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Abstract

For autonomous driving of a RC car, having precise motor control is a must since it is one of the fundamental building blocks of motion planing. The most common problem is having smooth motion at lower speeds, as it is challenging to achieve with the commony used 6-Step/Trapezoidal Commutation. This work focuses improving BLDC Motor performance, especially at low speed driving. It also serves as a general introduction to BLDC motor control, illustrating all relevant concepts: BLDC principles, inverters, related PWM schemes and lastly three most common control strategies (Trapezoidal, Sinusoidal and F.O.C). Afterwards it moves on with a guide on implementation of chosen control method, namely Sinusoidal Commutation. Although it is not implemented, F.O.C (Vector Control or Field Oriented Control), including the SVPWM technique will be also covered in detail.

Contents

Abstract **ix**

Contents **xi**

1 Introduction **1**

2 Related Work **3**
- 2.1 BLDC Principles 3
- 2.2 Commutation Strategies 5
- 2.3 Inverters and Common Operation Techniques 19

3 Chosen Control Scheme **27**

4 Implementation **29**
- 4.1 Hardware Overview 29
- 4.2 Sensor-Microcontroller Communication 30
- 4.3 Current-Sense 31
- 4.4 SPWM (Sinusoidal Pulse Width Modulation) 31
- 4.5 Inverter Control and First Successful Motor Operation 32
- 4.6 Angle Feedback Integration 34
- 4.7 Speed and Torque Control 35

5 Conclusion **37**
- 5.1 Results of the Implementation 37
- 5.2 Future Continuation 38
- 5.3 Concluding Remarks 38

6 Appendix **41**
- 6.1 A 41
- 6.2 B 43

List of Figures **45**

Bibliography **47**

CHAPTER 1

Introduction

In many robotic applications, the usage of BLDC motors is widespread due to high torque density, power efficiency, variable speed and torque, silent and spark-less operation and longer lifetime they offer[1][2]. Since the main distinguishing factor of a BLDC motor is the electronic commutation, various control strategies present themselves due to endless potential offered by ever-growing micro-controller capabilities. The currently employed scheme, Trapezoidal Commutation is preferred due to easy implementation and high torque characteristics. Unfortunately, mainly due to abrupt switching between commutation zones a serious torque ripple is induced, making driving at low speeds, if not impossible, a truly fruitless endeavor. Although it is suitable for numerous applications, this drawback severely limits autonomous driving since it makes position control, which is a key aspect, challenging.

In this work, after a short summary of BLDC principles, both the 6-step and the other two common approaches, namely Sinusoidal and Field Oriented Control, will be studied in order to determine the optimal BLDC motor control method for autonomous driving of RC cars. In addition, a brief overview of power electronics aspect of motor control, including inverters and PWM techniques which go hand in hand with optimal control will be given.

After the theoretical background has been covered, a comparison of three commutation schemes will be made. After determining Sinusoidal Commutation as the chosen control scheme, a detailed guide on implementation will be presented.

Lastly, the ensuing results will be compared with the current setup and discussed thoroughly in the conclusion.

CHAPTER 2

Related Work

2.1 BLDC Principles

In this section, a brief summary of the BLDC motors working principle and their inherent structure, as well as a short history of its development will be given.

BLDC motors are originated from the brushed DC motor, which was developed around 1840s, based upon the Faraday's electromagnetism induction phenomenon(1831) , but any research on BLDC's didn't start before 1930's. After the rapid advancement of solid state electronics around 1960, the BLDC's really made their entrance to the motor scene. In less than twenty years, it was already a commercially available product, used all around the world. With the advancements made in 90's in MCU's, DSP's and FPGA's, a further quality increase in BLDC's has been promoted [3].

The main distinguishing factor between BLDC motors and their brushed counterparts is the electronic commutation, which has eliminated the need for brushes[2]. In brushed DC motors, commutation is done mechanically, with the help of brushes, which results in noisy operation, sparks and an inevitable maintenance since the brushes wear down in time[4]. In BLDC motors commutation is controlled digitally to supply current to motor windings in synchronization with the rotor position, which brings considerable advantages like high efficiency, noiseless operation, higher speed ranges, better speed/torque characteristics etc. [1][2].

Another important physical factor is the position of stator (stationary part of the motor) and rotor (rotating part of the motor). BLDC motors can be either "in-runner" or "out-runner". In a in-runner setup, the stator on which the windings are installed, is in the outer side of the motor and the rotor which has the permanent magnets mounted on, is encased inside the stator. Brushed DC motors are also designed in this way. The out-runner on the the other hand, implements the opposite setup (rotor - outside, stator

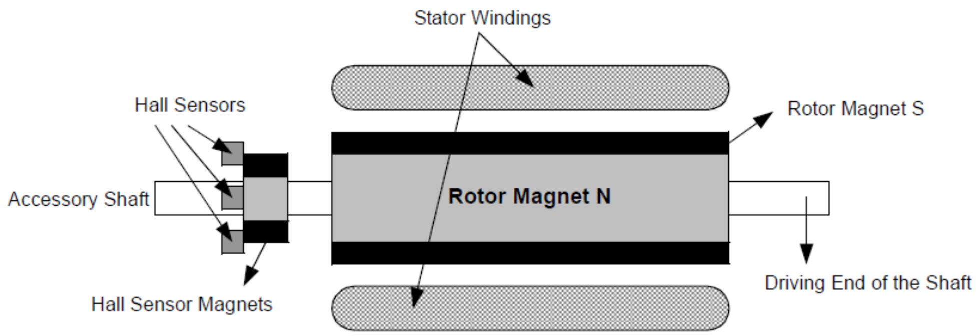


Figure 2.1: BLDC Motor Transverse Section. [1]

inside) [5]. [5]. The transversal section of a inner-runner BLDC can be seen in Figure 2.1 for better illustration.

Another key aspect of the BLDC design is the winding method, which differs from motor to motor. Windings are formed up by two or more interconnected coils, placed on stator slots. They are connected to each other either in "star - Υ" or "triangle - Δ" fashion and are distributed around the stator to create an even number of poles[5]. The two main types of windings are concentrated or distributed. The concentrated winding is the simplest option and mostly found in trapezoidal-wave BLDC motors. In this setup, all N turns are in placed in two stator slots (per pole per phase), meaning each slot has N conductors, forming 2 poles [6, p.281] [1]. The other variation, namely distributed windings places the N turns differently throughout the stator, thus forming a more complex structure, mostly in order to form up a sinusoidal back-EMF.

The theory of operation is as it is in electrical machines; a rotational force is created due to the magnetic field generated by the stator windings and permanent magnets (See Figure 2.2). The maxiumum torque is generated when these two fields are at a 90° angle in respect to each other. To keep the motor rotating, the magnetic field created by the windings should shift position, in order to be aligned in an opposing fashion with the permanent magnets field[5][7][1][2]. The methods to achieve this, i.e commutation methods will be discussed in the following sections.

As mentioned before, the electronic commutation thats necessary to operate BLDC motors require two things, an inverter to supply the motor with appropriate current and a controller on which the chosen commutation algorithm will run [2]. The commutation algorithm will control the inverter switches, usually with PWM, in order to energise motor phases accordingly. Although it will not be focused on different inverter topologies in this paper, a brief coverage can be found in the "extras" section.

Before going any further it would be appropriate to address a situation which arises

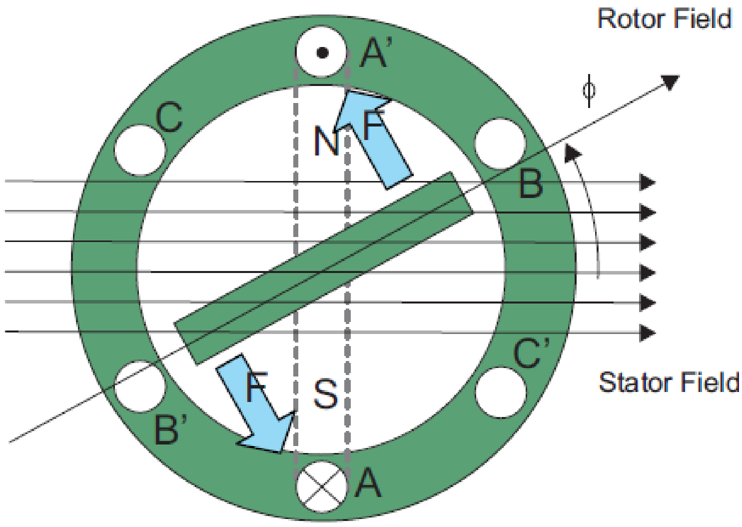


Figure 2.2: Interaction between rotor and stator fields generates the torque that rotates the motor[8].

quite often and is rather confusing : What should be called a BLDC? In many papers and literary work, there is a discord about the definition of BLDC's [6]. Some call only motors with trapezoid/square wave form as BLDC's and insist that sine-wave brushless motors should be identified as PMSM - Permanent Magnet Synchronous Machine. On the other hand other scholars consider both as a BLDC motor [3, p. 1]. It should also be noted that this sinusoidal/trapezoidal differentiation comes from the BACK-EMF form, which is related to the wounding of the motor, rather than the commutation method [9] [1] [6, p.281]. Finally, its important to know that each motor, independent of its wounding, can be controlled with any commutation method [10][6, p.61].

2.2 Commutation Strategies

In order to drive a BLDC motor, an inverter and a controller is required. The inverter topology is usually basic 6-switch, that will feed the corresponding motor terminal with current, according to the shifting rotor flux, controlled by the algorithm that is being executed by the controller[11]. To be able to perform the commutation the rotor position must be known to some degree, depending on the particular commutation strategy. Although sensorless commutations methods (Sliding-mode Observer, Extended Kalman Filter, Model Reference Adaptive System, Adaptive observers) exist and are well-used[4], this paper will be focusing on sensor aided commutation.

The most common commutation methods for the BLDC motor are trapezoidal (or six-step), sinusoidal, and field oriented control (FOC). Each commutation method can be implemented in different ways, depending on control algorithms and hardware implementation to provide their own distinct advantages[9].

2.2.1 6-Step Commutation

The 6-Step commutation is also called trapezoidal commutation due to the trapezoidal the back-EMF of the motors that are ideally driven with the scheme. Those motors are commonly called BLDC motors. As mentioned before, this back-EMF form is not a result of the particular commutation, but a result of the physical placement of the motor windings. This method is the simplest of the available methods and is widely used, since it provides excellent variable speed and is easy to implement.

The idea behind 6-Step Communation is simple; two of three motor phases are powered at a given time, the third one floating[9]. The phases that are to be powered are determined according to the rotor position, which is given by Hall-Effect Sensors which work according to the Hall Effect theory.[6] Those sensors are mounted around the motor, 120° apart from each other. Whenever rotor magnetic poles pass through a Hall sensor, the sensor sends a 0 or 1 for North or South pole of the magnet. By combining those signals from 3 Hall effect sensors, 8 different combinations are acquired. Since all 3 sensors can not be high or low at then same time, only 6 different possible combinations remain, each adressing 6 seperate sectors of the motor. Thus the rotor position can be determined within 60° of resolution [1] [9]. It is also important to point out that, this model is only valid for a motor with only 1 pole pair rotor. If the number of pole pairs increase, the number of hall sensors has to increase accordingly.

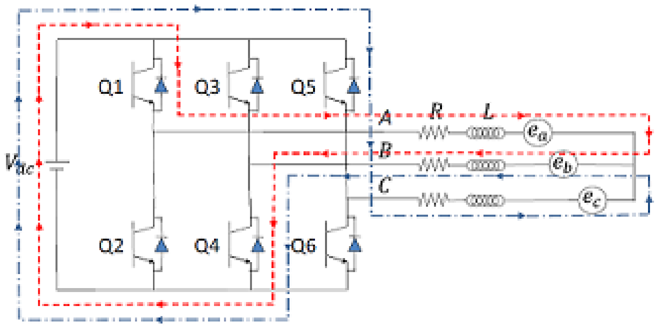
The name 6-step comes form the 6 different commutation zones (60°), in which different phases -only two of them as mentioned before - will be energized. Every time the rotor enters a new commutation zone, 2 new phases will be powered,current entering through one and exiting through the other [5][7].The current wave form will be flat-topped, ideally matching the Back-EMF shape (See Figure 2.4). The energized phases will create the electromagnetic field that will oppose the permanent magnets field, hence creating the rotational force[1].

As mentioned before, one of the main reason to prefer this method is the ease of implementation. A simple look-up table, which can be found in many application notes e.g. [1], defines which phases to energize, both CW and CCW, according to the received hall sensor signal combination [5][7][1].

