



SVPWM BASED FOC OF BRUSHLESS DC MOTORS

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SVPWM BASED FOC OF BRUSHLESS DC MOTORS

(M. Sc. Thesis)

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ABSTRACT

Due to their high torque density and high performance, Brushless Direct Current (BLDC) Motors are widely preferred in Control Actuation Systems of guidance kits. Since they do not have rocket motor, guidance kits have limited mobility. Thus, performance of the BLDC Motor is crucial for guidance kits. In order to improve the performance of BLDC Motor which has an incremental encoder, Space Vector Pulse Width Modulation (SVPWM) based Field Oriented Control (FOC) technique is applied in this thesis. PI controller is preferred for the position and speed control because of its superior response and simple implementation. ST Microelectronics's NUCLEO-F746ZG development board is used for implementation of the SVPWM based FOC technique. While NUCLEO-F746ZG is used as control board, the driver board which consists of driver electronics and current sensors have been designed and produced. The designed driver board, which has 4 layers, is connected directly to the NUCLEO-F746ZG. User Test Interface, which provides the communication with NUCLEO-F746ZG on UART protocol during no-load and under load tests, has been also developed. The applicability of the SVPWM based FOC technique for BLDC Motors has been proposed and tested in this thesis. The results of the MATLAB/SIMULINK simulations and laboratory tests for no-load and under various load configurations have proven that the proposed method can be successfully applied.

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Key Words : Brushless DC Motor, Field Oriented Control, Space Vector PWM, Position Control, Speed Control

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FIRÇASIZ DOĞRU AKIM MOTORLARININ UVDGM TABANLI ALAN
YÖNLENDİRMELİ KONTROLÜ

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ÖZET

Yüksek tork yoğunluğuna sahip olması ve yüksek performansla çalışması nedeniyle güdüm kitlerinin kanat tahrik sistemlerinde çoğunlukla Fırçasız Doğru Akım (FDA) Motoru kullanılır. Roket motorları olmadığı için, güdüm kitlerinin hareket kabiliyeti kısıtlıdır. Bu nedenle FDA Motorun performansı güdüm kitleri için hayati öneme sahiptir. Bu çalışma kapsamında, üzerinde artırılmış enkoder bulunan FDA Motorun performansını artırmak için Uzay Vektör Darbe Genişlik Modülasyon (UVDGM) tabanlı Alan Yönlendirmeli Kontrol (AYK) tekniği kullanılmıştır. Düzgün tepkisi ve uygulama kolaylığı açısından pozisyon ve hız kontrolcülerinde PI kontrolcüsü tercih edilmiştir. UVDGM tabanlı AYK tekniğinin uygulaması için ST Microelectronics Firmasının NUCLEO-F746ZG parça numaralı geliştirme kartı kullanılmıştır. NUCLEO-F746ZG kontrol kartı olarak kullanılırken, sürücü elektroniği ve akım sensörlerinden oluşan sürücü kartı tasarlanıp üretilmiştir. 4 katmanlı olarak tasarlanan sürücü kartı konektörü sayesinde doğrudan NUCLEO-F746ZG'ye bağlanmaktadır. Yüksüz ve yük altında yapılan testlerde NUCLEO-F746ZG ile UART üzerinden haberleşmeyi sağlayan Kullanıcı Test Arayüzü ayrıca geliştirilmiştir. Bu çalışma kapsamında, UVDGM tabanlı AYK tekniğinin FDA Motoruna uygulanabilirliği önerilmiş ve test edilmiştir. MATLAB/SIMULINK benzetim ortamında ve deneysel olarak hem yüksüz çalışmada hem de çeşitli yüklemeler altında gerçekleştirilen testlerin sonuçları yöntemin başarıyla uygulanabileceğini göstermiştir.

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SYMBOLS AND ABBREVIATIONS

Symbols and abbreviations which are used in this thesis are presented below with their explanations.

Symbols	Explanations
A	Ampere
Hz	Hertz
I	Current
kg	Kilogram
kHz	Kilohertz
L	Inductance
m	Meter
m²	Square meter
mH	Milihenry
MHz	Megahertz
N	Newton
ns	Nanosecond
P	Number of Pole Pair
R	Resistor
rad	Radian
s	Second
T	Torque
V	Volt
λ	Flux Linkage
μs	Microsecond

Abbreviations	Explanations
AC	Alternative Current
ADC	Analog-to-Digital Converter
AYK	Alan Yönlendirmeli Kontrol

Abbreviations**Explanations**

ARM	Advanced RISC Machines
ARR	Auto-Reload Register
BLDC	Brushless Direct Current
CCR	Capture Compare Register
CCW	Counter Clockwise
CW	Clockwise
DC	Direct Current
DMA	Direct Memory Access
EMF	Electromotive Force
EMI	Electromagnetic Interference
EOC	End of Conversion
etc.	et cetera
FDA	Fırçasız Doğru Akım
FOC	Field Oriented Control
FPGA	Field Programmable Gate Array
HGK	Hassas GÜDÜM Kiti
I/O	Input/Output
IC	Integrated Chip
IDE	Integrated Development Environment
IEEE	Institute of Electrical and Electronics Engineers
LQFP	Low-Profile Quad Flat Package
MCU	Microcontroller Unit
MMF	Magnetomotive Force
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
PC	Personal Computer
PCB	Printed Circuit Board
PWM	Pulse Width Modulation
SAGE	Savunma Sanayi Araştırma ve Geliştirme Enstitüsü
SI	Système Internationale
SMPS	Switching Mode Power Supply
SVPWM	Space Vector Pulse Width Modulation
TÜBİTAK	Türkiye Bilimsel ve Teknolojik Araştırma Kurumu

Abbreviations**Explanations****UART**

Universal Asynchronous Receiver-Transmitter

USB

Universal Serial Bus

UVDGM

Uzay Vektör Darbe Genişlik Modülasyonu



1. INTRODUCTION

Main working principle of electrical motors is converting electrical energy to electromechanical energy. They are roughly classified into the two main groups, namely AC Motors and DC motors based on their supply voltage type. The speed and position control of AC motors are more complex compared to DC motors, and that is why DC motors were preferred for these kinds of applications for several years.

Brushless DC Motors are very similar to the Permanent Magnet Synchronous Motor in terms of characteristic. Most of the authorities classify these two types of motors in same group. Main difference between them is their back electromotive force (EMF) waveforms. While PMSM has sinusoidal back EMF waveform, BLDC Motor has trapezoidal back EMF waveform. Sinusoidal back EMF waveform requires complicated placement of the windings inside the stator which increases the production cost.

Commutation can be defined as the process of switching the current applied to the motor phases in proper order to generate motion. In Brushed DC Motors as its name implies, commutation is achieved with help of brushes. Unlike Brushed DC Motors, Brushless DC Motors need external electronic driver circuit for commutation. Despite of driver circuit complexity, Brushless DC Motors have important advantages as compared with Brushed DC Motors [1].

- Higher torque density
- More efficiency
- Less production cost
- Simpler construction
- Noiseless working
- Longer lifetime
- Less maintenance cost

Thanks to advantages mentioned above, usage of the BLDC Motors has been increased in widely in industry, consumer electronics, robotics, defense industry in recent decades. In addition, developments in processor and power electronics which are the basis of driver circuit make BLDC Motors reasonable and useful.

Because of its implementation simplicity, generally traditional Six-Step method is used for the commutation of BLDC Motor [2]. In this method, commutation is achieved by the help of output signals of the Hall-Effect sensors which are mounted on rotor with 120 electrical degrees intervals. Only two out of three phases are activated during commutation; in other words, current flows through on two active windings of the motor. No usage of one of the three phases in a single commutation interval results in reduction of the producible torque amount. Significant ripples occur on torque because of low-resolution Hall-Effect sensors. In addition, termination of the current flowing through on active phase and starting the current flowing through the unused phase during commutation instantaneously cause to an increase in current ripple. There is a linear relationship between current and torque so this ripple also occurs on torque. The ripple that is arisen from these factors may reach to catastrophic levels that degrade system achievements for high frequency driver applications.

Beside the current commutation, speed and position control can also be achieved by processing Hall-Effect Sensor outputs [3]. The distance increment between the two consecutive Hall-Effect Sensors for BLDC Motor that contains two or less pole pair results in resolution decrease so the speed and position control get worse. For this reason, generally encoders are used together with Hall-Effect Sensor for speed and position control applications [4]. The usage of two type sensors together not only increases the cost, but it also becomes almost impossible to install them, especially on small BLDC Motors.

Researches on new commutation techniques have being continued for a long time for BLDC Motor to eliminate these drawbacks. Most of the researches generally have been focused on minimizing torque ripple and increasing the amount of producible torque [5-12]. One of the proposed techniques is “Space Vector PWM (SVPWM) based Field Oriented Control (FOC)” method [5]. The purpose of this method, which was originally developed for PMSM, is to perform operations on a 2-axis orthogonal rotating, dq , reference frame instead of on a 3-axis stationary, abc , reference frame. In dq reference frame, the motor quantities that change with respect to time and motor position become constant so nonlinearity is eliminated. Thanks to this method, all three phases are actively used at the same time throughout the commutation; in other words, stator currents become continuous. Since the stator currents become continuous, the torque ripples are considerably reduced. Unlike Six-Step method, the resolution of commutation is not

restricted to 60 electrical degrees. The efficiency of the commutation can be increased with the usage of high resolution position sensor. Thanks to all these mentioned features, the amount of torque is also increased.

In spite of all these advantages, the requirement of excessive mathematical calculations increases the load on the processor. New generation powerful processors have made this method applicable to the BLDC Motor control. Instead of a processor, motor control can also be done with an FPGA which operates with the logic of parallel processing and has a much higher processing capacity [13]. Also more than one motor can be controlled with the usage of single FPGA [14].

Thanks to the developments in the driver circuitry of the BLDC motor, it has been used frequently in defense industry projects in recent years. One of these projects is the guidance kits which are very important for the countries like us with their low cost and high demolition power features. In Figure 1.1, Hassas Gdm Kiti (HGK) designed by TBTAK SAGE is shown.



Figure 1.1. Guidance kit with bomb [15]

There are four independent fins which help to follow desired path in guidance kits that make general purpose bombs smart. A BLDC Motor is assigned to each fin. Generally, all four BLDC Motors are controlled with single electronic board consists of FPGA and inverter. Although this structure seems even so effective, it has some side effects. It can be seen in Figure 1.2, guidance kits usually consist of two main parts namely guidance section and control actuation section. While electronic board is located in the guidance section, BLDC Motors are located in the control actuation section. Two different main sections are connected to each other with harness so it is hard to locate these harnesses in a limited area

as well. Even if locating the electronic board in control actuation section seems most appropriate solution, this solution cannot be applied to every system because of the size of the electronic board. Thus, the idea of designing the electronic board which is specialized in the control of a single BLDC Motor and locating four identical electronic boards in the control actuation section becomes reasonable. This type of design not only increases the modularity but also shortens the design process because of its simplicity.

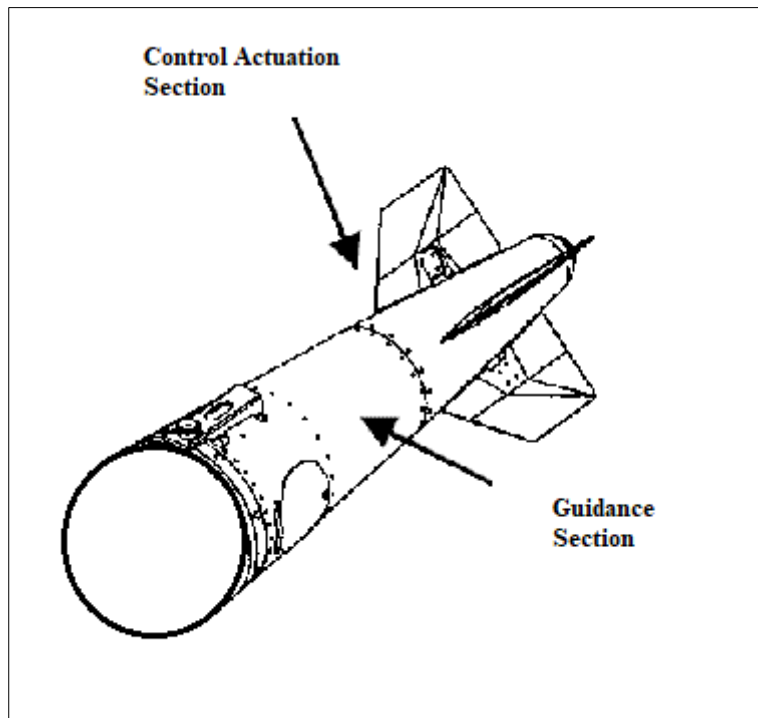


Figure 1.2. Structure of guidance kits [16]

Considering that every single board has its own FPGA, the design becomes difficult and the cost increases. After all these restrictions, the usage of the microcontrollers which are specialized for motor control applications becomes reasonable. These microcontrollers have dedicated I/O pins and features for processing of Hall-Effect sensor and encoder outputs with less effort. Thanks to their embedded ADCs, outputs of current sensors can be processed easily. They can also communicate with peripherals via UART and/or Ethernet interfaces. In addition, easiness of code development helps to the designer in design and test processes. The last but not the least it is cheaper than the FPGA.

In this thesis, the SVPWM based FOC technique is studied for the control of BLDC Motor with the simulation and the implementation in order to improve the performance of the BLDC Motor. To follow the position command with minimum error, three nested

controllers are benefited from position, speed and current respectively. PI Controller is preferred for the speed and position control. Commutation and current control are achieved with SVPWM based FOC technique. In the implementation phase, by using the microcontroller, both speeding up and simplification of the design and test processes are aimed. In addition, the cost reduction is also considered by designing of the four layers driver board. Thanks to the proposed low cost and high efficient solution, this method can be used in defense industry applications requiring high precision successfully. In addition, by providing the modularity, it shortens the design processes of the whole system and enables the usage in different systems without being changed.

In the next chapter, detailed information about the structure and mathematical model of BLDC Motor are given. Fundamental commutation types that can be adapted for BLDC Motors are also examined. Chapter three describes the system and its requirements. In addition, proposed design is modelled and tested in SIMULINK. In the fourth chapter, hardware design implementation is given. In the fifth chapter, features, which are actively used in design, of the microcontroller are examined. Furthermore, software architecture is defined in detail. The sixth chapter contains the results of the loaded and unloaded tests, which are performed in the laboratory, of the actual system. In the final chapter, the work is summarized and possible future works are suggested.



2. REVIEW OF BLDC MOTORS

BLDC Motor, also known as Permanent Magnet DC Motor, basically consists of a stator and a rotor which is made of permanent magnet. Optionally Hall-Effect sensors, encoder, resolver etc. may also be mounted on rotor to sense the position of the rotor. The basic BLDC Motor is illustrated in Figure 2.1.

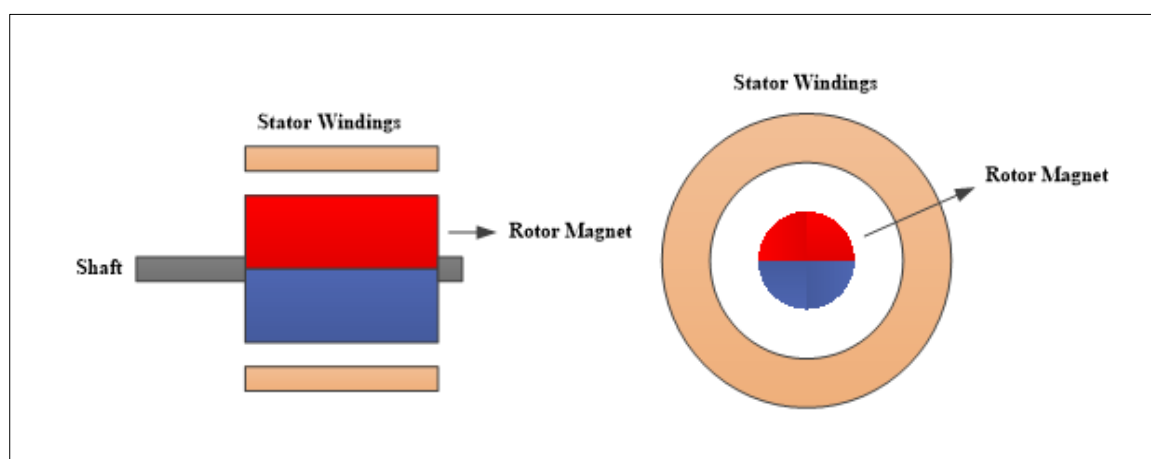


Figure 2.1. Cross sectional view of basic BLDC motor

BLDC Motors can be single-phase or multi-phase. Generally, multi-phase BLDC Motor is preferred in high power applications. Multi-phase motors are more stable than single-phase motors and efficient in terms of power consumption [17]. On the other hand, increased manufacturing cost and driver circuit complexity can be listed as drawbacks for multi-phase motor. Because of this trade-off, mostly three, four and five-phase BLDC Motors are preferred in industry.

Unlike Brushed DC Motor, windings are located on stator instead of rotor. These windings can be arranged in either star pattern or delta pattern according to the desired application. The current is passed through these windings in a proper order for generating magnetomotive force (MMF), which rotates the rotor. Direction and magnitude of MMF are directly related with sign and magnitude of stator currents. The control of BLDC Motor is based on this main principle.

Number of poles in the rotor may vary depending on the application it is designed for. As known, a simple magnet consists of north and south poles and this structure is also called

as a pole pair. While a revolution of rotor represents the mechanical revolution, the number of electrical revolution equals to the number of pole pairs.

$$\text{Electrical Revolution} = \text{Number of Pole Pairs} \times \text{Mechanical Revolution} \quad (2.1)$$

In order to obtain better torque performance, the number of pole pairs can be increased. In applications that require high torque, the usage of this type of motor becomes reasonable. High switching frequency has to be chosen with the usage of this type of motor otherwise motor performance gets worse. Working with high switching frequency causes to some important problems such as increasing switching losses, necessity of the usage of the powerful controller (microcontroller, FPGA) which has high clock frequency, and EMI etc. So increasing the number of pole pair would reduce the maximum speed of the motor that can work as well.

In order to move the rotor with full performance, the current has to be passed through appropriate windings in proper order according to the commutation table of motor. Generally, commutation table is given in the datasheet of the motor. There is also need an electronic driver circuit to commutate the BLDC Motor. The fundamental electronic driver circuit consists of controller and inverter. Figure 2.2 shows the connection of the inverter and stator of the 3 Phase Y-connected BLDC Motor. Each phase is controlled with two semiconductors, mostly MOSFETs. As can be seen the high side MOSFET is connected to the bus voltage, and the low side MOSFET is connected to the ground. These two MOSFETs cannot be at the on-state at the same time because of shoot-through phenomenon. When the high side MOSFET is activated then related phase becomes equal to the bus voltage or low side MOSFET is activated then related phase becomes equal to the ground. In order to pass current through the windings, two legs of the inverter should be used at least.

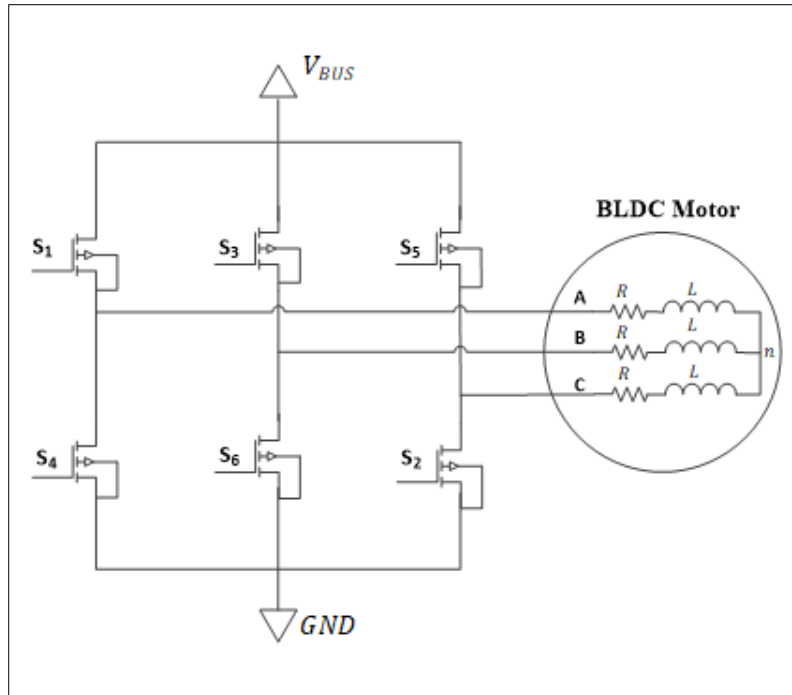


Figure 2.2. Driver circuit of BLDC motor

Commutation of the BLDC Motor can be handled with a sensor or sensorless. In sensed mode, Hall-Effect sensors, encoders or resolvers may be used to detect the rotor position. In addition to the commutation table, switching sequence with respect to Hall-Effect sensor outputs is also given in datasheets. After detecting the rotor position, it is decided which windings are to be energized according to the commutation table. Encoders and resolvers have much better resolution than Hall-Effect sensors. The control of BLDC Motor would be more efficient with the usage of one of the encoder or resolver. However, in spite of its low resolution, Hall-Effect sensors are very popular because of their implementation simplicity.

In sensorless mode, some special methods such as back EMF detection, inductance measurement etc. are used to detect rotor position [18-19]. In applications which need high precision, hybrid solutions may be applied rather than using one of the offered methods. Sensorless commutation obviously do not suffer from the errors caused by sensors and related harness, and as a result provide more stability when compared to sensed commutation, at the cost of hardware and software complexity.

2.1. Mathematical Model of BLDC Motor

The electrical model of Y-connected 3-phase BLDC Motor is shown Figure 2.3 [20]. Each phase is represented by an equivalent coil resistance and inductance, and back EMF voltage source.

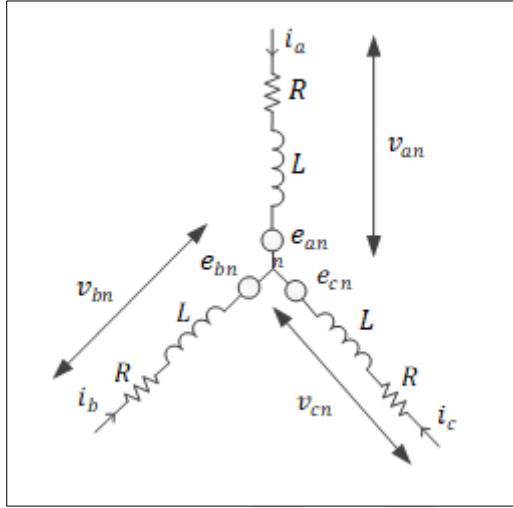


Figure 2.3. Y-connected 3-phase BLDC motor

The mathematical model of this circuit can be defined by the following set of equations presented in matrix form:

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_{an} \\ e_{bn} \\ e_{cn} \end{bmatrix} \quad (2.2)$$

In this equation,

$$L = L_S - L_M$$

L_S : self-inductance of stator coil

L_M : mutual inductance between stator coils

R : stator phase resistance

V_{xn} : stator phase voltage

i_x : stator phase current

e_{xn} : stator back EMFs,

The electromagnetic torque expression of BLDC Motor is

$$T_e = \frac{1}{w_r} (e_{an}i_a + e_{bn}i_b + e_{cn}i_c) \quad (2.3)$$

where, w_r = rotor speed (rad/s)

$$k_e = \frac{e_{xy}}{w_r} \quad (2.4)$$

where, $e_{xy} = e_{xn} - e_{yn}$ = Total back EMF of active phases

where, k_e = motor back EMF constant (V.s/rad)

In Six-step method, only two motor phases are actively used at the same time. If we assume that Phase A and Phase B are active phases so then

$$i_a = -i_b = |i| \quad (2.5)$$

In this case, total back EMF equals to the e_{ab}

$$T_e = \frac{1}{w_r} (e_{an}i - e_{bn}i) = \frac{1}{w_r} (e_{ab}i) = k_e i \quad (2.6)$$

Ideally,

$$k_e = k_t \quad (2.7)$$

where, k_t is motor torque constant in N.m/A.

Then the following torque formula which has the exact same form of the torque equation of a brushed dc motor is obtained.

$$T_e = k_t i \quad (2.8)$$

2.2. Commutation Types

One of the most important factor in motor control is commutation. Therefore, in order to increase the efficiency of the motor, various commutation techniques have been developed. In this section, three main types of commutation are examined in detail.

2.2.1. Trapezoidal commutation

The simplest method for the control of BLDC Motor is Trapezoidal Commutation which takes its name from the waveform of the phase currents. In this method, current is passed through only two of the motor windings, and the commutation is achieved by using the outputs of the Hall-Effect sensors which are mounted on rotor with 120 electrical degrees intervals. There are six possible combination in this method so it is called also Six-Step Method. As the motor rotates, the phase currents are switched every electrical 60 degrees. As can be understood, the current space vector, which is equal to the vector summation of two active phase's currents, is always within 30 degrees of the quadrature direction with respect to the rotor.

Block diagram of the trapezoidal commutation is shown in Figure 2.4.

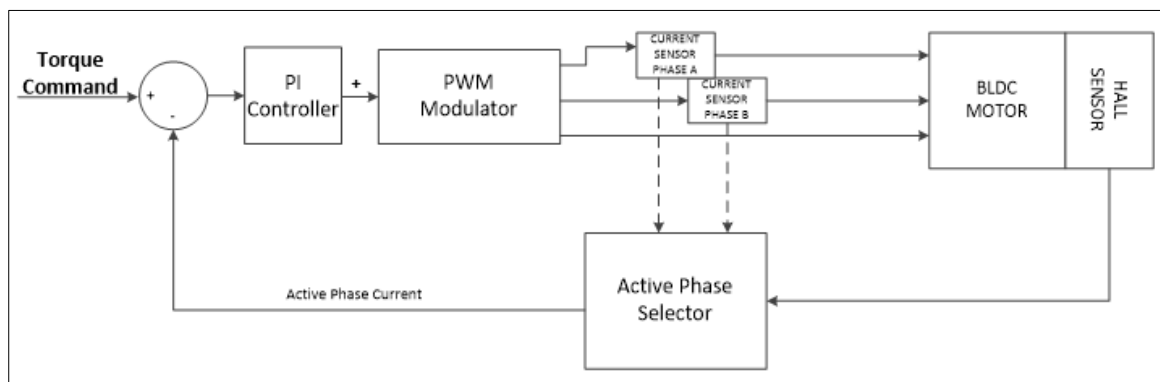


Figure 2.4. Block diagram of the trapezoidal commutation

In this method, it can be seen in Figure 2.4 that only one PI Controller is used. Thanks to Hall Sensors, one can know which two phases have to be actively used at any instant of time in the whole commutation period. Furthermore, it is known that while the magnitude of the active phases are equal to each other, directions of them are opposite. The phase, which has positive current value, is accepted as active phase in this method and this value

are directed to the PI Controller. In PWM Modulator Block, the bus voltage to be applied to the active phases is calculated.

Since the current space vector can only point in six discrete positions in a whole commutation period, produced torque gets lower. The other reason, which causes the decrement of produced torque, is not to use of one of the motor phase in each commutation step. Furthermore, the termination of the current flowing through on active phase and starting the current flowing through unused phase during commutation instantaneously causes an increase in current ripple. This ripple also occurs on the torque at the same manner because of the linear relationship between the current and torque. Another drawback of this method is that motor cannot be controlled precisely at low speeds.

2.2.2. Sinusoidal commutation

Despite having theoretically trapezoidal back EMF waveform, due to the smoothing effect of its own inductance, BLDC motor has almost sinusoidal back EMF waveform. Therefore, BLDC motor can be commutated with both trapezoidal and sinusoidal commutation methods.

While trapezoidal commutation does not yield a smooth and precise control of the BLDC motor especially at low speeds, sinusoidal commutation overcomes these weaknesses.

In this method, it is aimed that three currents, which vary sinusoidally as motor turns, are delivered to three motor windings. Each of them has 120 degrees phase difference with respect to each other. Thus, it is ensured that smoothly rotating current space vector which is equal to vector summation of each three phase currents always is in the quadrature direction with respect to the rotor and has constant magnitude. As a result, torque ripples and commutation spikes can be eliminated.

Since this method requires accurate motor position information, encoder or resolver must be used instead of Hall sensors which have 60 degrees resolution.

Block diagram of the sinusoidal commutation is shown in Figure 2.5.

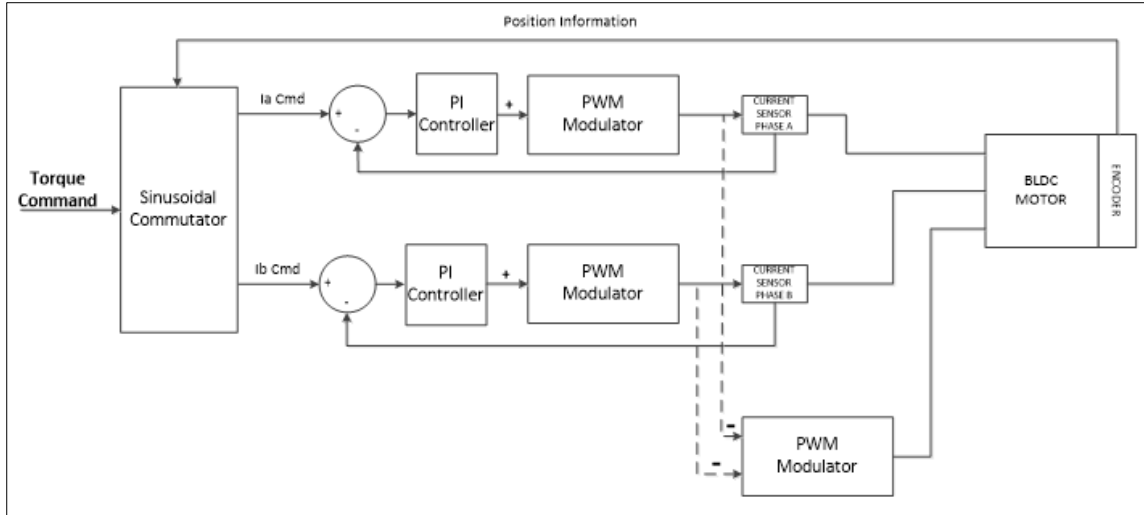


Figure 2.5. Block diagram of the sinusoidal commutation

$$I_a \text{ Cmd} = \text{Torque Command} \times \sin(\theta) \quad (2.9)$$

$$I_b \text{ Cmd} = \text{Torque Command} \times \sin(\theta + 120^\circ) \quad (2.10)$$

Two sinusoids, which have 120 degrees phase difference among themselves are synthesized by using position information that comes from the encoder.

Then these two signals are multiplied by torque command to make their magnitudes proportional to the desired torque. Following this, they enter PI Controller blocks that regulate phase currents as intended. The current of the third phase cannot be controlled independently of the other two phases. The voltage to be applied to the third motor winding is obtained from negative sum of the other two signals. The resulted sinusoidal voltages each are separated by 120 degrees.

While this commutation type works almost perfect at low speeds, unfortunately same thing cannot be said for high speeds. As the speed goes up the current loop controllers must track a sinusoidal signal of increasing frequency. Since PI Controller having limited gain and frequency response, phase lag and gain errors occur in the currents. The produced torque becomes lower as motor speeds up because the current space vector moves away from the quadrature direction with respect to the rotor.

2.2.3. Field oriented control

The Field Oriented Control, also known as Vector Control, was born as a result of the ongoing researches for improving the AC drivers in the late of 1960's. This method was firstly proposed by Hasse in 1968 and Blaschke in 1971 [21-22]. In the 1980s, it was developed that could improve the serious flux oscillations and torque responses seen in induction and synchronous motor drive circuits [5].

Unlike AC Motors, the flux and torque control can be achieved with high dynamic performance in Separately Excited DC Motors. The main factor underlying this is the ability to control the flux and torque independently. The Field Oriented Control was developed by inspiring from this independence. The Field Oriented Control method allows independent control of flux and torque, as in Direct Current (DC) motors, which have no relationship between excitation circuit and armature circuit in AC motors.

The basic principle of the FOC is based on the separation of the 3 phase motor currents into two current components, I_d and I_q , one of which is the torque generating and the other is the flux generating current. In addition, these components can be controlled independently from each other. In this method, the real I_a , I_b and I_c currents in the 3 phase stationary abc reference frame are converted to imaginary I_d and I_q currents defined in a 2 axis orthogonal rotating dq frame. While the current which is defined in the d axis is called as flux-producing current because of providing flux control, the current which is defined in the q axis is called as torque-producing current because of providing torque control.

The necessary steps for this control method are described in following paragraphs in order. To better analyze this control method, the 3 phase motor is first converted to a equivalent 2 phase motor [1].

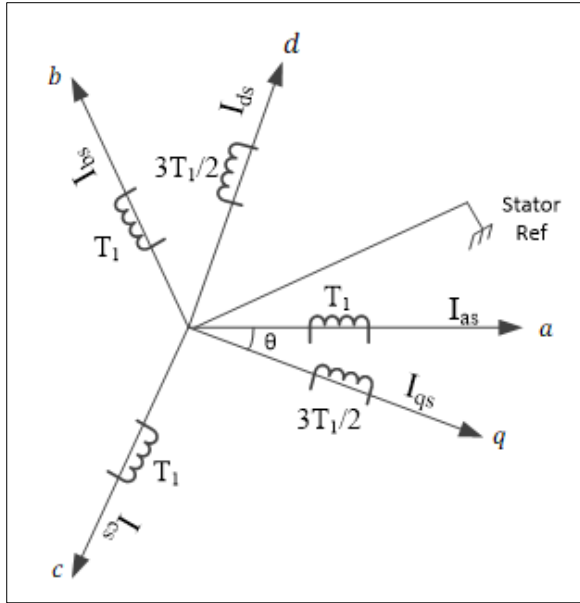


Figure 2.6. 3 phase to 2 phase transform

If we assume that each of the three-phase windings has T_1 turns per phase and the currents of the same magnitude, the two phase windings will have $3T_1/2$ turns to ensure the equivalence of produced MMFs.

$$\underline{i}_S = \frac{2}{3} (\underline{i}_a + \underline{i}_b + \underline{i}_c) \quad (2.11)$$

$$\underline{i}_S = \frac{2}{3} (i_a + e^{j120^\circ} i_b + e^{j240^\circ} i_c) \quad (2.12)$$

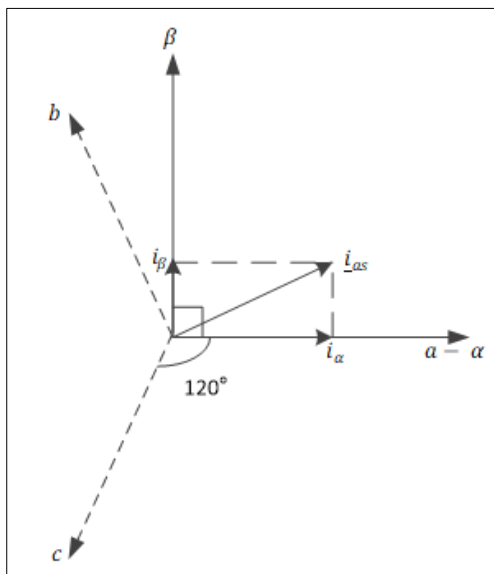


Figure 2.7. Clarke transformation

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2.13)$$

2/3 which is arisen in current transformation is called as transformation constant. It represents the change in the number of turns in winding that occurred during the transformation the 3 phase to 2 phase.

The zero sequence current, i_o , is added to the equations in case of imbalances in the a,b and c phase currents. The uniqueness of the transformation between 3 phase and 2 phase is provided in any case thanks to addition of this current component. In addition, the zero sequence current produces no magnetic field at all.

If the system is balanced, summation of the three phase currents is equal to the zero. In this case, since the i_c current is negative of the summation of i_a and i_b phase currents, the usage of the i_o current in the transformation is not necessary.

$$i_a + i_b + i_c = 0 \quad (2.14)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2.15)$$

The transformation of a 3 phase stationary reference frame to the 2 axis orthogonal stationary reference frame is called Clarke Transformation [23]. The new 2 axis orthogonal stationary reference frame also known as time variant system or stator reference frame.

$$i_\alpha = i_a \quad (2.16)$$

$$i_\beta = \frac{(i_a + 2i_b)}{\sqrt{3}} \quad (2.17)$$

Despite using Clarke Transformation, since the motor components are defined still in stator reference frame, their values change according to the motor position. So then the flux and torque control cannot be performed as desired because of this non-linear behavior.

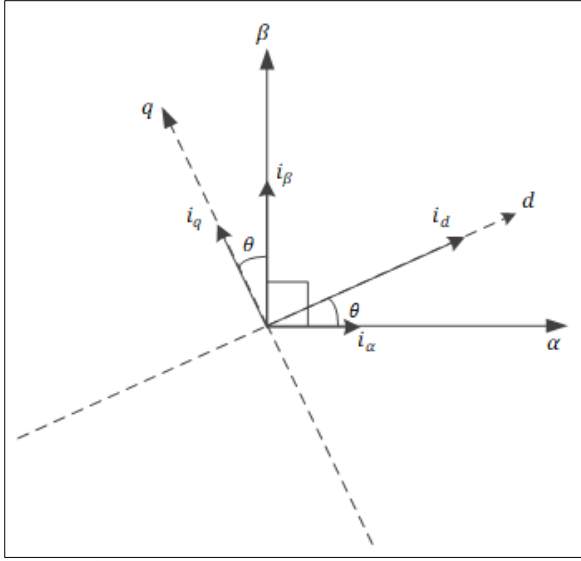


Figure 2.8. Park transformation

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (2.18)$$

The transformation of a 2 axis orthogonal stationary reference frame to the 2 axis orthogonal rotating reference frame is called Park Transformation [23]. The new 2 axis orthogonal rotating reference frame also known as time invariant system or rotor reference frame.

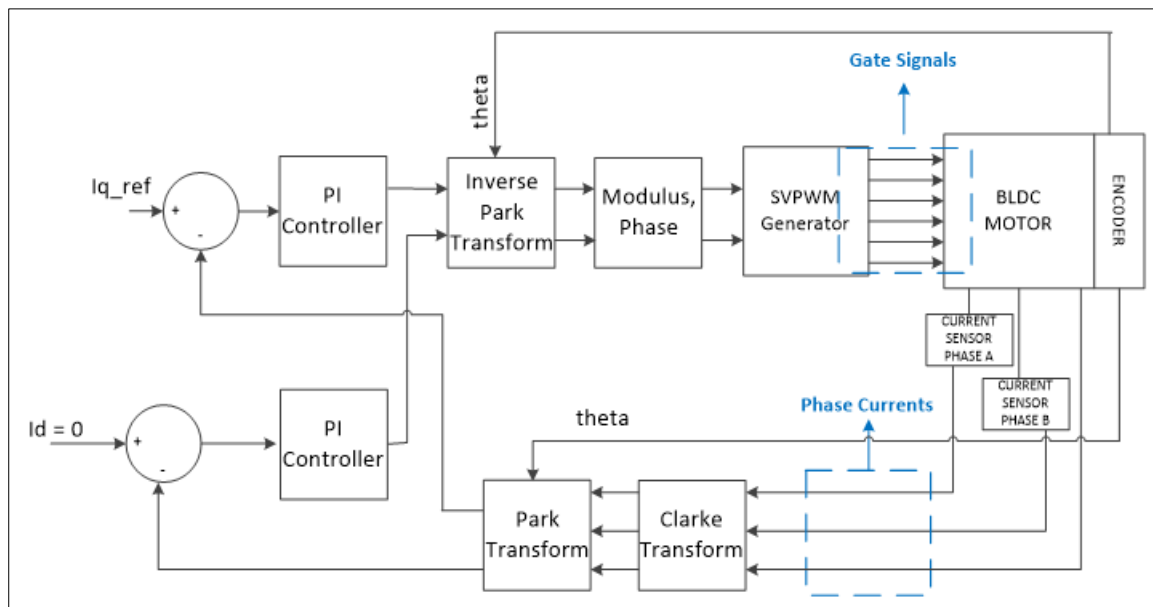


Figure 2.9. Block diagram of the SVPWM based FOC

Once the motor currents are represented in the dq reference frame then control becomes rather straightforward. Generally, PI Controller is used for the control of the direct current and the quadrature current components because of its simplicity. There are two independent PI Controllers in total, one for the direct current and the other for the quadrature current. The reference value for i_d is always kept zero not to produce flux whereas the i_q reference is generated from the torque command generated from the speed loop.

Outputs of the PI Controllers represent the voltage space vector in dq reference frame. Since the direct voltage component would be zero, this situation forces the voltage space vector to be exclusively in the quadrature direction. As we know that only the quadrature current produces useful torque so then torque efficiency becomes maximum as desired.

The v_d and v_q voltages are transformed back to the v_α and v_β voltages which are defined in the 2 axis stationary reference frame using Inverse Park Transformation [23].

