

UNIVERSITY OF GAZIANTEP
GRADUATE SCHOOL OF
NATURAL & APPLIED SCIENCES

**MODELING AND IMPLEMENTATION OF VARIABLE FREQUENCY
DRIVE BASED ON OPEN-LOOP Volt/Hertz**

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IN
ELECTRICAL AND ELECTRONICS ENGINEERING

BY
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**Modeling and Implementation of Variable Frequency Drive based
on open-loop Volt/Hertz**

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In

Electrical and Electronics Engineering

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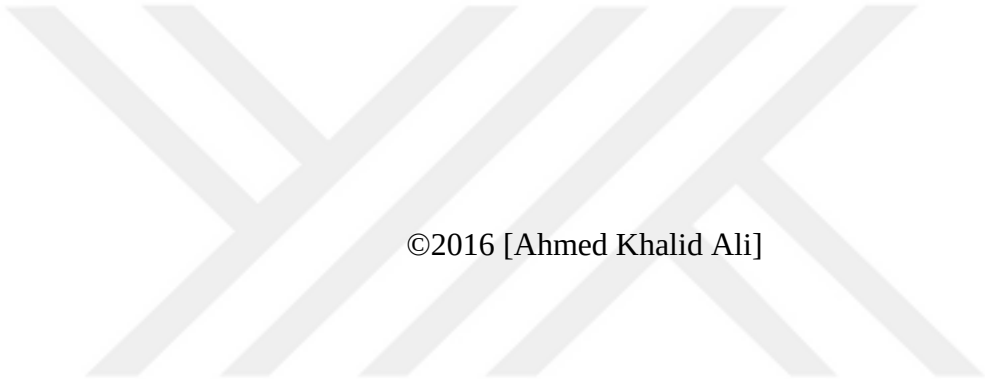
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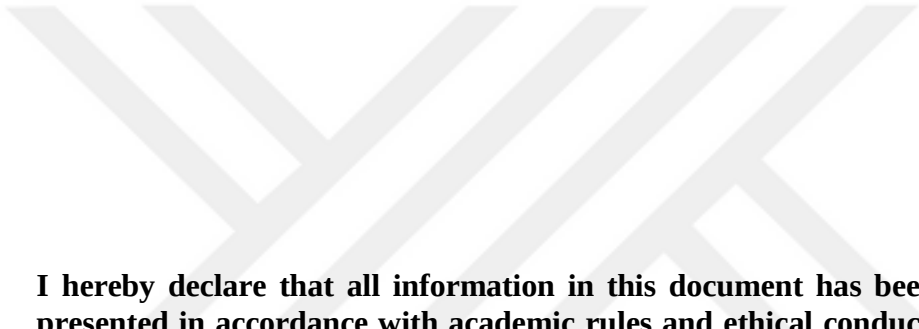


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Ahmed Khalid Ali

ABSTRACT

MODELING AND IMPLEMENTATION OF VARIABLE FREQUENCY DRIVE BASED ON OPEN-LOOP VOLT/HERTZ

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A single or three -phase squirrel cage motors are one of mostly used in many industrial applications this motors consuming more than half of the total generated electrical energy .The Induction motors can run only at their full speed when they are attached to the AC supply. However, speed control of squirrel cage motors is important to many industrial applications that require variable flow control of fluid (air, water and chemical liquid). Speed control method that has been developed with voltage-source inverter become a popular method for the speed control of induction machines. The purposes of this thesis are to model and implement an AC-Drive, by three type inverter switching techniques as Sinusoidal Pulse width Modulation (SPWM), Third Harmonic Injection Pulse Width Modulation (THIPWM), and Space Vector Pulse Width Modulation (SVPWM). These techniques are based on Voltage-Source Inverter (VSI) and open- loop speed controller, with principle (Volt/Hertz). The three switching techniques and open-loop (Volt/Hertz) control are compared with each other's. The mathematical model has been developed for AC-drive system. Also, the model has been simulated by a software to evaluate the performance of open-loop speed control system with three switching techniques. The results indicate that the mathematical model is accurate and practicable, also achieved to satisfy the requirements of the users. Moreover, in the thesis, a practical model of AC-Drive with SPWM technique has been realized. The practical model imitates to conceptions of power electronic module, (HY-DQ Inverter v 2.0) module used to control and drive of the three phase squirrel cage induction motor. This practical model has quality of completely implemented and exact results are obtained. The experimental results are based on the voltage measured in load side and rotor speed with actual load (1-hp IM). These results have shown satisfactory performance of the system from output voltage waveform and rotor speed.

Key Words: Motor speed control, induction Motor, inverter

ÖZET

AÇIK DÖNGÜ VOLT VE FREKANS DAYALI DEĞİŞKEN FREKANS SÜRÜCÜNÜN MODELLENMESİ VE GERÇEKLEŞTİRİLMESİ

Ahmed. Khalid Ali

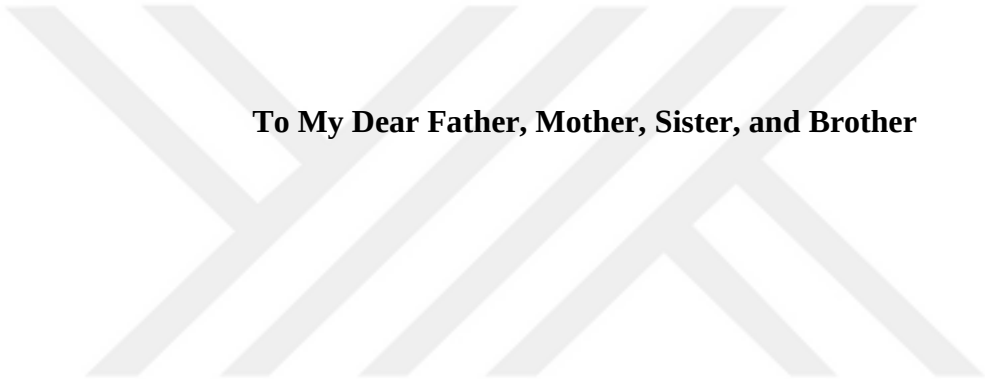
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Tek veya üç fazlı sincap kafesli motorlar toplam üretilen elektrik enerjisinin yarısından fazlasını tüketen endüstriyel uygulamalarda çoğunlukla kullanılan motorlardır. Endüksiyon motorlar tam hızlarında sadece dalgalı akıma bağlı iken çalışabilirler. Ancak, sincap kafesli motorların hız kontrolü değişken akış kontrolü gerektiren (hava, su ve kimyasal sıvı) birçok endüstriyel uygulamalar için önemlidir. Gerilim kaynaklı dönüştürücü ile geliştirilmiş hız kontrol yöntemi asenkron makinaların hız kontrolü için popüler bir yöntem haline gelmiştir. Bu tezin amacı, Sinüs Darbe Genişlik Modülasyonu (SDGM), Üçüncü Harmonik Enjeksiyon Darbe (ÜHEDGM) ve Uzak Vektör Darbe Genişlik Modülasyonu (UVDGM) gibi üç tip inverter anahtarlama teknikleri ile bir AC sürücünün modellenmesi ve gerçekleştirilmesidir. Bu teknikler gerilim kaynak inverter (GKI) ve (Volt / Hertz) prensibi ile açık-döngü hız kontrolörüne dayanmaktadır. Üç anahtarlama teknikleri ve açık-döngü (Gerilim / Hertz) kontrolü birbiri ile karşılaştırılmıştır. AC tahrik sistemi için matematiksel model geliştirilmiştir. Ayrıca, model üç anahtarlama teknikleri ile açık çevrim hız kontrol sisteminin performansını değerlendirmek için bir yazılım ile benzetimi yapılmıştır. Benzetim modellerinden elde edilen sonuçların karşılaştırılması; değişken hız takibi, yük bozucu ve inverter çıkış parametreleri (gerilim, akım toplam harmonik bozulma) açısından AC- tahrik sisteminin performansında iyileştirme olduğunu gösterdi. Sonuçlar matematiksel modelin doğru ve uygulanabilir olduğunu ilaveten kullanıcıların gereksinimlerini karşılamak için elde edilebilir olduğunu göstermektedir. Ayrıca, tezde, sinüs darbe genişlik modülasyonu tekniği ile AC-tahrik sisteminin pratik bir modeli hayata geçirilmiştir. Pratik model 3-fazlı sincap kafesli endüksiyon motorun sürülmesi ve kontrolü için kullanılan güç elektroniği modülünü (HY-DQ Inverter v 2.0) taklit eder. Bu pratik model tamamen uygulanır niteliktedir ve kesin sonuçlar elde edilmektedir. Deneysel sonuçlar yük tarafında ölçülen gerilim değerine ve gerçek yükteki rotor hızına dayalıdır. Sonuçlar çıkış gerilim dalga şeklinden ve rotor hızından sistem performansının tatmin edici olduğunu gösterdi.

Anahtar kelimeler: Motor hız kontrolü, asenkron motor, inverter.



To My Dear Father, Mother, Sister, and Brother

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LIST OF SYMBOLS

$a \ a^2$	Unity Vector Operator ($e^{j2\pi/3}, e^{-j2\pi/3}$)
A_m	Optimization Parameter
f	Rated Frequency (Hz)
f_r	Modulation frequency (Hz)
f_c	Carrier Frequency (Hz)
f_s	Sampling frequency (Hz)
f_{comn}	Command Frequency ratio (p.u.)
G_e	Open – Loop Controller Gain
V_{ao}, V_{bo}, V_{co}	Transistors Gating Signals
$V_{mod(a)}, V_{mod(b)}, V_{mod(c)}$	Three Reference Sinusoidal Waveforms
$V_{six-step}$	Fundamental Component of the Square Wave (V.)
V_{an}, V_{bn}, V_{cn}	Output Phase Voltage (V.)
V_{comn}	Desired command modulation Voltage (p.u.)
V_{DC}	Supplied DC Voltage (V.)
V_{in}	Applied Voltage (V.)
V_m	Induced EMF (V.)
$V_0 \dots \dots V_7$	Space Voltage Vectors
V_p	Peak Value of the Modulating Signal (V.)
V_β, V_ψ	Quadrature and Direct Voltage (V.)

V_{ref}	Reference Output Voltage (V.)
V_T	Peak Value of the Carrier Signal (V.)
N_r	Rotor Actual Speed (R.p.m)
N_s	Synchronous Speed (R.p.m)
I_1	Stator Phase Current (A.)
I_2	Rotor Phase Current (A.)
j	Total Moment of Inertia (rotor) (kg.m ²)
M	Modulation Index
M_i	SVPWM Modulation Index
P_{in}	Rotor Input Power (W.)
P_{mech}	Mechanical Power (W.)
Q1...Q6	Power Transistors
R_r	Rotor Resistance (ohm)
R_s	Stator Resistance (ohm)
s	Motor Slip
S_a, S_b, S_c	Transistors Switching States
T_a, T_b, T_c	Switching Time Intervals (sec.)
T_e	Electromagnetic Torque (N.m)
T_L	Load Torque (N.m)
T_{max}	Maximum Torque (N.m)
T_{mech}	Rotor Mechanical Torque (N.m)
T_s	Sampling Time or Switching Time of the PWM (sec.)
ω_e	Electrical frequency (rad./sec.)

ω_m	Rotor Speed (rad./sec.)
ω_s	Synchronous Speed (rad./sec.)
X_m	Magnetizing Reactance (ohm)
X_r	Rotor Reactance (ohm)
X_s	Stator Reactance (ohm)
ψ, β	Quadrature and Direct Rotating Frame Axis Rotor
φ	Air Gap Flux (wb.)
ℓ_e	Motor Fixed Losses
λ	Optimization Unity Factor
$\bar{u}$	Optimization Maximum Value
α	Variation Ratio of Applied Voltage and Supply Frequency
θ_e	Electrical Angle of Reference Voltage Vector (rad.)
θ	Space Vector Sector Position Angle (rad.)

List of Abbreviations

PWM	Pulse Width Modulation.
SPWM	Sinusoidal Pulse Width Modulation.
SVPWM	Space Vector Pulse Width Modulation.
THIPWM	Third harmonic Injection Pulse Width Modulation.
THD	Total Harmonic Distortion.
VSI	Voltage Source Inverter.
VFD	Variable frequency drive
VSD	Variable speed drive
E-VSD	Electrical variable speed drive

CHAPTER 1

INTRODUCTION

1.1 General

The main types of motors that are used in speed control are DC. Motors and induction motors (IMs). The induction motors particularly the cage type, are the most commonly used in industry due to their advantages over the DC motors. The main advantage is that induction motors do not require an electrical connection between stationary and rotating parts of the motor. Therefore, they do not need any mechanical commutator and brushes leading to the fact that they are maintenance free motors. Induction motors are cheap, robust, rugged structure, high efficiency (up to 80% higher), Furthermore, the induction motors can work in explosive environments because no sparks are produced [1, 2].

The wide developments in power electronics technology and power semiconductor devices, lead to replace the major variable speed applications use DC. Machine by AC .Machine, AC-Drives are replacing DC-Drives and they are used in many industrial and domestic applications.

However, a Variable Speed Drive (VSD) for AC machines are an important part in every industrial processes. They are an improvement and help to optimize the process, reduce an energy and operating costs. There are three types of (VSD) systems: mechanical drives, electrical drives, and finally hydraulic drives. In this study the focus is on the electrical drives, because they deal with our research [2]

In this Chapter how to control the induction motor, which is the most popular used AC. Machines will be discussed.

1.2 Electrical Variable Speed Drives (VSD):

The electric variable speed drive (VSD) system, also known as a Variable Frequency Drive VFD and other names, such as inverter, frequency converter or AC drive. It consists of a power electronic converter, control system, and electric motor as shown in figure (1.1). The converter is controlled to AC power flow from supply to the electric motors. It is controlled to power electronic switches by using PWM techniques. [2].

However, A VFD is a device which is widely used is setting the variation (V/f) Constants value that is being supplied to an electric motor. However, that controls the speed of motors, a VFD can control both torque and speed of the motor. Therefore, provides a widely range to adjustable motor's speed, and also improves system efficacy. [3] This will be discussed in Chapter three of this study.

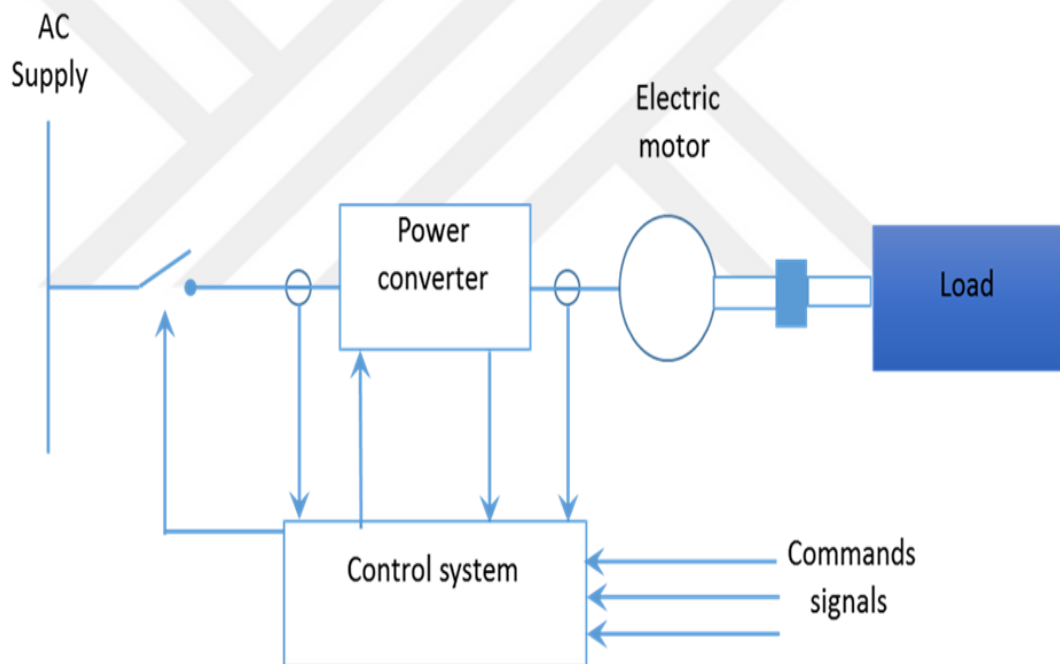


Figure 1.1 Electric variable speed drive (E-VSD) system scheme diagram [2]

1.3 Energy saving in electrical (VSD):

The electric variable speed drive (E-VSD) System is an important part in automation processes. The energy is saved indirectly, by reducing energy consumption. This way saves energy with centrifugal loads running at fixed speed such as fans and pumps. [2]

However, the energy can be reduced to 60%, for 90kw motor size during continuous operation. This can save £9,000 per year, because the VFD reduces the energy drawn by motor. Also a small reduction in motor speed can give a more energy saving centrifugal load running at 80% of rated speed. The energy drawn by motor is only half compared with one running at rated speed of motor [4].

1.4 Induction motor drive:

Figure (1.2) shows the approximately equivalent circuit of the induction motor, which represents the induction motor parameters at slip “s”:

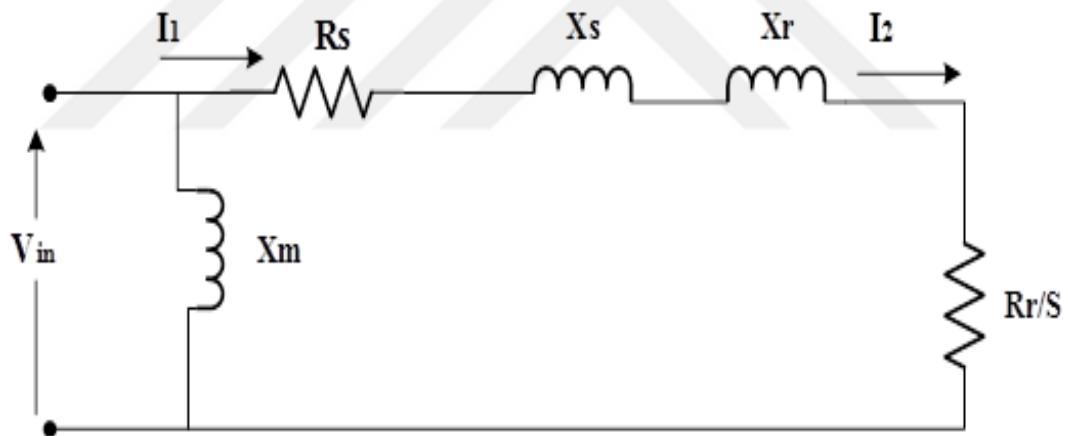


Figure 1.2 Induction motor equivalent circuit

Where:

“ R_s ” is the per-phase stator resistance, “ R_r ” per-phase rotor resistance (referred to stator) “ X_s ” per-phase stator reactance, “ X_r ” per-phase rotor reactance (referred to stator), “ X_m ” is the leakage reactance, “ I_1 ” input phase current, “ I_2 ” rotor phase current (referred to stator), “ V_{in} ” input phase voltage. [1, 2, 5]

From the equivalent circuit the following parameters can be found:

$$\text{Rotor input power (P}_{in}) = 3(I_2)^2 \frac{R_r}{S} \quad \text{Watt} \quad (1.1)$$

$$\text{Mechanical power (P}_{mech}) = P_{in}(1 - S) = 3(I_2)^2 \frac{R_r}{S} (1 - S) \quad \text{Wat} \quad (1.2)$$

$$\text{Rotor Torque(T}_e) = \frac{P_{mech}}{\omega_m} = \frac{3V_{in}^2 R_r}{2\omega_s [(R_s + \frac{R_r}{S})^2 + (X_s + X_r)^2]} \quad \text{N. m} \quad (1.3)$$

$$\begin{aligned} \text{Maximum Torque(T}_{max}) &= \frac{P_{mech}}{\omega_m} \\ &= \frac{3V_{in}^2}{2\omega_s \left[R_s + \sqrt{R_s^2 + (X_s + X_r)^2} \right]} \text{N. m} \end{aligned} \quad (1.4)$$

Where:

$$\text{The slip of motor (s)} = \frac{\omega_s - \omega_m}{\omega_s} \quad \text{P. u} \quad (1.5)$$

$$\text{Slip at maximum Torque(S}_{max}) = \pm \frac{R_r}{\sqrt{(R_s)^2 + (X_s + X_r)^2}} \text{P. u} \quad (1.6)$$

$$\text{Synchronous speed (N}_s) = \frac{120 f}{p} \quad \text{r. p. m} \quad (1.7)$$

And.

$$(\omega_s) = \frac{4 \cdot \pi \cdot f}{p} \quad \text{rad/sec} \quad (1.8)$$

Where; “P” “number of poles.

$$\text{The rotor speed } (\omega_m) = \omega_s(1 - S) \quad \text{rad./sec} \quad (1.9)$$

From equation (1.3) the speed-torque curve can be plotted as shown in Figure (1.3):

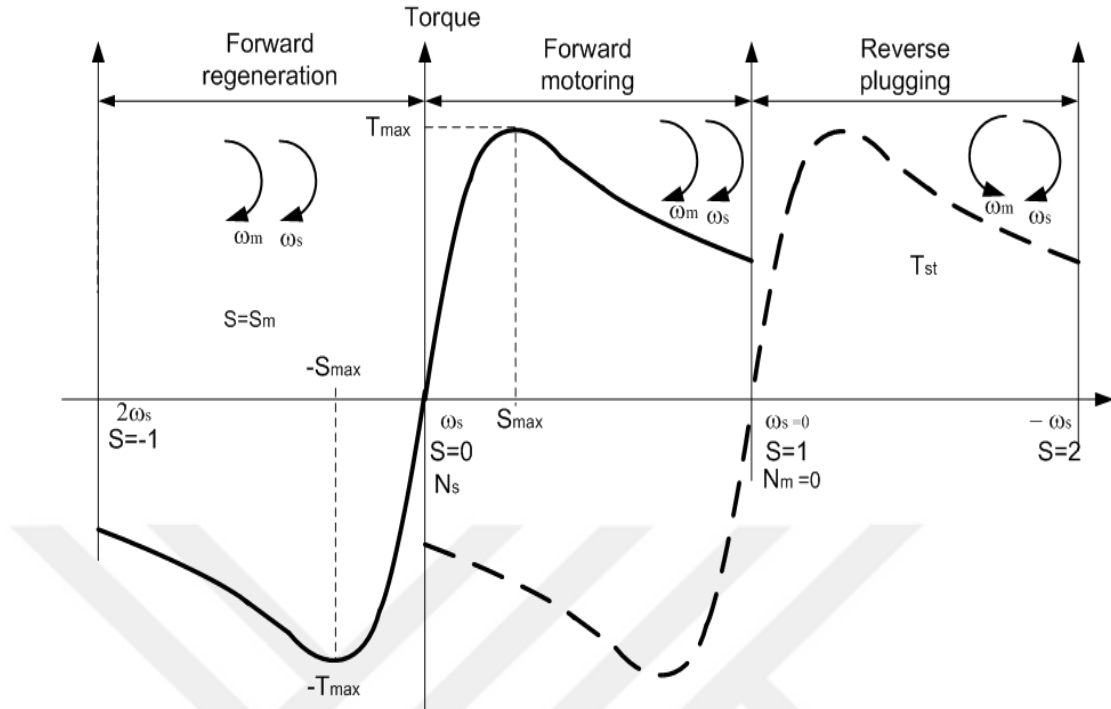


Figure 1.3 Speed torque characteristic

1.5 Speed control of induction motor:

There are several methods for controlling three or single phase induction motor. The main popular methods are:

- 1- Variation of applied voltage.
- 2- Variation of supply frequency.
- 3- Constant (V/f) variation.
- 4- Addition of balanced resistor or inductor to the stator circuit.
- 5- Addition of balanced resistor or inductor to the rotor circuit (for slip ring type).
- 6- Voltage injection in the rotor circuit (for slip ring type).

In this chapter the first three methods are concerned because they deal with our research of VFD (Variable Frequency Drive)

1.5.1 Variation of applied voltage

Obviously, from equation (1.3) it can be seen that the developed motor torque at any value of slip varies as the square of applied voltage, by using this property; several speed-torque curves at different steps of applied voltage can be obtained as shown in

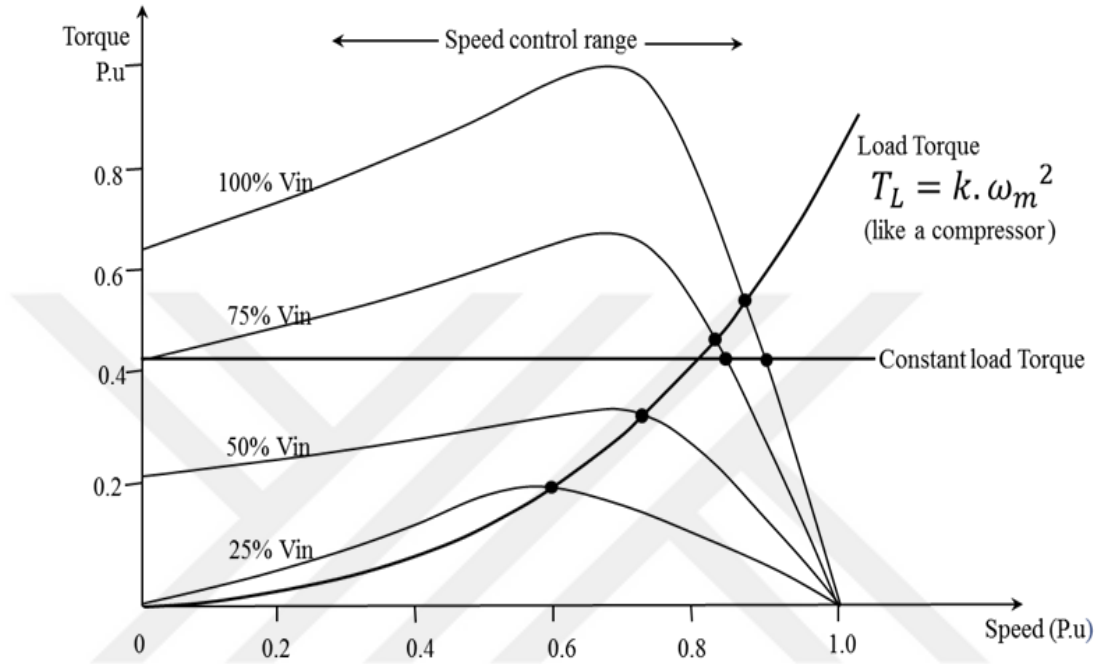


Figure 1.4 Applied voltage variation

From the previous curve it can be seen that the variation of speed when constant torque operation is very small and this method is not suitable to be used for such load. Whereas, it's suitable to be used with loads have torque depends on the motor speed like compressor, or, fan ($T_L = k \cdot \omega_m^2$).

1.5.2 Variation of supply frequency

It's obviously from equation (1.3) that the motor torque is inversely proportion to square of frequency variation, because of both " ω_s " & " X_s, X_r " varies with the frequency. If the applied voltage is maintained constant while frequency is reduced below its rated value, the flux increases because of $\phi = \frac{V_m}{k\omega}$ (where " V_m " is the induced EMF, " ϕ " is the air-gap flux).

This would cause saturation of air-gap flux and the motor parameters would not be valid in determining the speed-torque characteristics [1, 2, 5]. At low frequencies, the reactance decreases and the motor current may be too high. This type of frequency control is not normally used.

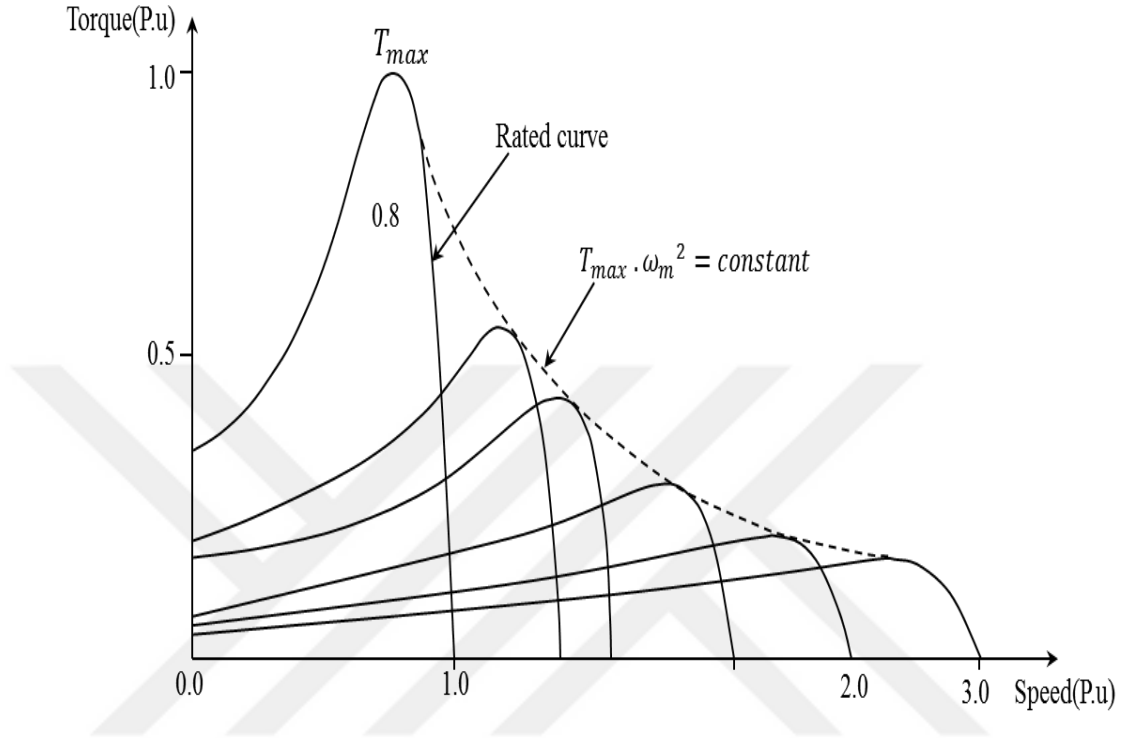


Figure 1.5 Variation of supply frequency

If the frequency is increased above its rated value, the air-gap flux and rotor Current decrease as the frequency increases, and correspondingly, the developed torque will decrease. The maximum torque of the motor will vary as a function of square of frequency or speed ($T_{max} \cdot \omega_m^2 = \text{constant}$), at this region the motor behaves like a DC series motor in variable-frequency operation as shown in Figure (1.5).

1.5.3 Constant (V/f) control

In order to obtain constant torque operation, it's necessary to maintain the air-gap flux at its normal value, since, the air-gap flux $\phi = \frac{V_m}{k\omega} = \frac{V_m}{k'f}$ (where “ V_m ” is the induced EMF and “ f ” is the operating frequency), it's obviously that to maintain “ ϕ ” constant, the applied voltage and the supply frequency “ V_m ” & “ f ” must be varied by the same ratio or to keep “ V_m / f ” constant. Since controlling the induced EMF “ V_m ” is difficult, the applied voltage “ V_{in} ” can be controlled to obtain constant air-gap flux.