Since the power distribution through the inverter is controlled by PWM signals sent by the controller, adjusting PWM's duty cycle will control the motor speed effectively. There are some practical considerations in the implementation of PWM duty cycles like dead-time generation etc., but those wont be covered in this paper. Many application notes cover the subject [7].

The 6-Step commutation offers better power density compared to Sinusoidal commutation but especially at low speeds a torque ripple is present. The torque ripple is due to:

1. Cogging (See Appendix A.)
2. the imperfect alignment of fluxes



Interval (Degree)	Switching Sequences Trapezoidal Commutation Transistor "ON"	Polarities A	B	C
0-60	T1,T6	+	0	-
60-120	T3,T6	0	+	-
120-180	T3,T2	-	+	0
180-240	T5,T2	-	0	+
240-300	T5,T4	0	-	+
300-360	T1,T4	+	-	0

Figure 2.3: Current flow in trapezoidal drive. [10]

3. non-linearities due to powering only two phases at a time[3][6][2].

For these reasons, this commutation strategy is not really well suited for applications that demand high precision at low speeds. On the other hand, in many applications that require good torque production, variable speed and high power density 6-step commutation is widely used[9].

Lastly, understanding how the torque is generated with is key to fully understand this commutation method. Although there are many depictions of torque, we will be focusing on two.

The first and very general one being :

$\tau = K * B_f * B_S * \sin(\theta)$

K: a constant
B_f: permanent magnet field flux vector
B_S: stator windings field flux vector
θ: the angle between two flux vectors

As this formula clearly illustrates, the torque production is highly related to the angle between rotor and stator fluxes. The maximum torque is generated at 90° which corresponds to the very center of a commutation zone. After or before this point the torque decreases, but surprisingly not so much. Even at a 30° offset, just before the the zone change, the torque loss is 13 % [12][13]. This behaviour can be clearly observed in the Figure 2.4. This is one of the main reasons of poor low speed performance, since the torque fluctuation is much more visible at lower RPM.

The second one which is more specific to BLDC motors with trapezoidal Back-EMF is:

$\tau\omega = e_A i_A + e_B i_B + e_C i_C$

i_A, i_B, i_C : phase currents
e_A, e_B, e_C : Back-EMF of each phase

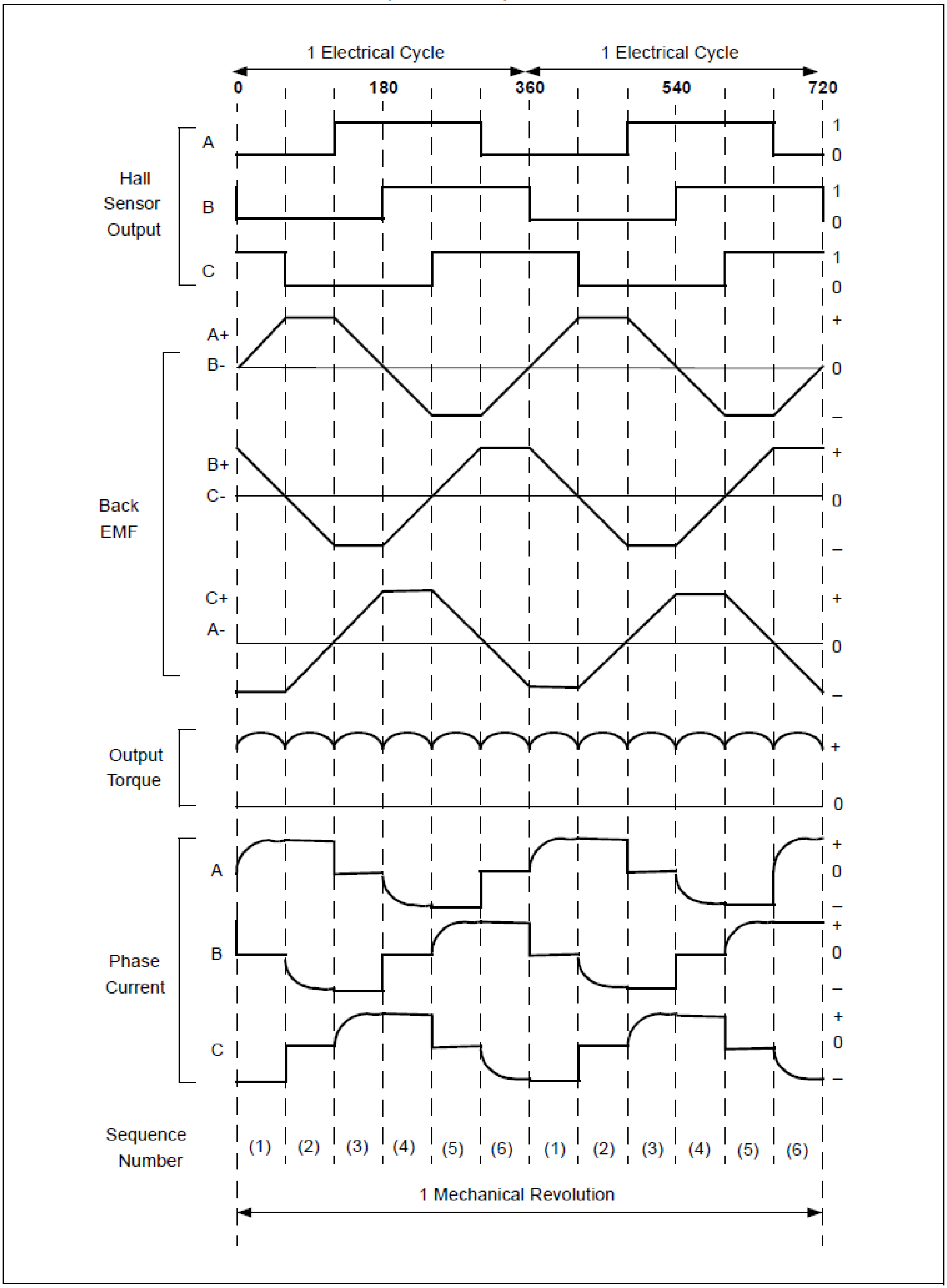


Figure 2.4: Switching sequence of a 6-step commutation. [1]

This equation can also be expressed as the following, depicting Back-EMF as a function of rotor position:

$$\tau = \frac{e_A}{\omega} i_A + \frac{e_B}{\omega} i_B + \frac{e_C}{\omega} i_C$$

By substituting $\frac{e_A}{\omega}$ with $k_{eA}(\theta_r)$ the following equation is acquired :

$$\tau = k_{eA}(\theta_r) * i_A + k_{eB}(\theta_r) * i_B + k_{eC}(\theta_r) * i_C$$

$k_{eA}(\theta_r)$: Back-EMF as a function of rotor position
θ_r : Rotor angle
i_A, i_B, i_C : Phase currents

By looking at this formula, the torque - Back-EMF relationship can be seen directly. Explaining where that relationship comes from is rather simple with energy conservation. Since the Back-Emf is working against the supply voltage, it can be depicted as:

Back-EMF $= V_{supplied} - IR$,

and Torque can be expressed as;

$$\tau_{(E_{mech})} = \textit{Supplied Energy - Energy lost in windgins}$$

$$\tau = V_{supplied} * I - I^2 R$$

$$\tau = I(V_{supplied} - IR) = I*(\text{Back-EMF})$$

This torque representation, if we view the total torque generated as the sum of torque generated by three induvidual phases, gives an idea how not following the inherent Back-Emf form or non uniform current can induce torque ripples[6]. The total torque produced can be expressed as

$$\tau = 2K_e I_p$$

where K_e is a variable that depicts rotor angle - Back-EMF relationship, and I_p is the peak value of the flat-topped current. This relationship can be seen clearly in Figure 2.5.

2.2.2 Sinusoidal Commutation

The sinusoidal commutation is usually used for aforementioned PMSM motors, which are basically BLDC motors with sinusoidal Back-EMF shape. Trapezoidal BLDC motors can also be driven with this technique, and the ensuing results have been studied in some papers, claiming the "overall" performance is hindered by doing so[10].

This method has the potential to produce smooth torque even at low speeds, but lacks the torque density and high speed operation capabilities of trapezoidal commutation. The reason behind smoother torque is the better flux alignment[12]. On the other hand the mentioned disadvantages are mainly due to:

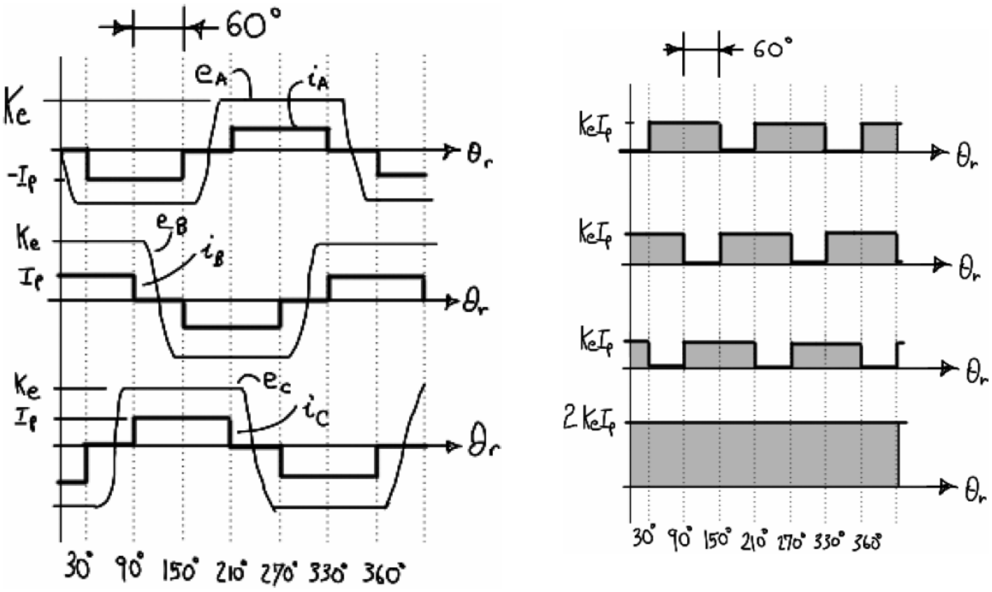


Figure 2.5: The total torque production viewed on a torque per phase model ob BLDC. Each phase contributes to torque production individually. [6]

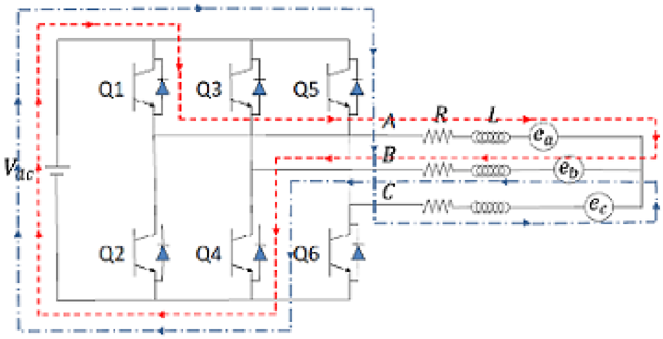
1. the Back-EMF, which is proportional to the speed of the rotor, starts to slow down the motor, working against it considerably. Also, the sinusoidal voltage waveforms utilize bus voltage less compared to the Trapezouidal Commutatuions's flat-topped waveforms, leading to less torque production and poorer high speed operation [13].

2. as the frequency of the sinusoidal currents increase, it get harder and harder for the controller to keep up with the rapid switching of the inverter[14].[13]

In addition, an absolute rotor position is a necessity, which will be discussed later in this chapter.

The main objective is still the same, supplying the motor phases with appropriate phase currents which are calculated according to the rotor position. The main difference with the trapezoidal commutation is the fact that all 3 motors phases are powered simultaneously with sinusoidal currents.[10][6][9].

