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Speed Control of High-Speed BLDC with Pulse Amplitude Modulation Control

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ABSTRACT

A novel drive method, which is different from the traditional motor drive techniques, for high-speed brushless DC (BLDC) motor is investigated and verified by a series of simulation studies. It is well known that the BLDC motor can be driven by either Pulse-Width Modulation (PWM) techniques with a constant DC-link voltage or Pulse-Amplitude Modulation (PAM) techniques with an adjustable DC-link voltage. However, to our best knowledge, there is rare study providing a proper drive method for high-speed BLDC motor with a large power over a wide speed range. Therefore, the detailed theoretical analysis comparison of the PWM control and the PAM control for high-speed BLDC motor is first given. Then a conclusion that the PAM control is superior to the PWM control at high speed is obtained because of decreasing the commutation delay and high frequency harmonic wave. Meanwhile, a new high-speed BLDC motor drive method based on the hybrid approach combining PWM and PAM is analyzed.

I. 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. For analysis of the BLDC motor drives system under various conditions, models such as d-q model and a b c 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. 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.

II. BRUSHLESS DC (BLDC)

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.

A few of these are:

- 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. In this application note, we will discuss in detail the construction, working principle, characteristics and typical applications of BLDC motors. Refer to **Appendix B: "Glossary"** for a glossary of terms commonly used when describing BLDC motors.

Sensor less Control of BLDC Motors

Until now we have seen commutation based on the rotor position given by the Hall sensor. BLDC motors can be commutated by monitoring the back EMF signals instead of the Hall sensors. The relationship between the Hall sensors and back EMF, with respect to the phase voltage, is shown in Figure 7. As we have seen in earlier sections, every commutation sequence has one of the windings energized positive, the second negative and the third left open. As shown in Figure 7, the Hall sensor signal changes the state when the voltage polarity of back EMF crosses from a positive to negative or from negative to positive. In ideal cases, this happens on zero-crossing of back EMF, but practically, there will be a delay due to the winding characteristics. This delay should be compensated by the microcontroller. Figure 10 shows a block diagram for sensor less control of a BLDC motor.

Another aspect to be considered is very low speeds. Because back EMF is proportional to the speed of rotation, at a very low speed, the back EMF would be at a very low amplitude to detect zero-crossing. The motor has to be started in open loop, from standstill and when sufficient back EMF is built to detect the zero-cross point, the control should be shifted to the back EMF sensing. The minimum speed at which back EMF can be sensed is calculated from the back EMF constant of the motor.

With this method of commutation, the Hall sensors can be eliminated and in some motors, the magnets for Hall sensors also can be eliminated. This simplifies the motor construction and reduces the cost as well. This is advantageous if the motor is operating in dusty or oily environments, where occasional cleaning is required in order for the Hall sensors to sense properly. The same thing applies if the motor is mounted in a less accessible location.

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 under 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 semi-closed loop or in 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 driven system. In these applications, the dynamic response of speed and torque are important. Also, these applications may have frequent reversal of rotation direction.

A typical cycle will have an accelerating phase, a constant speed phase and a deceleration and positioning phase, as shown in Figure 11. The load on the motor may vary during all of these phases, causing the controller to be complex. These systems mostly operate in 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.

Unipolar Excitation of BLDC Motors

THREE-PHASE MOTORS

Let us consider a 3-phase, 12-slot motor as shown in Fig. 4(a) and use the currents of Fig l(c). In this case, the commutation takes place before the back-emf of each phase reaches zero, and the ripple is reduced as shown in Fig. 6(b).When we use the currents in Fig. l(d), the torque ripple is worse as shown in Fig. 6(c). This is because different numbers of phases contribute to the torque at different instants of time. From the previous two cases, we realize that we need a combination of 180' unipolar currents and small back-emf width to reduce the torque pulsation.

To investigate this case, we consider the 6-slot motor shown in Fig. 4(h). The back-emf plots as a function of rotor position for both the 3-phase motors are shown in Fig. ***5.*** We find that the 6-slot motor has a higher peak and smaller back-emf width than the 12-slot motor. This can be explained as follows.