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix} \quad (2.19)$$

Finally, these 2 axis stationary reference frame voltages must become meaningful in the 3 axis stationary axis reference frame for generation of the PWM signals. This last step varies respect to the applied PWM generation method. In our case, we use polar coordinate transformation to get the magnitude and angle information of the reference voltage vector, which is applied to the BLDC Motor.

$$Magnitude = \sqrt{v_\alpha^2 + v_\beta^2} \quad (2.20)$$

$$Angle = \arctan(v_\beta/v_\alpha) \quad (2.21)$$

2.3. Space Vector Pulse Width Modulation

In the inverter, there are three switching arms dedicated to three phases of motor, so eight different switching combinations (i.e. base space vector) are obtained. While six base space vectors have non-zero magnitudes, the other two have no magnitudes.

$\underline{u}_{100}$ is equal to 100 where the first digit represents the status of Phase A, second digit represents the status of Phase B and third digit represents the status of Phase C respectively. Status 0 and 1 logics indicate followings;

- 0, if the winding is connected to the GND
- 1, if the winding is connected to the V_{BUS}

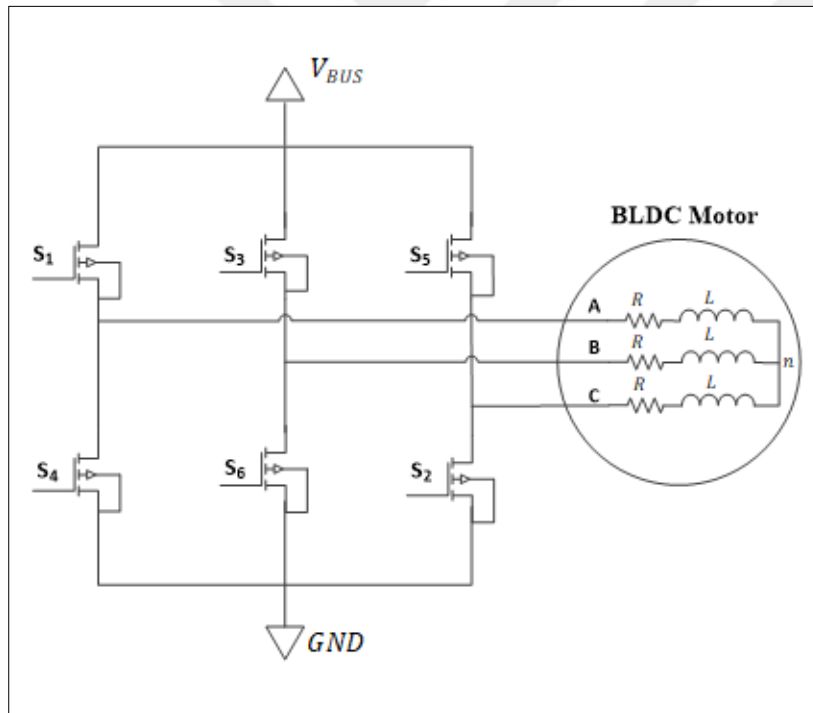


Figure 2.10. Inverter with BLDC motor

In Figure 2.11, the dashed hexagon inside the circle is called as Space Vector Region. An arbitrary reference vector can be generated with an appropriate combination of eight base space vectors. If we take $\underline{u}_s$ vector as a reference voltage vector to be applied to the motor, it can be clearly seen it is inside the boundary of the subregion formed by $\underline{u}_{000}$, $\underline{u}_{111}$, $\underline{u}_{100}$

and $\underline{u}_{110}$ base space vectors so the generation of $\underline{u}_s$ vector is possible with the combination of these base space vectors.

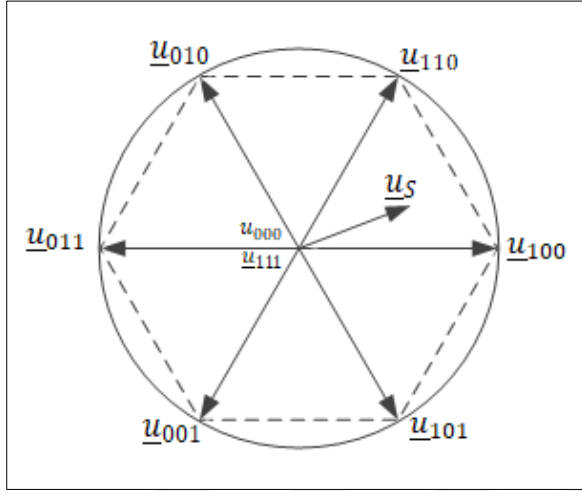


Figure 2.11. Space vector region

To determine the exact switching times, we can utilize from Figure 2.12 with the help of basic trigonometric knowledge [24].

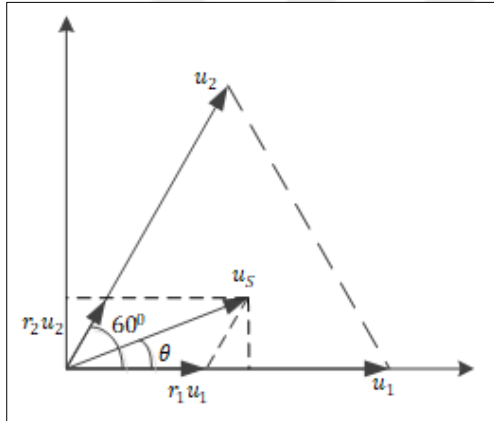


Figure 2.12. $\underline{u}_s$ reference space vector in first region

$$\underline{u}_s = r_1 \underline{u}_1 + r_2 \underline{u}_2 \quad (2.22)$$

$$r_1 = \sqrt{3} \frac{u_s}{U} \sin(60 - \theta) \quad (2.23)$$

$$r_2 = \sqrt{3} \frac{u_s}{U} \sin \theta \quad (2.24)$$

where, $u_s = |\underline{u}_s|$

$$u_1 = u_2 = |\underline{u}_1| = |\underline{u}_2| = \frac{2}{3}U \quad (2.25)$$

For θ between 0° and 60° , r_1 and r_2 are within the range $[0,1]$.

$$T_0 = (1 - r_1 - r_2)T \quad (2.26)$$

$$T_1 = r_1 T \quad (2.27)$$

$$T_2 = r_2 T \quad (2.28)$$

In case of $r_1 + r_2 < 1$, rest of time is fulfilled with zero length space vector.

According to switching time calculations performed above, there are some conditions that violate the boundary of hexagon. The reason of this is vector summation of $\underline{u}_1$ and $\underline{u}_2$ is not identical to scalar summation of r_1 and r_2 . To prove we generate the worst condition that can happen;

where, $|\underline{u}_s| = \frac{2}{3}U$ and $\theta = 30^\circ$,

When these values are substituted in Eqn. 2.23 and Eqn. 2.24;

$$r_1 = \frac{\sqrt{3}}{2} \quad (2.29)$$

$$r_2 = \frac{\sqrt{3}}{2} \quad (2.30)$$

$$r_1 + r_2 = \sqrt{3} > 1 \quad (2.31)$$

We have already known that summation of $r_1 + r_2$ cannot be bigger than 1 so to prevent this situation we have to divide it with $\sqrt{3}$. Then under this condition r_1 and r_2 would be $\frac{1}{2}$. If we use Eqn. 2.23 again.

$$\frac{1}{2} = \sqrt{3} \frac{u_s}{U} \sin(60 - \theta) \quad (2.32)$$

where, $\theta = 30^\circ$

$|\underline{u}_S|$ can be maximum $\frac{1}{\sqrt{3}}U$.

After this calculations, the boundary of utilizable space vector region should be renewed. The renewed boundary is presented with dashed inner circle in Figure 2.13.

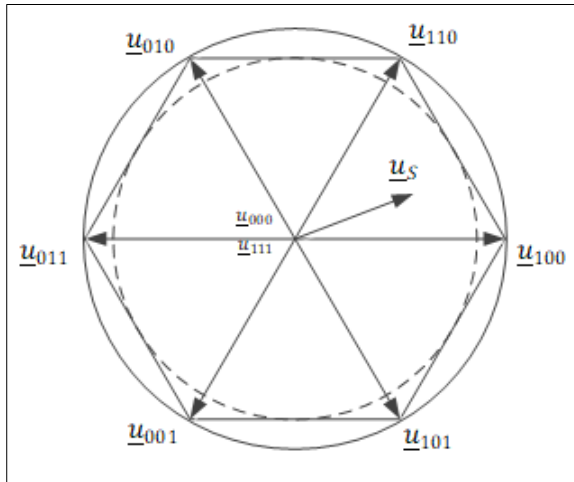


Figure 2.13. Utilizable space vector region

Switching sequence

As mentioned before, any reference state vector can be obtained from the combination of the 4 base space vectors. At obtaining reference state vector, it is vital to determine which 4 base space vectors to be used and the corresponding switching times correctly. In addition, another important thing is the order in which the 4 base space vectors are applied to the motor. As known each base state vectors are obtained from the switching combination of the 6 MOSFETs. During the switching of the MOSFETs, the ripple occurs on the phase currents and DC Bus voltage. For this reason, some basic switching patterns are examined to minimize the noise that stems from switching sequence [24].

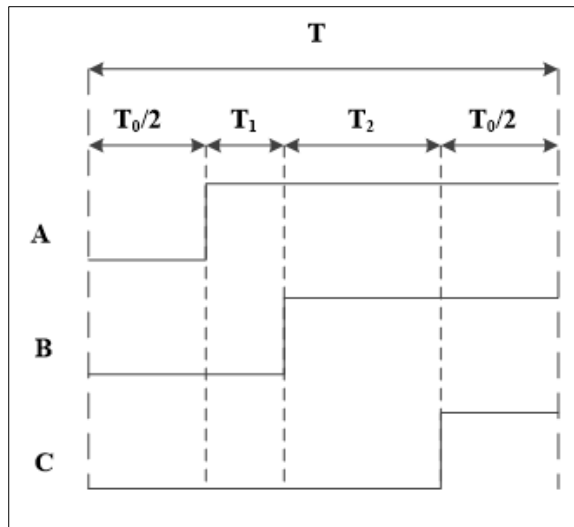


Figure 2.14. Right aligned switching sequence

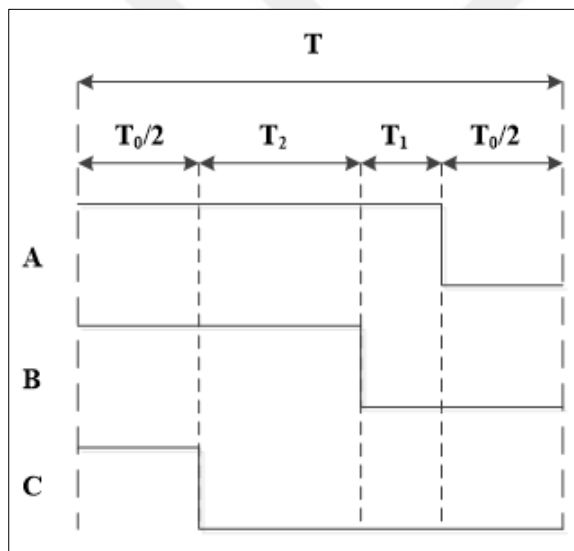


Figure 2.15. Left aligned switching sequence

The proposed switching sequences in Figure 2.14 and Figure 2.15 actually have the same effect in overall. At the beginning or at the end of the period, all 6 MOSFETs in the inverter structure change their states at same time. Therefore, the ripple which may reach catastrophic levels occurs on the phase currents and DC Bus voltage at the beginning or at the end of the period. This situation also causes harmonic noise.

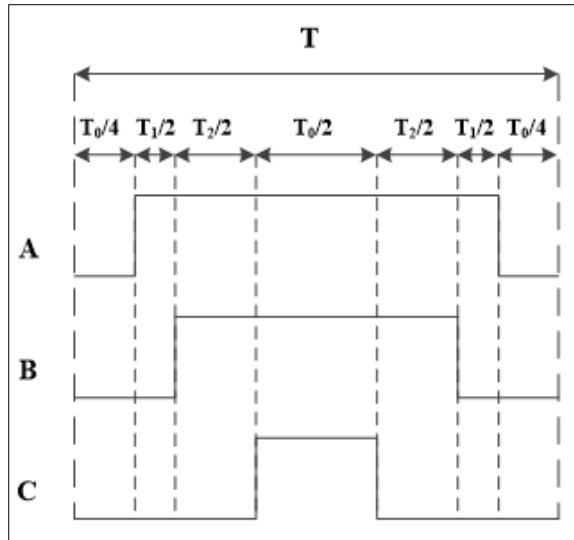


Figure 2.16. Center aligned switching sequence

The switching sequence shown in Figure 2.16 is center-aligned rather than edge-aligned like previous ones. In this pattern, the MOSFETs of an only single phase change their state at the same time. Thus the ripple which occurs on the phase currents and DC Bus voltage is quite minimized. As a drawback, the increment of the total number of the switching the MOSFETs in the period shorten the usable duration of time in the period in return.



3. SYSTEM AND MODELLING

In this section, the system in which the proposed method is used, is introduced and is examined in detail. Then proposed method and its improvements are explained. Finally, the performance of the design which is simulated in SIMULINK is examined according to simulation results.

3.1. System Overview

The fins that make the guidance kit to follow the desired path are controlled with BLDC Motor. Since this type of weapon systems do not have the rocket motor, their mobility is poor as well. From this point of view, the importance of the task of the fins is clearly understood for the guidance kits. The total weight of the guidance kits may exceed 1 ton depending on type of the bomb. Considering the weight of the kit and the amount of load torque it will be subjected to, either very large motors should be preferred or the smaller motors which is custom design and have high torque density should be used. As can be understood, these two choices create design problems such as increased production cost, the necessity of bigger structure that affects aerodynamics of the kit negatively. To avoid these handicaps, the fins are not directly connected to the shaft of the BLDC Motors.

Instead, the electromechanical actuator structure shown in Figure 3.1 is used. The main parts of this structure are as follows;

- 1- Fin
- 2- Transfer Lever
- 3- Nut
- 4- Screw
- 5- Gear Box
- 6- BLDC Motor

The rotor is attached to one end of the screw through gear box. The direction of rotation of the screw can be either parallel or perpendicular according to the connection type. In the case handled here, the screw and the rotor rotate in the same direction. In this structure,

according to the direction of rotation of the screw, nut moves upwards and downwards along the screw. Thanks to this structure which is called a linear actuator, the rotational movement is converted to the linear movement. There are balls between the screw and nut in order to minimize the friction. This sub-structure which consists of screw, nut and balls is called a balls screw. One of the factor that determines the operating range of the fin is length of the screw. Another factor is the arm length of the transfer lever. By this length and gear box, transmission ratio between the motor shaft and fin is adjusted. Due to the perpendicular connection, while transfer lever mechanism moves upwards and downwards, fin rotates clockwise and counterclockwise.

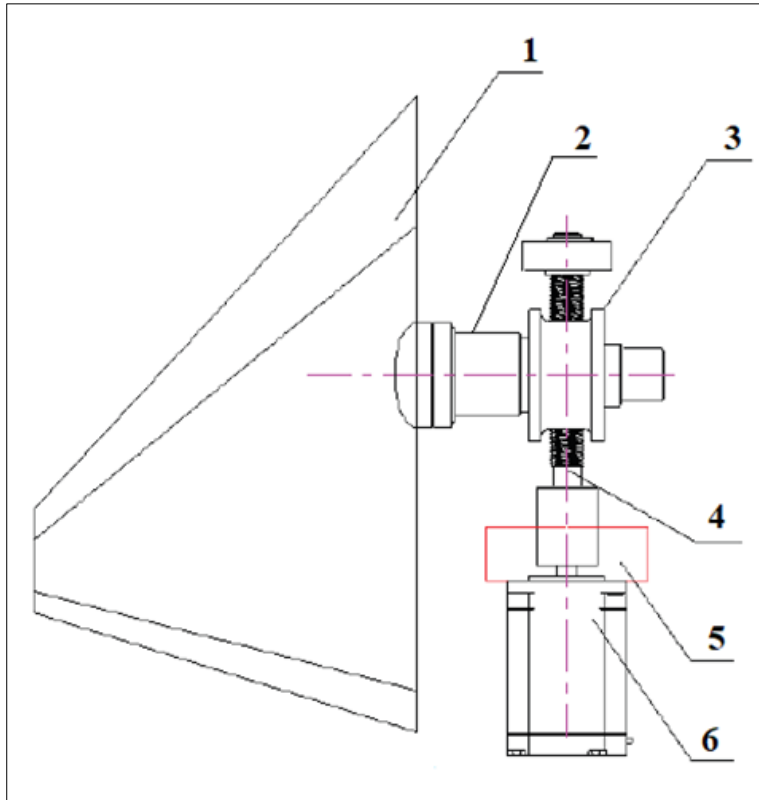


Figure 3.1. Electromechanical actuator structure [25]

Thanks to this structure, the load applied to the fin is not directly applied to the shaft of the motor. The load seen on the shaft of the motor is as follows:

$$\text{Load on Fin} = \text{Transmission Ratio} \times \text{Load on Shaft} \quad (3.1)$$

While this situation provides the gain in terms of the load to be applied to the motor, in return it causes the disadvantage in terms of total displacement of the shaft. The correlation between them is as follows.

$$\text{Displacement of Fin} = \text{Transmission Ratio} \times \text{Displacement of Shaft} \quad (3.2)$$

Since overcoming the load torque is more important criterion for the kit, this situation is acceptable.

Position control requirements in guidance kits are derived according to the fin instead of shaft of the BLDC Motor. In the scope of the thesis, since tests are not performed with fins, the control requirements are tried to be met for the shaft of the BLDC Motor. Therefore, position control requirements are recalculated for the shaft of the BLDC Motor.

Again, since the supply voltage of the BLDC Motor, in other words DC Bus voltage, is used as 28 V in guidance kits, DC Bus voltage is selected as 28 V in this thesis.

In guidance kits, Six-Step method is used for the commutation of the BLDC Motor, so the current controller's performance is not very good. The poor current controller also means poor torque performance. Since both the presence of these mentioned handicaps and the stiffness of the position control requirements, complex controllers which use H Infinity method are preferred in position control. Even though our objective is position control of the motor, the main proposed improvement in the scope of this thesis is the usage of SVPWM based FOC method in the current controller. Thanks to this method, the stress on the position controller is decreased. Thus, the necessity of using complex position controller is tried to be eliminated.

In order to get the maximum torque that motor can produce, the waveform of the stator current and the waveform of the back EMF must be similar and in-phase. The different types of commutation techniques such as Trapezoidal and Sinusoidal commutations are developed for this purpose. Although it is known that theoretically BLDC Motor has trapezoidal back EMF waveform, in real its waveform also has sinusoidal characteristic because of its stator inductance. Thus, not only trapezoidal commutation but also different types of commutation techniques can be applied to the BLDC Motor.

Even if the sinusoidal commutation, which is more efficient at low speeds, has higher torque performance than the trapezoidal commutation, unfortunately it is almost useless at high speeds. For this reason, the SVPWM based FOC, which is efficient both at low and high speeds and has high torque performance, is preferred.

In this thesis, block diagrams, which is seen in Figure 3.2 and Figure 3.3, is applied for the position control of BLDC Motor. While PI Controller is used for position and speed controller, Field Oriented Control is preferred for current controller. Within the FOC, PWM signals are generated with SVPWM technique.

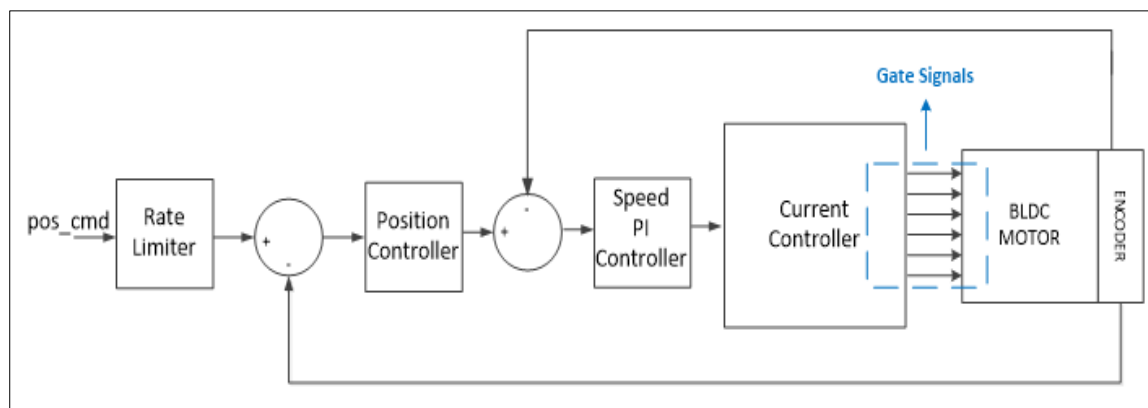


Figure 3.2. Block diagram of the system

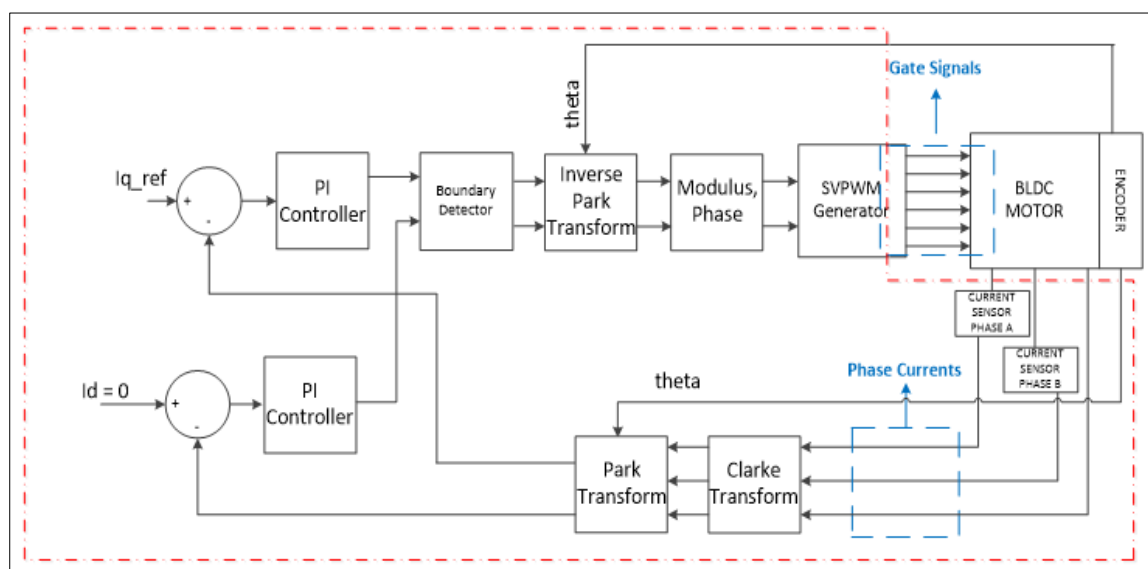


Figure 3.3. Block diagram of the proposed SVPWM based FOC

PI controller

In literature researches, it has been observed there are so many controller structures such as PI, PID, I-PD, adaptive, fuzzy logic etc. Because of its implementation simplicity and well response to its input, PI Controller is preferred in this thesis. In addition, the whole system consists of three nested control loop so this structure also aids to the response quality of the PI Controller that is simpler than other controller structures.

This controller structure consists of proportional and integral terms. While proportional term responses only instant error, integral term responses the history of the error. Thanks to integral term, the offset error is eliminated in steady state.

The mathematical expression of PI Controller is

$$u(t) = K_p e(t) + K_i \int e(t) dt \quad (3.3)$$

where,

K_p : Proportional gain

K_i : Integral gain

$e(t)$: error

$u(t)$: output

The block diagram of the PI Controller is shown in Figure 3.4

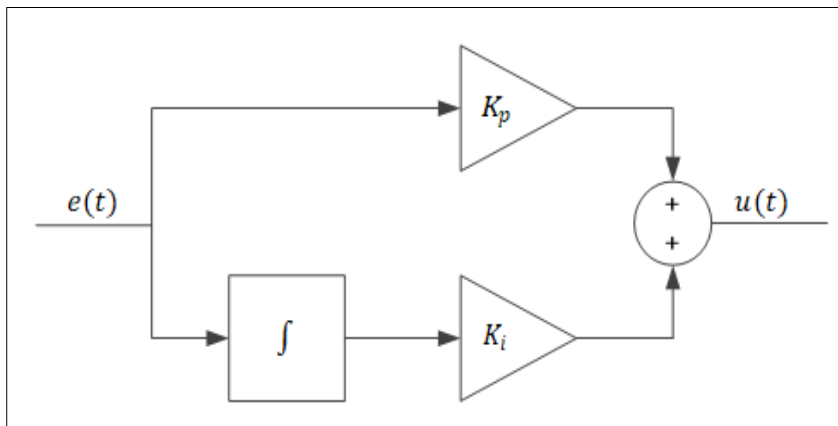


Figure 3.4. PI controller

In Figure 3.2 and Figure 3.3, all the controllers which are used in the design are seen. It is paid attention that the operating frequency of the inner loop must be at least 10 times higher than the operating frequency of the outer loop as a rule of thumb while choosing the operating frequency of the controllers. The operating frequencies of the controllers are as follows.

- The operating frequency of the I_d and I_q PI Controller : 10 kHz
- The operating frequency of the Speed Controller : 1 kHz
- The operating frequency of the Position Controller : 100 Hz

Rate limiter

When we take a closer look at the Figure 3.2, the other design improvement is the Rate Limiter Block. Instead of applying position command coming from User Test Interface directly into the PI Controller as an input, it is directed to Rate Limiter block to limit the rate of change of the position command. This limit value which comes from the controller's requirement is equal to the maximum rate of change of the position command, which can be applied to the motor. Thanks to Rate Limiter block it is guaranteed that only the allowed position command is applied to the PI Controller so this makes system more stable. PI Controller can follow the position command even without Rate Limiter but for some input values, oscillations which would affect the controller performance in a bad way that may occur at the output.

Boundary detector

As can be seen in Figure 2.9, outputs of the I_d and I_q current PI Controllers which are orthogonal to each other, directly enter into the Inverse Park Transformation Block. Then enter to the Polar Transformation block to be meaningful for the SVPWM Generator Block. These transformation blocks between the current PI Controllers and SVPWM generation block do not change the magnitude of vector summation mathematically.

In design, the maximum output values of the I_d and I_q PI Controllers are fixed to the radius of the utilizable space vector circle. For some conditions, the vector summation of these two independent controllers may violate the boundaries of the utilizable space vector

region. The violation of utilizable space vector region boundary cause the erroneous PWM calculations. Then system's performance is affected in a bad way. In order to prevent this erroneous case, the Boundary Detector Block which is seen in Figure 3.3 is designed.

The working principle of Boundary Detector is as follows

$$v_{sum} = \sqrt{Id_{out_n}^2 + Iq_{out_n}^2} \quad (3.4)$$

If $v_{sum} \geq r_{spv}$;

Then Id_{out_n} and Iq_{out_n} are recalculated

$$Id_{out_n} = Id_{out_n} / v_{sum} \quad (3.5)$$

$$Iq_{out_n} = Iq_{out_n} / v_{sum} \quad (3.6)$$

where,

r_{spv} : radius of utilizable space vector region : 1

Id_{out_n} : normalized output of I_d PI Controller, can be maximum 1

Iq_{out_n} : normalized output of I_q PI Controller, can be maximum 1

v_{sum} : vector summation of Id_{out_n} and Iq_{out_n}

Thanks to this block, it is guaranteed that the vector summation of the outputs of these two independent controllers always within the boundaries of the utilizable space vector region.

3.2. Requirements of Position Controller

The controller's requirements with respect to fins as follows

- The operating range of the fins in terms of degree : 26°
- The maximum rate of change of the position command which has to be fulfilled by fins : $100^\circ/\text{s}$
- The maximum torque load which is applied to the fins : 32 N.m
- The maximum acceptable ripple on position : 10%

- The transmission ratio which is used in guidance kit : 100

Then controller's requirements with respect to motor shaft becomes as follows

- The operating range of the motor shaft in terms of radian : $(26 \times 100 \times \pi)/180 = 45,35$ rad
- The maximum rate of change of the position command which has to be fulfilled by motor : $(100 \times 100 \times \pi)/180 = 45$ rad/s
- The maximum torque load which is applied to the motor: 320 mN.m
- The maximum acceptable ripple on position : 10%

3.3. Motor Parameters

Important parameters of BLDC Motor are given below in Table 3.1. Motor parameters are generally examined under two main section namely, electrical and mechanical. In order to avoid calculation errors which stem from unit mismatch, all the motor parameters are written with SI units.

Table 3.1. Motor parameters

Motor Parameters	
Electrical	
Resistance (Ohm)	0,3
Inductance (mH)	2,5
Pole Pair	4
Mechanical	
Torque Constant (N.m/A)	0,048
Speed Constant (rad/V.s)	0,048
Inertia (kg.m^2)	3.10^{-6}
Viscous Damping (N.m.s)	2.10^{-5}

3.4. System Modelling

The system shown in Figure 3.2 and Figure 3.3 is modeled in the SIMULINK. The model of the whole system is shown in Figure 3.5.

In order to obtain realistic results, I_d and I_q PI Controllers are run at their own operating frequencies. The frequencies of the PI Controllers are adjusted using the SIMULINK's "Rate Transition" block.

To model the Rate Limiter in the real system, SIMULINK's "Rate Limiter" block which has same name is used.

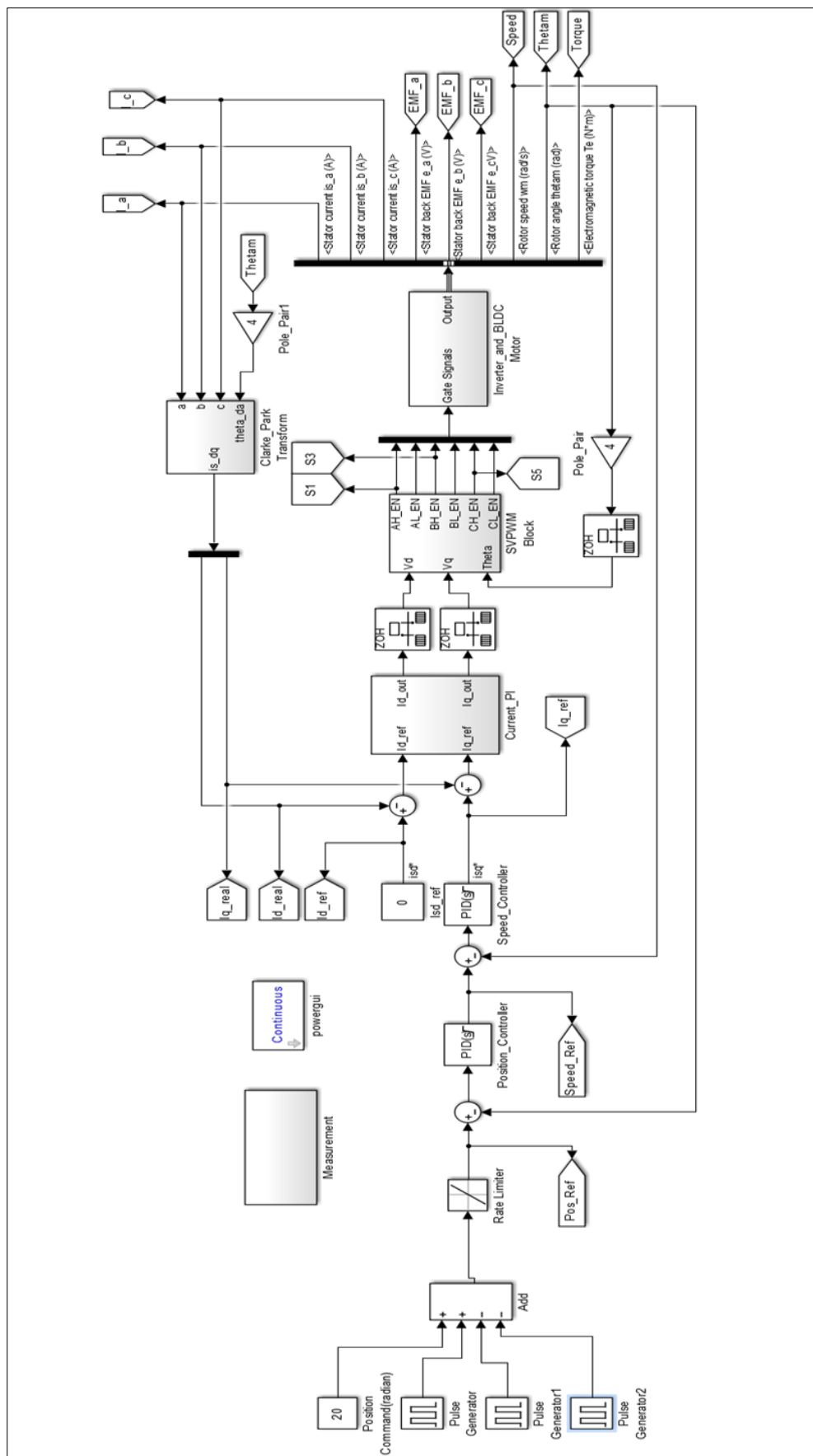
Because the rotor is initially at $a = \alpha$ axis - can be adjusted in motor model-, unlike actual system there is no need to position alignment in simulation.

In order to increase traceability, the model is created from sub-blocks.

All of the PI coefficients are tuned by experimentation.

Table 3.2. PI coefficients for SIMULINK

Controller	K_p	K_i
Position	125	2,76
Speed	0,6	19,32
I_d current	0,1	13,8
I_q current	5	0,276



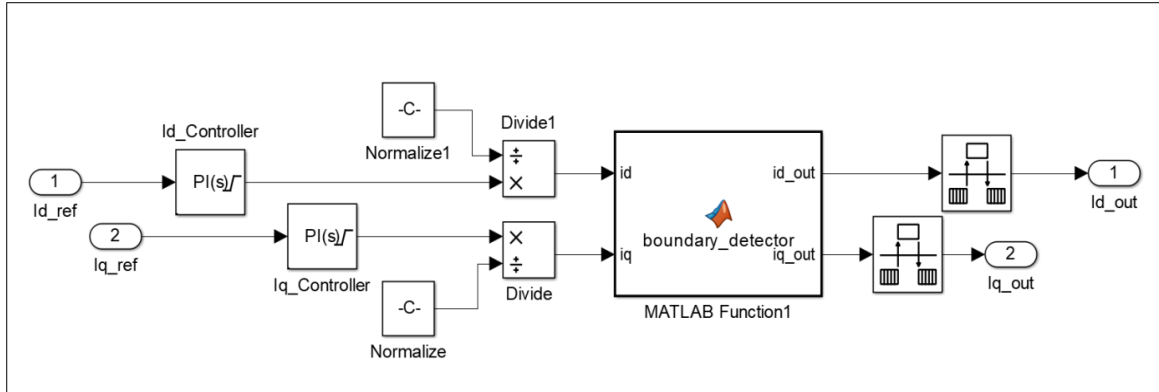


Figure 3.6. Current PI block

Current PI block consists of I_d and I_q PI Controllers and Boundary Detector block. The outputs of the I_d and I_q PI Controllers are divided by maximum output value, 16.16, of the PI Controllers so their outputs are normalized. Thus, it is provided that outputs of the PI Controllers are mapped to the Utilizable Space Vector Region whose radius equals to 1.

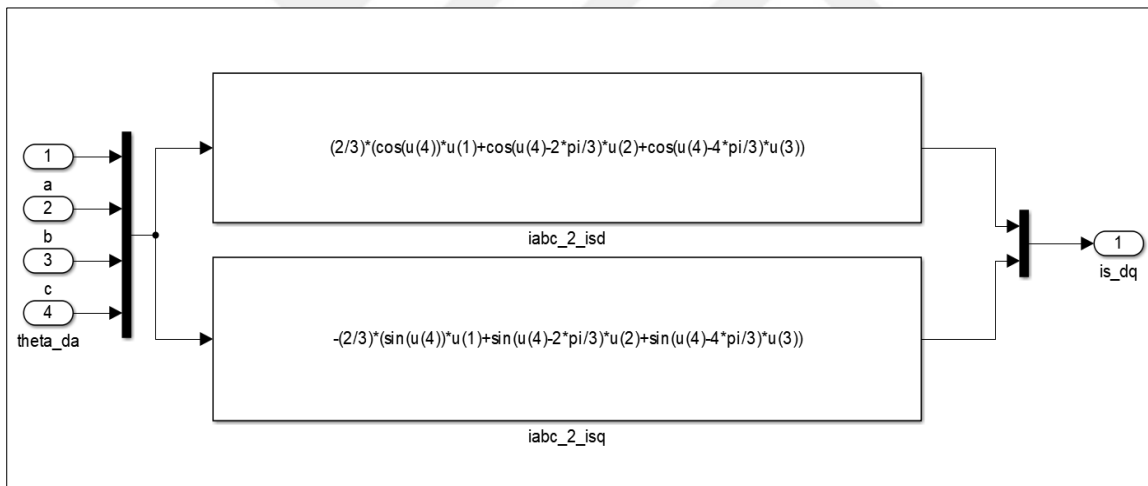


Figure 3.7. Clarke_Park transform block

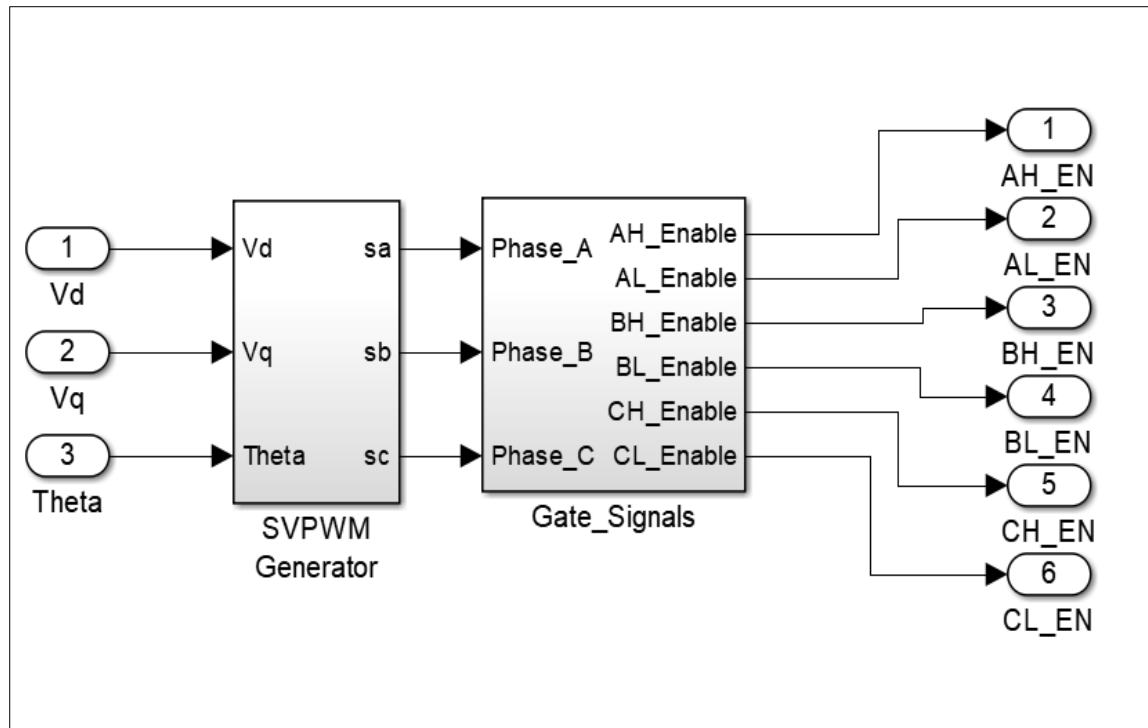


Figure 3.8. SVPWM block

SVPWM block consists of SVPWM Generator and Gate_Signals sub-blocks. The inside of the SVPWM Generator block is shown in Figure 3.9. As mentioned before, outputs of the I_d and I_q PI Controllers are transformed into magnitude and angle information in last step by means of polar transform. This information is directed into "svpwm" function [26]. Outputs of this function are switching signals of high side MOSFETs.