"The current control scheme must keep sinusoidal currents aligned in time with the rotor position, In its most basic form, this requires a continuous position sensor (resolver) or near-continuous sensor (absolute encoder). While the rotor is rotating the required instantaneous value of phase current changes continuously, even when the commanded torque is constant. Thus for the sinusoidal motor, current control can not be separated from the commutation" [6, p. 59]



Interval (Degree)	Switching Sequences — Sinusoidal Commutation: Transistor "ON"	Polarities A	B	C
0-60	T1,T6,T5	+	-	+
60-120	T1,T6,T2	+	-	-
120-180	T1,T3,T2	+	+	-
180-240	T4,T3,T2	-	+	-
240-300	T4,T3,T5	-	+	+
300-360	T4,T6,T5	-	-	+

Figure 2.6: Current flow in sinusoidal drive. [10]

Since those rotor position sensors are rather expensive requirements, an interpolation method based on Hall Effect sensors, or other sensorless schemes e.g. Back-EMF zero crossing detection can be applied but they add up to the already high implementation complexity. [12] [10]

The torque production of PMSM's is in essence similar to BLDC motors that are controlled with the 6-step Commutation. There are just two things worth noting : Firstly, the Back-EMF constant K_e which depicts the peak value of rotor position/Back-EMF relationship, is modified by a sinus term. This sinus term is 120° phase shifted for each phase.

$$\tau = -K_e sin(\theta_r) \cdot i_A - K_e sin(\theta_r - 120°) \cdot i_B - K_e sin(\theta_r + 120°) \cdot i_C$$

Secondly, the phase current value I_p, is also modified with a sinus term in order to match the Back-EMF form. The resulting equation is:

$$\tau = [-K_e sin(\theta_r)] \cdot [-I_p sin(\theta_r)] + [-K_e sin(\theta_r - 120°)] \cdot [-I_p sin(\theta_r - 120°)] + \\ [-K_e sin(\theta_r + 120°)] \cdot [-I_p sin(\theta_r + 120°)]$$

$$\tau = K_e I_p [sin^2(\theta) + sin^2(\theta - 120°) + sin(\theta + 120°)]$$

$$\tau = \frac{3}{2} K_e I_p$$

Each phase contribute to the total torque generated with a sin^2 term, with a phase shift of 120°, which results in a constant torque. (Figure 2.5). If the phase currents are kept in alignment with Back-EMF, the resulting torque is proportional to phase current I_p [6]. This also clarifies the smaller torque density compared to a trapezoidal machine.

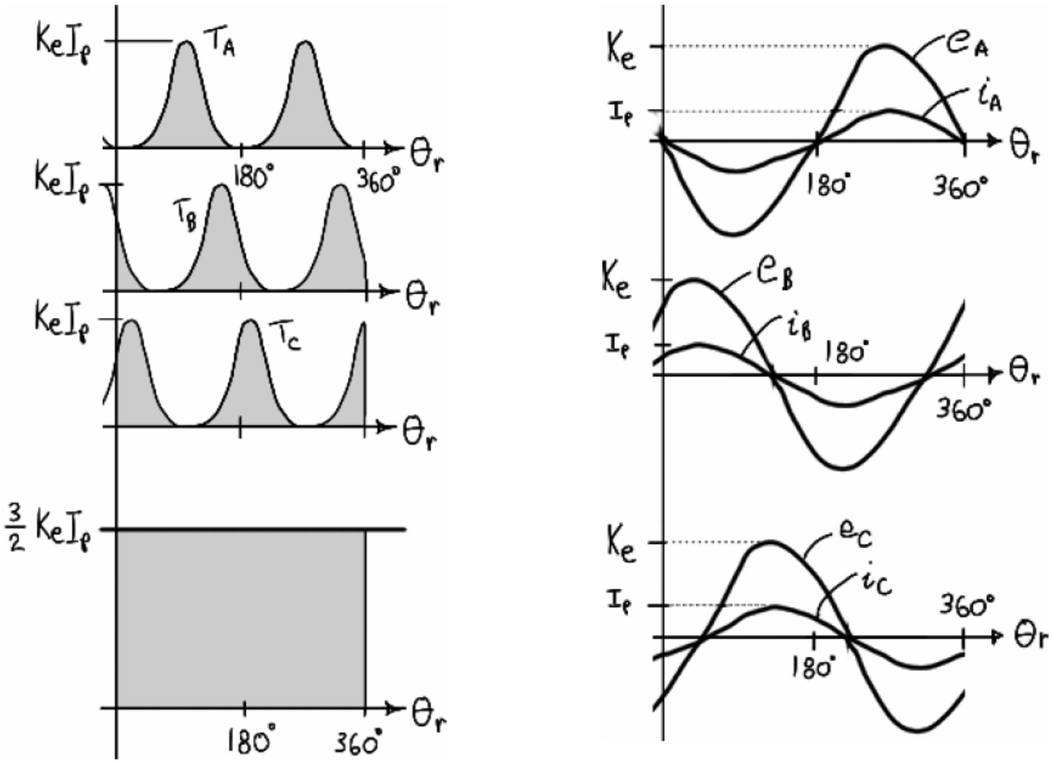


Figure 2.7: Total torque production on a per phase model in a PMSM. Total torque production is smaller than a BLDC motor

The torque production of three individual phases can be seen in the Figure 2.7, but it should be noted that normally the torque production is not visualized on a per phase basis. Mostly a single phase or a vector representation is used.

Lastly, a guide to the actual implementation can be found on chapter 4, where every necessary step is thoroughly discussed.

2.2.3 F.O.C (Field Oriented Control)

Among the three control algorithms FOC is the most complex, computationally expensive but at the same time the most effective algorithm. It is well suited for both trapezoidal and sinusoidal machines. FOC simply utilizes the best parts of trapezoidal and sinusoidal commutation, offering excellent performance, not even only at low speeds, but also at high RPM[9][13][15] [16].

The main goal in motor control is to control the torque, since a speed loop can be wrapped around it. FOC is essentially a torque control algorithm[15]. The main idea is still the same, aligning stator flux perfectly with the rotor flux. This is done in a very precise way with high frequency closed loop control which is the main distinguishing factor of FOC. To summarize the process :

There are three phase currents entering three motor phases/terminals. Those currents go through the motor windings and produce three different fluxes. The sum of those fluxes is called the stator flux. Although there are three components (i_a, i_b, i_c) at the beginning, the resulting stator flux vector can be expressed in a 2-axis system, rather than 3 ($(abc) \rightarrow (\alpha\beta)$).

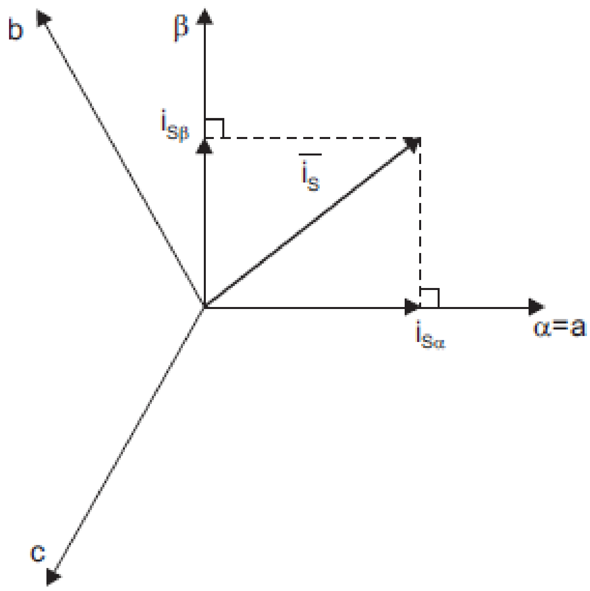


Figure 2.8: The $(abc) \rightarrow (\alpha\beta)$ Projection (Clarke Transformation). Three phase currents are represented in $(\alpha\beta)$ reference frame as i_s. [8]

On the other hand, the rotor flux which is produced by the permanent magnets is a constant as long as no field-weakening is desired. The rotor flux is expressed on a 2-axis system called the d-q coordinate system. This is a rotating reference frame which rotates with the rotor. The d-component (direct) is aligned with the rotor flux and q-component (quadrature) is perpendicular to the d-axis. They are referred as torque generating (q-axis) and flux generating (d-axis) parts (Figure 2.9).

The aim of F.O.C is to carry the stator flux vector to the d-q reference frame and control it directly there((α, β) -> (d, q)). When the stator flux is projected to d-q reference frame, the q-component of it will be commanded to a desired value since this is the torque generating part. On the other hand, the d-component which is the flux generating part will be suppressed because it only generates heat and applies to force to motor bearings which is unwanted (See Figire 2.10).[8, p.5][17]

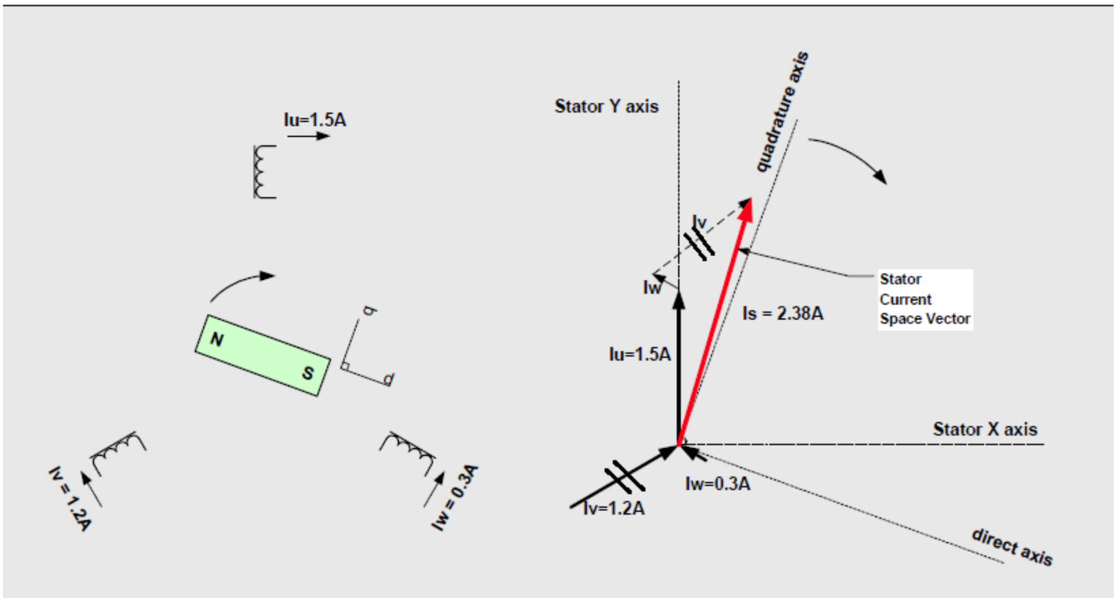


Figure 2.9: Projection of three stator flux vectors to rotating dq reference frame. $((abc) \rightarrow (\alpha\beta) \rightarrow (dq))$ [13]

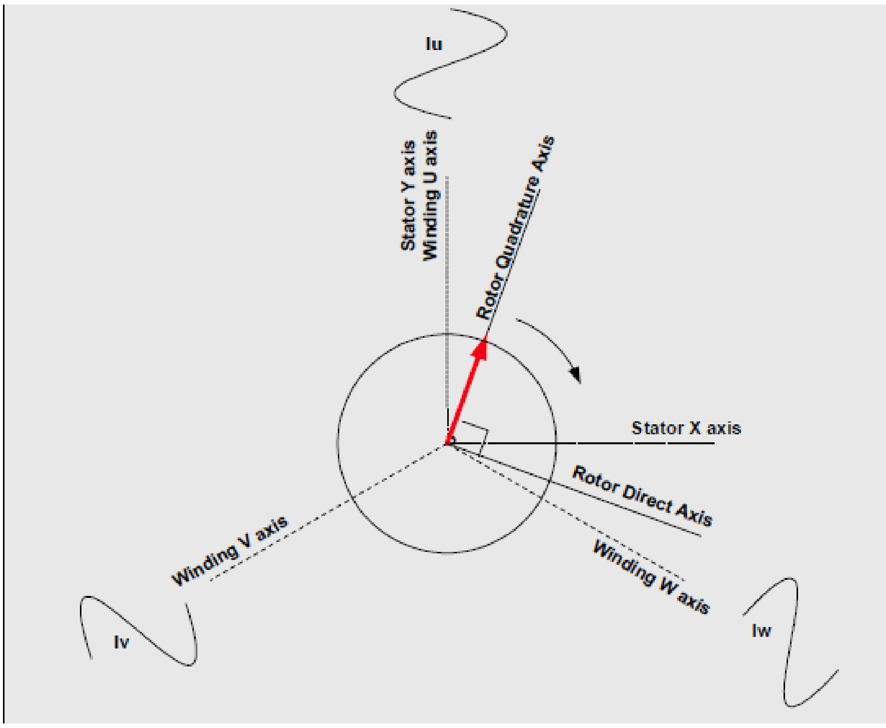


Figure 2.10: The desired result: Stator flux vector is in quadrature direction with rotor flux vector [13]

After the projection and determining the error (desired stator flux vector - momentary stator flux vector), the adequate voltage values are fed to the motor terminals. This is done by feeding the error factor to PI regulators since after the transformation, everything is in DC form and can be easily regulated by PI controllers. In the end, the calculated current values are modulated to motor terminals, which results in maximised torque production and smooth motion. This is due to the fact that, the motor is supplied with the optimal current values according to the rotor position.

