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Modeling and Performance Analysis of BLDC Motor under Different Operating Speed Conditions

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Abstract: ***The modeling and performance analysis of BLDC motor under different operating speed conditions has been presented in this paper. BLDC motors have been gaining attention from various Industrial and household appliance manufacturers, because of its high efficiency, high power density, and low maintenance cost. After many research and developments in the fields of magnetic materials and power electronics, their applications to electric drives have increased to a significant extent. In this paper, the modeling of Brushless DC motor drive system along with control system for speed and current has been presented using MATLAB / SIMULINK. In order to evaluate the model, various cases of simulation studies are carried out. Test results thus obtained show that the model performance is satisfactory.***

Keywords: BLDC motor, Hall sensor, Speed control.

1. Introduction

Brushless DC motors have been used in various industrial and domestic applications. Due to overweighing merits of this motor, there is continuing trend to propose improved control schemes to enhance the performance of the motor [1]. For analysis of the BLDC motor drives system under various conditions, models such as d-q model and abc phase variable models have been developed. Several simulation models were proposed based on non-linear state-space equations.

BLDC Motor considered in these models is star connected with neutral grounding, but several applications require isolated neutral. Keeping merits of these developments in view, in this paper the motor is modeled as star connected with isolated neutral and the voltages supplied are line-line. Modeling the complete control scheme is beneficial in carrying out the comprehensive simulation studies. Such comprehensive simulation studies are not reported [2]. This paper deals with simulation models of PWM inverter and the controllers for the BLDC motor. The performance of this simulation is examined under no-load, variable load at variable speeds, blocked rotor, and intermittent loads. In addition, four quadrant operation of BLDC motor is also carried out.

2. Brushless DC Motor

Brushless Direct Current (BLDC) motors are one of the motor types rapidly gaining popularity. BLDC motors are used in industries such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment, and Instrumentation. As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors [3]. The complete drive system is shown in Fig. 1. It can be categorized into BLDC motor, Inverter, Current Controller, Speed Controller and Quad Determination Block for Four-Quadrant Operation. Each block is modeled separately and integrated together.

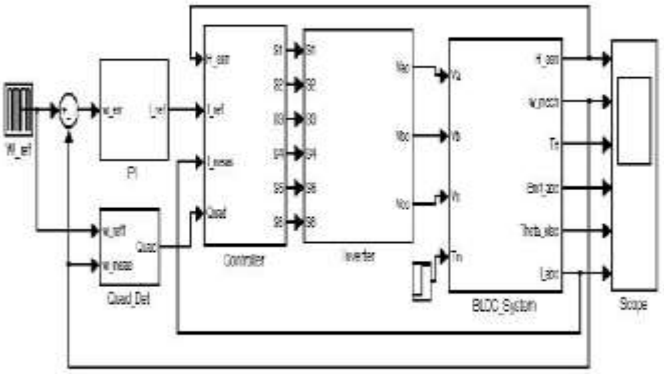

Figure 1: Simulink model of BLDC drive system

- Better speed versus torque characteristics
- High dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges

In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors.

2.1 Construction and Operating Principle

BLDC motors are a type of synchronous motor. This means the magnetic field generated by the stator and the magnetic field generated by the rotor rotates at the same frequency. BLDC motors do not experience the “slip” that is normally seen in induction motors [4]. BLDC motors come in single-phase, 2-phase and 3-phase configurations. Corresponding to its type, the stator has the same number of windings. Out of these, 3-phase motors are the most popular and widely used. This application note focuses on 3-phase motors.

a) Stator

The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery. Traditionally, the stator resembles that of an induction motor; however, the windings are distributed in a different manner. Most BLDC motors have three stator windings connected in star fashion. Each of these windings is constructed with numerous coils interconnected to form a winding. One or more coils are placed in the slots and they are interconnected to make a winding. Each of these windings is distributed over the stator periphery to form even numbers of poles. There are two types of stator windings variants: trapezoidal and sinusoidal motors.

This differentiation is made on the basis of the interconnection of coils in the stator windings to give the different types of back Electromotive Force (EMF). Refer to the **“**What is Back EMF**?”** section for more information.

As their names indicate, the trapezoidal motor gives a back EMF in trapezoidal fashion and the sinusoidal motor’s back EMF is sinusoidal, as shown in Fig. 2 and Fig. 3. In addition to the back EMF, the phase current also has trapezoidal and sinusoidal variations in the respective types of motor. This makes the torque output by a sinusoidal motor smoother than that of a trapezoidal motor [5]. However, this comes at an extra cost, as the sinusoidal motors take extra winding interconnections because of the coils distribution on the stator periphery, thereby increasing the copper intake by the stator windings.

Depending upon the control power supply capability, the motor with the correct voltage rating of the stator can be chosen. Forty-eight volts or less voltage rated motors are used in automotive, robotics, small arm movements and soon. Motors with 100 volts, or higher ratings, are used in appliances, automation and in industrial applications.