The end-turns are shorter for the 6-slot motor, because of which the number of turns per coil is more for the same amount of copper. This increases the peak value of the back-emf. The maximum coil span or winding pitch is determined by dividing the number of slots by the number of poles and rounding off to the next lowest integer. For the 12-slot motor, the slots/pole is 3, and the coils are full-pitched, which maximizes the width of the back-emf. In the 6-slot motor, the slots/pole is 1.5, and the coil span used is 1 because of which the width of the back-emf waveform is smaller.

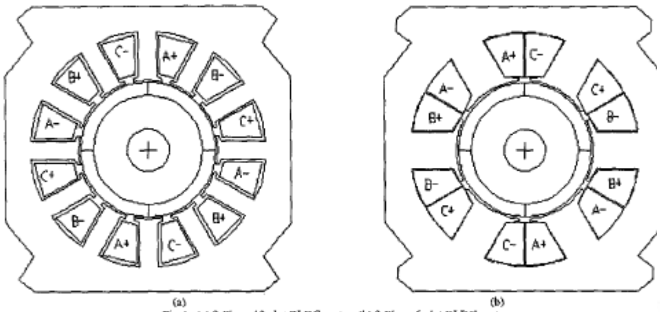
This effect can also be achieved by short-pitching the coils in an integral slots/pole design. The possible short-pitch coil spans for the 12-slot motor are 1 and 2. Using a coil span of 1 would make the back-emf width too narrow and increase the torque ripple. A coil span of 2 would be ideal, but would leave half the slots unutilized. Using a fractional slots/pole motor has the additional advantage of reducing the cogging torque. If the number of slots is increased to 24 or 32, many more combinations are possible for obtaining smaller back-emf width, and the designer can then make a choice based on other considerations.

However, in general, the smallest number of slots gives the lowest labor cost in winding, and a coil span of 1 or 2 slots minimizes the end turns. Note that similar results could also be obtained by using full-pitch stator coils and a magnet pole arc of 120' electrical as discussed.

From Table 11, we see that the 3-ph 6-slot motor excited with 180' unipolar currents gives better performance in terms of torque ripple, with some loss in peak and average torque. This is explained as follows. In Fig. l(d), we have one phase conducting during intervals 2,4 and 6 and two phases conducting during intervals 1,3 and *5.* In particular, when the back-emf of phase A reaches its peak during interval 2, only phase A is conducting.

When the back-emf of phase A starts decreasing in interval 3, phase B also comes into conduction. The decreasing torque contribution of phase A is compensated by the increasing contribution from phase B. The result is an almost constant torque over the entire cycle. The remaining case of the 6-slot motor excited with 126 unipolar currents results in high torque ripple because the back-emf during the commutation instants is low.

Both the unipolar and the bipolar drives require three hall-effect sensors, with the second and third displaced by 120" and *240"* electrical respectively from the first. The bipolar drive requires six switches while the unipolar drive requires only three, albeit with higher current ratings. The advantage of using 120" currents is that we require only one current sensor in the dc link. However, the torque ripple is not low enough. It can be reduced further by increasing the number of phases to four.


(a) (b)
Fig.4. (a) 3-Phase 12-slot BLDC motor, (b) 3-Phase 6-slot BLDC motor.

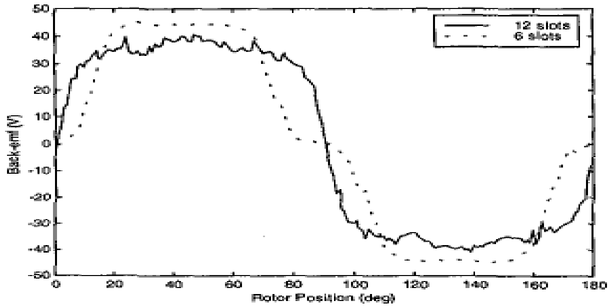


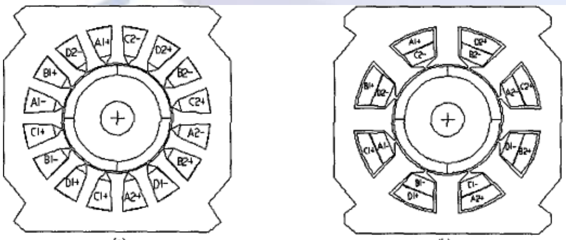
Fig.5. Back-emf plots of 3-Phase Motors.