Figure (1.6) shows the typical speed-torque characteristics of different (V/f) variation steps [1], where “ α ” is the variation ratio of the applied voltage and the supply frequency:

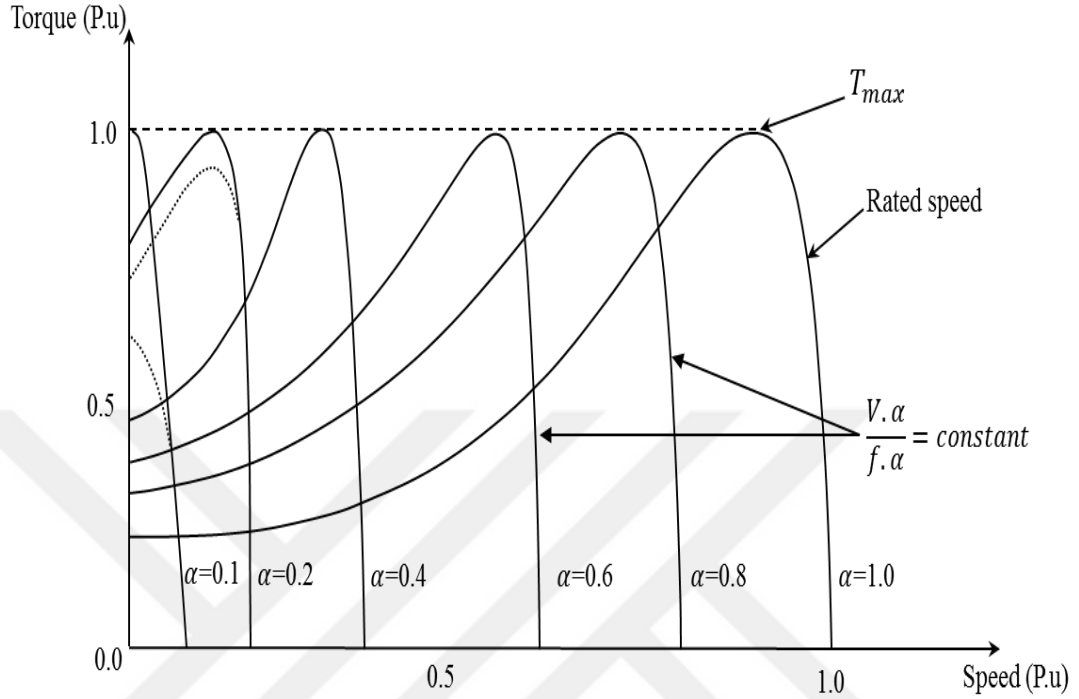


Figure 1.6 Constant (V/f) operation

From the previous characteristics the following properties can be recorded [1, 2, 5]

- 1- The motor usually has low slip characteristic in the operation region, which giving high efficiency.
- 2- The synchronous speed varies with frequency variation, because:

$$\text{Synchronous speed } (\omega_s) = 2 \cdot \pi \cdot f \cdot \alpha = k \cdot \alpha$$

Where: “ f ” is the rated operating frequency, “ α ” is the variation ratio.

- 3- The maximum torque maintains constant for under rated variation, and that can be proved as following:

$$\text{Maximum Torque}(T_{\max}) = \frac{3V_{\text{in}}^2 \cdot \alpha^2}{2\omega_s \cdot \alpha \cdot \left[R_s + \sqrt{R_s^2 + (X_s + X_r)^2} \right]} \text{ N.m} \quad (1.10)$$

By neglecting “ $\mathbf{R}_s$ ”:

$$(T_{\max}) = \frac{3V_{in}^2 \cdot \alpha^2}{2\omega_s \cdot \alpha [\sqrt{\alpha^2(X_s + X_r)^2}]} \quad \text{N. m}$$

$$\Rightarrow (T_{\max}) = \frac{3V_{in}^2 \cdot \alpha}{2\omega_s \cdot (X_s + X_r)} \quad \text{N. m}$$

$$\xrightarrow{\text{yields}} (T_{\max}) = \text{Constant (approximately)}$$

- 4- The slip of maximum torque varies with frequency variation, and that can be proved as following:

$$\text{Slip at maximum Torque}(S_{\max}) = \frac{R_r}{\sqrt{(R_s)^2 + \alpha^2(X_s + X_r)^2}} \quad (1.11)$$

By neglecting “ $\mathbf{R}_s$ ” :

$$(S_{\max}) = \frac{R_r}{\alpha \cdot (X_s + X_r)}$$

$$\Rightarrow (S_{\max}) = \frac{k}{\alpha} (\text{approximately})$$

- 5- The starting torque increases with speed decreasing, and the motor can be started by maximum torque, and that can be proved as following:

$$\begin{aligned} T_{\text{starting}} &= \frac{3V_{in}^2 \cdot \alpha^2 \cdot R_r}{\omega_s \cdot \alpha [(R_s + R_r)^2 + \alpha^2(X_s + X_r)^2]} \\ &= \frac{3V_{in}^2 \cdot R_r}{\frac{\omega_s \cdot (R_s + R_r)^2}{\alpha} + \alpha \cdot \omega_s (X_s + X_r)^2} \end{aligned} \quad (1.12)$$

$$\therefore T_{\text{Strat}} = \frac{3V_{in}^2 \cdot \alpha \cdot R_r}{\omega_s (R_s + R_r)^2 + \alpha^2 \cdot \omega_s (X_s + X_r)^2}$$

$$\xrightarrow{\text{yields}} = \frac{k_1 \cdot \alpha}{k_2 + k_3 \alpha^2}$$

From (T_{start}) equation the starting torque increases in the range between (100%) to approximately (20%) of rated ($V \& f$), and then decreases in the range below (20%) because of increasing the stator's drop voltage.

- 6- Absence of a high in-rush starting current in the direct starting drive, because of the high starting torque at low applied voltage, which reduces stress and therefore improves the effective life of the motor.

By far, the majority of variable-speed AC. drives operate with variable-voltage & variable-frequency power supply, this will be discussed further in the next chapter.

Operating regions:

The different operating regions of speed-torque characteristic for variable-voltage & variable-frequency operation are shown in figure (1.7), and the corresponding applied voltage, torque, flux, stator current and slip are shown in figure (1.8) [1]. From these two figures three operating regions can be defined

- 1 **Constant torque region:** in this region the operating frequency and applied voltage vary from zero to its rated value by constant (V/f) ratio steps and give the following characteristics [1]:
 - Constant torque
 - Constant stator current
 - Constant air-gap flux
 - Constant slip and
 - Variable applied voltage.

It's important to be mentioned here, in the low frequency region the air-gap flux is reduced by the effect of stator impedance drop. Therefore, in this region, the stator drop must be compensated by an additional boost voltage so as to restore the " T_{max} " value as shown in figure (1.8).

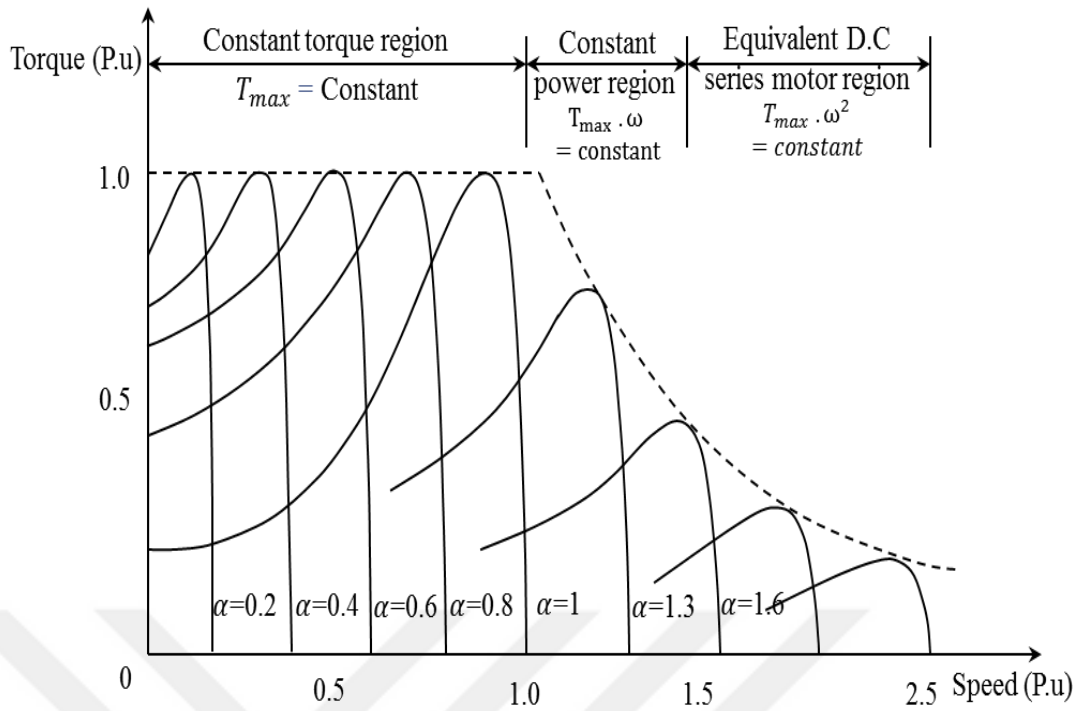


Figure 1.7 Speed-torque operating regions

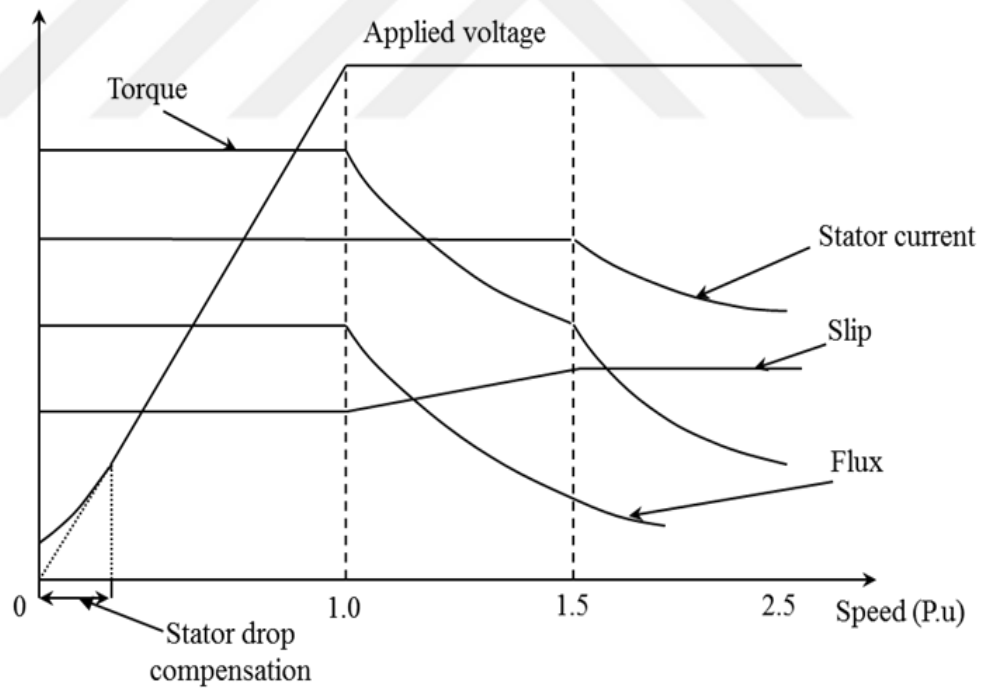


Figure 1.8 Machine parameters

- 2 **Constant power region:** in this region the operating frequency varies between $1 \rightarrow 1.5$ of its rated value, while the applied voltage is maintained fixed. Also in this region the air-gap flux decreases, but the stator current is maintained constant by increasing the slip. The operating parameters characteristic are [1]: Constant applied voltage • Constant stator current • Reducing torque • decreasing air-gap flux and • increasing slip.
- 3 **Equivalent D.C. series motor operating region:** in this region the operating frequency exceeds (1.5) of its rated value while the applied voltage still constant. The stator current cannot be maintained constant, in spite of increasing slip, accordingly, the stator current decreases. The operating parameters characteristic are [1]: Constant applied voltage • decreasing stator current • decreasing air-gap flux • decreasing torque and • Increasing slip.

1.6 Objective of study:

This thesis presents the behavior and performance of the Variable Frequency Drive (VFD) feeding three phase induction motor, for speed control the primary objectives of this work have studied the concept of speed control of a three phase induction motor with open-loop (Volt/Hertz) control system. The model is analyzed by using Computer simulation environment. The study can be summarized by the following points.

- 1 Simulation and implementation of open-loop speed control with Volt/Hertz strategy based into three PWM techniques, (SPWM, THIPWM, SVPWM) of voltage source inverter fed three phase induction motor the simulation studied PWM techniques, inverter and controller.
- 2 Proposed a simple, practical design of an AC-Drive with SPWM technique fed three phase induction motor. This model are studied and compared by simulation and experimental results.
- 3 Comparing between the three PWM inverter techniques. Were applied into open -loop speed control with Volt/Hertz principle. And shows which one is the best for speed control against parameters and disturbances, and which one make the system robust.

1.7 Organization:

This thesis consists of six chapters. The **first chapter** gives an introduction to the AC drives and brief details about some popular methods of speed control of induction motor.

The second chapter: Presents a previous study about three techniques of inverter, SPWM, THIPWM, SVPWM and AC drive system the relevant research papers in this field are summarized briefly

Third chapter: In this chapter presented the modern PWM techniques. A SPWM, THIPWM, SVPWM. These techniques are discussed in details over this chapter, by explaining how to generate, furthermore the idea of open-loop (Volt/Hertz) control was explained. Also explains in details a voltage-fed source inverter and rectifier

Fourth chapter: Explains how to simulate and implement the overall drive system in three parts the first part is to explain how to simulate the PWM inverter coupling with an induction motor. The second part is to explain how to simulate the proposed open-loop (Volt/Hertz) control system model which is was used to drive a squirrel cage induction motor stationary reference frame. Finally the overall system and the individual subsystems are shown. Also results and graphs, which describe the operation of the motor under different loads, reference speeds and inverter parameters, are shown.

Fifth chapter: Explains how to design a simple VFD practical model. It also gives experimental test results of different speed steps, with respects to both voltage and frequency.

Sixth chapter: Includes some conclusions that were obtained from the simulation and experimental results. Also, it proposes suggestions for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 General overview

This chapter deals with reviewing literature that studied the speed control of induction motor using (VFD). In 1886 the WardLeonard built the first electric variable speed drive (E-VSD) system. After the invention of the squirrel cage motor in 1889 in 1930 a first DC to AC inversion. After the rapid development in the field of semiconductor switches, the variable speed drive has become available after invention Thyristors in 1960. In 1970 the concept of packaging industrial drives was presented. Then after developing the Integrated power modules in 1990, the VSI voltage source inverter with medium voltage range type by using PWM technique it has become a Commercial product in 1998 [2]. This chapter focuses on the primary parts of variable frequency drive. Many papers are published in the field of AC-Drive a few papers are with respect to filters of DC-link and PWM inverter techniques (SPWM) (THIPWM) (SVPWM) the relevant research reports in our literature are summarized briefly below:

2.2 Sinusoidal Pulse Width Modulation (SPWM):

Sekhar, K. C. (2006)[6] proposed design and simulation of a five level inverter feeding three phase induction motor with open- end winding .The inverter proposed a three-level inverter from one side and two-level from the other end. The three-level inverter realized into a cascade connects of two 2-level H-bridge inverter which is used to drive open- end winding induction motor. The drive system operation in multilevel modes which is (K) refers to a number of levels, such as (2, 3... 5) depending on the speed range. The combined inverter into both sides of the open-end winding induction motor produces a space phasor voltage .The voltage is symmetric to a five level inverter. The multilevel carrier frequency based on SPWM is used to control the switches of inverters. The DC bus value is changed depending upon motors speed range .

The main feature of this designed at higher DC-link voltage is the inverter switching with low frequency. **Shao-Lin, L. a. (2008)**[7]described and implanted SPWM inverter .The proposed inverter is based on the digital signal processor (DSP) (chipTMS320LF2407) as controllers, which are used to generate(PWM) waveform to four soft switches using chip TMS320LF2407 to give low switches loses also improved the inverter efficiency ,a design build with double feedback loops for current and voltage. PI controllers are used for adjustments .The difference between reference signal and feedback value gives more stability to the system. The laboratory results show the inverter supply is a good power characteristic for static and dynamic load .The total harmonic is less than 5%, in no load and full load condition. Moreover, the voltage regulation value is less than 5%, when translates from no load to full load.

Shan, H. Z. (2009) [8] investigated the effect of digital control on stability of sinusoidal pulse width modulation inverter and the analog control system stability for discreet system. The two cases in control system are studied in this paper: the first one is without delay in discrete steps of the controller and, the second is with one step delay in discreet analysis. As a result, is also determined the relation of sampling period for inverter with controller parameters. A result the one step of delay in controller makes stability in parameters of controller, larger than it is with no step delay in the control system

Maiti, A. S. (2010) [9] proposed design to develop Sinusoidal Pulse Width Modulation SPWM of the single phase inverter. The proposed design used a personal computer (PC) as a local control to remote control for a microcontroller that can get variable output frequency from the inverter. The experimental test is conducted for both resistive and inductive loads. The output result is very close to the simulation. The Total Harmonic Distortion less than 10% that compatibility with IEEE standard the design is better in performance with a high inductive load that is more suitable for (V/f) drive

P.S. Chaudhari, D. P. (2010)[10] studied the characteristics and performance of three-phase squeal cage induction motor. The system is simulated by a computer program "MATLAB ".The mathematical model proposed a of PWM inverter fed three-phase induction motor. The model gives reliable performance, at steady state the mathematical model is built from differential equation used for implementation model

In the proposed model the operating frequency is 50Hz. The performance and characteristics of motor have been analyzed, under sinusoidal PWM inverter. The result of SPWM inverter mathematic model at base frequency it found as when

decreasing the modulation index is decreased, the line voltage of the inverter is reduced also, and when the ratio of carrier frequency is increased the output current is close to sinusoidal waveform. **Yao, W. K. (2011)**[11] proposed and analyzed a single phase unipolar SPWM inverter with dual loop current and voltage. The simulation proposed inverter with 25Hz frequency domain and suggested a new method of compensation dead time for resistive load. In design used, (TMS320F2812) is used as the controller of inverter module, the result give a parameter of suggested design and dead time compensation methods.

Goyal, G. N. (2012)[12]proposed the nine switch topology of SPWM inverter. The inverter generates multiphase output. The six phase output voltage of SPWM inverter with single common on DC bus. The paper compared between two techniques of PWM inverter topologies: SPWM and SVPWM. It also presented a simulation and hardware scheme of nine switch inverter controller. The operation result of nine switch inverter with two PWM techniques is the SVPWM technique had effect on output voltage of inverter compared to SPWM. However the nine switch inverter is better in performance and of high reliability. **Colak, I. a. (2013)**[13]Focused on develop SPWM by minimized THD Total Harmonic Distortion, the proposed scheme to eliminate a higher order harmonic which are located at the side band of carrier frequency .The simulation and operation of SPWM inverter by using simulation software (MATLAB/SIMULINK) environment. The experimental result was studied performed utilizing used (TMS320F2812 DSPm) as controller. The SPWM inverter was tested according to variation of modulation index and switching frequency. The model successfully eliminated higher order harmonics, and the THD is decreased .The result calculated the interval of switching frequency.

Jian-bao, L. L. (2013)[14] investigated circulating current of parallel inverter with Sinusoidal Pulse Width Modulation SPWM for AC motor. The proposed relationship between a circulating current and the phase difference of carrier waves. The study is based on restarting method for circulating .The summation results are verified that the proposed method was effective. **Sharma, C. S. (2013)**[15] reduced the Total Harmonic Distortions THD in voltage and current, by varying modulation index (M) of SPWM between (0.1 to 1). The result shows when the modulation index is varied from low value to high the total Harmonic Distortions value is going to be minimized for both current and voltage waveforms. Also the changing in modulation index effects the speed, starting torque and motor stator current.

Huang, J. a. (2014)[16] inveigled how the electromagnetic (EMI) of the SPWM inverter can be reduced. The paper analyzed carrier frequency modulation CFM based on inverter by changing frequency devotion ratio. It also studied effect on the peak of interference .A new scheme of CFM was proposed the spectrum of inverter output voltage, a new scheme was proposed a carrier frequency twice modulated in this scheme. The optimized frequencies were selected and periodic waveform signal, the scheme was applied into a single phase inverter with SPWM. The main idea of the scheme is to develop multiple modulation method. The result was proved in summation and experiment.

Paikray, A. a. (2014)[17] proposed a novel technique for multicarrier frequency PWM based on multilevel inverter .The technique used a trapezoidal triangular as carrier waveform, a 1KW three phase five level inverter was proposed. The level shifted PWM (LS-PWM) used for drive a cascade multilevel inverter, the switching frequency is 2 kHz. The model was analyzed using a simulation software environment “MATLAB/SIMULINK”. The THD and line voltage of inverter was obtained for level shifted PWM (LS-PWM) technique and compared with triangular carrier wave methods, the compression based on the effected modulation index on THD and line voltage .A result of Trapezoidal triangular carrier waveform that was offered gave better THD Total Harmonic Distortion performance compared to the traditional triangular carrier.

K. Vijayakumar, R. S. (2014)[18] studied the applications of one phase matrix inverter and converter, as a cycloinverter and cycloconverter, a sinusoidal plus width modulation SPWM was use to generate pluses, the cycloinverter and cycloconverter was a simulation which was operated by “MATLAB/SIMULINK” software environment, the evaluated result proved the functionality of single phase matrix converter combined as several function of power electronics converters with SPWM switching technique

Siddiqui, K. M. (2015)[19] behavior of three phase induction motor during a bearing fault condition, However, the aim of the paper has proposed a bearing fault model by a computer simulation and analysis of this model in time domain . The result proved a dynamic model based on SPWM inverter fed three phase squirrel cage motor was successful in eliminating bearing faults for no-load and full load condition during transient beforehand to rated mechanics parameters.

Das, B. F. (2015)[20]discussed and analyzed the performance of VSI fed three phase induction motor, the three PWM techniques are used, space Vector Pulse Width Modulation SVPWM, and Third Harmonic Injection Pulse width modulation THIPWM technique.

The paper studied the output parameters of voltage source inverter. The stator current supply from inverter to motor, rotor current of motor and Total Harmonic Distortions (THD) on line and phase voltage of VSI under different value of modulation index, the mechanical parameters of motor, speed and electromagnetic torque are listed in results. The simulation model was analyzed by a computer program environment “MATLAB/SIMULINK” The result was compared between these three techniques, the results of comparison are listed .In Table 2.1. These results illustrated the value of %THD with different modulation index ranges for the three techniques of PWM, also in Table 2.2, when there is an increase in the switching frequency .The inverter current fed to the stator will be closer to sinusoidal, and reduces in acoustic noise of the motor, than improved on output voltage and current of the inverter.

Table 2.1 Comparison between (SPWM), (THIPWM) and (SVPWM) on the basis of Harmonics and fundamental voltage.

M	SVPWM		SPWM		THIPWM	
	%THD _v	Voltage (V)	%THD _v	Voltage (V)	%THD _v	Voltage (V)
0.7	75.94	323.2	81.83	152	90.91	278.87
0.8	61.59	369.5	54.88	275.7	79.13	312.4
0.9	49.19	410	54.83	349.8	64.13	360.7
switching frequency : 2000Hz						
Base frequency :50 Hz						
Base Modulation index : 0.8						

Table 2.2 Comparison between (SPWM, THIPWM and SVPWM) for different carrier frequency on inverter current feeding stator of induction motor.

Switching Frequency(Hz)	SVPWM %THD _i	SPWM %THD _i	THPWM %THD _i
1000	3.90	10.61	2.95
2000	2.61	11.89	2.05
3000	2.30	5.54	1.74

2.3 Space Vector Pulse Width Modulation (SVPWM):

Villalva, M. G. (2004)[21] presents a detailed discussion about the three-dimensional (3D) SVPWM for three-leg four wire voltage source inverters. This subject appeared with necessity of feeding nonlinear or unbalanced loads with sinusoidal or non-sinusoidal voltage and current. **Li, S. H. (2005)**[22] this paper focuses on a SVPWM method for double fed three-phase induction machine, in order to minimize the harmonic current. **Kim, L.-H. N.-K.-Y.-H. (2005)** [23] A new control method of induction motor is proposed in this paper to reduce the pulsation of motor torque and magnetic flux linkage, which, as a great disadvantage, exists in the direct torque control system. According to the conclusion, the required voltage vector is provided which can be composed by SVPWM. Simulation results show that it effectively solves the problem of torque ripple and flux ripple.

Sanjeevikumar, P. (2007)[24] presents the successful application of Space Vector Pulse Width Modulation SVPWM for a three phase VSI and it is the standard PWM techniques to be utilized for the DC-AC power conversion. A solution to have harmonic free mitigation in high power converters is to use PWM control techniques. Instead of having a continuous pulse as in classical square wave inverter multiple pulses in the output can have control over harmonic content; and the RMS value of the output voltage in SVPWM. The angular position of the pulses varies in sine fashion with the Injected third harmonic voltage component as the control signal.

Satean Tunyasirirut, T. S. (2007)[25] A voltage source inverter with SVPWM techniques, for speed control of induction motor which was presented in this paper the design and implementation of SVPWM inverter leads to the ability to adjust the speed of the motor by controlling the frequency and amplitude of the stator voltage, the relation of stator voltage to frequency should be kept constant. The fuzzy logic

controller is also introduced to the system for keeping the motor speed constant. When the load varies, the experimental results are testing the 0.22Kw IM from no-load to rated condition show the effectiveness of the proposed control scheme.

Khoudir Marouani, F. K. (2007)[26] a comparison between continuous and discontinuous SVPWM control of six-phase VSI fed a double-star induction motor drive (DSIM) is proposed. The induction motor has two sets of three-phase stator windings spatially shifted by 30 electrical degrees. Each set of three-phase stator windings is fed by a three-phase inverter. The harmonics of the VSI feeding DSIM are investigated and presented graphically as function of the modulation index. Implementation on a DSP controller board is achieved and experimental results on a 15Kw DSIM prototype machine are carried out.

Guo, G. a. (2008)[27] studied the operation and principle work of SPWM inverter, also calculated the space vector equations in easy and simple formula ,the aim of this paper is calculates the output voltage of SPWM inverter ,and compare the voltage with different value of modulation index, also calculate the THD of output voltage

Fadhil, S. T. (2006)[28] proposes design, simulation, and implementation of three-phase induction motor driver, using voltage fed Space Vector Pulse Width Modulation technique SVPWM, which is an advanced and modern technique, and it is quite different from other pulse Width Modulation (PWM) methods. A computer program is prepared for simulating “MATLAB/SIMULINK” the overall drive system, which includes; voltage fed space vector PWM inverter model and three-phase induction motor model. A practical model is designed by imitating the conceptions of TMS320 (DSP) microcontroller. This practical model is completely implemented and exact results are obtained. The worst state of the harmonics content of the voltage and current (no-load condition) are analyzed in different speeds and compared with square wave. This analysis shows high reduction in the dominant harmonics and very low Total Harmonic Distortion (THD) when SVPWM is used (less than 5%), compared to (more than 20%) in square wave.

Chengwu, L. Z. (2013) [29] studied and analyzed the space vector pulse width modulation (SVPWM) techniques. The results of theoretical analysis and experimental are based on (digital signal processor) DSP, in experiment can get when changing in the SPWM initial phase can control on output voltage of inverter, then can adjust the power factor of the motor, when adjusting the power factor that reduces the power consumption and energy saving.

2.4 DC-Link Filter:

In this section some examples of rated works for (DC-link filter) are surveyed; **KHALID, K. B. (2003)**[30] discusses the harmonic analysis of a SVPWM inverter based induction motor drive system. The study was based on the harmonics measured in supply and load side waveforms. The Harmonic Distortions are measured and analyzed at balanced and unbalanced conditions. The results show that the level of harmonics is very low for a well-designed PWM inverter operating with liner modulation and balanced load.

Grinberg, R. a. (2005)[31] presented and described the problem of selected capacitor size in voltage source inverter, modeling analyzes using computer program (P spice) software environment. The paper advanced to reeducation size of capacitor can limit the maximum ripple current of Dc source, the current ripple spectrum is analyzed under modern pulse width modulation (PWM) techniques.

Jin-Woojung. (2005)[32] this thesis proposed the simulation of SVPWM technique for three- phase voltage source inverter with L–C output filter and inductive load, using a simulation computer program “MATLAB/SIMULINK” environment the results show that the load of harmonic is very low in the output voltage and currents .**Ramasamy, A. V. (2007)**[33] proposed the dynamic voltage restorer (DVR) which is a custom power device that is used to compensate voltage sag. The efficiency of the (DVR) depends on the efficiency of the control technique involved in switching the inverters. The inverters are switched using SVPWM technique to maximize the usage of (DC link voltage). The implementation of the control (TMS320) is tested using 3KVA lab prototype IM .**Swetha.S.G, N. P. (2013)**[34] proposed design, simulation, and implementation of DC link and output filter of the three phase inverter feeding induction motor, the proposed design a simple approach to reduce the Total harmonic distortion THD, in current waveform of three phase system, the low pass filter (L-C) and 3- phase filter can reduce the problem of harmonic in waveform, the value of capacitor and inductor in (L-C) filter it will reduced the harmonic in the drive system. The scheme proposed based on (ds pic30f4011) as control to the three phase voltage source inverter. From result of experimental, the value of capacitor and inductor at the output filter of inverter and rectifier are affected on THD of driver system, the advantage of that design is to improve life of the induction motor, high efficiency and power factor.

Sher, H. A. (2015)[35] studied and analyzed the failure in DC- link capacitor of voltage source inverter, the paper presented experimental and theoretical of an (AC-DC-AC) inverter with DC-link capacitor, the open circuit condition of the DC link capacitor was studied, the analysis was applied to both types of rectifier single and three phase, the fault affected on characteristic of voltage source inverter and induction motor properties, and presenting the effect of an open circuit fault on pulsating torque of the machine when opening circuit in DC- link capacitor occurs. The simulation is analyzed by a computer program prototype software environment, the result of the experiment is close to the computer simulation, in single phase supply of voltage source inverter the fault in DC-link capacitor is much serious, compared with three phase supply.

2.5 Related works to the control strategy:

The investigation of a (VFD) for speed control of the three phase induction motor under scalar control strategy or (Volt/Hertz) is a modern study. Therefore, many researches and papers published in this field.