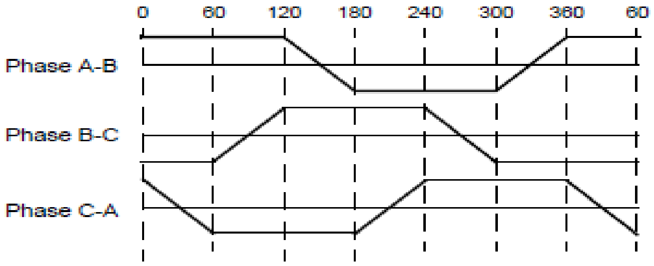

Figure 2: Trapezoidal back EMF

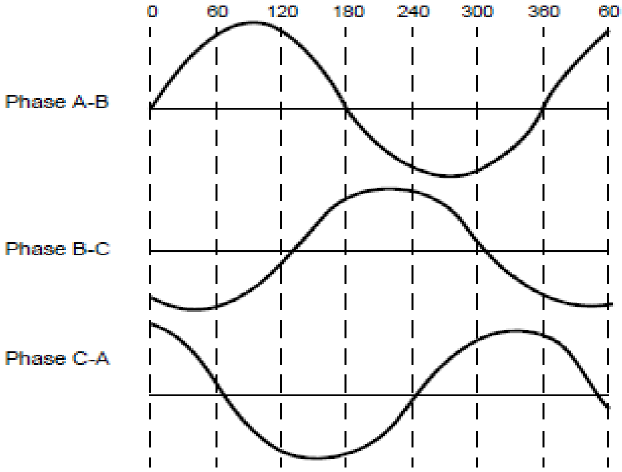

Figure 3: Sinusoidal back EMF

b) Rotor

The rotor is made of a permanent magnet and can vary from two to eight pole pairs with alternate North (N) and South (S) poles. Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets are traditionally used to make permanent magnets [6]. As the technology advances, rare earth alloy magnets are gaining popularity. The ferrite magnets are less expensive but they have the disadvantage of low flux density for a given volume. In contrast, the alloy material has a high magnetic density per volume and enables the rotor to compress further for the same torque.

Also, these alloy magnets improve the size-to-weight ratio and give higher torque for the same size motor using ferrite magnets. Neodymium (Nd), Samarium Cobalt (SmCo) and the alloy of Neodymium, Ferrite and Boron (NdFeB) are some examples of rare earth alloy magnets. Continuous research is going on to improve the flux density to compress the rotor further.

Fig. 4 shows cross sections of different arrangements of magnets in a rotor.

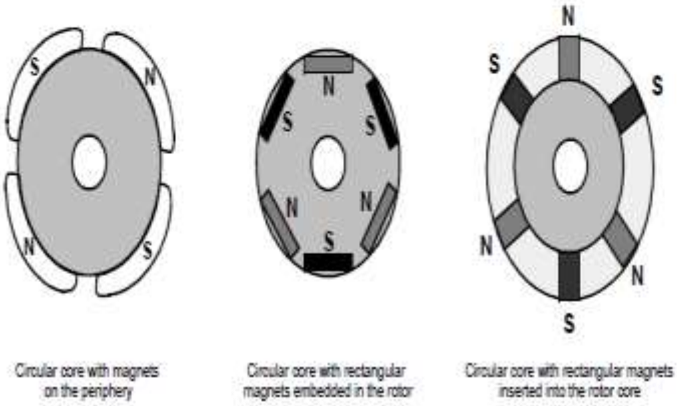

Figure 4: Rotor magnet cross section

c) Hall Sensors

Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence [7]. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall effect sensors embedded into the stator.

TABLE 1: Hall sensors modeled as a function of rotor angle

Theta_ele	h_1	h_2	h_3
0^0 - 60^0	1	0	1
60^0 - 120^0	0	0	1
120^0 - 180^0	0	1	1
180^0 – 240^0	0	1	0
240^0 – 300^0	1	1	0
300^0 - 360^0	1	0	0

It regulates the actual current within the hysteresis band around the reference currents. The reference currents are generated by a reference current generator depending upon the steady state operating mode. The reference currents are of quasi –square wave. They are developed in phase with the back-emf in the motoring mode and out of phase in a braking mode. The magnitude of the reference current is calculated from the reference torque. The reference torque is obtained by limiting the output of the PI controller. The PI controller processes on the speed error signal (i.e. the difference between the reference speed and actual speed) and outputs to the limiter to produce the reference torque. The actual speed is sensed back to the speed controller and processed on to minimize the error in tracking the reference speed. Thus, it is a closed loop control drive system.

Most BLDC motors have three Hall sensors embedded into the stator on the non-driving end of the motor. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined.

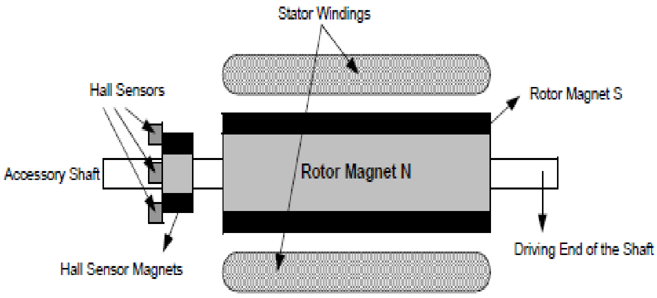

Figure 5: Transverse section of BLDC motor

Fig. 5 shows a transverse section of a BLDC motor with a rotor that has alternate N and S permanent magnets. Hall sensors are embedded into the stationary part of the motor. Embedding the Hall sensors into the stator is a complex process because any misalignment in these Hall sensors, with respect to the rotor magnets, will generate an error in the determination of the rotor position.

