Switching Techniques for Brushless DC Motors

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***Abstract*— this paper presents a Simulink model for BLDC (Brushless DC) motors, using trapezoidal commutation. First, presents some common switching techniques for sensored Brushless DC motors type, using Hall Effect sensors, followed by a description of brushless DC motors' characteristics, its manufacturing structure, and their operation, torque curves comparison for several commutation techniques. Concluding with simulation for speed control, using trapezoidal commutation.**

Keywords*— *Brushless DC motor; commutation techniques; Back Electromotive Force; BLDC; sensored; sensorless;

I. INTRODUCTION

Brushless DC (BLDC) motors are increasingly becoming a common an alternative in fields of industrial electronics, home appliances, automotive and robotics. This is due to their higher efficiency and lower maintenance compared to conventional brushed DC motors. This increasing demand opens the need for low cost efficient motor control drives, and a series of new techniques, tools and circuits are available [1].

BLDC motors are electronically commutated and use three main types of commutation techniques: trapezoidal commutation, sinusoidal commutation and vectorial commutation. 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).

Trapezoidal commutation is the simplest technique to control the EMF. However, due to a misalignment between the stator current and rotor position, the output torque has a 15% ripple, causing loss of speed and mechanical wear. On the other hand, sinusoidal switching corrects the ripple that trapezoidal commutation presents, but at high speeds the torque quickly tends to a point of "zero torque ". Finally, vectorial commutation holds constant torque. Nevertheless vectorial commutation, because of its complexity is difficult to implement.

The main objective on this paper is to have an appropriate model for BLDC motors, to test different kinds of control, and validate its operation before implementation in hardware; such as FPGAs based control.

II. BLDC MOTORS

BLDC motors have a high efficiency and, due to its capabilities can operate similar to servomotors. Also, these machines present similar characteristics to DC motors, but these are electronically commutated. For other hand, these motors are built of different way, these machines have rotor of permanent magnet and windings in stator [2]. The brushes, and the commutation bar of traditional DC motors, are changed for electronic circuits with Hall Effect sensors, to know the rotor position. These are positioned inside of stator windings, and are connected to commutation circuits of solid state [2].

The rotor is an element permanent magnetic, and stator is winding like AC motors of several phases, as shown in Figure 1. However, these two kinds of motors have a big difference in the form to detect the rotor position, then to know the location of the magnetic poles and then generate the control signals through of electronic circuits. Commonly, BLDC motors know their rotor position using Hall effect sensors. However, there are some models that use encoders or other optical sensors [2].

Once know the rotor position, is necessary use an inverter bridge to energize the windings the motor, and so generate a movement sequence. The typical control system for a BLDC motor is shown in Figure 2. It can be divided into two parts, one is the inverter block, and the other one is the BLDC motor [3]. The typical inverter drive system for a BLDC motor is shown in Figure 3. [4].

Moreover, there are different kinds of Brushless DC motors. By the form of manufacturing there are the inrunner and the outrunner. Also, according to the method used to know the rotor position, there are the sensored and sensorless [5].

Likewise, there are various methods of switching for sensored BLDC motors as follows:

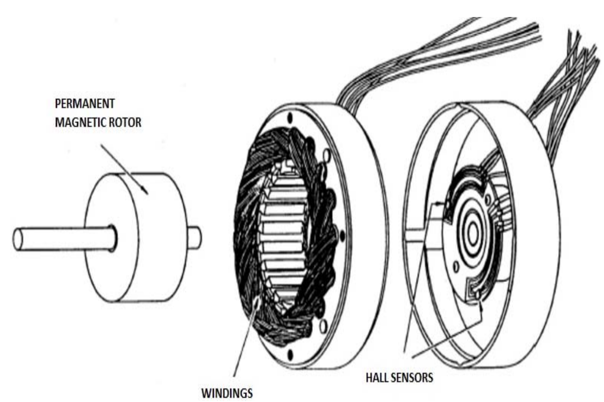

Figure 1. Brushless DC Motors [2].