Barsoum, N. N. (2011)[36]proposes design, simulation and implementation of remote control and monitoring of (VFD)fed three-phase induction motor. In this study used (PLC) as a controller and Ethernet rotor module will used a remotely control and computer program software (LabVIEW) which used to design and interface with (PLC).The project result shows the time delay during extrication, the (LabVIEW) program will take a long time approximately 30 second to send signal to (PLC), the delay time gives poor specification to the system, the time delay depends on the specification of computer, also the connection between computer and PLC is easily disconnected **Consoli, A. G. (2011)**[37]presented a scalar control strategy to control 3-phase IM. The effects of changing IM parameters will be discussed and the dynamic behavior of scalar are analyzed in this paper. The paper proposed a new strategy, which advances to reduce the motor losses, and rotates closely to the desired speed. This allows to save some energy to the power system.

Aditya, T. (2013)[38] studied the principle and working of variable frequency drive. The proposed model was analyzed and simulated in computer software “MATLAB/SIMULINK” environment, the main aim of that work is showing how to save energy when connected VFD with IM as a drive. The result leads to a

change of the frequency of supply. The harmonic also changes. When the speed decreases the THD in current and voltage is increased. **Dorjee, R. G. (2014)**[39] developed the monitoring scheme of controlled to (VFD) using (PLC), also study all hardware and software component functions and performance, the ladder programming was used to programming (PLC) the experimental study consist of two modes, speed and position, this mode runs systematically depending on program of (PLC).A program is developed to make the motor enabled to obtain two different positions, the program successfully and to reach position with time interval

Agamloh, E. B. (2015)[40]presented the efficacy and power measurement for (VFD), and induction motor .The paper overview the international stander related to (VFD), and also discussed the challenges during a measurement of the power from two different sources sinusoidal supply and PWM inverter. Two different hours were taken to power induction motor. The results in two cases illustrate the system efficiency .**Hemish R. Choksi, H. I. (2015)**[41] presented the (V/f) techniques to control the speed of IM, the paper summarized up the principle and operation (V/f) technique .The experimental result shows inverter output voltage, current and rotor speed when variance supply frequency. The result shows a variance in IM speed directly maintains (V/f) constant ratio.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Variable-voltage, variable-frequency inverter drives are the most important methods used as speed control of induction motors. For long time a square wave inverter has been used as speed control of low- and medium-power induction motor [2], which consists of variable AC to DC converter that produces controllable DC voltage which is used to generate single, two or three phase output square wave at variable frequency, using semiconductor devices like transistors or thyristors. The main disadvantage of this method is the high number of harmonics which cause many operation problems.

After the developments in power electronic technology, the pulse width modulation technique which minimized harmonic effects appeared. In PWM inverter the DC link kept constant by a front end diodes bridge and the fundamental output frequency can be controlled within the inverter using PWM technique, the inverter power bridge devices switched “ON “and “OFF "many times within half-cycle in order to generate variable output voltage which has low harmonics content used as speed control of a few hundreds of kilo watts induction motors [1].

The control methods which generate the necessary PWM patterns have been classified as voltage controlled and current controlled PWM methods. This thesis deals with voltage control PWM method. Several voltage controlled PWM methods have been proposed in the literature review chapter, sinusoidal PWM, sinusoidal PWM with third harmonic injection and space vector modulation. All these methods aim at generating a sinusoidal inverter output voltage free of low-order harmonic. This is possible if the sampling frequency is high compared to the fundamental output frequency of the inverter. The performance of each of these control methods is usually judged based on the following parameters [28]:

- 1) Total Harmonic Distortion (THD) of the voltage and current at the output of the inverter.
- 2) Switching losses within the inverter.
- 3) Peak to peak ripple in load current.
- 4) Maximum inverter output voltage for a given DC rail voltage.

It is generally accepted that the performance of an inverter, with any switching strategies, can be related to the harmonic contents of its output voltage. Power electronics researches have always studied many novel control techniques to reduce harmonics in the waveforms. Currently, there are many techniques, which are applied to inverter topologies and multilevel inverter technology, those techniques well-known modulation topologies as follows:

1. Sinusoidal PWM.
2. Sinusoidal PWM with third harmonic injection
3. Space Vector Pulse Width Modulation (SVPWM)
4. Selected harmonic elimination (SHE) PWM.
5. Hysteresis band current control PWM.

The way of understanding a first three PWM technique, a short review about Square-Wave inverter is essential in this chapter before discussing of PWM inverter techniques.

3.2 Square-Wave, or Six-Step Inverter:

Three-phase bridge inverters are widely used for AC motor drives and general-purpose AC supplies. Figure (3.1) shows the inverter circuit, and Figure (3-2) explains the fabrication of the output voltage waves in square-wave, or six-step, mode of operation. The circuit consists of three half-bridges which are mutually phase-shifted by “120° “angle to generate the three-phase voltage waves. The input DC supply is usually obtained from a single-phase or three-phase utility power supply through a diode-bridge rectifier and LC or C filter, as shown in Figure (3.1) The square-wave phase voltages with respect to the fictitious DC center tap can be expressed by Fourier series as

$$V_{ao} = \frac{2V_{DC}}{\pi} [\cos(\omega t) - \frac{1}{3}\cos(3\omega t) + \frac{1}{5}\cos(5\omega t) \dots \mp] \quad (3.1)$$

$$V_{bo} = \frac{2V_{DC}}{\pi} [\cos(\omega t + 2\pi/3) - \frac{1}{3}\cos(3\omega t + 2\pi/3) \dots \dots \pm] \quad (3.2)$$

$$V_{co} = \frac{2V_{DC}}{\pi} [\cos(\omega t - 2\pi/3) - \frac{1}{3}\cos(3\omega t - 2\pi/3) \dots \dots \pm] \quad (3.3)$$

Where “ V_{DC} ” “DC supply or DC-link voltage.

The line voltages can therefore be constructed from Equations (3.1), (3.2), (3-3) as.

$$V_{ab} = V_{ao} - V_{bo} \quad (3.4)$$

$$V_{bc} = V_{bo} - V_{co} \quad (3.5)$$

$$V_{ca} = V_{co} - V_{ao} \quad (3.6)$$

Assume ($n_a = \omega t + \pi/6, n_b = \omega t - \pi/2, n_c = \omega t + 5\pi/6$).

$$V_{ab} = \frac{2\sqrt{3}V_{DC}}{\pi} [\cos(n_a) + 0 - \frac{1}{5}\cos(5n_a) - \frac{1}{7}\cos(7n_a) + \dots] \quad (3.7)$$

$$V_{bc} = \frac{2\sqrt{3}V_{DC}}{\pi} [\cos(n_b) + 0 - \frac{1}{5}\cos(5n_b) - \frac{1}{7}\cos(7n_b) + \dots] \quad (3.8)$$

$$V_{ca} = \frac{2\sqrt{3}V_{DC}}{\pi} [\cos(n_c) + 0 - \frac{1}{5}\cos(5n_c) - \frac{1}{7}\cos(7n_c) + \dots] \quad (3.9)$$

Note that the line fundamental voltage amplitude is “ $\sqrt{3}$ ” “times that of the phase voltage, and there is a leading phase-shift angle of “ 30° ”.

The line voltage waves, shown in Figure (3-2), have the characteristics of six-stepped wave shape. The characteristic harmonics in the waveform are **$6n \pm 1$** . Where n = integer number. The three-phase fundamental as well as the harmonic components are balanced with a mutual phase-shift angle of “ **120°** ”. Because of the characteristic wave shape, this type of inverter is called a square-wave, or six-stepped, inverter. [1, 2, 42]

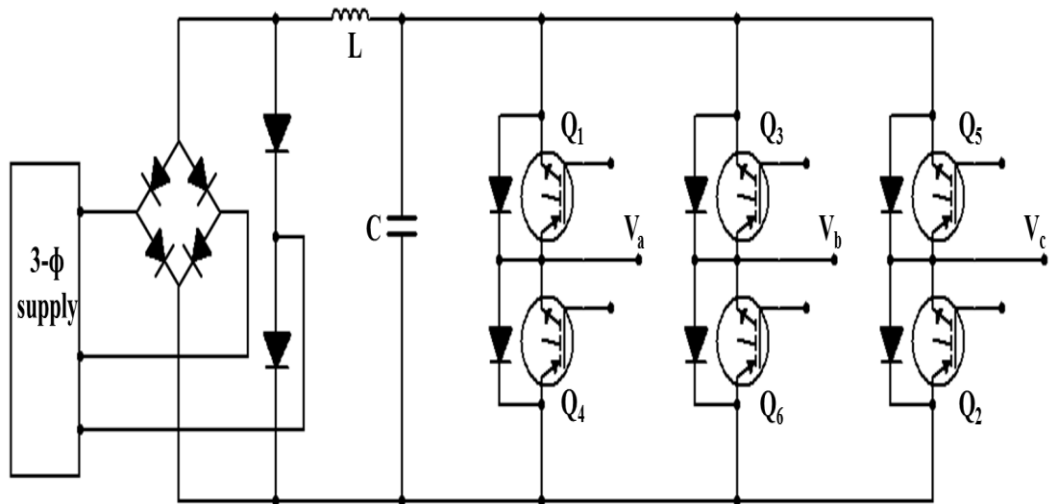


Figure 3.1 Three phase inverter (with a diode rectifier in the front end)

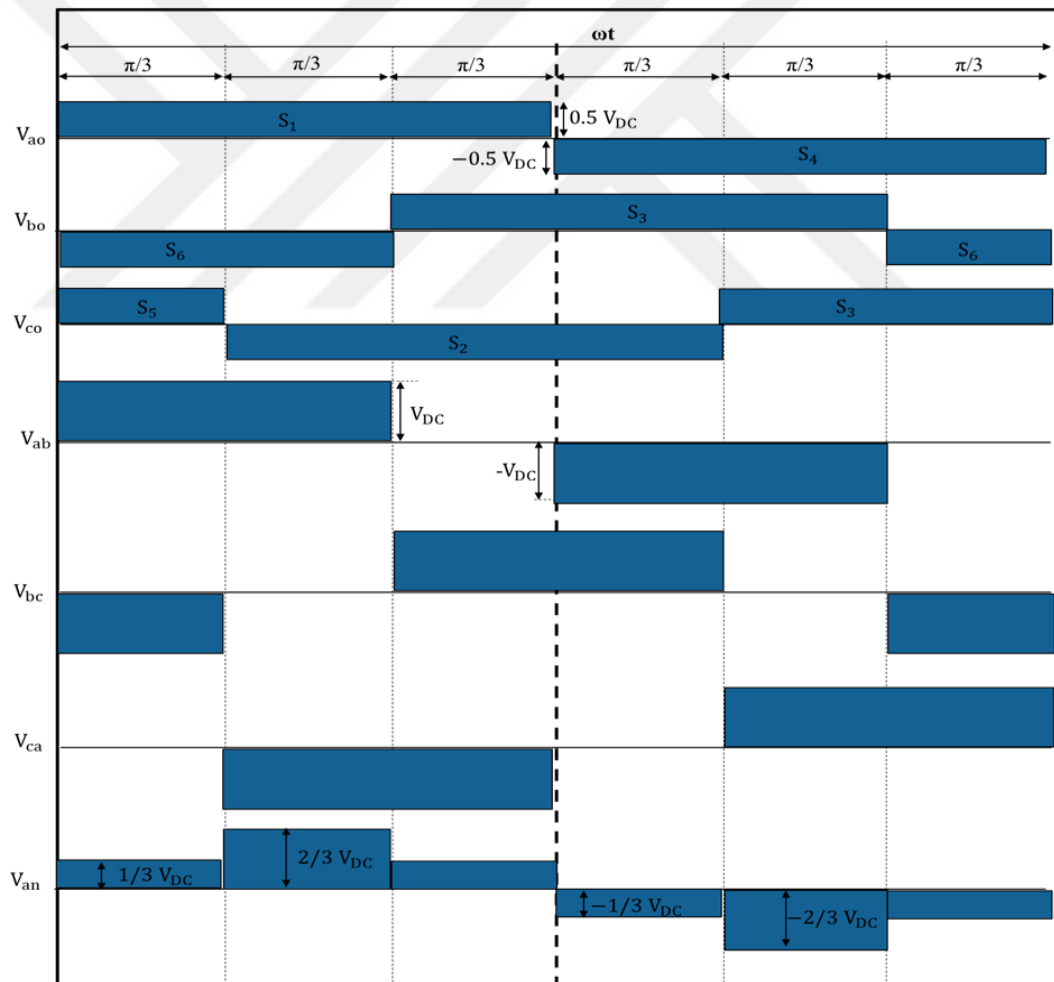


Figure 3.2 Synthesis of output voltage waves in square-wave mode

3.3 Pulse Width Modulation Techniques

The three-phase, six-step inverter discussed before has several advantages and limitations. The inverter control is simple and the switching loss is low because there are only six switching per cycle of fundamental frequency. Unfortunately, the lower order harmonics of the six-step voltage wave will cause large distortions of the current wave unless filtered by bulky and uneconomical low-pass filters. Besides, the voltage control by the line-side rectifier has the usual disadvantages.[1]

3.3.1 PWM Principle

Because an inverter contains electronic switches, it is possible to control the output voltage as well as optimize the harmonics by performing multiple switching within the inverter with the constant DC input voltage. The PWM principle to control the output voltage is explained in Figure (3.3). The fundamental voltage V_1 has the maximum amplitude " $4V_{DC}/\pi$ " at square wave, but by creating two notches as shown, the magnitude can be reduced. If the notch widths are increased, the fundamental voltage will be reduced. [1]

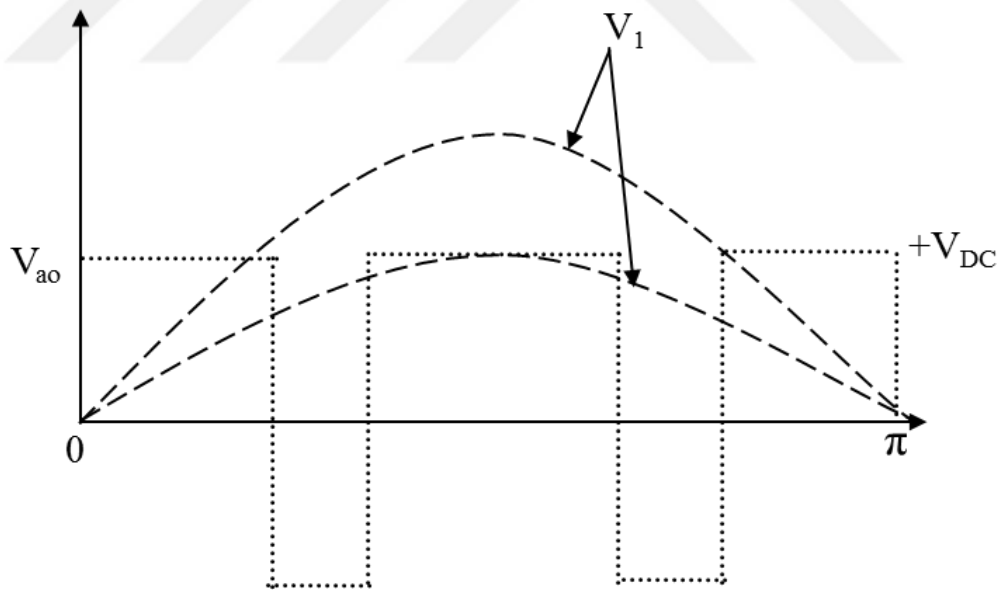


Figure 3.3 PWM principle to control output voltage

3.3.1.2 Sinusoidal PWM (SPWM)

The generation of gating signals with sinusoidal PWM is shown in figure (3.5), there are three sinusoidal reference waves ($V_{\text{mod(a)}}$, $V_{\text{mod(b)}}$, $V_{\text{mod(c)}}$) each shifted by 120° called “the modulating signals or control signal”, where a triangle wave signal called “carrier wave” with high frequency “ f_c ”, a high carrier frequency leads to a better filtering, and the output waveform is more close to sinusoidal, a high frequency triangular waveform (V_T) is compared with a low frequency reference waves ($V_{\text{mod(a)}}$, $V_{\text{mod(b)}}$, $V_{\text{mod(c)}}$) as shown in Figure (3.4), to generate gating signals (V_{ao} , V_{bo} , V_{co}) respectively at the points of intersection between the modulating signals and the carrier signals as shown in figure (3.5). The line-to-line output voltages are (V_{ab} , V_{bc} , V_{ca}) as shown in figure (3.4), [42,43]

The normalized carrier frequency “ f_c ” should be odd multiple of three of the fundamental frequency. Thus, all phase voltages (V_{an} , V_{bn} , V_{cn}) are identical and 120° out of phase, without even harmonics and harmonics of multiple frequencies of three of rated frequency [1,2].

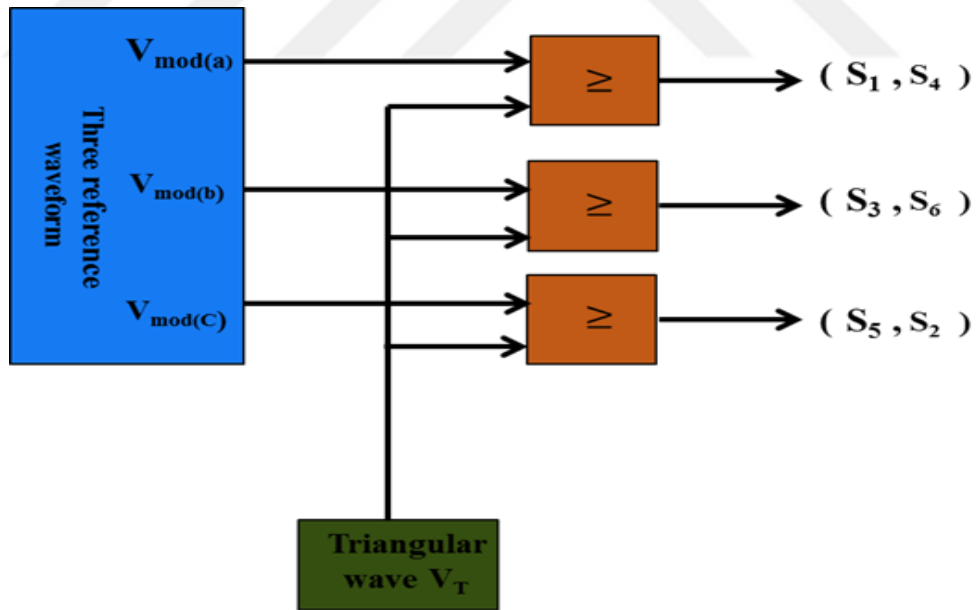


Figure 3.4 Generator Control Signal of SPWM

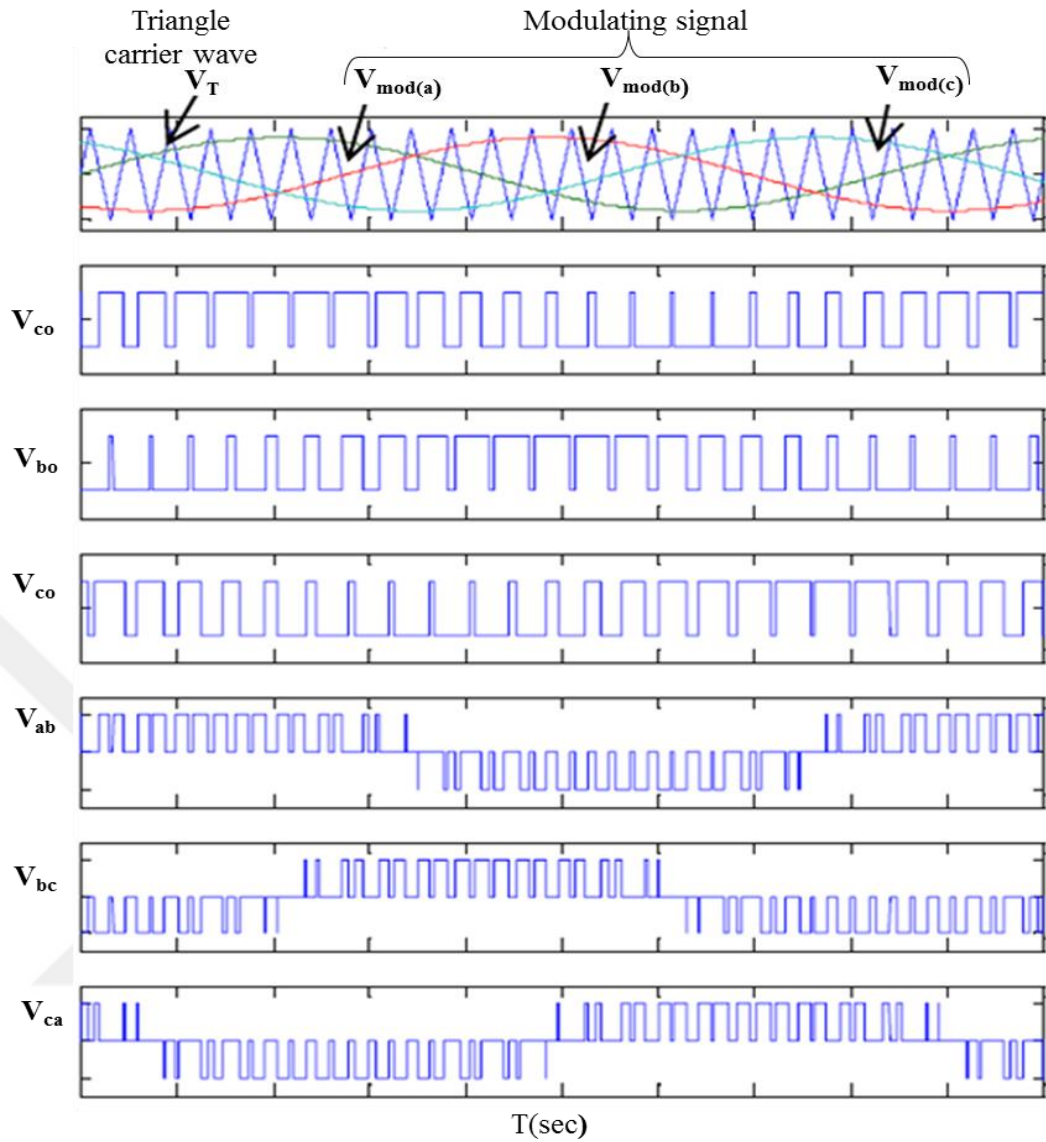


Figure 3.5 Sinusoidal pulse width modulation for three-phase inverter [44]

A six-step inverter is composed of three half bridges, each half bridge consists of two switches "S-upper & S-lower". The output of each phase is connected to the middle point of each half bridge as shown in Figure (3.1). The output signal of comparators.

In the Figure (3.4) each bus makes up one half bridge and "ON and OFF" in a complementary fashion.

This means when the upper switch is "ON", the lower is "OFF" and vice-versa. The pole voltage ($V_{mod(a)}, V_{mod(b)}, V_{mod(c)}$) of inverter switching between $(0.5V_{DC}$ and $-0.5V_{DC}$) where V_{DC} is the DC Supply or DC link voltage.

The peak of the triangle carrier voltage waveform (V_T) is always greater than, the peak of the sinusoidal reference waves. When the sine waveform is greater than the triangular waveform, the upper switch is turned on and the lower switch is turned off. Similarly, the Table (3.1) summarizes this process [44]

Table 3.1 The logic for the control signals.

IF	Then			
	Switch number	status	Pole voltage	
$V_{\text{mod}(a)} \geq V_T$	S_1	on	V_{ao}	$0.5V_{DC}$
$V_{\text{mod}(b)} \geq V_T$	S_3	on	V_{bo}	$0.5V_{DC}$
$V_{\text{mod}(c)} \geq V_T$	S_5	on	V_{co}	$0.5V_{DC}$
$V_{\text{mod}(a)} \leq V_T$	S_4	on	V_{ao}	$-0.5V_{DC}$
$V_{\text{mod}(b)} \leq V_T$	S_6	on	V_{bo}	$-0.5V_{DC}$
$V_{\text{mod}(c)} \leq V_T$	S_2	on	V_{co}	$-0.5V_{DC}$

3.3.1.2.1 Modulation index is defined as

$$m = V_p / V_T \quad (3.10)$$

Where: V_p = peak of the modulating wave, V_T = peak of the carrier wave. Ideally, “m” can be varied between 0 and 1 to give a linear relation between the modulating wave and output wave. At “m=1” the maximum value of fundamental peak voltage ($0.5V_{dc}$), represent 78.54 percent of the peak fundamental voltage of the square wave [45].

3.3.1.2.2 Over-modulation region:

To further increase the amplitude of the output voltage, the amplitude of the modulating signal ($V_{\text{mod}(a)}, V_{\text{mod}(b)}, V_{\text{mod}(c)}$) can be made higher than the amplitude of the carrier signal, which leads to over-modulation region [1,2]. The relationship between the amplitude of the fundamental AC output voltage and the DC link voltage becomes nonlinear. Thus, in over modulation region the phase voltage range be:

$$\frac{1}{2}V_{DC} \leq V_{an} = V_{bn} = V_{cn} \leq \frac{2}{\pi}V_{DC}$$

A Large value of “M” in SPWM leads to full over modulation, this case is known as square-wave operation as illustrated in Figure (3.2) where the power switches are “ON for “180°[2].

In this mode the inverter cannot vary the load voltage except by varying the DC supply voltage (V_{DC}). The fundamental phase voltage equal to:

$$V_{an} = \frac{2}{\pi} V_{DC} \quad (3.11)$$

Contains the harmonics for “n “frequency (f_n) where $n = 6k \pm 1$ & ($k = 1, 2, 3 \dots$) and their amplitudes are inversely proportional to their harmonic order “n “:

$$(V_{an})_n = \frac{2}{n\pi} V_{DC} \quad (3.12)$$

3.3.1.3 Third Harmonic Injection PWM (THIPWM)

The traditional PWM triangular carrier method has been overcome by the THIPWM. Because of its superior performance characteristics, it has been unable to fully utilize the DC-link supply voltage. Due to this problem the Third harmonic injection modulation THIM technique was developed, the performance of inverter is improved, the output voltage is increased 15% more compared with SPWM. [46] it is equal to the performance of space vector pulse width modulation SVPWM, in high switching frequency THIPWM technique improved the harmonic distortion that makes a more better inverter output waveform. For these features, a third harmonic injection pulse width modulation THIPWM is replacing sinusoidal pulse width modulation SPWM and used in many PWM converter applications.[45]

3.3.1.3.1 Calculation of Optimum Distortion

Consider the “u “is a sinusoidal waveform consisting of the fundamental component with addition a triple –frequency term is given by the following equation:

$$u = \sin(\theta) + A_m \sin(3\theta) \quad (3.13)$$

Where “ $\theta = \omega t$ “is angler frequency and “ A_m “is a optimization parameter to keep the maximum amplitude of “ $u(t) < 1$ “ to find the maximum value of “ $u(t)$ “ it’s by derivative with respect to “ θ “ equal to zero. Thus;

$$\frac{\partial u}{\partial \theta} = \cos(\theta) + 3 A_m \cos(3\theta) \quad (3.14)$$

Using the followings trigonometric identity.

$$\sin(3\beta) = \sin(\beta). (3 - 4 \sin^2(\beta)) \quad (3.15)$$

$$\cos(3\beta) = \cos(\beta). (4 \cos^2(\beta) - 3) \quad (3.16)$$

By substituting (3.16) into equation (3.14).

$$\cos(\theta)(12 A_m \cos^2(\theta) - (9 A_m - 1)) = 0 \quad (3.17)$$

The maximum and the minimum of signal is;

$$\cos(\theta) = 0 \quad (3.18)$$

And.

$$\cos(\theta) = \sqrt{\frac{(9A_m - 1)}{12A_m}} \quad (3.19)$$

That yields, respectively.

$$\sin(\theta) = 1 \quad (3.20)$$

$$\sin(\theta) = \sqrt{\frac{(1 + 3A_m)}{12A_m}} \quad (3.21)$$

To determine the peak value of “u “substituting the result of an equation (3.20) &

(3.21) into (3.13) with using identity (3.15) .The Equation becomes.

$$u = \sin(\theta). ((1 + 3A_m) - 4 A_m \sin^2(\theta)) \quad (3.25)$$

Substituting result of “sin (θ) “in equation (3.20) and (3.21).

$$\bar{u} = 1 - A_m \quad (3.26)$$

And.

$$\bar{u} = 8A_m \sqrt{\frac{(1 + 3A_m)}{12A_m}} \quad (3.27)$$

Where “ $\bar{u}$ “is the maximum, or' peak value of “u “.

The optimum value of “ A_m ” which gives minimizes value of “ $\bar{u}$ ”, that can be found by differentiating the equation (3.27) with respect to “ A_m ” and the result equal to zero.

$$\bar{u} = 8A_m \sqrt{\frac{(1 + 3A_m)}{12A_m}}$$

$$\frac{\partial \bar{u}}{\partial A_m} = \left(2 - \frac{1}{3A_m}\right) \sqrt{\frac{(1 + 3A_m)}{12A_m}} \quad (3.28)$$

Thus, get two possible value of “ A_m ”.

$$A_m = -\frac{1}{3} \text{ \& } A_m = \frac{1}{6} \quad (3.28)$$

Substituting in Equation (3.26).

$$\bar{u} = \frac{4}{3} \text{ and } \bar{u} = \frac{5}{6}$$

From substituting in Equation (3.26). The negative value for “ A_m ” is neglected because it makes the result of “ $\bar{u}$ ” greater than unity. Therefore the valid solution is

“ $A_m = 1/6$ ”. The waveform will be.

$$u = \sin(\theta) + \frac{1}{6} \sin(\theta) \quad (3.30)$$

From Equation (3.18).

$$\cos^{-1}(0) = \frac{\pi}{2} \quad (3.31)$$

And substituting the value of “ $A_m = 1/6$ ” in Equation (3.19).

$$\cos(\theta) = \sqrt{\frac{(9 \cdot \frac{1}{6} - 1)}{(12 \cdot \frac{1}{6})}} = \frac{1}{2} \quad (3.32)$$

That yields. “ $\theta = \frac{\pi}{3}, \frac{2\pi}{3} \dots \frac{n\pi}{3}$ ”. Where “n” is integer number “ $n=1, 2, 3, 4 \dots$ ”. We can see that all the third harmonics pass through zero. Also if substitute “ $\theta = \frac{n\pi}{3}$ ” in Equation (3.30) and $n=1$, thus, obtained the maximum value of “ u ”.

$$u = \sin\left(\frac{\pi}{3}\right) + \frac{1}{6} \sin\left(3 \frac{\pi}{3}\right) = \pm \frac{\sqrt{3}}{2} \quad (3.33)$$

And, the peak amplitude at this angle becomes. $\bar{u} = \pm 0.866$

In the Figure 3.6, we can see clearly when adding the third harmonic with a peak magnitude “**1/6**” to the modulation waveform that has the effect of reducing the peak value of the output waveform by a factor of “ **$\bar{u} = 0.866$** ” without changing in the amplitude of the fundamental. It is possible to increase the amplitude of the modulating waveform by multiplying Equation (3.30), in factor “ **λ** ”, so that the full output voltage range of the inverter is again utilized. If the reference waveform is expressed as. [46]

$$u = \lambda. (\sin(\theta) + \frac{1}{6} \sin(3\theta)) \quad (3.34)$$

The required of “ **λ** ”, makes a peak value “ **$\bar{u}$** ” equal to unity. The previous peak value of “ **u** ” was “ **$\sqrt{3}/2$** ” Therefore.