To simplify the process of mounting the Hall sensors onto the stator, some motors may have the Hall sensor magnets on the rotor, in addition to the main rotor magnets. These are a scaled down replica version of the rotor. Therefore, whenever the rotor rotates, the Hall sensor magnets give the same effect as the main magnets. The Hall sensors are normally mounted on a PC board and fixed to the enclosure cap on the non-driving end. This enables users to adjust the complete assembly of Hall sensors, to align with the rotor magnets, in order to achieve the best performance.

Based on the physical position of the Hall sensors, there are two versions of output. The Hall sensors may be at 60° or 120° phase shift to each other. Based on this, the motor manufacturer defines the commutation sequence, which should be followed when controlling the motor.

d) TYPICAL BLDC MOTOR APPLICATIONS:

BLDC motors find applications in every segment of the market. Automotive, appliance, industrial controls, automation, aviation and so on, have applications for BLDC motors. Out of these, we can categorize the type of BLDC motor control into three major types:

- Constant load
- Varying loads
- Positioning applications

Applications with Constant Loads

These are the types of applications where a variable speed is more important than keeping the accuracy of the speed at a set speed. In addition, the acceleration and deceleration rates are not dynamically changing. In these types of applications, the load is directly coupled to the motor shaft. For example, fans, pumps, and blowers come with these types of applications. These applications demand low-cost controllers, mostly operating in open-loop.

Applications With Varying Loads

These are the types of applications where the load on the motor varies over a speed range. These applications may demand a high-speed control accuracy and good dynamic responses. In home appliances, washers, dryers, and compressors are good examples. In automotive, fuel pump control, electronic steering control, engine control and electric vehicle control are good examples of these. In aerospace, there are a number of applications, like centrifuges, pumps, robotic arm controls, gyroscope controls and so on.

These applications may use speed feedback devices and may run in a semi-closed loop or in the total closed loop. These applications use advanced control algorithms, thus complicating the controller. Also, this increases the price of the complete system.

Positioning Applications

Most of the industrial and automation types of application come under this category. The applications in this category have some kind of power transmission, which could be mechanical gears or timer belts, or a simple belt is driven system. In these applications, the dynamic response of speed and torque are important. Also, these applications may have a frequent reversal of rotation direction.

A typical cycle will have an accelerating phase, a constant speed phase and a deceleration and positioning phase. The load on the motor may vary during all of these phases, causing the controller to be complex. These systems mostly operate in a closed loop. There could be three control loops functioning simultaneously: Torque Control Loop, Speed Control Loop, and Position Control Loop. Optical encoder or synchronous resolvers are used for measuring the actual speed of the motor.

In some cases, the same sensors are used to get relative position information. Otherwise, separate position sensors may be used to get absolute positions. Computer Numeric Controlled (CNC) machines are a good example of this. Process controls, machinery controls, and conveyer controls have plenty of applications in this category.

3. Four-Quadrant Operation of BLDC Motor

Firstly, the steady-state speed is determined by the applied voltage, so we can make the motor run at any desired speed in either direction simply by applying the appropriate magnitude and polarity of the armature voltage [8]. Secondly, the torque is directly proportional to the armature current, which in turn depends on the difference between the applied voltage V and the back e.m.f. E. We can, therefore, make the machine develop positive (motoring) or negative (generating) torque simply by controlling the extent to which the applied voltage is greater or less than the back e.m.f. An armature voltage controlled d.c. the machine is therefore inherently capable of what is known as four-quadrant operation, with reference to the numbered quadrants of the torque-speed plane shown in Fig. 6.

Fig. 6 looks straightforward but experience shows that to draw the diagram correctly calls for a clear head, so it is worth spelling out the key points in detail. A proper understanding of this diagram is invaluable as an aid to seeing how controlled-speed drives operate.

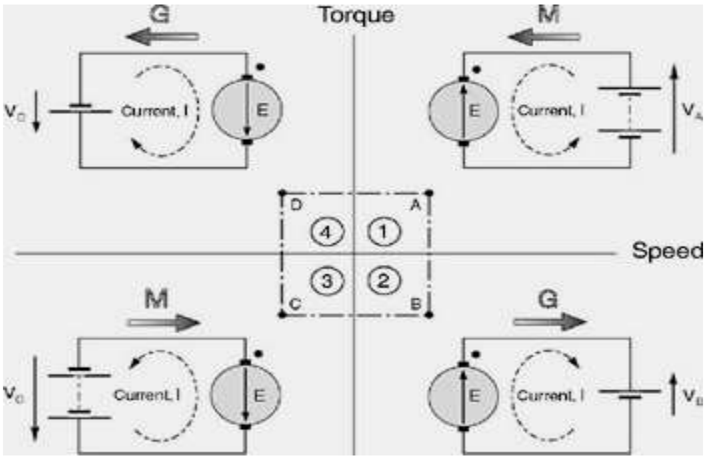

Figure 6: Operation of d.c. the motor in the four quadrants of the torque-speed plane

Firstly, one of the motor terminals is shown with a dot, and in all four quadrants, the dot is uppermost. The purpose of this convention is to indicate the sign of the torque: if current flows into the dot, the machine produces positive torque, and if current lows out of the dot, the torque is negative. Secondly, the supply voltage is shown by the old-fashioned battery symbol, as the use of the more modern circle symbol for a voltage source would make it more difficult to differentiate between the source and the circle representing the machine armature. The relative magnitudes of applied voltage and motional e.m.f. are emphasized by the use of two battery cells when V > E and one when V < E.