The key aspect of this method is being able to control flux and torque independent of each other, as it is done in a separately excited DC motor[9][17][15]. This type of motor has 2 independent voltage sources, one feeding the armature, the other one supplying the stator field windings. The flux is produced and controlled by the stator field windings, on the other hand the armature current, which is completely independent from the flux generation, controls the torque output. Thus the desired quantity can be controlled independently[8][17].

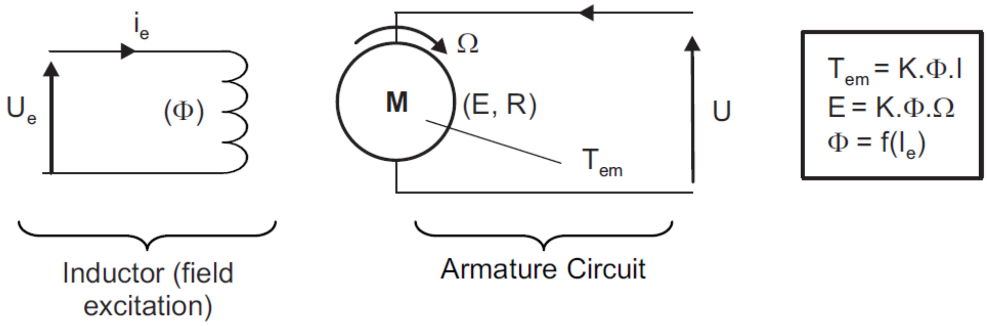


Figure 2.11: Simplified diagram of a seperately excited dc motor. Flux and torque generating components are independent. [8]

In sinusoidal control, since the current is a function of rotor position, this separation is not possible. Also in trapezoidal control scheme, the torque is dependent on the speed and cannot be separately controlled.

Unfortunately, all these benefit come with a price, first one being the absolute rotor position information. The second one is higher mathematical complexity that also reveals itself in form of higher processing requirements[8][9]. Lastly the implementation is much more complex than other two commutation schemes. To fully understand and implement FOC, concepts as Stationary and Rotational Reference Frames, Park and Clark Transformations, Space Vector Representation and Field Weakening must be understood.

In order to properly explain FOC, a step by step guide to the idea of implementation would be much useful. The aforementioned mathematical concepts will be studied when they are needed.

Since this is a torque control algorithm, and the linear relation between torque and current has been well established, current control is a crucial aspect of FOC. The whole process can be divided into 4 simple steps :

1. Measure the currents entering the motor
2. Calculate the desired current and compare with the measured current, in order to generate an error signal
3. Regulate the error signal to generate a correction voltage
4. Modulate the voltage to the motor terminals

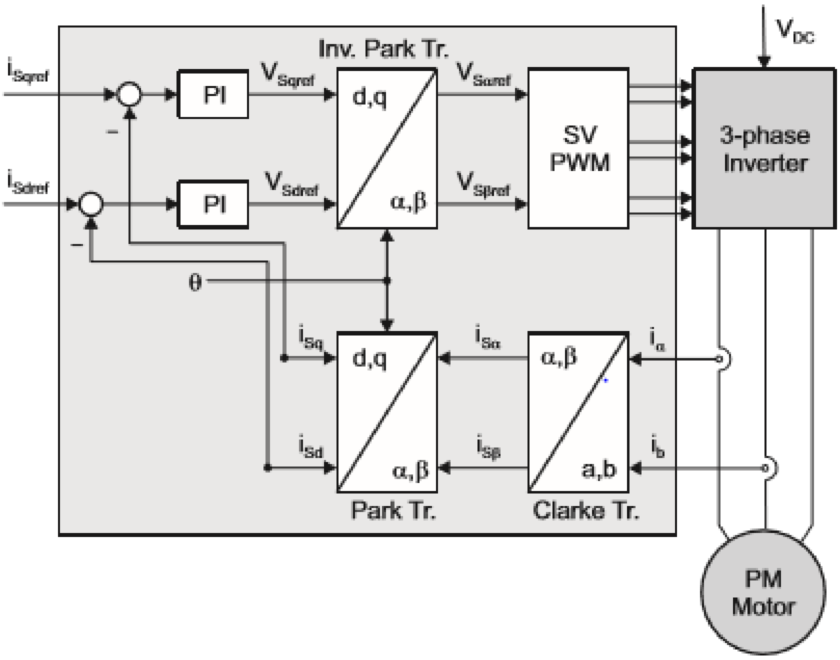


Figure 2.12: Simplified diagram of FOC [8].

With these mere four steps, the flux/torque decoupling is done and the optimal drive performance is achieved. These steps will be covered in detail.

1. Measure the current entering the motor :

   In order to control the motor current in an accurate way, its necessary to measure the current going into the motor terminals. In a star wounded motor, measuring just two phase current will suffice, since the other one can be reconstructed due to Kirschoff's Current law.

$i_a + i_b = -i_c$

The measured currents are just scalar numbers, but since they go to 3 different winding, which are arranged spatially 120° apart from each other, they form a current vector. This current vector can be considered as the direct representation of the flux vector. It should be in quadrature with the rotor flux, i.e in q-axis, to generate the maximum torque.

2. Calculate the reference currents and compare them with the measured currents, in order to generate an error signal :

   This part is the most complex and cumbersome part of the whole endeavour. The idea is to calculate the appropriate reference current vector in quadrature with the rotor and compare it with the actual measured current vector i_S,.

   First of alll, the absolute rotor position must be determined. After doing so, the current vector that is perpendicular to the rotor flux can be simply calculated and compared with the measured current vector. With three different PI regulators, the desired currents can be produced and fed into the motor. Although this method makes sense and is relatively easy to understand, it is done in a different way. The more efficient thing to do is to transform the i_S, in such a way that comparison with the reference current vector is much easier.

   The current vector i_S is represented in a 3-axis system, which is redundant, since it is just a two-component vector. Transforming it to a 2-axis domain will simplify the procedure notably. This is achieved by the afore mentioned Clark Transformation (See Figure 2.8).

   After this transformation, regulation 2 of variables, i_β and i_α, instead of 3 i_a, i_b, i_c would be much simpler. Of course, an inverse-transformation will be required afterwards.

   This transformation creates a vector, that is constant in magnitude and is still in a stationary frame[8][14][13]. The measured current vector must rotate with the rotor flux, making it time-variant in nature and hard to regulate by traditional PI controllers.

   By going through another transformation, namely Park Transformation, the stationary reference frame is transformed into a rotationary reference frame, which makes the system time-invariant. Now the components can be viewed as mere DC, making it much easier to regulate[8][14][13].

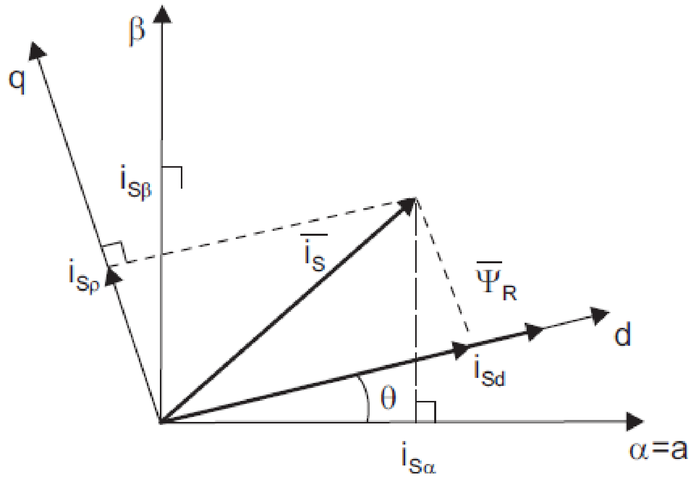


Figure 2.13: The stator flux vector i_s is projected to the dq reference frame. This is achived with Park Transformation. $(\alpha\beta) \rightarrow (dq))$ [8]

Through this transformation, two separate components are acquired in the dq reference frame : i_q and i_d. Since these are the components of the measured current vector, its better to address them as $i_{q(measured}$ and $i_{d(measured)}$ to avoid any confusion. The next thing to do is compare them with the desired components, $i_{q(desired)}$ and $i_{d(desired)}$.

Since $i_{d(desired)}$ has no contribution to the torque, this reference value should be set to zero, as long as field weakening is not desired. Field weakening is used to counter Back-EMF which is the main limitation against driving in high speeds. By setting $i_{d(desired)}$ to a non zero value, the permanent magnets flux will be suppressed, thus limiting Back-EMF. This is quite useful in operating out of rated speed, but it should be kept in mind that in this operating mode, torque can not be controlled since it is also a dependent on the flux generated by permanent magnets[17].

As mentioned before, the current-torque relationship is linear therefore $i_{q(desired}$ can be set to an arbitrary value that corresponds to the desired torque output. By comparing $i_{d(desired}$ with $i_{d(measured}$ and $i_{q(desired}$ with $i_{q(measured}$, the necessary error value is calculated.

3. Regulate the error signal to generate a correction voltage:

   With the error value known between desired and measured current, the next step is to calculate a correction voltage for 2 axes, d and q. After this is achieved by feeding the error value to PI regulators, simply applying them to the motor terminals wouldn't work, since:

   - 3 terminal voltages are required, 2 are present.

- the calculated values are still at a rotating frame.

Those issues will be addressed at the last step.

4. Modulate the voltage to the motor terminals :

   Normally with just the inverse of aforementioned Park and Clark transformations, it is quite simple to return to 3 phases in the stationary reference frame. Although it is possible to implement it that way, a better way exists which offers better inverter efficiency. This technique is called SVPWM, which is used to create balanced AC-waveforms with 15 % higher power efficiency. Since creates an AC voltage form, it enables staying in the rotating frame, hence eliminating one of the required transformations.

After these steps, the result is a decoupled torque and flux control, which leads to perfect operation in any speed range.

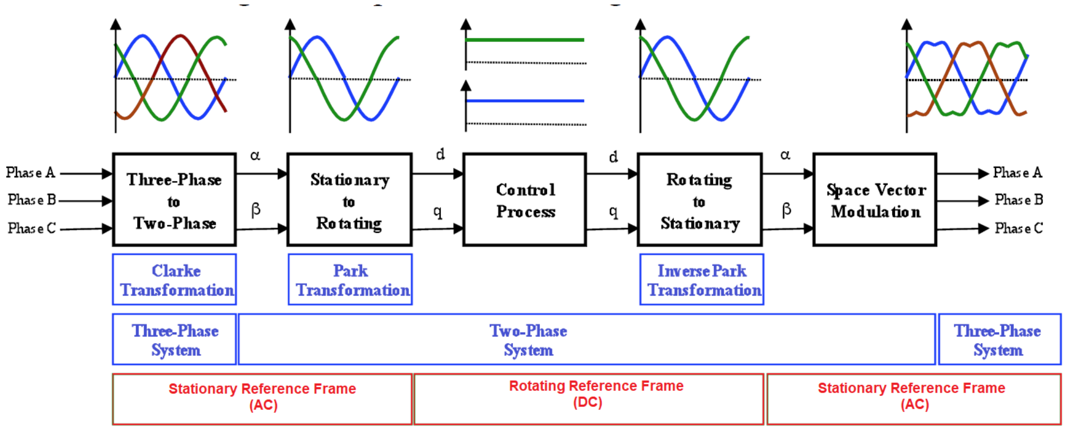


Figure 2.14: An illustration of all the transformations required for FOC [9].

2.3 Inverters and Common Operation Techniques

2.3.1 Common Inverter Topologies

This section briefly explains the inverter technologies since they are an inseparable part of motor control. An inverter - sometimes referred as motor shield - is in essence a PCB equipped with transistors to convert the supplied voltage (referred as Bus Voltage or Line Voltage) to the appropriate voltage form required to drive the motor. This, is of course done by the PWM signals sent by the microcontroller. This section only deals with 3-phase (3-leg) 6-switch inverters since they are most relevant to motor control.