TABLE II
COMPARISON OF 3-PHASE MOTORS WITH THE REFERENCE

Motor Description	Turns/phase	Current Waveform	Max. Torque (Nm)	Avg. Torque (Nm)	Torque Ripple
3-ph 12 slot	208	120° Bipolar	0.4943	0.4632	13%
3-ph 12 slot	208	120° Unipolar	0.3662	0.3272	23.7%
3-ph 12 slot	208	180° Unipolar	0.4972	0.3525	73.6%
3-ph 6 slot	262	120° Unipolar	0.4065	0.3726	70%
3-ph 6 slot	262	180° Unipolar	0.3383	0.3247	8.53%

FOUR-PHASE MOTORS

Two 4-phase motors are considered: One with **I6** slots, and the other with 8 **slots** as shown in Fig. 7. Both motors are integral slots/pole designs. The 16-slot motor is short-pitched by a factor of ***2,*** while the 8 slot motor is full-pitched, which


(a) (b)
Fig.7. (a) 4-Phase 16-slot BLDC motor, (b) 4-Phase 8-slot BLDC motor.

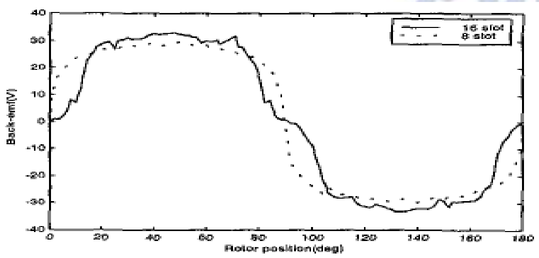


Fig.8. Back-emf plots of 4-Phase Motors.

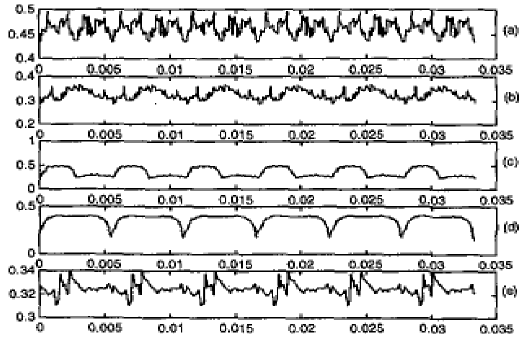


Fig. Torque outputs of 3-Phase Motor(a) 12-slot motor with 120" bipolar current, (b) 12-slot motor with 120" unipolar current, (c) 12-slot motor with 180' unipolar current. (d) 6-slot motor with 120' unipolx current, (e) 6-slot motor with 180' unipolar current.

Explains the difference in the width of their back-emf wave forms shown in Fig 8. The number of turns/phase is more in the 16-slot motor because of the shorter end-turns, which explains the higher peak of its back-emf. These motors are excited with the current waveforms of Fig. l(e) and *(0.* The torque outputs are shown in Fig. 9 and Table 111 gives the numerical values. For both motors, using 90' conduction gives better results because the commutation between phases takes place when the back-emfs are high.

In addition, it requires the use of only a single current sensor in the dc link. In the 180" conduction scheme, two phases conduct at all times, and the back-emfs of the incoming and outgoing phases are low, resulting in large torque ripple. It also requires the use of a current sensor in each phase.

