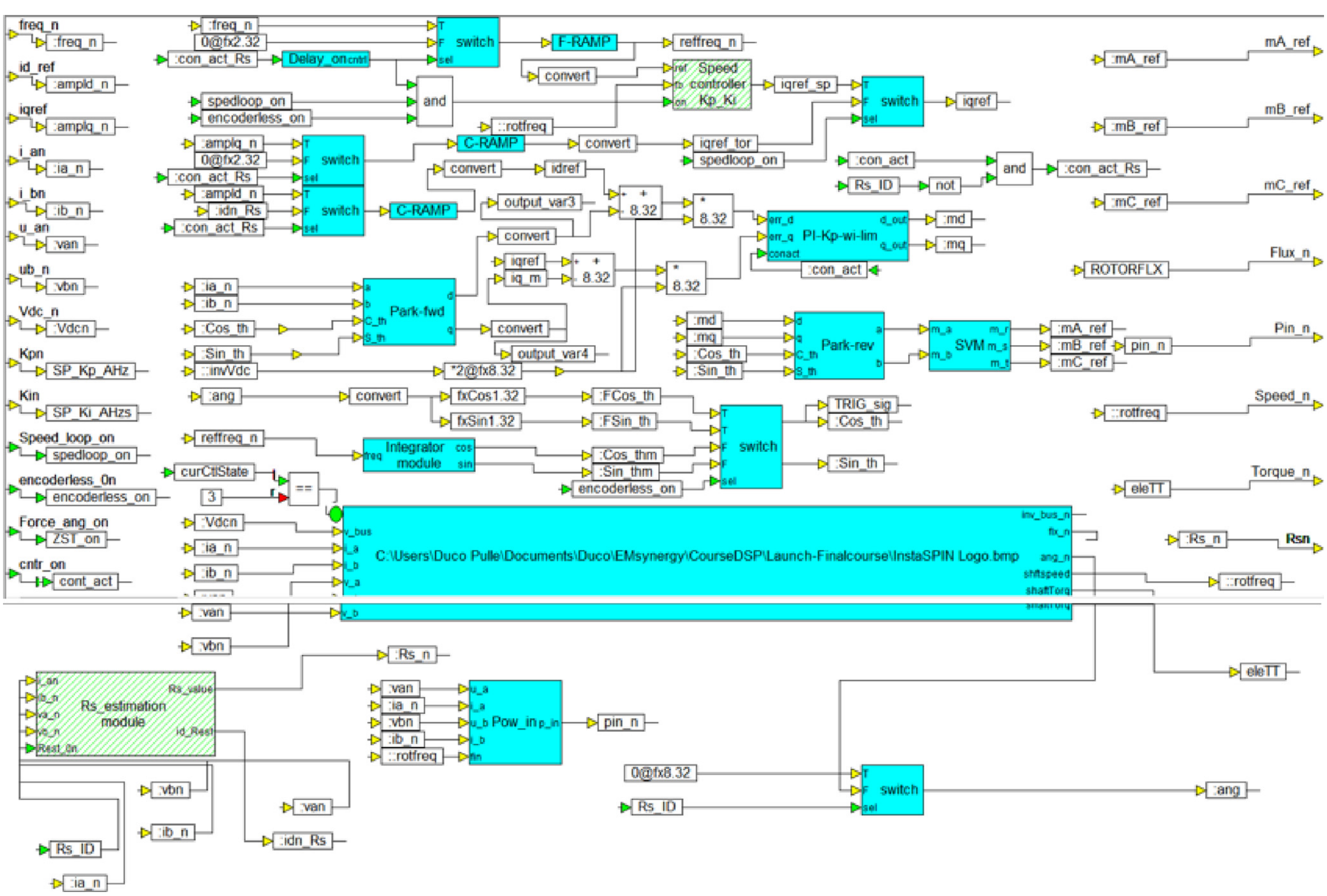


Fig. 4. Main Motor Control Blocks.