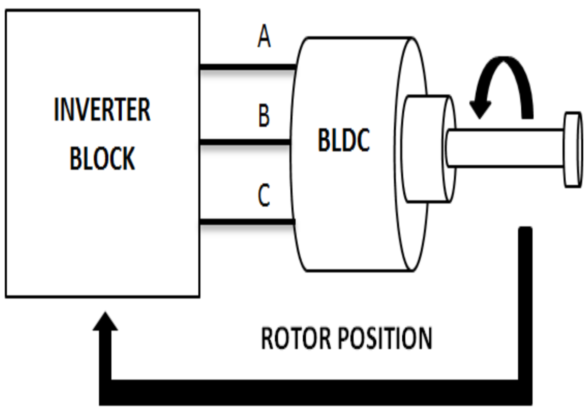

Figure 2. Control Brushless DC Motors.

- Trapezoidal commutation.
- Sinusoidal commutation.
- Vectorial control.

These techniques have as their main objective to energize each phase of the motor, and depending on the method used; the back Electromotive Force (EMF) presented in their windings of the motor will have different waveform. Furthermore, each method of commutation presents advantages over other. Moreover, there are special modulation techniques to generate excitation signals for BLDC motors [6].

III. SWITCHING TECHNIQUES

A. Trapezoidal Commutation

Trapezoidal commutation method is the simplest and the most used way to control BLDC motors and straight forward to implement the control aspects of it. This technique controls the current in the windings of the motor; then, only a pair of terminals will be energized while the third is disconnected. This is done successively to alternate the pair of energized terminals, and so it is able to complete the six possible combinations [5].

For proper commutation and motor rotation, the rotor position information is crucial [7]. Only with the help of rotor position information, the electronic switches in the inverter bridge will be switched ON and OFF to ensure proper direction of current flow in respective coils. Hall Effect sensors are used in general as position sensors for trapezoidal commutation. Each hall sensor is typically placed 120 degrees apart and produces “1” whenever it faces the North Pole of the rotor [7]. The waveform of the back EMF and current; are shown in Figure 4.

The speed of BLDC motors is directly proportional to the applied voltage. The commutation logic specifies the coils that need to be energized for every 60 degree of electrical revolution based on Hall inputs [7].

Because at every instant of time, two of the windings are energized, present currents equal in magnitude while the third one is always zero, the resultant vector of the stator currents, which is simply the vector sum of currents, only can point in six directions [8].Then, this vector will be out of phase respect to the rotor position and, therefore, will generate a ripple in the torque of fifteen percent, as shown in Figure 5. [8]. This ripple is a serious problem, as it is very noticeable at low speed applications. It also causes mechanical noise and wearing down, which causes significant life reduction of the motor.

B. Sinusoidal Commutation

The sinusoidal commutation control is more sophisticated and accurate than trapezoidal, as it controls the position of the rotor continuously [5]. For this it is necessary to apply to each of the motor windings a sinusoidal current. These current values must be 120° out of phase with each other, so that in this way the resulting current vector is in phase with the rotor position and thus obtain a more accurate torque and without the typical ripple of trapezoidal switching [5]. However, to generate this modulation is required an accurate measurement of the rotor position, which is difficult to achieved with Hall effect sensors, therefore, it takes encoders or resolvers high resolution [5].

Since the BLDC motors do not have a neutral phase, and taking into account the Kirchoff's current law $(i_a + i_b = i_c)$, just controlling two currents of the motor can implicitly control the third one [8]. At low speeds, this control method has better performance and efficiency than trapezoidal commutation. However, at high speeds do not have a good response, because some controllers, for example PI controllers cannot generate sinusoidal signals to this speed, because they have a limited response in gain and frequency. In other words, when the speed increases, the efficiency decreases and the error increases, tending to a point of zero torque [5], this is shown in Figure 6.

