3 Phase Brushless Permanent Magnet Motor Control Methods

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ABSTRACT

This paper presents an overview of contemporary control methods of brushless permanent magnet motors. It focuses primarily on the algorithms and control strategies commonly implemented for automotive traction motor control, introducing some of the background theory, advantages and disadvantages, and a basic overview of their implementation. During the preparation and research phase, it was identified that the necessary theory and information for implementing brushless motor control is distributed across the existing academic literature. Hence, this paper provides a concise basis in motor control theory that can be utilized in the development of an efficient and robust electric vehicle traction application.

Keywords—motor, inverter, motor control, PWM

I. INTRODUCTION

Electric motors are at the heart of many applications such as hybrid and battery electric vehicles, industrial machinery, home appliances and more. A significant part of the electrical energy produced goes into powering electrical motors of some type. In order to maximize performance, efficiency and dynamics, advanced and sophisticated control methods are required.

For an automotive traction application, the focus is on methods for torque and speed control of 3 phase brushless motors. Induction motors are also used in such applications, but the advantages inherent to brushless permanent magnet motors render induction motors as an inferior choice in this role. It can be safely stated that the battery electric vehicles of the future will frequently employ one or more brushless permanent magnet motors in propulsion duty.

To understand the different control methods and their principles of operation, it is first necessary to have a basic understanding of the fundamentals of brushless permanent magnet machines, in particular their mechanism for generating torque and back EMF. Using these principles, effective control strategies can be developed that maximize torque to current ratio, maintain high efficiency and have minimum complexity for implementation. All control theories discussed in this paper use simple two-level inverters to drive the motors, showing that complex power electronic converters are not mandatory to achieve high performance control. Finally, the different PWM techniques for modulating the inverter output voltage according to the control outputs are also discussed.

II. BRUSHLESS MOTOR FUNDAMENTALS

A. Overview

An overview of the fundamental theory of Brushless motor is presented in this section. Primarily, this section is concerned with the concepts of back EMF induction and torque generation in a brushless motor, and as such, does not delve into the topics of motor construction, magnetic circuits etc. The theory presented is with a perspective towards controller design, hence only the sections pertaining to that are discussed. A more general discussion on motor taxonomy can be found in chapter 2 of [1].

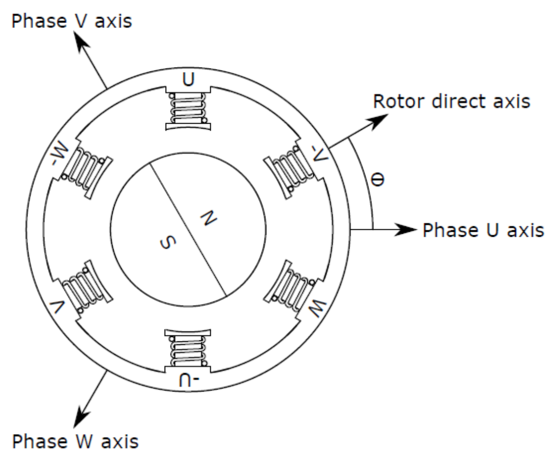

Figure 1: An example brushless motor with phase angle indicated [2]

Brushless Motors are one of the motor types that have gained popularity in the automotive field, especially in traction applications where high responsiveness and efficiency is desired. As the name suggests, Brushless motors do not use brushes for commutation, instead they are electronically commutated [three]. In comparison to brushed DC motors or induction motors, brushless motors have several advantages, some of them being:

- Improved torque-speed characteristics
- Better efficiency
- Quick dynamic response
- Low maintenance
- Long operating life

B. Motor Back EMF profiles

Depending on their back EMF profiles, Brushless Motors are classified into two main categories: Brushless DC Motors (BLDCs) and Permanent Magnet Synchronous Motors (PMSMs). BLDC motors are characterized by their trapezoidal-shaped back EMF profiles, whereas PMSMs have a sinusoidal back EMF profile. The differences in their back 2 EMF profile can be seen from Figures 2 and 3 [3]. In this paper motors with trapezoidal back EMF profiles will be referred to as BLDCs and motors with sinusoidal back EMF profiles will be referred to as PMSMs, in keeping with the conventions used by most academic literature on this topic.