We have seen that in a d.c. machine speed is determined by applied voltage and torque is determined by the current. Hence on the right-hand side of the diagram, the supply voltage is positive (upwards), while on the left-hand side the supply voltage is negative (downwards). And in the upper half of the diagram current is positive (into the dot), while in the lower half it is negative (out of the dot). For the sake of convenience, each of the four operating conditions (A, B, C, D) have the same magnitude of speed and the same magnitude of torque: these translate to equal magnitudes of motional e.m.f. and current for each condition. When the machine is operating as a motor and running in the forward direction, it is operating in quadrant 1.

The applied voltage VA is positive and greater than the back e.m.f. E, and positive current, therefore, flows into the motor: in Fig. 6, the arrow representing VA has accordingly been drawn larger than E. The power drawn from the supply (VAI) is positive in this quadrant, as shown by the shaded arrow labeled M to represent motoring. The power converted to mechanical form is given by EI, and an amount I2R is lost as heat in the armature. If E is much greater than IR (which is true in all but small motors), most of the input power is converted to mechanical power, i.e. the conversion process is efficient. If with the motor running at position A, we suddenly reduce the supply voltage to a value VB which is less than the back e.m.f., the current (and hence torque) will reverse direction, shifting the operating point to B in Fig. 6. There can be no sudden change in speed, so the e.m.f. will remain the same. If the new voltage is chosen so that E — VB = VA — E, the new current will have the same amplitude as at position A, so the new (negative) torque will be the same as the original positive torque.

But now power is supplied from the machine to the supply, i.e. the machine is acting as a generator, as shown by the shaded arrow.

We should be quite clear that all that was necessary to accomplish this remarkable reversal of power flow was a modest reduction of the voltage applied to the machine. At position A, the applied voltage was E + IR, while at position B it is E-IR. Since IR will be small compared with E, the change (2IR) is also small. Needless to say, the motor will not remain at point B if left to its own devices. The combined effect of the load torque and the negative machine torque will cause the speed to fall, so that the back e.m.f. again falls below the applied voltage VB, the current and torque become positive again, and the motor settles back into quadrant 1, at a lower speed corresponding to the new (lower) supply voltage. During the deceleration phase, kinetic energy from the motor and load inertias is returned to the supply.

This is, therefore, an example of regenerative braking, and it occurs naturally every time we reduce the voltage in order to lower the speed. If we want to operate continuously at position B, the machine will have to be driven by a mechanical source. We have seen above that the natural tendency of the machine is to run at a lower speed than that corresponding to point B, so we must force it to run faster, and create an e.m.f greater than VB, if we wish it to generate continuously.

It should be obvious that similar arguments to those set out above apply when the motor is running in reverse (i.e. V is negative). Motoring then takes place in quadrant 3 (point C), with brief excursions into quadrant 4 (point D, accompanied by regenerative braking), whenever the voltage is reduced in order to lower the speed.

3.1 Modeling of Hysteresis Controller

Hysteresis controller limits the phase currents within the Hysteresis band by switching ON/OFF the power devices. The switching pattern is given as:

If $i_a^{err} > UL$, S1 is on and S4 is off.

If $i_a^{err} < LL$, S1 is off and S4 is on.

If $i_b^{err} > UL$, S3 is on and S6 is off.

If $i_b^{err} < LL$, S3 is off and S6 is on.

If $i_c^{err} > UL$, S5 is on and S2 is off.

If $i_c^{err} < LL$, S5 is off and S2 is on.

Where $i_k^{err} = i_k^{ref} - i_k^{meas}$ and UL, LL are the upper and lower limits of hysteresis band. Thus, by regulating the current desired quasi-square waveforms can be obtained.

3.2 Modeling of Reference Current Generator

The desired reference currents are injected into the hysteresis controller. The magnitude of the reference current is determined from the reference torque and back-emf constant. The incoming or outgoing direction of the current is determined from hall sensors output and the operating mode [9]. The reference currents for four steady state operations are modeled as shown in Table 2 (Forward motoring and reverse braking) and Table 3 (Reverse motoring and forward braking:

TABLE 2: Reference currents for forwarding motoring and reverse braking

h_1	h_2	h_3	Ref I_a	Ref I_b	Ref I_c
1	0	1	0	I^*	$-I^*$
0	0	1	I^*	0	$-I^*$
0	1	1	I^*	$-I^*$	0
0	1	0	0	$-I^*$	I^*
1	1	0	$-I^*$	0	I^*
1	0	0	$-I^*$	I^*	0

TABLE 3: Reference currents for reverse motoring and forward braking

h_1	h_2	h_3	Ref I_a	Ref I_b	Ref I_c
1	0	1	0	$-I^*$	I^*
0	0	1	$-I^*$	0	I^*
0	1	1	$-I^*$	I^*	0
0	1	0	0	I^*	$-I^*$
1	1	0	I^*	0	$-I^*$
1	0	0	I^*	$-I^*$	0

3.3 Modeling of Speed Controller

Conventional PI controller is used as a speed controller for recovering the actual motor speed to the reference. The reference and the measured speed are the input signals to the PI controller. The *KP* and *KI* values of the controller are determined by trial and error method for each set speed. The controller output is limited to give the reference torque [10].