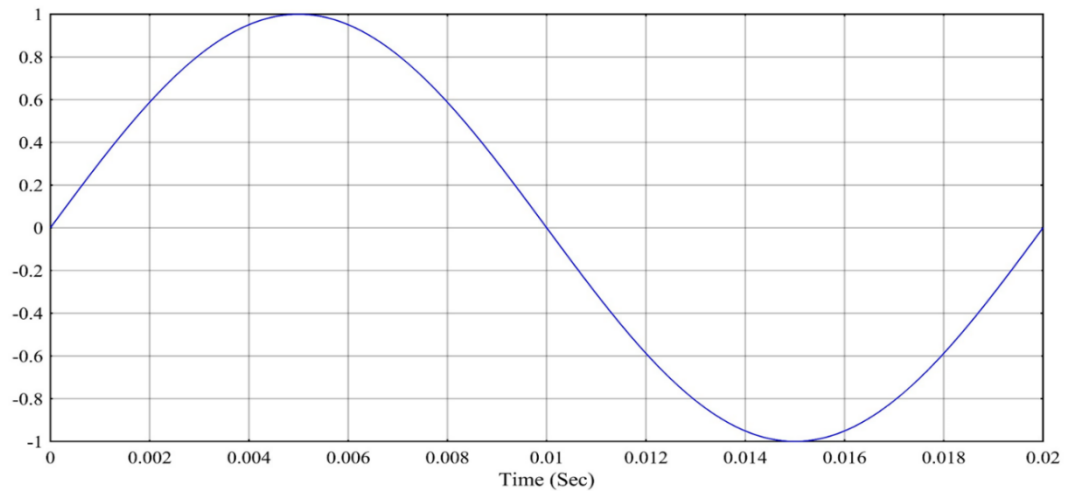
That yields.

$$1 = \lambda \left(\frac{\sqrt{3}}{2} \right)$$

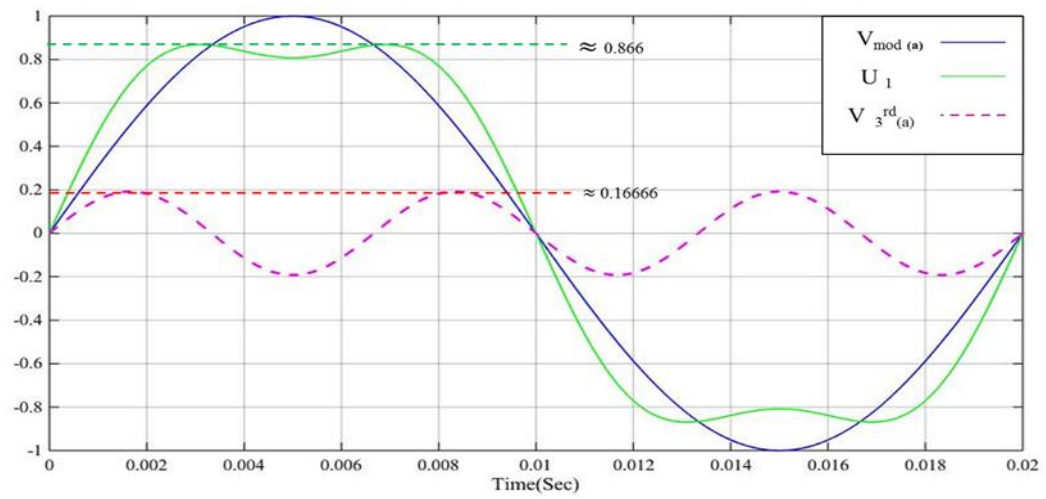
$$\lambda = \frac{2}{\sqrt{3}} \quad (3.36)$$

The figure 3.6(a) illustrated fundamental component of the modulation waveform without addition the third harmonic, and the peak amplitude value is equal to one. In the Figure 3.6(b) the peak amplitude value is “**0.866**” with one-sixth of the third harmonic added. Whereas, the peak value of fundamental component is unity. In the same figure (c), with one-sixth of third harmonic added to the peak value is one and amplitude fundamental component is “**1.155**”. Also in the figure (3.6) it can be seen that when adding the third harmonic. The amplitude of the fundamental phase voltage was increased more 15%. The injection of the third harmonic component to the fundamental component can be done by the following formula [46]:

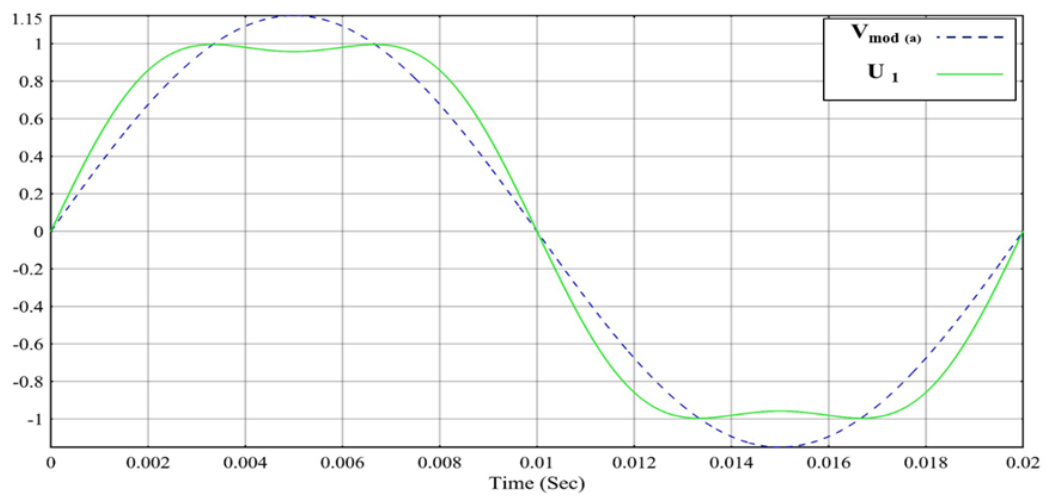
$$\begin{bmatrix} V_{\text{mod(a)}} \\ V_{\text{mod(b)}} \\ V_{\text{mod(c)}} \end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix} \sin(\omega t) & \frac{\sin(3\omega t)}{6} \\ \sin(\omega t + \frac{2\pi}{3}) & \frac{\sin(3\omega t)}{6} \\ \sin(\omega t - \frac{2\pi}{3}) & \frac{\sin(3\omega t)}{6} \end{bmatrix} \quad (3.37)$$



(a)



(b)



(c)

Figure 3.6 Fundamental component of the modulation waveform for the THIPWM

The implementation of third harmonic injection PWM is the same as the sinusoidal-wave PWM, the three reference modulation signal is compared with a high frequency triangular waveform, that is leading to the amplitude of the fundamental component of the modulation waveform is greater than the DC-link supply voltage " V_{DC} " but, the amplitude of the modulation waveform does not reach $V_{DC}/2$, that is mentioned above in Equation (3.37), this is approximately extended in the amplitude 15-percent more compared with normal sinusoidal waveform PWM. The three modulation voltages and triangular waveforms for implementing THIPWM are shown in Figure (3.7).

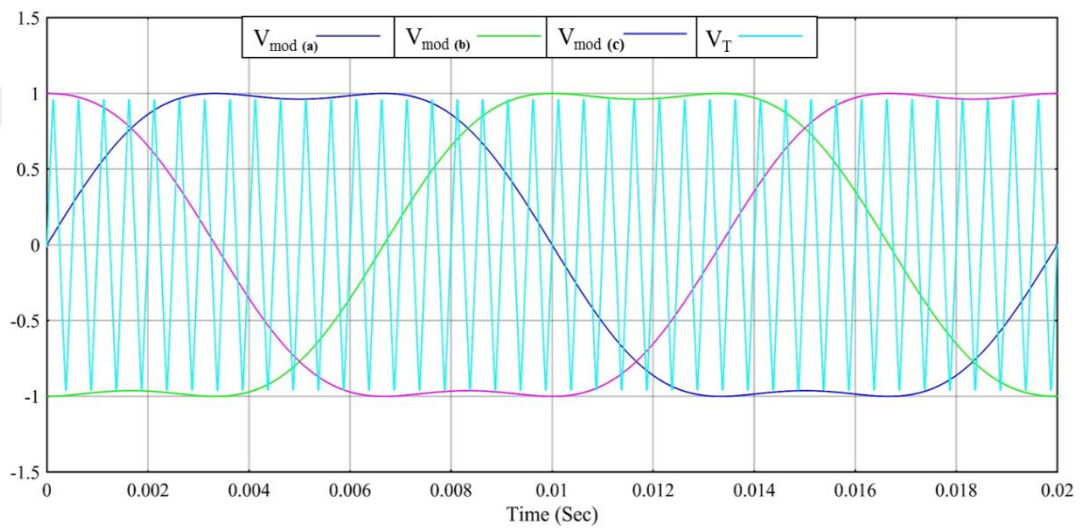


Figure 3.7 Three reference Voltages (a,b,c), and Triangular Waveforms (V_T)

3.3.1.4 Space Vector Pulse Width Modulation technique

The circuit model in the figure (3.1) shows a practical three-phase voltage source inverter "**VSI**". A voltage source inverter should have a stiff voltage source at the input, that is, its Thevenin impedance should ideally be zero. Thus, a large capacitor can be connected at the input if the voltage source is not stiff. The circuit of the "**VSI**" consists of power bridge devices, with three half bridge, each consisting of two power switches and two freewheeling diodes. The inverter is supplied from DC voltage source (either battery or diode-based bridge rectifier) via LC or C filter.[47]

However, switching states vector for the inverter with three- legs in Figure (3.8), has ($2^3 = 8$) permissible switching states. If leg (a) which is connected between (Q_1, Q_2) is represented by an indicator “ S_a ”, also leg (b) by an indicator “ S_b ” and leg(c) by “ S_c ”, since the upper switching devices and the lower switching devices are complementary (i.e. $Q_4 = 1 - Q_1$), then, the switching states can be represented by binary values (0,1).

When, “ $S_a = 0$ ” that equal to ($Q_1 = \text{off and}, Q_4 = \text{on}$), when “ $S_a = 1$ ”that equal to ($Q_1 = \text{on and}, Q_4 = \text{off}$), and that is true for “ S_b ” and “ S_c ”. The eight switching states of the three-phase inverter can be shown in Figure (3.9) [1, 2, 43]:

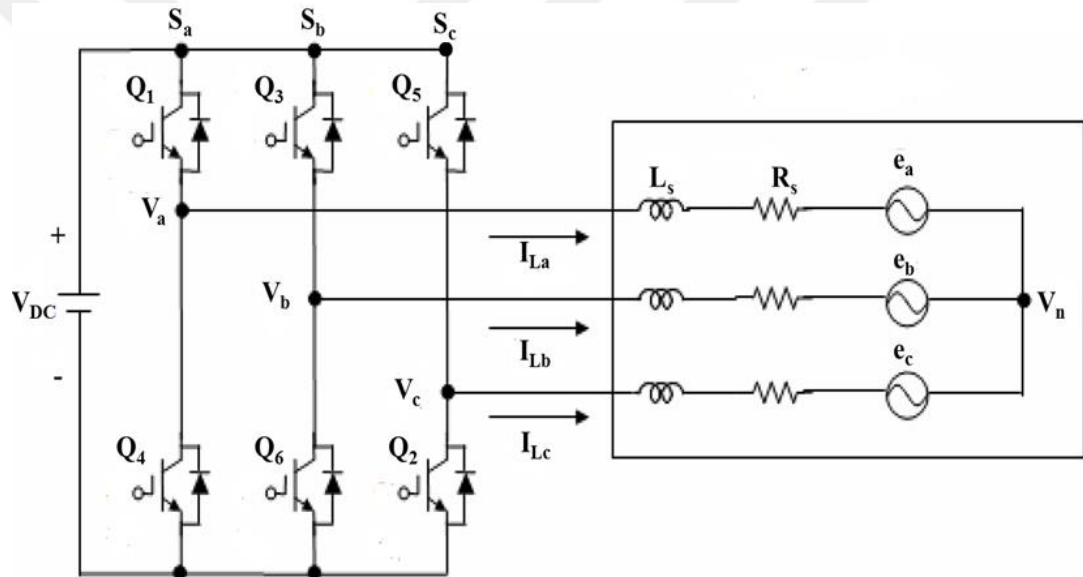


Figure 3.8 Voltage source inverter “VSI”.

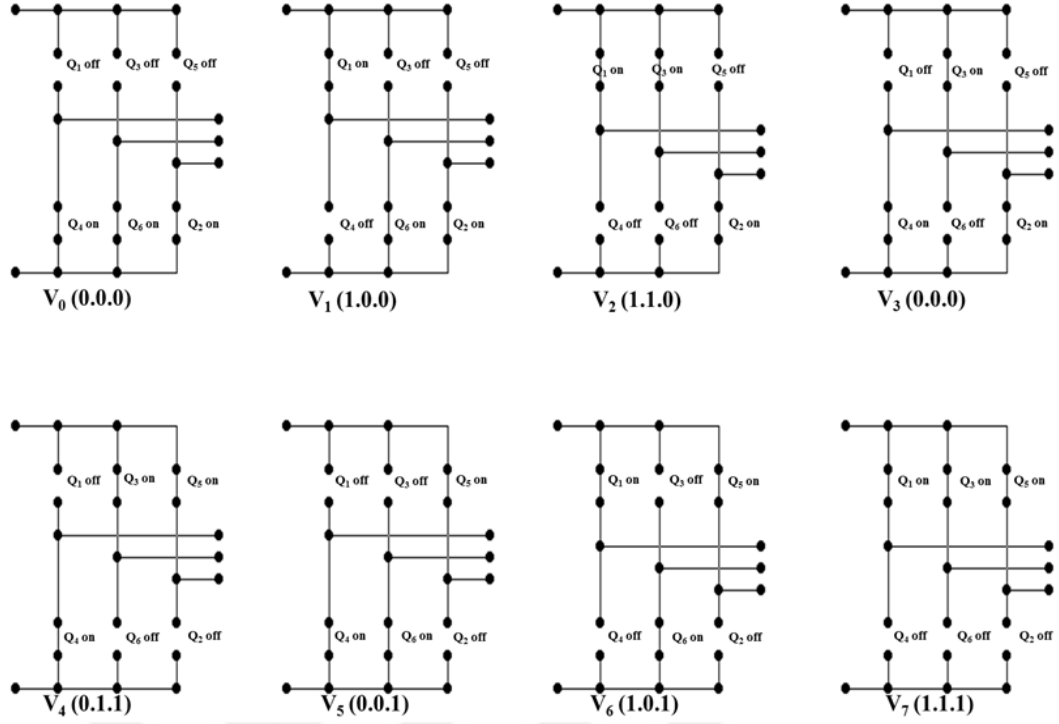


Figure 3.9 Eight switching states of transistor.

The relationship between the switching variable vector $[S_a, S_b, S_c]^T$ and the line-to-line output voltage vector $[V_{ab}, V_{bc}, V_{ca}]^T$, and the phase voltage vector $[V_{an}, V_{bn}, V_{cn}]^T$ are given by the following equations [1,2]:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{DC} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \quad (3.38)$$

Or, phase voltage.

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{DC}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \quad (3.39)$$

By applying the eight logical states of $[S_a, S_b, S_c]^T$ in equations (3.37) & (3.39) gives the line-to-line and line-to-neutral voltages space vectors shown in Table (3.2):

Table 3.2 Line and phase voltages of the eight state vectors.

State no	Switching vectors			Line to natural voltage			Line to line voltage			Space voltage vector
	S_a	S_b	S_c	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}	
0	0	0	0	0	0	0	0	0	0	$V_0(0.0.0)$
1	1	0	0	$\frac{2}{3}V_{DC}$	$-\frac{1}{3}V_{DC}$	$-\frac{1}{3}V_{DC}$	V_{DC}	0	$-V_{DC}$	$V_1(1.0.0)$
2	1	1	0	$\frac{1}{3}V_{DC}$	$\frac{1}{3}V_{DC}$	$-\frac{2}{3}V_{DC}$	0	V_{DC}	$-V_{DC}$	$V_2(1.1.0)$
3	0	1	0	$-\frac{1}{3}V_{DC}$	$\frac{2}{3}V_{DC}$	$-\frac{1}{3}V_{DC}$	$-V_{DC}$	V_{DC}	0	$V_3(0.1.0)$
4	0	1	1	$-\frac{2}{3}V_{DC}$	$\frac{1}{3}V_{DC}$	$\frac{1}{3}V_{DC}$	$-V_{DC}$	0	V_{DC}	$V_4(0.1.1)$
5	0	0	1	$-\frac{1}{3}V_{DC}$	$-\frac{1}{3}V_{DC}$	$\frac{2}{3}V_{DC}$	0	$-V_{DC}$	V_{DC}	$V_5(0.0.1)$
6	1	0	1	$\frac{1}{3}V_{DC}$	$-\frac{2}{3}V_{DC}$	$\frac{1}{3}V_{DC}$	V_{DC}	$-V_{DC}$	0	$V_6(1.0.1)$
7	1	1	1	0	0	0	0	0	0	$V_7(1.1.1)$

Where, V_{DC} the DC link voltage of the inverter.

3.3.1.4.1 Space Vector Principle and representation

The Space Vector Modulation (SVPWM) is quite different from the PWM methods. With PWM, the inverter can be thought of as three separate push-pull driver stages. Which creates each phase waveform independently. SVPWM however, treats the inverter as a single unit. To understand the SVPWM technique, the concept of a rotating space vector and axis transformation is very important [1, 2, 28]. Any three-phase quantities can be represented by two axis frames, as shown in Figure(3.10) , which are a complex axis frame; β -axis represents quadrature imaginary or complex axis and ψ -axis represents a direct real axis. The transformation procedure can easily be done by the following [32]:

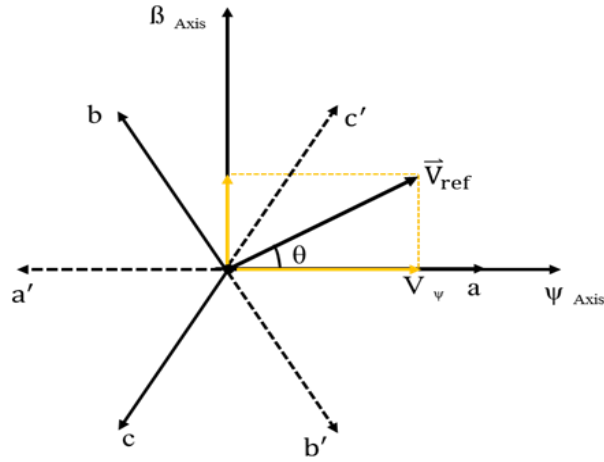


Figure 3.10 The relationship between “a, b, c” frame and “β,ψ” stationary reference frame with voltage space.

From above Figure;

$$V_{\psi} = V_{an} - V_{bn} \cdot \cos(60) - V_{cn} \cos(60) = V_{an} - \frac{1}{2} V_{bn} - \frac{1}{2} V_{cn} \quad (3.40)$$

$$V_{\beta} = V_{an} \cos(90) + V_{bn} \cdot \cos(30) - V_{cn} \cos(30) = V_{an} + \frac{\sqrt{3}}{2} V_{bn} - \frac{\sqrt{3}}{2} V_{cn} \quad (3.41)$$

Or, can be written.

$$\begin{bmatrix} V_{\psi} \\ V_{\beta} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \quad (3.42)$$

$$\begin{aligned} \vec{V}_{ref} &= V_{\psi} + jV_{\beta} \\ &= \frac{2}{3} \left[\left(V_{an} - \frac{1}{2} V_{bn} - \frac{1}{2} V_{cn} \right) + j \left(\frac{\sqrt{3}}{2} V_{bn} - \frac{\sqrt{3}}{2} V_{cn} \right) \right] \\ &= \frac{2}{3} \left[V_{an} + \left(-\frac{1}{2} + j \frac{\sqrt{3}}{2} \right) V_{bn} + \left(-\frac{1}{2} - j \frac{\sqrt{3}}{2} \right) V_{cn} \right] \\ \vec{V}_{ref} &= \frac{2}{3} [V_{an} + aV_{bn} + a^2V_{cn}] \end{aligned} \quad (3.43)$$

Where “a = e^{j2π/3}” and “a² = e^{-j2π/3}”. Than angle “θ”.

$$|\vec{V}_{\text{ref}}| = \sqrt{V_{\psi}^2 + V_{\beta}^2} \quad (3.44)$$

$$\theta = \tan^{-1}\left(\frac{V_{\beta}}{V_{\psi}}\right) = \omega t = 2\pi f_r t \quad (3.45)$$

Where “ f_r ” is fundamental modulation frequency

By applying the phase and line voltages from previous Table (3.2) for different states in equation (3.43) the phase and magnitude of the eight switching space vector voltage can be gotten as shown in Table (3.3).

For example, to evaluate the space vector voltage of state-2 [$\mathbf{V}_2(1.1.0)$]:

$$\vec{V}_2(1.1.0) = \frac{2}{3} [V_{an} + aV_{bn} + a^2V_{cn}]$$

$$\vec{V}_2(1.1.0) = \frac{2}{3} \left[\frac{V_{DC}}{3} + a \frac{V_{DC}}{3} + a^2 \left(-\frac{2V_{DC}}{3} \right) \right] = \frac{2V_{dc}}{3} e^{j\frac{2\pi}{6}}$$

The phasor diagram of space voltage “ $\vec{V}_2(1.1.0)$ ” as shown in figure (3.11):

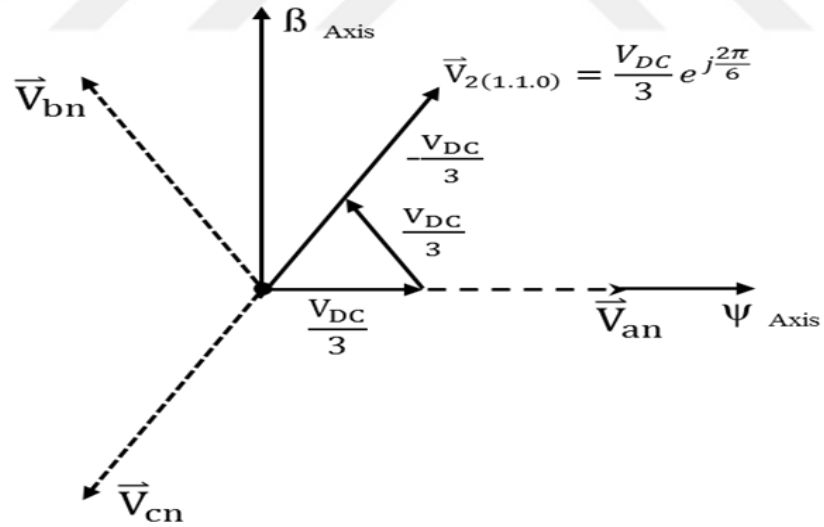


Figure 3.11 Phasor diagram of space vector “ $\vec{V}_2(1.1.0)$ ”.

Table 3.3 Line and phase voltages of the eight space vectors.

Space vector	$\vec{V}_{\text{ref}}$ – Phase	$\vec{V}_{\text{ref}}$ – line
$V_0(0.0.0)$	0	0
$V_1(1.0.0)$	$\frac{2}{3} V_{\text{Dc}} e^{j0}$	$\frac{2}{\sqrt{3}} V_{\text{Dc}} e^{j\frac{2\pi}{12}}$
$V_2(0.0.0)$	$\frac{2}{3} V_{\text{Dc}} e^{j\frac{2\pi}{6}}$	$\frac{2}{\sqrt{3}} V_{\text{Dc}} e^{j\frac{2\pi}{4}}$
$V_3(0.1.0)$	$\frac{2}{3} V_{\text{Dc}} e^{j\frac{2\pi}{3}}$	$\frac{2}{\sqrt{3}} V_{\text{Dc}} e^{j\frac{5\pi}{6}}$
$V_4(0.1.1)$	$\frac{2}{3} V_{\text{Dc}} e^{j\pi}$	$\frac{2}{\sqrt{3}} V_{\text{Dc}} e^{j\frac{7\pi}{6}}$
$V_5(0.0.0)$	$\frac{2}{3} V_{\text{Dc}} e^{j\frac{4\pi}{3}}$	$\frac{2}{\sqrt{3}} V_{\text{Dc}} e^{j\frac{3\pi}{2}}$
$V_6(1.0.1)$	$\frac{2}{3} V_{\text{Dc}} e^{j\frac{5\pi}{3}}$	$\frac{2}{\sqrt{3}} V_{\text{Dc}} e^{j\frac{11\pi}{6}}$
$V_7(0.0.0)$	0	0

Table 3.3 shows that there are six non-zero space vectors and two zero space vectors. The active vectors are “60°” angle apart and describe a hexagon boundary with six sectors as shown in Figure (3.12):

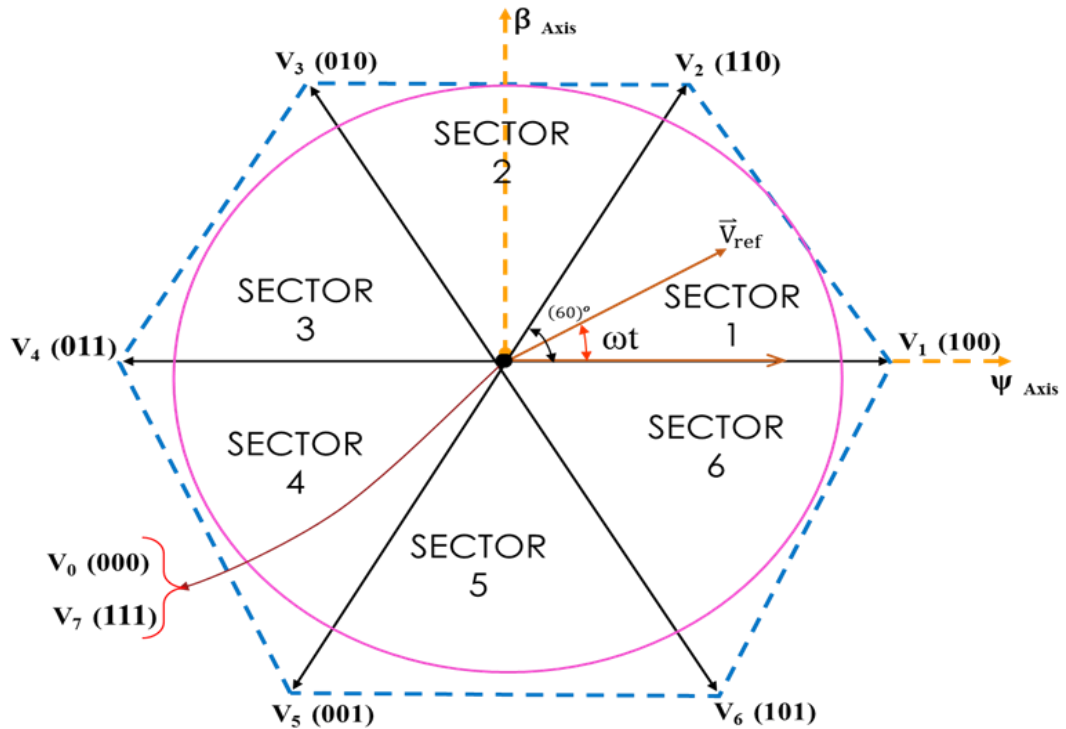


Figure 3.12 Non-zero space voltage vectors with two zero vectors.

The two zero vectors " $\vec{V}_0(0.0.0)$ & $\vec{V}_7(1.1.1)$ " are represented as two dots at the origin. The desired 3-phase voltage called reference voltage " $\vec{V}_{ref}$ " as shown in the above figure the magnitude and rotational speed of " $\vec{V}_{ref}$ " is the same as the fundamental magnitude and frequency. If the output space vector " $\vec{V}_{ref}$ " moves through the six states " $\vec{V}_1 \rightarrow \vec{V}_6$ " the output voltage will have square waveform [2].

Usually, each sector of the hexagon is divided into sub-sectors in which the reference voltage " $\vec{V}_{ref}$ " will move in angular steps, the width of steps (sub-sector angle) depends on the maximum permissible switching rate of the power switching devices, whenever step width is small and switching rate is high the shape of the output fundamental voltage will be close to sine wave but with increase in the switching losses [28, 43].

In SVPWM the space reference voltage moves from state-1 to state-2 by time sharing PWM between " $\vec{V}_1$ " and " $\vec{V}_2$ ". For example if the vector " $\vec{V}_{ref}$ " lies in sector-1, the PWM adjusted between " $\vec{V}_0(1.0.0)$ & $\vec{V}_7(1.0.0)$ " by duty cycle of each being " T_a " and " T_b " respectively, and the zero vectors " $\vec{V}_0(0.0.0)$ & $\vec{V}_7(1.1.1)$ " of duty cycle " T_0 " the Figure 3.13a and 3.13b shows respectively, phasor diagram and duration time of the sector one [32]:

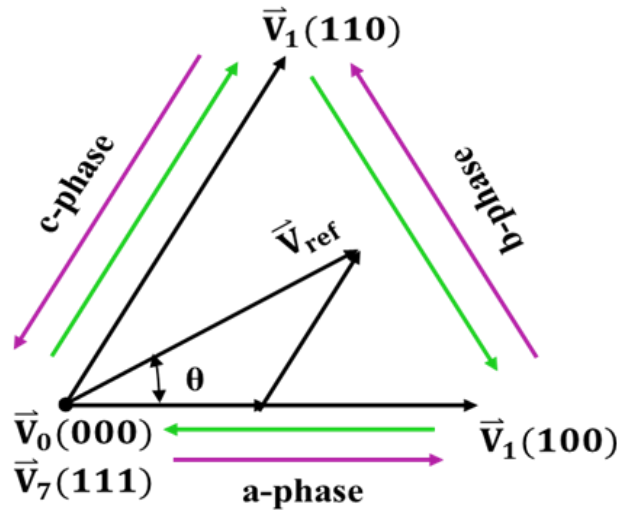
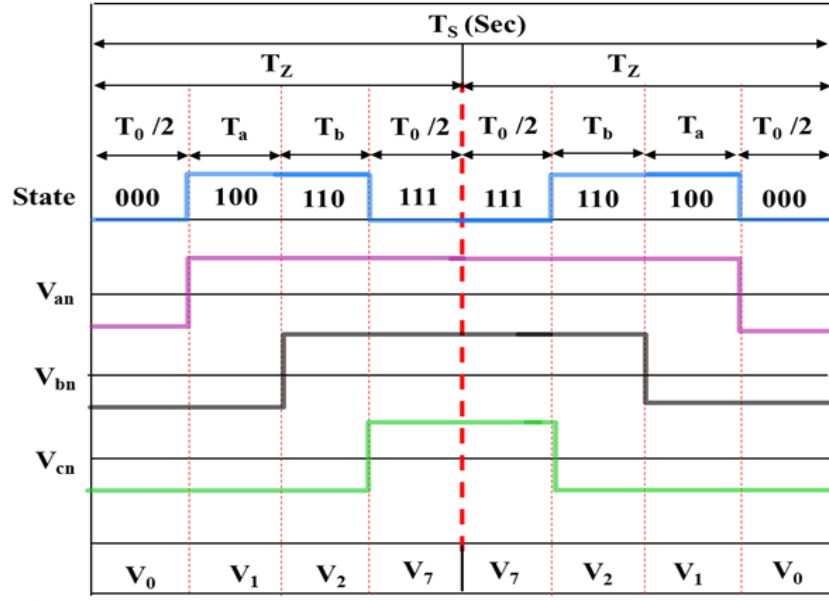


Figure 3.13a Phasor diagram of switching sequence in the sector one.