C. Vectorial control

Since the BLDC Vectorial control is a complex technique of commutation. This overcomes limitations of frequency of the switching sinusoidal. This method operates controlling currents and voltage, with reference to the direct and quadrature axis rotor. This requires a constant field and quadrature with the rotor field [9].

The currents detected in the stator are transformed in direct and quadrature components, through of Clarke transforms and Park. The direct component controls the flow, and the quadrature component the torque. The two transforms are discussed below:

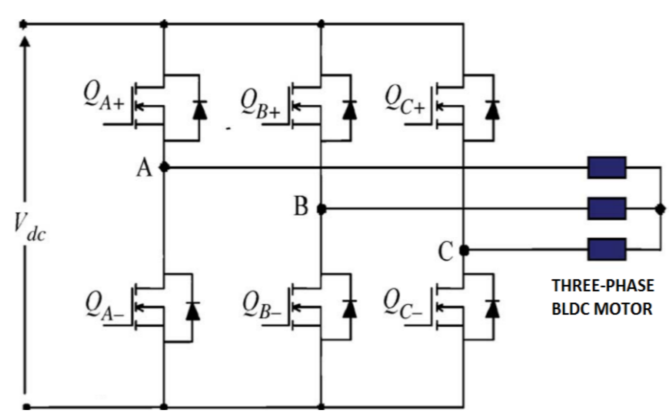

Figure 3. Inverter drive [4].

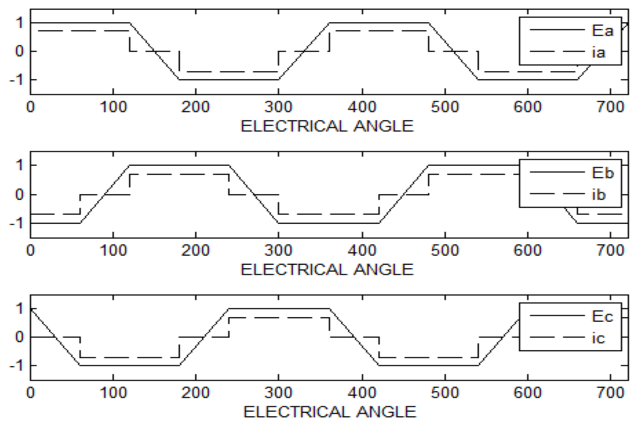

Figure 4. Waveform of the bac EMF and current

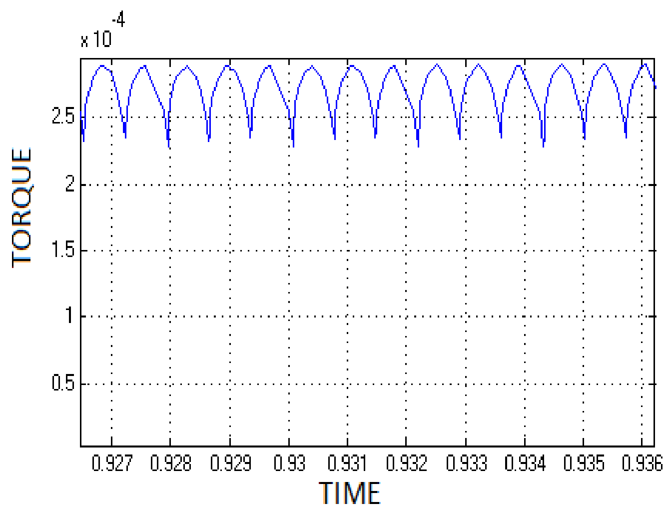

Figure 5. Torque in trapezoidal commutation.

- Clarke Transformation: Transformation of a three phase system equispaced (a, b, c) to two phase orthogonal (α, β).

- Park Transformation: Transformation of stationary orthogonal system (α, β) to rotational (d, q).