III. FOUR-QUADRANT OPERATION

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. 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 dc 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 Figure

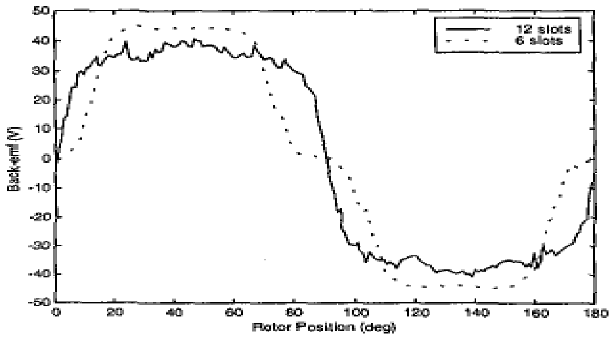


Fig.5. Back-emf plots of 3-Phase Motors.

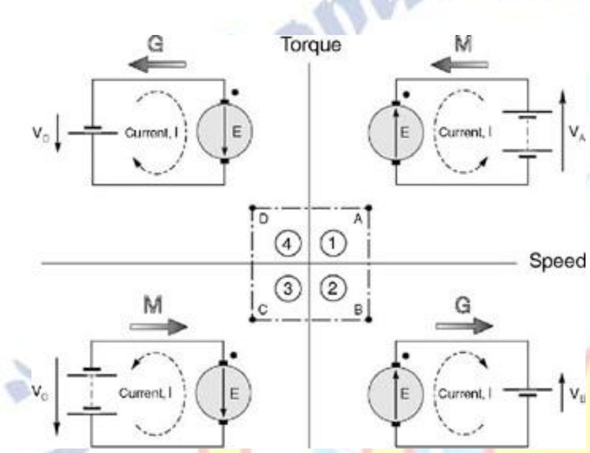


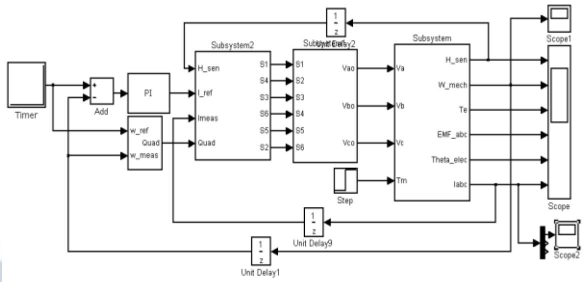
Figure Operation of dc motor in the four quadrants of the torque-speed plane

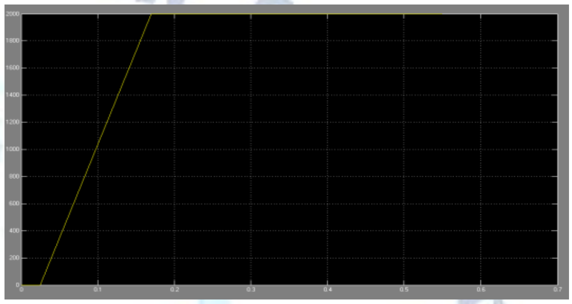
Above Figure looks straightforward but experience shows that to draw the diagram correctly calls for a clear head, so it is worth spelling out the key points in detail. A proper understanding of this diagram is invaluable as an aid to seeing how controlled-speed drives operate.

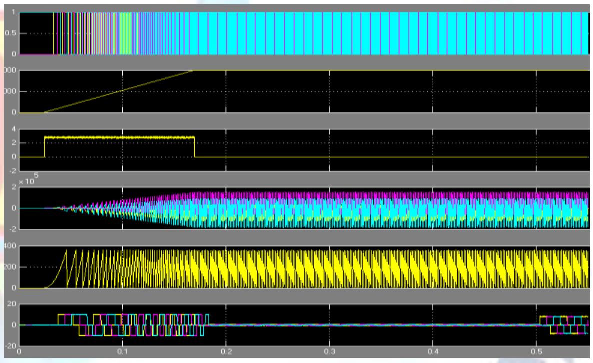
Firstly, one of the motor terminals is shown with a dot, and in all four quadrants the dot is uppermost. The purpose of this convention is to indicate the sign of the torque: if current flows into the dot, the machine produces positive torque, and if current lows out of the dot, the torque is negative. Secondly, the supply voltage is shown by the old-fashioned battery symbol, as 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 emf are emphasized by the use of two battery cells when V > E and one when V < E.