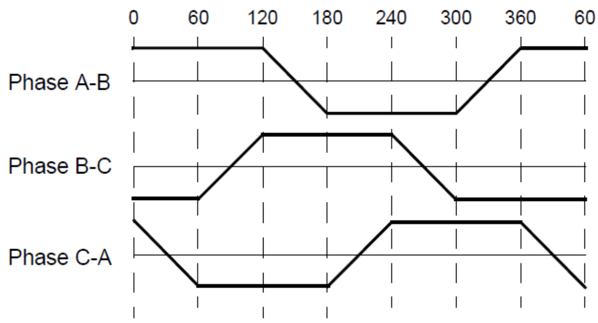

Figure 2: Trapezoidal Back EMF Profile commonly seen in BLDC Motors [3]

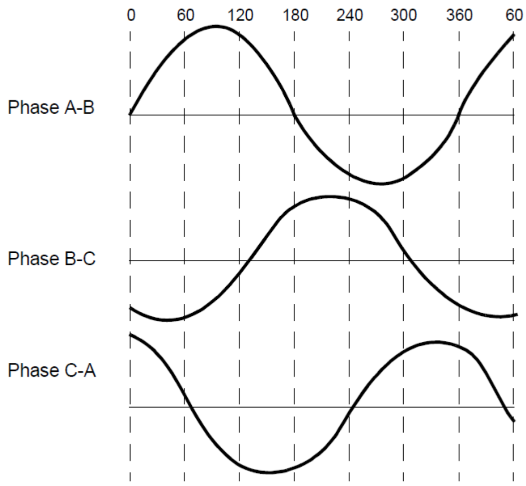

Figure 3: Sinusoidal Back EMF profile commonly seen in PMS Brushless Motors [3]

Both brushless motors are a part of a broader category of motors called Synchronous motors. This means the magnetic field generated by the stator and the magnetic field generated by the rotor rotate at the same frequency. BLDC motors do not experience the “slip” that is normally seen in induction motors. The relative angle between the stator and rotor magnetic fields, called the load angle, controls the current flowing through the motor, and thus the torque produced by it [3]. The control strategies discussed later in this paper all focus on controlling this load angle to a certain value to keep the motor rotating and satisfying the torque reference given to them.

The equation for the electromagnetic torque of the 3 phase brushless permanent magnet motor is given by:

$$T_e = P\varphi(I_a K_a[\Theta] + I_b K_b[\Theta] + I_c K_c[\Theta])$$

Where:

- P is the number of poles of the motor
- φ is the flux linkage of the motor
- I_x is the current through phase x of the motor, where x can be A,B or C
- K_x is the back EMF of phase x of the motor as a function of electrical position of the generated field Θ

Further, the relationship between the generated field Θ and rotor position θ is given as:

$$\Theta = P\theta$$

Where P is the number of poles of the motor.

For a PMSM motor, the back EMF of each of the 3 phases can be written as:

$$I_a = \sin(\Theta)$$

$$I_b = \sin(\Theta - \frac{2\pi}{3})$$

$$I_c = \sin(\Theta + \frac{2\pi}{3})$$

For a BLDC motor, the equations for per-phase back EMF turn out to be piece-wise linear with respect to rotor angle upon derivation, and the back EMF profile is more simply explained by referring to Figure 2. Due to the trapezoidal shape of the back EMF, the developed torque by the motor usually contains a lot of high frequency harmonics and ripple, which is undesirable. PMSMs are generally preferred in applications where torque ripple minimization is required, since their sinusoidal back EMF profiles results in less high frequency harmonics in their torque output.

C. *Torque Production in Brushless Motors*

The next stage after discussing the back EMF generation of the motor is to discuss the torque production characteristics of the motor. The theory for discussing this section was gathered from [1] and [2]. Additional information can be found in [4], [5] and [6]. Continuing from equation 2.2, we discuss further to calculate the current required to generate maximum torque from the motor. Since motor back EMF (and preceding that, the rotor magnetic flux) and phase currents must exist simultaneously in order to provide electromagnetic torque (and the power balance equation $E * I = \tau * \omega$ has to be satisfied), we can conclude that the current waveform provided to the motor must be of the same shape as that of its back-EMF profile. Thus a PMSM needs a sinusoidal phase current and BLDCs a trapezoidal phase current to produce torque without considerable ripples. A more thorough and rigorous derivation of the motor torque can be found in [1]. A simpler way to find the ideal current waveform is illustrated in [2]. The rotor was locked at Θ = 0 and phase currents were chosen to provide stator magnetic field vectors for different angles, and the resulting torque for all possible angles is plotted. An additional explanation is found in [7].

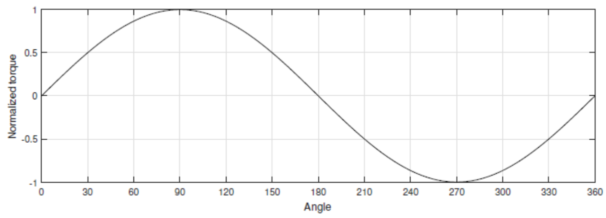

Figure 4: Plot of Torque vs Rotor Angle for a PMSM with Locked Rotor [2]

Figure 4 shows that maximum torque is achieved when the angle between the rotor and stator magnetic fields is 90 degrees. This to maximize the motor efficiency, the phase current must ideally be controlled such that the magnetic field generated in the stator due to it leads the rotor field by 90 degrees. Once this is achieved, the current magnitude can be adjusted to the minimum required to provide the reference torque to the system. Hence our goal for developing a control system is to tune the control algorithm to achieve and maintain this angle between rotor and stator magnetic fields.