For this purpose requires not only a very good measurement of the rotor position, but prior mathematical processing of the signals. This is the control that has better response in all speed ranges, due that the pair remains constant. However, it is the most complex and expensive to implement [5].

IV. SIMULATIONS CONTROL SPEED

A. BLDC motor

In all simulations will be used trapezoidal commutation and a motor produced by Maxon Precision Motors Inc, model EC 6 215550. The parameters used here are shown in TABLE I. [10].

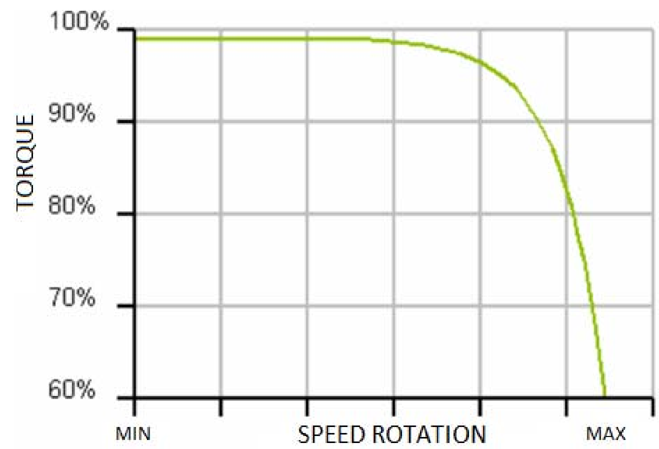

Figure 6. Torque in sinusoidal commutation [8].

B. Open loop control BLDC motors

To simulate open loop control of BLDC motors, is necessary to implement three main blocks. The first block is called inverter block, this implements a bridge with six ideal switches, which allow energizing the motor that generate motion sequences.

The second block is the BLDC motor, here a BLDC motor has been modeled using the parameters shown in TABLE I. the mathematical model is taken from [10].

Finally, the block called control block is in charge to activate the switches in the inverter block. For this, receives a signal of the rotor position, and activate two switches depending on the input signal.

The blocks implemented in Simulink are shown in Figure 7. and the torque obtained for this simulation is shown in Figure 5. In this figure appears a ripple in the torque that is generated because the current vector is out of phase respect to the rotor position.

C. Close loop control BLDC motors

To control the motor speed, the voltage must be controlled; A Proportional-integral controller was used in the simulation. The values that were used for k_p and k_i are:

$$k_p = 13.11 \qquad k_i = 1310.6$$

The reader is referred to [11], for clarity description on how to compute k_p and k_i.The new blocks diagram has the same three blocks that were shown in Figure 7. and its operation remains the same. But now, there will be two new blocks, one is the reference speed block and the other is the PI block. These new blocks diagrams are shown in Figure 8.

For the verification of the control scheme, the motor is controlled at a desired rate of $1000\frac{rad}{seg}$. Finally, the plots obtained for speed, the back emf, and the current of phase A are respectively shown in Figure 9. and Figure 10. The waveform of back emf is trapezoidal due to the type of commutation used for the simulations.

TABLE I. PARAMETERS MOTOR

Motor Data Maxon EC 6 215550		
Numbers of poles		2
Resistance	Ω	12.5
Inductance	H	$0.091 * 10^{-3}$
Friction constant	$Nm * s$	$1.38 * 10^{-8}$
Torque constant	$\frac{Nm}{A}$	$1.05 * 10^{-3}$
Electrical constant	$\frac{Nm}{\sqrt{W}}$	$1.05 * 10^{-3}$
Rotor inertia	$Kg * m^2$	$5 * 10^{-9}$

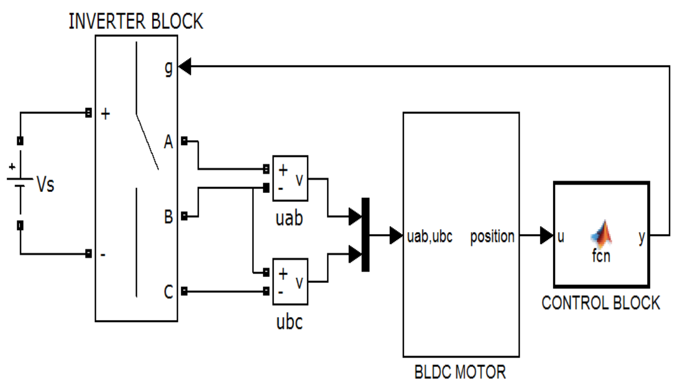

Figure 7. Open loop control BLDC motors.