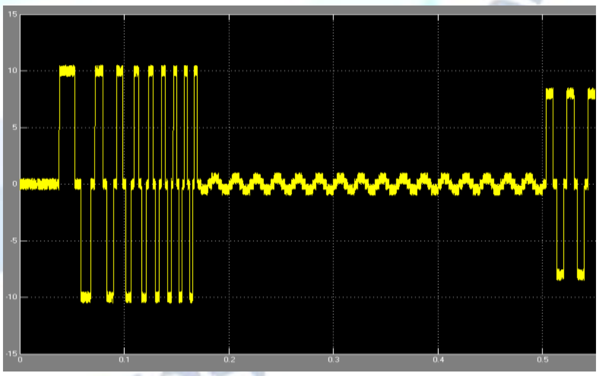
IV. MATLAB DESIGN OF CASE STUDY

CASE I: BLDC_fourquadrant

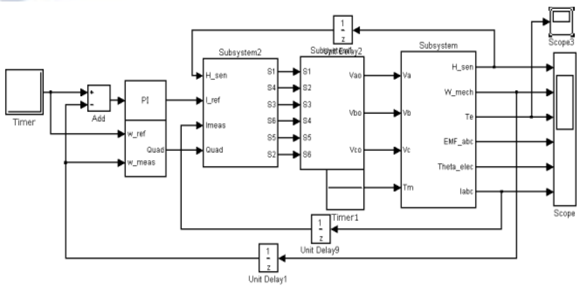


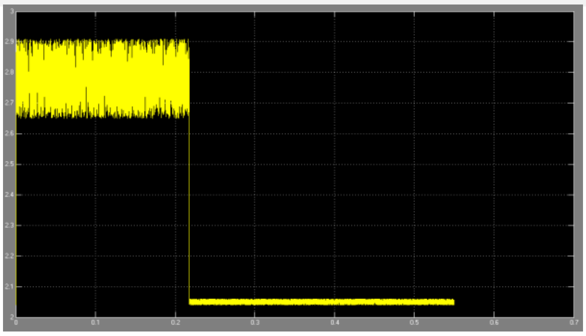


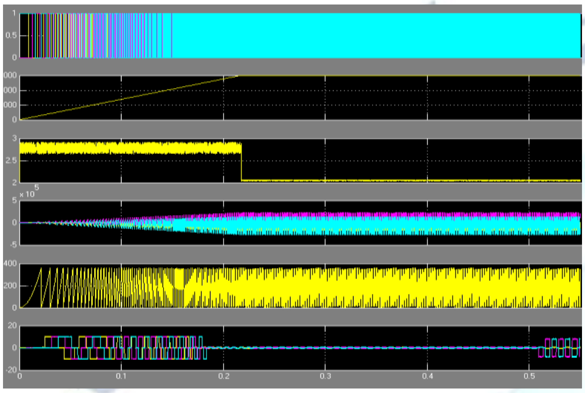




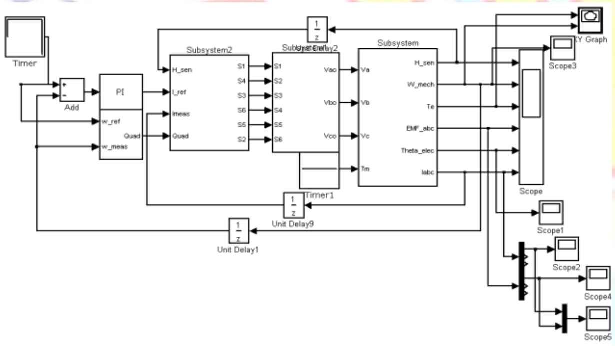
CASE II: BLDC four quadrant loaded

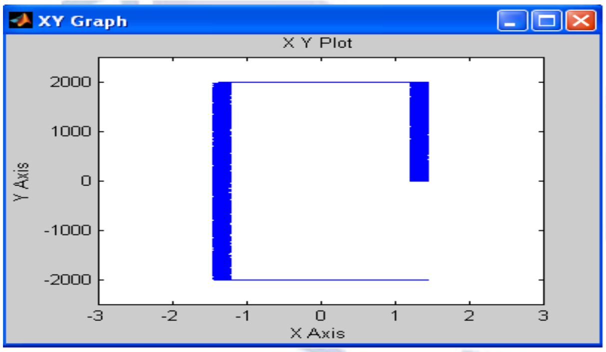