III. The Voltage source inverter and PWM Control

The Voltage Source Inverter (VSI) is a Power Electronic circuit that is used to convert DC to AC, in this case 3 Phase AC. It consists of 6 switches arranged in 3 parallel half bridges, as shown in Figure 5. Each of the motor phases is connected to the output midpoint of the respective half bridge. In the figure, switches S1 and S1' represent the half bridge for phase A, and similarly for the other 2 phases. The switches traditionally used in VSI circuits are fully controlled switches such as IGBTs, MOSFETS or even Wide Bandgap devices such as Silicon Carbide (SiC) and Gallium Nitride (GaN) FETs in recent years.

The desired phase voltages and currents are generated by turning the switches on and off at high frequency in a very specific pattern, in a process called modulation. The task of the motor controller is to take an input in form of a torque request or RPM request and regulate the motor to generate the desired value by switching the transistors in the correct manner. For an automotive traction application, it is assumed the driver of the vehicle in responsible for modulating the speed of of the vehicle, and hence the input given to the motor controller through the accelerator pedal will be in the form of a torque request.

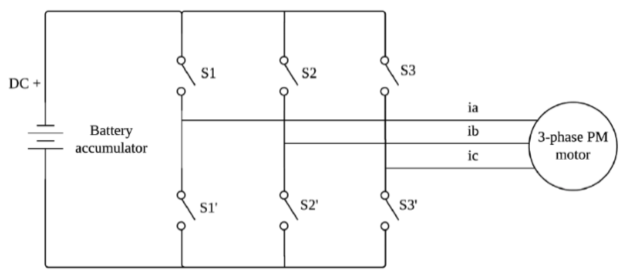

Figure 5: A typical 3 phase Voltage Source Inverter with Battery Input and Motor shown

The common method for modulating the transistors in a VSI is to use a form of Pulse Width Modulation (PWM). PWM works by continuously comparing a reference wave (the desired average value of the output) and a carrier wave (either a sawtooth or a center-aligned triangular wave) with each other. If the value of the reference wave is greater than the value of the carrier wave, the output goes high. There are different approaches for the specific implementation of PWM, each with their own advantages, disadvantages and complexities.

A. Square Wave Pulse Width Modulation

In this method, the reference wave is simply a constant value signal that is compared with the carrier wave. The result is a rectangular or square wave with a duty cycle that is always constant. The output voltage of the VSI can thus be controlled by turning its switches on and off in accordance to the PWM input. The faster the frequency of the PWM input, the more accurate the average output voltage is compared to the reference input. Figure 6 graphically shows the effect of changing pulse widths on the output modulated voltage.

Figure 6: The voltage averaging effect of PWM [8]

However, the average PWM output matches the reference input only in an ideal case. In case of a motor drive application, the motor inductance and parasitic capacitances in the drive circuits resist the rapid changes in output voltage and current. In this scenario, the motor voltage cannot track the PWM generated voltages quickly enough, resulting in ripples in the voltage, as shown in Figure 7. The magnitude of the ripple is directly proportional to the time period of the PWM cycle as seen in the figure. Thus to reduce ripple, the carrier frequency should be increased as to as much as the inverter switches and gate drive circuitry can support.

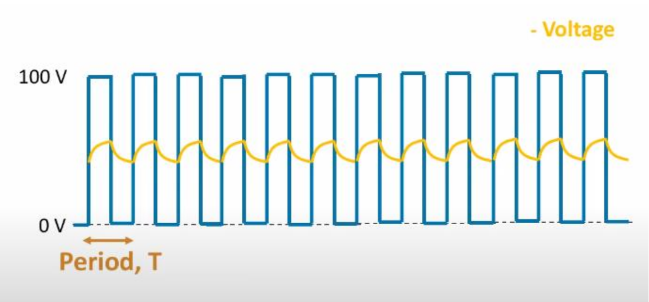

Figure 7: Voltage ripple caused due to square wave PWM [8]

Using this method, we obtain square wave outputs with different duty cycles, according to the reference input provided to the PWM comparator. These square wave output waveforms get filtered out to trapezoidal waveforms after low-pass filtering by the motor [2]. These resulting trapezoidal waveforms are suitable for driving BLDC motors, hence this PWM technique is used in BLDC drives. For PMSM motors, a sinusoidal output is required, hence the sinusoidal PWM technique is used in those cases, which we discuss next.