(b)

Figure 3.13b Duration time in sector one.

The total duration time is.

$$T_z = T_a + T_b + T_0 \quad (3.46)$$

Where, “ $T_z = \frac{T_s}{2}$ ” and “ T_s ” is the sampling time period of the switching frequency. The volt-second integral to reference voltage in the sector one is given by this formula.

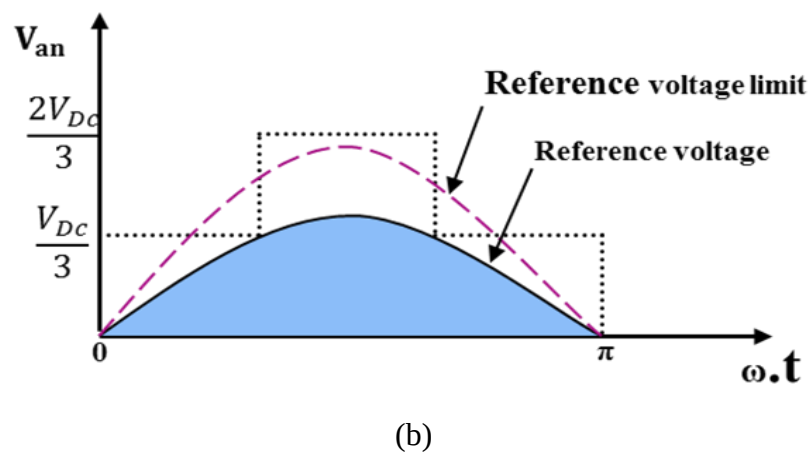
$$\int_0^{T_z} \vec{V}_{ref} dt = \int_0^{T_a} \vec{V}_1 dt + \int_{T_a}^{T_a+T_b} \vec{V}_2 dt + \int_{T_a+T_b}^{T_0} \vec{V}_{0or7} dt$$

$$\vec{V}_{ref} \cdot T_z = \vec{V}_1 \cdot T_a + \vec{V}_2 \cdot T_b + \vec{V}_0 \cdot T_0 \quad (3.47)$$

3.3.1.4.2 Space Vectors Modulation index

For full utilization of the DC-link voltage to the three-phase induction motor, which is the most commonly load used with the SVPWM drives. It is important for achieving a maximum output torque under all operating conditions in AC machine drive applications. The modulation range can be divided into two region liner modulation, or under-modulation and over-modulation region. In this thesis the non-liner modulation region is not considered, the model depends on liner-modulation region. During this region the maximum peak fundamental voltage is “ $0.577V_{DC}$ ”, this means that SVPWM can be produced 15% of output voltage compared with sinusoidal, PWM the highest possible peak fundamental voltage is “ $0.5V_{DC}$ ”, [45] However, the

As an example, a convenient way to generate the PWM output is to use the space vectors “ T_1 ” and “ V_2 ” of sector-1 on a part-time basis to satisfy the average output demand:



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We are calculating “ $\mathbf{V}_{an}$ ” “ $\mathbf{V}_{bn}$ ”.

$$V_{an} \cdot \sin(60^\circ) = \vec{V}_{ref} \cdot \sin(\frac{\pi}{3} - \theta) \quad (3.48)$$

$$V_{bn} \cdot \sin(60^\circ) = \vec{V}_{ref} \cdot \sin(\theta) \quad (3.49)$$

By solving Equation (3.48) and Equation (3.49).

$$V_{an} = \frac{2}{\sqrt{3}} \vec{V}_{ref} \cdot \sin(\frac{\pi}{3} - \theta) \quad (3.50)$$

$$V_{bn} = \frac{2}{\sqrt{3}} \vec{V}_{ref} \cdot \sin(\theta) \quad (3.51)$$

The “ $\mathbf{V}_{ref}$ ” is result of voltages.

$$\vec{V}_{ref} = V_{an} + V_{bn} \quad (3.52)$$

By equating Eq (3.52) with Eq (3.47).

$$\begin{aligned} \vec{V}_{ref} &= \vec{V}_1 \cdot \frac{T_a}{T_z} + \vec{V}_2 \cdot \frac{T_b}{T_z} + \vec{V}_0 \cdot \frac{T_0}{T_z} \\ V_{an} + V_{bn} &= \vec{V}_1 \cdot \frac{T_a}{T_z} + \vec{V}_2 \cdot \frac{T_b}{T_z} \end{aligned}$$

Where “ $\vec{V}_0 \cdot \frac{T_0}{T_z}$ ” Zero voltage is applied to the load.

$$V_{an} = \vec{V}_1 \cdot \frac{T_a}{T_z}, \quad V_{bn} = \vec{V}_2 \cdot \frac{T_b}{T_z}$$

From space voltage table. $\vec{V}_1 = \frac{2}{3} \mathbf{V}_{DC}$ $\vec{V}_2 = \frac{2}{3} \mathbf{V}_{DC}$ And substations in Eq(3.50) and Eq (3.51) we can calculates “ $\mathbf{T}_a, \mathbf{T}_b, \mathbf{T}_0$ ” at sector one.

$$T_a = \sqrt{3} \frac{\vec{V}_{ref}}{V_{DC}} \cdot T_z \sin(\frac{\pi}{3} - \theta) \quad (3.53)$$

$$T_b = \sqrt{3} \frac{\vec{V}_{ref}}{V_{DC}} \cdot T_z \sin(\theta) \quad (3.54)$$

$$T_0 = T_z - (T_a + T_b) \quad (3.55)$$

The switching time “ $\mathbf{T}_a, \mathbf{T}_b, \mathbf{T}_0$ ” for any sector is given by

Assume $\{n= 1, 2, 3 \text{ to } 6\}$ is number of sector and “ $0 \leq \theta \leq 60^\circ$ ”.

$$T_a = \sqrt{3} \frac{|\vec{V}_{ref}|}{V_{DC}} \cdot T_z \sin(\frac{n\pi}{3} - \theta) \quad (3.56)$$

$$T_b = \sqrt{3} \frac{|\vec{V}_{ref}|}{V_{DC}} \cdot T_z \sin(\theta - \frac{(n-1)\pi}{3}) \quad (3.57)$$

$$T_0 = T_z - (T_a + T_b)$$

The time interval “ T_a ” and “ T_b ” satisfies the reference voltage, but “ T_0 ” fills up the remaining gap in “ T_z ” [2].

In the linear region the vector “ $\vec{V}_{ref}$ ” always remains within the hexagon. The region ends when “ $\vec{V}_{ref}$ ” equals to the radius of biggest circle can be drawn within the hexagon as shown in Figure (3.14 a). The ratio between the reference vector “ $\vec{V}_{ref}$ ” and the fundamental peak value of the square-phase voltage wave “ $\frac{2}{3}V_{DC}$ ” called the modulation index “ M ”:

$$M = \frac{|\vec{V}_{ref}|}{V_{six-step}} \quad (3.58)$$

The maximum modulation index can be obtained when “ $\vec{V}_{ref}$ ” equal to the radius of the inscribed circle:

$$(\vec{V}_{ref})_{max} = \frac{2}{3} V_{DC} \cos\left(\frac{\pi}{6}\right) = 0.577V_{dc} \quad (3.59)$$

Therefore the maximum modulation index. $\{M_{max} = 0.577V_{dc}/(2/\pi)V_{dc} = 0.907\}$, which means that “90.7” percent of the square wave fundamental voltage is available in the linear region of SVPWM.

3.3.1.4.3 Switching pattern schemes

The distribution of “ T_a , T_b , and T_0 ” over the “ T_z ” interval lead to formulate four main schemes of SVPWM, and they are different to each other by the choice of the zero vectors “ $\vec{V}_0, \vec{V}_7$ ” and the sequence in which they are applied within the switching cycle [42]. The main commonly SVPWM algorithms are:

1. The right aligned sequence
2. Symmetric sequence
3. Alternating zero vector sequence
4. Highest current not switched sequence

Studies show that a symmetric sequence pattern gives minimal output harmonics, but it needs high switching frequency approximately twice of that in other pattern. Figure (3.15) shows the symmetric sequence pattern of each transistor “ Q_1 , to Q_6 ” for six

sector, the Table 3.4 summarizes switching time calculation for each transistor during “ T_z ,” parodic [2][32].

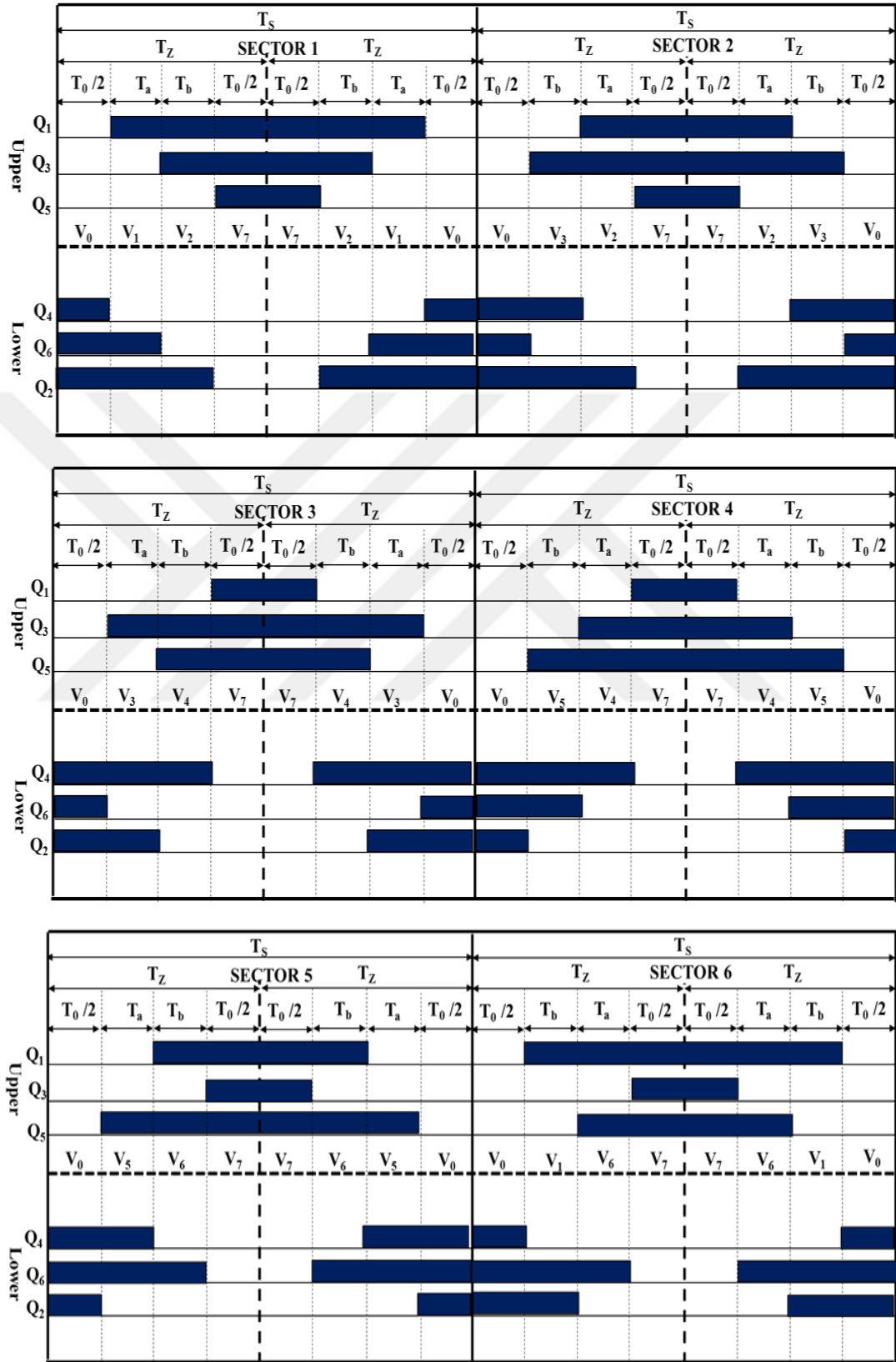


Figure 3.15 Symmetric sequence pattern of each transistor “ Q_1 , to Q_6 ” for six sectors.

Table 3.4 Summarized the conduction time for each transistor to the six sector.

Sector(n)	Upper Transistor	Lower Transistor
1	$Q_1 = T_a + T_b + \frac{T_0}{2}$ $Q_3 = T_a + \frac{T_0}{2}$ $Q_5 = \frac{T_0}{2}$	$Q_4 = \frac{T_0}{2}$ $Q_6 = T_a + \frac{T_0}{2}$ $Q_2 = T_a + T_b + \frac{T_0}{2}$
2	$Q_1 = T_a + \frac{T_0}{2}$ $Q_3 = T_a + T_b + \frac{T_0}{2}$ $Q_5 = \frac{T_0}{2}$	$Q_4 = T_a + \frac{T_0}{2}$ $Q_6 = \frac{T_0}{2}$ $Q_2 = T_a + T_b + \frac{T_0}{2}$
3	$Q_1 = \frac{T_0}{2}$ $Q_3 = T_a + T_b + \frac{T_0}{2}$ $Q_5 = T_b + \frac{T_0}{2}$	$Q_4 = T_a + T_b + \frac{T_0}{2}$ $Q_6 = \frac{T_0}{2}$ $Q_2 = T_a + \frac{T_0}{2}$
4	$Q_1 = \frac{T_0}{2}$ $Q_3 = T_a + \frac{T_0}{2}$ $Q_5 = T_a + T_b + \frac{T_0}{2}$	$Q_4 = T_a + T_b + \frac{T_0}{2}$ $Q_6 = T_a + \frac{T_0}{2}$ $Q_2 = \frac{T_0}{2}$
5	$Q_1 = T_b + \frac{T_0}{2}$ $Q_3 = \frac{T_0}{2}$ $Q_5 = T_a + T_b + \frac{T_0}{2}$	$Q_4 = T_a + \frac{T_0}{2}$ $Q_6 = T_a + T_b + \frac{T_0}{2}$ $Q_2 = \frac{T_0}{2}$
6	$Q_1 = T_a + T_b + \frac{T_0}{2}$ $Q_3 = \frac{T_0}{2}$ $Q_5 = T_a + \frac{T_0}{2}$	$Q_4 = \frac{T_0}{2}$ $Q_6 = T_a + T_b + \frac{T_0}{2}$ $Q_2 = T_b + \frac{T_0}{2}$

3.4 Motion Control of AC Drives:

The high performance AC drives motion control is based on the method of the control which is used and it's necessary to introduce them:

1. Scalar Control
2. Vector Control
3. Direct torque control
4. Intelligent Control

3.4.1 Scalar Control

Despite the fact that a controller with a constant voltage of frequency ratio is the simplest controller, it is the most widespread, being in the majority of the industrial applications. It is known as a scalar controller and acts by imposing a constant relation between voltage and frequency [49].

The structure is very simple and is normally used without speed feedback. However, this controller doesn't achieve a good accuracy in both speed and torque responses, mainly due to the fact that the stator flux and the torque are not directly controlled. Even though, as long as the parameters are identified, the accuracy in the speed can be within 2% except in a very low speed [2].

3.4.2 Principles of constant Volts/Hz for open loop Control

The open loop **volts/Hz** control of an induction motor is by far the most popular method of speed control because of its simplicity, and these types of motors are widely used in industry. For adjustable speed applications, frequency control is natural. However, voltage is required to be proportional to frequency so that the flux " $\varphi = V_s/\omega_e$ " Remains constant (see Figure 1-8), neglecting the stator resistance " R_s " drop. Figure (3-51) shows the block diagram of the volts/Hz speed control method. The power circuit consists of a diode rectifier with a single- or three-phase AC supply, LC filter, and PWM voltage-fed inverter. Ideally, no feedback signals are needed for the control. The frequency " ω_e ," is the primary control variable because it is approximately equal to speed " ω_r " Neglecting the small slip " s " of the machine. The phase voltage " V_s " command is directly generated from the frequency command by the gain factor G , as shown, so that the flux " φ " remains constant. If the stator resistance and leakage inductance of the machine are neglected, the flux will also correspond to the

air gap flux “ ϕ_m ” or rotor flux “ ϕ_r ”. As the frequency becomes small at low speed, the stator resistance tends to absorb the major amount of the stator voltage, thus weakening the flux. The boost voltage “ V_0 ” is added so that the rated flux and corresponding full torque become available down to zero speed. Note that the effect of the boost voltage becomes negligible at higher frequencies. The “ ω_e^* ” signal is integrated to generate the angle signal “ θ_e^* ” and the corresponding sinusoidal phase voltages (V_a^* , V_b^* , and V_c^* signals) are generated by the expressions shown in the figure 3.16. The PWM controller is merged with the inverter block [2] (where V_a^* , V_b^* , and V_c^* are the desired three phase voltage output)

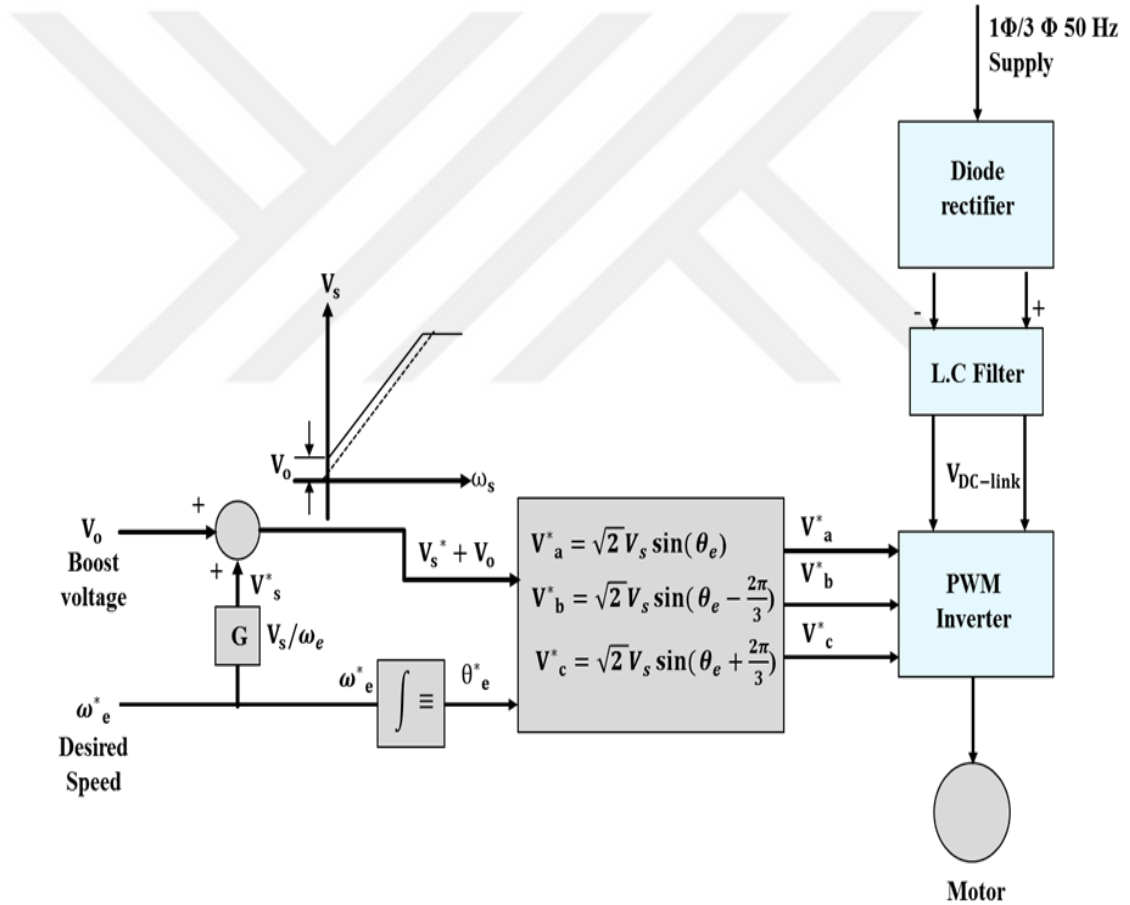


Figure 3.16 Open loop volt/Hz speed control with voltage-fed inverter.

CHAPTER 4

DISCUSSION OF THE RESULTS OF THREE MODELS OF PWM INVERTER BASED ON OPEN –LOOP (VOLT/ HERTZ)

4.1 Introduction:

In order to examine the performance of the PWM inverter based on the variable frequency drive VFD, firstly it must be connected to a three-phase induction motor, which is the most commonly load used with the AC drives. Secondly, the overall system (drive, controller, switching bridge & motor) must be converted to an equivalent mathematical representation (mathematical equations or constant and variables quantity). Thirdly, these equations must be simulated by using any computer program, to study system operation and optimization its performance by iteration of its parameters, although a simulation enables us to examine the transient response of the system in addition the steady state behavior.

One of the most commonly used programs is a Sim-power, which provides us an excellent mathematical representation of the system. The overall simulation model of the system can be shown in figure (4.1):

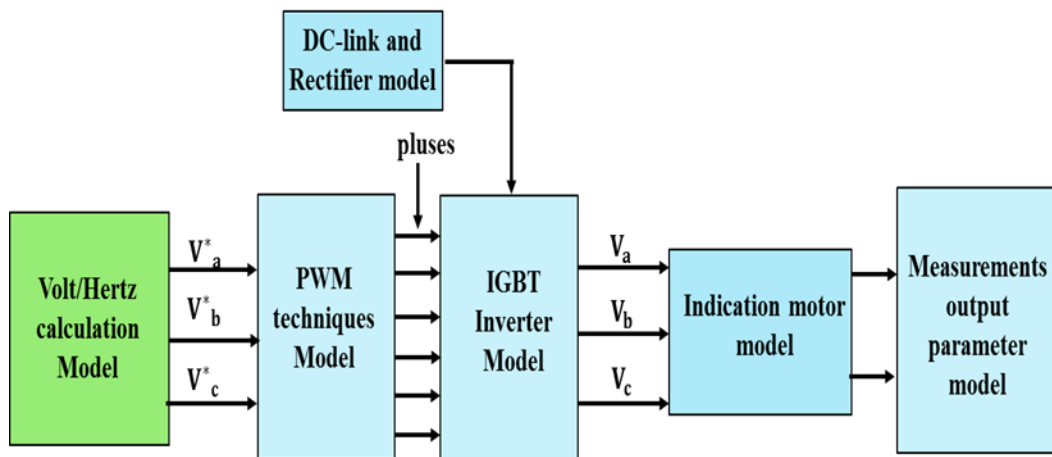


Figure 4.1 Overall system simulation

Where, V_a^* , V_b^* , V_c^* the desired inverter output voltage.

The advantage of Sim-power at Simulink environment over other simulators is the ease of modelling the transients of electrical machines and drives to include drive controls in the simulation. The mathematical model of the system must be defined by differential and algebraic equations and express it in a state variable or transfer function form. However, the equations by themselves are not always enough; some experience with differential equation solving is required.

Once the block diagram has been developed, it can be simulated using any number of different solvers. These compute the internal state variables of the blocks by solving their respective ordinary differential equations. Choosing the appropriate solver can significantly decrease the computation time and improve the accuracy of the simulation. This decision is largely dependent on whether the controller model is implemented in discrete or continuous time variable. The main difference between a discrete and continuous model, is that the discrete time blocks respond to input changes with a fixed period and hold their outputs constant between successive samples. Although, discrete time models can be solved using any of Simulink's solvers, the fixed step setting is usually the fastest. This assumes that the model is entirely discrete and that every state variable is calculated at the same time. For this reason, the model in this thesis was built by using discrete time, fixed step solver setting.

Thus, in this chapter the following models have to be simulated:

- 1- Open loop Volt/hertz controller model.
- 2- SPWM, THIPWM, and SVPWM the three PWM model at liner -modulation region.
- 3- IGBT inverter model
- 4- Induction motor model.
- 5- Measurements output parameter model

The steps of simulation are includes detailed subsystems of the Simulink models as well as an explanation of the role of every subsystem.

4.2 Open loop Volt/hertz controller:

4.2.1 Voltage setting

In order to make the model suitable for different voltages with respect to speed motor speeds, an input frequency which represents the desired frequency “ ω_e^* ” is multiplied by a constant gain “ G_e ”, the results represent the desired output voltage “ V_s^* ”

$$V_s^* = G_e \cdot \omega_e \quad (4.1)$$

$$G_e = \frac{V_{base}}{\omega_{base}} \quad (4.2)$$

Where “ V_{base} ” is a motor rated voltage in volt, in this model used “ $V_{base} = 220 \text{ v}$ ”, and “ $\omega_{base} = 2\pi f_r$ ” is base frequency in “red/sec” usually used the rated frequency of the system, in this system “ $f_r = 50 \text{ Hz}$ ”. Thus, “ $\omega_{base} = 100\pi \text{ red/sec}$ ”.

$$G_e = \frac{220}{100\pi} \quad (4.3)$$

$$V_s^* = \left(\frac{220}{100\pi} \right) \omega_e^* \quad (4.4)$$

In order to keep the synchronization between the variation of (V & f), the three sinusoidal phase voltages (V_a^* , V_b^* , and V_c^* signals) are generated by the following expressions.

$$\begin{bmatrix} V_a^* \\ V_b^* \\ V_c^* \end{bmatrix} = V_s^* \begin{bmatrix} \sin(\theta_e^*) \\ \sin(\theta_e^* - \frac{2\pi}{3}) \\ \sin(\theta_e^* + \frac{2\pi}{3}) \end{bmatrix} \quad (4.5)$$

Where “ θ_e^* ” can be defined as a desired electrical angle, to generate this function, an integral block is used to make integration of the angular frequency “ ω_e^* ” (see in Figure 3.15).

4.2.2 Boost voltage setting

The boost voltage “ V_o ” is added at low frequency to keep a torque available at low speed. Note that the effect of the boost voltage becomes negligible at higher frequencies

In this system a “10 Hz” is selected as low frequency .However, the effect of boost voltage is active below this value .Threshold function used in the simulation, to generate this function in this study negating this option.

4.2.3 Modulation index setting:

In order to make the model suitability for different PWM techniques, a per unit command voltage input “ V_{com}^* ” is chosen, which represents the desired output voltage with respect to base voltage:

$$V_{com} = \frac{V_s^*}{V_{base}} \text{ P. u} \quad (4.6)$$

$$\begin{bmatrix} V_a^* \\ V_b^* \\ V_c^* \end{bmatrix} = V_{com} \begin{bmatrix} \sin(\theta_e^*) \\ \sin(\theta_e^* - \frac{2\pi}{3}) \\ \sin(\theta_e^* + \frac{2\pi}{3}) \end{bmatrix} \quad (4.7)$$

“ V_{com} ” Varies from “0” (zero output) to “1” (desired output voltage is **100%** of the rated voltage). In fact, the value of “ V_{com} ” is equal to the value of the modulation index “ M “.the signals of modulation index shown in the Figure 4.3

The Simulink block diagram of the calculation (Volt/Hertz) for the open loop Control system of a three phase induction motor is shown in Figure .4.2 which are built by using a computer simulation software environment.

4.3 The three PWM model:

4.3.1 Sinusoidal Pulse Width Modulation SPWM

The implement of SVPWM is very easy and popular by using comparators. The SPWM Simulink system model consists of, reference signal (V_a^* , V_b^* , and V_c^*), High-frequency triangular wave generator blocks "ramp function", logic comparators. The overall Simulink block diagram of the sinusoidal pulse width modulation SVPWM and the signal for three legs can be shown in Figure. 4.4&4.5 respectively

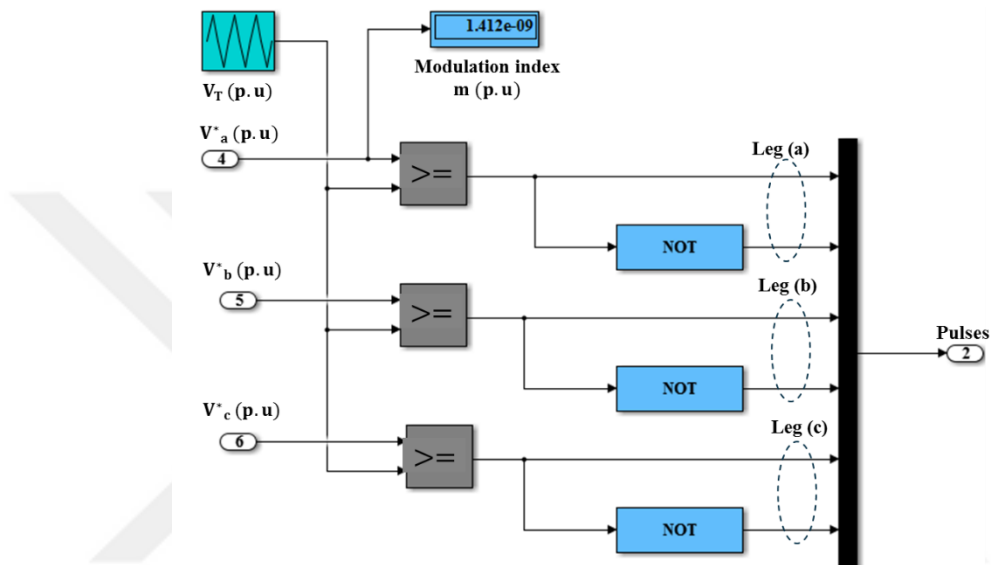


Figure 4.4 Block diagram of implementation SPWM

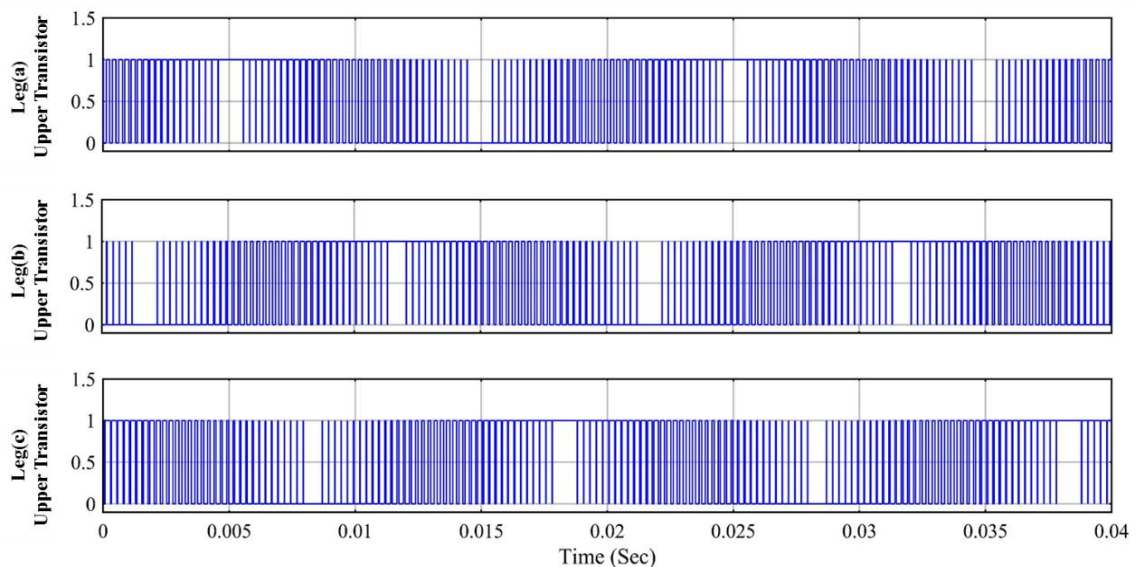


Figure 4.5 Gets signal for three legs generated by SPWM.