Inverters can be divided into two categories in the broadest sense [6] [2]:

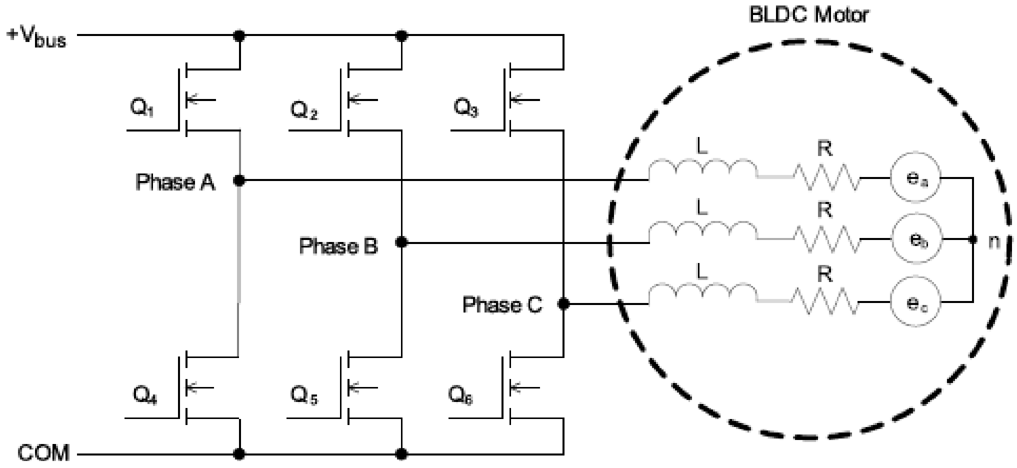


Figure 2.15: Basic represantation of a 3-phase inverter and motor connection [9]

VSI (Voltage Source Inverter)

CSI (Current Source Inverter)

VSI is the most common inverter topology, although controlling the current is the main goal in motor control. CSI are only involved in motors with very large power ratings and are not covered in this report.

The inverter technologies are a huge field of research in the domain of power electronics and going through the details are far beyond the scope of this report. Instead, a general overview about VSI's will given since they are crucial for motor control. The VSI's can be divided into two divisions [6] :

180 ° Inverters : are inverters that only operate the transistors in one leg complementary which means that only one of the two transistors can be on at a given time (one open one closed). In no inverter design, switching on both transistors is allowed since it leads to a shoot-through [21], but in this topology, it is also impossible to turn both transistors off. This usually interpreted as not being able to control the transistors individually.

120 ° Inverters : allow switching off both transistor at the same time, so a leg can be totally non-conducting. In this topology, top and bottom transistors can be controlled independently.

There are an overwhelming number of PWM techniques to control VSI's. Even the number of methods just for motor control is daunting: selective harmonic elimination (SHE), delta modulation, sigma-delta modulation, random pulse width modulation (RPWM), sliding

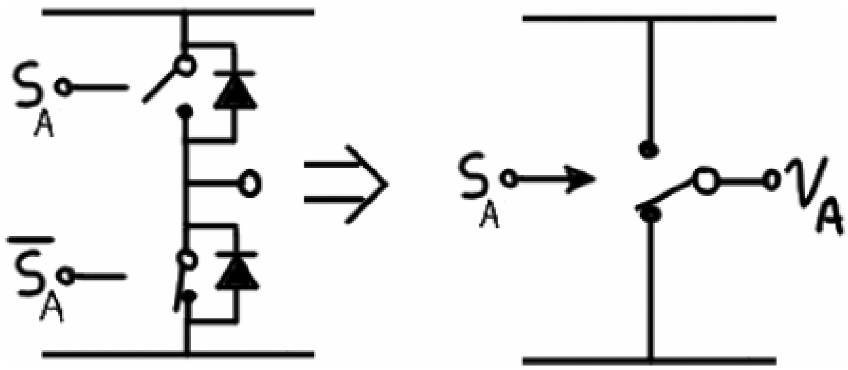


Figure 2.16: Representation of a 180° inverter. [6]

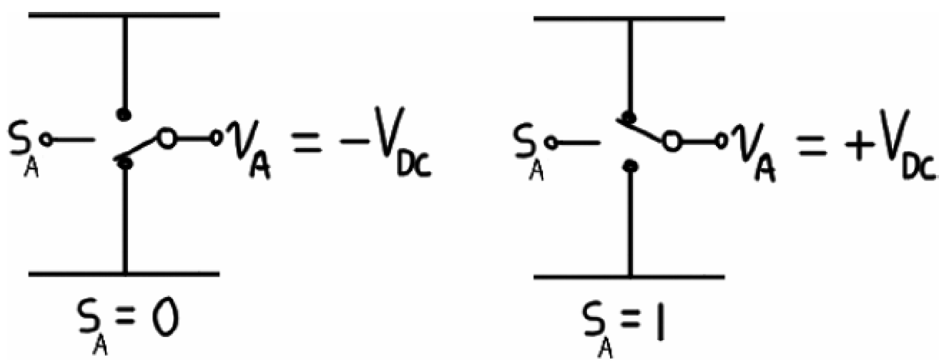


Figure 2.17: Possible operating states of a 180° inverter. [6]

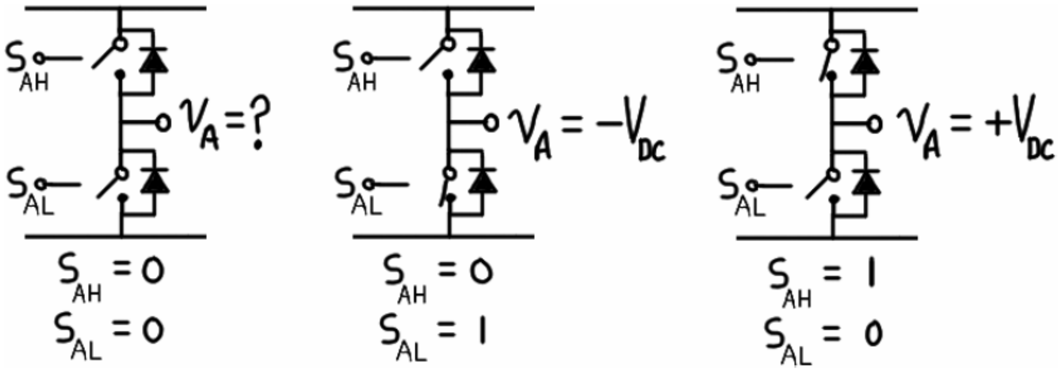


Figure 2.18: Possible operating states of a 120 ° inverter. [6]

mode control (SMC), fuzzy methods, and innumerable artificial intelligence schemes are some examples [6]. The very basic and most common used ones, that are relevant such as SVPWM, SVM are explained in the following sections.

Before concluding this section, the writer would like to state his personal opinion about the power electronics aspect of motor control. The aim of this work is to merely achieve smooth motion control which is also just a tool in autonomous driving; with better motor control the distinguished algorithms for motion control are employable. During the research necessary for this report, the writer has seen so many interesting and amazing power electronics concepts that can be employed to make motor control much more efficient. The writer is astonished by the fact that to make a motor simply spin, the inverter knowledge required is just the tip of the iceberg and there is always room for improvement.

2.3.2 SPWM (Sinusoidal Pulse Width Modulation)

For a sinusoidal control scheme, generation of sinusoidal voltages is necessary. The first things comes to mind is a DAC(Digital to Analog Converter), but it is never used to achieve this. This is mostly due to the fact that DACs are hard to find in many microcontroller boards and the inverter technology has evolved to work with PWM signals, rather than semi-continuous analog voltages.

The simplest PWM technique that can be utilised is Sinusoidal Pulse Width Modulation, which basically imitates a sinusoidal signal with rapidly changing PWM-duty cycles. The discontinuous nature of PWM is averaged out by the motor, allowing smooth motion [6][21].

The downside of this PWM technique is the less effective usage of the bus-voltage. Only 73 % of the actual bus-voltage can be used, which promotes the employment of the over-modulation techniques. This downside is mostly remedied by SVPWM (Space Vector Pulse Width Modulation) which will be discussed in the next section.

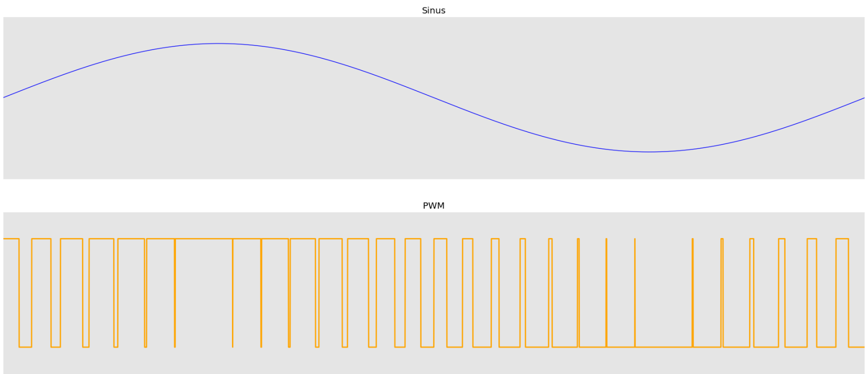


Figure 2.19: Sinusoidal PWM: Sinus signal and the corresponding PWM signal

2.3.3 SVPWM (Space Vector Pulse Width Modulation)

The space vector modulation is a PWM technique for controlling 3 phase VSI(Voltage Source Inverter) to create balanced 3-phase voltages. Unlike the sinusoidal PWM which generates sinusoidal currents separately in each leg of the inverter, this technique treats the inverter as a single unit to create sinusoidal currents. Although it is mostly associated with F.O.C., it can be utilized for a simpler sinusoidal commutation too. SVPWM has a 15 % higher bus voltage utilisation compared to SPWM [19].

As mentioned before, a reference voltage vector can be acquired if the rotor position is known. This reference voltage vector is the momentary optimal voltage value to drive the motor. The main idea of SVPWM is to create that reference voltage with a 3-phase VSI in the $\alpha\beta$ domain. This is very useful, especially for F.O.C, since the calculated reference voltage is already at $\alpha\beta$ domain.

In a very broad sense, a 3-phase VSI has 6 switches which can be ON or OFF. A total of 64 (2^6) switching combinations are possible. Since turning both of the switches on the same leg ON are not allowed, the total number of valid switching combinations are reduced to 8, which can be seen in the Figure 2.20.

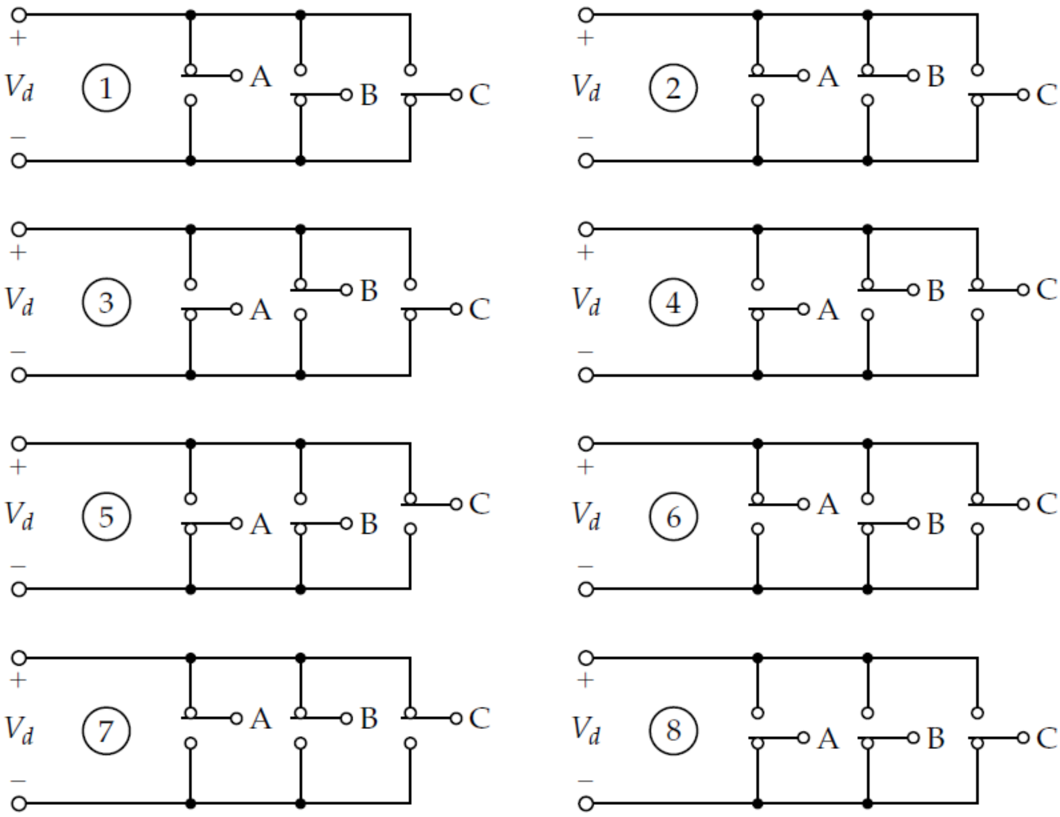


Figure 2.20: 8 possible states of a VSI [22].