B. Sinusoidal Pulse Width Moduulation (SPWM)

Sinusoidal Pulse Width Modulation, or SPWM, replaces the constant reference wave of the square wave PWM with a sinusoidal wave. The sinusoidal reference is computed by the control system according the rotor electrical speed so that the correct frequency signal is provided to the motor for it to spin. The carrier wave frequency is chosen to be far higher than the sinusoidal reference to avoid any timing conflicts or aliasing errors. The Pulse Width Modulated output thus contains the frequency components of both the carrier and the reference signals, and the highest frequency component of of the output determines the switching speed of the inverter switches. Thus, the carrier wave frequency has to be chosen carefully in accordance with the specifications of the inverter switches as well. Figure 8 shows the carrier and reference (the voltage error signal) wave, and the corresponding generated PWM. However, when driving the motor, the frequency of interest is the frequency of the reference sine wave. Assuming ideal switches, the output voltages of the 3 phase VSI will contain all the input frequency components as well. In grid-connected applications, an additional filter is used to convert the PWM wave output to a sine wave. In motor control applications however, the motors' windings act as an RL filter and filter out most of the high frequency components, so an additional filter is not crucial. In some cases, harmonics may be left in the output signal that can cause torque ripple, but they too can be removed by proper tuning of the current regulators.

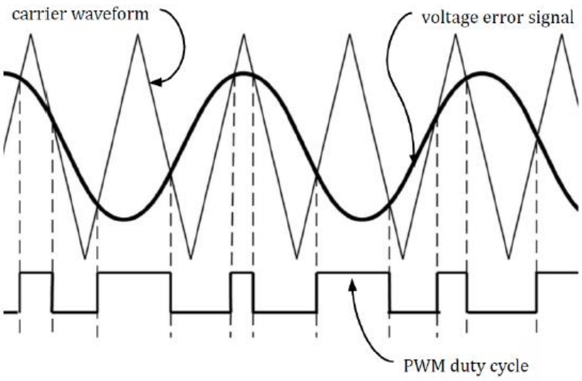

Figure 8: Example of Sinusoidal PWM with Center-Aligned carrier wave

In practice, the implementation of SPWM for a 3-phase inverter is done by using three sine reference waves and one common carrier wave. The output PWM signal is complemented and amplified to drive the gate inputs of the inverter switches. An additional gap time called dead time is added in which the switching of one pole is slightly delayed to ensure the complementary pole has turned off. This is done to ensure that the voltage bus is not short-circuited by any chance. SPWM, since it produces a sine wave output after low-pass filtering, is generally used to drive PMSMs, as their back EMF profiles are sinusoidal too.

C. Space Vector Pulse Width Modulation (SVPWM)

The Space Vector PWM method is an advanced PWM method that provides better utilization of the connected DC bus voltage as compared to Sinusoidal PWM, as well as reduced harmonic distortion [9]. In SVPWM, the inverter is treated as a single entity with a set of three states (for each half bridge). Each half bridge can be either 1 (upper leg switched on) or 0 (lower leg switched on). Hence, a total of 8 voltage vectors can be formed. Two of these are considered null or zero vectors, in which all 3 half bridges are either all switched high (111) or switched low (000). The remaining six vectors divide the voltage plane into six sectors as shown in fig 9. In this plane, the reference vector is shown to rotate with a certain angular velocity with respect to the stationary orthogonal reference frame.

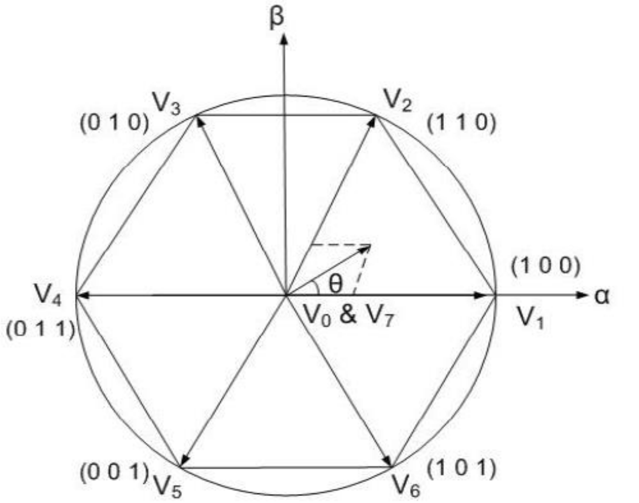

Figure 9: Vector Diagram of Space Vector PWM [3]

The desired three phase output voltage equations are as shown below:

$$V_a = V_m \cos \omega t$$
$$V_b = V_m \cos(\omega t - 120°)$$
$$V_c = V_m \cos(\omega t + 120°)$$

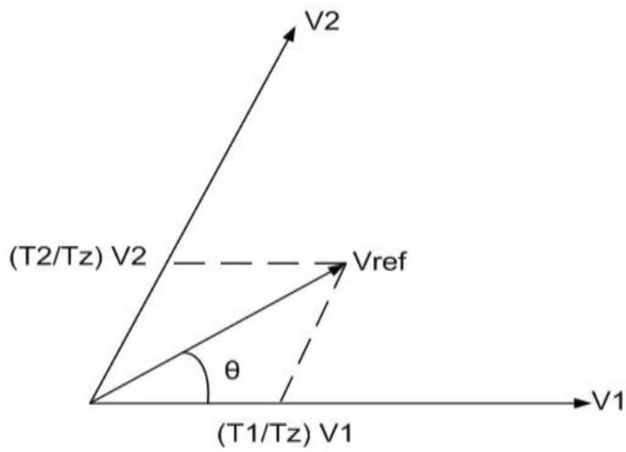

Figure 10: Zoomed in Representation of Sector 1 for reference [9]