4. Simulation Results and Discussion

The modeling and performance analysis of BLDC motor under different operating speed conditions are simulated in the MATLAB/Simulink environment and its performance of the BLDC motor presented in the Fig. 7 to Fig. 20 under different load and speed conditions.

CASE I: BLDC four quadrant modes of operation

The motor is operated in four steady-state operating modes of the torque-speed plane. At initial conditions, the motor is operated in (Quad-I) Forward motoring mode. When a speed reversal command is issued, the motor undergoes braking operation in the forward direction, with speed tending to zero and starts rotating in reverse direction as soon as the speed is zero.

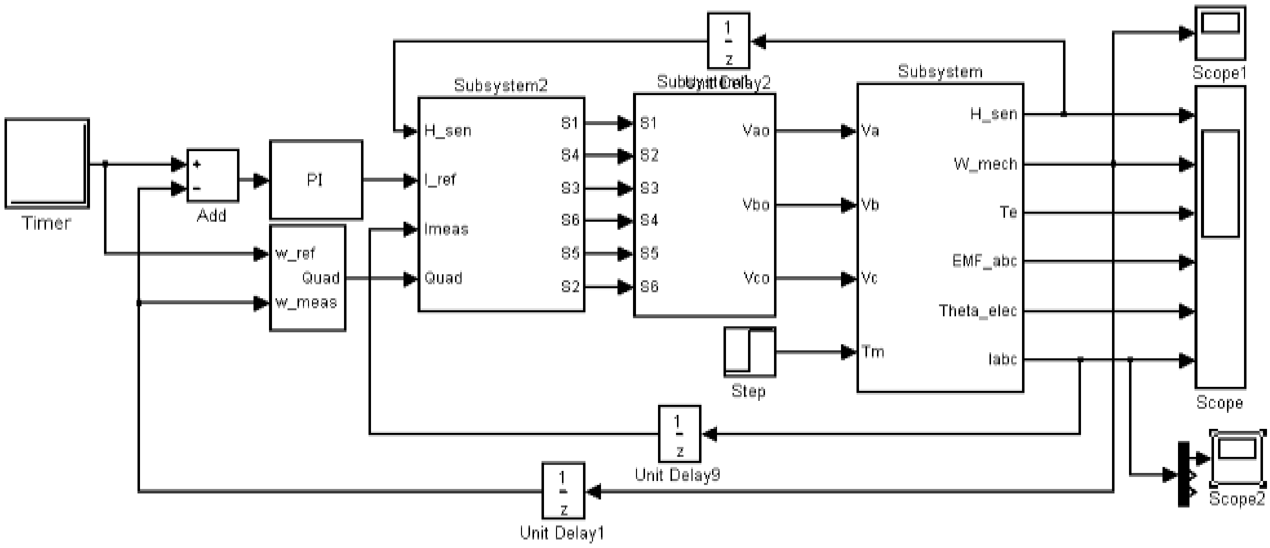

Figure 7: Simulation of BLDC four quadrant modes of operation

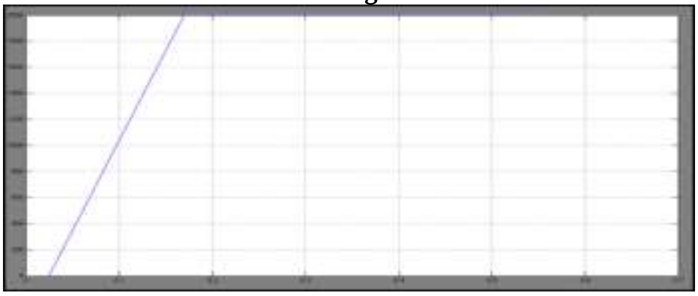

Figure 8: Speed profile

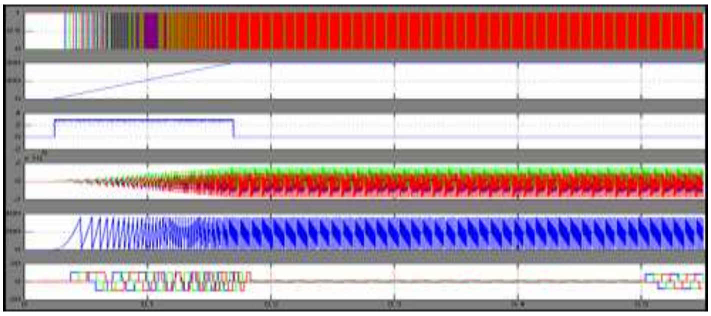

Figure 9: Performance characteristics

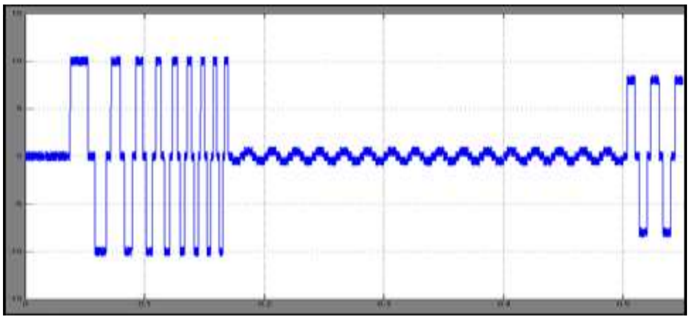

Figure 10: Load profile