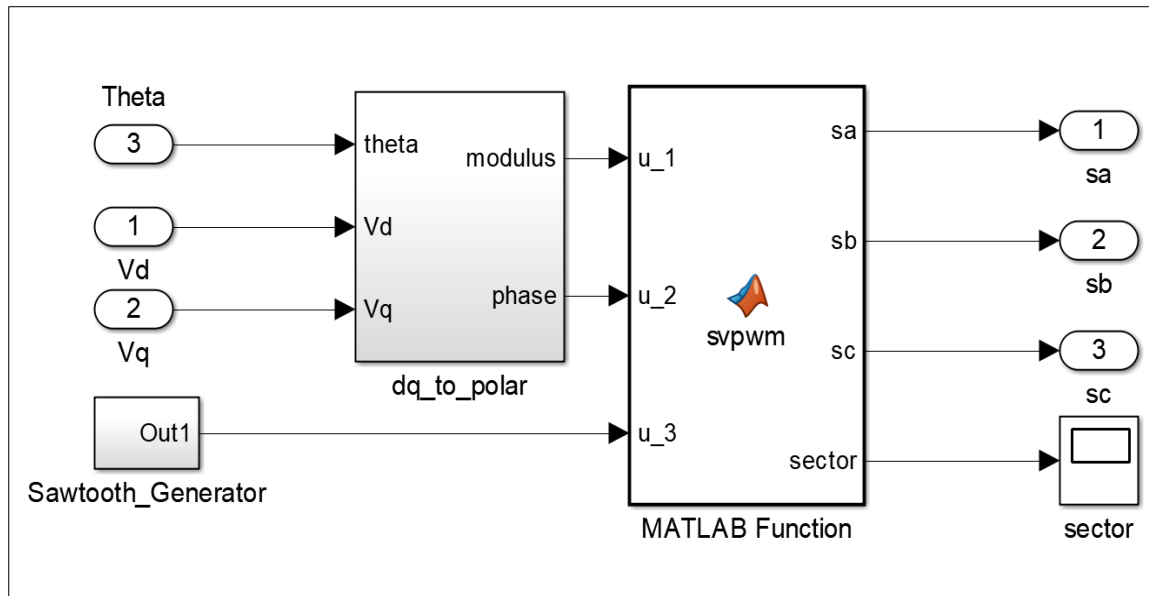


Figure 3.9. SVPWM generator block

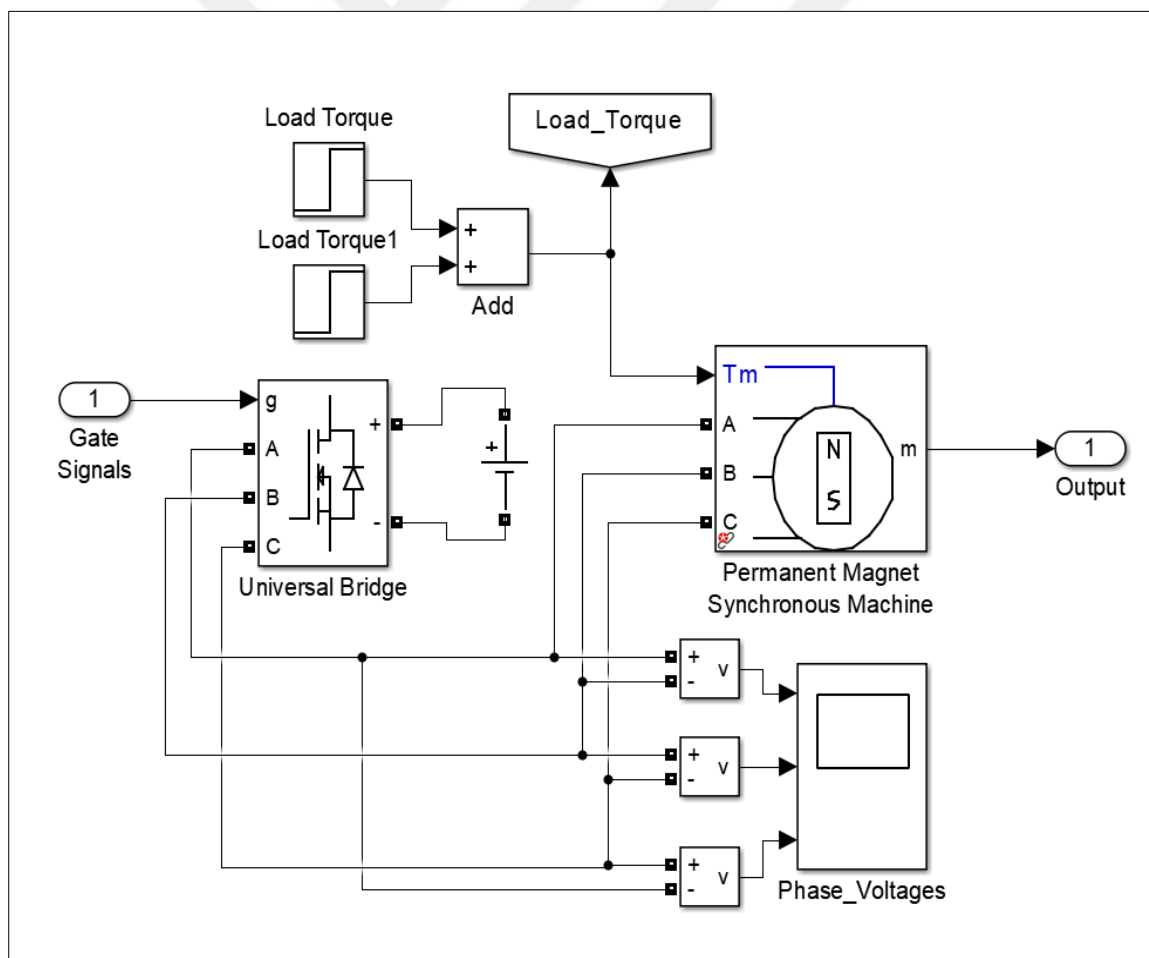


Figure 3.10. Inverter and BLDC motor block

The Block which is shown Figure 3.10, consists of the Inverter and BLDC Motor. Even if the name of the motor appears as Permanent Magnet Synchronous Machine, since its back EMF waveform is adjusted as trapezoidal, it behaves like BLDC Motor.

3.5. Tests

The test scenario in Table 3.3 is run to see the response of the system under the worst possible conditions.

Table 3.3. Test scenario for SIMULINK

Test Scenario	
Time (s)	Case
0 ⁻	Rotor position is equal to 0 radian, there is no load torque
0	20 radian position command comes
0,25	Load torque becomes 0,16 N.m
0,4	40 radian position command comes
0,7	Load torque becomes 0,32 N.m
0,85	20 radian position command comes
1,1	Load torque becomes 0 N.m
1,2	0 radian position command comes

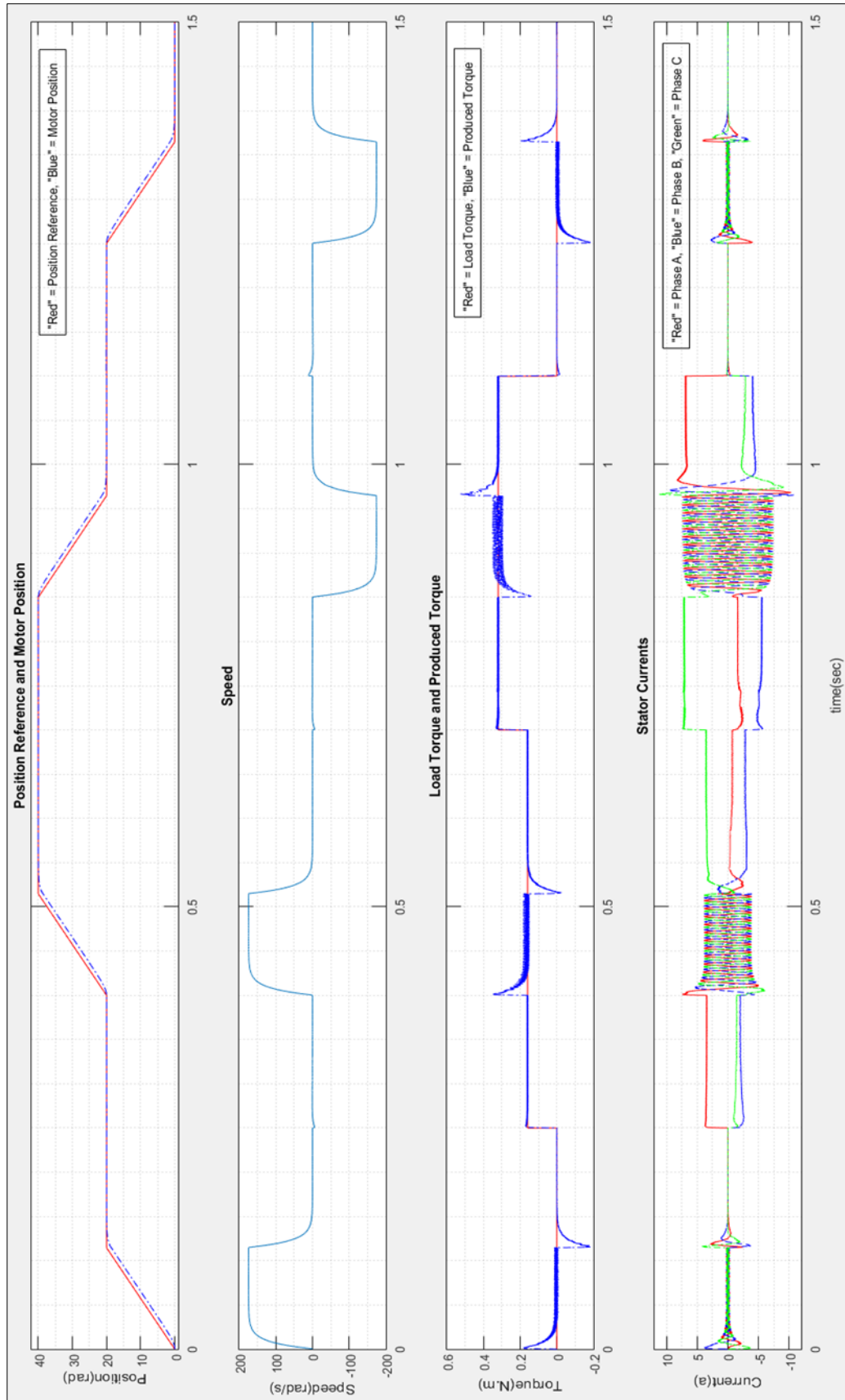


Figure 3.11. Position reference, motor position, speed , load torque, produced torque and stator currents on same time axis

In Figure 3.11, important parameters are plotted together in common time axis to understand and interpret system's dynamics better.

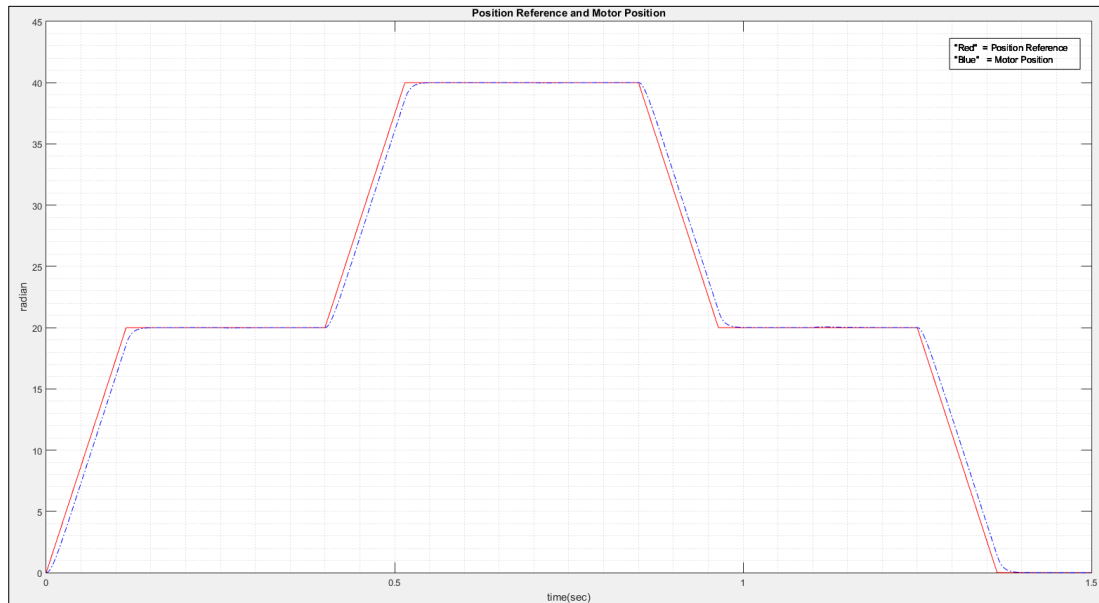


Figure 3.12. Position command and rotor position

In Figure 3.12, it is shown that position command is followed successfully. Like there is no offset error in steady-state, there is no overshoot or undershoot in dynamic response of the position controller. In addition, it is observed that any load torque change does not disturb the stability of the performance of the position controller.

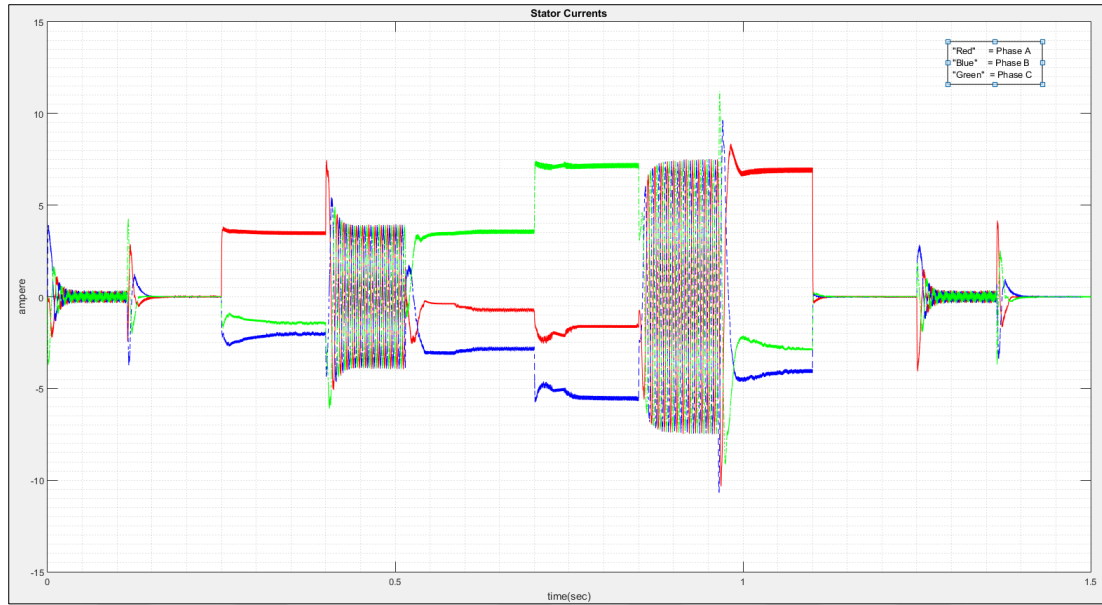


Figure 3.13. 3 phase current waveforms

In Figure 3.13, 3 phase current waveforms are shown for whole test. As expected, 3 phase current waveforms are almost sinusoidal when motor rotates. When the motor is stationary, if it is under load, 3 phase currents have DC values otherwise they all are equal to zero. Magnitudes of the 3 phase currents during 40 to 20 radian transition are greater than ones during 20 to 40 radian transition because of the amount of the load torque. These observations are shown in detail in Figure 3.16, Figure 3.15, Figure 3.16 and Figure 3.17.

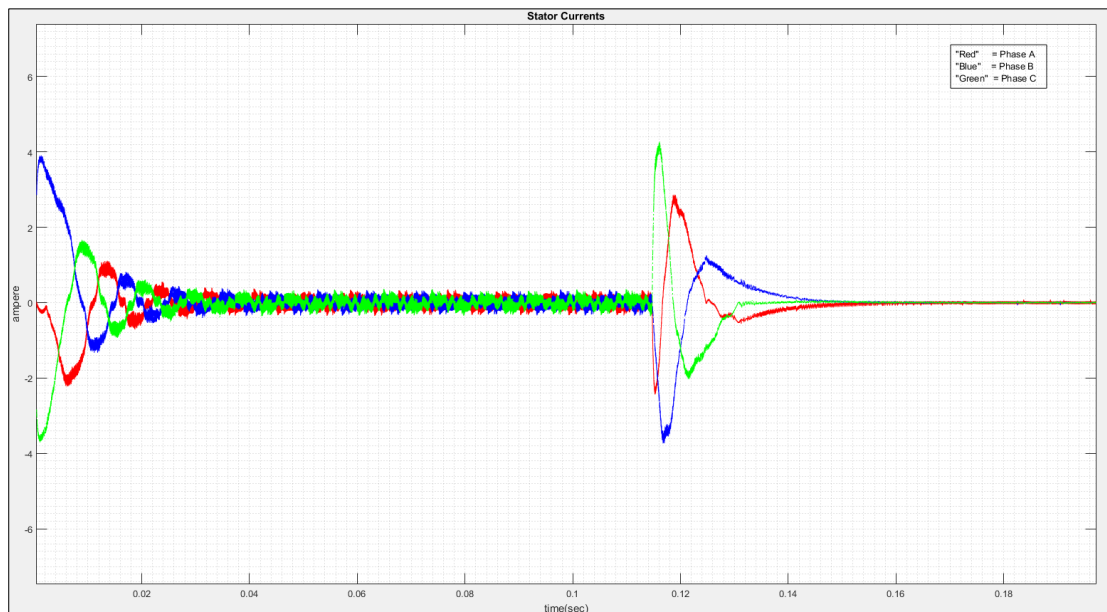


Figure 3.14. 3 phase current waveforms at starting

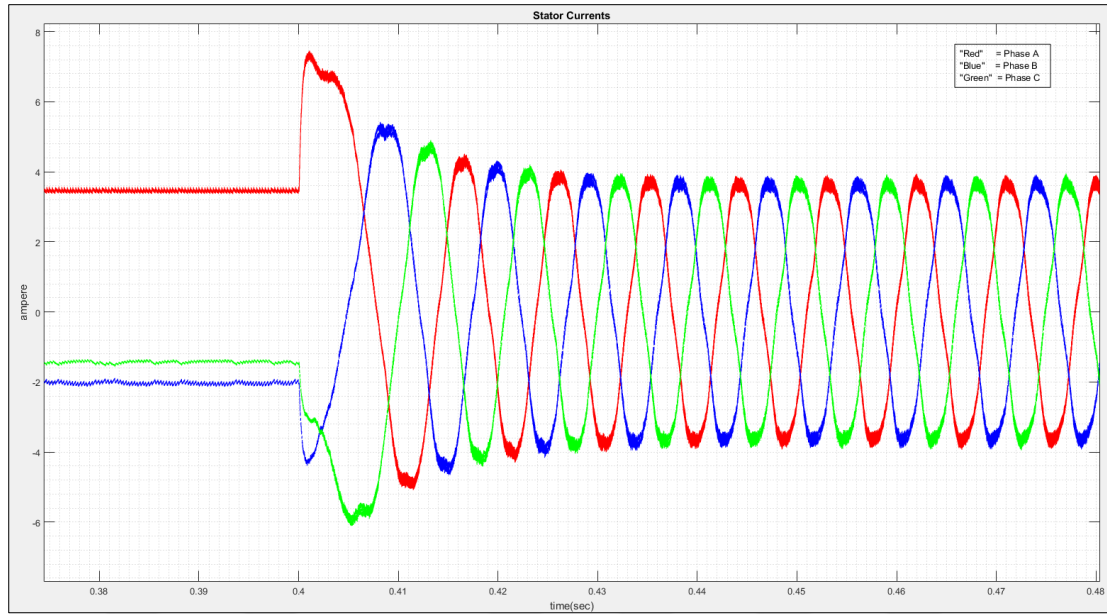


Figure 3.15. 3 phase current waveforms for 20 to 40 radian transition under 0,16 N.m load torque

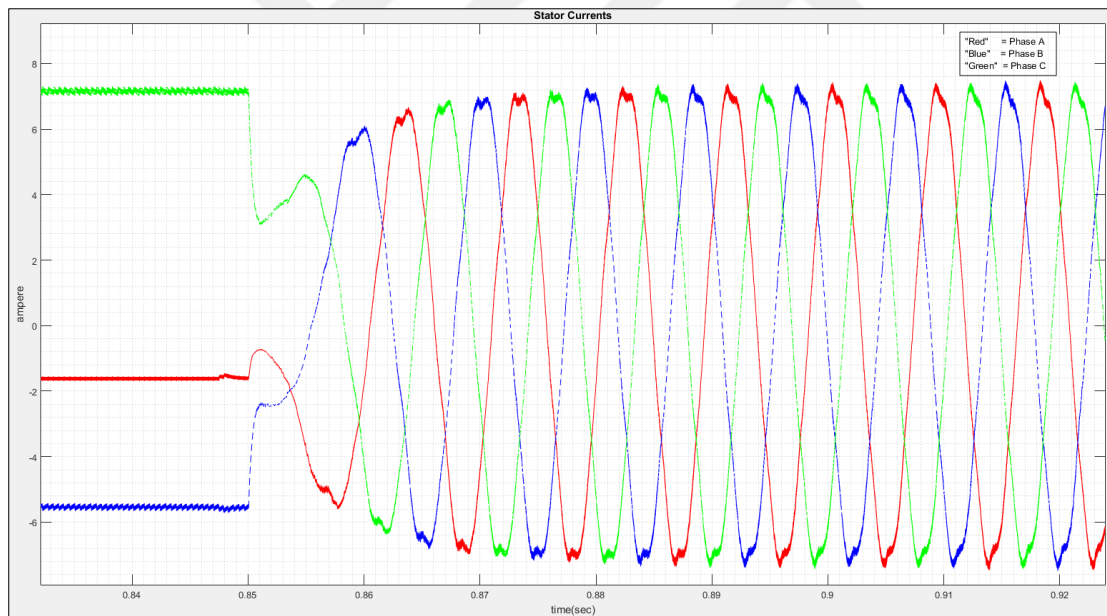


Figure 3.16. 3 phase current waveforms for 40 to 20 radian transition under 0,32 N.m load torque

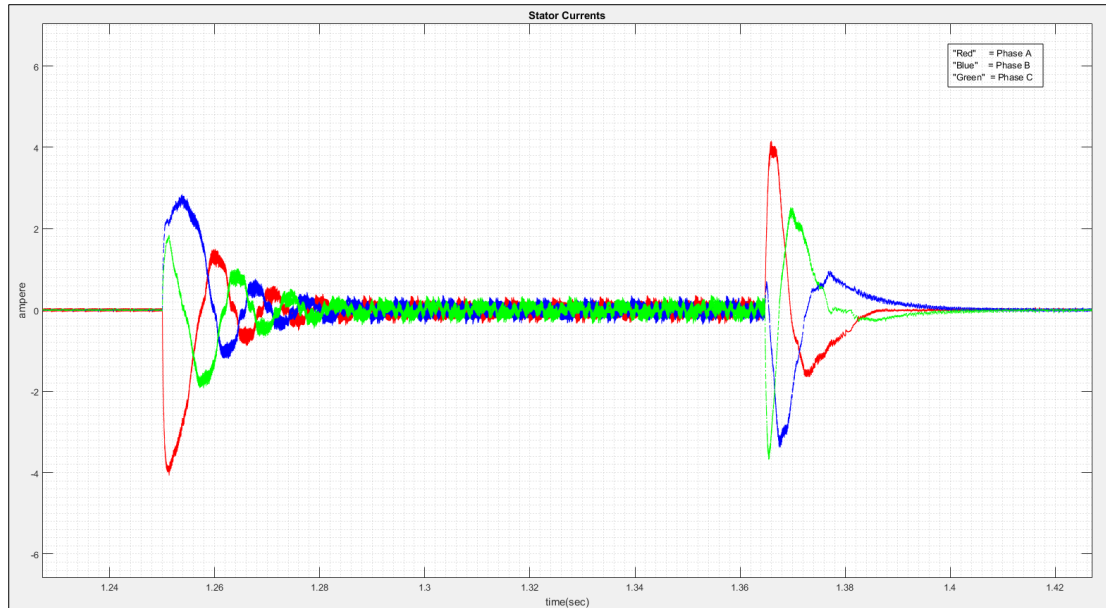


Figure 3.17. 3 phase current waveforms for 20 to 0 radian transition

In Figure 3.17, it shows that 3 phase current waveforms are almost similar to the current waveforms at starting as expected.

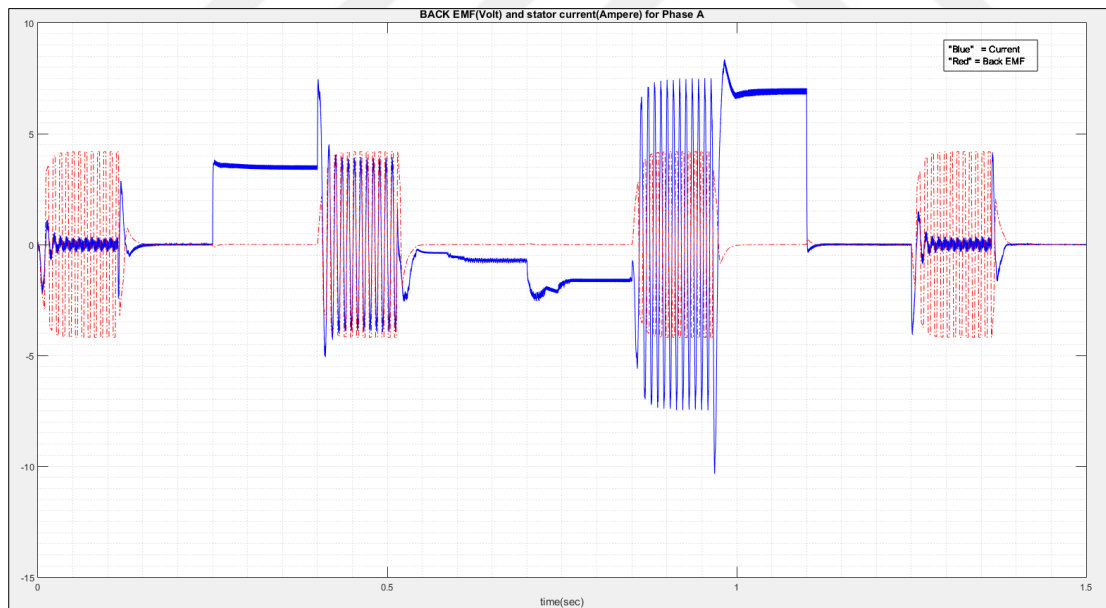


Figure 3.18. Current and back EMF waveforms of phase A

In Figure 3.18, the dashed red line represent the back EMF voltage waveform. When motor is stationary, the back EMF voltage is equal to zero as expected.

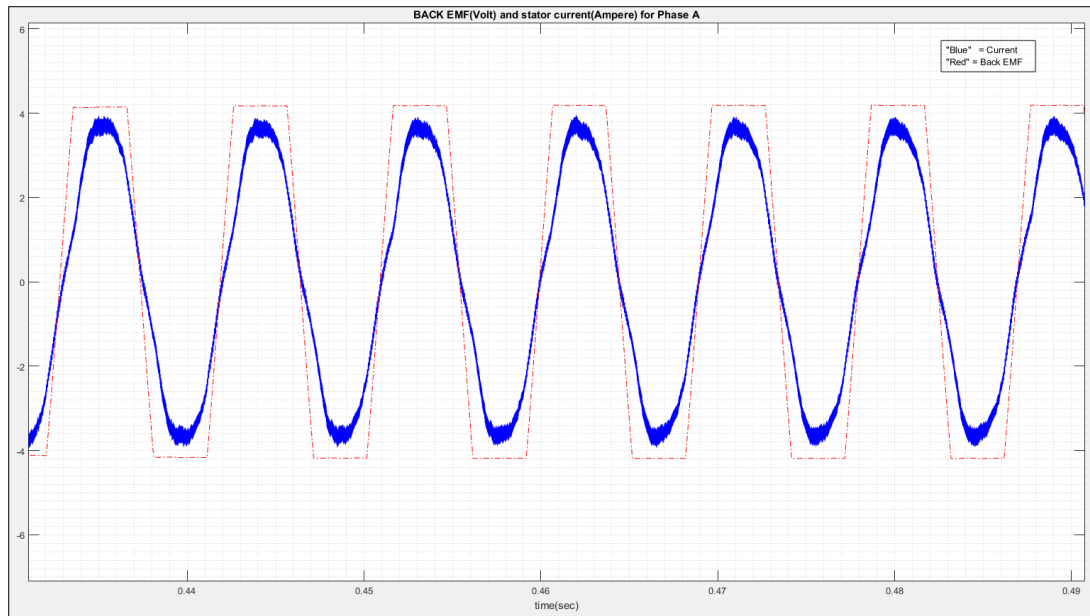


Figure 3.19. Current and back EMF waveforms of phase A for 20 to 40 radian transition under 0,16 N.m

As desired, the motor phase current and the back EMF are in-phase when motor phase current waveform is sinusoidal. Thus, this ensures the production of maximum positive power.

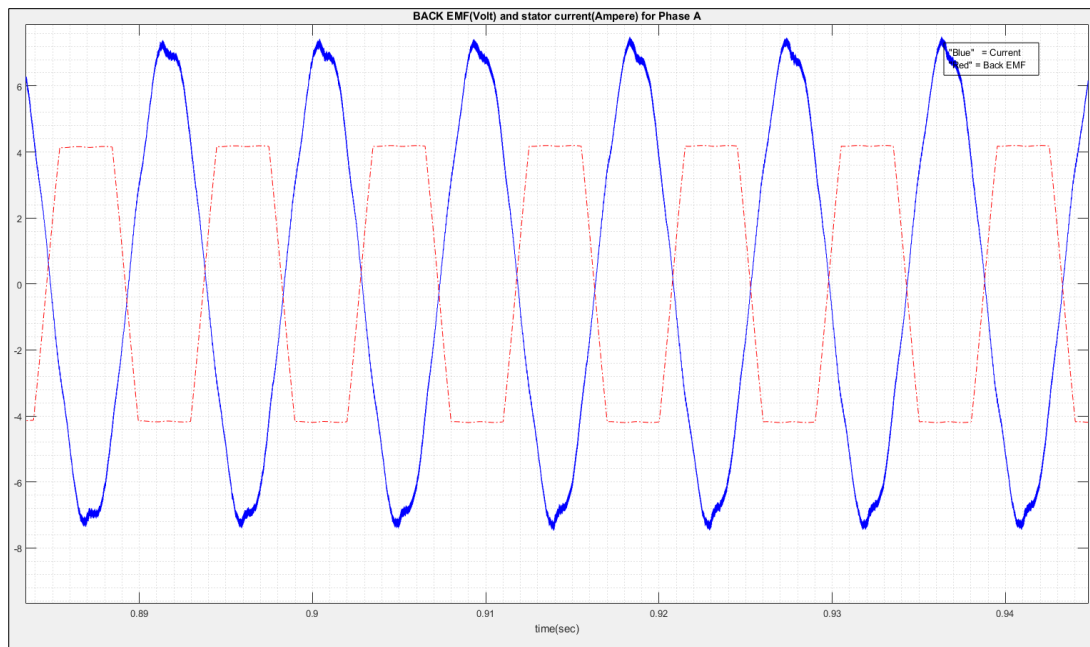


Figure 3.20. Current and back EMF waveforms of phase A for 40 to 20 radian transition under 0,32 N.m

In Figure 3.20, it is observed that the motor phase current and the back EMF are 180 degrees out of phase. The reason of this situation is the motor rotates in the direction in which the torque is applied. The production of maximum negative power is guaranteed thanks to presence of the 180 degrees out of phase.

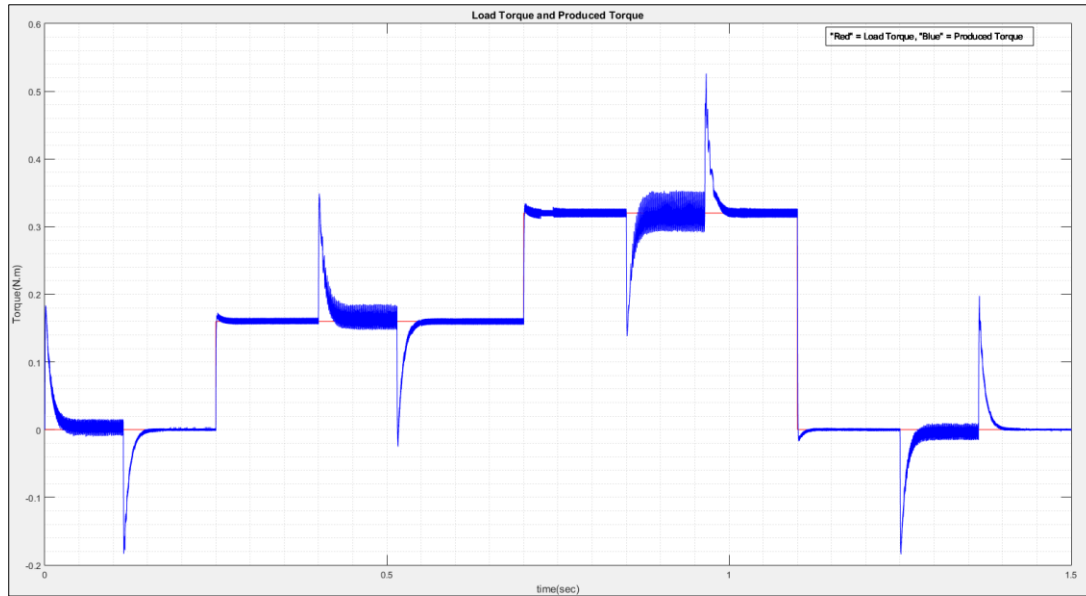


Figure 3.21. Load torque and produced torque

In Figure 3.21, the load torque and the produced torque are plotted on common time axis. As can be seen, overshoots and undershoots only occur when the position command is received and at the time of settling. At the steady-state, fluctuations are almost zero.

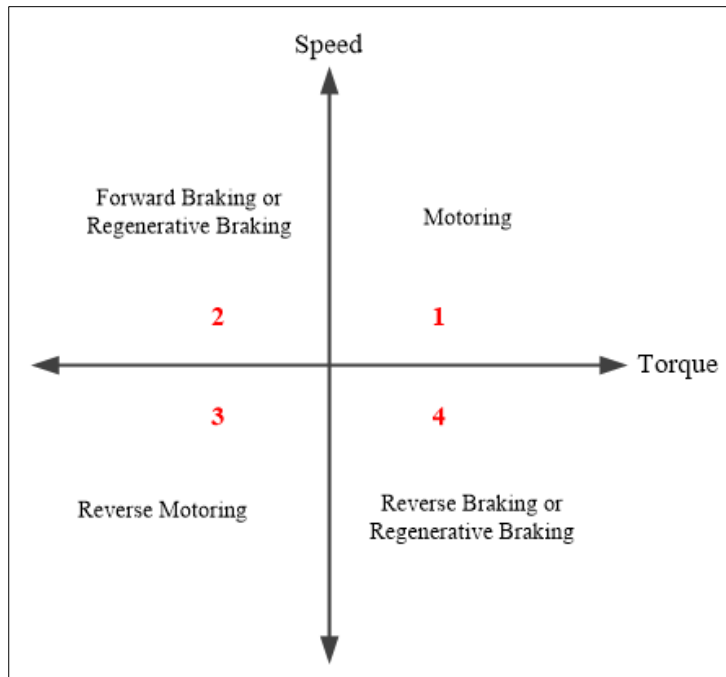


Figure 3.22. Four-quadrant operation of BLDC motor

One of the important criterion for motor control is four-quadrant control. Figure 3.22 shows the situations in which four-quadrant correspond in terms of torque and speed.

The four-quadrant control performance of the proposed SVPWM based FOC technique is examined with the help of Figure 3.23.

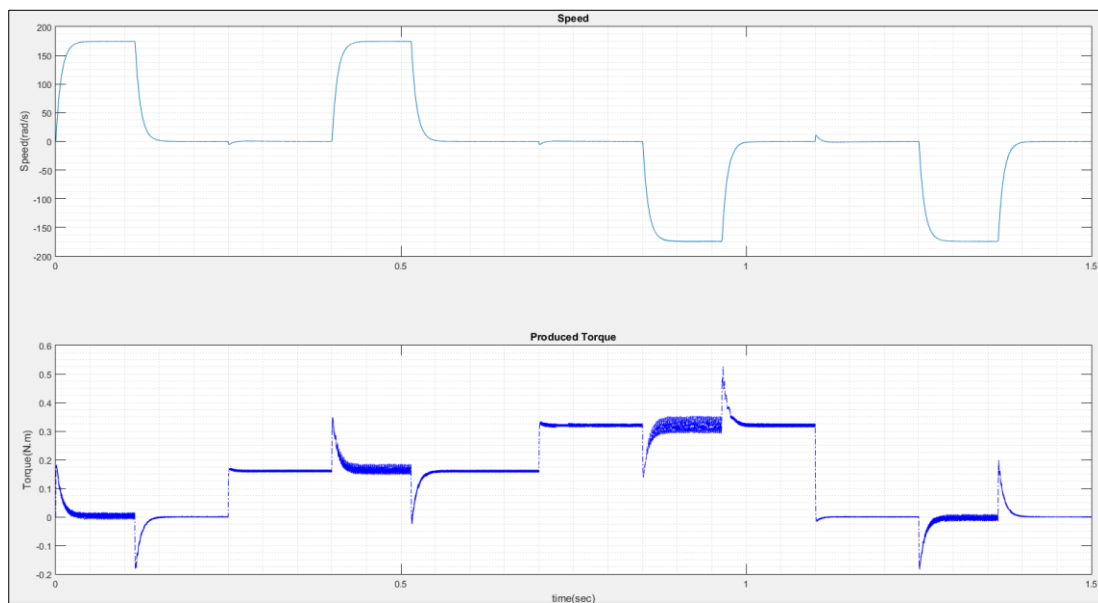


Figure 3.23. Speed and produced torque

At $t = 0$; a positive position command is applied to the motor. Since the large amount of instantaneous current are passed through motor phases as a response, the overshoot occurs on the produced torque. After then, the motor brakes down when it approaches the position command. This causes to the undershoot on the produced torque. During this position command, the motor operates in driving and forward braking modes, respectively.

At $t = 1,2$ s; a negative position command is sent to the motor. Since the motor speeds up in reverse direction, the undershoot occurs on the produced torque. After then, the motor brakes down when it approaches the position command. This causes overshoot on the produced torque. During this position command, the motor operates in reverse motoring and reverse braking modes, respectively.

It is proven that, the four quadrant control of the motor can be achieved by using SVPWM based FOC technique.

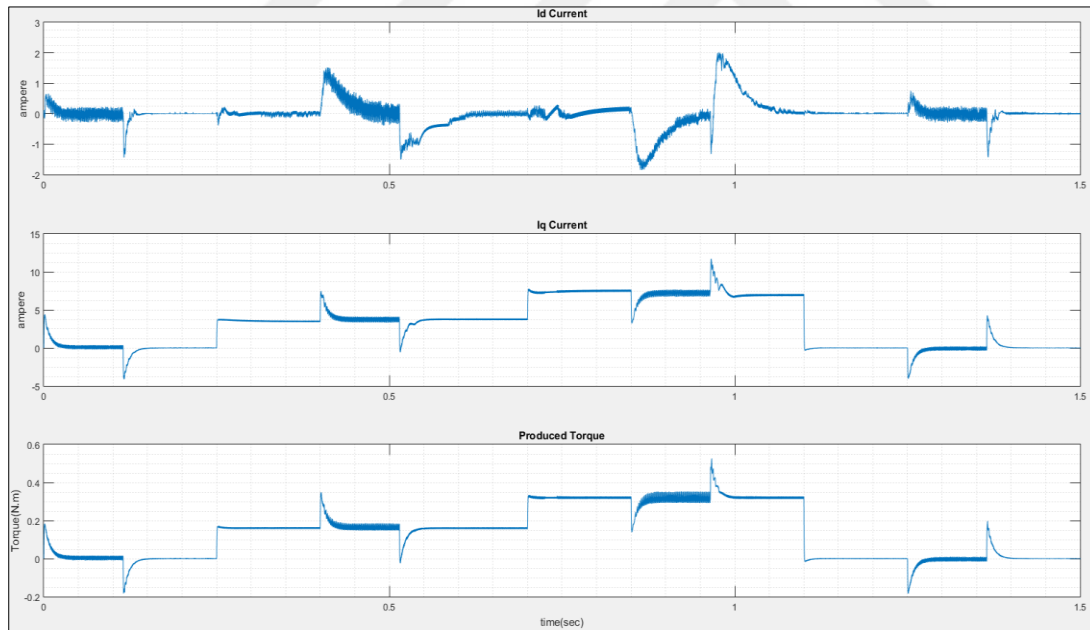


Figure 3.24. I_d current, I_q current and produced torque

The last but not the least criterion is dq axis currents. I_q current is called as torque producing current and as can be seen its shape is almost same with produced torque. This situation verify the torque expression in dq frame [27].

$$T = \frac{3P}{2} (\lambda_{pm} I_q + (L_d - L_q) I_d I_q) \quad (3.7)$$

where,

P : number of pole pairs

λ_{pm} : flux linkage of permanent magnet

L_d : inductance of motor on d-axis

L_q : inductance of motor on q-axis

For $L_d = L_q$ the torque Eqn. 3.7 becomes

$$T = \frac{3P}{2} (\lambda_{pm} I_q) \quad (3.8)$$

While I_q current produces torque, I_d current causes loss in torque. In steady-state, I_d current is nearly equal to zero as intended but it has non-zero values at transitions. As I_q current values are much smaller with respect to the I_d current values so this condition make the system more efficient.