4.3.2 Third Harmonic Injection Pulse Width Modulation (THIPWM)

To simulate THIPWM system, the three reference voltage signal (V_a^* , V_b^* , and V_c^*), are obtained by using equation (3.37). The THIPWM sub-system block as same as the SPWM system. The s-function code was written in the Appendix (A). The output gets signal for three legs can be shown in figure 4.6

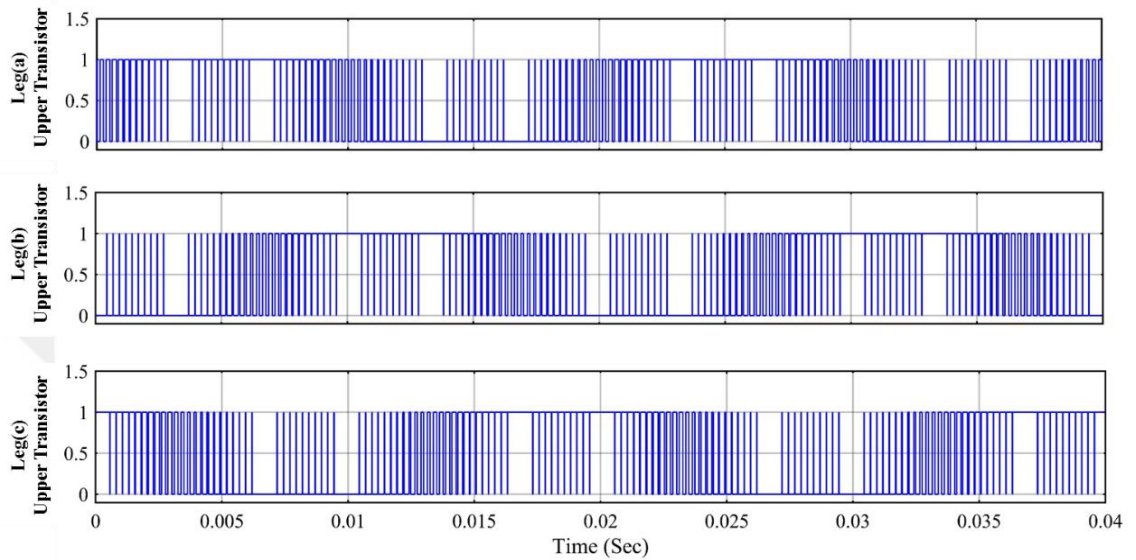


Figure4.6 Gets signal for three legs generated by THIPWM.

4.3.3 Space Vector Pulse Width Modulation (SVPWM)

The steps of simulating system model are explained in the flowing

- 1) Space Vector voltage Calculation and vector Location
- 2) Time Interval Calculation.
- 4) Switching time pattern of each transistor

4.3.3.1 Space Vector voltage Calculation and vector Location

The three sinusoidal voltages waveform (V_a^* , V_b^* , and V_c^*), are converted into compotes " V_ψ, V_β ", with variable frequency, amplitude, that can be obtained by using equation (3, 40), a Simulink block diagram in the figure 4.7 shown to generate this parameter " $V_\psi, V_\beta, \theta, \vec{V_{ref}}$ " a simulation program code see in (Appendix-A) was written, the main features of this program are

$$\vec{V_{ref}} = V_\psi + jV_\beta$$

$$\theta = \omega t = 2\pi f_r t$$

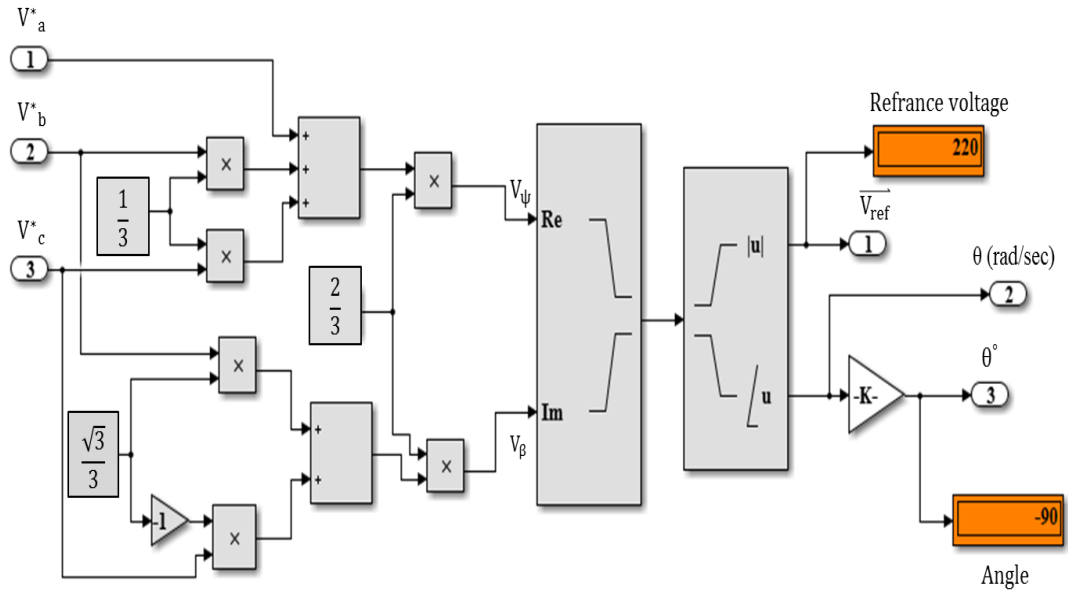


Figure 4.7 Sub-system axis transformation and generated “ $\theta, \overrightarrow{V_{ref}}$ ”.

4.3.3.2 Time Interval Calculation

In order to calculate the time periods “ T_a, T_b, T_o ” and generate the corresponding states vector “ $[S_a, S_b, S_c]^T$ ”, first determine “ n ” which refers to number of sector 1-6 to implantation using Table 4.1. The sub-system Simulink block diagram in Figure 4.8 obtained the sector selection

Table 4.1 Angle for each sector.

Angle θ°	Number of sector
$0 \leq \theta \leq 60$	1
$60 \leq \theta \leq 120$	2
$120 \leq \theta \leq 180$	3
$180 \leq \theta \leq 240$	4
$240 \leq \theta \leq 300$	5
$300 \leq \theta \leq 360$	6

Limits of the value of “ θ ” between (0 to 60°) in each sector, and indicated sector number. The changing in the number of sectors “ n ” with respect to angle “ θ ” can be shown in Figure 4.9

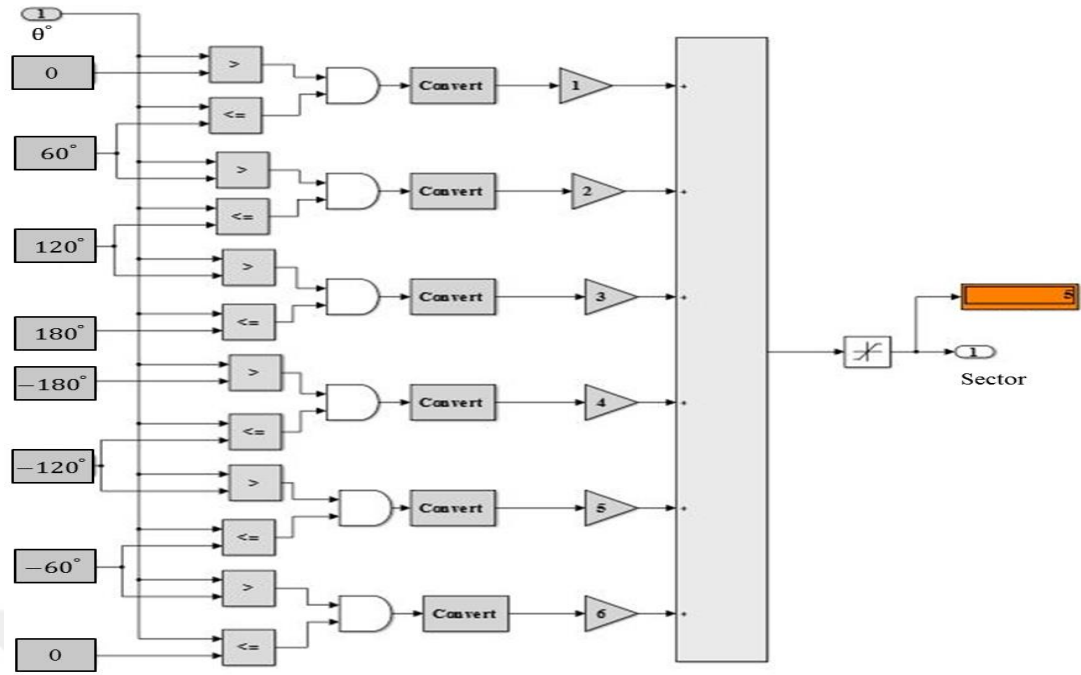


Figure 4.8 Sub-system Simulink block diagram of sector selection.

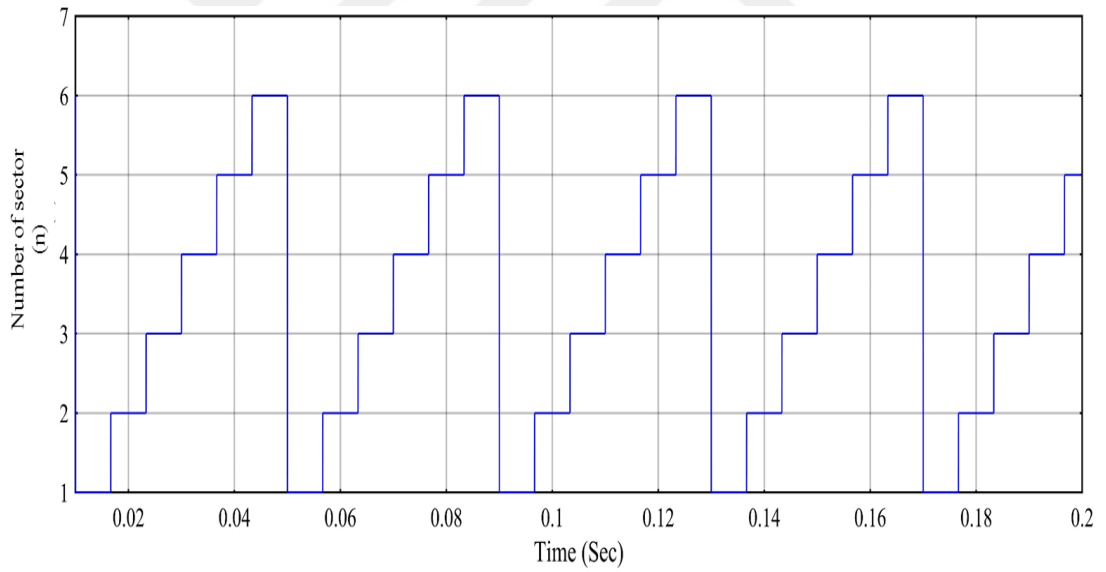


Figure 4.9 Changing in sectors “n” with respect to angle “θ”

After obtained sector the “ T_a , T_b , T_o ” can be calculated by using equations (3.55), (2.56), (2.57). The sub-system simulation blocks to generate time interval “ T_a , T_b , T_o ” can be shown in Figures 4.10. For more details on S-function code see in (Appendix-A) the main features of S-function are:

$$M_i = \sqrt{3} \frac{|\bar{V}_{ref}|}{V_{DC}}$$

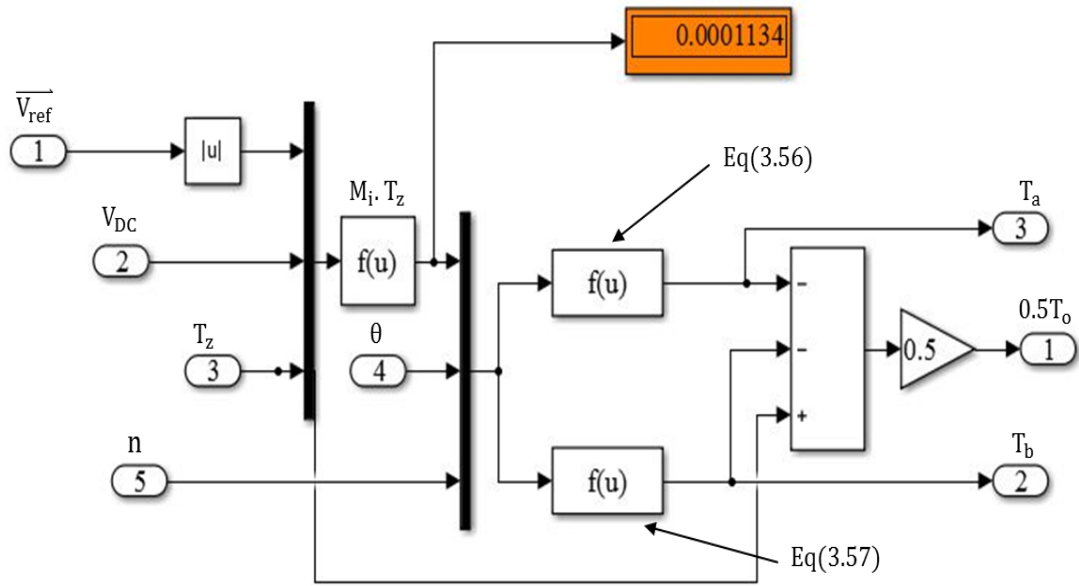


Figure 4.10 Sub-system simulation to generated “ T_a , T_b , T_o ,”

4.3.3 Switching time pattern of each transistor

The sub-system block in the Figure 4.11 is used to generate upper and lower pulses for each transistor. The duty cycle of upper switches “ Q_1 , Q_3 , Q_5 ,” with respect to number of sector can be obtained from table 3.4. Figure 4.12 shows the PWM time for three upper switches “ Q_1 , Q_3 , Q_5 .” The s-function details are illustrated in (Appendix A).

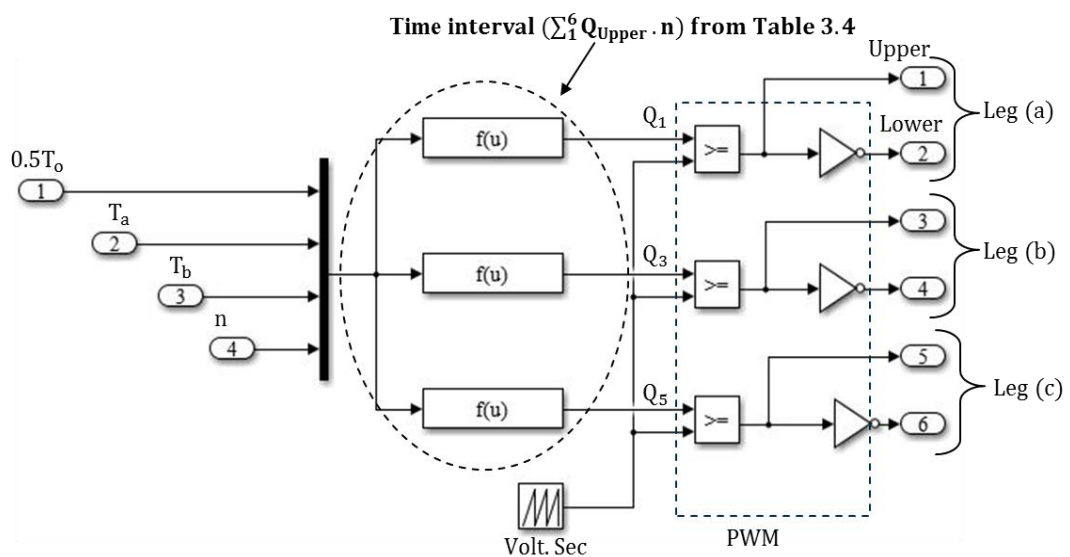


Figure 4.11 Sub-system blocks to generate gets pulses for each transistors

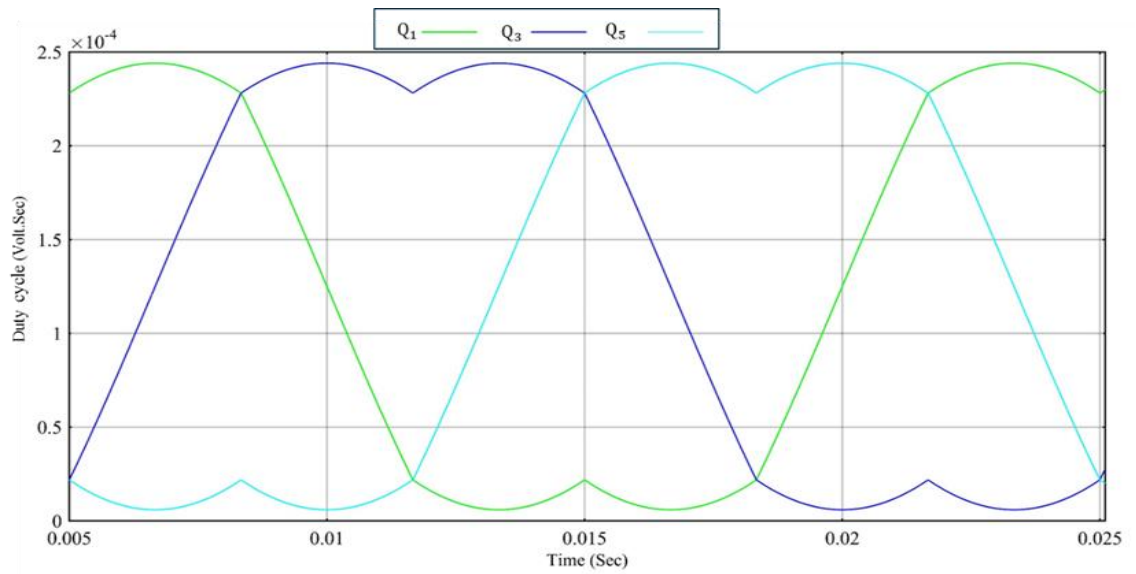


Figure 4.12 Space vector duty cycle for upper three legs with respect to six sector

Finally, by collecting all the previous sub-systems, **the overall system of SVPWM can be obtained as shown in Figure (4.13):**

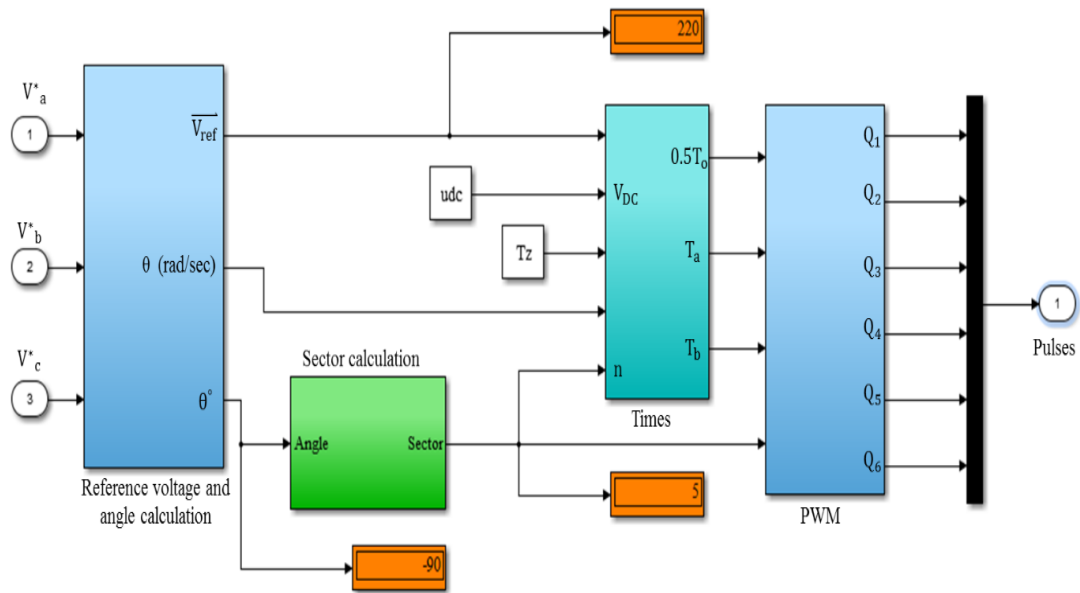


Figure 4.13 Space vector PWM simulation model.

4.4 IGBT inverter model:

The simulation sub-systems in the Figure 4.14 obtained a three phase full bridge inverter. A full bridge is built of six-switch power module. A six Insulated Gate Bipolar Transistor (IGBT) used as switches, which is widely used in medium power applications

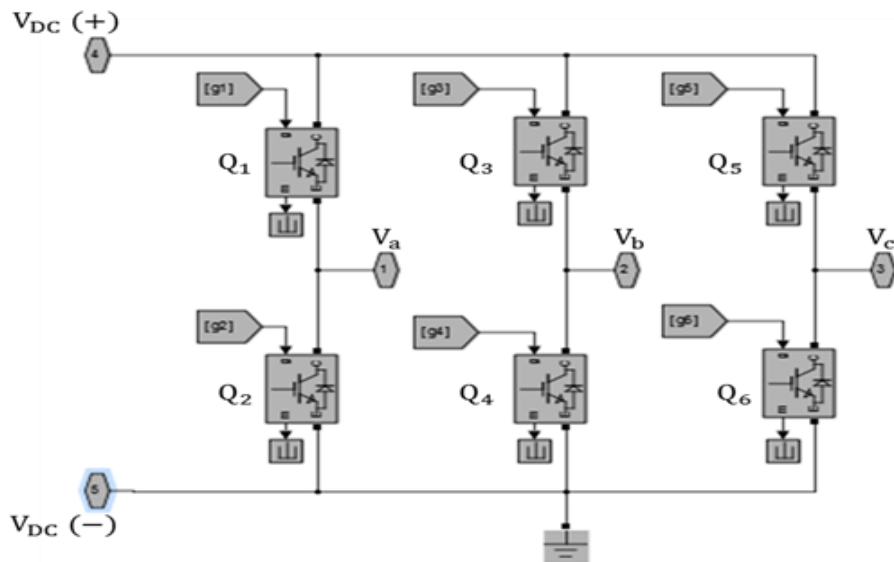


Figure 4.14 Sub-systems blocks of IGBT inverter.

4.5 Induction motor model:

The machine sub-system simulation model in Figure 4.15. Both electrical and mechanical variables in the model can be chosen, the main features of this model are.

$$K = \frac{Hp \times 746}{(\omega_m)^3} \quad (4.8)$$

$$\ell_T = K (\omega_m)^2 (1 - \eta/100) \quad (4.9)$$

Where ℓ_T a fixed is losses of machine such as core losses, fraction and windage losses and η efficiency of the motor.

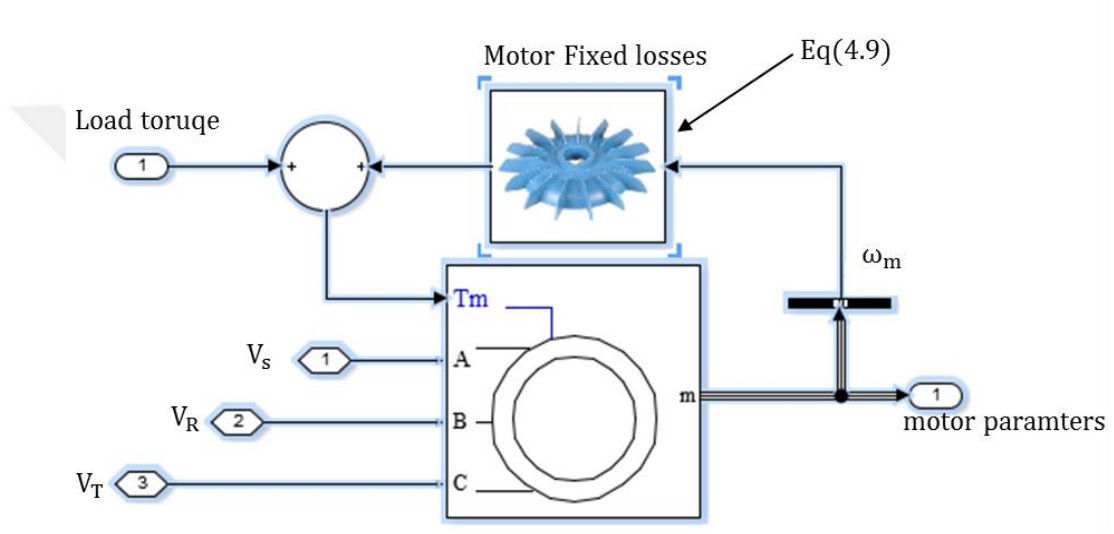


Figure 4.15 Sub-systems blocks of the dynamic model of the induction motor.

4.6 Measurements output parameter model:

The sub-system simulation .Measurement Simulink block divided into two models the first model Measurement the inverter parameter such as line and phase voltage, moreover, voltage after discrete low pass filter with “4. f_r ” Cut of frequency or 200Hz, the second model Measurement a machine parameter , The sub-system simulation of the two models can be shown in Figures (4.16)&(4.17) respectively:

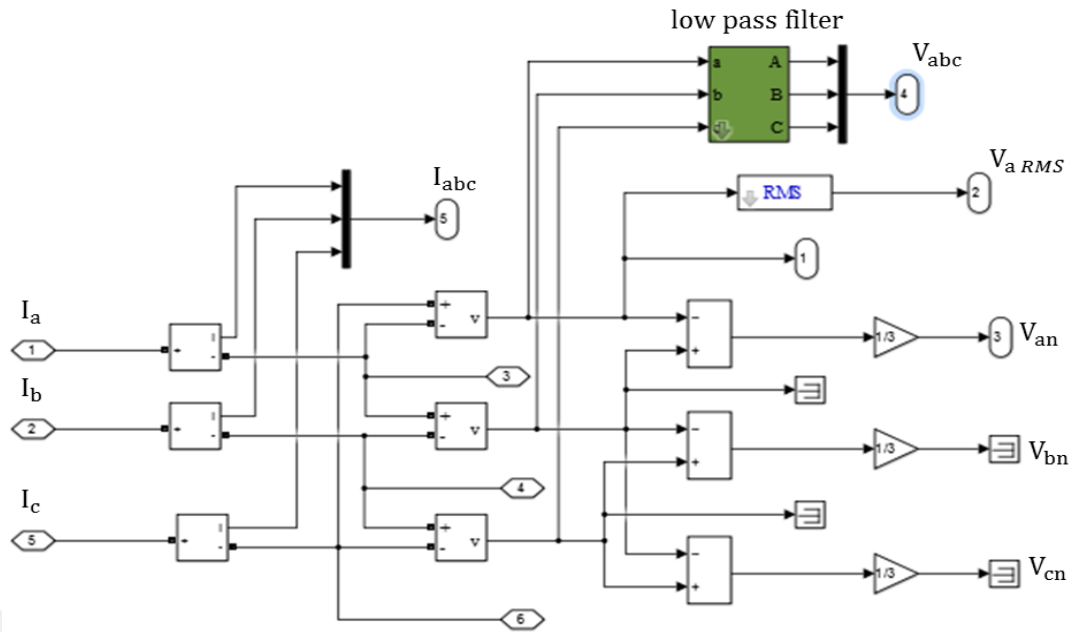


Figure 4.16 Sub-system simulation of inverter parameter measurements.

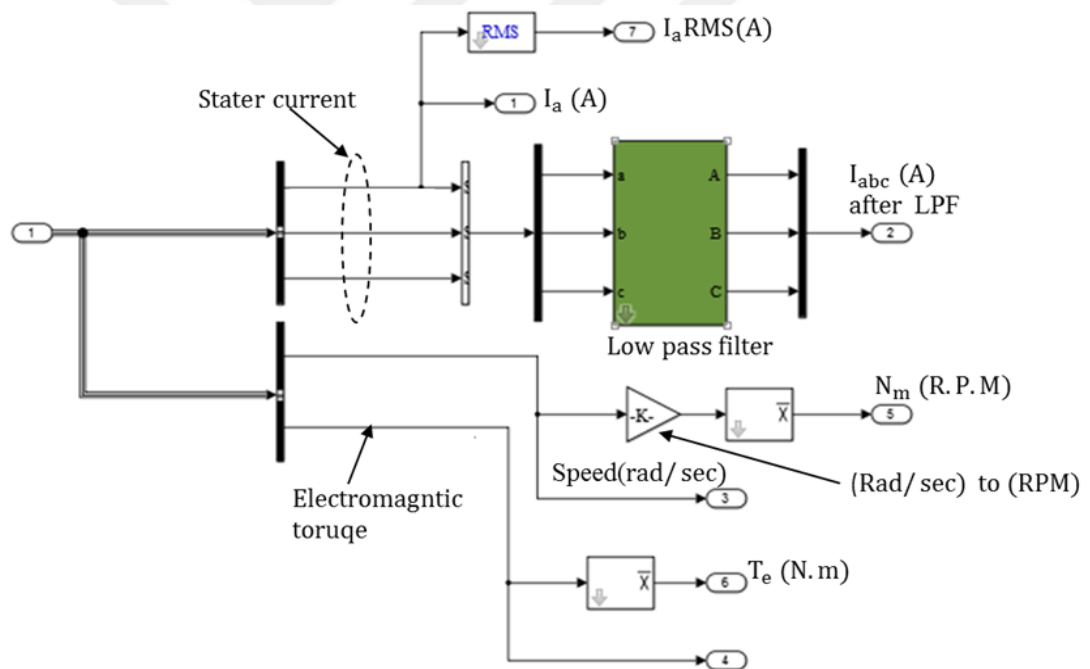


Figure 4.17 Sub-system simulation of motor parameter measurements

More detailed about measurements model see-in (Appendix-A)

Finally, by collection of all the previous sub-systems the overall system of Variable Frequency Drive can be obtained as shown in Figure (4.18):

4.7 Simulation results:

4.7.1 DC supply setting

Choosing the value of DC supply depends on the desired output voltage, which is measured with respect to the magnitude of the fundamental harmonic of the square-wave ($2V_{DC}/\pi$). For example, if it is desired to produce rated output fundamental sine-wave equal to 220 volt (peak), the DC supply will be:

$$220 = 2 \frac{V_{DC}}{\pi} \rightarrow V_{DC} \approx 300 \text{ V}$$

In liner modulation region for SVPWM

$$M_i = \sqrt{3} \frac{|\vec{V}_{ref}|}{V_{DC}} \leq 0.95 \rightarrow V_{DC} \approx 400 \text{ V}$$

4.7.2 PWM setting:

The modulation index varies under modulation region ($0.1 \geq m \geq 0.95$), also the carrier frequency of proposed PWM $f_s = 8 \text{ KHz}$.