Figure 10 shows a zoomed in view of Sector 1. Here, the reference voltage V_{ref} is defined as:

$$V_{ref} = \sqrt{\frac{3}{2}}\, V_m e^{j\theta}$$

Where θ = ωt

Here, V_{ref} can be generated by the time-weighted average of vectors V_1 and V_2 as shown:

$$V_{ref}T = V_1T_1 + V_2T_2$$

Where T = 1 / switching frequency, and T_1 and T_2 are the switching periods of vectors V_1 and V_2 respectively. T_0 is the time when both V_1 and V_2 are inactive. Φ is the angle within each vector from 0 to 60 degrees.

$$T_1 = T\, \frac{2}{\sqrt{3}} \frac{V_{ref}}{V_1} \sin(60 - \emptyset)$$

$$T_2 = T\,\frac{2}{\sqrt{3}}\frac{V_{ref}}{V_2}\sin(\emptyset)$$

$$T_0 = T - (T_1 + T_2)$$

Using combinations of these 3 vectors (V_1 , V_2 and zero vectors, any voltage V_{ref} can be generated in the voltage vector plane. Overmodulation schemes to boost DC bus utilization and line-to-line voltage can be designed on top of SVPWM to provide increased performance. Proper selection of zero voltage vector sequences can help in minimizing the number of times a given inverter leg has to switch, thus reducing the switching losses of the inverter and thus improving efficiency. A comprehensive treatment of different SVPWM implementations is beyond the scope of this paper, and some of the sources that can be referred to for additional material is [10] and [11].

IV. Control Strategies for motor control

The control strategy for the motor controller is required to ensure that the given torque, current or speed commands given to the motor are faithfully followed. An appropriate control strategy has to be chosen that takes these references as an input and provides output signals appropriate for the type of motor being controlled. Thus, the motor properties as well as the inverter properties have to be taken into account for the same. A general overview of such as control system is shown in Figure 9. Here, a PI controller is used to control the phase current, and thus torque, of the motor. Sinusoidal references are considered in this diagram as the motor is assumed to be a PMSM, but this system can be readily generalized to include other motors and reference types as well. Since our application involves a voltage source (battery pack) and a VSI, additional components have to be added into the system to control the same. All these components require a unified control strategy for optimal response, and 2 of these strategies are discussed next.

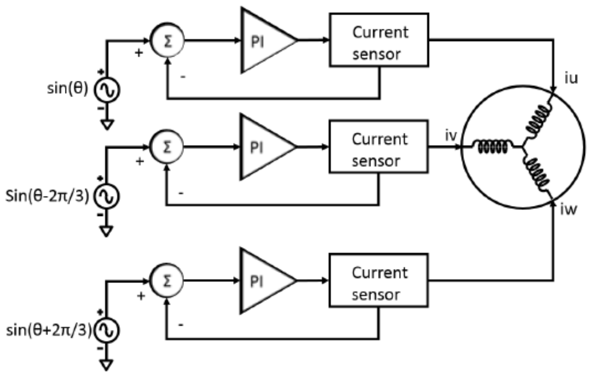

Figure 11: Generalized overview of a 3 phase motor control system

A. Six Step or Trapezoidal Control

Six step control works by dividing the possible rotor angles (from 0 to 360 degrees) into 6 sectors of 60 degrees each. The motor rotor position sensor signals when the rotor enters the next sector, and the phase current is commutated to the next sector, so that the stator magnetic field is always leading the rotor field. This ensures the motor rotation is continuous. This method is especially useful for controlling BLDC motors, since the square waves generated by the commutation sequence are filtered to trapezoidal waves by the RL equivalent windings of the motor. This method is very popular for controlling low performance motors [2], where the smoothness of the torque output is not of prime concern. This method is also simple, since only two transistor switches are to be switched on at any given point in time. Figure 10 shows an example of the winding energizing sequence of a BLDC motor [3].