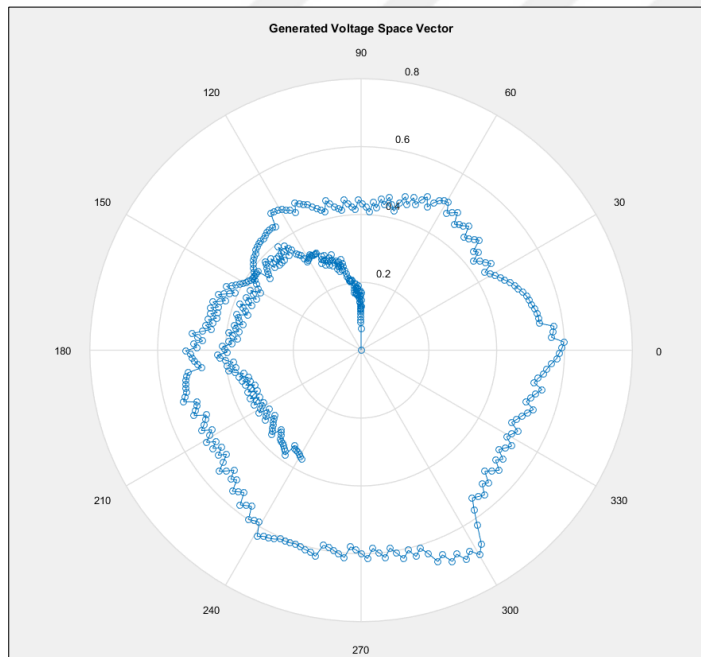


Figure 3.25. Generated voltage space vector in polar axis

In Figure 3.25, generated voltage space vectors which are applied to the motor, are shown in polar axis when motor rotates in positive, clockwise, direction. As expected, while motor rotates in clockwise direction, generated voltage space vectors rotate in counter clockwise direction because of the nature of the polar axis.

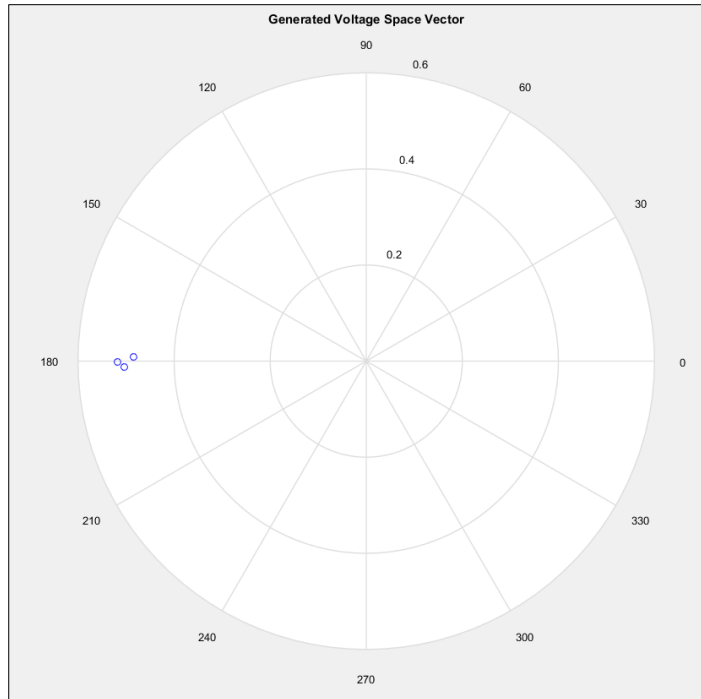


Figure 3.26. Some of the generated voltage space vector in polar axis

In Figure 3.27, it is shown that switching signals which are generated for generating voltage space vectors in Figure 3.26. In addition, sector information of the generated voltage space vectors can be seen in Figure 3.27. In Figure 3.27, it is verified that the period of switching signals is equal to $100\ \mu\text{s}$.

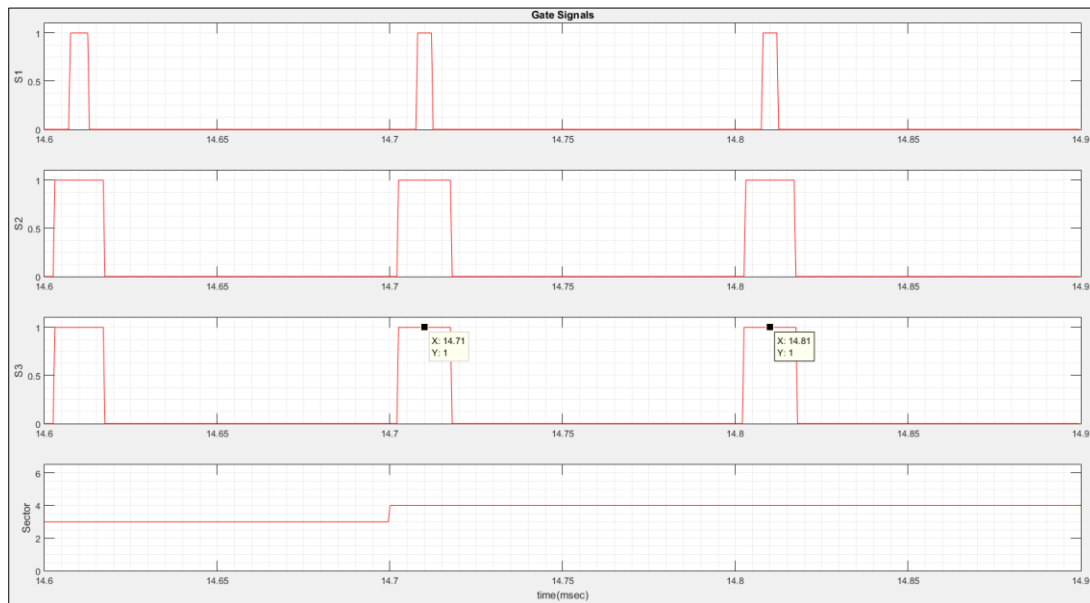


Figure 3.27. Gate signals of high side MOSFETs and sector information



4. HARDWARE DESIGN

The Hardware configuration which is seen Figure 4.1 are designed for position control of 3-phase BLDC Motor.

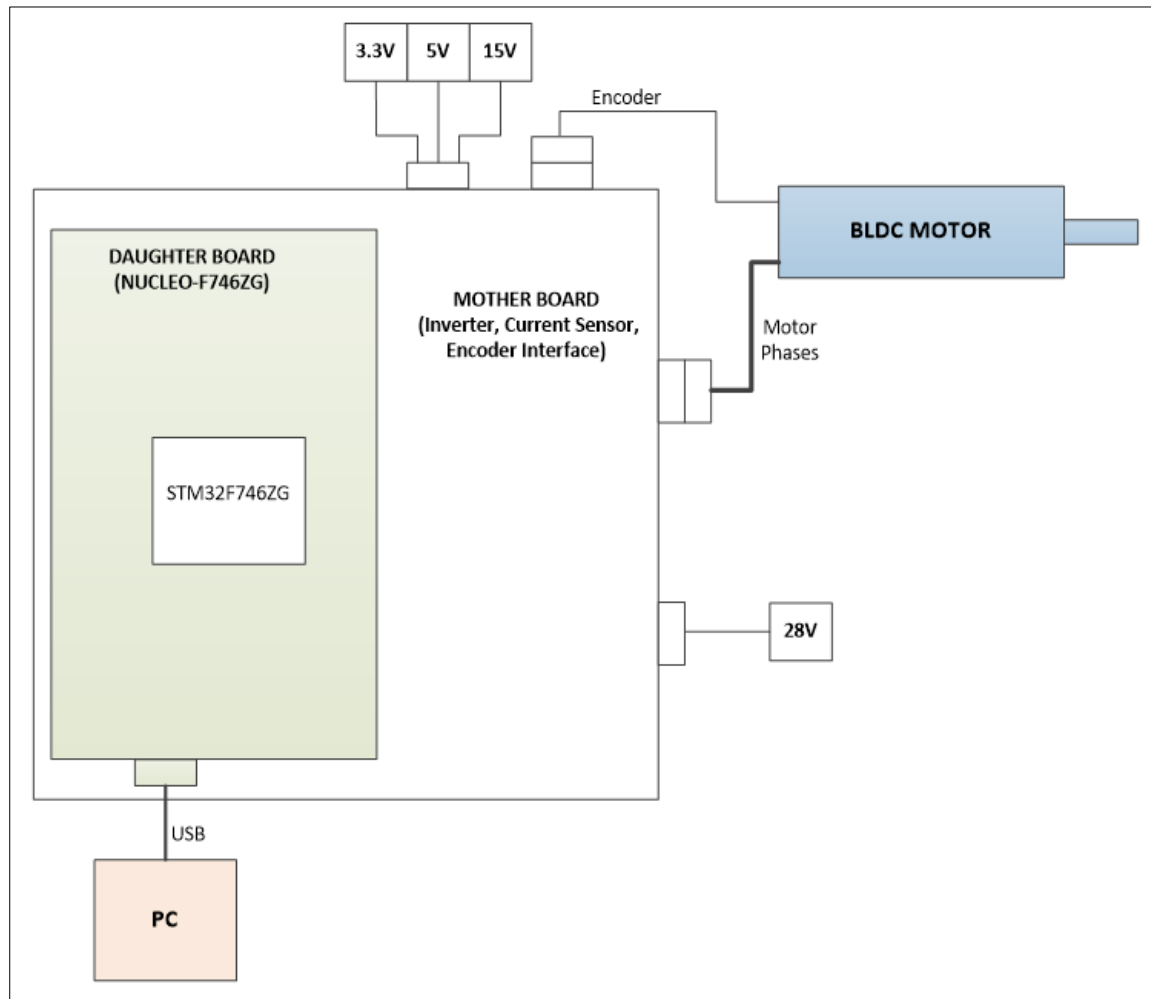


Figure 4.1. Hardware configuration

4.1. NUCLEO-F746ZG Development Board (Daughter Board)

Since SVPWM based FOC method requires very high processing power, the microcontroller to be used must have high clock frequency. As a result of researches, the product of the ST Microelectronics Company, 32 bits floating-point type ARM based CORTEX-M7 STM32F746ZG microcontroller, which has 216 MHz clock frequency, is chosen. Besides having 18 timers and 3 ADCs, it also has specific features for motor control such as incremental encoder interface, generation of complementary PWM signals.

The other main factors that play an important role in this choice are the support of the ARM library, its own HAL library and having the large number of open sources that are easily accessible on the internet.

After the choice of the microcontroller, it is decided to use the NUCLEO-F746ZG development board with STM32F746ZG instead of designing the board that consists of the microcontroller and necessary components for the microcontroller such as power block, oscillator, UART module etc.

Main features of the NUCLEO-F746ZG development board [28];

- STM32 microcontroller in LQFP144 package
- 3 user LEDs
- 2 user and reset push-buttons
- 32.768 kHz crystal oscillator
- Flexible power-supply options: ST-LINK, USB VBUS or external sources
- On-board ST-LINK debugger/programmer with USB re-enumeration capability: mass storage, Virtual COM port and debug port
- Comprehensive free software libraries and examples available with the STM32Cube MCU Package
- Support of a wide choice of Integrated Development Environments (IDEs) including IAR™, Keil® and GCC-based IDEs
- External or internal SMPS to generate V_{core} logic supply
- Ethernet compliant with IEEE-802.3-2002
- USB OTG full speed or device only
- Board connectors:
 - USB with Micro-AB or USB Type-C™
 - Ethernet RJ45
 - SWD
 - ST Zio expansion connector including Arduino™ Uno V3
 - ST morpho expansion connector
- Arm® Mbed Enabled™ compliant

In order to access to the 144 pins of the microcontroller, 2 x (2x36) pins female header were soldered to the development board.

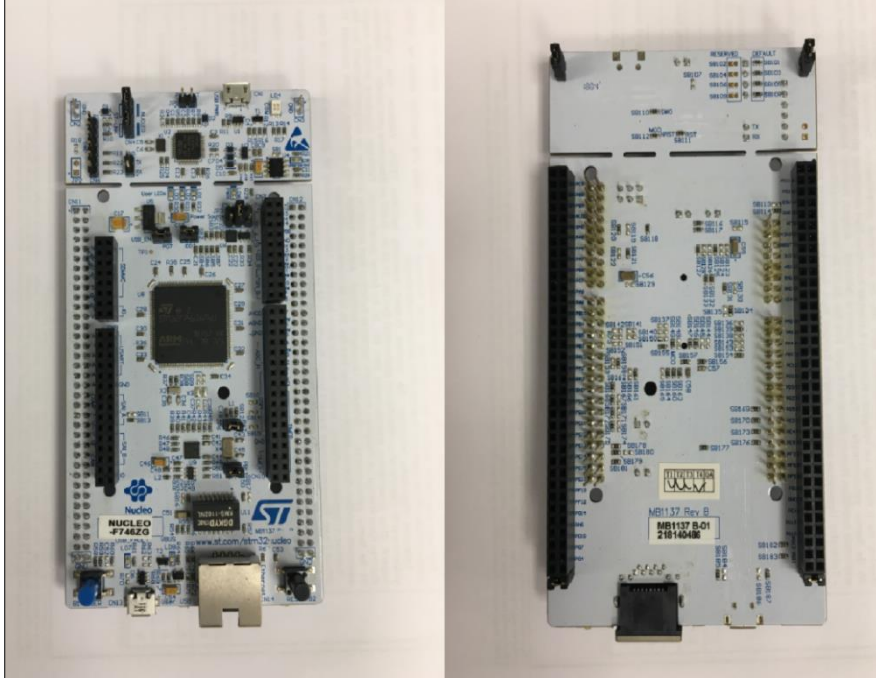


Figure 4.2. NUCLEO-F746ZG development board

4.2. Motor Driver Board (Mother Board)

While NUCLEO-F746ZG development board is used as the controller board, the motor driver board is designed within the scope of the thesis. The designed motor driver board mainly consists of driver electronics circuits, current sensors and encoder interface circuit. The schematics and printed circuit board of the motor driver board are drawn on Cadence.

If we examine the design of the board in detail;

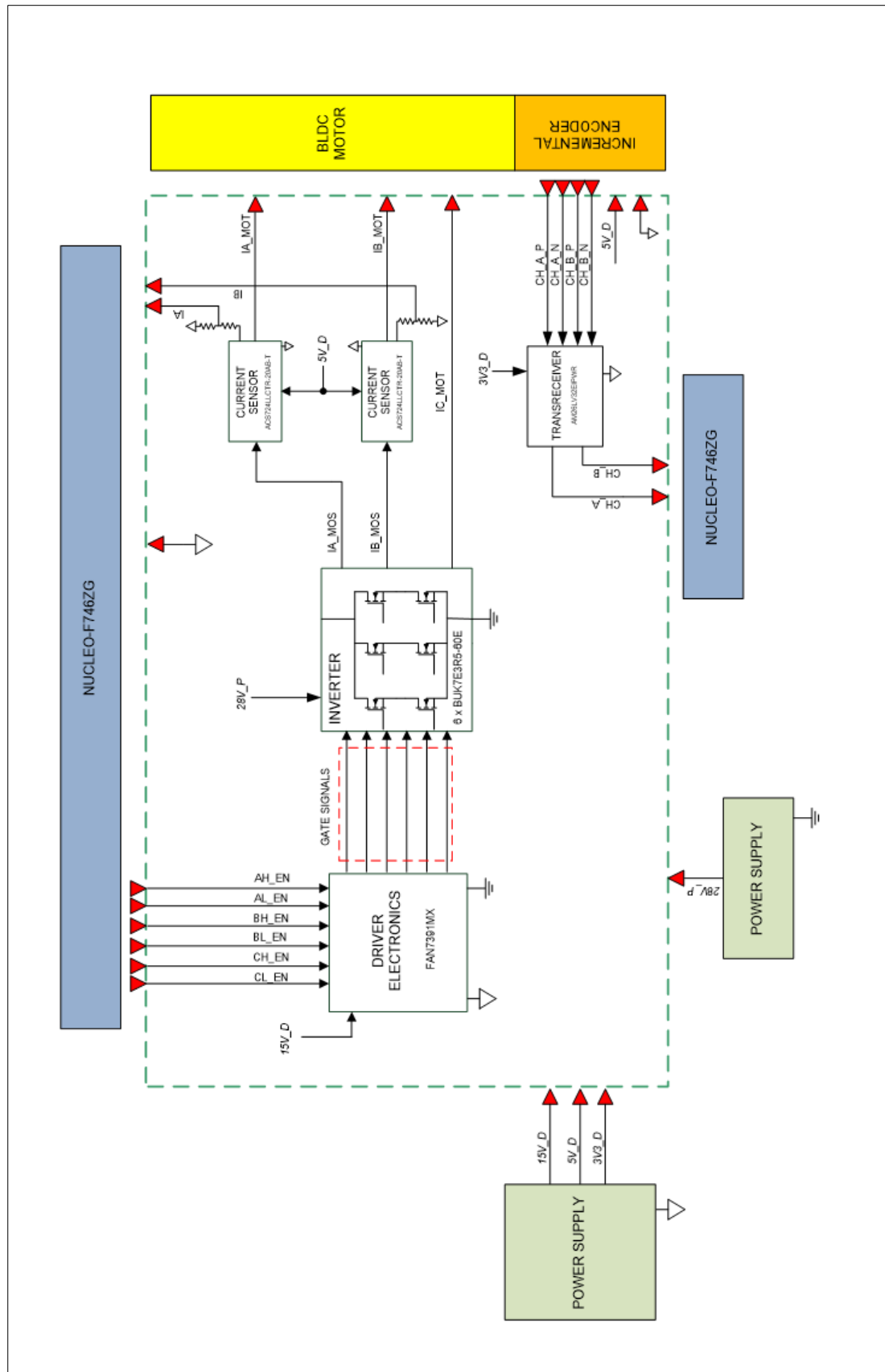


Figure 4.3. Block diagram of the driver board

To make design and production process of board simpler, all the power requirements are met directly from power supplies. While 3,3 V, 5 V and 15 V are digital ground referenced, 28 V BUS voltage which is required for BLDC Motor is power ground referenced. Therefore, two different ground references are used on board.

The switching signals generated by the microcontroller are sent into the FAN7391MX which can drive low and high side MOSFET. This integrated circuit utilises the bootstrap topology for driving the high side MOSFET. This IC is preferred as a gate driver in this thesis, although it is not normally Half-Bridge driver, because having the input noise filter and merging two different ground within itself. Since the Half-Bridge driver ICs are specialized to drive high and low side MOSFETs at the same time, they can either add dead-time to the driver signals themselves to prevent the shoot-through phenomenon. In addition, the duration of dead-time can be adjusted via the value of passive element which is connected to the related pin of the IC. The dead-time must be provided by software because of FAN7391MX does not have this feature. The usage of the single IC without any ground isolation made easier the design process of both schematic and PCB of the driver electronics.

In order to improve the noise immunity, the incremental encoder which is used in the thesis generates differential output signals. Because of the encoder has to be supplied by 5 V, the outputs are 0 and 5 V as well rather than 0 and 3,3 V, which is the acceptable logic voltage range of the microcontroller. On the other hand, the encoder interface of the microcontroller is compatible with single ended signal instead of differential signal. In order to eliminate these two important handicaps, AM26LV32EIPWR transceiver IC is used. This IC can accept input signals up to 5 V magnitude, although its supply voltage is 3,3 V. In this way, differential signals magnitude of 5 V generated by the encoder are converted to the single ended signals magnitude of 3,3 V. In addition, possible data losses are prevented thanks to high bandwidth of the IC.

ACS724LLCTR-20AB-T part numbered current sensor is used to sense the motor phase currents. It offers so many advantages such as bi-directional current sensing, high bandwidth and low cost. All these advantages put ACS724LLCTR-20AB-T forward among the other current sensors. Like incremental encoder, the current sensor has to be supplied by magnitude of 5 V. For this reason, output of the current sensor is in the 0-5 V

range. The ADC which is on board the microcontroller does accept the input signals which are in the 0-3,3 V range so the output of the current sensor is not connected directly to the ADC. Instead of this, the voltage divider circuit is used to convert 5 V to the 3 V. The reason why 5 V is not directly converted to 3 V instead of 3,3 V is current sensor may generate 5,5 V as an output in error situation. If the voltage divider ratio is not adjusted properly, this erroneous output voltage violates the maximum acceptable input voltage level of the ADC and harms the ADC permanently. Since the amount of current that can be drawn from the output of the current sensor is limited, a buffer is placed near the connector to be close to the ADC. In addition, an RC filter is added to the back of the buffer in order to minimize the fluctuation of the line voltage when the ADC takes sample.

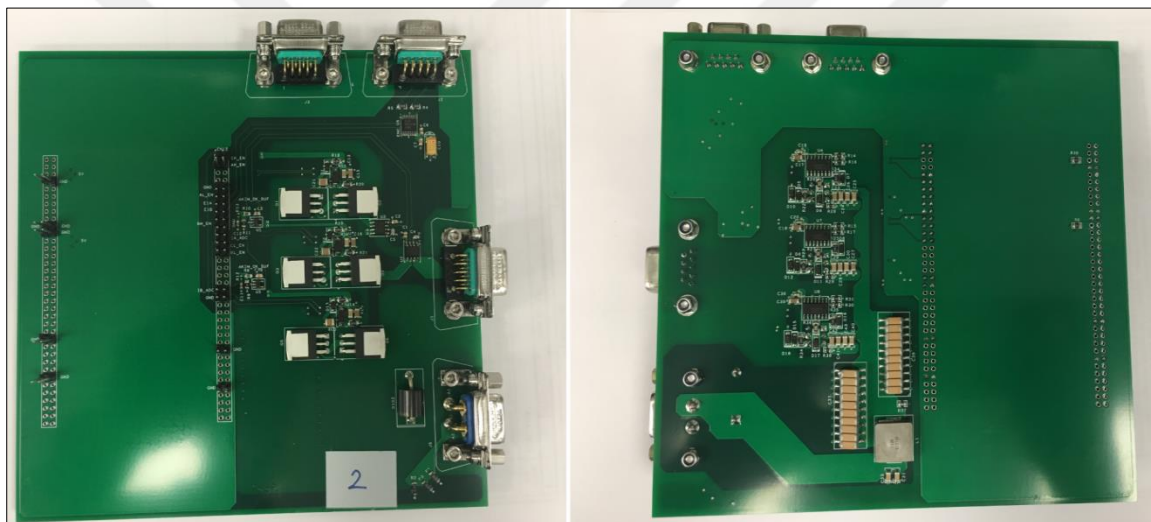


Figure 4.4. Driver board

The variations on the BUS voltage which supplies the motor phases adversely affects the performance of the BLDC Motor and therefore the performance of the controller. In order to make these variations minimum, ST205C107MAL10 part numbered turbo capacitors which can give high amount of current to the motor phases even at high frequencies, are placed to the high side MOSFETs as close as possible. In order to ensure that only DC and/or low frequency currents are drawn from the power supply, inductor is placed between the power supply and turbo capacitors. In this way, the protection of the power supply is provided.

In order to make ground continuity, the ground of the NUCLEO-F746ZG and the digital ground of the driver board are merged. Thus, offset error which can be caused by voltage difference between grounds on the signals is prevented.

The digital ground and the power ground are merged near the connector of the 28 V power supply. Thanks to this method, the voltage difference between the grounds is prevented and the high frequency motor phase currents are guaranteed to go directly to the 28 V power supply without polluting the digital ground.

In order to connect the driver board to the NUCLEO-F746ZG, the female pin headers which can be directly connected to the male pin headers on the bottom side of the NUCLEO-F746ZG, are placed on the top side of the driver board.

In PCB design, it is aimed that two different grounds should not intersect each other in any layer to prevent the noise coupling. In addition, stack up is designed properly to eliminate noise coupling and to protect noise sensitive signals especially current sensor outputs. Regarding to current and voltage constraints, lines and shapes are drawn. Finally, in order to decrease the production cost, the via in pad technique is never used and PCB is designed in 4 layers.

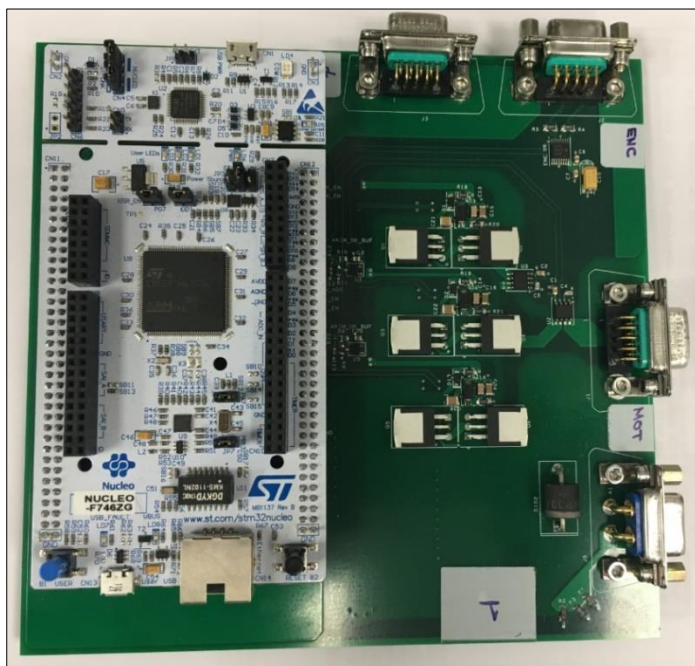


Figure 4.5. Motor driver board block



5. SOFTWARE DESIGN

STM32F746ZG microcontroller is selected as a result of researches for the implementation of the system modeled in SIMULINK.

Developing the microcontroller code is multidisciplinary study because it requires both hardware and software background. In order to learn about microcontroller's internal structure, capabilities, and how its features work, its Reference Manual must be read in detail. Starting software design without being aware of the capabilities of the microcontroller both extends the process and reduces the quality of the design.

Before developing code, since microcontroller works with serial data processing principle, being familiar to the interrupt based software is required. Since C language based code is developed for microcontroller, having at least basic knowledge about this language is highly recommended.

In this chapter, firstly a brief information about the tools used in software development is given and then the basic features of the microcontroller are examined. Finally, the software design architecture used in the thesis is explained in detail.

5.1. Software Development Tools

In software development and testing part, STM32CubeMx and Atollic True Studio which are licensed products of ST Microelectronics are preferred.

Firstly, a new project is created at STM32CubeMx. After creating the project, the microcontroller or the evaluation board has to be selected with true package type in order to start configuring the microcontroller which will be used, properly.

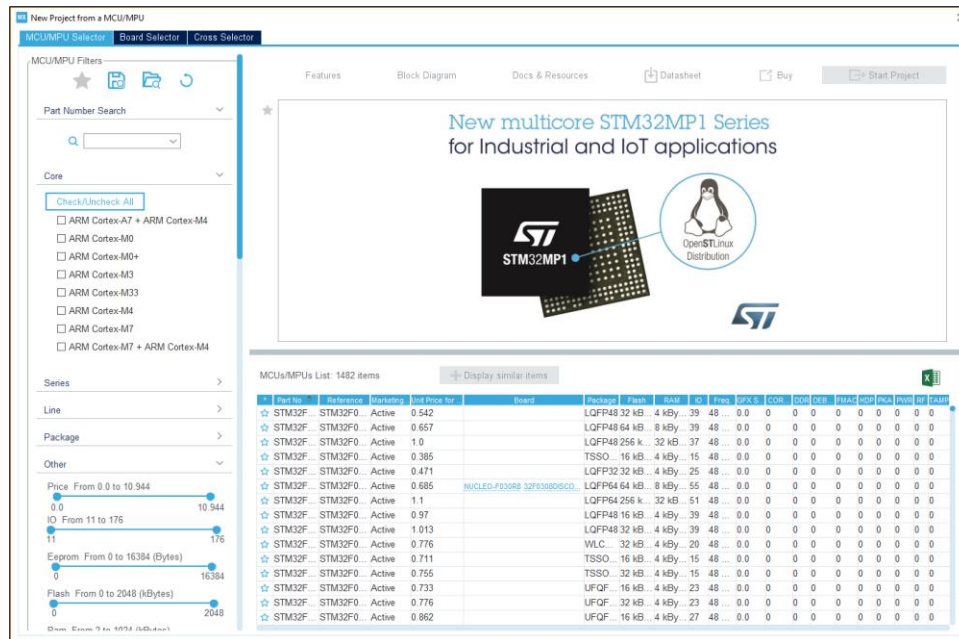


Figure 5.1. Microcontroller selection window

The pinout diagram of the selected microcontroller is displayed according to the selected package type. Almost every pin of the microcontroller can be easily reached and configured with this tool. The uneditable pins are dedicated to the special tasks namely, power and ground connections. Thanks to this feature, I/O, timers and ADCs are all easily configured via CubeMx.

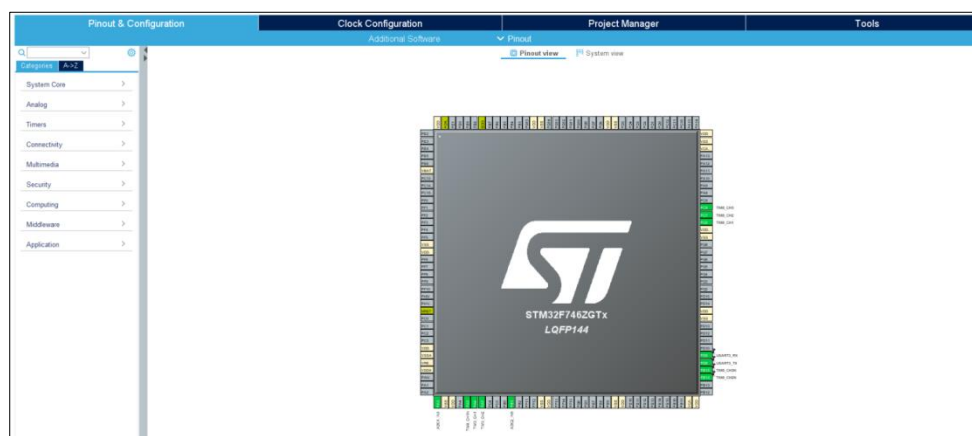


Figure 5.2. STM32F746ZG pinout diagram

One of the biggest problem when working with IC chips such as microcontroller, FPGA etc. is clock management. The desired clock/operating frequencies are written to the related boxes then clock configuration of the microcontroller is done automatically by the

CubeMx. In case of improper clock configurations, this tool gives alert to prevent the clock related errors.

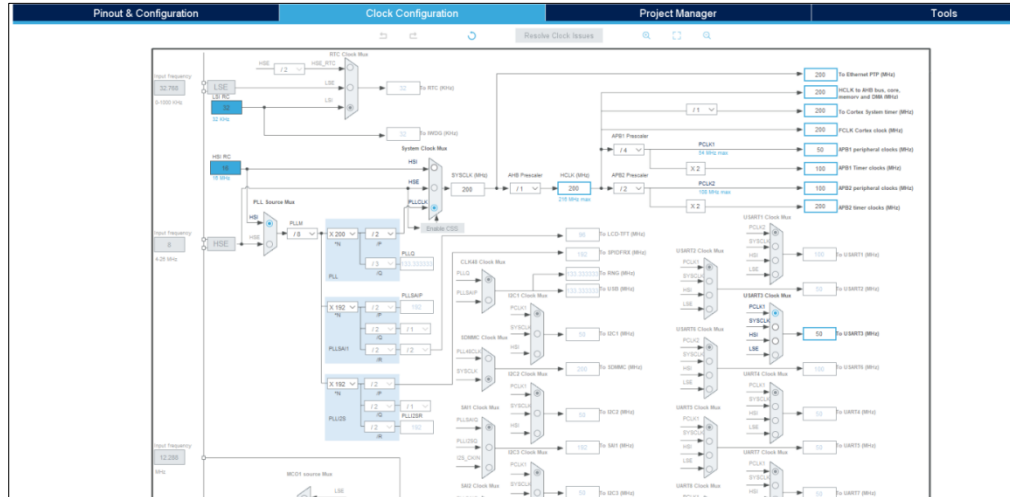


Figure 5.3. Clock configuration window

All this configuration can be converted into the proper source code by selecting desired IDE via this tool. In our case, we selected Atollic True Studio as IDE.

Project	Project Settings Project Name deneme_yunus Project Location C:\Users\Lenovo\Desktop\stm32_exercises
Code Generator	Application Structure Basic v ☐ Do not generate the main() Toolchain Folder Location C:\Users\Lenovo\Desktop\stm32_exercises\deneme_yunus\ Toolchain / IDE TrueSTUDIO v ☒ Generate Under Root
Advanced Settings	Linker Settings Minimum Heap Size 0x200 Minimum Stack Size 0x400
	Mcu and Firmware Package Mcu Reference STM32F746ZGTx Firmware Package Name and Version STM32Cube_FW_F7 V1.15.0 ☒ Use Default Firmware Location C:\Users\Lenovo\STM32Cube\Repository\STM32Cube_FW_F7_V1.15.0 Browse

Figure 5.4. Code generation window

The functional code is developed in Atollic True Studio on the generated source code. Since STM32 is ARM based microcontroller, ready to use ARM libraries are used in code. In addition, own libraries, HAL, of the ST are also benefited from.

The NUCLEO board connects to the PC with USB cable and thanks to this cable its power requirement, 5 V, is met by PC. The compiled code is sent to the microcontroller via ST-LINK. NUCLEO board does not need any other cable for this process, it uses the same USB cable. Also the code on the microcontroller can be run in debug mode via this cable.

5.2. Important Features of Microcontroller

The commonly used features of microcontroller in design are examined in detail to better understand the software system architecture [29].

5.2.1. ADC

There are 3 independent ADCs on the microcontroller. Each of them have 16 channels that can be reached from the connector on the board. These 16 channels, are connected to the same SAR ADC via a multiplexer. For this reason, two different channels of same ADC cannot be used same time. Although an external voltage source could be connected to the ADC as reference voltage, its internal reference voltage magnitude of 3,3 V is preferred. The main features of ADC are as follows.

The operating frequency of ADC is PCLK2 which is derived from the main clock frequency, HCLK, with help of prescaler instead of the main clock frequency.

ADCs can be configured at different resolution options such as 6, 8, 10 and 12 bits. In order to obtain more resolution, in other words to read data with high precision, ADCs are configured as 12 bits. As expected, this value affects the conversion time of the ADC as well.

The sampling time of the ADCs can be adjusted to the certain values. These values are 3, 15, 28, 56, 84, 112, 144 and 480, respectively. This value is adjusted as 28 in the design. As the name implies, this value affects the sampling time of the ADC.

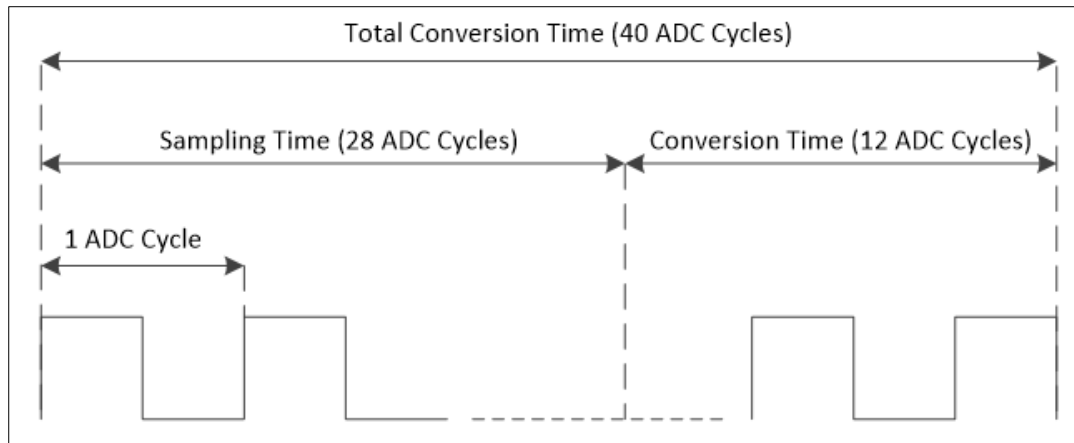


Figure 5.5. A total conversion period of ADC

A total conversion period of the ADC consists of two main parts namely, sampling time and data conversion time. As expected, in every single ADC cycle, just 1 bit process can be performed. In Figure 5.5, the values which are written inside the parentheses refer the values which are used in the design. The block diagram of single ADC is shown in Figure 5.6.

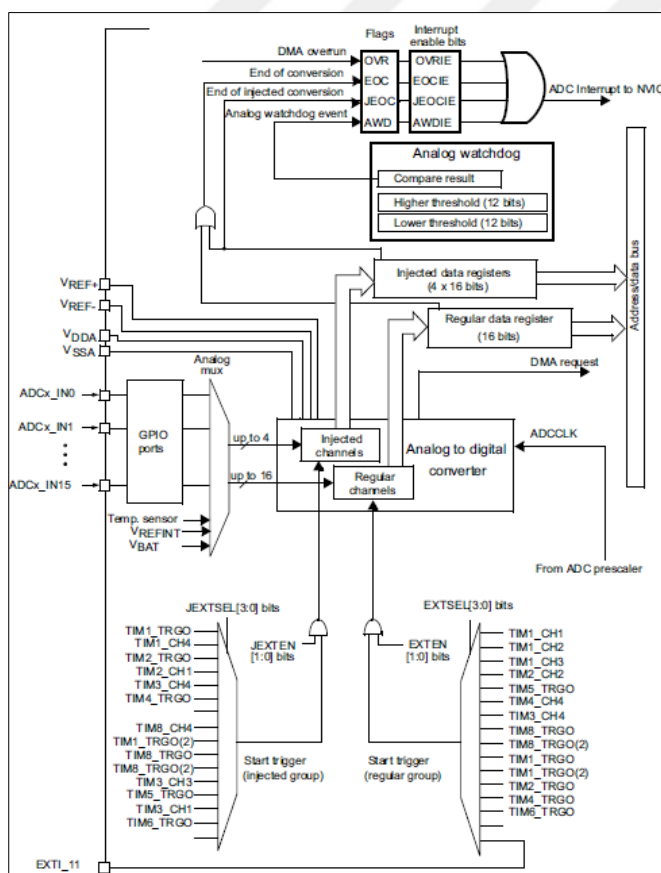


Figure 5.6. Block diagram of single ADC [29]

Rather than mentioning all the features of ADC, the features used in the design are explained below.

Since the current value of the related motor phase is calculated only once in each current controller loop, continuous conversion or multi conversion features of the ADC are not used. Since only one channel of the each ADC is being used actively, scan mode feature of the ADC also is disabled. Instead of them, single conversion mode is preferred. In this mode, ADC works only one time and waits new trigger signal to start new conversion.

Instead of forcing the ADC to make conversion instantly, we use an external trigger that allows us to run the ADC at any time. There are internal trigger lines between the ADCs and some special timers. Each of these single trigger lines could be active provided that the happening of the own special events. In the design, OC4REF signal which is generated by 4th channel of the TIM8 is used to trigger the ADC. This signal is shown in Figure 5.6 with the name of TIM8_TRGO(2).

Thanks to the Direct Memory Access feature, while the microcontroller is busy with another task, ADC data can be read via internal special data buses. In this way, the efficiency of the microcontroller is increased as well.

As ADCs are worked in interrupt mode instead of polling mode, the microcontroller is utilized effectively. If it is wanted, when the conversion process of the single or the multi ADC has ended, the interrupt request can be generated. The converted value which is written to the data register of the ADC can be read with this interrupt request.

Since there are two current sensors in the system, Dual Mode feature of the ADC is used. Dual Mode is divided into several subgroups. Dual Regular Simultaneous Mode which meets our requirements is preferred in our design. In this mode, Master ADC, ADC1, is triggered with the external event generated by timer. Same trigger signal is delivered by Master ADC to the Slave ADC, ADC2, immediately.

These two ADCs start to take sample simultaneously thanks to this mode. The consistency of the transformations, Park and Clarke Transformations, is increased and the performance of the current controller is maximized thanks to the sampling feature in the same time interval.

In this mode, outputs of the ADC are read via DMA. Outputs of the ADCs are stored to 32 bits ADC_CDR register. While first 16 bits are allocated to store the output of the ADC1, second 16 bits are allocated for the output of the ADC2. Whenever both ADCs end conversion of data, EOC event occurs. The interrupt request which means that both ADCs have completed conversion process successfully, is generated with this EOC event. ADC Interrupt Routine which is one of the most important interrupt routine in the main program is generated with this interrupt request.