4.7.3 System Performance

In order to test the performance of three types of PWM based on inverter fed three phase induction motor, the simulation test consists of two parts. The first part will show the System performance under no-load condition. The no-load results are obtained by applying different frequencies to the inverter which fed a practical induction motor, the name- plate of motor will be show in Table 4.2. From these data the parameters of motor can be estimated by using optimization function in simulation software “power_ Asynchronous Machine Params”. The estimation of parameters of the motor is listed in Table 4.3

Table 4.2 Practical induction motor, name plate.

Number of phase	3
Motor Power	1Hp
Frequency	50 Hz
Number of Poles	4
Volts (Δ)	230V
Rated current	3.6A
Motor Speed	1420 R.P.M
Efficiency	79%
PF	0.67

Table 4.3 Estimation parameter of practical induction motor.

Synchronous speed	1500 R.P.M
Slip	0.053
Mechanic Torque	5 N.M
Stator resistance (R_s)	6.5 Ω
Rotor resistance (R_r)	5 Ω
Stator inductance (L_s)	0.0065 H
Rotor inductance (L_r)	0.0065 H
Magnetizing inductance (L_m)	0.125 H
Friction constant (F)	0.0 N.m.s
Moment of inertia (J)	0.0041 Kg.m ²

The second part will show the System performance under load condition. The simulation test obtained by using different induction motors, and the parameters of this motor are listed in Table 4.4

Table 4.4 Parameters of motor used to test performance under load condition [50]

Motor Power	3 Hp
Frequency	50 Hz
Number of Poles	4
Volts	300 V
Stator resistance (R_s)	0.435 Ω
Rotor resistance (R_r)	0.816 Ω
Stator inductance (L_s)	4 mH
Rotor inductance (L_r)	2 mH
Magnetizing inductance (L_m)	69.31 mH
Friction constant (F)	0.02 N.m.s
Moment of inertia (J)	0.0057Kg.m ²

4.7.3.1 Calculation of THD used (FFT)

The Fast Fourier Transforms (FFT), which is a fast algorithm for calculation of the transform time domain data into frequency domain data makes it possible to frequency domain analysis of power systems, such as the measurement and analysis of power system harmonics [51]. In the summation result, the FFT technique is used to calculate the THD for current and voltage.

4.7.3.2 System Performance under No Load Conditions

To check the system performance under no load conditions, the system behavior has been predicated under no load conditions on the (Volt/hertz) control systems and the output inverter voltage from frequency estimated, Table 4.5 shows an inverter phase voltage and speed tracking against the variation frequency with different percentage ratio. Figure (4.19) shows the (Volt/hertz) curves of system for three PWM techniques. This curve describes the behavior of (Volts/hertz) controller when applying different frequency ratio.

$$f_{diserd}(\text{Hz}) = \left(\frac{50}{100} \right) * f_{comn}$$

Table 4.5 Inverter phase voltage and motor speed when applied a different ratio of frequency.

PWM	SPWM		THIPWM		SVPWM	
$f_{comn}(\%)$	$N_r(\text{r. p. m})$	$V_{\text{phase}}(\text{V})$	$N_r(\text{r. p. m})$	$V_{\text{phase}}(\text{V})$	$N_r(\text{r. p. m})$	$V_{\text{phase}}(\text{V})$
20	294	100	296	106	297	107
40	584	138	588	143	588	144
60	870	171	876	180	877	180
80	1147	196	1158	206	1159	207
100	1418	220	1435	230	1437	231
120	1698	220	1718	230	1720	231
140	1910	220	1948	230	1952	231
160	2075	220	2140	230	2147	231

Where $\%f_{comn}$ refers to the rated frequency (50 Hz)

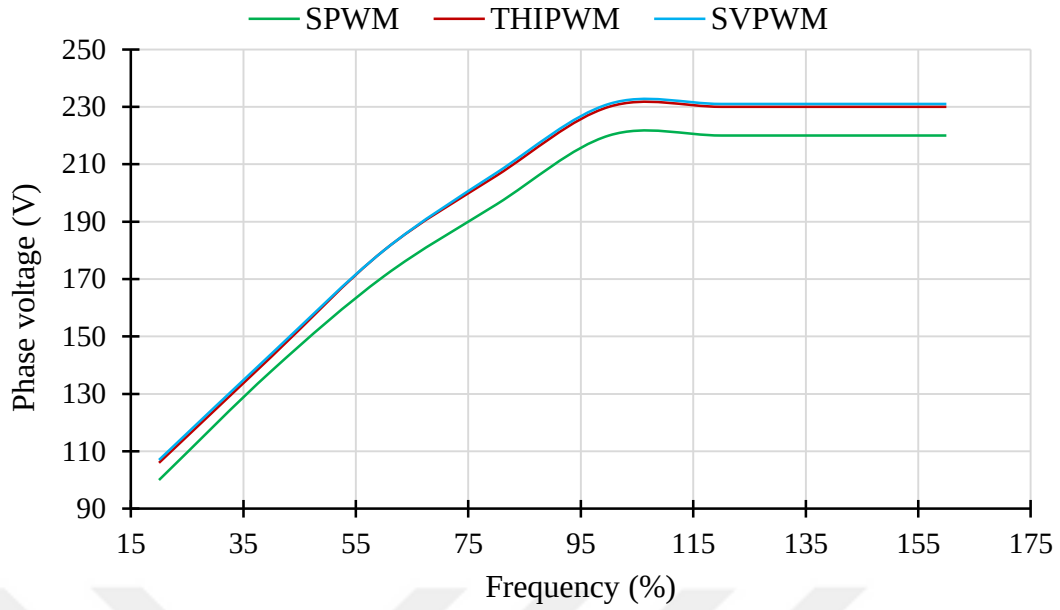


Figure 4.19 (V/f) curve of AC drive system for three PWM techniques under no-load condition.

In Table 4.5 the initial value of phase voltage is (100v), when SPWM inverter technique is used and after (100% of $f_{comm}(\%)$) the value is set to (220v). In case of THIPWM the output voltage increased to (230v), then SPWM, and the initial value of voltage is (231V) when SVPWM technique is used. Hence the THIPWM and SVPWM allow a better utilization of DC-link power, compared with SPWM technique. This can be seen clearly in figure 4.19. In the same Figure a motor stator voltage is estimated by (volt/hertz) controller and (PWM inverter) system. It is possible to see voltage produced by SPWM less than that of the (SPWM, THPWM) system with respect to ratio step change in frequency.

By sequence, the harmonics magnitude measurements and the performance parameters (THD %) are calculated in different steps of frequency ratio f_{comm} , the most frequently encountered and potentially harmful harmonics are (5th, 7th and 11th) which are calculated. A higher harmonics are neglected in this calculation. The voltage and current harmonics magnitude (%) respect to magnitude of fundamental these are drawn in Figure 4.20(a, b, c), Figure 4.21(a, b, c) respectively, which refer to three PWM techniques SPWM, THIPWM, and SVPWM (See Appendix C).

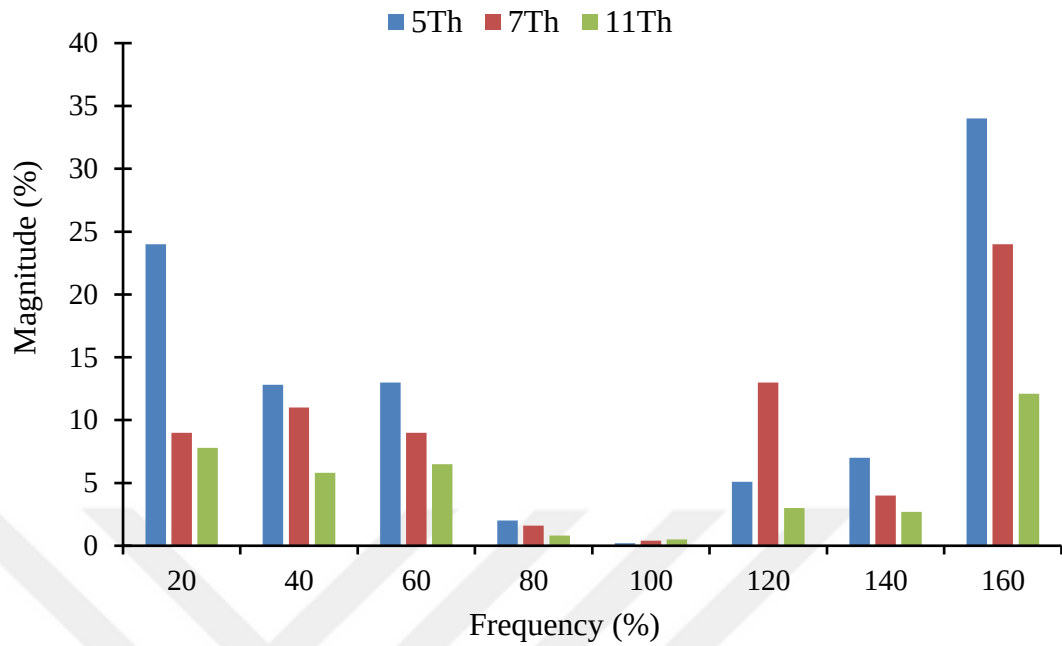


Figure 4.20a Analysis of the Magnitude of 5th, 7th and 11th Harmonics of line voltage waveform for the SPWM inverter technique with different steps of frequency ratio.

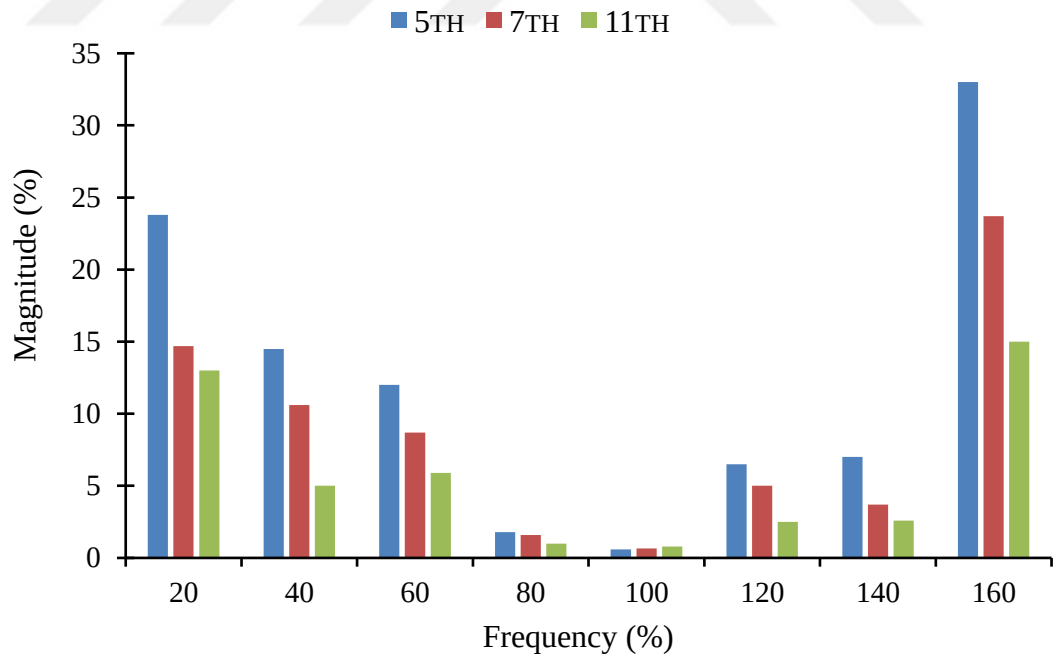


Figure 4.20b Analysis of the Magnitude of 5th, 7th and 11th Harmonics of line voltage waveform for the THIPWM inverter technique with different steps of frequency ratio.

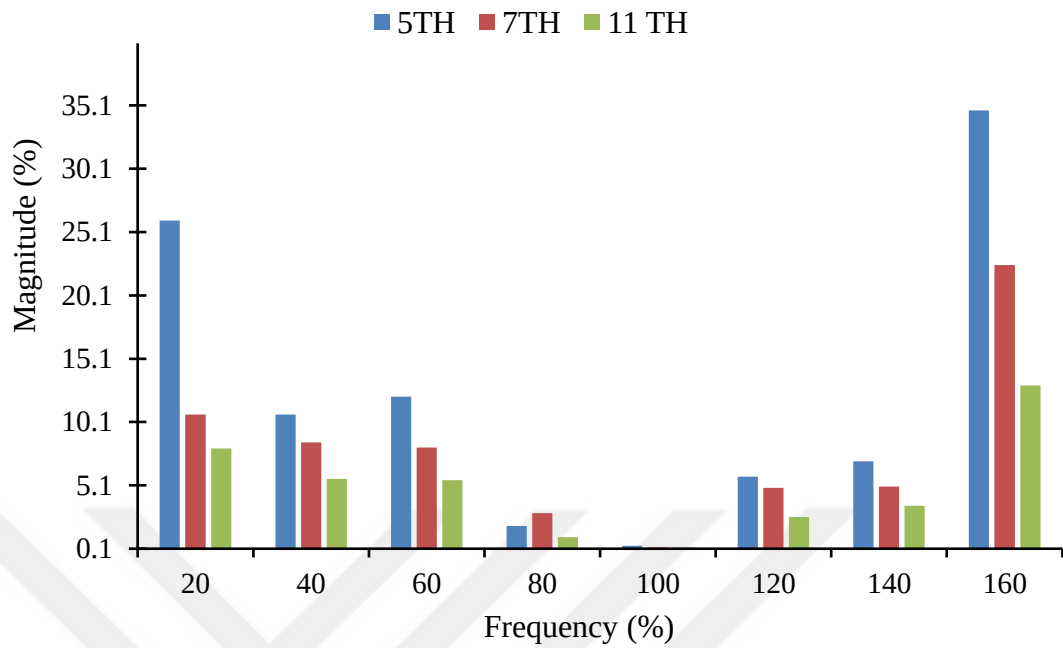


Figure 4.20c Analysis of the Magnitude of 5th, 7th and 11th Harmonics of line voltage waveform for the SVPWM inverter technique with different steps of frequency ratio.

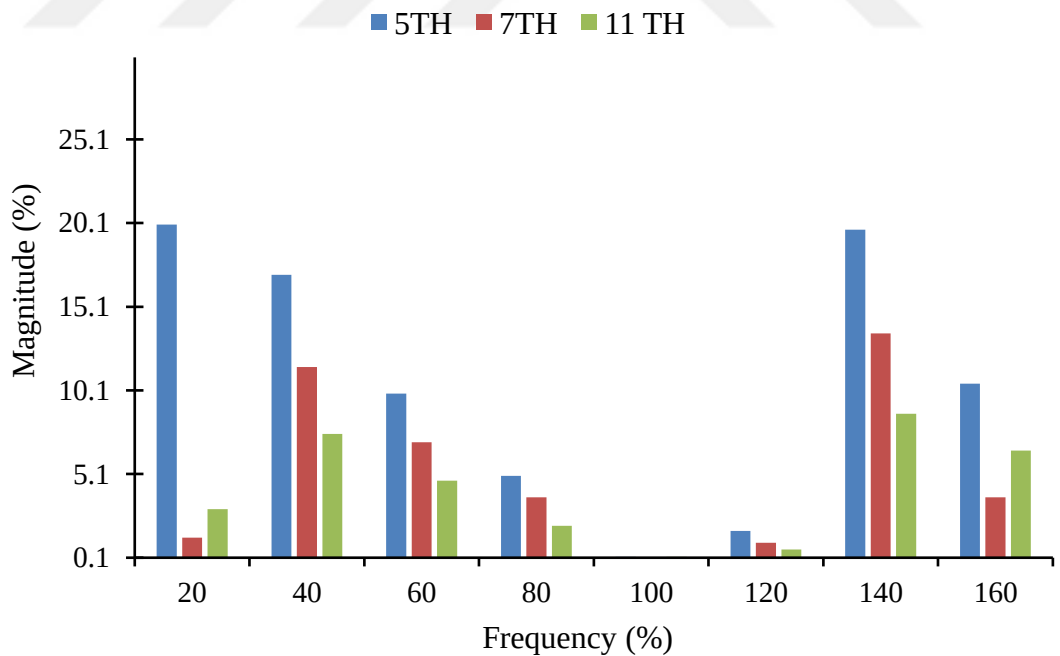


Figure 4.21a Analysis of the Magnitude of 5th, 7th and 11th Harmonics of motor stator current waveform for the SPWM inverter technique with different steps of frequency ratio.

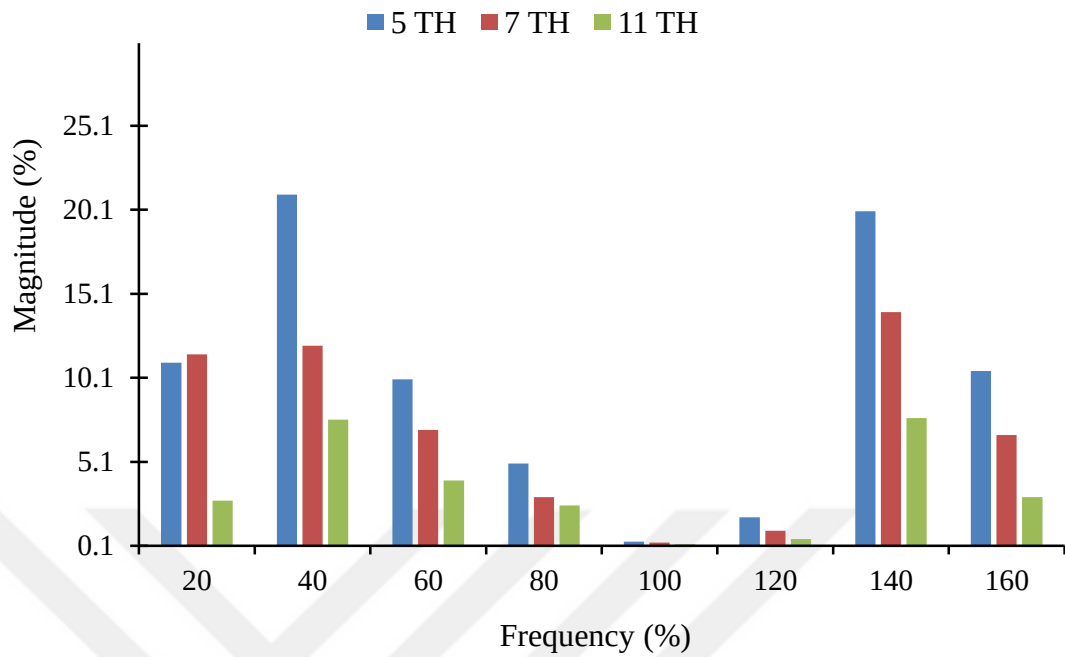


Figure 4.21b Analysis of the Magnitude of 5th, 7th and 11th Harmonics of motor stator currents waveform for the THIPWM inverter technique with different steps of frequency ratio.

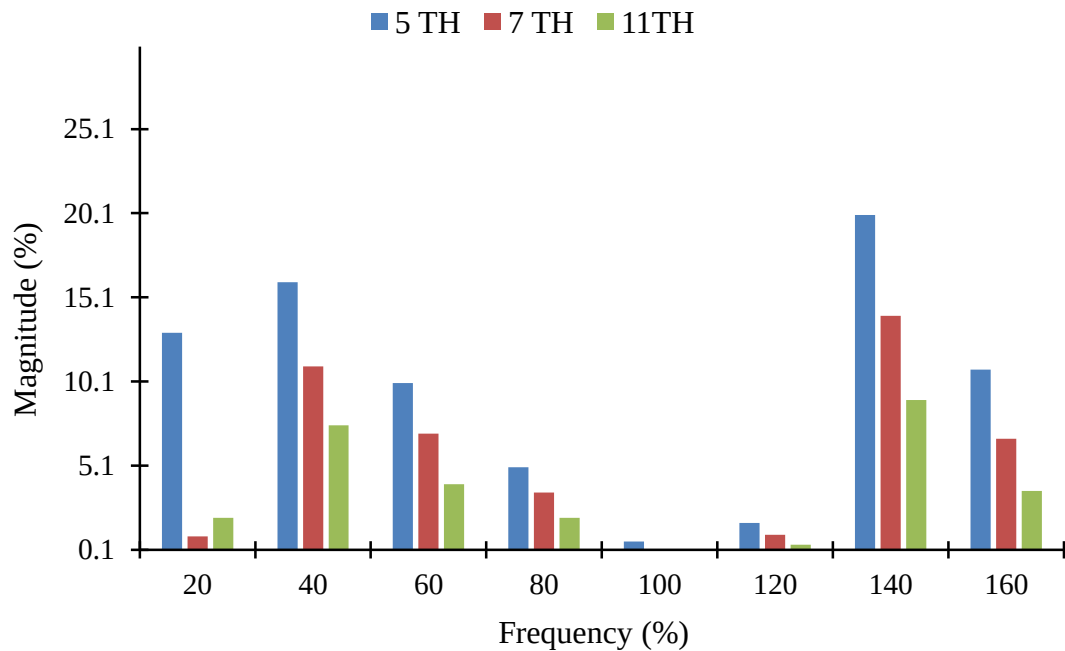
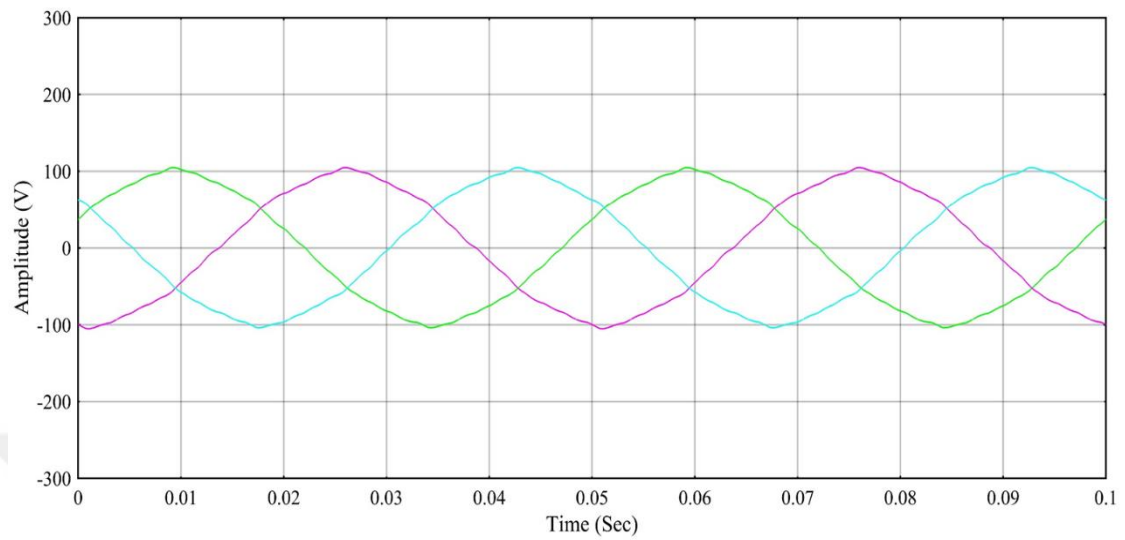


Figure 4.21c Analysis of the Magnitude of 5th, 7th and 11th Harmonics of motor stator currents waveform for the SVPWM inverter technique with different steps of frequency ratio.

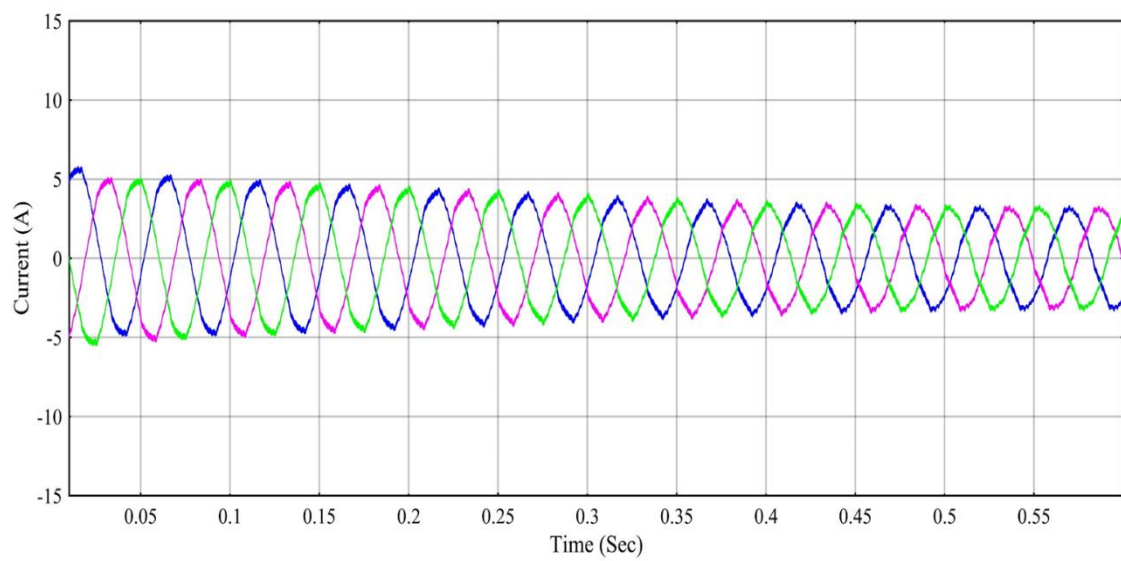
4.7.3.2.3 Performance of (Volt/Hertz) controller and PWM inverter

The following test shows the performance of (Volt/Hertz) controller and the PWM inverter response to different percentage ratio changes in frequency. The results are summarized briefly below: (See Appendix C):

1. The three-phase voltage of the inverter based on SPWM techniques after second order low- pass filter and the motor stator current (at no-load) can be shown in Figure 4.22..... 4.24 with respect to percentage ratio of frequency
2. The three phase voltage of the inverter based on THIPWM techniques after second order low- pass filter and the motor stator current (at no-load) can be shown in Figure 4.25..... 4.27 with respect to percentage ratio of frequency
3. The three phase voltage of the inverter based on SVPWM techniques after second order low- pass filter and the motor stator current (at no-load) can be shown in Figure 4.28..... 4.30 with respect to percentage ratio of frequency

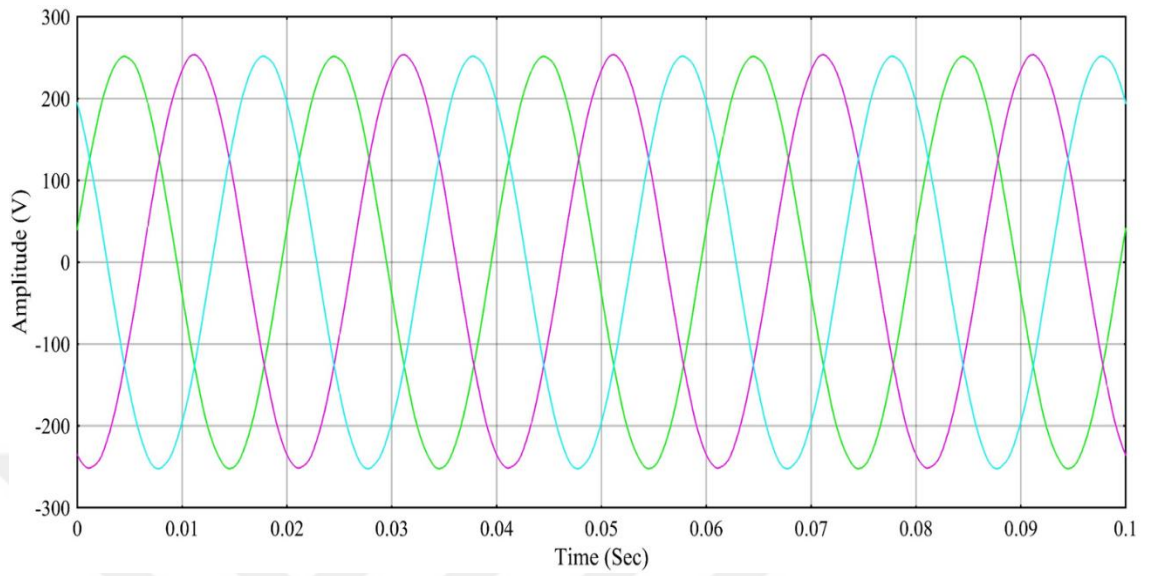


a. Three phase voltage after second order low-pass filter

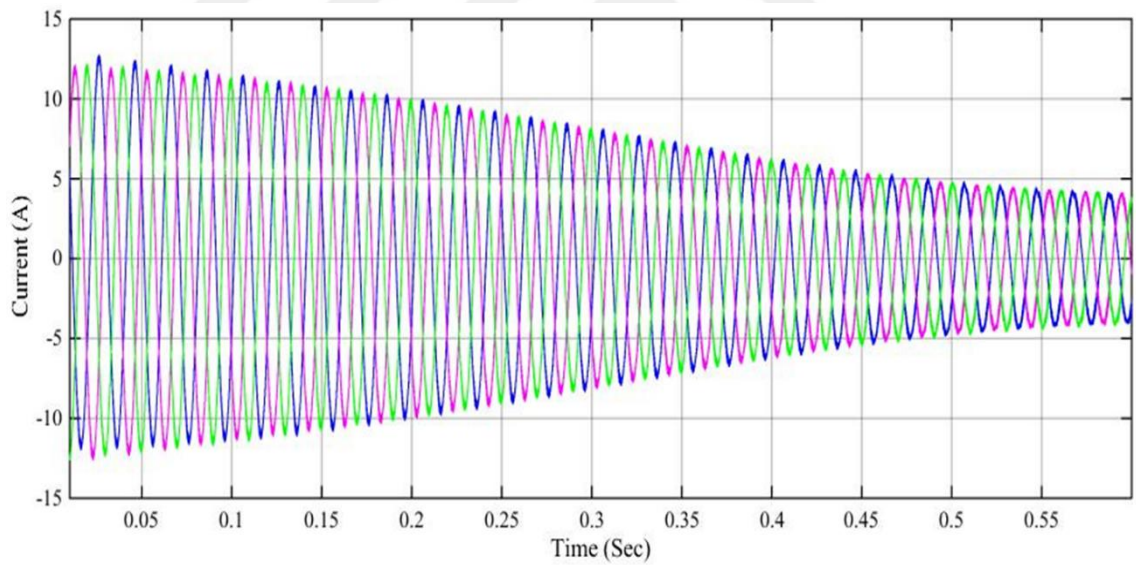


b. Three phase current feeding stator of motor.