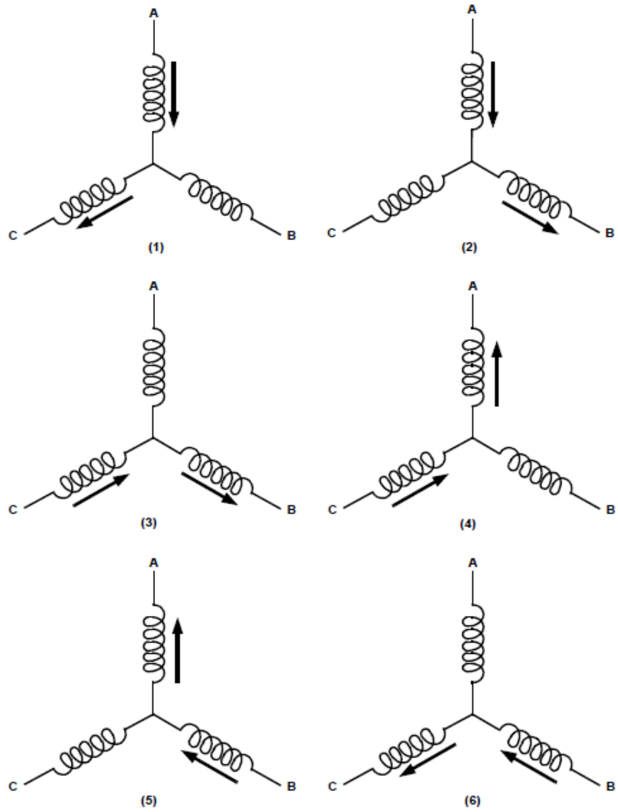

Figure 12: Winding energizing sequence for 6 step control

An overview of the Trapezoidal Control System is given in Figure 11. The block diagram shows an example of speed control loop using this control scheme. Hall Sensor based position sensing is used for determining the sector information of the rotor. A commutation logic block is designed that converts the rotor sector into 6 gate drive signal vectors, each having six elements (high and low side switches for three half bridges). The power switches in the inverter are switched according to these signals to provide the electromagnetic torque to the motor. A current controller is also added as in inner control loop to control the torque of the motor and ensure that it is operating within safe limits.

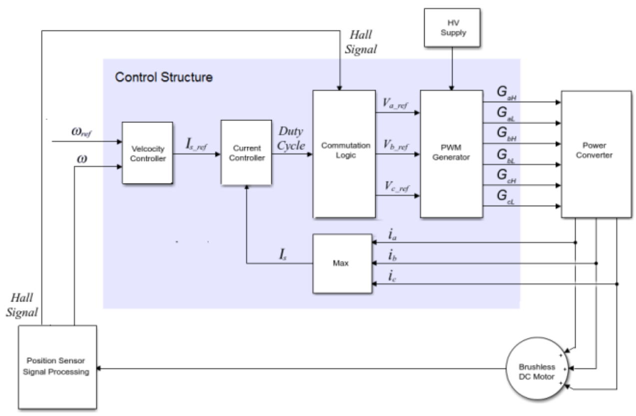

Figure 13: Block Diagram overview of BLDC six step control

An advantage of this control scheme is that knowing the absolute position of the rotor is not essential for commutating the stator current. It is sufficient to know that the rotor field has transitioned from one sector to the next, and commutating the phases accordingly. This allows use of simple sensors such as Hall effect sensors for position feedback, which reduces the cost of the motor and complexity of the logic in the controller. However, the simplicity of the 6 step control method also has a few drawbacks. The first is that using this control method results in significant amounts of ripple in both the torque as well as the phase currents. This occurs because the angle of the stator field takes one of six possible values from 30,90,150,210,270 and 330 degrees, whereas the rotor field periodically takes any value from 0 to 360 degrees. Hence, due to the commutation sequence, the angle between the rotor field and stator field varies periodically from 60 to 120 degrees. As we saw in the motor theory section, the electromagnetic torque is maximum when the angle between the rotor and stator fields is exactly 90 degrees. Hence the torque increases as the angle varies from 60 to 90 degrees, and decreases from 60 to 120 degrees in a sinusoidal manner, which creates ripples in the torque output. Second is that the phase currents travel through only two out of the three motor windings at any given time, and the third winding is left floating. This means that only two-thirds of the motors copper is effectively used by this control scheme, which increases the copper losses of the motor. High performance control schemes such as vector control utilize all three phase windings at the same time to utilize all three windings and reduce copper losses. Both of these drawbacks can be addressed by using advanced control schemes such as Field Oriented Control, which is discussed next.

B. *Field Oriented Control*

As the name suggests, Field Oriented Control (FOC), sometimes called as Vector Control, directly controls the angle and magnitude of the stator magnetic field generated through the switching pattern of the 3 phase VSI to provide the necessary electromagnetic torque for the motor to spin. From section II, we know that the maximum torque is generated when the stator magnetic field is leading the rotor magnetic field by 90 degrees. So FOC maximizes the torque that can be produced by the motor by reading the angle of the rotor and the rotor magnetic field and generating the stator field exactly 90 degrees leading to it. Then the actual magnitude of torque required is generated by modulating the magnitude of stator current through PWM techniques. This ensures a smoother torque output from the motor as well as maximizing the benefits of brushless motors, including fast dynamic response and high efficiency.