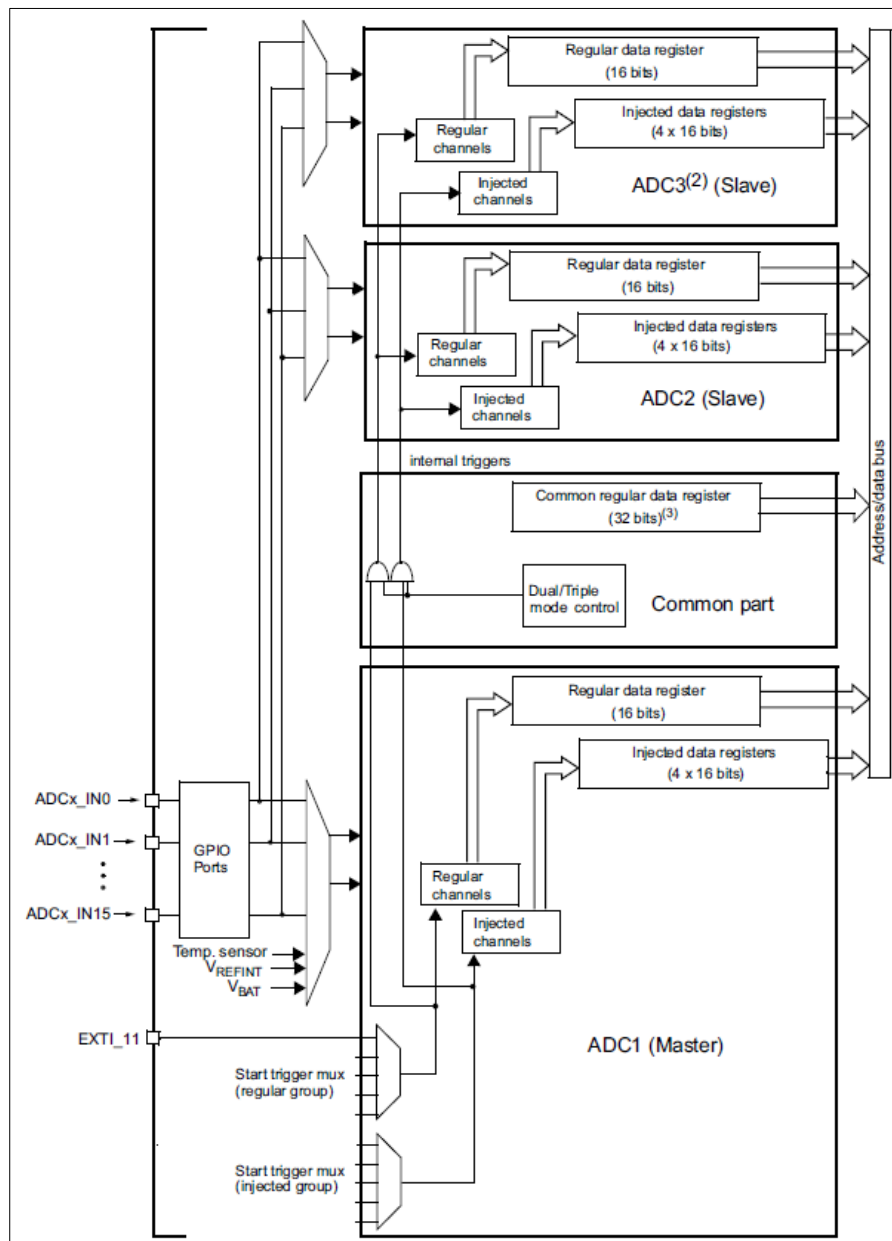


Figure 5.7. Block diagram of multi ADC [29]

5.2.2. Timer

Timers on the microcontroller are divided into 4 groups as “Advanced-Control Timers”, “General Purpose Timers”, “Basic Timers” and “Low Power Timers”. Since only “Advanced-Control Timers” and “General Purpose Timers” are actively used in design, these two kinds of timer are going to be examined.

"Advanced-Control Timers" and "General Purpose Timers" are completely independent of each other and do not share any resource but, on the other hand, they can be synchronized each other.

Timers can be used for general purposes such as measuring the length of the input signal (input capture) or generating an output signal (output compare, PWM).

While "General Purpose Timers" have 4 channels most, "Advanced Control Timers" have 6 channels. We know that 6 PWM signals are necessary for commutation of 3 Phase BLDC Motor. As mentioned in the previous paragraph, while both of them can generate PWM signals ("Edge-aligned mode" or "Center-aligned mode"), only "Advanced-Control Timers" can generate complementary PWM signal. In addition, dead-time can be added to these complementary PWM signals. "Advanced-Control Timers" become ideal option for commutation of the 3 Phase BLDC Motor thanks to these features.

Both these timers include several common features that are specialized for motor control such as "Encoder Mode" and "Hall Sensor Mode". This not only makes the code simpler, but also reduces the load on the microcontroller.

Interrupt/DMA generation features that make more efficient the performance of the microcontroller are available in these two type of timers. Interrupt/DMA generation is provided by the following events;

- Update: counter overflow/underflow, counter initialization (by software or internal/external trigger)
- Trigger event (counter start, stop, initialization or count by internal/external trigger)
- Input capture

- Output compare

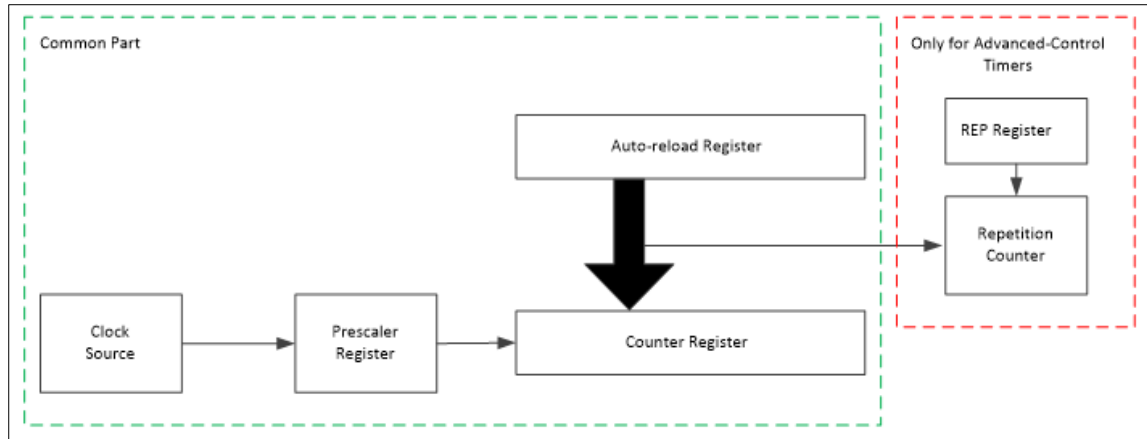


Figure 5.8. Time base unit of timer

By examining the Time Base Unit which is core mechanism of the timer, we can understand the working principle of timers better. For this unit, the distinct difference between these two type timers is Repetition Counter Register.

The clock frequency of the timer is adjusted with prescaler block. The value of 16 bits Prescaler Register can be any value from 0 to 65535. The clock frequency of the timer is obtained with following formula;

$$\text{Clock Frequency of Timer} = \frac{\text{Main Clock Frequency}}{(1 + \text{Prescaler})} \quad (5.1)$$

The Counter is capable of up-counting, down-counting and up/down-counting. While TIM2 and TIM5 from "General Purpose Timers" have 32 bits Auto-Reload Register, the rest of them have 16 bits ARR like "Advanced Control Timers". This value determine the maximum value that counter can be. In up-counting mode, timer starts to count from 0 and when counter reaches the ARR value, it returns to 0 again. In down-counting mode, timer starts to count from ARR value and when counter reaches the 0, it returns to ARR value again. The period of timers that works in up-counting and down-counting mode is obtained with following formula.

$$\text{Period} = \frac{(1 + \text{Prescaler})}{\text{Main Clock Frequency}} \times (\text{ARR} + 1) \quad (5.2)$$

In Center Aligned (Up/Down Counting) Mode, the direction of the counter changes whenever counter value equals to the ARR or 0. In this mode, the period of the timer is calculated by the following formula.

$$Period = \frac{(1+Prescaler)}{Main\ Clock\ Frequency} \times (2 \times (ARR + 1)) \quad (5.3)$$

As can be noticed, period of timer is doubled for same values in Center Aligned Mode.

As can be seen from Figure 5.8, there is also Repetition Counter Register in the "Advanced Control Timers". Whenever the counter value overflows or underflows, the Update Event is generated. Actually, this event is generated only when the value of the Repetition Counter equals to 0. The value of Repetition Counter is decremented by one if any of the following conditions occur;

- At each counter overflow in upcounting mode,
- At each counter underflow in downcounting mode,
- At each counter overflow and at each counter underflow in center-aligned mode.

If we assume value of the Repetition Counter is N then occurrence of the every (N+1)th overflow or underflow condition, Update Event is generated.

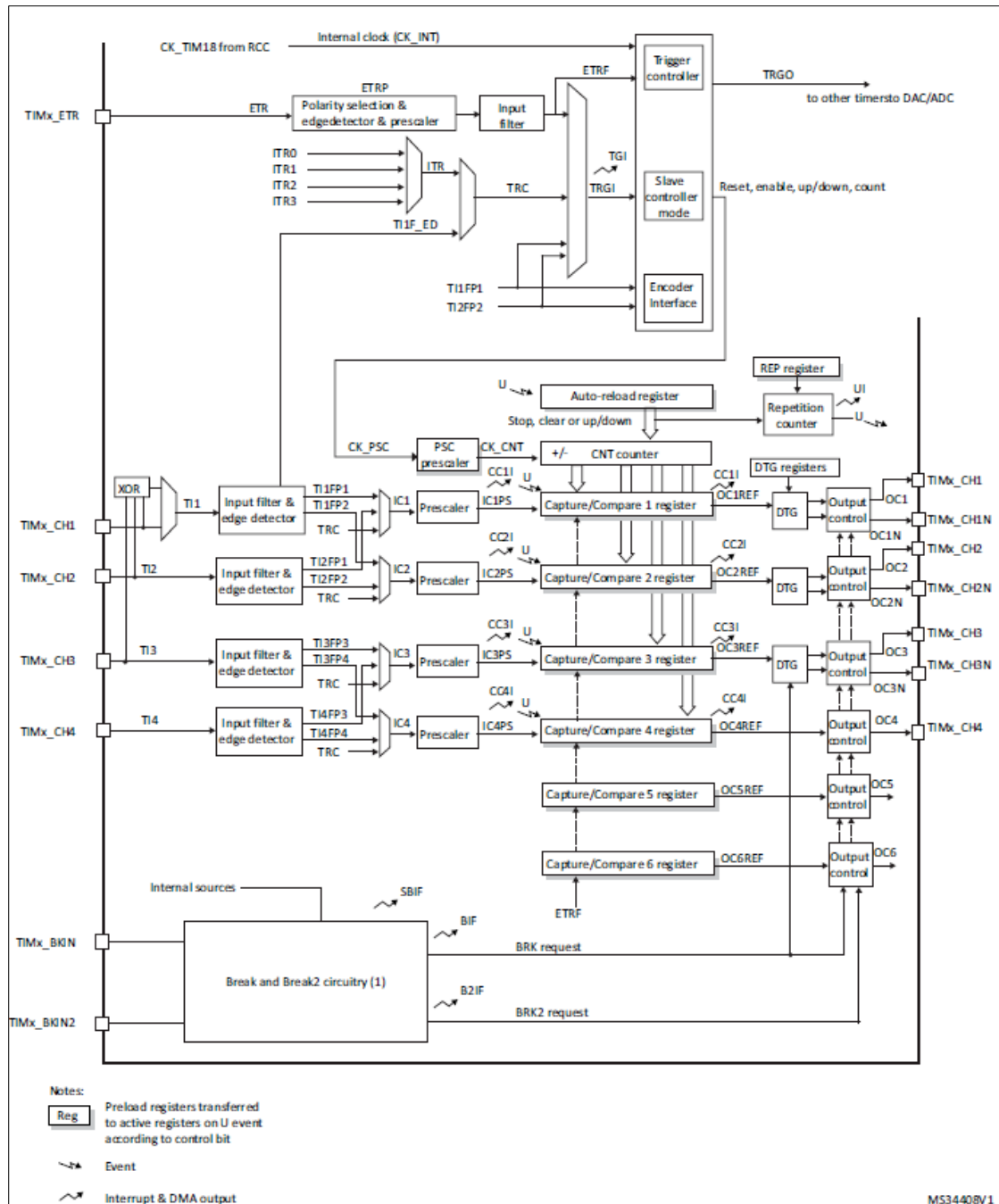


Figure 5.9. Block diagram of advanced control timers [29]

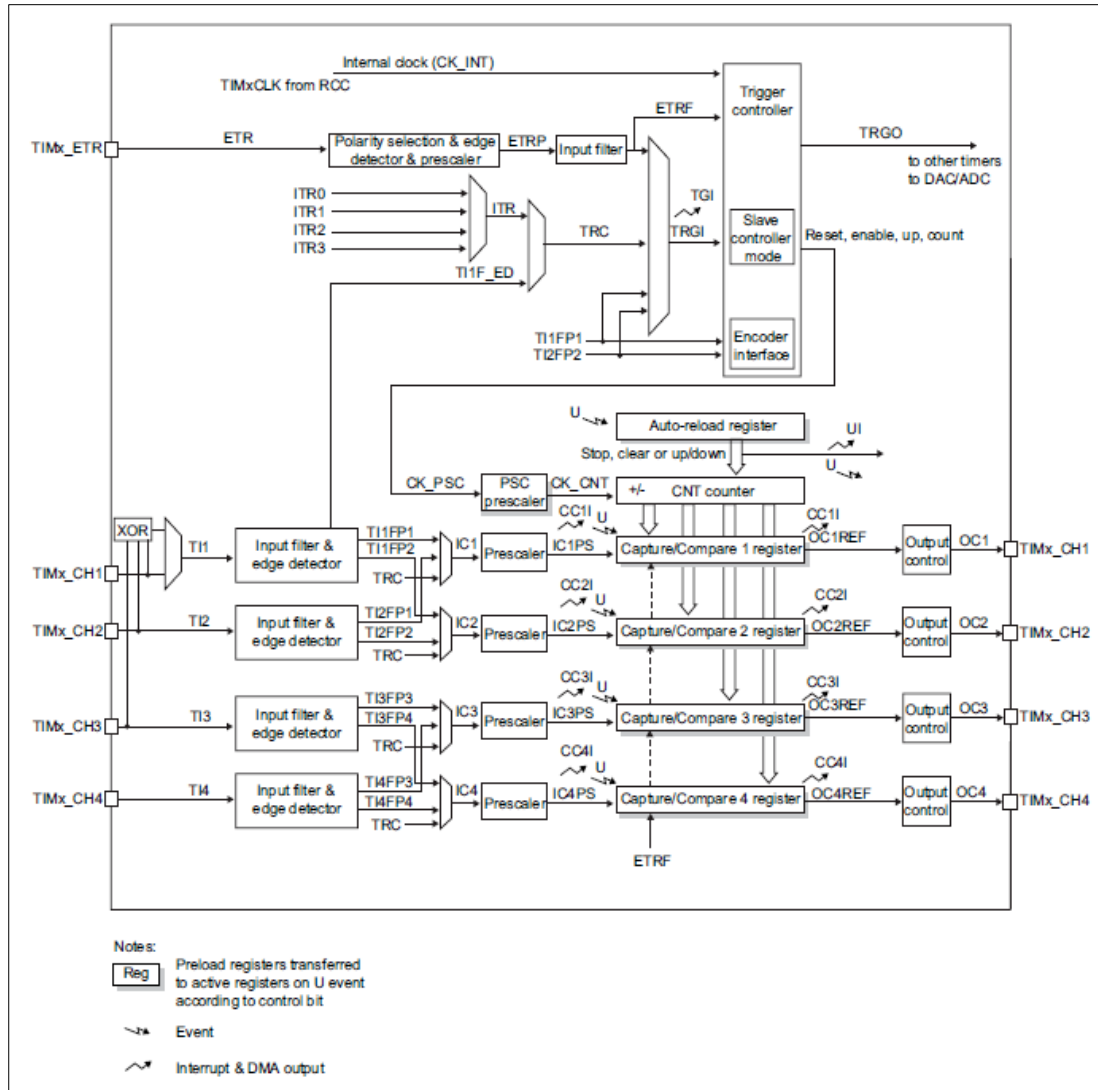


Figure 5.10. Block diagram of general purpose timers [29]

Encoder mode

Since both "Advanced-Control Timers" and "General Purpose Timers" have encoder mode feature, we prefer to use one of the "General Purpose Timers" for this task instead of "Advanced-Control Timer".

This mode offers two different options such as Encoding (x2) and Encoding (x4) at processing of encoder signals. In Encoding (x2) type, only edges of the channel A or B are counted and resolution of encoder is doubled. In Encoding (x4) type, both edges of the channel A and B are counted and resolution of encoder is quadrupled.

In this mode, like Center Aligned Mode the counter counts upward and downward. The direction of the counter is obtained by DIR bit. While DIR = 0 refers up-counting, DIR = 1 refers down-counting. This bit is recalculated each time the edges of channel A and B are counted.

The value which will be written to the ARR register changes depending on the Encoding (x2) and Encoding (x4) for the same incremental encoder. The value of the counter can change both upward and downward in the range of 0 to ARR value. For this reason, the value which is written to the ARR register is crucial.

The value which will be written to the ARR register in Encoding (x2) type;

$$\text{Value in ARR} = (2 \times (\text{Number of Pulses Generated by Single Channel})) - 1 \quad (5.4)$$

The value which will be written to the ARR register in Encoding (x4) type;

$$\text{Value in ARR} = (4 \times (\text{Number of Pulses Generated by Single Channel})) - 1 \quad (5.5)$$

If this value is not entered correctly, since it cannot be understood how much the rotor actually rotates, the calculated position values will be inaccurate..

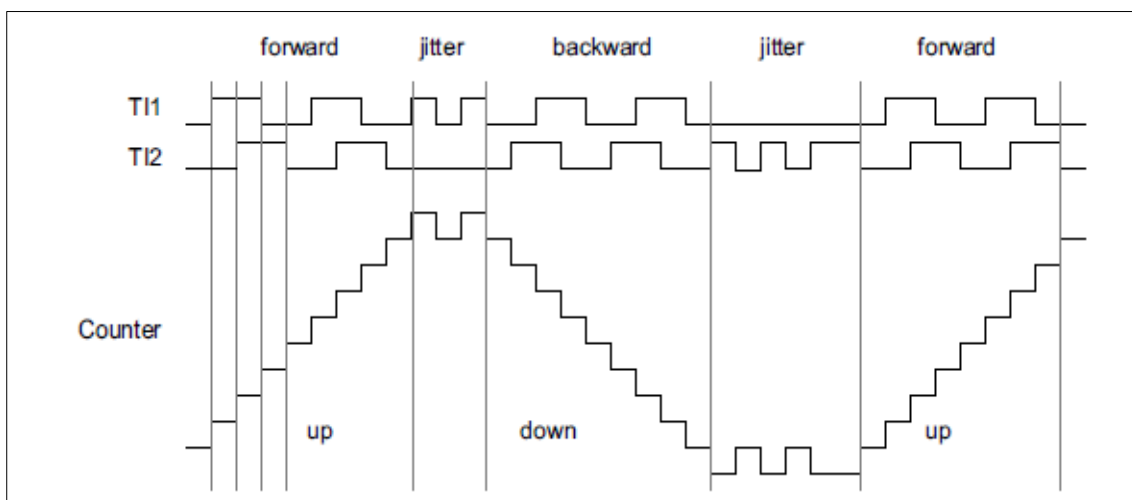


Figure 5.11. Example of counter operation in encoder interface mode [29]

In addition, the encoder mode is only compatible with the incremental encoder which generates single-ended signal. Unless the transreceiver IC or the circuit that converts

differential signal to single-ended signal is added to back end of the incremental encoder which generates differential signal, the output of the incremental encoder cannot be read correctly.

PWM generation

Totally, 6 control signals are required to drive a 3 Phase BLDC Motor. Since we know that each of the signals are generated from the different channel of the same timer, the timer which will be used should have 6 channels at least. For this reason, one of the "Advanced Control Timers", TIM8, is used for PWM generation.

The microcontroller can generate three kinds of PWM signals namely, right aligned, left aligned and center aligned. According to our requirements, Center Aligned Mode PWM generation is selected to minimize the ripple on the current and torque.

The OCxREF, which is the reference PWM signal, is obtained by comparison of the value of counter with the value which is written to the CCR register of the timer. The polarity of this signal changes depending on whether PWM1 mode or PWM2 mode is used.

- In PWM1 mode, while the value of the counter increases, in other words in up-counting mode, OCxREF reference signal equals to logic high under the condition $TIMx_CCRx > TIMx_CNT$, otherwise equals to logic low. While the value of the counter decreases, in other words in down-counting mode, OCxREF reference signal equals to logic high under the condition $TIMx_CCRx \leq TIMx_CNT$, otherwise logic equals to low.

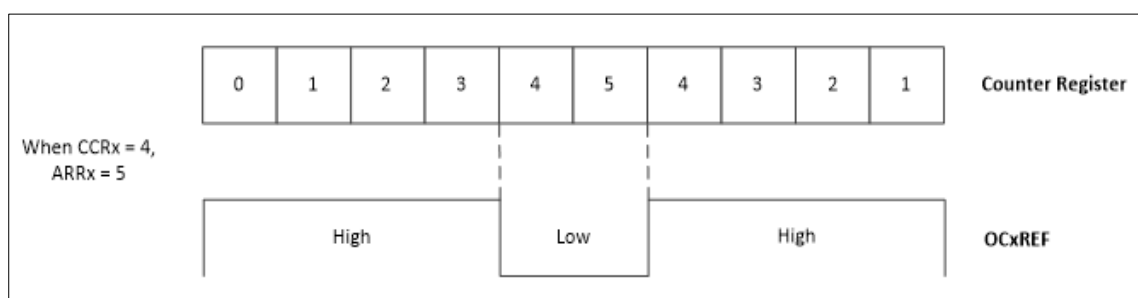


Figure 5.12. OCxREF reference signal for PWM1 mode

- In PWM2 mode, while the value of the counter increases, in other words in up-counting mode, OCxREF reference signal equals to logic low under the condition $TIMx_CCRx > TIMx_CNT$, otherwise equals to logic high. While the value of the counter decreases, in other words in down-counting mode, OCxREF reference signal equals to logic low under the condition $TIMx_CCRx \leq TIMx_CNT$, otherwise logic equals to high.

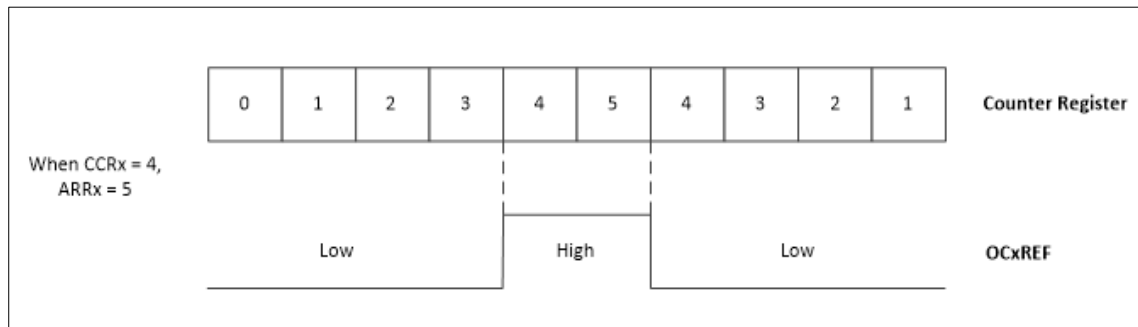


Figure 5.13. OCxREF reference signal for PWM2 mode

In PWM signal generation, since we want that all high side MOSFETs are on-state in the middle of the period, PWM2 mode is preferred.

Then duty-cycle is calculated as follows;

$$Duty\ Cycle = \frac{CCRx}{ARRx} \quad (5.6)$$

Two of the total six control signals to be generated are sent to the MOSFET's of the Phase A, two of them to the MOSFET's of the Phase B and two of them to the MOSFET's of the Phase C. So then, the control signals of each phases must be complementary among themselves. Thanks to the microcontroller's complementary output feature, desired control signals can be obtained. The resulting reference signals are called as OCx and OCxN.

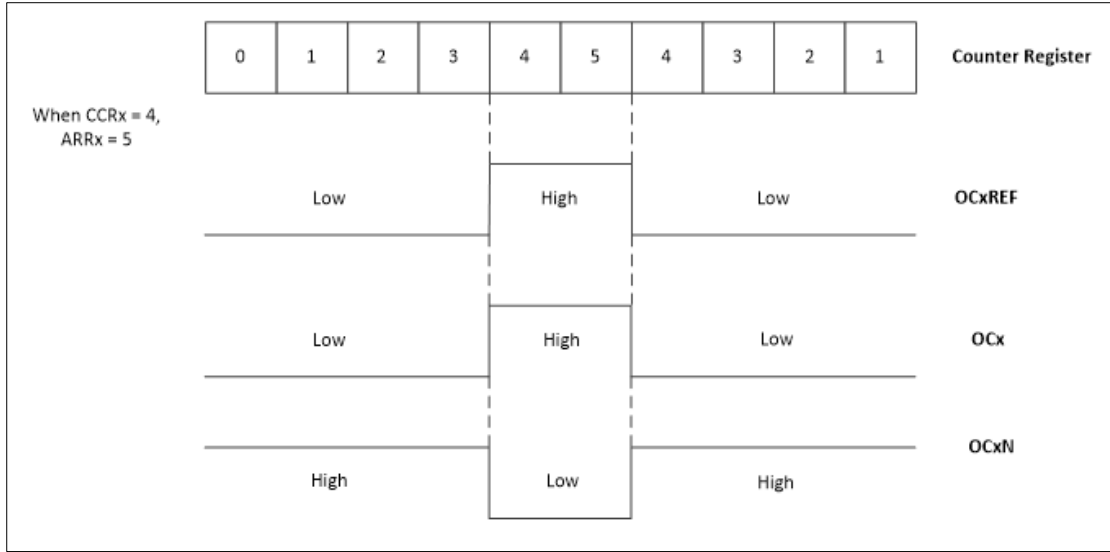


Figure 5.14. OCx and OCxN reference signals for PWM2 mode

As shown in Figure 5.14, the control signals, which are complement of each other, are obtained. However, if these signals are sent to the gates of the MOSFETs' like in Figure 5.14, shoot-through phenomenon occurs since both MOSFETs of the same phase are on-state at the same time. To avoid this phenomenon, it is necessary to add dead-time to the control signals.

1 byte Dead-Time Generator, DTG[7:0], determines the duration of the dead-time. The microcontroller adds dead-time to the control signals according to the following formulas:

$$DTG[7:5] = 0xx \rightarrow DT = DTG[7:0] \times t_{dtg} \text{ with } t_{dtg} = t_{DTS} \quad (5.7)$$

$$DTG[7:5] = 10x \rightarrow DT = (64 + DTG[5:0]) \times t_{dtg} \text{ with } t_{dtg} = 2 \times t_{DTS} \quad (5.8)$$

$$DTG[7:5] = 11x \rightarrow DT = (32 + DTG[4:0]) \times t_{dtg} \text{ with } t_{dtg} = 8 \times t_{DTS} \quad (5.9)$$

$$DTG[7:5] = 111 \rightarrow DT = (32 + DTG[4:0]) \times t_{dtg} \text{ with } t_{dtg} = 16 \times t_{DTS} \quad (5.10)$$

where, t_{DTS} : main clock frequency

This value is entered as 60 in the code. The binary equivalent of 60 is 00111100. In this case, DTG becomes [7: 5] = 001.

$$DT = DTG[7:0] \times t_{dtg} = DTG[7:0] \times t_{DTS} = 60 \times (5 \times 10^{-9}) = 300ns \quad (5.11)$$

The polarity of the OCx and OcxF signals is determined by the CCxP and CCxPN bits, respectively. When these values are equal to 0, it means active high. When the related bits are set to active high, the generated OCx and OcxF signals is as follows according to the OCxREF reference signal.

- The OCx output signal is the same as the reference signal except for the rising edge, which is delayed relative to the reference rising edge.
- The OCxF output signal is the opposite of the reference signal except for the rising edge, which is delayed relative to the reference falling edge.

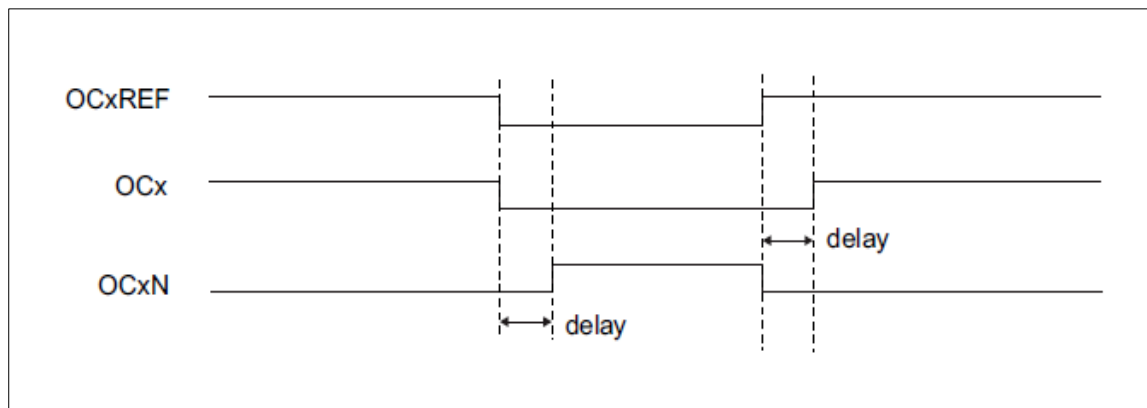


Figure 5.15. Insertion of dead-time for PWM2 mode [29]

In Figure 5.15, control signals with dead-time are shown.

In our design, the OCx signal is adjusted parallel to the OCxREF signal for ease of use.

If the delay is greater than the width of the active output (OCx or OCxF) then the corresponding pulse is not generated.

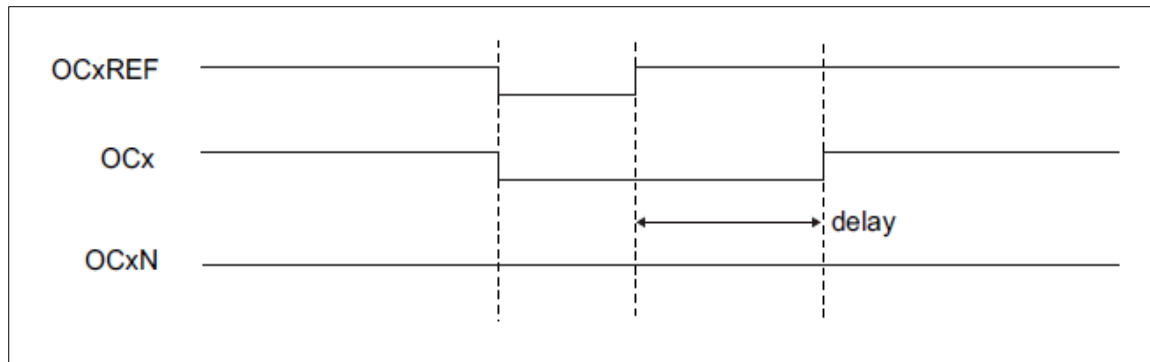


Figure 5.16. Dead-time waveforms with delay greater than the negative pulse [29]

Timer synchronization

Some of the timers are linked together via special internal lines for timer synchronization. All these timers which can be synchronized have several trigger inputs and outputs. They can be synchronized in several modes, namely Reset mode, Gated mode and Trigger mode.

When TIMX is configured as master, TRGO signal, which is generated by TIMX, can be sensed as internal trigger signal by the other timers. To sense this signal, slave timers have to be configured properly. The following signals can be used as trigger output signals;

- Reset
- Enable
- Update
- Compare Pulse
- OC1REF
- OC2REF
- OC3REF
- OC4REF

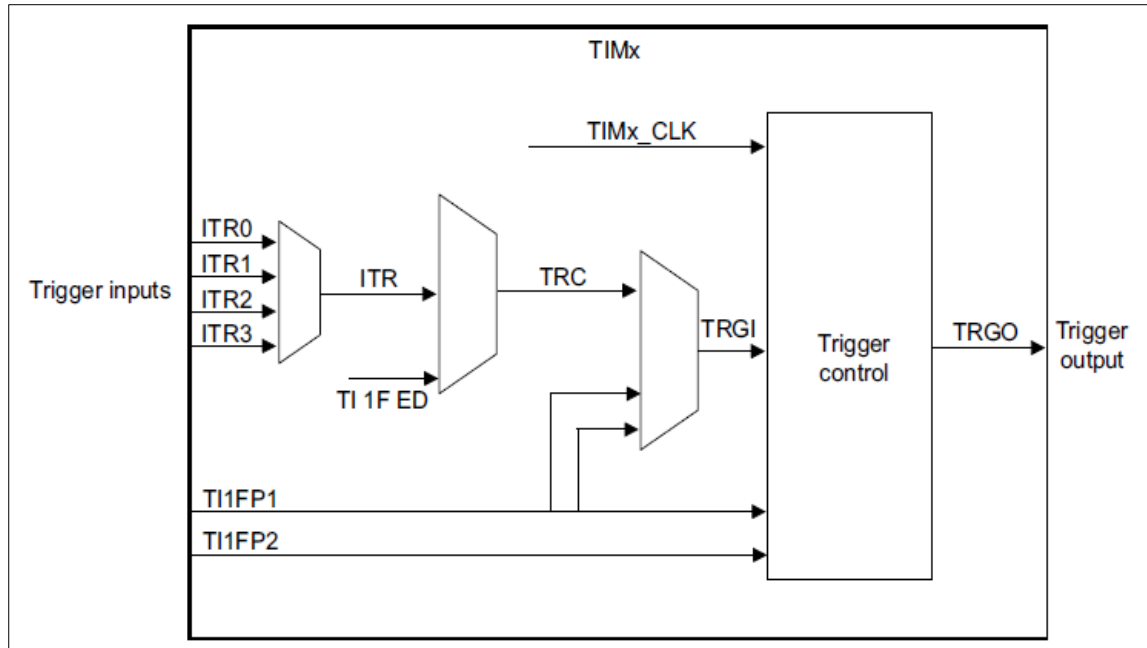


Figure 5.17. Master/slave controller unit of timer [29]

Since Gated mode is used as the slave mode in the thesis, only this configuration will be examined.

Although TIM8 generates the PWM signals, the interrupt request is generated when the counter both overflows and underflows. While in the interrupt routine, which is generated by underflow situation, position and speed controllers are performed, there is no activity inside the interrupt routine which is generated by overflow situation. Moreover, this resulting interrupt request blocks the sampling processes of the ADCs. For this reason, a timer is set that would work synchronously to TIM8 and generates the Update Event only once during the period. However, as the possible time delays between the two timers would reduce the performance of the controllers, arrangements are made to ensure the synchronous operation of the two timers.

TIM2 is configured as master timer and its operating frequency is adjusted to the 10 kHz. "Enable" signal is used as TRGO signal. In this way, the trigger signal is sent to the slave timer as soon as TIM2 is enabled.

TIM8 is configured as slave timer and its operating frequency is adjusted to the 10 kHz too. In addition, trigger source is selected as ITR1 signal and slave mod is configured as gated mode.

Whenever TIM2 is activated then TIM8 is also activated at the same time thanks to the settings above. Since the operating frequencies and the starting times of them are same, the speed and position controllers are performed in the interrupt routine of TIM2 instead of TIM8. In this way, TIM8 is started in normal mode and unnecessary interrupt request generation is prevented.

5.3. Software Architecture

Since the microcontrollers work based on serial working principle, they can perform only one task at a time. For this reason, interrupt based software is developed in the system. Totally there are four interrupt routines, two of which are periodic. These;

Periodical ones;

- Timer Interrupt Routine
- ADC Interrupt Routine

Non-Periodicals;

- Encoder Interrupt Routine
- UART Interrupt Routine

Periodical interrupt routines start to work after the command is received from the User Test Interface and continue until the "Test Stop" command is received. Non-periodical interrupt routines are in operation from the start of the main program until to the "Test Stop" command is received.

The flowchart of the microcontroller code used in the system is shown below.

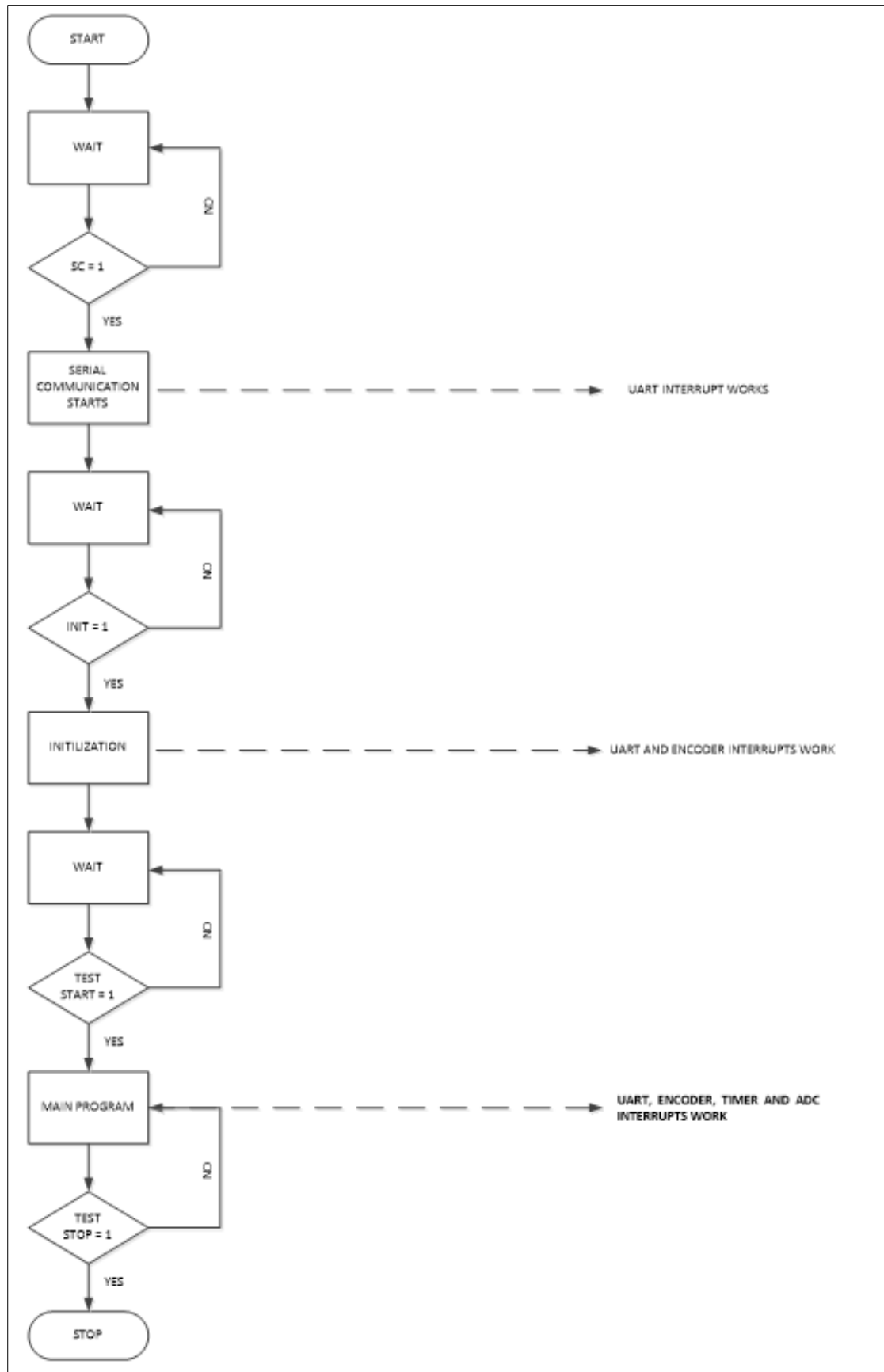


Figure 5.18. Microcontroller code flowchart

The electronic board which is connected to PC via USB interface, cannot exchange data with PC until fulfilling necessary UART protocol regulations. In order to establish communication between PC and microcontroller, correct "COM" port and data exchange rate, in other words "Baud Rate", must be selected from User Test Interface. After then data exchange can be done between PC and microcontroller. In this step, main program enters wait state for initialization process.

In the Initialization part, BLDC Motor and electronic board are got to the ready to start condition to perform the position command. Current sensors which sense motor phase currents have numerous major error components such as offset error, linearity error etc. In order to minimize the offset error effects, current measurement is made for a duration of certain time during no current passes through the motor phases. In this condition, the measured voltage value is subtracted from the voltage value that should be, which equals to the zero current voltage value. The remained value is defined as offset error voltage. This value is actively used by adding to the measured voltage value in all current measurements, in the rest of the program.

The position of the rotor is determined by the incremental encoder on the BLDC Motor. As the name implies, this type of encoders do not give absolute position information. For this reason, neither the certain mechanical nor the certain electrical position of the BLDC Motor can be determined by incremental encoder. On the other hand, although absolute encoder, which is another type of encoder, produces unique output for the mechanical position of the rotor, unfortunately from this information electrical position cannot be determined. For the Park and Clarke Transformations which are performed in SVPWM based FOC technique, the value of angle between d axis and alpha axis is required. If the position of the alpha axis is not known exactly at the starting, due to the incorrect transformations neither produced torque would be maximum nor would be smooth. In other words, I_d current wouldn't be zero. Therefore, during initialization, it is provided that the rotor goes to a known position by passing current throughout all three phases of the BLDC Motor [30].

High side MOSFET of Phase A and low side MOSFETs of Phase B and C are turned on for a certain period of time. The period of this pattern and the magnitude of current to be applied are tuned can rotate the rotor to the known position even if it would be under load.

In this way, rotor is fixed to the $a = \alpha$ axis. The position of rotor may change when the all MOSFETs are turned off suddenly. In order to measure this displacement, the encoder is activated after fixing rotor. Thanks to the encoder, decrement of efficiency of commutation is prevented.

Initialization part ends after detecting offset error of the current sensor and fixing the rotor to the known position.

The main program stays in wait state until "Test Start" command comes from User Test Interface. As can be seen from main program flow chart, only UART and encoder interrupt routines are actively used so far. Timer and ADC interrupt routines are activated with "Test Start" command. Without any time restrictions, the main program keeps on working until "Test Stop" command comes.

In order to analyze microcontroller code better it is necessary to know how the interrupt routines are activated and which processes are done in each interrupt.