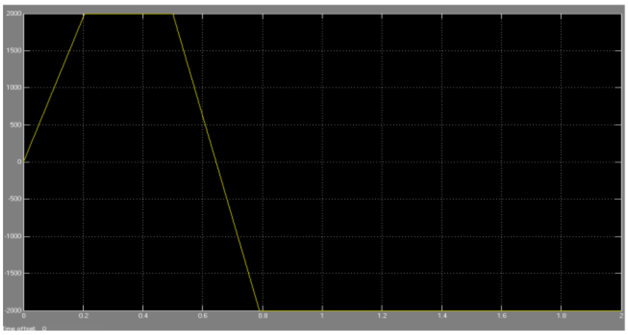


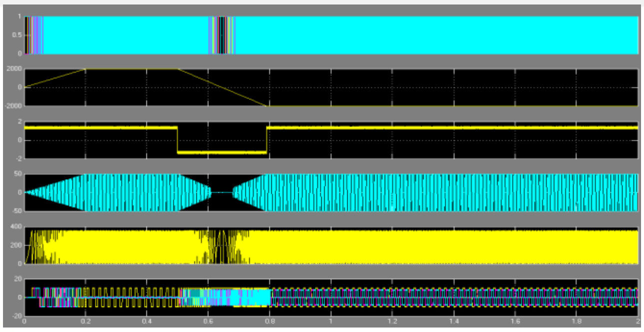


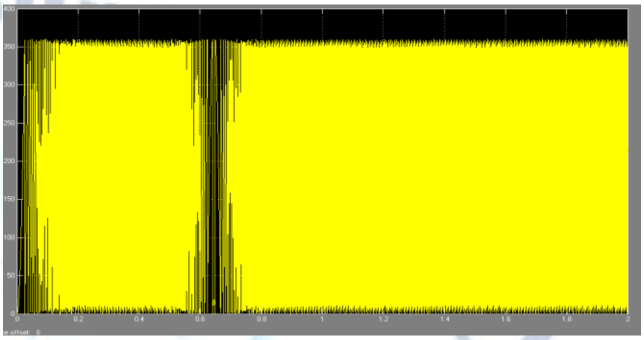
CASE III: BLDC four quadrant reverse

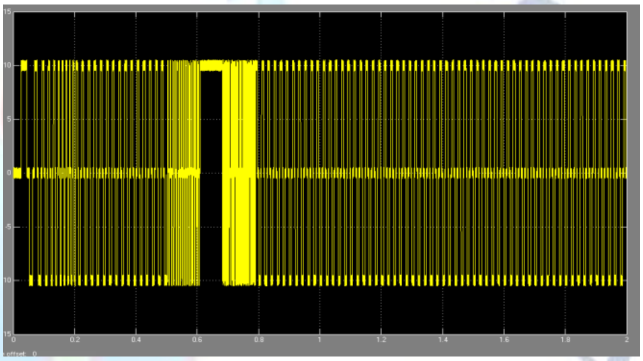


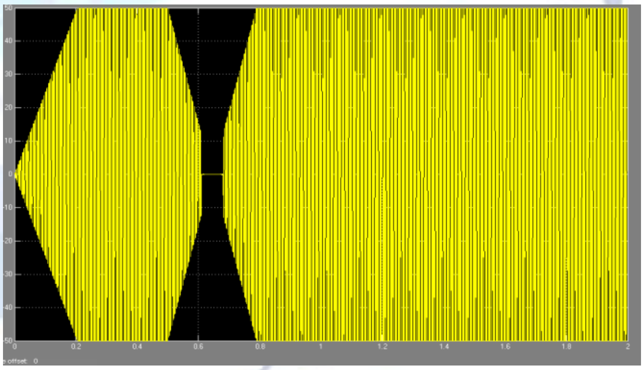


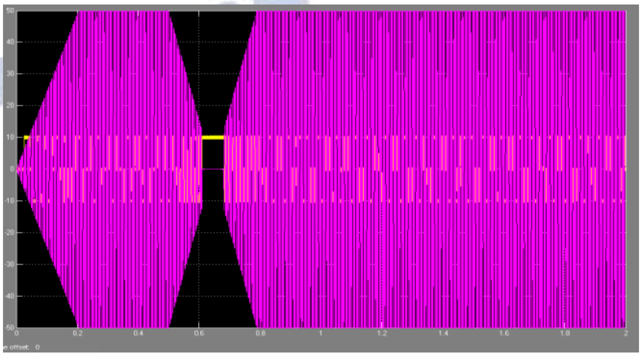




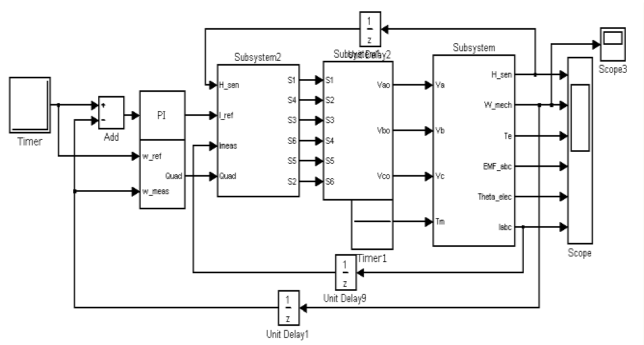


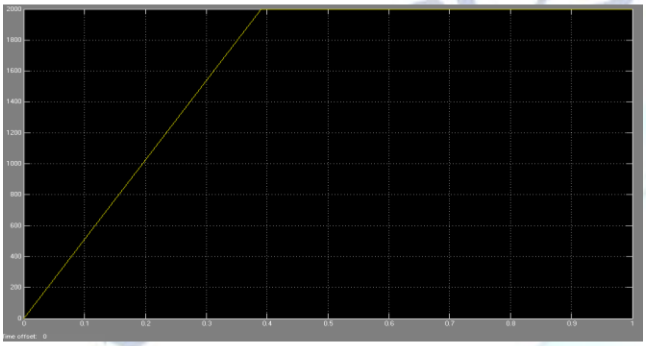


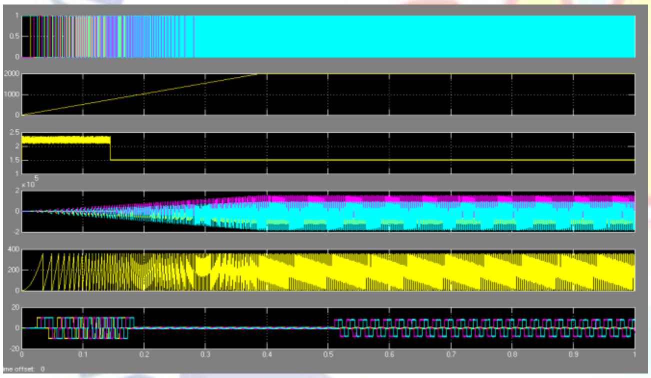




CASE IV: BLDC four quadrant variable loaded







V. CONCLUSIONS

The modeling procedure presented in this paper helps in simulation of various operating conditions of BLDC drive system. The performance evaluation results show 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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