Two of eight combinations(000 and 111) are called null or zero vectors, since they do not let any current pass. The remaining 6 vectors divide the $\alpha - \beta$ plane in to 6 equal parts. The reference voltage is also represented as a space vector and mapped into the same $\alpha\beta$ domain. It should be clear that the reference voltage space vector falls in one of the 6 sectors (See Figure 2.21).

The main idea of SVPWM is to create an equal of the reference, by spending an appropriate time in each of neighbouring vectors over a modulation period T_m. The amount time spent in each neighbouring vector defines the angle.

The magnitude of each sector defining vector is equal and constant, which raises the question of how to control the magnitude of the created vector. The null-vectors (000 and 111) come in handy in this case. By spending some time in a null vectors in the modulation period, the magnitude can be controlled.

After establishing the fundamentals, the last stage of SVPWM is generate the appropriate switching sequences to ensure the most efficient operation. To achieve this many alternatives exists. To name a few:

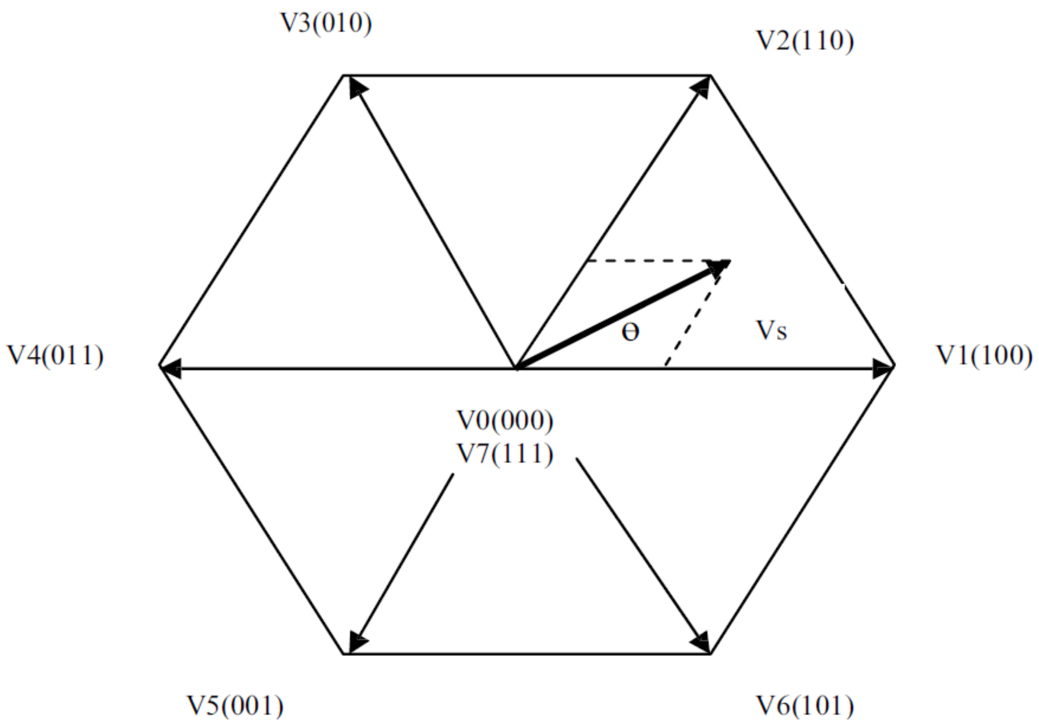


Figure 2.21: Each vector represents an inverter state. The reference vector falls in one of the 6 sectors [19].

1. Center weighted pulse pattern
2. Discontiniuos SVM sequence
3. Alternate reverse switching

Each sequencing pattern has advantages and disadvantages, producing different effects on the inverter efficiency. There wont be any detailed study of these patterns, but the reader can find some examples in [6][19][11][22]. Especially [22] is a nice guide for implementation.

CHAPTER 3

Chosen Control Scheme

After studying the 3 most common control methods, a decision is to be made on which scheme is better suited for the race car. The current commutation method, trapezoidal commutation is clearly not the best choice, since the desired amount of precision on low speeds is basically unreachable. Although there are proposed methods to overcome this issue [17], they are complex in nature and contradict with one of the main trademarks of trapezoidal commutation : Ease of implementation.

The second alternative, Sinusoidal commutation, offers smooth operation at low speeds, but begins to fall apart at high RPM. In addition to that the torque production is worse compared to other alternatives. This project doesn't necessarily require operation at high speeds and the load being driven, namely the race car, is a non-dynamical load which does not require high torque production. Extra hardware requirements like an absolute

Commutation Methods	Speed Control	Torque Control		Required Feedback Devices	Algorithm Complexity
		Low Speed	High Speed		
Trapezoidal	Excellent	Torque Ripple	Efficient	Hall	Low
Sinusoidal	Excellent	Excellent	Inefficient	Encoder, Resolver	Medium
FOC	Excellent	Excellent	Excellent	Current Sensor, Encoder	High

Figure 3.1: Comparison of three commutation methods. [9]

position sensor are already met. Finally, the implementation complexity, although higher than 6-step, is definitely far lower than FOC, making this scheme a possible candidate.

The last commutation method, FOC, offer the best aspects of first two methods, but it is much more complex to implement. In addition current sensing and rotor position are a must. Although those hardware requirements are already present in the race car and the author is willing to take care of the implementation complexity, due to pressing time issues and the writers doubt if the microcontroller has the required computational power, this method doesnt seem optimal. In addition, the benefits offered by FOC are most probably not necessary at this point. Still, the writer hopes to implement FOC sometime in the future since it is clearly the best possible control scheme and simply ingenious.

In conclusion, Sinusoidal commutation has been chosen as the control scheme to replace the current 6-step commutation. It offers the desired smoothness at lower speeds, which is the main goal, in addition to being not so demanding at computational complexity and implementation time.

CHAPTER 4

Implementation

After the control scheme has been chosen, the implementation will be illustrated in this chapter. Every crucial step will be thoroughly discussed, also including the problems that have been encountered and their solutions or workarounds. The organisation is as follows: Every coherent step will be discussed on its own subsection, forming an incremental guide of implementation, starting with the hardware overview.

4.1 Hardware Overview

In this section an overview of the present hardware will be given.

Motor :

The motor used to in the implementation is a small 7-pole BLDC motor with no data sheet present. The number of poles has been observed by the writer. No hall effect sensors are present which compels the utilisation of sensorless techniques or an extra position sensor. In our case, the latter has been employed.

Rotor Position Sensor :

Since precise rotor angle/position is a must in any commutation scheme other that 6-step, a rotor position sensor ADC-5157 has been utilized. The sensor offers a resolution of 14 bits, i.e 0.025 ° of accuracy for one mechanical revolution. Since our motor has 7 poles, this roughly corresponds to 0.15° electrical degrees. This is more than enough to do any of the possible commutation schemes.

The provided method of communication with an DSP/micro-controller is SPI, which unfortunately requires 6 cables, that adds up to the clutter.

Micro-controller :

The micro-controller in use is an Arduino M0 Pro which is basically an overgrown version of widely-used Arduino UNO. M0 employes an ARM-Cortex M0 (52 MHZ) and 32 Kb of RAM. The board has the required processing power and adequate number of I/O pins.

Motor Shield/Inverter :

The PCB is a custom design made by Dr. Bader which features 3 IC's (Infineon BTN7930) designed for motor control with current-sense ability. Each IC is a high current PN Half Bridge and works as an individual leg of the inverter. The high and low side switches work complementary with PWM. Dead-time generation is handled by the hardware, offering shoot-through protection. It is also possible to turn one leg completely of, making it possible to operate as a 120° inverter.

4.2 Sensor-Microcontroller Communication

The first step in the implementation was setting up the communication between Arduino M0 and the rotor position sensor AN-5157. Although an implementation of I2C was already present in the project and could have been directly used, the particular sensor was providing only SPI for means of communication.

SPI (Serial Peripheral Interface), is a synchronous serial communication interface specification used for short distance communication, primarily in embedded systems. It establishes the communication in full duplex mode using a master-slave architecture with a single master.

Since SPI is widely-used, a library was already present for Arduino. The implementation should normally be quite straightforward, since there are a couple of good examples throughout the web. Unfortunately, this was not the case for the writer due to various reasons. Firstly, the whole project was running on a former version of Arduino-software which made some of the existing examples obsolete. To remedy this, a further search had to be concluded to substitute for the one line functions offered by the up to date Arduino firmware. Secondly, the "try-out" implementation that worked on UNO, did not work on M0 making the writer spend some time trying to figure out why. Oddly enough the solution was as simple as updating the Arduiono IDE (not the firmware version), which magically did the trick.

In the end, the code is not more than a couple of lines that are easy to understand. The communication specifications (word-length, baudrate etc.) can be seen in the code provided in the corresponding section.

4.3 Current-Sense

Closed loop control is an essential part of any decent motor control technique and the required feed-back to is in form of current in this project. The means to have current feedback has already been included in the motor shield designed by Dr. Bader. The only thing that had to be done for the writer was to check the BTN7930 datasheet and the PCB design. After figuring out that the sensed current is conveyed as voltage based on the used resistance, it was rather easy to use Arduino's ADC pins to calculate the current. It also should be noted that although there are 3 terminals, in theory measuring only 2 suffices due to Ohm's Current Law.

4.4 SPWM (Sinusoidal Pulse Width Modulation)

After doing every step that is irrelevant or not necessarily important for making the motor simply "spin", the writer has finally proceeded with the first necessary step for a Sinusoidal commutation: SPWM. This section will be divided into to two parts : PWM generation for M0 and SPWM generation.

4.4.1 PWM for Ardunino M0 pro

For rather simple PWM utilization, Arduino Libraries provide a function called "AnalogWrite" which provides a resolution of 255 and an approximately 1K frequency. Since this specifications does not suffice for SPWM, the writer had to use M0's Timers.

M0 offers 3 timer/counter units, namely TCC0, TCC1 and TCC2 that can control up to 8 PWM pins. Because TCC0 alone can control up to 4 PWM pins(D2,D4,D6 and D7), this timer unit has been chosen. The resulting PWM was at 10KHz frequency and 4800 resolution, outputted by 3 digital pins. For more details the reader can refer to the code provided and the M0 data-sheet.

Lastly, it should be noted that by utilizing TCC0, the usage of built-in "AnalogWrite" becomes impossible, since it also operates with the same timer.

4.4.2 SPWM Generation

As explained before in the corresponding section (2.3.2), a sinusoidal signal can be approximated by varying PWM duty-cycles. The writer has chosen to utilize a look up table that discretizes a full period sine-wave into 1024 points. The granularity can be increased or decreased arbitrarily but it should be noted that using a low number of points will decrease the smoothness of the approximated sine-wave, thus jeopardizing the smoothness of motion. On the other hand, going higher than the PWM resolution(4800 in our case) doesn't make any sense. The writer would also like to point out that, if the memory for the look-up table is an issue, the size can be reduced 4 times for the same granularity since a sinus can be divided into 4 symmetrical parts.