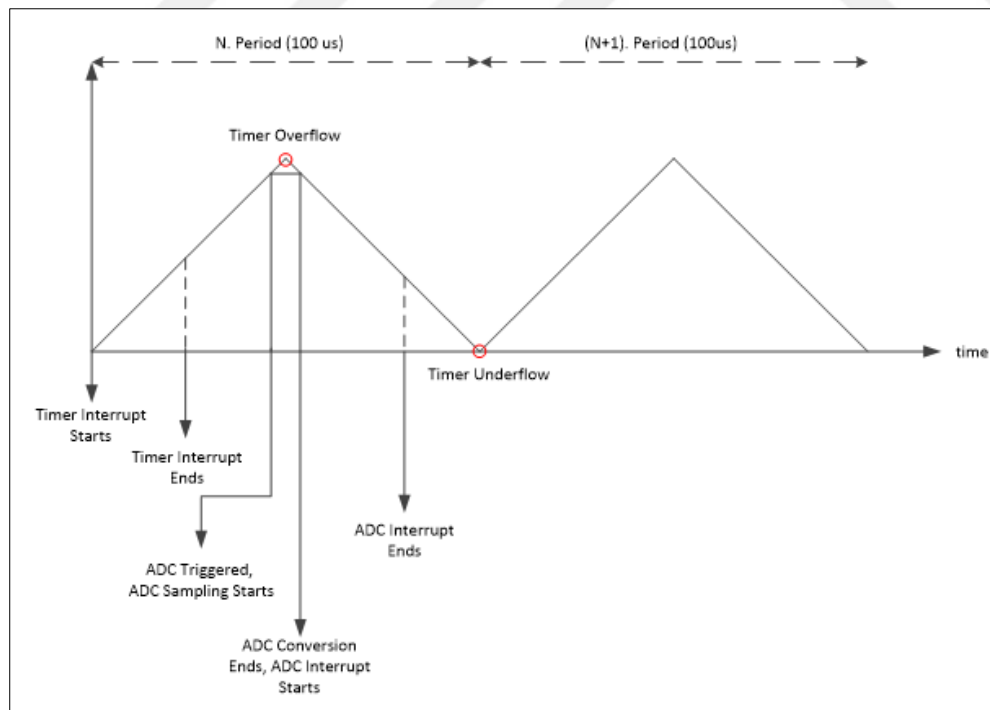


Figure 5.19. Sequence of timer and ADC interrupt routines in a period

As can be understood from Figure 5.19, Timer and ADC interrupt routines are repeated in every 100 μ s period and these interrupts do not intersect each other within this period. In

order to avoid any delays on the code, care has been taken to ensure that the two interrupt routines do not intersect. These points on the figure that refer ending of interrupt routines do not represent exact points on time axis and just added for better understandings. In the Timer interrupt routine, position and speed PI Controller operate and in the ADC interrupt routine, current PI Controller operates. These nested three controllers should be worked synchronously for getting maximum efficiency and preventing time based problems. Using the timer synchronization feature of the microcontroller, it is ensured that these interrupt routines work synchronously.

5.3.1. ADC interrupt routine

ADC Interrupt routine starts after completion of the analog to digital conversion and ends with calculating durations of the gate signals. ADC starts to conversion by trigger signal which is generated by TIM8. This timer, which has a period of 100 μ s, triggers the ADC at the moment when the motor phase currents are the comparatively less noisier within the whole period. In this moment, all the high side MOSFETs are active and there is no MOSFET switching activity. In Figure 5.21, switching signals and ADC trigger signal are shown in same time axis. The value which is written to the CCR4 register is constant and cannot be changed on run-time. The values which are written to the CCR1, CCR2 and CCR3 registers are recalculated in each ADC Interrupt routine but any of these cannot bigger than threshold value. The time interval which is represented between two red dashed lines is reserved for ADC to take sample from motor phase currents.

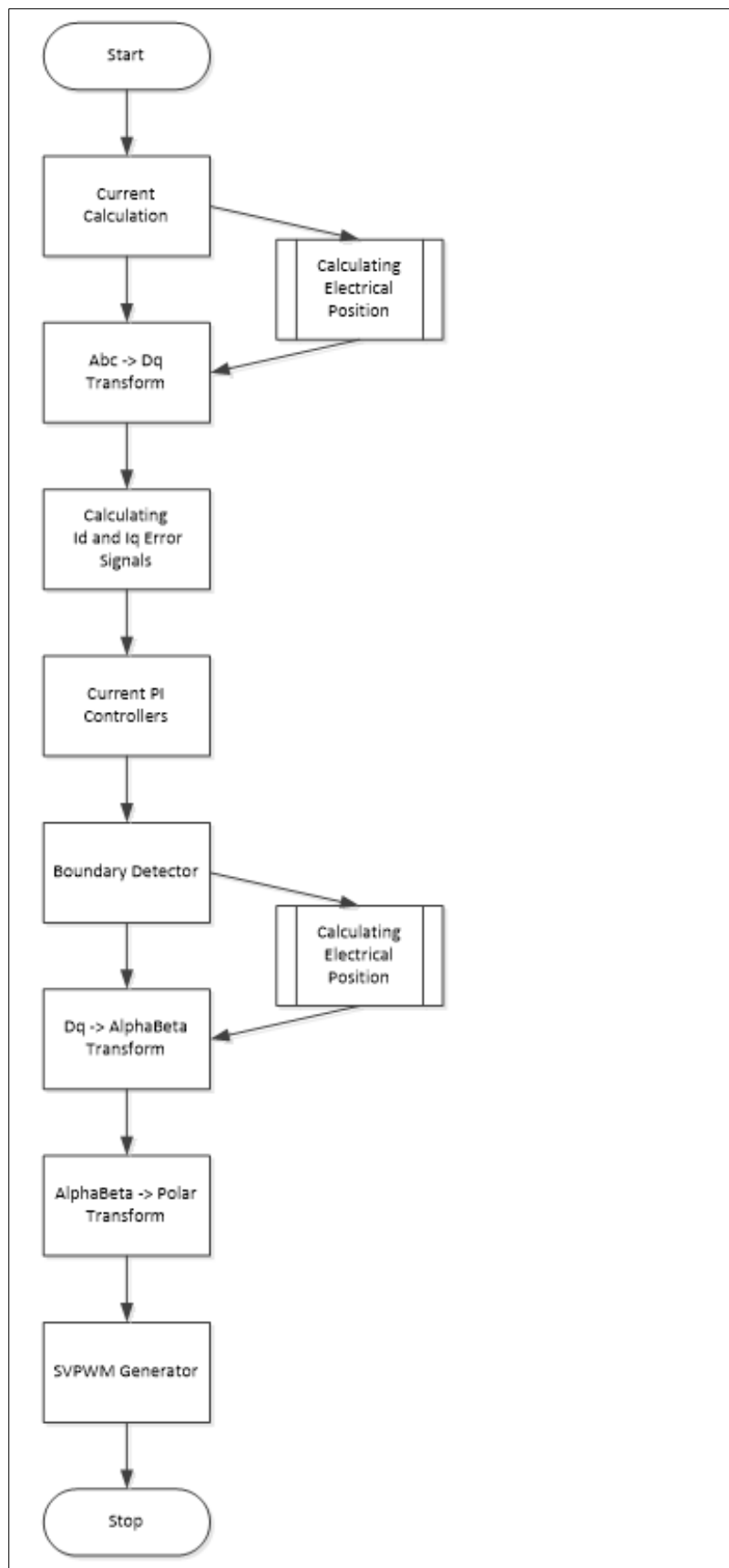


Figure 5.20. ADC interrupt routine flowchart

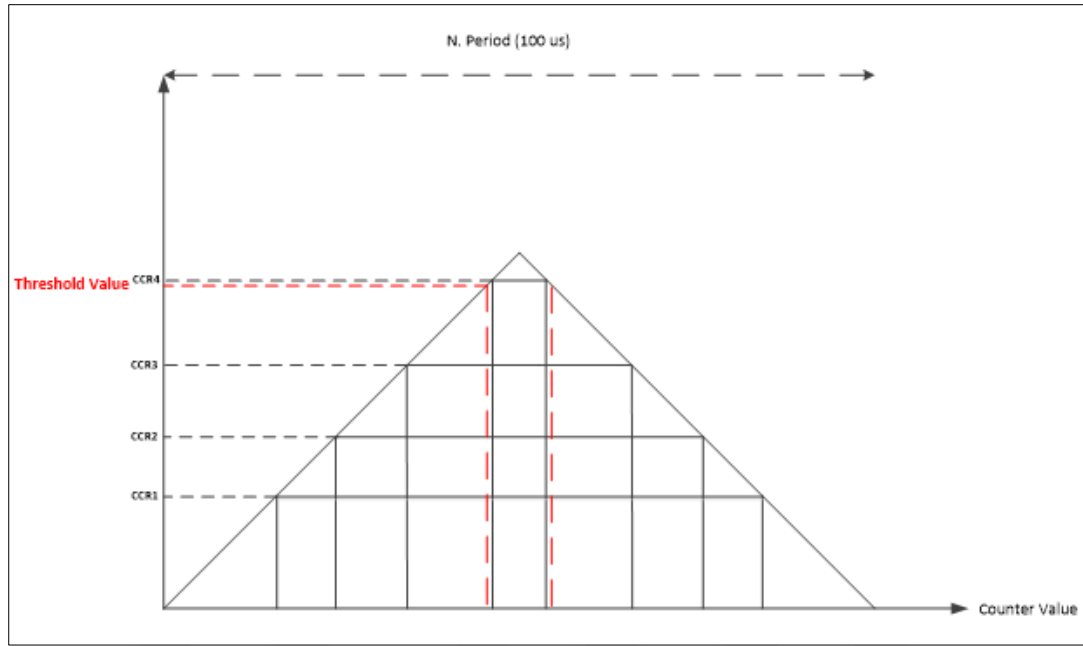


Figure 5.21. ADC trigger signal and MOSFET switching signals in a period

Only Phase A and Phase B currents are measured so two different ADCs are actively used. Thanks to DMA feature of ADC, both ADCs can take sample at the same time. It is too important that sampling be performed at the same time to get realistic and accurate results. After both of them have completed the conversion process, the code leaves the main program and execute the ADC Interrupt routine.

Phase A and Phase B current values are calculated in 3 phase stationary reference frame. In balanced three phase systems, according to the Kirchoff's Current Law, summation of phase currents should be equal to the 0. Phase C current value can be calculated from Eqn. 5.12.

$$I_c = -(I_a + I_b) \quad (5.12)$$

At this stage, Clarke and Park Transformations are performed respectively for mapping the calculated current values to the 2 axis orthogonal rotating frame from 3 phase stationary reference frame. The electrical angle information required for transformation is obtained from the encoder.

I_d current value should equal to the zero to produce maximum possible torque. For this reason, I_d current reference signal always equals to the zero. I_q current reference value,

known as torque produce current, is the output of speed PI Controller and varies according to the instantaneous requirement. The calculated I_d and I_q current values are subtracted from reference current values to obtain current error signals that provide input to the current PI Controllers.

The vector summation of these two independent current controller's outputs should not violate the boundary of the undermodulation circle so these output signals are directed to the Boundary Detector block for recalculation.

Inverse Park Transformation is performed to map the calculated values from 2 axis orthogonal rotating reference frame to 2 axis orthogonal stationary reference frame. The electrical angle information required for transformation is obtained from the encoder.

There is a one more necessary transformation to calculate PWM signals. At this stage, vector summation of calculated I_α and I_β currents are transformed to modulus and phase information using Polar Transformation. These information enters to the SVPWM Generator block and PWM values which will be written to the CCR registers in the next current loop are calculated.

5.3.2. Timer interrupt routine

The tasks are performed in Timer Interrupt routine are not same in each loop. Microcontroller code enters to the this interrupt routine when counter of TIM2 underflows. The common task which is performed every single Timer Interrupt routine is to be written of PWM values which is calculated in ADC interrupt routine to the CCR registers of TIM2. In this way, it is ensured that applying calculated signals to the gates of each Mosfet during current period.

Current controller's operating frequency is 10 kHz. The operating frequencies of speed and position controllers are 1 kHz and 100 Hz respectively. Like current controller, frequency of timer interrupt routine is 10 kHz too. Therefore, the speed controller must operate in 1 out of every 10 timer interrupt routines. As can be guessed, position controller must operate in 1 out of every 100 timer interrupt routines. In order to obtain the fastest possible response, both speed and position controllers operate in the first timer interrupt routine that

occurs in the system. This mentioned algorithm is ensured with usage of modulus operator inside the code.

In each speed controller loop, in order to obtain the speed of rotor firstly mechanical position of rotor has to be calculated.

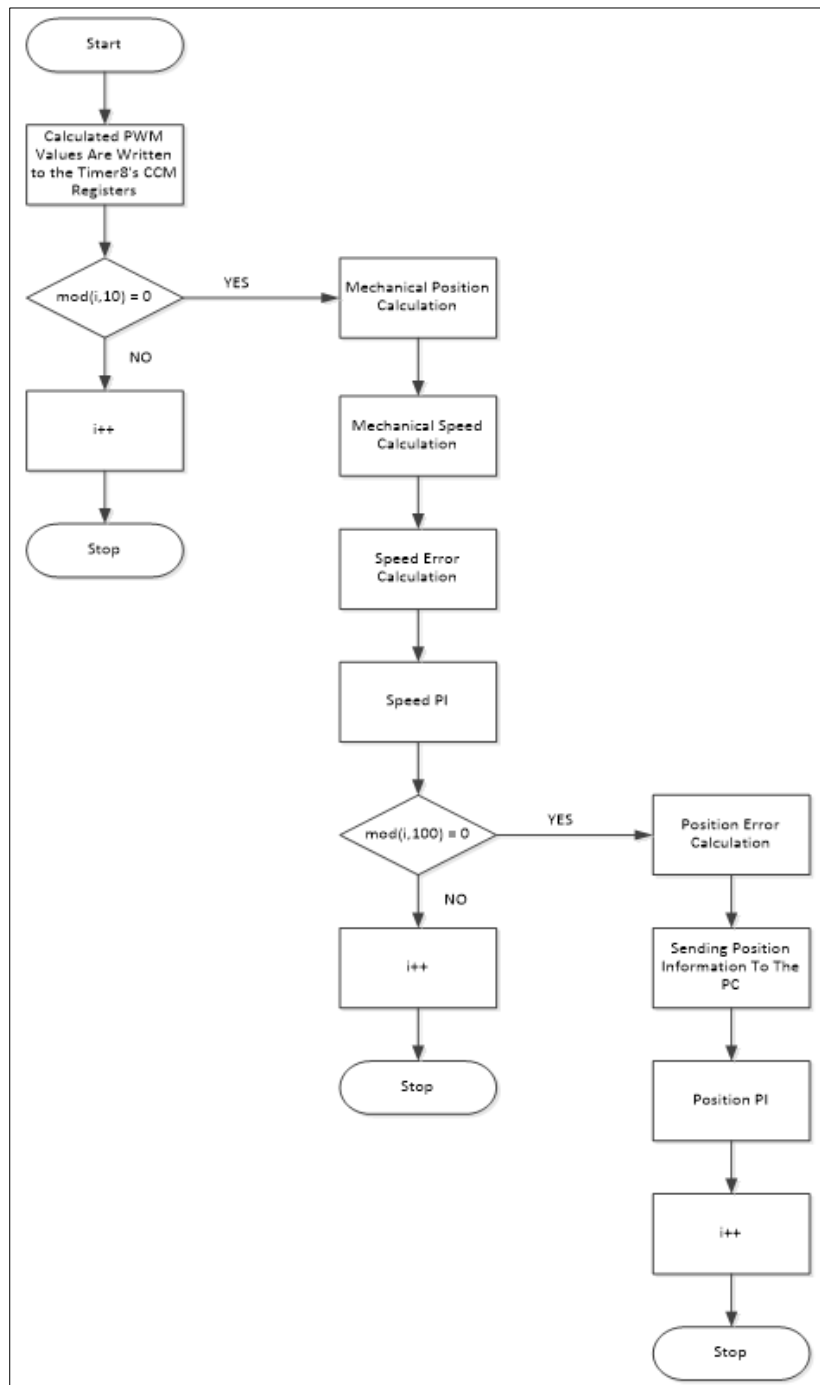


Figure 5.22. Timer interrupt routine flowchart

5.3.3. Encoder interrupt routine

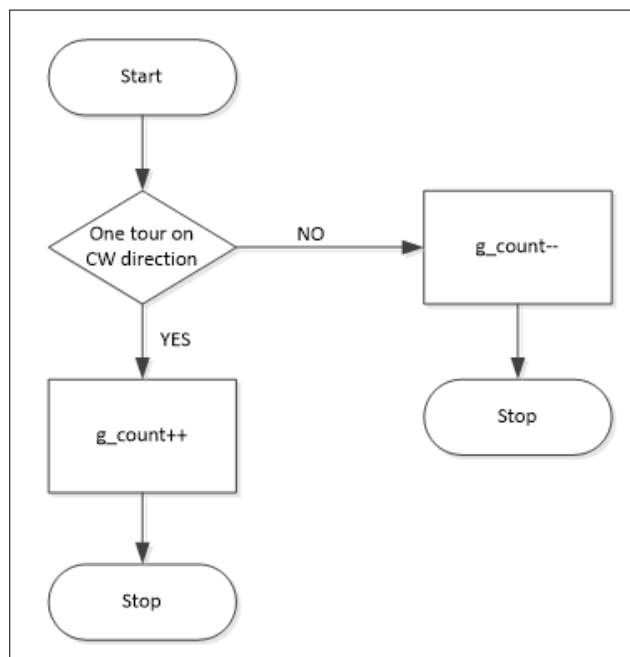


Figure 5.23. Encoder interrupt routine flowchart

The encoder used in the system normally send an index signal which means completion of one mechanical revolution. Unfortunately, where the index signal occurs cannot be changed by hardware or software; it always occurs at same point. Because where the index signal occurs cannot be the same as the initialized rotor position in each case, this feature is not useful for our design. Instead, the initialized rotor position is accepted as both mechanical and electrical zero degree.

Period of the TIM3 which is specialized for counting of encoder pulses is equaled to 8192, the number of pulses to be generated in one complete revolution of the encoder. Whenever TIM3's counter overflows or underflows, it is entered to the Encoder Interrupt routine. As soon as entering the interrupt, firstly direction of the counter of the TIM3 is detected thanks to DIR bit. If a positive, clockwise, direction is detected, DIR = 0, the total number of revolutions is increased by 1, or if negative, counterclockwise, direction is detected, DIR = 1, the total number of revolutions is reduced by 1. As expected, the total number of rounds is equal to zero at first.

5.3.4. UART interrupt routine

The command, aka message package, is sent from the User Test Interface to the microcontroller by the user request or periodically. The commands, which are sent by user request, are "INIT", "TEST_START" and "TEST_STOP" commands. The command, which is sent periodically, is "POS_CMD" command which is sent every 100 ms after test starts. A message package which consists of 64 bits contains message type and message content information so that the microcontroller can understand what the command is. While the first 32 bits refer message type, the remaining 32 bits refer message content. The value which is sent to the position controller as position command is kept in the message content. Instead of working in polling mode, serial communication related tasks are performed only when 64 bits data is received. This is because the size of the meaningful data from the PC is 64 bits, ie it is equal to the size of the expected message packet.

Whenever 64 bits data is received from PC, the microcontroller enters to the UART Interrupt Routine to read the data.

Since the tasks to be performed depend on the message type, the message type is read first. Message type can be equal to four different options:

- INIT = 1
- TEST_START = 2
- POS_CMD = 3
- TEST_STOP = 4

The following describe what tasks the microcontroller performs with respect to the message type.

INIT = 1;

This message package is sent from User Test Interface by the user request. When the microcontroller sees this message type, it only performs the tasks in initialization part. The message content for this message type is omitted.

TEST_START = 2;

This message package is sent from User Test Interface by the user request. When the microcontroller sees this message type, it leaves the "Wait" state and enters the main program loop. The message content for this message type is omitted.

POS_CMD = 3;

After the “TEST_START” command is sent, the “POS_CMD” command is sent by PC Interface every 100 ms periodically. When the microcontroller sees this message type, it reads the message content as well.

TEST_STOP = 4;

This message package is sent from User Test Interface by the user request. When the microcontroller sees this message type, it leaves the main program loop and enters the main "Stop" state. The message content for this message type is omitted.

5.3.5. Interrupt priority

Since the interrupt based code is developed; when the interrupt request comes the microcontroller leaves current task and performs the task which is in the interrupt routine. After the task which is in the interrupt routine is finished, the microcontroller continues to perform the interrupted task. If all the interrupt requests are adjusted that not to intersect each other, the microcontroller can fulfill all given tasks without any delay. Unfortunately, it is almost impossible to achieve this ideal condition for the system which works at runtime and interacts with external factors. In such a system, if the interrupt priority is not configured correctly, system response will not be at desired level.

When the microcontroller performs the task in the interrupt routine which has high priority, if the interrupt request which has low priority comes, it continues to perform current task. After finishing the task, it performs the task in the interrupt request which has low priority. When the microcontroller performs the task in the interrupt routine which has low priority, if the interrupt request which has high priority comes, it leaves the current task.

Immediately, it performs the task in the interrupt routine which has high priority. After finishing the task in the interrupt routine, it performs the interrupted task.

So far it seems there is no problem with interrupt request priority. What if the interrupt request which has equal priority comes while the microcontroller performs the task in the interrupt routine?

In order to overcome this chaos, the sub-priority feature of STM32F746ZG is benefited from. In this case, the interrupt request which has high sub-priority gains the priority.

The microcontroller allocates 4 bits field for the priority and sub-priority. This 4 bits field is editable so that the user can allocate the different number of bits to priority and sub-priority as wanted. In code, three bits are allocated to the priority and one bit for sub-priority.

So then the value of priority can be 7 at most or 0 at least. The value of sub-priority can be 0 or 1. 0 represents the highest priority, and the greater the value written to this field, the smaller the priority. After these given information, the priority order of interrupt requests in the code is configured as in Table 5.1.

Table 5.1. Priority configuration of interrupt requests

Name	Priority	Sub-Priority
ADC Interrupt Request	0	0
Timer Interrupt Request	0	0
Encoder Interrupt Request	1	0
UART Interrupt Request	1	1

Since the most important tasks are performed in the ADC and Timer Interrupt Routines, the highest priority is assigned to the interrupt requests of these interrupt routines. Equal sub-priority is assigned to both interrupt requests because in the code precaution is taken about intersection.

The lower priority, which is equal to the 1, is assigned to the interrupt requests of Encoder and UART Interrupt Routines. Even if a delay occurs at the data exchange with PC, response of system is not affected too much. Therefore, higher sub-priority is assigned to the Encoder Interrupt Request.

5.3.6. Calculation of motor phase current

The phase current reading process is handled with current sensor which is placed in series to the motor phase and ADC, which converts analog output of current sensor to the digital. Settings of the ADC which is on-board to the microcontroller is selected as followings.

- Resolution : 12 bits
- Operating frequency : 25 MHz
- Sampling time : 28 cycles

The operating frequency of the ADC could be maximum 30 MHz. The main clock frequency of the microcontroller is adjusted as 200 MHz. 30 MHz cannot be obtained when 200 MHz value is divided by any integer so the operating frequency of the ADC is selected as 25 MHz. In order to obtain high-resolutioned phase current data, the resolution of the ADC is adjusted as 12 bits. The last but not the least criterion for obtaining proper phase current data is sampling time of the ADC. Unless sampling time is enough, calculated phase current value will not be correct. Considering all factors, this value is selected as 28 ADC cycles, possible maximum value.

The motor phase current is calculated once in each current controller loop. Therefore, it is paid attention to sample the phase current at the noise-free moments of each current controller loop.

There are 6 times MOSFET switching activity within the one current controller loop. The MOSFET switching times are symmetrical to the mid-time of the current controller loop because of the usage of Center Aligned PWM mode. For this reason, analysis carries out until to the mid-time of the current controller loop is quite enough.

The switching times of the MOSFET are adjusted with CCR of the timer. The switching signal is sent to related MOSFET's gate when the value of the counter is equal to the value which is written to CCR. In order to avoid the shoot-through phenomenon, 300 ns of dead-time is added in microcontroller code. A current controller loop consists of 2000 timer cycles and counter value could be 1000 as a maximum because of PWM method. The value which is written to the CCR of timer could be 980 as a maximum due to physical constraints related with bootstrap capacitor [31]. Thus at least 4% of each period is allocated for bootstrap capacitor charging. In order to avoid the intersection of MOSFET switching activity with sampling the phase current, the value of 990 is written to the CCR of the 4th channel of TIM8 that triggers the ADC. The above information is visualized in Figure 5.24.

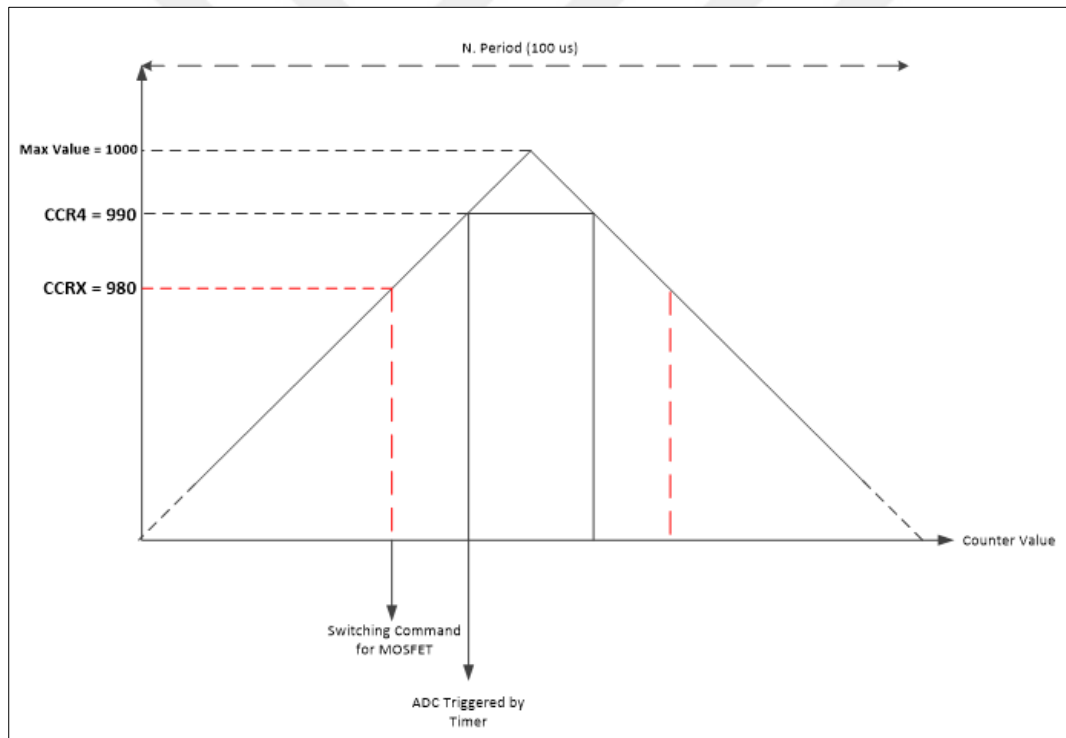


Figure 5.24. Forbidden region for MOSFET switching in a period

In order to understand the relationship between the switching the MOSFET and sampling the motor phase current, some simple time calculations are performed.

$$\text{MOSFET Switching Command } (t) = \frac{980}{1000} \times 100 = 49 \mu\text{s} \quad (5.13)$$

$$\text{Triggering of ADC } (t) = \frac{990}{1000} \times 100 = 49,5 \mu\text{s} \quad (5.14)$$

$$Total\ Sampling\ Time = Sampling\ Cycle \times \left(\frac{1}{Operating\ frequency\ of\ ADC} \right) \quad (5.15)$$

$$Total\ Sampling\ Time = 28 \times \frac{1}{25 \times 10^6} = 1,12\ \mu s \quad (5.16)$$

The calculated time values are shown in Figure 5.25 on the same time-axis. It is proved thanks to Figure 5.25 that there is no intersection between switching the MOSFET and sampling the motor phase current.

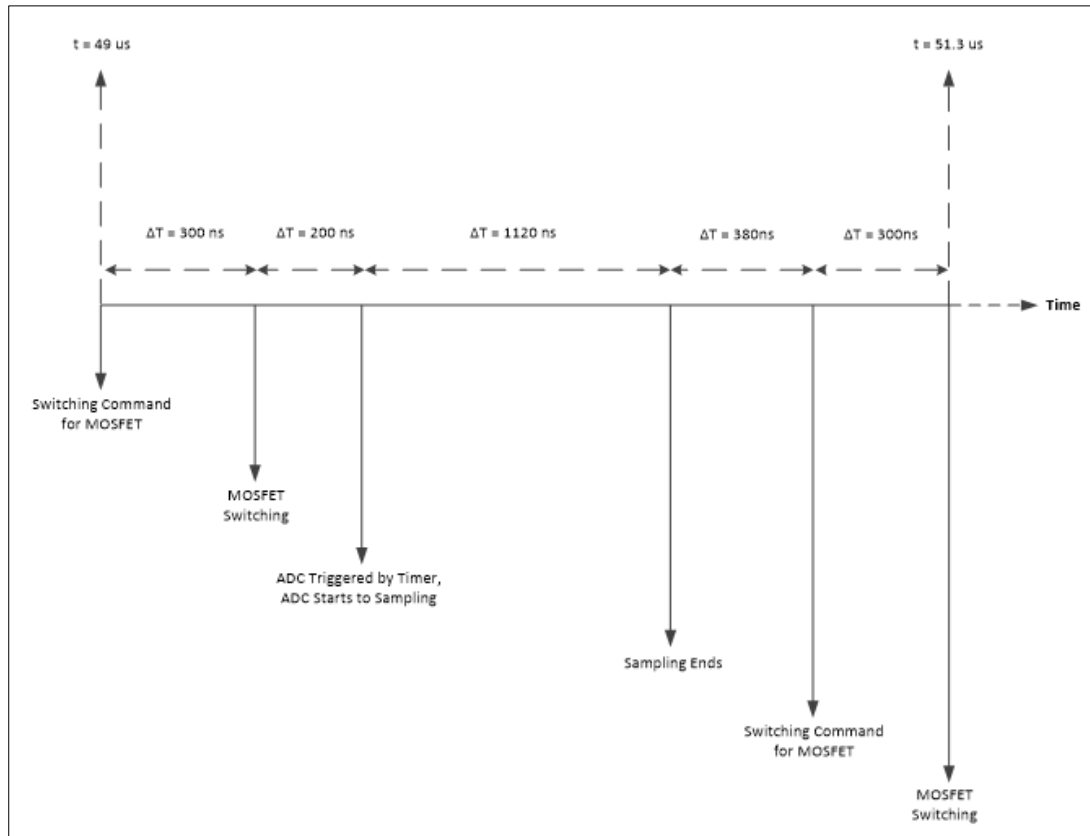


Figure 5.25. Mid-time of a period

In order to minimize the effect of offset error of current sensor, the offset error voltage of the current sensor is calculated first.

$$v_{OFFSET} = \frac{V_{REF}}{2^{12}} \times (Bit\ Value) = \frac{V_{REF}}{4096} \times (Bit\ Value) \quad (5.17)$$

$$v_{OFFSET_ERROR} = v_{OFFSET} - v_{ZERO_CURRENT} \quad (5.18)$$

where, $v_{ZERO_CURRENT} = 1,5\ V$

In the initialization stage, it is taken 2000 phase current samples in order to analyze to the reasonable period of time for considering that there can be some other noises, which can couple to the offset error. Equation 5.17 is renewed as following.

$$v_{OFFSET} = \frac{V_{REF}}{2000 \times 2^{12}} \times (\sum_{i=1}^{2000} (Bit\ Value(i))) \quad (5.19)$$

$$v_{OFFSET_ERROR} = v_{OFFSET} - v_{ZERO_CURRENT} \quad (5.20)$$

In the initialization stage, it is not necessary to take phase current sample in the middle of the period since there is no MOSFET switching activity. Like during the normal operation, there is difference of 100 μ s between the two consecutive samples.

The processes for calculation of motor phase current are repeated in each ADC Interrupt routine until test stop command is received. During the calculation of the motor phase current, calculated offset error voltage value is used to eliminate the offset error of the current sensor. The calculation of the motor phase current is performed as followings.

$$v_X = \frac{V_{REF}}{2^{12}} \times (Bit\ Value) \quad (5.21)$$

$$v_Y = v_X - v_{OFFSET_ERROR} \quad (5.22)$$

If $0,3\ V \leq v_Y \leq 2,7\ V$;

$$I_Y = \frac{v_Y - 1.5}{Sensitivity\ (mV/A)} \quad (5.23)$$

$$v_Y < 0,3\ V\ then\ I_Y = -20\ A \quad (5.24)$$

$$v_Y > 2,7\ V\ then\ I_Y = 20\ A \quad (5.25)$$

where,

$Sensitivity = 0.06\ (mV/A)$

I_Y : Calculated phase current

5.3.7. Detection of speed and position by encoder

Encoding (x4) method is selected for increasing the resolution of rotor position. In this method, whole increasing and decreasing edges of Channel A and Channel B are counted. Counter value is incremented or decremented with respect to leading Channel. Direction of rotor is accepted as positive, CW, when the channel A leads. In this situation, counter value is incremented. Otherwise, direction of rotor accepted as negative, CCW, and counter value is decremented. In Figure 5.26, working principle of Encoding (x4) method is shown [32].

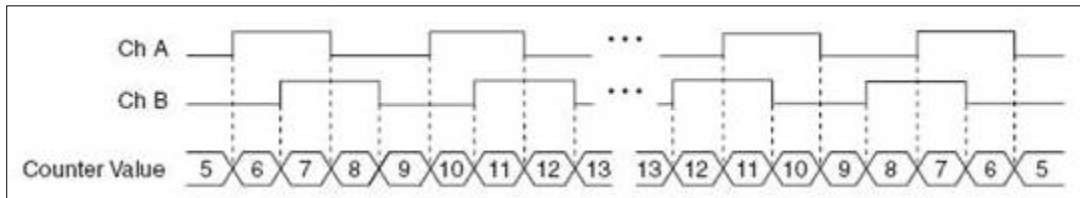


Figure 5.26. Encoding(x4) method [32]

The following formula is used for rotational position calculation

$$Position(rad) = \frac{Edge\ Count}{Total\ Edge} \times 2\pi \quad (5.26)$$

As can be understood from the formula, only the current rotor position information can be obtained. In the thesis, in order to control the motor properly we have to know how many degrees the motor rotates totally. By adding the value of completed revolution of motor to the above formula, this mentioned restriction is prevented. Thus the following formula is obtained.

$$Position(rad) = Completed\ Revolution + \frac{Edge\ Count}{Total\ Edge} \times 2\pi \quad (5.27)$$

The value of the Completed revolution both can be positive or negative.

The Eqn. 5.27 gives us mechanical position of the motor. The angle which is required for transformations is obtained from the electrical position of the motor. Therefore, a new equation must be derived for detection of electrical position of the motor. As we know,

number of electrical revolution and number of mechanical revolution are directly proportional.

$$\text{Electrical Revolution} = \text{Mechanical Revolution} \times \text{Number of Pole Pairs} \quad (5.28)$$

The BLDC Motor that is used in the thesis has 4 pole pairs. According to the Eqn 5.28., the total edge count in the one electrical revolution is one fourth of the total edge count in the one mechanical revolution.

Since there is no need to the number of completed revolution to obtain the electrical position of the motor, the new equation should be derived from Eqn 5.27. In this case, the equation will be as follows.

$$\text{Electrical Position(rad)} = \frac{4 \times \text{Edge Count}}{\text{Total Edge}} \times 2\pi \quad (5.29)$$

Unless rotor position is fixed to the electrically zero degree during the initialization part, an electrical phase value must be added to the Eqn 5.29.

The speed information which is used in speed controller is obtained from two consecutive rotor position information that comes from encoder. At this stage, mechanical position value must be used instead of electrical position value. The equation used is as follows.

$$\text{Speed(rad/s)} = \frac{x_1 - x_0}{\Delta t} \quad (5.30)$$

where,

x_1 : Current position of the rotor in radian

x_0 : Previous position of the rotor in radian

Δt : Period of speed controller, 1 ms,

6. EXPERIMENTS

In this chapter, some test scenarios, which are designated according to requirements of position controller, are run in order to examine the performance of the proposed method.

6.1. User Test Interface

The User Test Interface is developed at Microsoft Visual Studio in order to communicate with NUCLEO-F746ZG on UART. By User Test Interface, rotor position can be aligned and position command can be sent to the NUCLEO-F746ZG. Thanks to User Test Interface, rotor position can also be monitored in real-time.

The correct COM port of the PC must be selected from the User Test Interface to communicate with the NUCLEO-F746ZG. In addition, the value of Baud Rate must also be correct to start to communicate. After correct adjustments are done, it is clicked to the "Bağlantı Aç" button. Now, microcontroller waits for the command to be sent from the User Test Interface to pass to the initialization phase.

The screenshot displays a Windows application window titled "Form1". It contains several functional areas:

- Gönderilecek Veriler:** A text input field for data to be sent, with a "Verileri Gönder" button and a dropdown menu currently set to "SATIR SONU YOK".
- Pozisyonlama:** A section for setting position and time. It includes a table with columns "Poz(rad)" and "Zaman(sn)":

Poz(rad)	Zaman(sn)
1	1
3	2
1	1
2	2
5	2
3	4

 Below the table is a scrollable list box. To the right of the table are buttons: "İklendir", "Bağlat", and "Bitir".
- Gelen Veriler:** A large text area on the right for receiving data.
- Serial Port Settings:** A section with "SerPort" (set to COM5), "COM Port" (set to COM5), and "Hız" (set to 115200). A "BAĞLANTI AÇ" button is located below these settings.
- Legend:** A legend in the bottom right corner showing a blue line for "PozisyonFeedback" and a red line for "PozisyonKomut".

Figure 6.1. User test interface

Since incremental encoder is used in the design, rotor must be fixed to a known position each time the system is started. This process is achieved by clicking "İlklendir" button. Since the rotor's erroneous initial position adversely affect the performance of the controller, a simple precaution is taken to avoid error may be caused by user. The "Başlat" button is not activated until initialization process is done to prevent the user proceed with respect to the test procedure improperly.

The commands to be applied to the motor are in terms of radian and the duration of the commands in seconds. After filling this part, the test is started by clicking "Başlat" button. Even though the duration of the last position command to be applied is determined from the interface, the system continues to follow this command without any time limitation until to the clicking the "Bitir" button.

6.2. Test Setup

The required equipments for the Test Setup are as follows;

- PC with User Test Interface
- Oscilloscope
- 3 current probes
- 3 voltage probes
- 1 differential voltage probe
- 28 V 10 A power supply
- 3 channel power supply (15 V, 1 A; 5 V, 1 A; 3,3 V, 1 A)
- NUCLEO-F746ZG
- Driver Board
- 3 Phase BLDC Motor
- Necessary cables

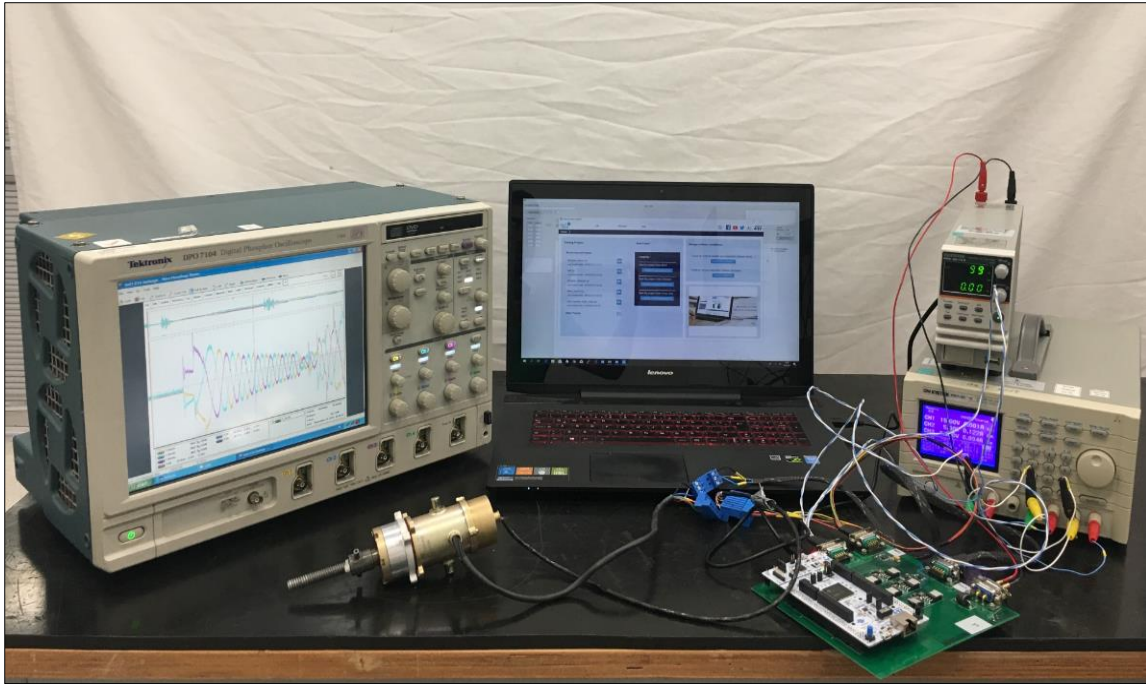


Figure 6.2. Test setup

6.3. Prerequisite Tests

Before starting the position tests, duration of dead-time which is added to switching signals, sequence of the applied switching signals and initialization current pattern are verified.