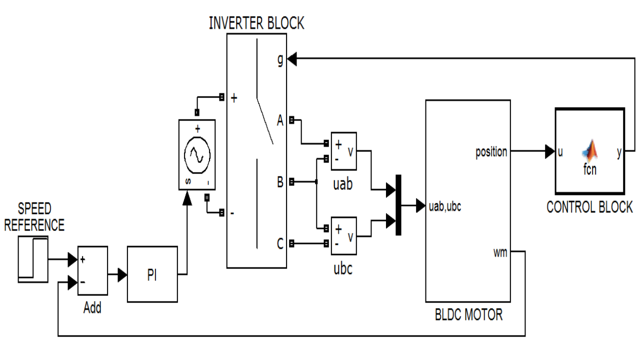

Figure 8. Close loop control BLDC motors.

V. CONCLUSION

This paper presented a Simulink model for BLDC motors, using trapezoidal commutation. First, were presented some common switching techniques for sensored Brushless DC motors, using Hall Effect sensors. After this, were presented characteristics of brushless DC motors, its manufacturing structure, and the operation of this type of motors, comparing the torque curves several commutation techniques. Finally, were presented graphics simulations for speed control, using trapezoidal commutation.

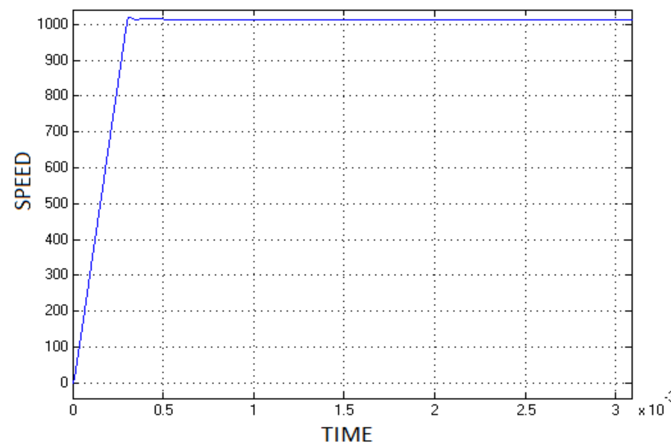

Figure 9. Speed BLDC motor.

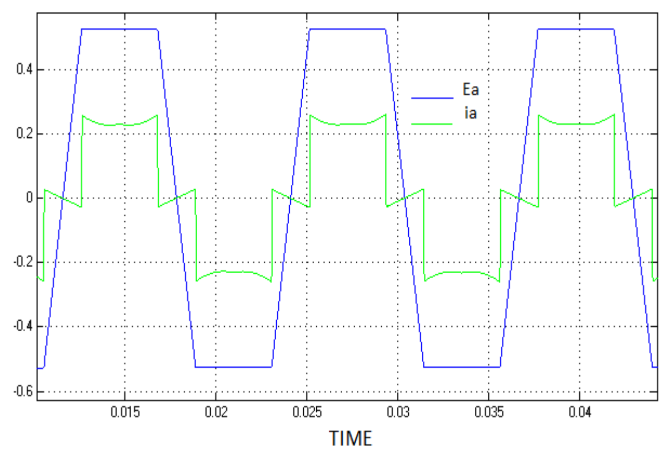

Figure 10. Back emf and current phase A for BLDC motor.

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