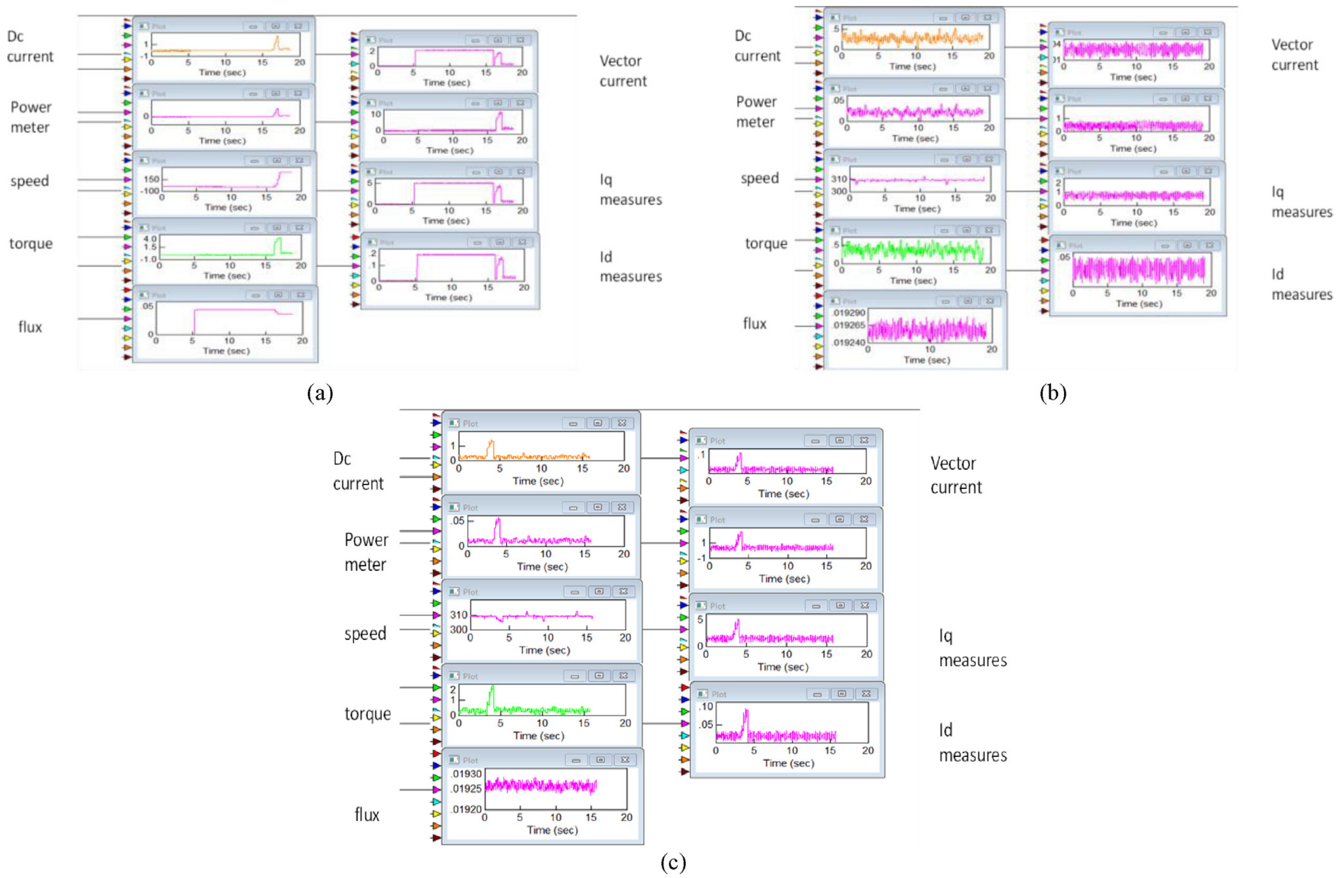
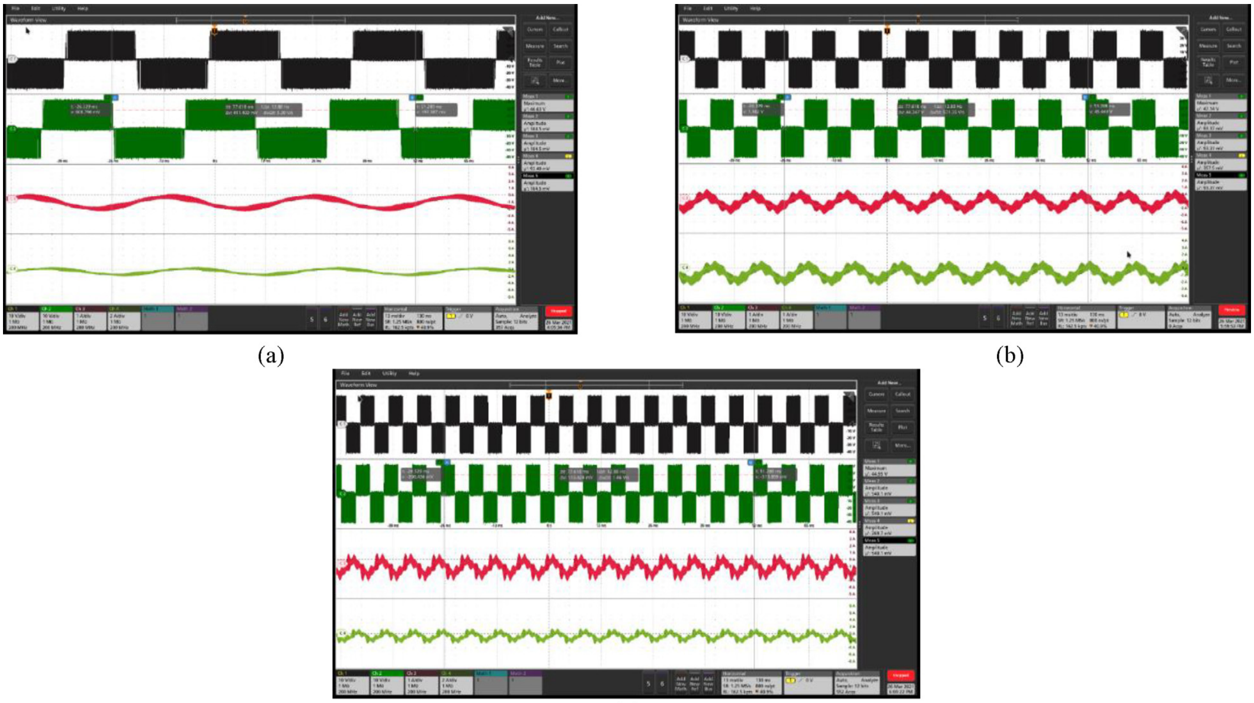