Dead-time measurements are taken from gate and source legs of the both high and low side MOSFETs of same phase.

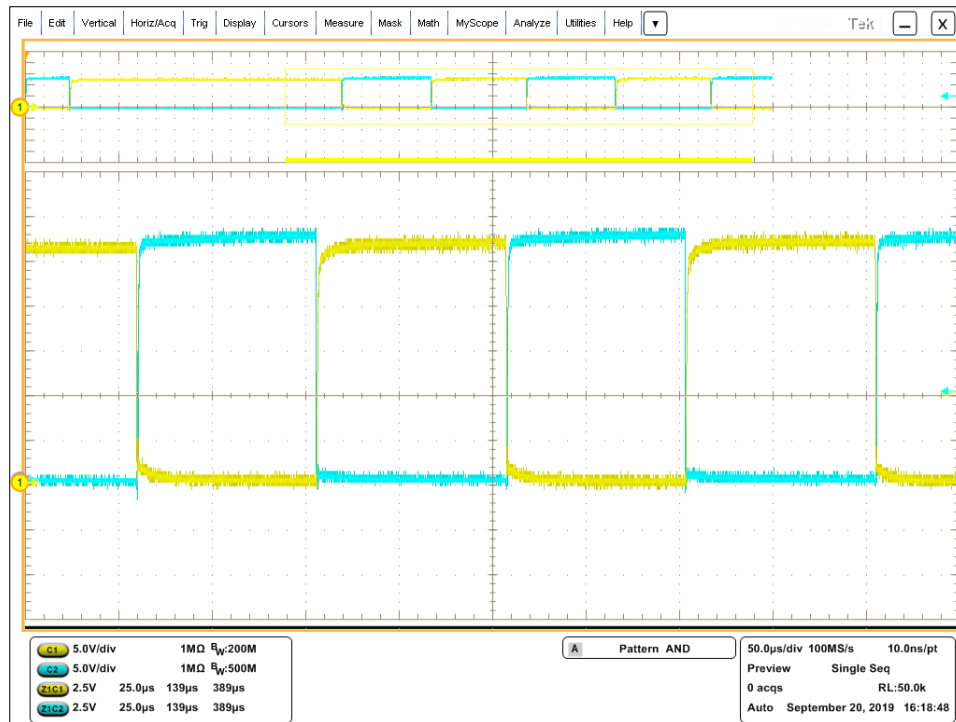


Figure 6.3. Switching signals

In order to measure the duration of the dead-time exactly, the switching signals are closely monitored. At this stage, to guarantee that shoot-through phenomenon is prevented, it has to be looked high to low and low to high transitions of the switching signal which is sent to high side MOSFET.

In Figure 6.4 and Figure 6.5, it is verified that addition of the 300 ns dead-time to the switching signals thanks to cursor feature of the oscilloscope. It is also verified that prevention of the shoot-through phenomenon.

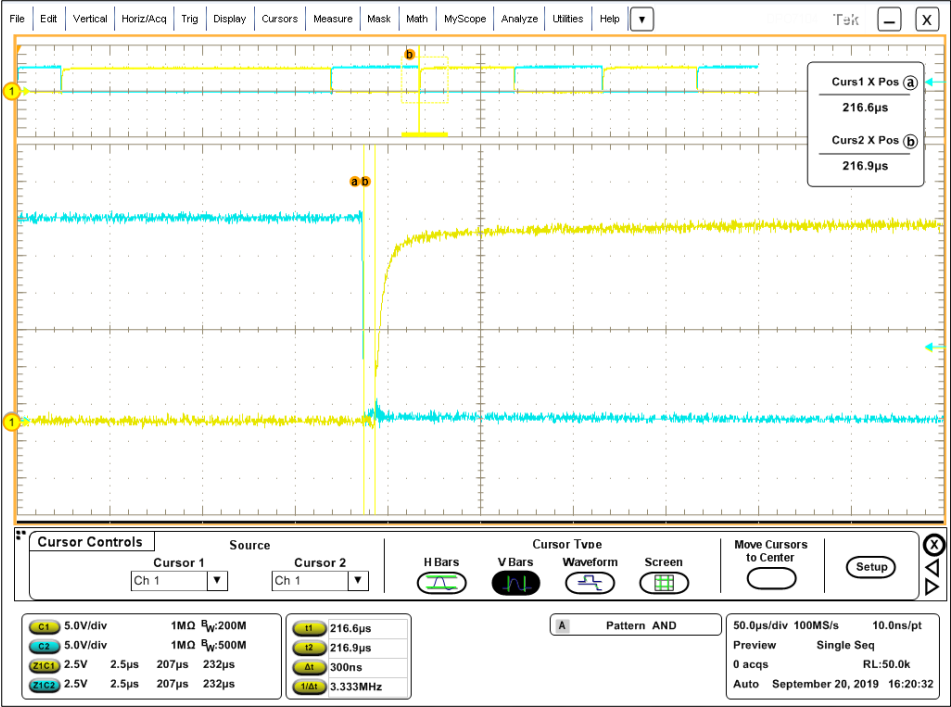


Figure 6.4. Low to high transition

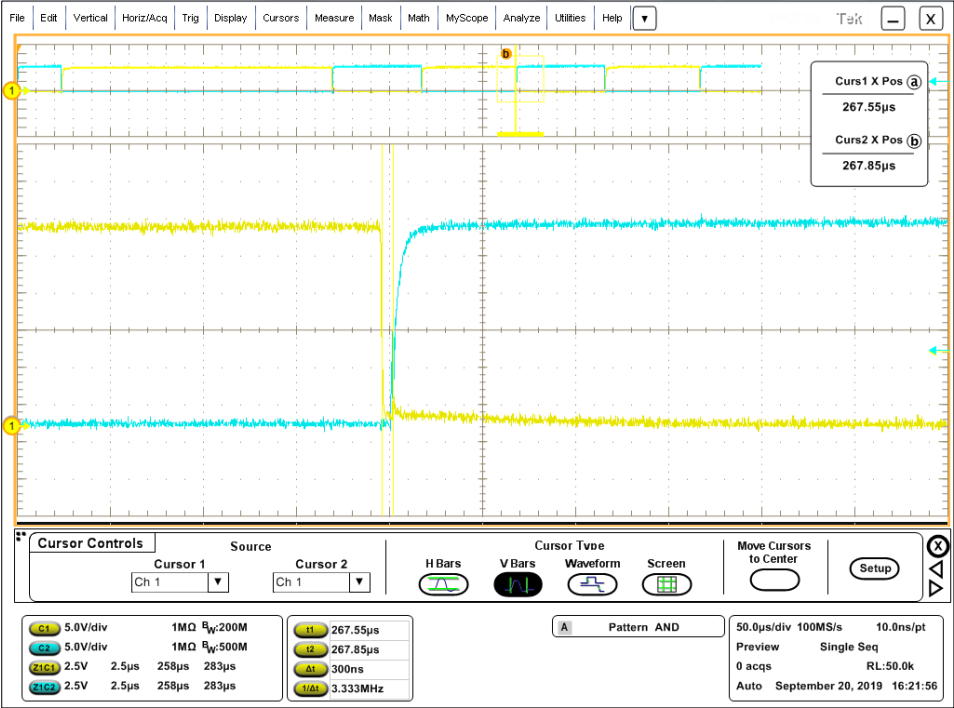


Figure 6.5. High to low transition

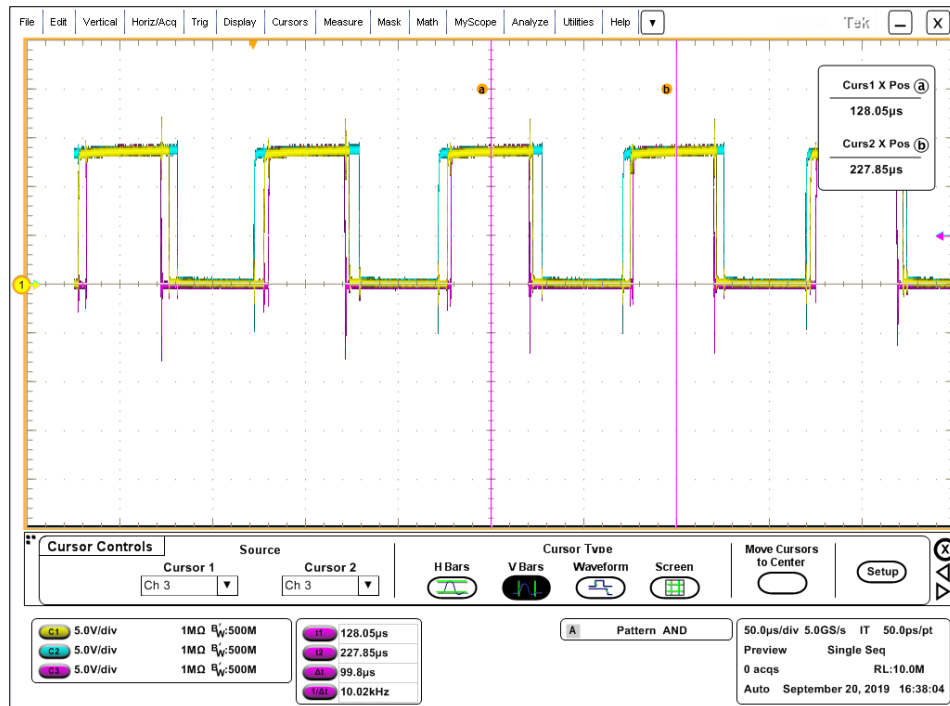


Figure 6.6. Switching sequence of gate signals

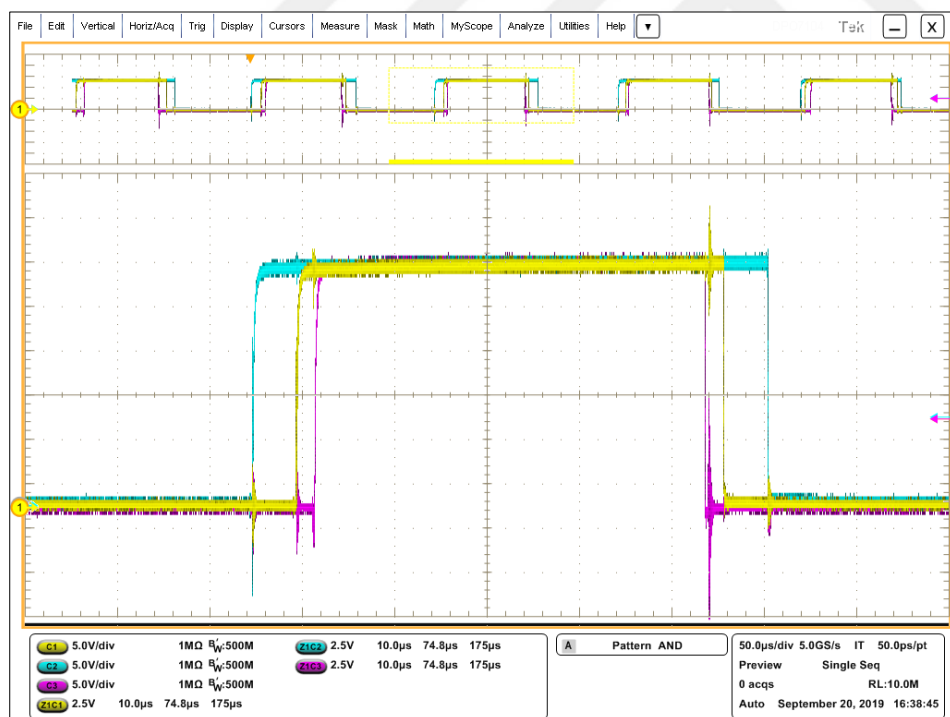


Figure 6.7. Switching sequence of gate signals in a period

In Figure 6.7, it is shown that Center Aligned Mode PWM signals are generated. It is also seen that the switching period is 100 µs with the help of cursor tab. The measurements are taken from gate and source legs of the low side MOSFET of each phase.

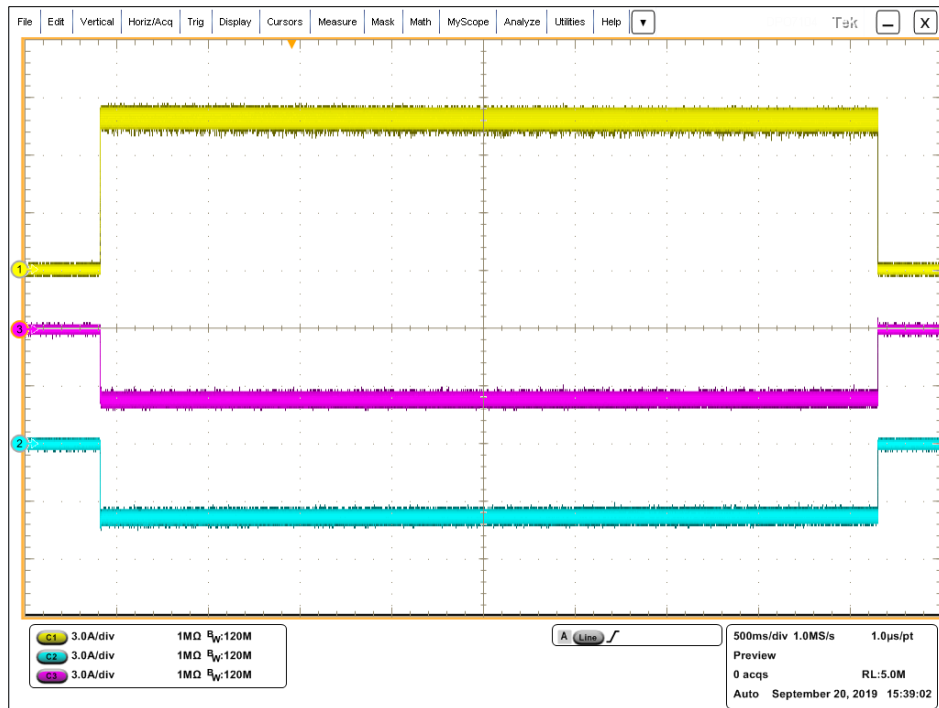


Figure 6.8. Applied current pattern in initialization phase

In Figure 6.8, it is shown that the current pattern which is applied to the motor phases in the initialization phase. The yellow represents the current of Phase A, the turquoise represents the current of Phase B and the pink represents the current of Phase C. Currents of Phase B and C have same magnitude and they are in same direction. Current of Phase A in opposite direction and its magnitude is equal to the sum of other two phases. The voltage space vector, which is applied in this pattern, is equal to the $\underline{u}_{100}$ base voltage space vector. Thus, rotor position is fixed to the $a = \alpha$ axis as intended.

6.4. No Load Tests

In the "Requirements of Position Controller" section, the operating range of the motor shaft is stated as 43,5 radian. In real, the changement of the rotor position such a wide range generally happens in the erroneous conditions. However, in order to enforcethe position controller, position commands, which are not expected in operating conditions, are sent.

PI Controller coefficients in the design are determined by experimentation.

Table 6.1. PI coefficients for actual system

Controller	K_p	K_i
Position	40	3
Speed	0,1	-
I_d current	0,6	0,276
I_q current	0,6	0,276

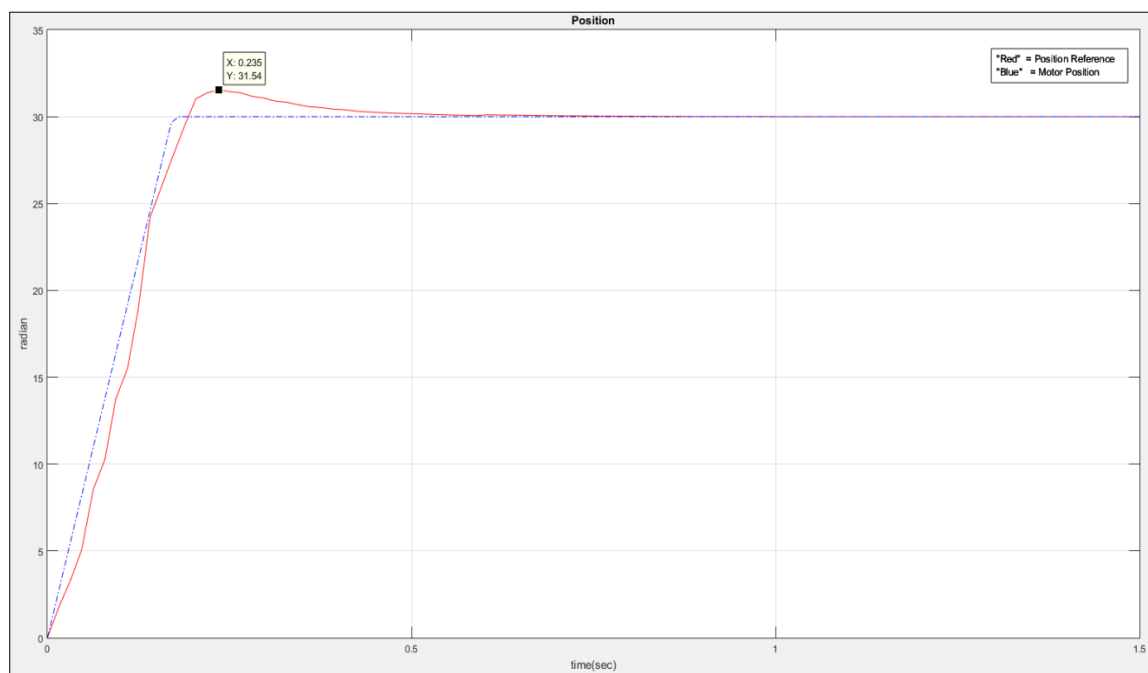


Figure 6.9. 30 radian position command

As can be seen in Figure 6.9, the overshoot on position response is about 5% and this value is within the acceptable range. In steady-state, there is no offset error.

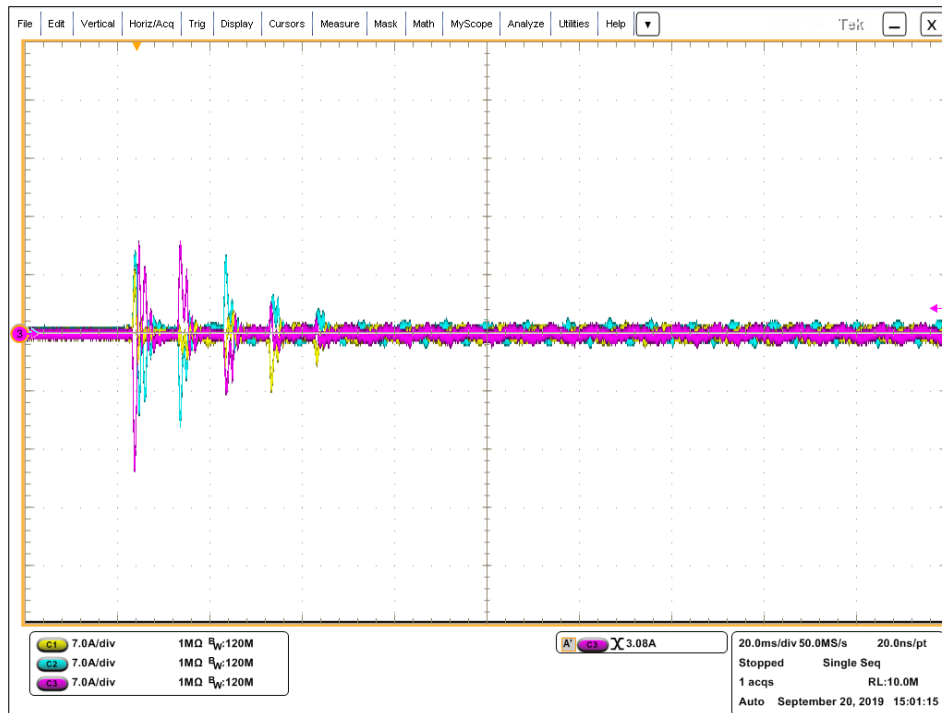


Figure 6.10. 3 phase current waveforms for 30 radian position command

In Figure 6.10, 3 phase current waveforms are shown. As can be seen the current passes through the motor phases only when motor rotates, at the steady-state the magnitude of the 3 phase currents are nearly zero as expected.

In Figure 6.11, a closer look at the phase currents shows that they have a sinusoidal waveform. The amount and duration of the drawn current are less because of the applied position command and inertia.

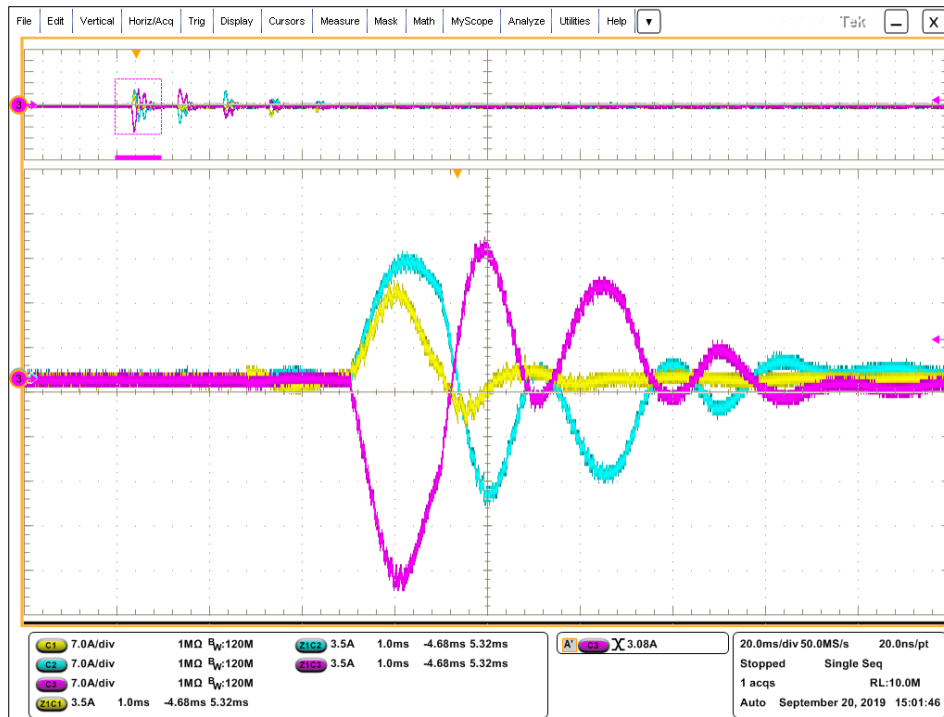


Figure 6.11. Zoom of 3 phase current waveforms for 30 radian position command

The previous test scenario is repeated for 40 radian position command.

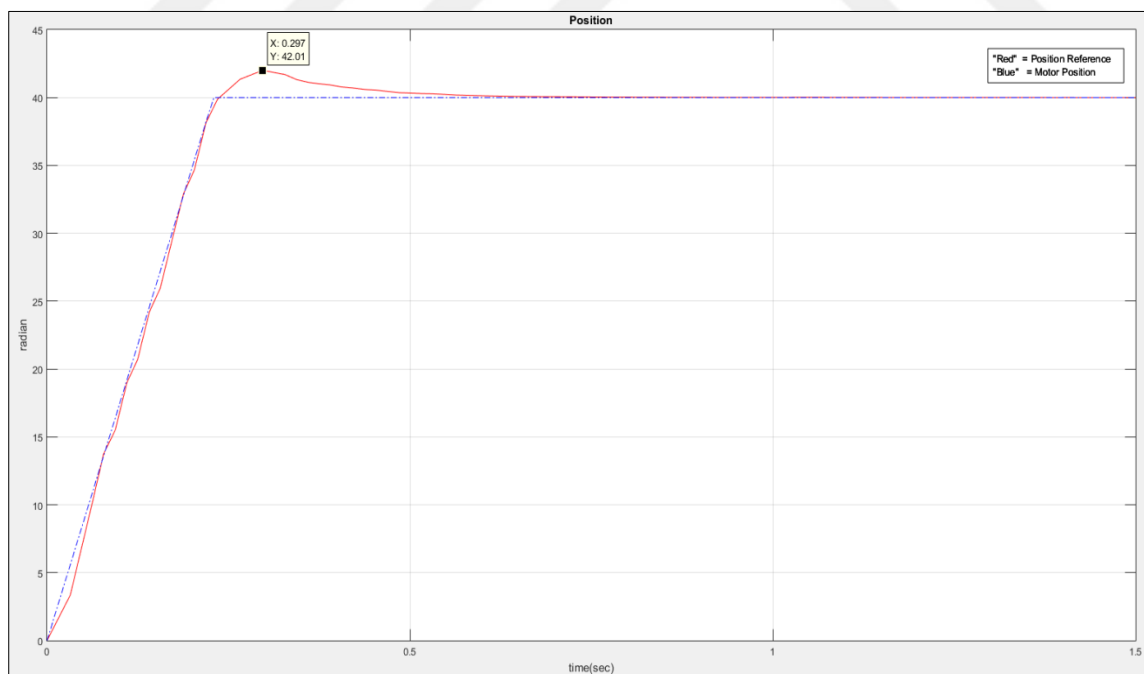


Figure 6.12. 40 radian position command

As can be seen in Figure 6.12, the overshoot on position response is about 5% and this value is within the acceptable range. In steady-state, there is no offset error. The increase in the position command does not affect the performance of the controller.

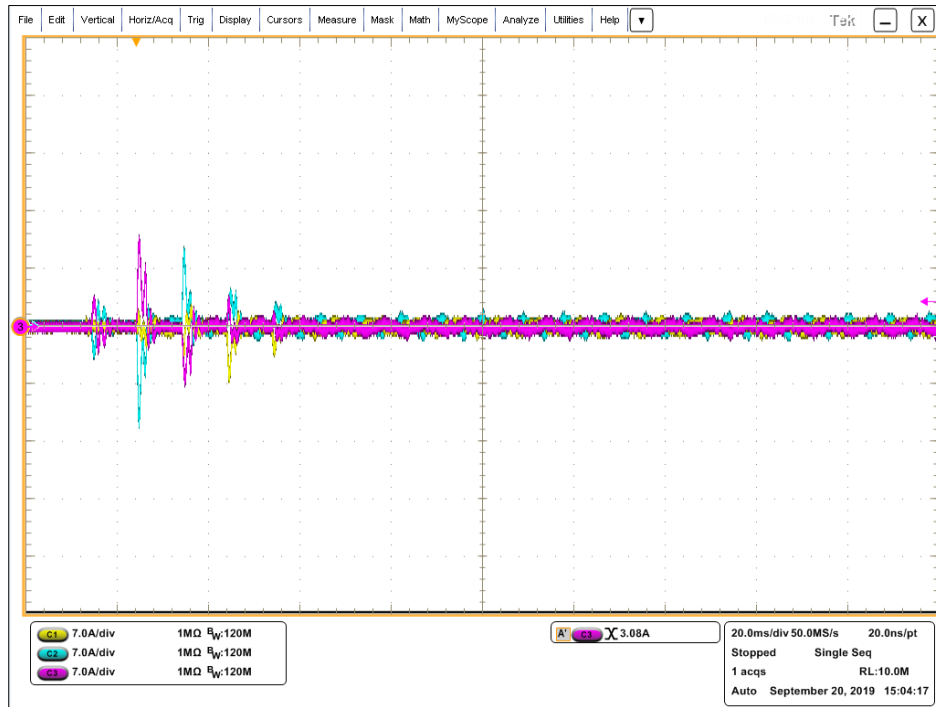


Figure 6.13. 3 phase current waveforms for 40 radian position command

In Figure 6.13, 3 phase current waveforms are shown. As can be seen the current passes through the motor phases only when motor rotates, at the steady-state the magnitude of the 3 phase currents are nearly zero as expected.

In Figure 6.14, a closer look at the phase currents shows that they have a sinusoidal waveform. The amount and duration of the drawn current are less because of the applied position command and inertia.

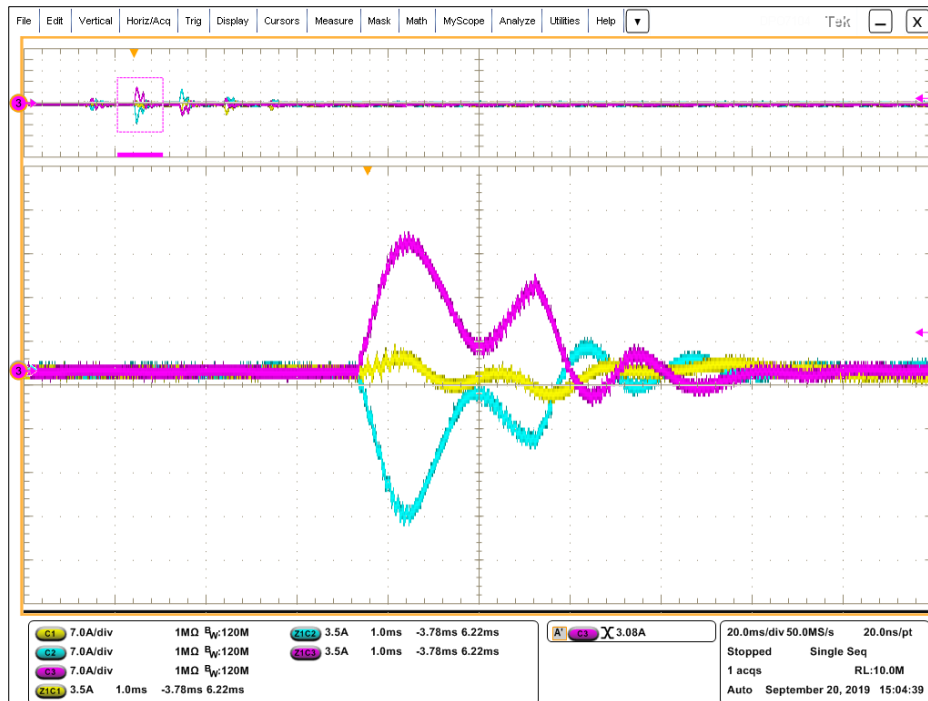


Figure 6.14. Zoom of 3 phase current waveforms for 40 radian position command

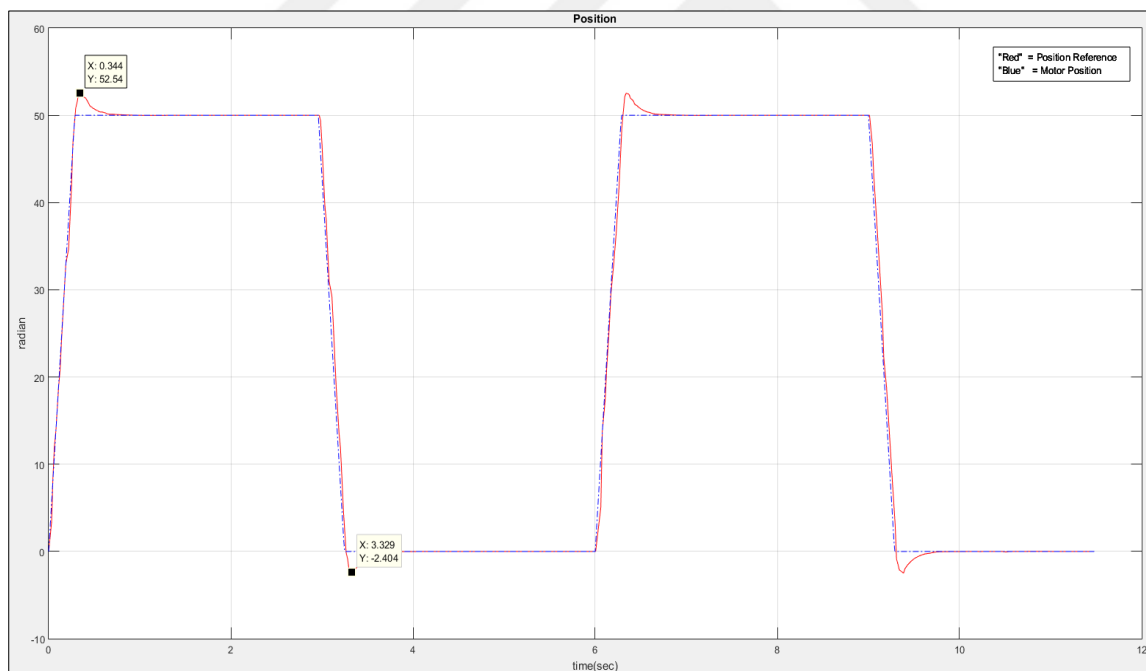


Figure 6.15. 50 to 0 to 50 to 0 radian position commands

Finally, the position commands whose magnitudes are larger than maximum value in opposite directions are sent to observe response of the position controller. The overshoot on position response is about 5% in both positive and negative position commands. At the steady-state, there is no offset error.

The another achievement criterion of the driver electronics is amount of the fluctuation on the DC Bus voltage. The fluctuations on this voltage may affect the performance of the motor in bad way. These fluctuations cannot only be reduced with hardware related precautions. In addition, waveforms of the motor phase currents during the commutation also create stress on the DC Bus voltage as well.

As can be seen in Figure 6.16 and Figure 6.17, the amount of fluctuations on DC Bus voltage is little because the waveforms of the motor phase currents are sinusoidal. The bus voltage reaches a minimum of 26,6 V and a maximum of 29,1 V when the motor rotates. These levels of fluctuations do not adversely affect the performance of the motor.



Figure 6.16. DC bus voltage for 10 to 40 radian position command

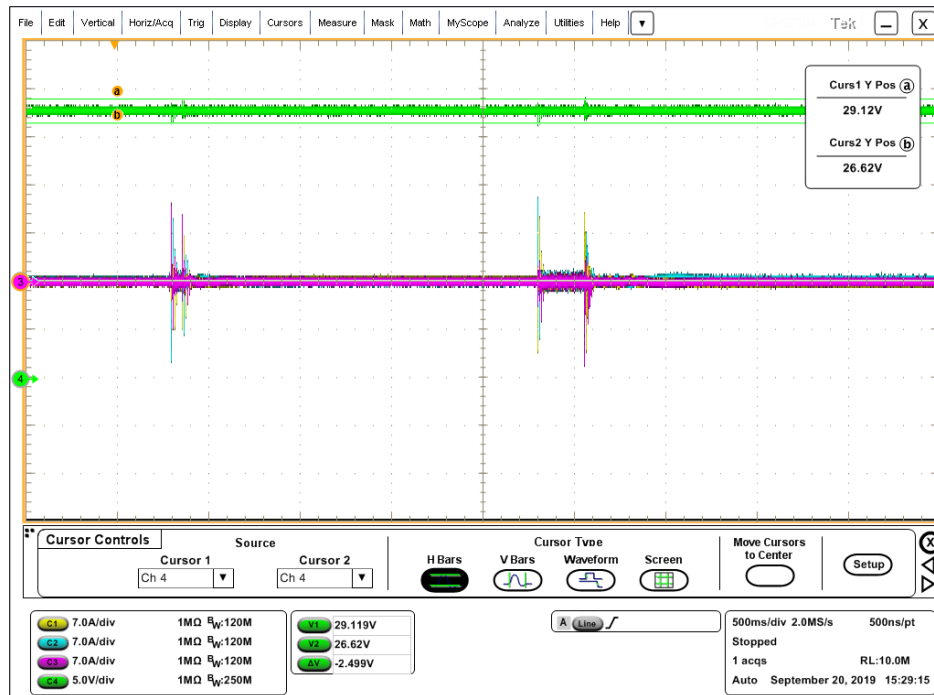


Figure 6.17. DC bus voltage for 10 to 50 radian position command

6.5. Load Tests

Testing the motor only under no load condition is not sufficient to verify the achievement of both the position controller and the proposed SVPWM based FOC technique. Therefore, similar tests should be done with the loads to which the motor may be exposed.

The load torque structure used in the tests is shown in Figure 6.18.

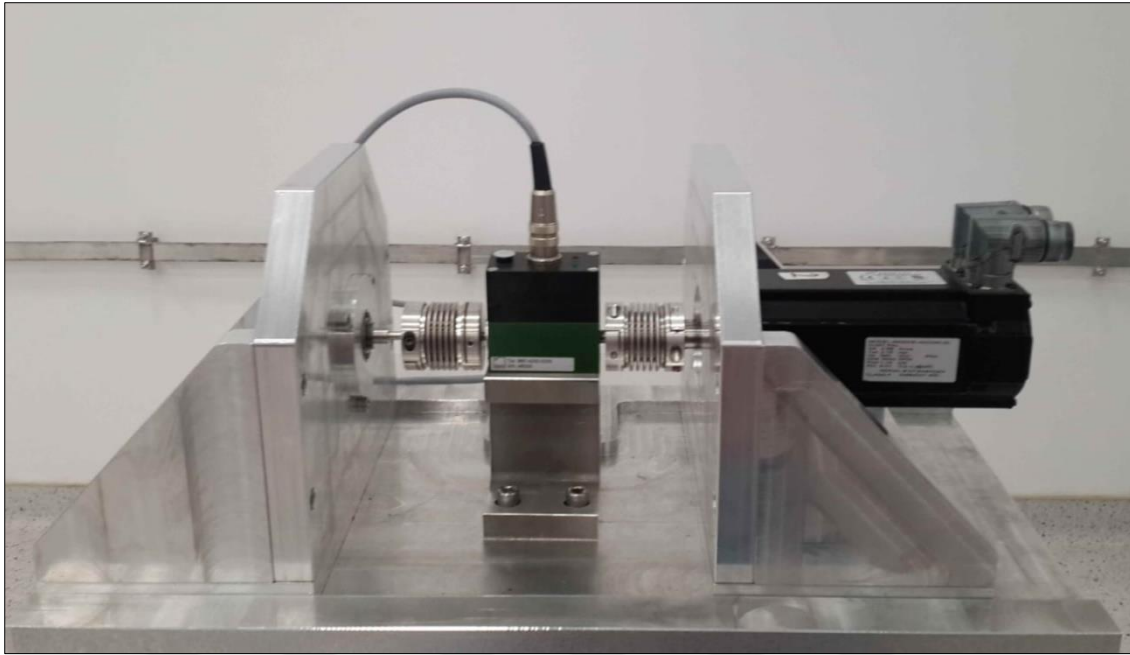


Figure 6.18. Load torque structure

In this setup, shaft of the motor, which is driven by another driver board, is connected to the shaft of the motor under test via proper coupling. The connection must be done properly otherwise produced load torque cannot be transferred to the motor under test. In order to produce constant torque, the constant current is applied to the motor which produces the load torque. As can be understood, since these two motors are not isolated from each other, they affect each other. For example, because of extension of its shaft, during the test the inertia of the motor under test is not equal to the own original inertia value. Unfortunately, this type of interactions affect the dynamics of the motor. Again, the performance of the two independent controllers are in interaction during test, so the performance degradation of one of them directly affect the other side in bad way. These negative effects will be taken into account when interpreting the test results.

Because of its driver electronics design, the load torque structure cannot work in regenerative mode. Therefore, during tests it is paid attention to the direction of rotation of the motors not to be same. As will be seen, position commands, which are all in same direction, are sent to the motor under test.

Before applying load torque, it is also paid attention that the motor under test is in steady state condition.

The PI Controller coefficients that are tuned in no load tests, they are not changed for the under load tests. This decision is made, since it does not happen such an inertia increment and a changement of motor dynamics in the real system. Although it is known that the performance degradation will occur during the load tests, this situation is accepted. Thus, test configuration based effects on the performance of the position controller are observed better.

Since the motor which produces load torque is driven by the another independent interface, the rotor position and the produced torque are plotted on different time axes. The interface which send torque command accepts the moment of starting torque production as the starting time of the test. Thanks to the response of the position controller when the load torque is applied to the motor under test, the intersection moment of two different axes can be detected.

Firstly, 0,16 N.m which is half of the maximum torque load is applied to the motor.

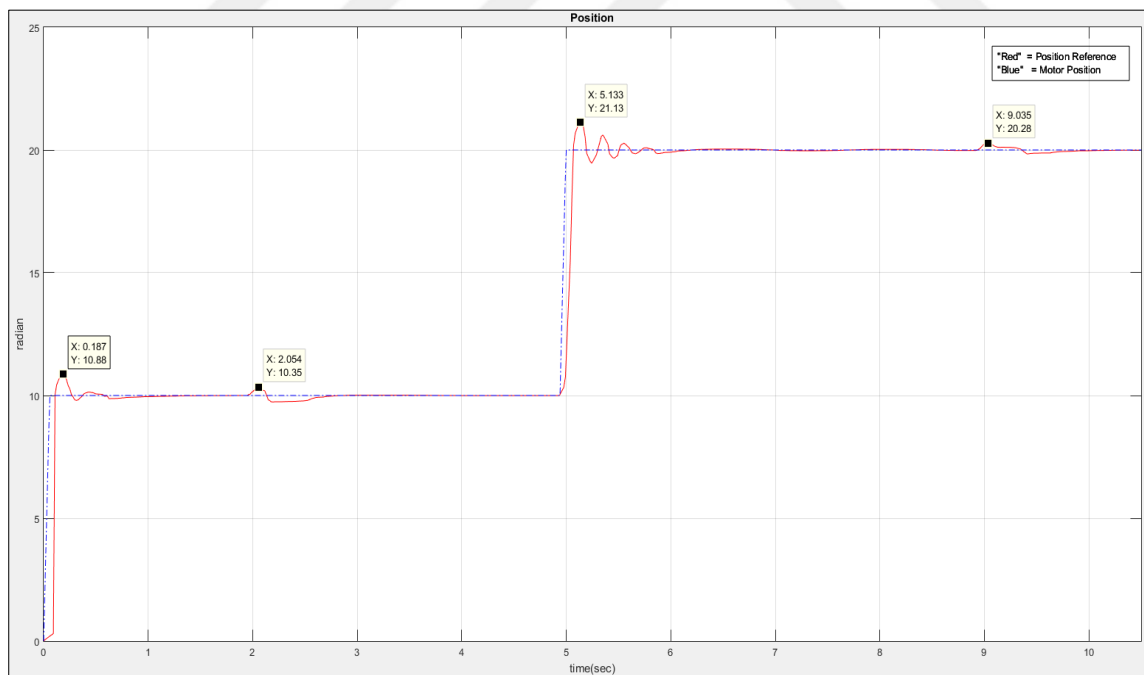


Figure 6.19. 10 to 20 radian position command under 0,16 N.m load torque

The overshoot on position response is 8,8% during the 0 to 10 rad transition. The reason of the increment of this value when it is compared with no load condition is increment of the motor inertia. However, this value is within the acceptable range.