CASE II: BLDC four quadrant operation with loaded

When a load is suddenly applied at 0.5s, there is a dip in the speed, but the controller recovers the speed to set value and thereby is no appreciable change in back-emf voltage. The current increases to 7.5 A to meet extra load with an increase in Te to 2.05 N-m as shown in Fig. 4. Once the load is removed all the parameters returns to no-load condition state. The Fig. 4

shows the efficiency of the current controller in achieving the rectangular load current.

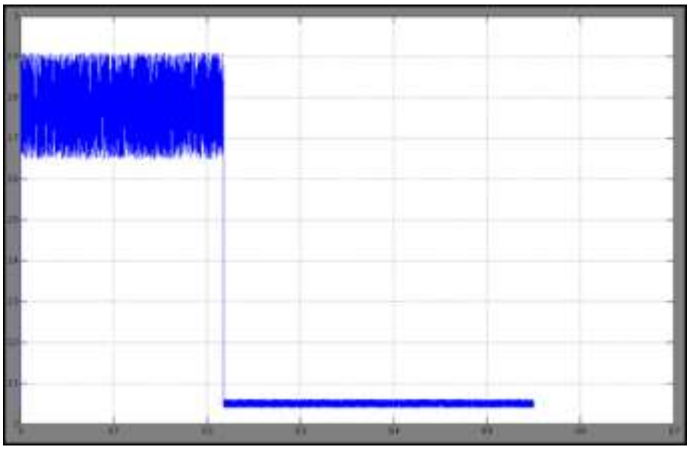

Figure 12: Speed profile

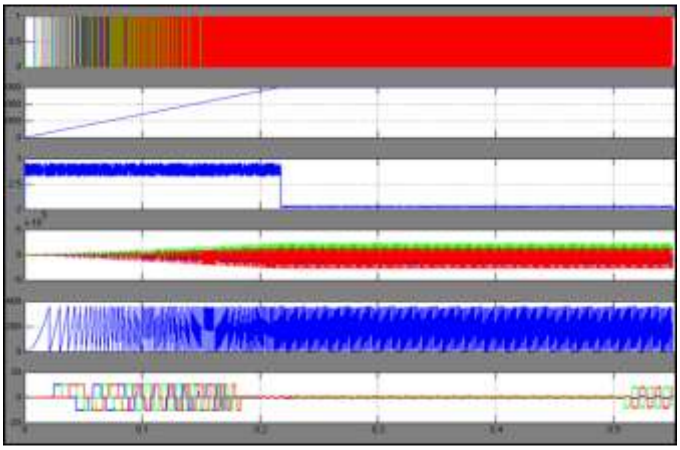

Figure 13: Performance characteristics

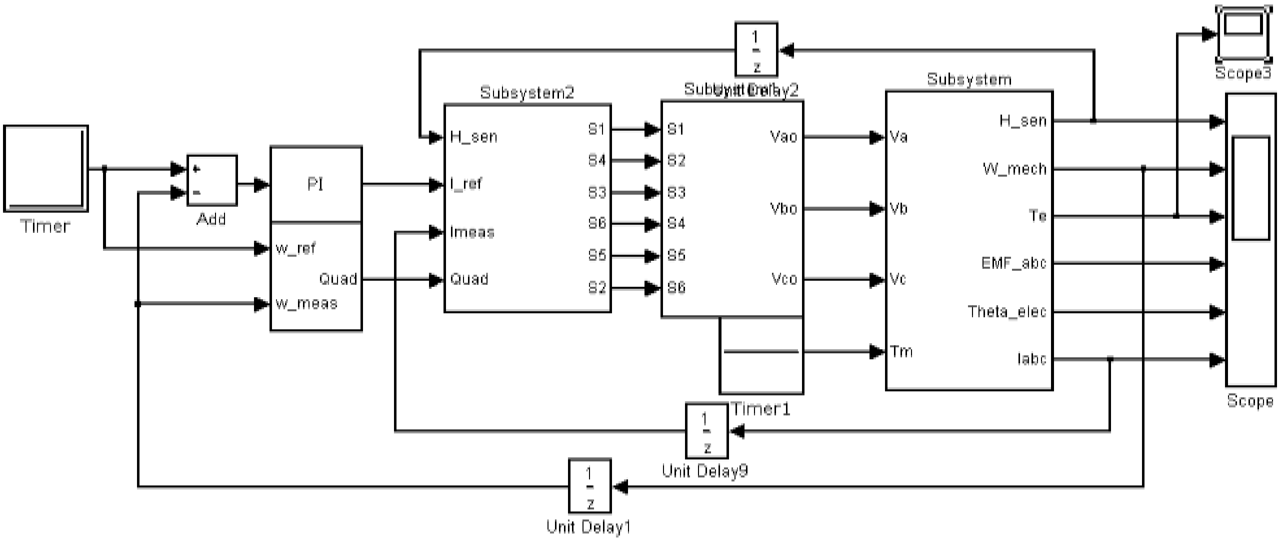

Figure 11: Simulation of BLDC motor modes of operation with load

CASE III: BLDC four quadrant reverse

The motor drive system model also meets the intermittent loads. The motor speed performance at intermittent loads is shown in Fig. 9. It can be seen that the speed controller is capable of tracking the changes in the reference speed efficiently.