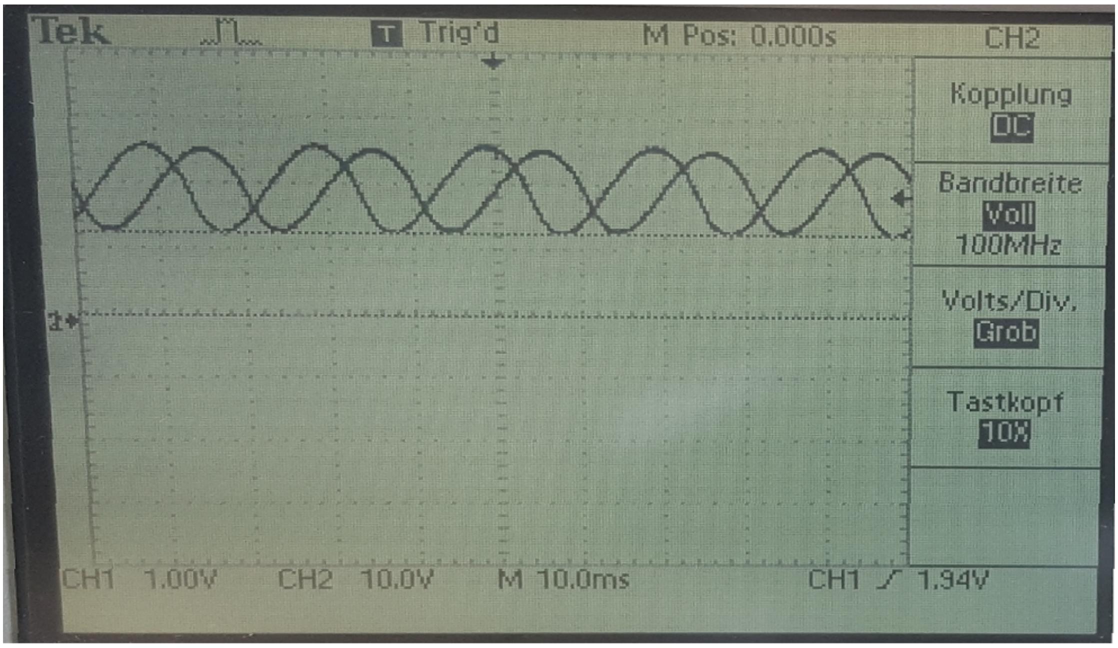


Figure 4.1: Two 120° phase-shifted sinus waves created with PWM and filtered by a low pass filter.

By feeding the values in the look up table to the PWM duty-cycle register, a sin wave is acquired which can be observed with an oscilloscope and a first order Low-Pass filter. Without the filter cutting off higher frequencies, one can only observe the changing duty cycles of PWM.

In order to change the frequency, the number of indices traversed in the look up table at a given time has to be increased. As the reader might have guessed, by doing so the approximation of the sine-wave gets cruder which is one of the main reasons for poor high speed performance.

Lastly, creating 2 more 120° shifted signals are simple by just using the same look-up table, but with indies 1/3 * length of look up table apart from each other.

4.5 Inverter Control and First Successful Motor Operation

The inverter has to be controlled in order to supply the voltage to the motor. The IC's (BTN7279) are specifically designed for motor control and they basically mimic the PWM. Each of three legs are being controlled by 3 different PWM pins. In addition 3 more pins are connected to each leg, which control either the corresponding leg is on or off. Those 3 pins are always kept ON, since a sinusoidal commutation requires all three legs being operational at the same time.

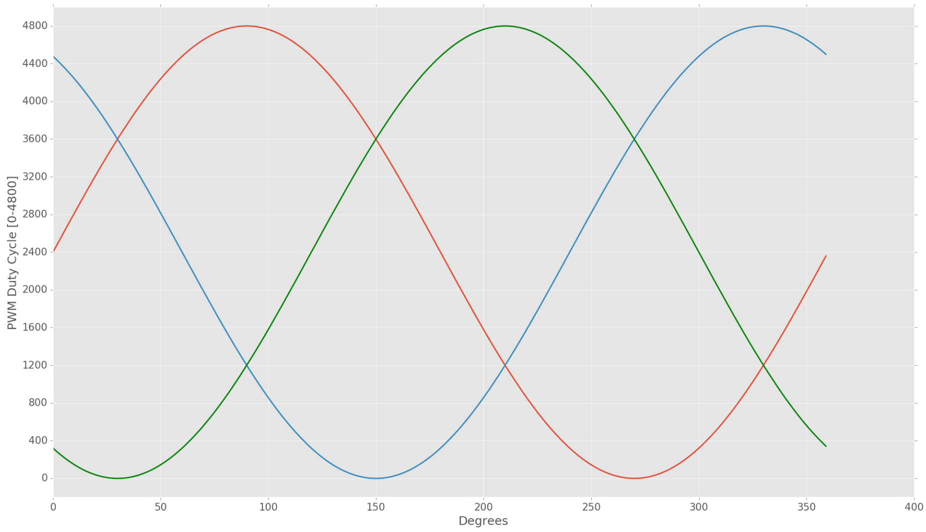


Figure 4.2: Three 120° phase-shifted sinus waves and corresponding PWM duty cycles.

After turning the legs On, simply connecting the PWM pins should be enough to produce the desired inverter output. It does but with one caveat: The look up table has to start from the middle of the PWM resolution rather that zero, since the middle of the BUS voltage(neutral point) is represented by 50 % PWM duty cycle (See Figure 4.2). Upper the PWM duty cycle goes, higher the positive side of the sinus gets. On the other hand, by decreasing the duty cycle, the corresponding leg opens the LOW-SIDE switch for a longer time, thus going towards the peak in the negative side of the sinus.

After the required steps has been performed, the writer managed to make the motor spin. The low speed performance was smooth and the high-speed operation was poor as expected.

4.5.1 A better bus voltage Utilization - Saddle-top instead of pure Sinusoids

After implementing 3 120° phase shifted pure sinusoidal waves, the writer has moved on to another scheme commonly called "Saddle-Top" in order to achieve better bus voltage utilization with Dr. Bader's suggestion. The main idea is still the same: Creating 3 waveforms with a 120 ° phase-shift, but to achieve this it is actually not necessary to generate pure sinusoids as long as the phase shift, voltage difference in other words, is maintained. By exploiting this notion, one of the inverter legs is always set to GND and the two other is set in respect to GND in such a way that the phase-shift is maintained (See Figure 4.2). The advantage is better power dissipation and less switching losses due to one leg being always connected to GND which enables higher speed and torque

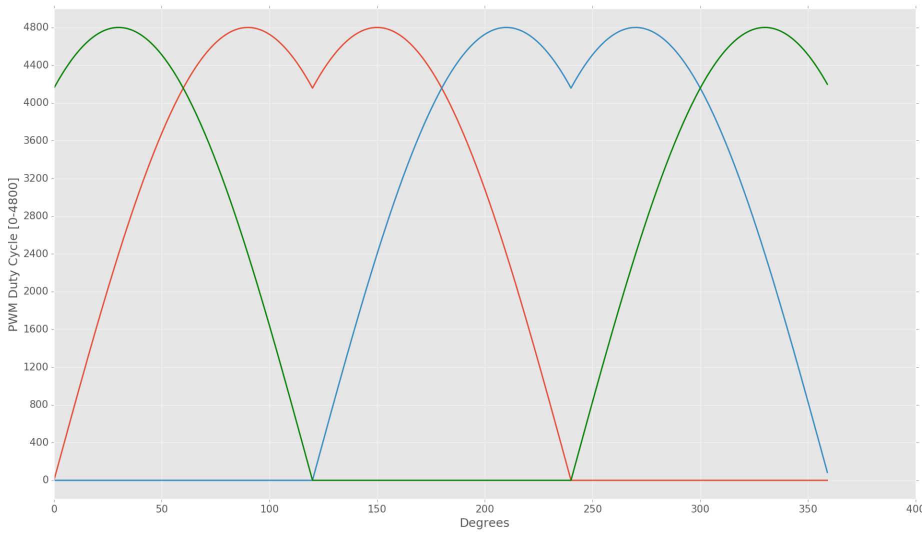


Figure 4.3: Three saddle top waves and correspongding PWM duty cycles. The voltage differences imitate a 120°

production. On the other hand, due to deviating from a pure sinusoid, the smoothness at lower levels is hindered by just a small amount. All of this is still achieved with a look-up table [21].

Finally, its the writers opinion that this method somewhat resembles "Triplen-Harmonic-Injection" witch distorts the waveform for better bus voltage utilization.

4.6 Angle Feedback Integration

After driving the motor blindly, i.e without any sensor feedback, the writer has moved on to integrate the rotor angle provided by the sensor. The main disadvantage of blind driving is the fact that the rotor follows the created current waveform. Because of this, at the start-up the rotor has to align itself to a certain place and continue driving from that location. Another issue is, if the motor is stalled or held, the produced wave-from continues to advance, without any regard to the rotor position. This results in very poor performance for any dynamical load change. Lastly, the motor gets hot quickly which decreases the lifetime.

To remedy all the issues arising from blind driving, the rotor angle has to be acquired via a sensor and the corresponding momentary voltage values must be calculated. For this end, a vector decomposition technique, namely Inverse-Clark Transform is used. The basic idea is; after acquiring the rotor angle and adding 90 ° to it, the resulting vector is decomposed from a 2 -axis system to a 3-axis system . The 3 components represents the momentary values of 3 balanced sinus waves which will create the desired vector if added up together. Lastly 90 ° is theoretically the optimum angle shift to achieve maximum torque, but in reality this is dependent on speed and motor parameters and can be tweaked.)

4.6.1 Online calculation of PWM values

In the initial version, the corresponding PWM values were being calculated on the fly. Whenever an angle feedback is received, the aforementioned decomposition technique is applied to determine the PWM duty cycle values. The resulting waveforms are pure-sinusoids. The whole process were taking around 500 micro seconds.

4.6.2 Back to look up tables

After successfully operating with online calculation, the writer has chosen to utilize three look up tables with 360 elements, which store every corresponding PWM value to every possible rotor angle. Although the sensor granularity is better, going less than 1 ° doesn't add much to the performance. As a result, the writer has reduced the process from 500 microseconds to 35 microseconds. This is important because with 35 microseconds, this operation can be squished into an PWM interrupt cycle.

4.6.3 Saddle-top look-up tables

The aforementioned look up tables create pure sinusoids, which is not optimal. As it has been done in the blind driving scheme, a "saddle-top" look up table has been formed, but the difficult part was relating the rotor angle to this look-up table. The writer has managed to solve this issue by first relating the saddle top look up tables to pure sine look up tables and then relating the index from there to the rotor angle. The resulting operation was as expected.

4.7 Speed and Torque Control

As mentioned before with the blind driving scheme, the speed is a function of how many indies are traversed at a given time, in other words the frequency of the created sine-wave. Assuming constant voltage amplitude the torque is highest at the lower speeds and lowest at higher speeds. This relation has been well established in the previous chapters. To further control the torque, a scaling value to the PWM duty cycles can be used. With the PWM duty cycle being scaled down, the produced torque at any given speed will be lowered. This can be regarded as decoupling torque and speed, although an index correction from a sensor is necessary for proper operation.

On the other hand, in the sensor integrated version, speed only depends on the supplied voltage. In other words, the speed is controlled by the torque. When the PWM duty cycles are scaled down, the motor currents drop, thus decreasing the torque. Since the

PWM duty cycle values only change when there is a new angle information, lower torque results in less frequent change of angle, which in return makes the motor turn slower.

The main idea here is to control the speed by controlling the torque since there is an established relationship between them (speed-torque curves).

4.7.1 Integrating Current Feedback

If the exact amount of current fed to the motor is known, the exact value of torque can be calculated from the motors data-sheet, which in return controls the speed. In order the due to so, the aforementioned current sense function of BTN7930 has been employed. Unfortunately, due the low torque produced at lower speeds in sensored scheme, the resulting current was too small to be effectively measured. Still the speed is controlled essentially by torque, but due to the lack of current measurements, the exact torque value is unknown.

CHAPTER 5

Conclusion

In this chapter, the final results of the implementation and the possible future continuation of the existing work will be discussed. Finally in the Concluding Remarks section, insights gained throughout the writing of this report will be briefly addressed.

5.1 Results of the Implementation

At the final stage of the implementation, the resulting control scheme was a in essence controlling the torque with sinusoidal currents. As mentioned in the implementation, the speed is controlled by changing the torque. The idea behind using that scheme, is to control the lowest possible variable in a cascade loop. It can be summarized as the following: By controlling the voltage amplitude via a scaler, the torque output can be controlled and by controlling the torque the desired speed can be achieved. In a real application a higher level controller will determine the desired speed and the voltage level will be controlled (via a PID) which in return commands the torque which outputs the desired speed.

Unfortunately the outputted current can't be measured due to the fact that it falls below the proper measurement range of the current sense units. Still by using a larger, more powerful motor and a higher voltage source, the currents will be high enough to be measured. By being able to measure the current, the exact torque can be calculated which in return enables more precise speed control.

The low speed performance is satisfying as expected. Still, the lowest RPM that can be reached is not as low as blind driving. This is due the fact that, after a certain threshold on scaling down the voltage (< 0.15), the generated torque is simply not enough to overcome the friction, but this is for the no-load case. By adding the friction, weight of the vehicle and mechanical losses of a wheel, the commanded torque will be much higher but it will be slowed down by the aforementioned losses. So achieving a satisfying low speed should not be an issue which was the whole aim of this work.