Fig. 5. Motor Output during (a) Starting Condition, (b) Normal Condition and (c) Loading Condition.

Fig. 6. Experimental Setup of proposed sensor-less field orientation control.

ture Depicts The Main Motor Controller Designing And The Code Generated Is Also Shown In The Upcoming Slides. Since FOC with sensor is used, the flux, resistance and inductance are not estimated. They are fed as input to the motor controller from motor. The used sensors are speed encoders, voltage and current transducer.

The motor control block in the altair embed software is shown in Fig. 4 while output of the motor during starting condition, normal condition and loading condition is obtained as shown in Fig. 5. The proposed experiment hardware platform is shown in Fig. 6 includes a brushless direct current motor, regulated power supply, Altair embed software, mixed scale oscilloscope and DRV C2-H2 kit motor controller which use TMS320F280 DSP as microcontroller. This Altair embed software is a emulator which can be used for coding various microcontrollers using visual simulation. The only disadvantage is that the simulation is very complex and not user friendly. Fig. 7(a)–(c) represents the motor back EMF and output current at various speeds such as low speed, medium speed and



(a) (b) (c)

Fig. 7. Phase current and line-line voltage waveform at (a) low speed, (b) medium speed and (c) high speed.

high speed respectively. Low speed is designated to be 60 rpm and medium speed as 180 rpm and high speed at 380 rpm.

6. Conclusion

This work deals about the sensor-less FOC of brushless direct current motor with regulated power supply as input. The FOC technique controls the speed of BLDC motor based on the reference speed input. The performance of the motor drive is evaluated at various speeds and the results are evaluated by MATLAB/SIMULINK. Hardware evaluation is done through Altair embed emulation software which implements the FOC control method to drive the motor. The speed of BLDC motor is controlled by varying the reference speed in the altair embed software. We infer that sensor-less FOC provides good response at various speeds. The proposed scheme provides an effective solution for various transient condition.

CRediT authorship contribution statement

P. Ramesh: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **A. Ranjeev:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **C. Santhakumar:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **J. Vinoth:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **C. Bharatiraja:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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