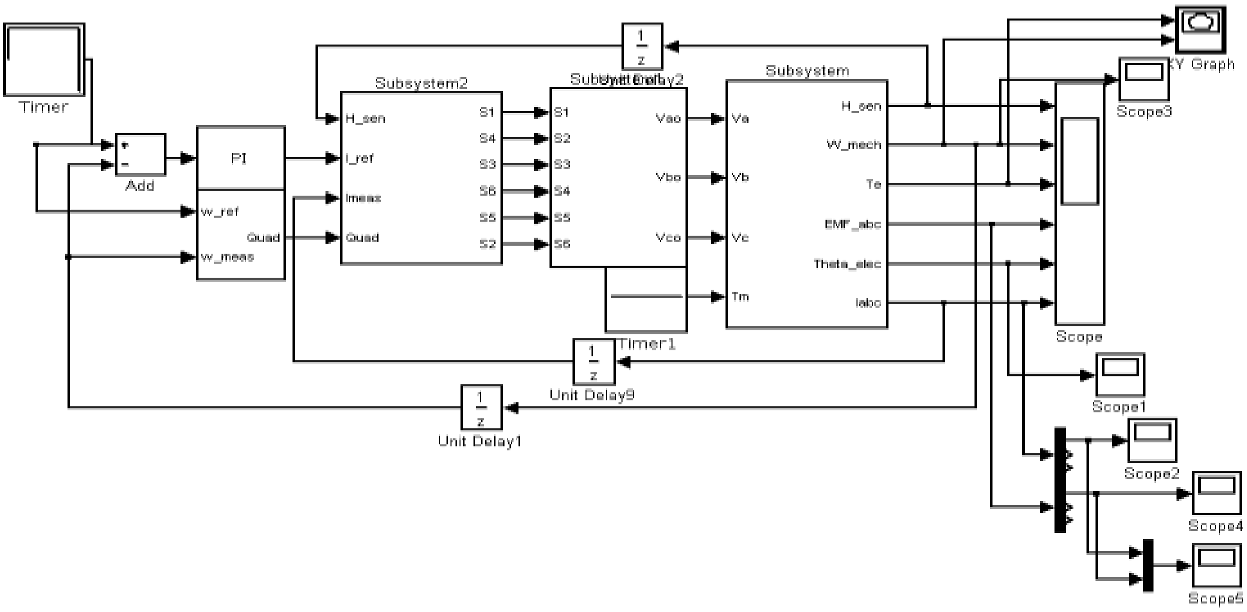

Figure 14: Simulation of BLDC motor reverse mode of operation

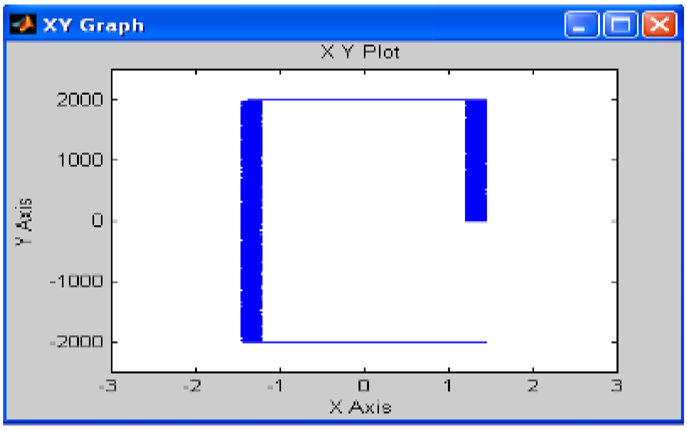

Figure 15: X-Y plot

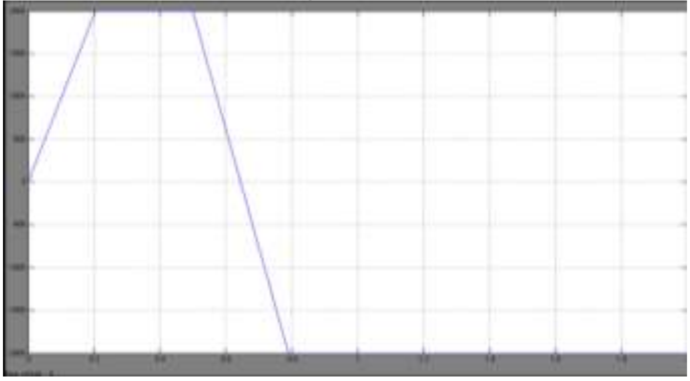

Figure 16: Speed profile

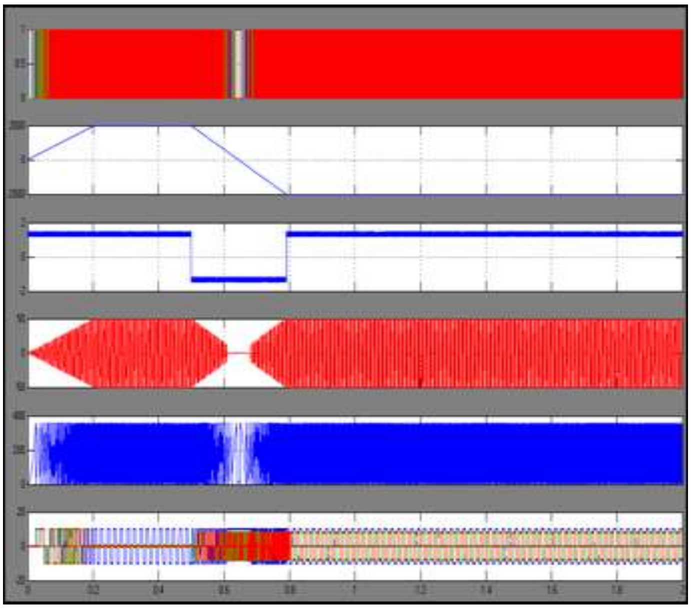

Figure 17: Performance characteristics

CASE IV: BLDC four quadrant variable loaded

Under loaded conditions, at different speeds, motor dynamic behavior is analyzed. As the speed increases, time required to reach the steady state speed increases. Table VI shows the rise time and PI controller values.

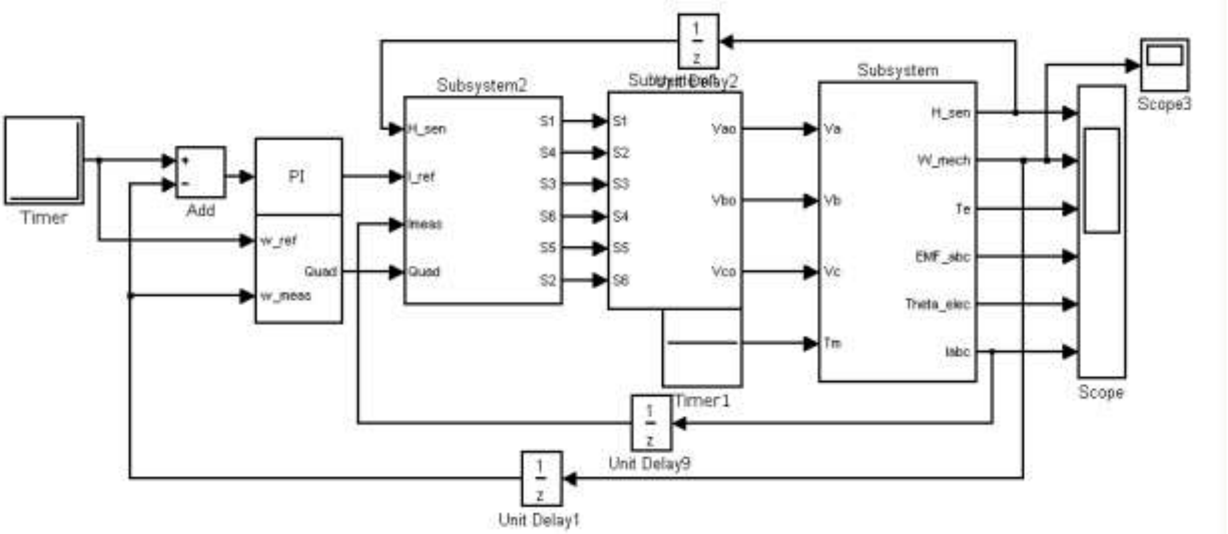

Figure 18: Simulation of BLDC motor under variable load mode of operation