The load torque is applied around $t = 2$ seconds. The position controller fixes the rotor position to the position command after little fluctuations.

It is observed that the amount of overshoot on position response increases during the 10 to 20 rad transition when it is compared with 0 to 10 rad transition. In addition, there is also some undesired fluctuations on position response. Thus, it takes more time for reaching of the rotor position to steady state. The main reasons are increment of the motor inertia and interactions between the motors, respectively. Since the controller of the torque producing motor is also affected by fluctuations, it cannot produce constant torque as expected during this interval. Therefore, the amount of fluctuations on the torque increases. Similar fluctuations are observed in the position response as the oscillation on the torque also affects the performance of the position controller. The overshoot on position response is about 11,1% and it is greater than tolerated amount. This value is acceptable due to the mentioned effects.

The applied load torque is removed around $t = 8$ seconds. The position controller fixes the rotor position to the position command after little fluctuations.

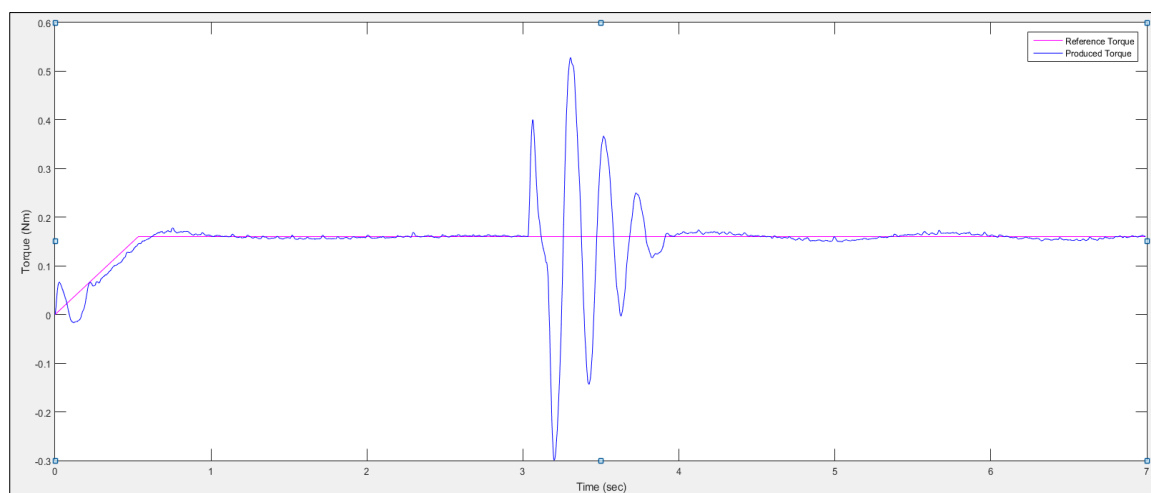


Figure 6.20. Produced torque for 10 to 20 radian position command under 0,16 N.m load torque

In Figure 6.20, while the pink represents torque reference, the blue colour represents produced torque.

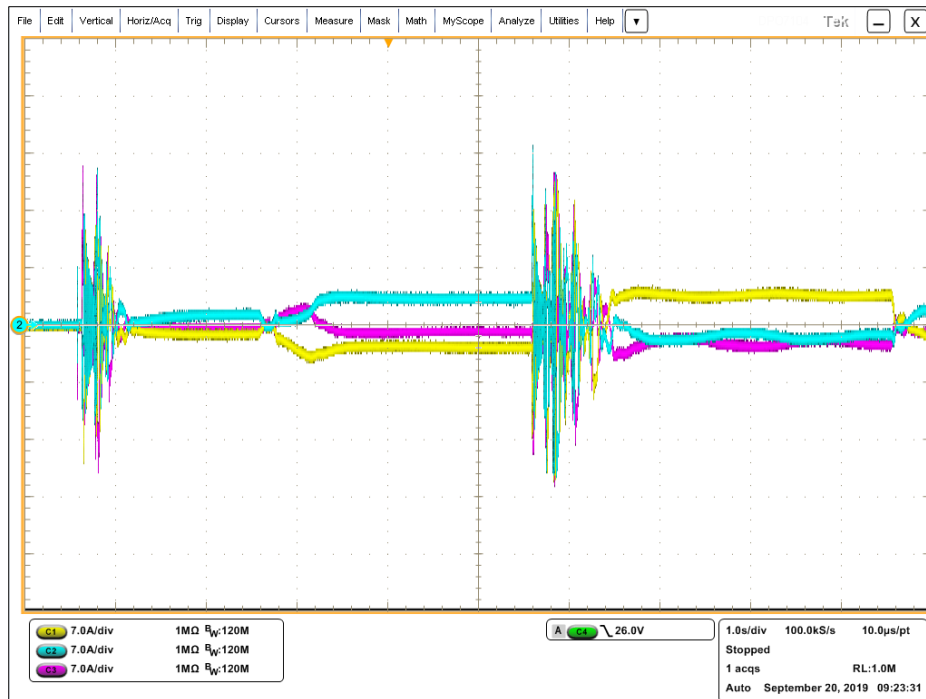


Figure 6.21. 3 phase current waveforms for 10 to 20 radian position command under 0,16 N.m load torque

In Figure 6.21, 3 phase currents waveforms are sinusoidal as expected when the motor rotates and they are constant when the motor is standstill. The difference at under load condition is that the current is passed through the motor phases in order to produce torque against to the applied load torque. Since the generated voltage space vector is always same when the motor is standstill, 3 phase current waveforms have DC value as expected. In this period, there is no commutation occurs so sinusoidal current waveforms are not observed. Contrary to expectations, it is observed that the motor draws constant current in steady-state even though there is no load torque. Since the load torque structure causes friction, this unexpected case is occurred.



Figure 6.22. 3 phase current waveforms for when rotor position is equal to 10 radian and under 0,16 N.m load torque

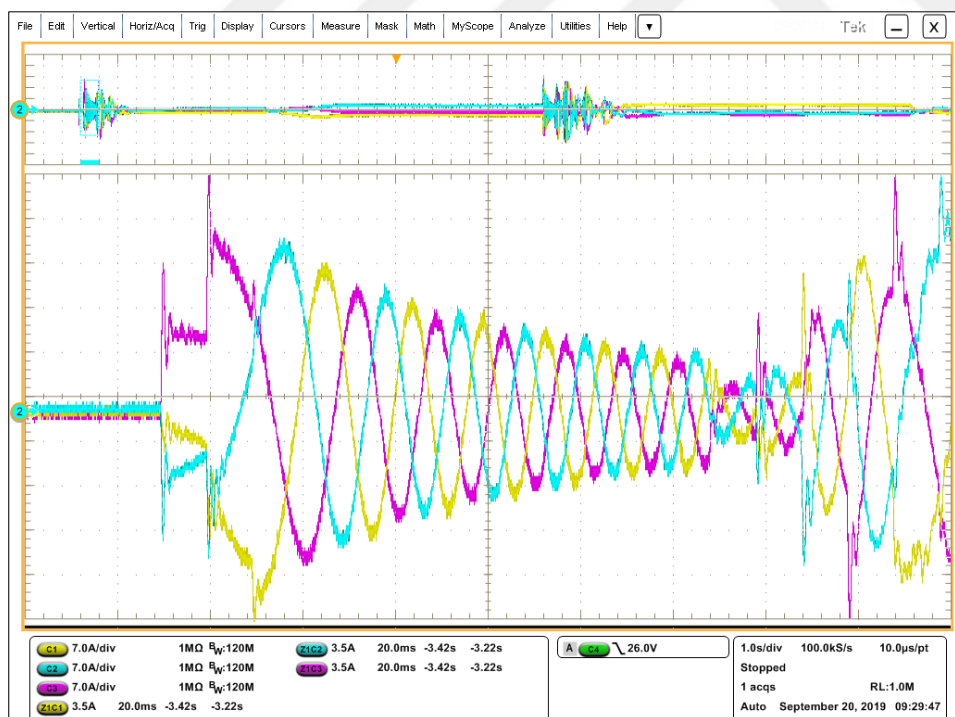


Figure 6.23. Zoom of 3 phase current waveforms for 0 to 10 radian transition

In Figure 6.23, 3 phase current waveforms are shown at the moment of the test starts. Even if there is no applied load, it is observed that duration of starting current is longer than when it is compared with the duration in the no load tests. The reasons are increment of the

motor inertia and presence of the friction stemmed from load torque structure. Due to the these effects, more current are passed through the motor phases as the motor needs to produce more torque at starting.

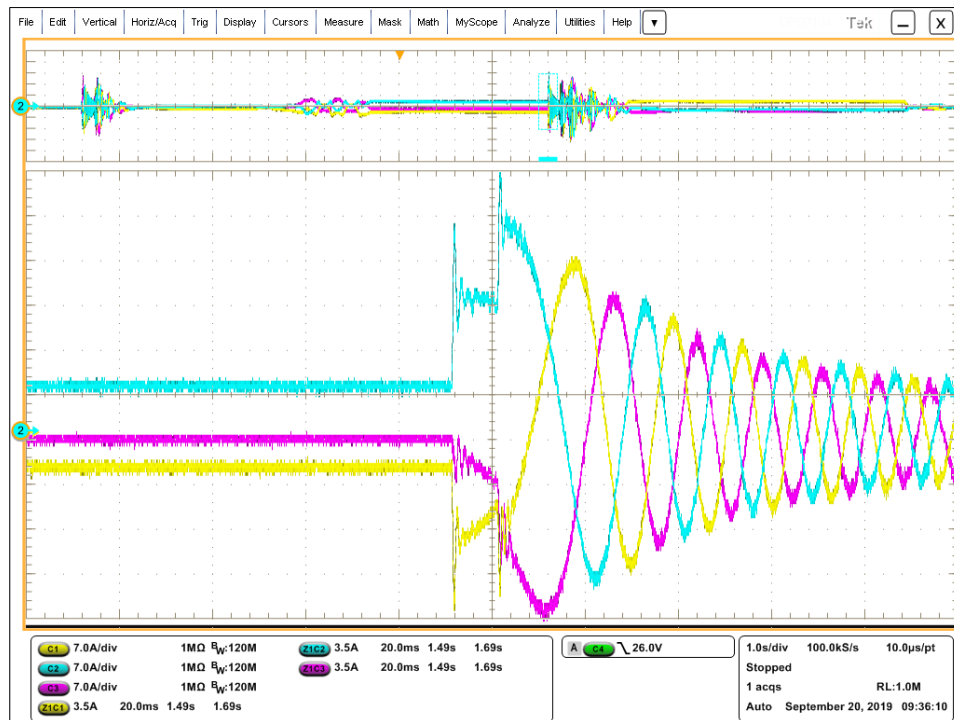


Figure 6.24. Zoom of 3 phase current waveforms for 10 to 20 radian transition under 0,16 N.m load torque

In Figure 6.24, 3 phase current waveforms are shown for 10 to 20 radian transition. The reaching time to the steady-state is increased because of load torque and fluctuations on the position response. Therefore, the amount of current drawn is also increased.

The previous test scenario is repeated by changing the applied load torque with 0,32 N.m which equals to the maximum load torque value.

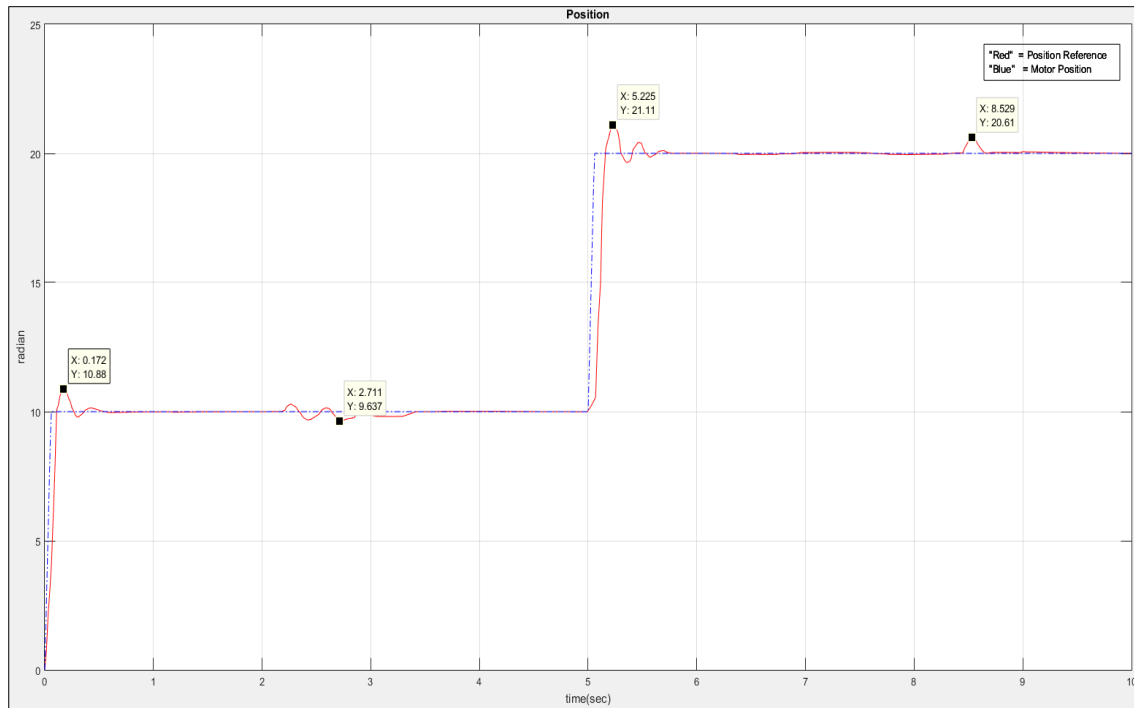


Figure 6.25. 10 to 20 radian position command under 0,32 N.m load torque

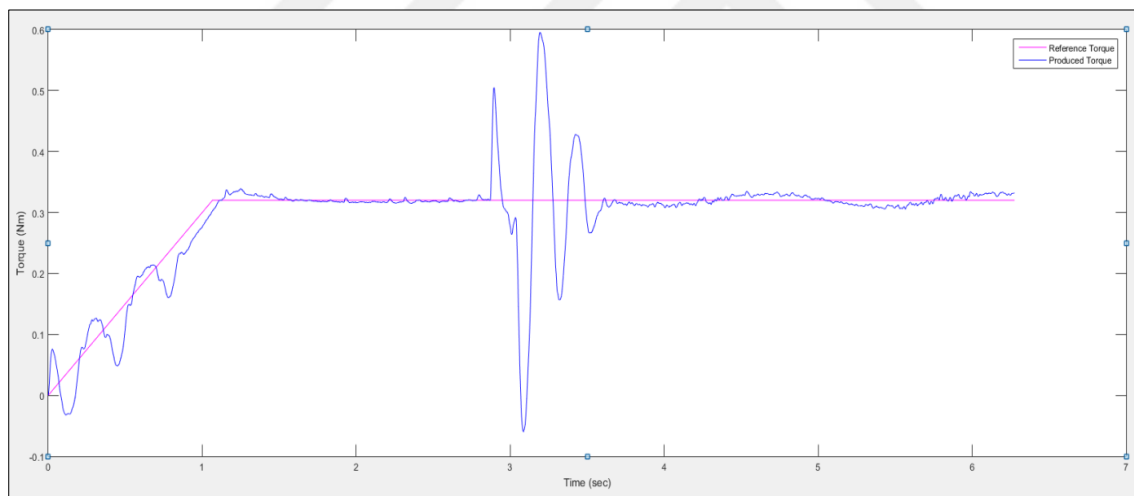


Figure 6.26. Produced torque for 10 to 20 radian position command under 0,32 N.m load torque

Although the applied torque is increased, the fluctuations on the produced torque during the 10 to 20 radian transition decrease when it is compared with previous test. The reason of reduction in the fluctuations can be interpreted by the nonlinear relationship between the two motors.

In steady-state, fluctuations on produced torque is increased when it is compared with 0,16 N.m. Even if this fluctuation which happens when exposed to the maximum load torque is not desired, it can be accepted because of well performance of position controller.



Figure 6.27. 3 phase current waveforms for 10 to 20 radian position command under 0,32 N.m load torque

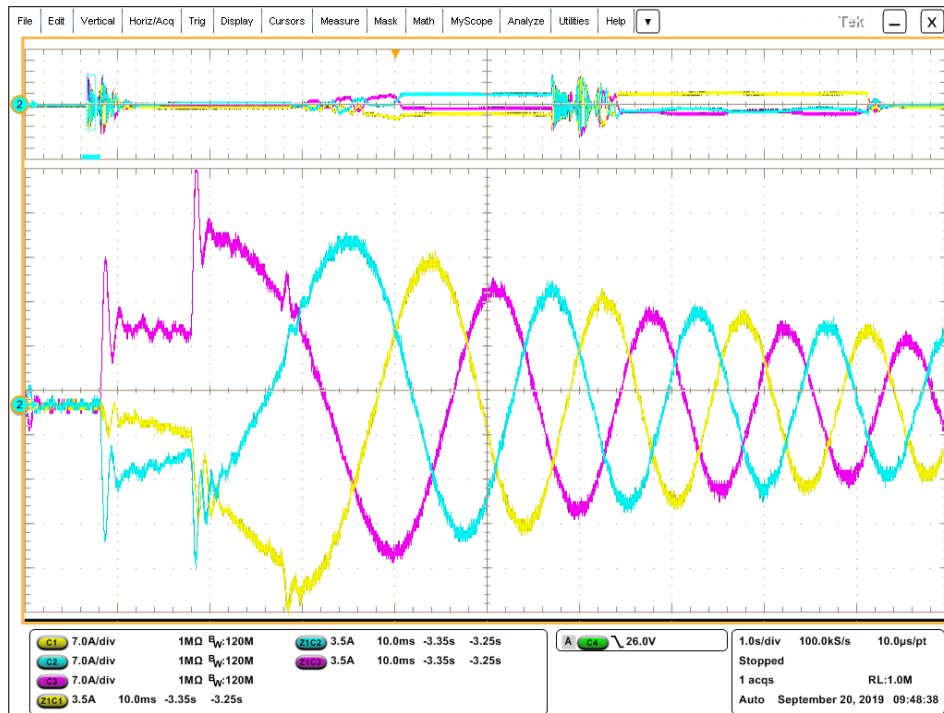


Figure 6.28. Zoom of 3 phase current waveforms for 0 to 10 radian transition

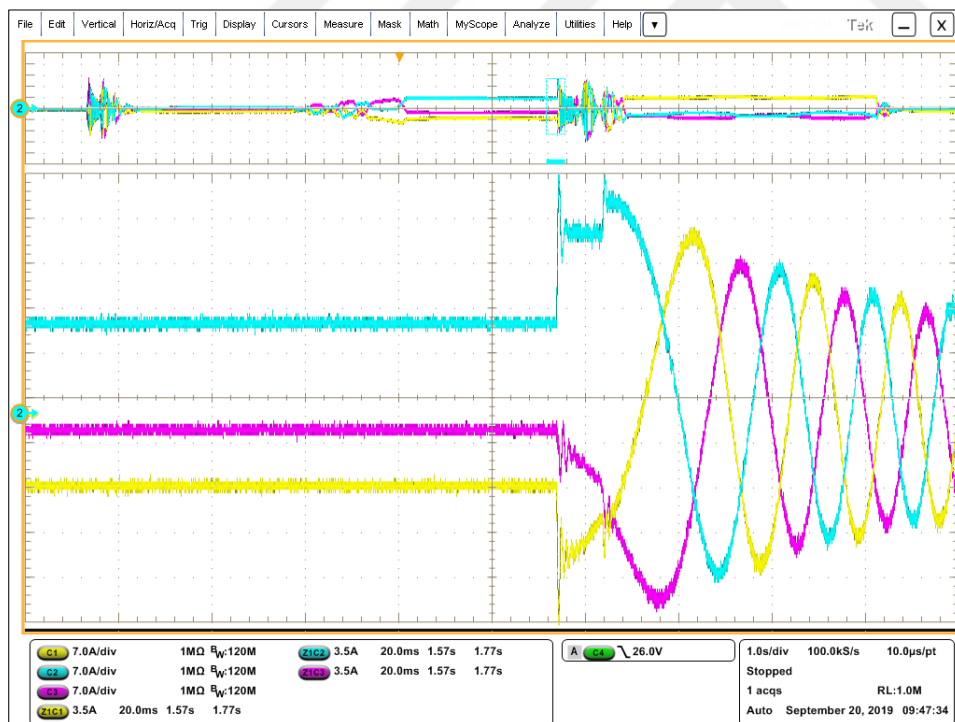


Figure 6.29. Zoom of 3 phase current waveforms for 10 to 20 radian transition under 0,32 N.m load torque

In order to create the worst condition, the maximum operating range position command is sent under maximum load torque. If we return to the "Requirements of Position Controller" section, it is seen that the value of the maximum operating range is 43,5 radian. The

position of the rotor at start is accepted as 0 rad in guidance kits. According to this information, the operating range of the motor is renewed as $[-21,25; 21,25]$ radian. Since the movement between these boundaries is occurred only during the erroneous situations, only uni-directional movement of the rotor is examined to run realistic test scenario. Therefore, maximum position command is accepted as 20 radian.

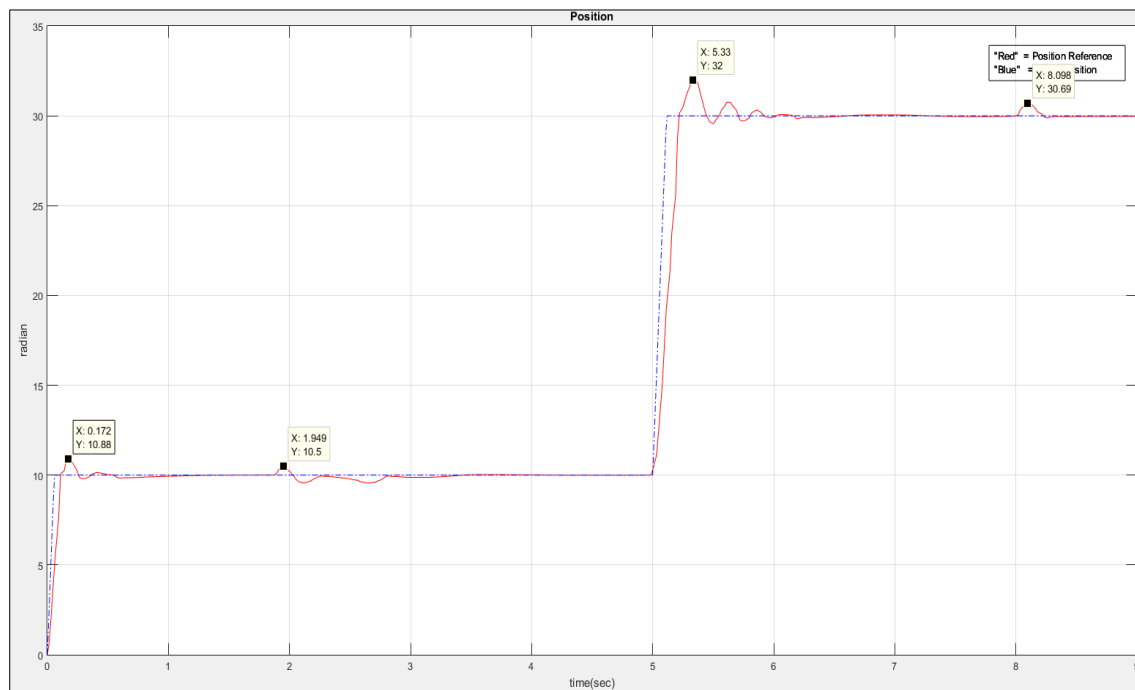


Figure 6.30. 10 to 30 radian position command under 0,32 N.m load torque

In Figure 6.30, it is observed that the amount of fluctuation for 10 to 30 radian transition less than the amount of fluctuation for 10 to 20 radian transition. Since it takes more time to reach the applied position command, the amount of fluctuation on the position response increases due the effect of integral parameter.

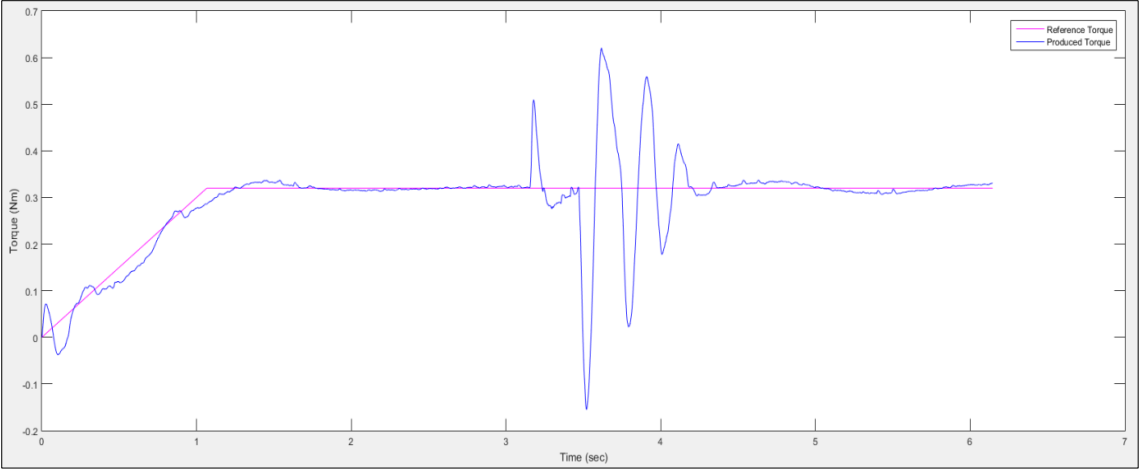


Figure 6.31. Produced torque for 10 to 30 radian position command under 0,32 N.m load torque



Figure 6.32. 3 phase current waveforms for 10 to 30 radian position command under 0,32 N.m load torque

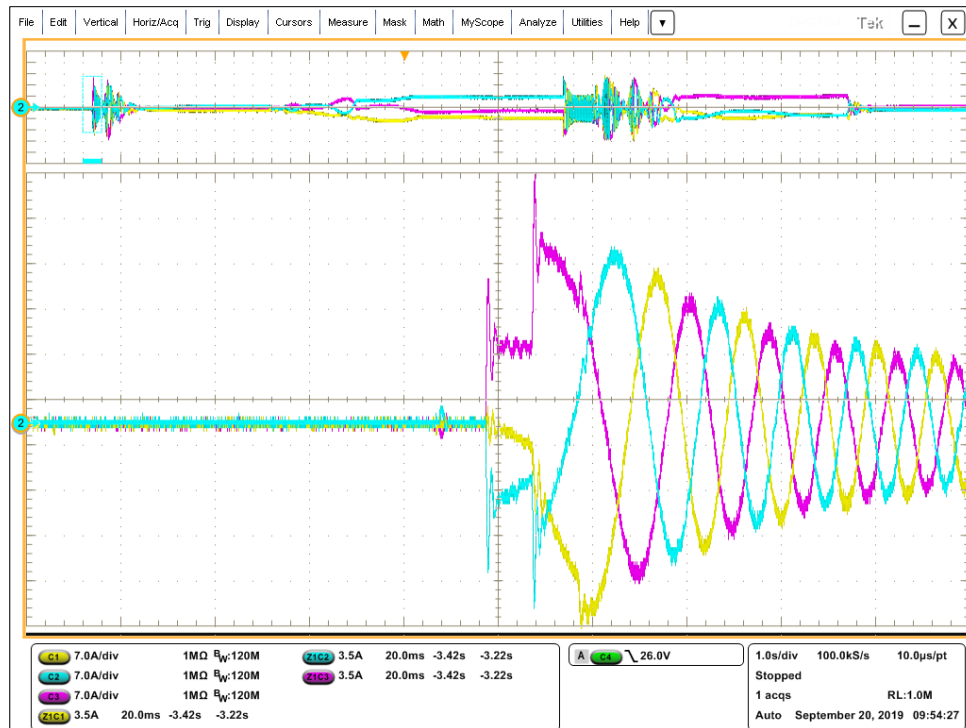


Figure 6.33. Zoom of 3 phase current waveforms for 0 to 10 radian transition

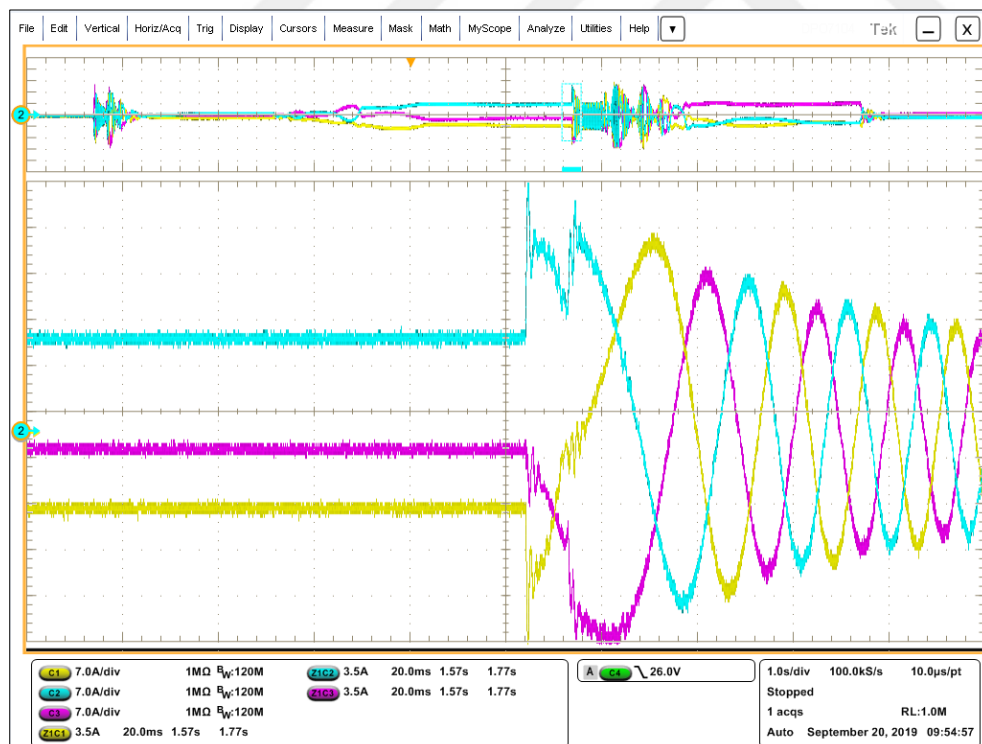


Figure 6.34. Zoom of 3 phase current waveforms for 10 to 30 radian transition under 0,32 N.m load torque

The stability of the DC Bus voltage is also examined under load torque. The decrement in the DC Bus voltage because of fluctuations, may degrade the torque response of motor by

limiting the amount of producible torque. In Figure 6.35 and Figure 6.36, fluctuations on DC Bus voltage under 0,20 N.m load torque are shown. As expected, the voltage dip is happened when the motor rotates under load torque. Although the voltage level of DC Bus is nearly equal to 25 V at this moment, this voltage value is sufficiently high so that it does not limit the torque response of motor.

The increase in DC Bus voltage is due to the motor is working in regenerating mode. The voltage level reaches 35 V. Since the voltage breakdown values of the components used in the design are at least 60 V, this voltage increase does not adversely affect the components and performance of the controller.



Figure 6.35. DC bus voltage for 10 to 40 radian position command under 0,2 N.m load torque

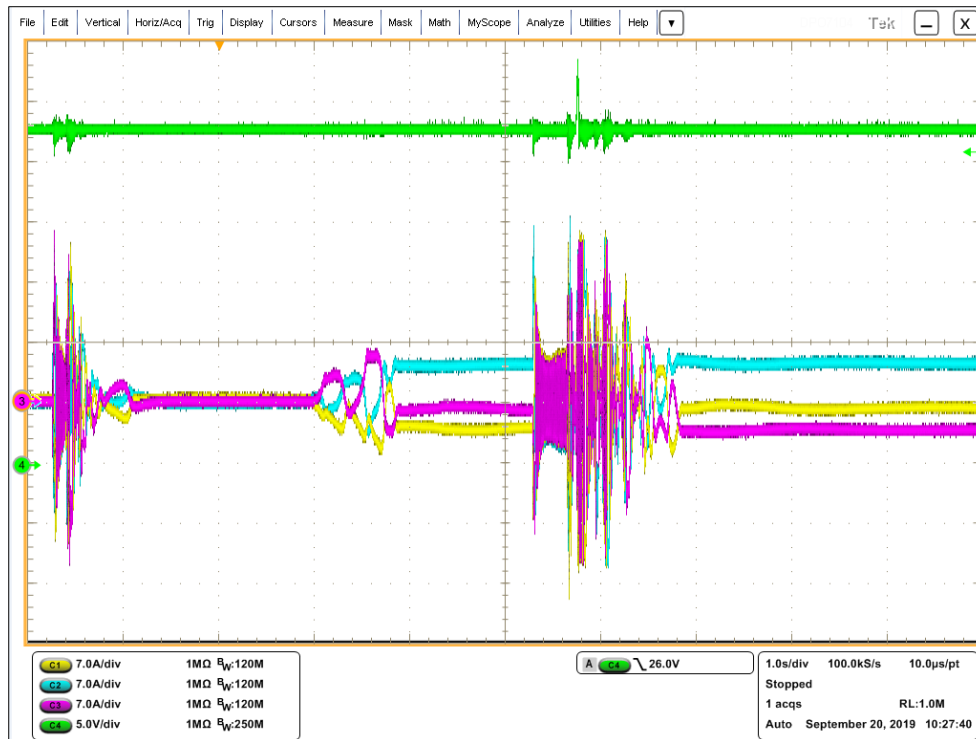


Figure 6.36. DC bus voltage for 10 to 50 radian position command under 0,2 N.m load torque

6.6. General Evaluation

As a result of the tests, some differences were observed between the simulation and the actual system in terms of position controller performance.

The reasons why overshoot, undershoot and fluctuations which were occurred in the actual system did not arise in simulation can be listed as follows:

- The infinite bandwidth of speed and position PI Controller in the simulation
- The usage of the comparatively large PI Controller coefficients in the simulation
- The absence of the actual system restrictions such as necessity of the dead-time insertion, turn on and turn off time of the MOSFETs, the time requirement for the bootstrap capacitor charge, unstable DC Bus voltage and side effects of the PCB design etc.
- The non-isolated load torque which was used in the actual system
- The unstable performance of the load torque which was used in the actual system
- The increase in inertia of the motor in the actual system because of load torque structure

- The presence of the sensor-related errors in the actual system
- The inability to tune the controller coefficients as desired due to the data monitoring restrictions

While there were some deviations at the performance of the position controller, results of the SVPWM based FOC technique which is applied for commutation and current controller were almost same as simulation results. Thus, the simulations were used as a guidance during the development and the testing of the design.

In the actual system, it was observed that 3 phase current waveforms contain more sinusoidal characteristic than ones in the simulation. The reason for this is the fact that while the back EMF was purely trapezoidal in the simulation, in real it consisted of sinusoidal and trapezoidal waveforms due to the inductance effect.



7. CONCLUSION

The main motivation of this thesis is to verify that the applicability of the SVPWM based FOC technique for the control of the BLDC Motor and increasing the modularity for actual systems by using the microcontroller.

In the thesis, SVPWM based FOC technique was applied for commutation and current control of the BLDC Motor. In addition, speed and position control of the BLDC Motor was achieved with the usage of the PI Controller.

In order to verify the performance of the SVPWM based FOC technique to be used for the control of the BLDC Motor, it was aimed to meet the basic requirements of this technique during the design process. For this reason, recent studies such as, working in the “overmodulation space vector region” instead of the “undermodulation space vector region” to develop the SVPWM based FOC technique were not applied to the design. In this design, all voltage space vectors were generated within the undermodulation space vector region. Furthermore, by using the proposed "Boundary Detector" block, the generation of the erroneous voltage space vector was blocked.

Before starting hardware and software design, the proposed system was first modeled in SIMULINK. In order to make simulation more realistic, the SVPWM based FOC was modeled with its own operating frequency. In this way, design errors stemming from some phenomena that might occur in the actual system were avoided. In addition, due to monitoring the limited amount of data from the microcontroller because of its limited processing power, detailed information about the dynamics of the system was obtained through simulation.

In the hardware design, the driver board, which consists of driver electronics and current sensors, was designed and produced. Since NUCLEO-F746ZG was used as the controller board, it was taken care that the driver board, which was designed to increase the compactness of the system, can be connected to the NUCLEO-F746ZG without the use of cables. The driver board which was designed with 4 layers contains two different ground references namely digital ground and power ground. Since the designed driver board

contains extremely noisy AC motor phases and sensitive signals such as analog outputs of current sensors and digital switching signals, the stack-up was adjusted properly and drawing of the PCB were paid attention.

STM32F746ZG microcontroller was preferred for software implementation. Instead of designing board for STM32F746ZG, the NUCLEOF746ZG development board with STM32F746ZG was used as control board. Interrupt-based software that communicates with PC over UART was developed. Because it is an Arm-based microcontroller, the developed code can be adapted to any other Arm-based microcontrollers easily. In this way, the flexibility and the configurability of the system were increased.

The simulations were supported by tests with and without load in the lab environment. The requirements of the position controller were fully met at no-load tests. The requirements were also met when motor under load, but some undesired situations observed on position response such as fluctuation and long setting time because of the working principle of the load.

As a result of this study, it was proven that SVPWM based FOC technique can be used for control of the BLDC Motor successfully. Thanks to the success of the prototype design that works with SVPWM based FOC technique, it was also proven that the electronic board, which both contains controller and driver sections, can be integrated to the actual weapon systems with little effort.

As a future work, the performance of the system can be improved with the usage of powerful microcontroller. By this way, the operating frequency of the current controller can be increased in order to support the usage of wide range of BLDC Motor.

It is also planned that improving the new SVPWM based FOC technique, which works with overmodulation principle and can adapt its voltage space vector region according to variable DC Bus voltage.

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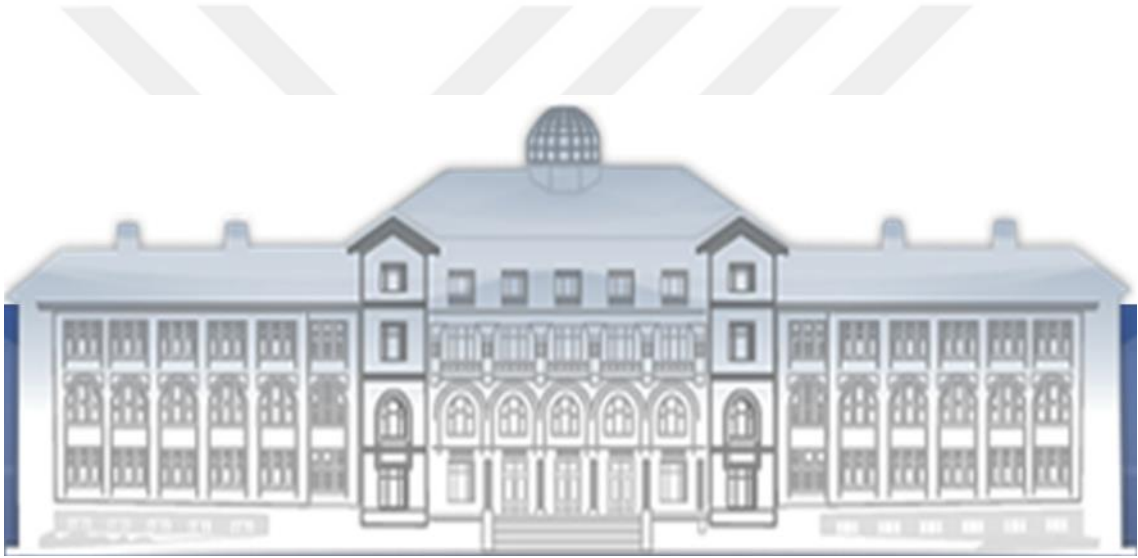
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Kokundu, S. (In Press). UVDGM Tabanlı AYK Yöntemiyle Fırçasız Doğru Akım Motorunun Konum Kontrolü. *Gazi Üniversitesi Fen Bilimleri Dergisi Part C: Tasarım ve Teknoloji*.

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GAZİ GELECEKTİR...