However, as we know, the back EMF profile and the required currents for the PMSM is sinusoidal in nature, hence the current setpoint for achieving a desired torque value is also sinusoidal. Generating and tracking a sinusoidal reference is tricky and computationally expensive for a digital control system, hence a series of mathematical transforms are used to convert the 3 phase sinusoidal currents in stator reference frame into 2 constant currents in a rotor reference frame. These transforms are known as Clarke and Park Transforms. The Clarke Transform takes in the 3 phase values and transforms them into 2 quadrature values, and the Park transform converts these values from stator reference frame to rotor reference frame. The process can be seen in Figure 12.

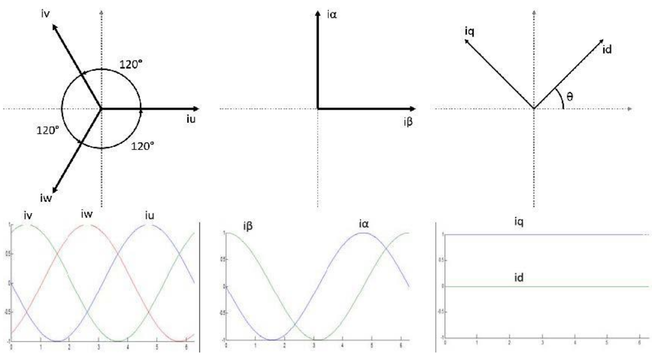

Figure 14: Illustration of Clarke and Park Transforms [2]

Using the Clarke and Park Transforms, the 3 sinusoidal phase current references are converted to 2 quadrature constant current references, which greatly simplifies the control design. Also only two current regulators are required instead of three, saving both the effort and complexity of implementing an additional sensor and regulator setup. The equations of the Clarke and Park transforms, and their inverse, can be found in [12].

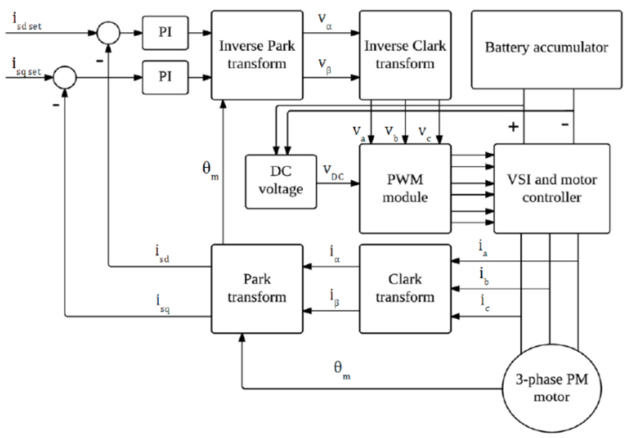

Figure 15: Block Diagram overview of Field Oriented Control Scheme [4]

Figure 13 shows an overview of the FOC system implemented with a battery pack as voltage source. Two PI controllers are used to regulate the direct and quadrature axis currents in the system. Inverse Park and inverse Clark transforms are used to convert the error values of the currents into 3 phase currents in stator reference frame.

According to these values, the PWM module generates the requisite switching patterns for the 6 gate inputs for the VSI. The output 3 phase currents from the VSI are read and converted to rotor quadrature reference frame using Clarke and Park Transforms, which are then compared to the provided reference to generate the error values for the PI controller. FOC has many advantages over six step control, such as reduced torque ripple and smoother motor speed response. FOC also provides easy provisions for regenerative braking and field weakening operations. To achieve regenerative braking, simply providing a negative torque command or quadrature current reference is sufficient. Doing so results in the stator magnetic field now lagging the rotor field by 90 degrees instead, which provides torque in the opposite direction. Field weakening can also be achieved by providing a negative command to the direct axis current, which opposes the rotor magnetic field and reduces its magnitude. Hence the induced back EMF is reduced and higher motor RPM can be achieved using the same supply voltage. The main drawback of the FOC technique is the higher computational complexity involved due to the matrix multiplications, trigonometric and floating point calculations. These drawbacks can be overcome by proper programming techniques and selection of a sufficiently fast microcontroller. FOC techniques have been discussed in many places in motor control literature. The theory for this section was gathered from [1], [2],[4]. Additional information can be found in [5], [13] and [14].

C. Direct Torque Control

The method of Direct Torque Control (DTC), as its name suggests, seeks to directly control the motor torque and flux linkage by selecting the appropriate output voltage space vectors, according to the relationship between torque and slip angle. Most of the theory regarding Direct Torque Control in this section is cited from [13]. Additional sources for direct torque control theory are [15] and [16].