On the other hand, the high speed performance is poorer compared to what could be achieved with a 6-step scheme. This is all expected, and has been discussed in the corresponding section.

Lastly, the motor operates noiseless and cool, without vibrating. The overall result is a success overall.

5.2 Future Continuation

Although implementation results are satisfactory, there is much that can be improved as it always is in motor control. In this section, the writer will briefly talk about the envisioned improvements.

To begin with, the Saddle-Top is to be replaced with SVPWM, which will result in higher range of operation and better torque production. This can be achieved without much difficulty.

Secondly, a proper current feedback is to be implemented which also filters the jagged current waveform. To achieve this a control theory scheme called Derivative Filter can be utilized. By doing so, the exact value of the produced torque can be determined.

In addition, the writer would like to adapt the whole implementation in such a way that it will work with a motor equipped only with Hall effect sensors, thus reducing the costs and the hurdle for extra sensor space.

Lastly, it has always been the writers desire to implement a full F.O.C, which can be achieved by just adding the first two future goals to the current implementation.

5.3 Concluding Remarks

Firstly, by going through the whole implementation process, the writer has come to understand that making the motor simply spin is relatively simple. As long as the fundamental principles are understood, operating the motor with a simple no-feedback, low performance scheme doesn't take too much effort.

Once simple motion is achieved, a vast number of possibilities to achieve better performance present themselves. Depending on the needs and limitations of the application, e.g. operating at high or low RPM, adjusting to dynamical load change, variable torque, higher bus voltage utilization vs smoothness, limited computational power, sensor resolution, there are many different schemes that can applied. Although there are 3 main schemes (6-step,Sinusoidal, F.O.C) it is possible to deviate from them depending on the situation. For example, although this implementation is focusing on Sinusoidal Commutation with Saddle-Top waveform, a SVPWM scheme(that is usually associated with F.O.C) could have been easily employed which would provide better bus voltage utilization in exchange for more computational power. By also applying current-feedback, the initial Sinusoidal Scheme nearly becomes F.O.C. It was also possible to cut down the costs, and operating just with Hall-Sensor feedback, which would be more in the direction of 6-step commutation. It should also be noted that any scheme can be applied together, for example driving with Sinusoidal Commutation at lower RPM and switching to 6-step at higher RPM.

CHAPTER 6

Appendix

In the section, some of the concepts that have been mentioned so far will be illustrated in a more detailed fashion. This section is divided into two parts namely A and B. The information in part A is directed at readers that might not be familiar with some aspects of motor control and have trouble at continuing before grasping the missing parts. On the other hand, part B is directed at readers that show further interest in the topic and focuses on the concepts that the writer finds interesting or important.

6.1 A

6.1.1 Back-EMF

A prominent concept in electrical machines, Back-EMF (Electromotive force) can be described as motor acting as a generator and opposing the supply voltage in layman terms. The scientific background can be expressed with the help of Faraday's Law and Lorrentz Law respectively. The Back-EMF is mainly related to

1. Angular velocity of the rotor
2. Magnetic field generated by permanent magnets
3. The number of turns in the stator windings

Back-EMF $= N * l * r * B * w$

N is the number of winding turns per phase,

l is the length of the rotor,

r is the internal radius of the rotor,

B is the rotor magnetic field density and

w is the motor's angular velocity.

As it can be seen from the above formula, when the motor is operating the back-EMF is only dependent on the angular velocity of the rotor, since all other quantities are constants. The higher the angular velocity goes, the greater Back-EMF becomes. As explained in this report, the torque generation is a function of current, which in return is a function of the voltage fed to the motor. As the speed goes up, the back EMF gets bigger working against the supply voltage, thus reducing the current and accordingly the torque production [1]. This explains the notion of having higher torque at lower speeds, also depicted as DC motors being "self-regulating" devices.

The calculate the back-EMF at a given speed, a parameter called back-Emf constant can be found in motor data sheets. This relationship only holds for the rated speed in which the motors are designed in such a way that they draw the rated current and produce the rated torque.

Back-EMF is also a crucial concept for sensorless BLDC operation. As the permanent magnets turns, the floating terminal of the stator gets energised("works as a generator" as state above). This produced voltage can be detected by a micro-controller / DSP and utilised in a way to indicate the rotor position. Unfortunately this method has some disadvantages, especially at lower speeds leading to more complex schemes [2][7].

Finally, motor taxonomy mostly depends on the Back-EMF shape. For example, what is usually called a PMSM, is a motor with a sinusoidal Back-EMF shape and on the other what is commonly called a BLDC, is a motor with a more trapezoidal back-EMF shape. The common misconception about this matter is, it is usually thought as the back-EMF shape is a result of the chosen commutation scheme. The truth is, back-EMF shape is a result of how the stator windings are formed up as stated before.(See BLDC principles) That basically means it is inherent to the motor design and can not be changed.

6.1.2 Cogging

An inherent problem with the iron-core motor design, cogging is the torque generated due to the interaction between permanent magnets in the rotor and the stator teeth on a permanent magnet machine. The rotor has some "favourite spots" and tries to align itself to them. This behaviour can be easily observed when there is no current by just turning the motor by hand. The torque generated is a function of rotor position, number of permanent magnet poles and stator teeth.

This effect is highly undesired, since the torque must vary during motor operation to nullify it. Especially at lower RPM, it is much more dominant which contributes to the low speed torque ripple in 6-step commutation. On the other hand, at high speeds, the motor inertia filters much of it, allowing smoother torque production.

There many approaches to overcome cogging, mostly by improving the physical motor structure. This report focuses on using better commutation schemes to diminish the effects of cogging.

6.2 B

6.2.1 An attempt at Sensorless Rotor Angle Estimation

In any other commutation scheme other than 6-Step, the precise position of the rotor is a must since the main idea behind Sinusoidal commutation and F.O.C is to produce the adequate currents for the specific rotor positions. By the the time the writer had started working on this subject, there was no absolute position sensor for the rotor was present and some thought had been given on motor control without it. This subsection talks about an attempt made to estimate the rotor absolute rotor position with the help of hall sensors.

At first, an approach based on "Moving average" was proposed by Dr. Bader, which was relatively simple and might have worked to some degree, but the writer of this paper choose to first exhaust his options by checking the papers written on this topic for reasons known only to him.

After reading a couple of papers, it became clear to the writer that it is a rather well studied subject and there are many different approaches to achieve precise control without a position sensor, even without Hall effect sensors. The only problem was any of those approaches e.g. vector tracking observer(VTO), Extended Kalman Filter, Sliding Mode Observer etc. [4] , were rather too complicated to be implemented on the scope of this paper. While trying to find a relatively simpler solution, the writer came by a paper, which offers a rather easy to implement approach.

The paper a proposes a linear interpolation based on least squares, which basically estimates the rotor position based on the time spent in the last 6 sectors (60° apart), since the boundary crossings of those sectors are given by the Hall effect sensors. The paper also claims to remedy any problem which might be caused by the non-symmetrical placement of Hall effect sensors[18].

A demo implementation had been done with Python, also simulating the motor and the results were looking promising. The actual position of the rotor and the estimated one had been plotted and they were quite similar to the plots in the paper. But in writers opinion, the estimator wasn't responding well to abrupt speed changes and the estimated position was deviating from the real position for a considerable amount. Although the estimator recovers in a timely fashion, feeding the motor with inappropriate currents even for a short time would produce unwanted torque ripples. But still, it had been planned to try this approach on a real motor, since the needs of the actual application is most probably less demanding than the tests this method had gone through the simulation.

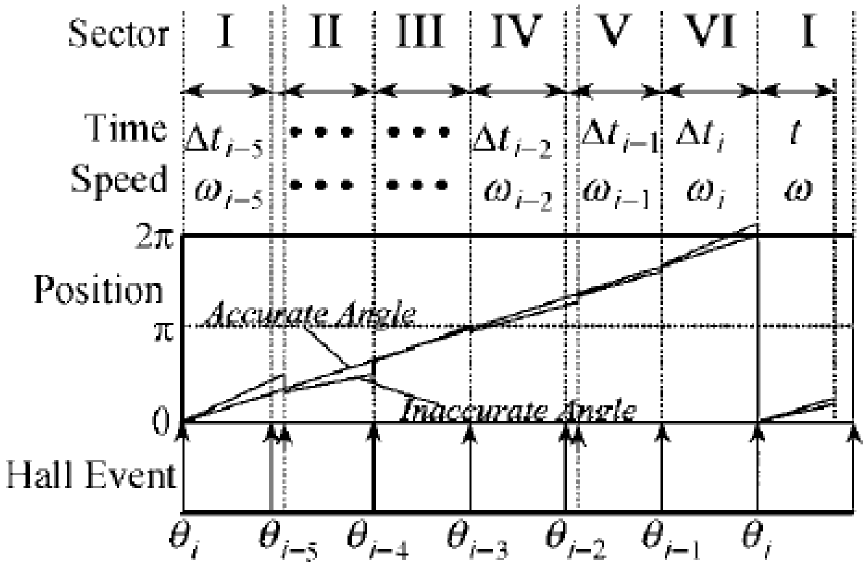


Figure 6.1: Angle estimation with Hall-Effect Sensors based on linear interpolation [18]

Just before any attempt was made on implementing on the real hard-ware, an absolute position sensor was provided so it was not possible to see how this approach performs in reality. In any case, the writer firmly believes that, this method is worth a try since it is easier to implement compared to other approaches and should performs quite well on rather simply applications.

6.2.2 Clark Transformation

This transformation maps the 3 phase currents(abc) to a 2-axis ($\alpha\beta$) system. ($\alpha\beta$) reference frame is still time-variant (See Figure 2.8). [8]

$$i_\alpha = i_a$$

$$i_\beta = \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b$$

6.2.3 Park Transformation

This transformation take a vector from a stationary reference frame ($\alpha\beta$) and projects it to a rotating reference frame (dq). In FOC, the rotor position (θ) has to be known for this transformation (See Figure 2.13) [8].

$$i_d = i_\alpha cos\theta + i_\beta sin\theta$$

$$i_q = i_\alpha sin\theta + i_\beta cos\theta$$

List of Figures

2.1 BLDC Motor Transverse Section. [1] 4
2.2 Interaction between rotor and stator fields generates the torque that rotates the motor[8]. 5
2.3 Current flow in trapezoidal drive. [10] 7
2.4 Switching sequence of a 6-step commutation. [1] 8
2.5 The total torque production viewed on a torque per phase model ob BLDC. Each phase contributes to torque production individually. [6] 10
2.6 Current flow in sinusoidal drive. [10] 11
2.7 Total torque production on a per phase model in a PMSM. Total torque production is smaller than a BLDC motor 12
2.8 The $(abc) \rightarrow (\alpha\beta)$ Projection (Clarke Transformation). Three phase currents are represented in $(\alpha\beta)$ reference frame as i_s. [8] 13
2.9 Projection of three stator flux vectors to rotating dq reference frame. ($(abc) \rightarrow (\alpha\beta) \rightarrow (dq)$) [13] 14
2.10 The desired result: Stator flux vector is in quadrature direction with rotor flux vector [13] 14
2.11 Simplified diagram of a seperately excited dc motor. Flux and torque generating components are independent. [8] 15
2.12 Simplified diagram of FOC [8]. 16
2.13 The stator flux vector i_s is projected to the dq reference frame. This is achived with Park Transformation. $(\alpha\beta) \rightarrow (dq)$) [8] 18
2.14 An illustration of all the transformations required for FOC [9]. 19
2.15 Basic represantation of a 3-phase inverter and motor connection [9] 20
2.16 Representation of a 180° inverter. [6] 21
2.17 Possible operating states of a 180° inverter. [6] 21
2.18 Possible operating states of a 120 ° inverter. [6] 22
2.19 Sinusoidal PWM: Sinus signal and the corresponding PWM signal 23
2.20 8 possible states of a VSI [22]. 24
2.21 Each vector represents an inverter state. The reference vector falls in one of the 6 sectors [19]. 25

3.1 Comparison of three commutation methods. [9] 27

4.1 Two 120° phase-shifted sinus waves created with PWM and filtered by a low pass filter. 32
4.2 Three 120° phase-shifted sinus waves and corresponding PWM duty cycles. 33
4.3 Three saddle top waves and correspongding PWM duty cycles. The voltage differences imitate a 120° 34

6.1 Angle estimation with Hall-Effect Sensors based on linear interpolation [18] 44

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