Figure 19: Load profile

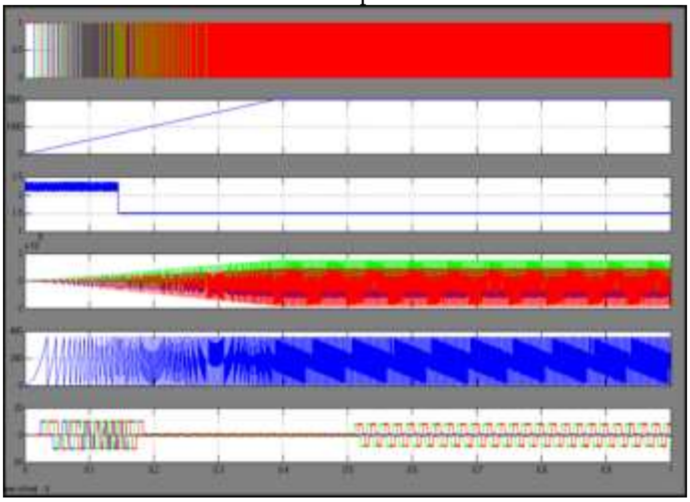

Figure 20: Performance characteristics

5. Conclusion

The modeling and performance analysis of BLDC motor under different operating speed conditions has been presented. It helps in simulation of various operating conditions of BLDC drive system. The performance analysis of BLDC motor under different operating speed conditions are presented it shows that, such a modeling is very useful in studying the drive system before taking up the dedicated controller design, accounting the relevant dynamic parameters of the motor.

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