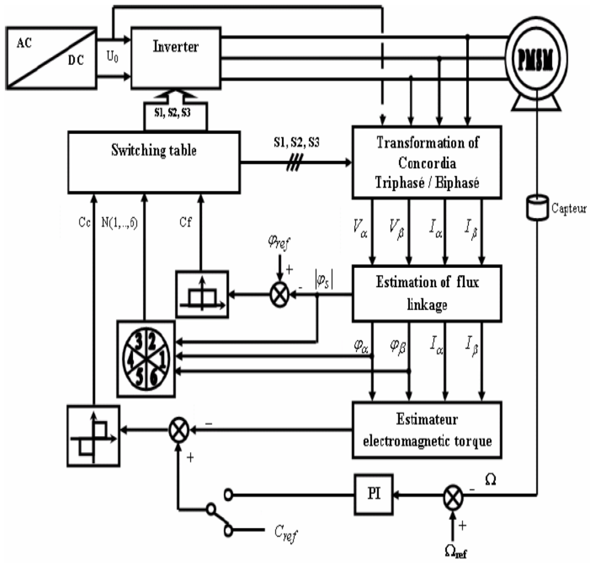

Figure 16: System Diagram of Direct Torque Control PMSM Drive System [13]

The basic principle of Direct Torque Control is to select the proper voltage vectors according to the control input from a pre-defined switching table. The stator voltage, or the 3 phase output voltage from the inverter is directly dependent on the switching states of the three half bridges of the inverter. The stator flux linkage can be estimated as:

$$\varphi_s(t) = \int_0^t (V_s - R_s I_s)dt + \varphi_{s0}$$

Where φ_{s0} is the initial value of the stator flux linkage.

The inverter output voltage as well as the output current are both functions of the state of the inverter as shown:

$$V_s = \frac{2}{3}U_o(S_A + S_B e^{j2\pi/3} + S_C e^{j4\pi/3})$$

$$I_s = \frac{2}{3}(I_A + I_B e^{j2\pi/3} + I_C e^{j4\pi/3})$$

From these equations, composite $\varphi_{s\alpha}$ and $\varphi_{s\beta}$ for the quadrature α and β axes can be obtained, and the total stator flux linkage is calculated as the magnitude of the vector sum of these two quantities. The rotor angle θ_s is found as the inverse tangent of these quantities, and the stator torque is calculated as:

$$T_e = \frac{3}{2}P(\varphi_{s\alpha}I_{s\beta} - \varphi_{s\beta}I_{s\alpha})$$

The switching table of the direct torque control scheme as presented in [7] is reproduced here. The voltage vector plane is divided into 6 equal sectors of 60° each. In each sector, up to four of the six non-zero voltage vectors can be used. In this control scheme, hysteresis controllers are used in lieu of the PI controllers of the FOC scheme. These comparators are used to control the torque and flux components. The torque comparator is a three-valued comparator with outputs -1, 0 and 1. A value of -1 indicates torque above and out of range of hysteresis, 1 indicates torque below and out of range, and 0 indicates in range. The flux comparator is a two-valued comparator with 0 indicating above the reference and 1 indicating below the reference.

Table I

Switching Table of Direct Torque Control

θ, τ, ϕ		**θ_1**	**θ_2**	**θ_3**	**θ_4**	**θ_5**	**θ_6**
ϕ = 1	τ = 1	V_2	V_3	V_4	V_5	V_6	V_1
	τ = 0	V_7	V_0	V_7	V_0	V_7	V_0
	τ = -1	V_6	V_1	V_2	V_3	V_4	V_5
ϕ = 2	τ = 1	V_3	V_4	V_5	V_6	V_1	V_2
	τ = 0	V_0	V_7	V_0	V_7	V_0	V_7
	τ = -1	V_5	V_6	V_1	V_2	V_3	V_4

D. Comparison of 6 Step, FOC and DTC Schemes

In this section, all the three control schemes are compared based on their advantages and disadvantages, as well as the following criteria:

- Best Static and Dynamic Performance
- Best resistance to external disturbance
- Best following of given control input
- Least complexity of implementation

Table II
Comparison of Motor Control Schemes

	6 Step Control	FOC	DTC
Coordinate Axis Transformation	Absent	Present	Absent
Torque Step Response Rise Time	Slower	Fast	Very Fast
Constant PWM Frequency	Yes	Yes	No
Ripple in Torque output	Significant	Negligible	Significant
Speed Fluctuation from change in load	High	Very Low	Low

V. Conclusion

In this paper, the different motor control schemes are presented and reviewed, along with the requisite motor fundamentals and overview of the necessary PWM techniques. The comparisons of the control schemes as well as the PWM techniques are also presented. After reviewing each strategy and analysing their merits and drawbacks, it is difficult to state a clear winner, due to the balance of merits of each. Final selection of the control methods depends on the exact priorities of the implemented design. We can conclude that, in scenarios where extremely fast response times are desired, the DTC method is best applicable. FOC can be used in areas where large torque variations are expected and low fluctuations in the speed are desired. Since DTC does not require a PWM scheme, one will not be suggested for it. As for FOC, a Space Vector PWM scheme is suggested due to improved system performance, smoother response and lower torque ripple. However, if a simplified system design is desired, then sinusoidal PWM can also be used without major reductions in performance. In addition, we can safely conclude that vector control methods such as FOC and DTC can easily outperform scalar methods such as 6 step control, and thus these methods should be relegated to low performance BLDC motors only.

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