Figure 4.22 Performance parameter (V&I) of SPWM inverter at 40% of rated frequency.

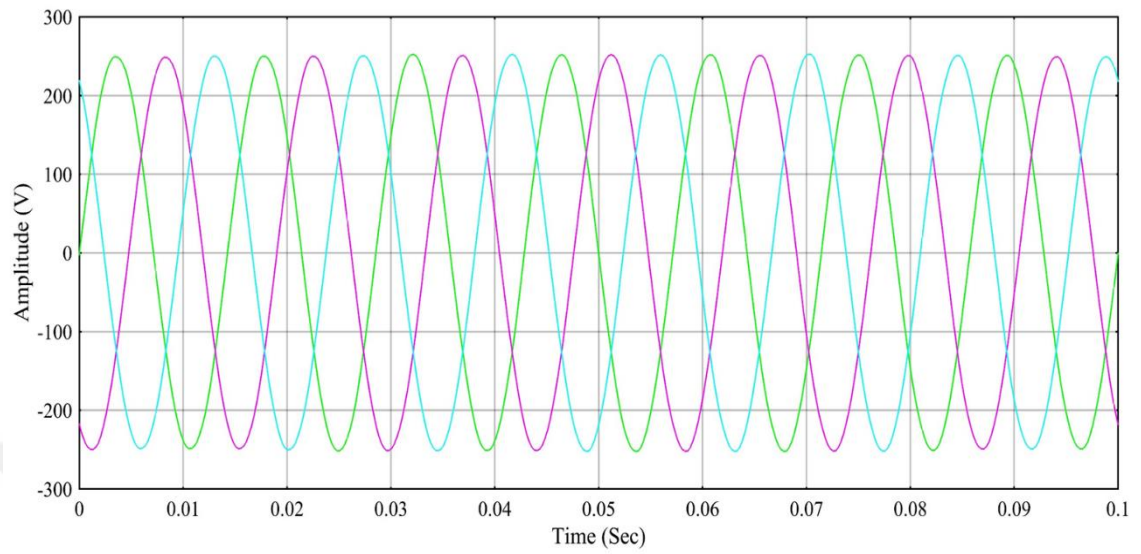


a. Three phase voltage after second order low-pass filter.

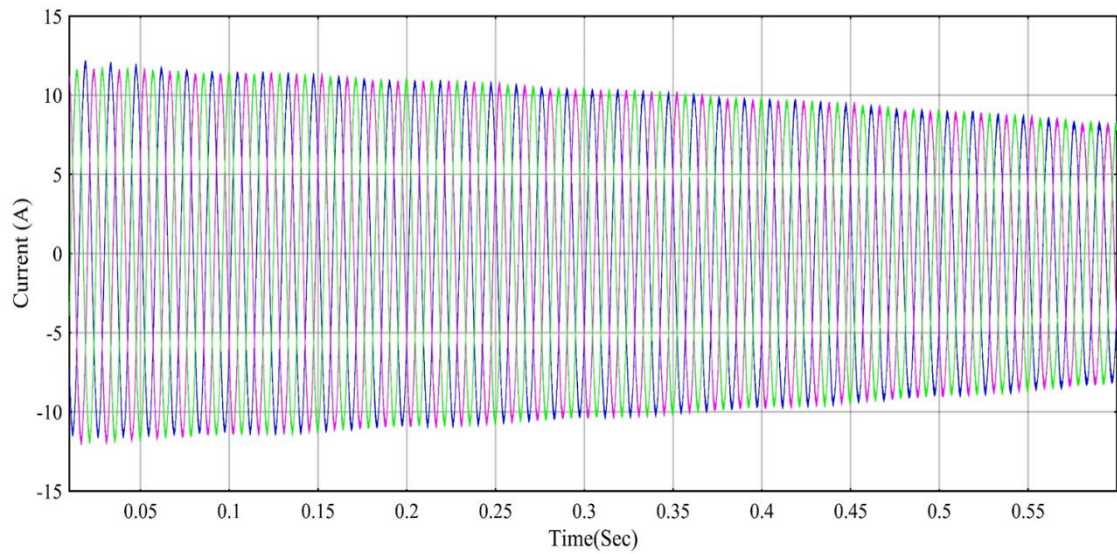


b. Three phase current feeding stator of motor

Figure 4.23 Performance parameter (V&I) of SPWM inverter at 100% of rated frequency.

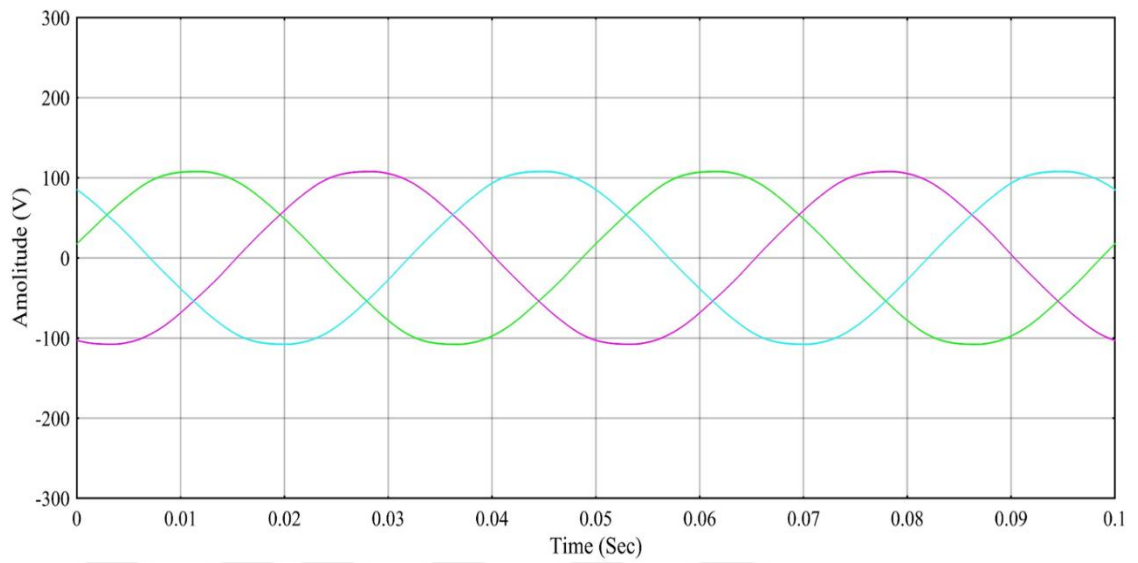


a. Three Phase voltage after second order low-pass filter.

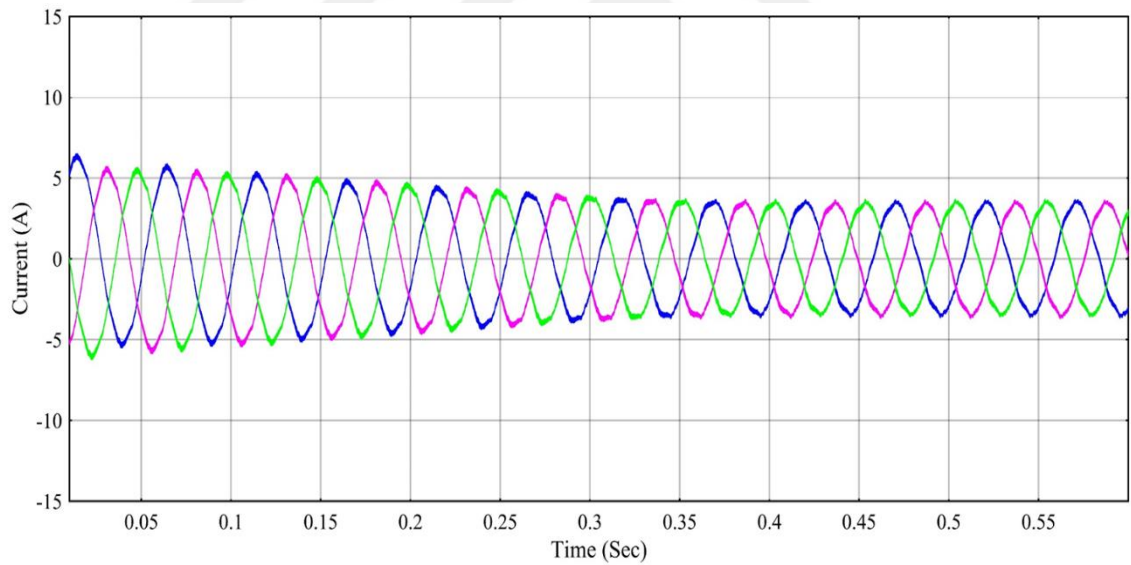


b. Three phase current feeding stator of motor

Figure 4.24 Performance parameter (V&I) of SPWM inverter at 140% of rated frequency.

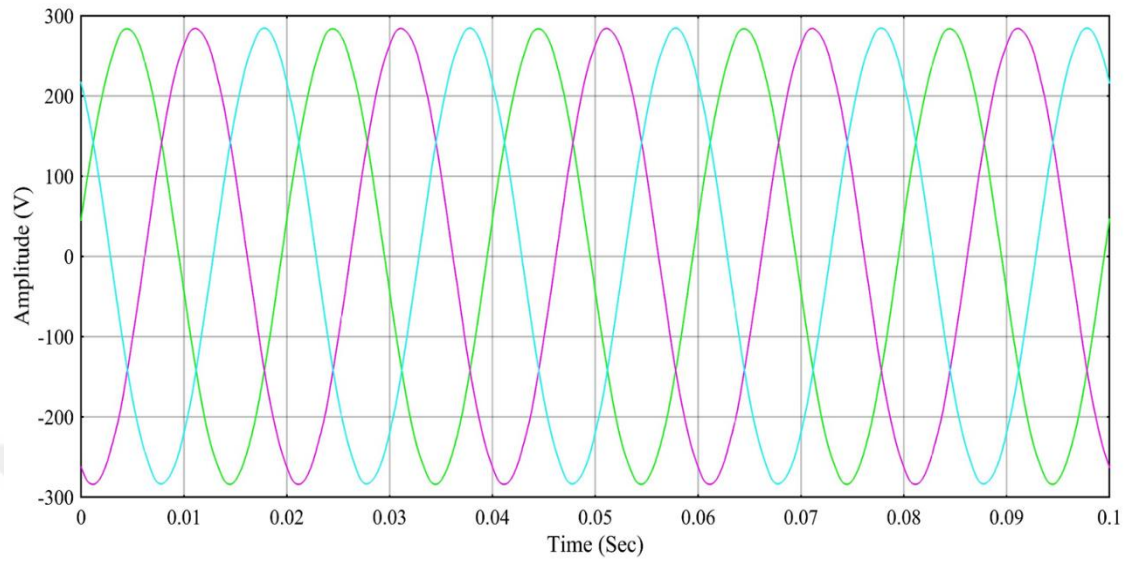


a. Three phase voltage after second order low-pass filter

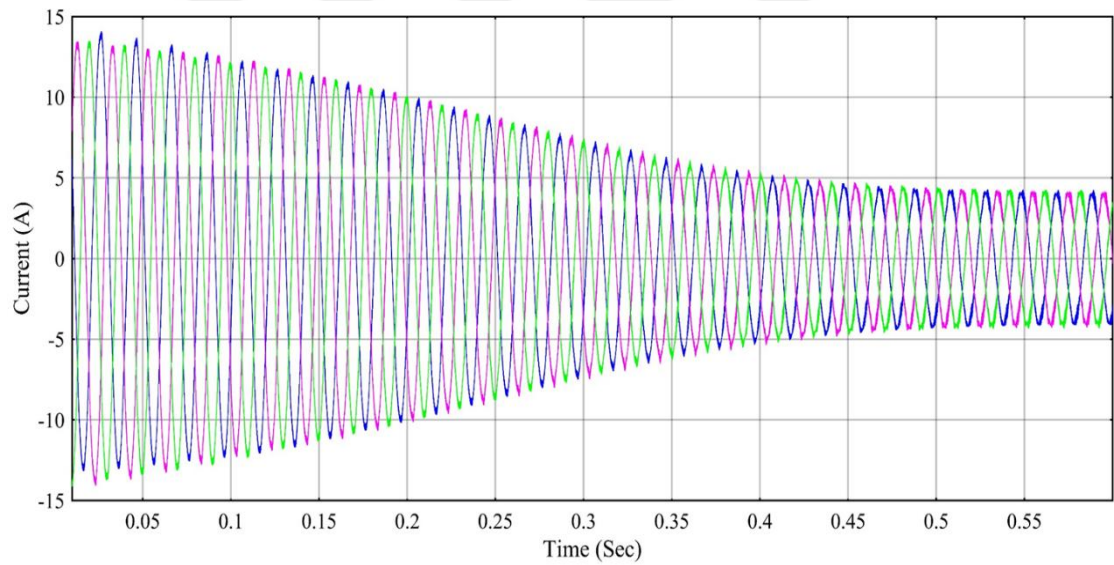


b. Three phase current feeding stator of motor

Figure 4.25 Performance parameter (V&I) of THIPWM inverter at 40% of rated frequency.

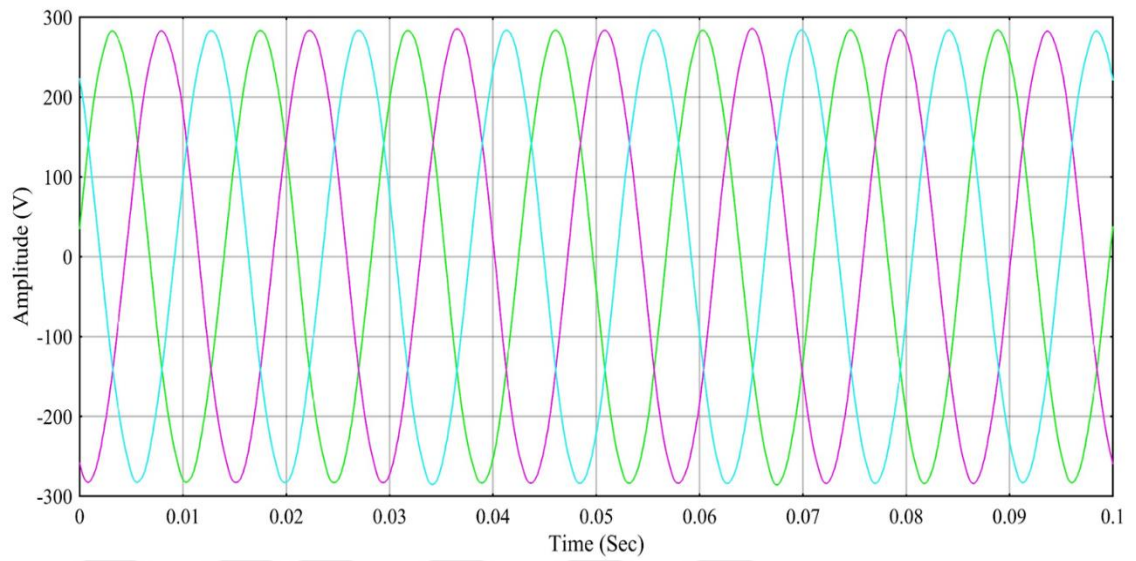


a. Three Phase voltage after second order low-pass filter

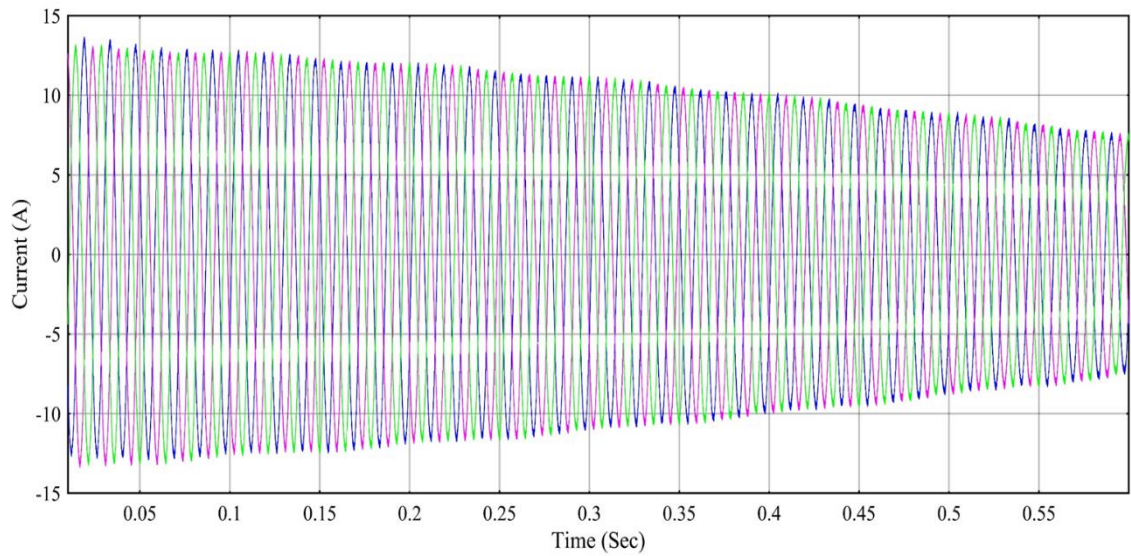


b. Three phase current feeding stator of motor

Figure 4.26 Performance parameter (V&I) of THIPWM inverter at 100% of rated frequency.

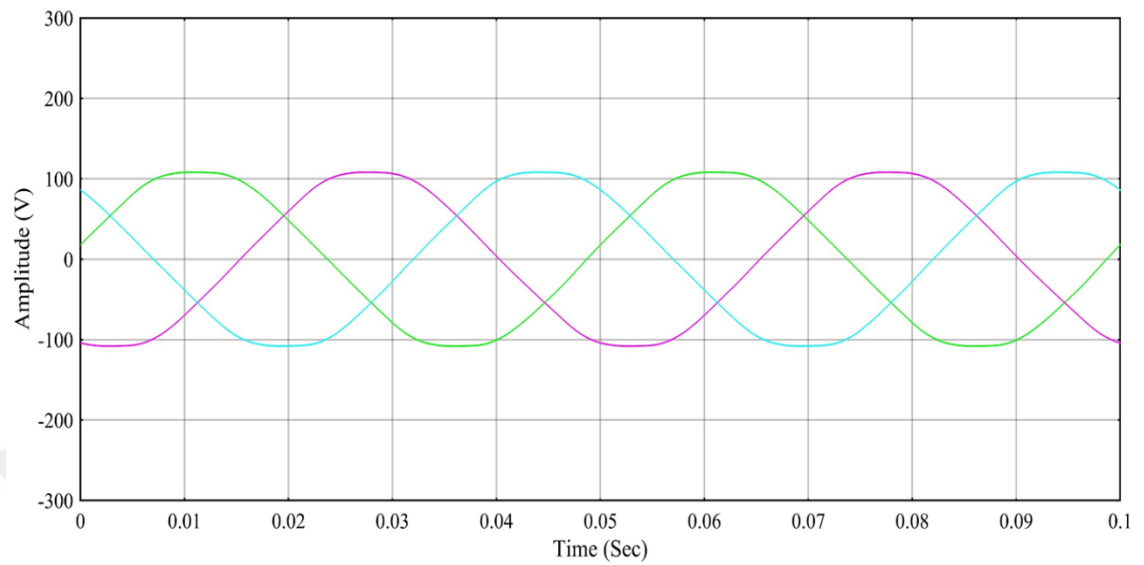


a. Three Phase voltage after second order low-pass filter

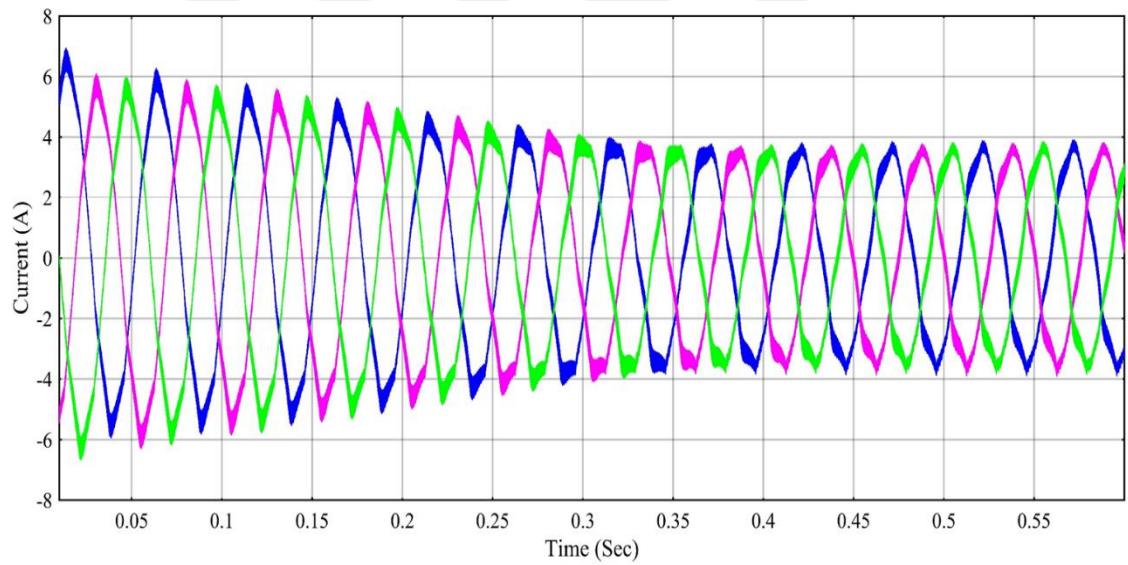


b. Three phase current feeding stator of motor

Figure 4.27 Performance parameter (V&I) of THIPWM inverter at 140% of rated frequency.

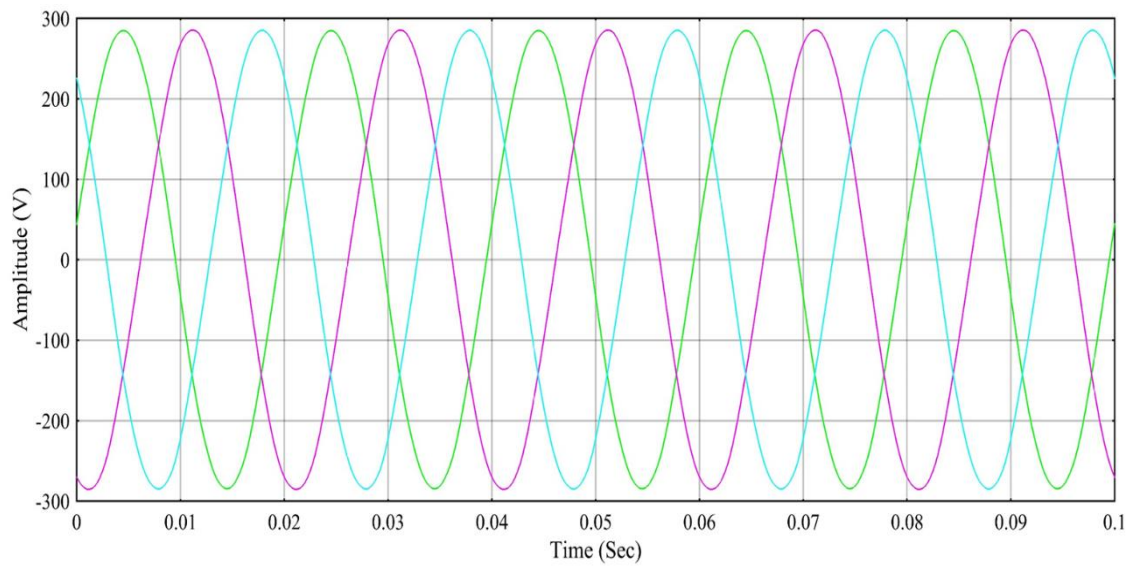


a. Three Phase voltage after second order low-pass filter

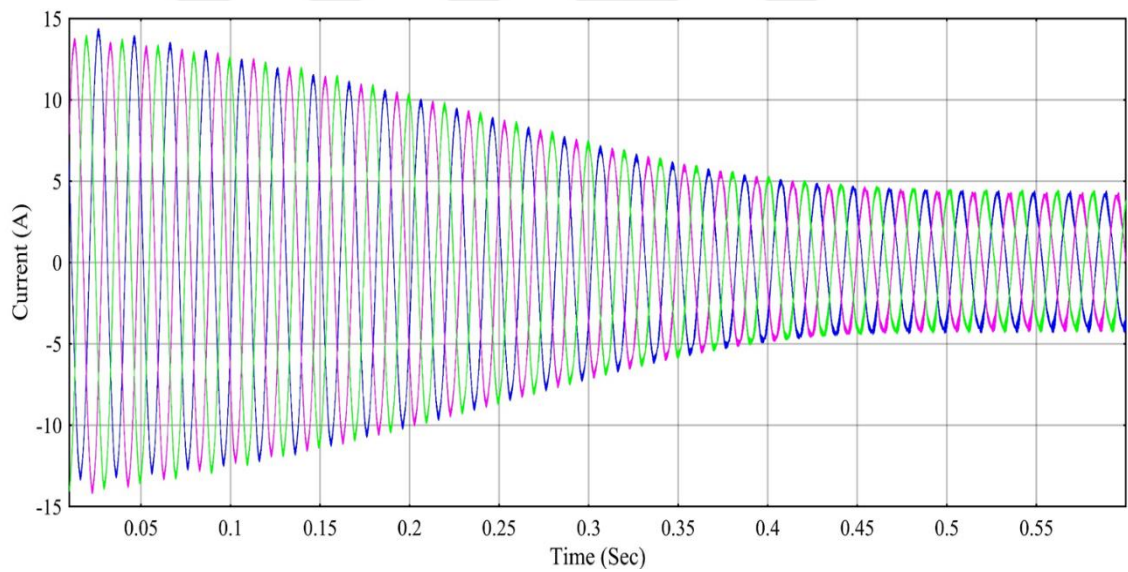


b. Three phase current feeding stator of motor

Figure 4.28 Performance parameter (V&I) of SVPWM inverter at 40% of rated frequency.

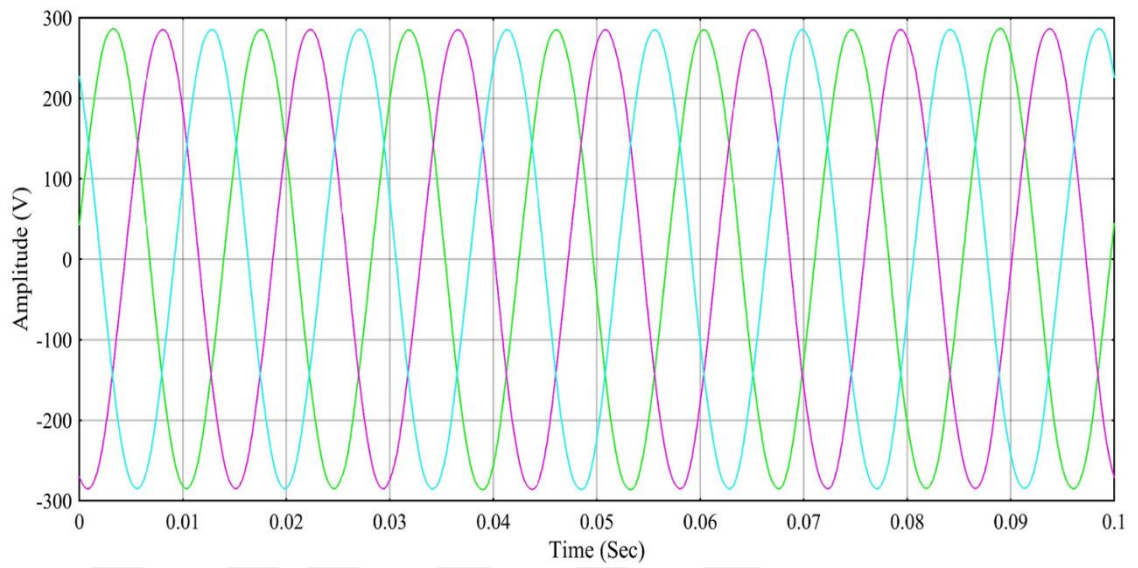


a. Three phase voltage after second order low-pass filter

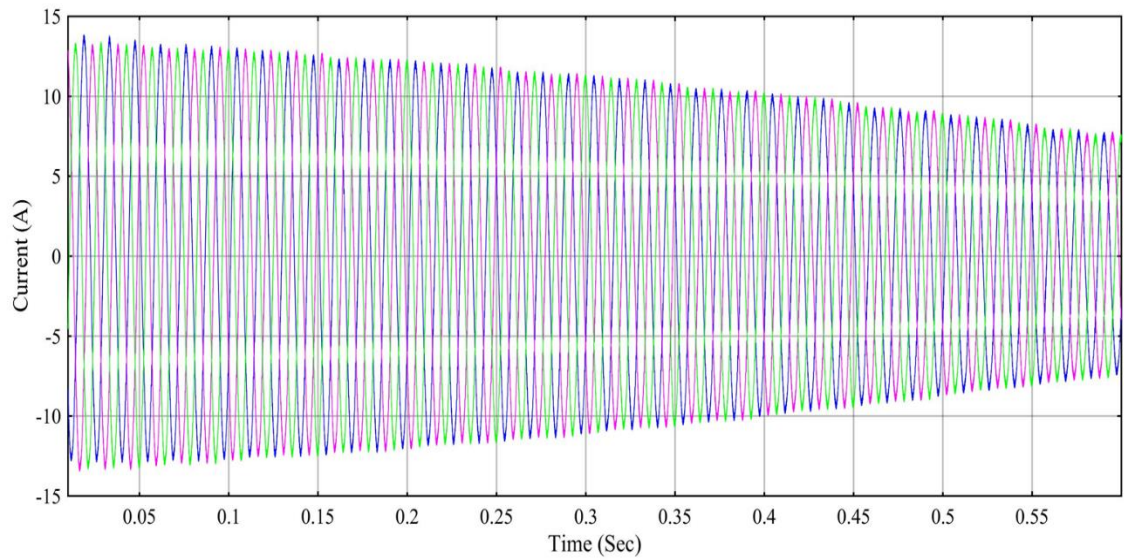


b. Three phase current feeding stator of motor

Figure 4.29 Performance parameter (V&I) of SVPWM inverter at 100% of rated frequency.



a. Three Phase voltage after second order low-pass filter



b. Three phase current feeding stator of motor

Figure 4.30 Performance parameter (V&I) of SVPWM inverter at 140% of rated frequency.

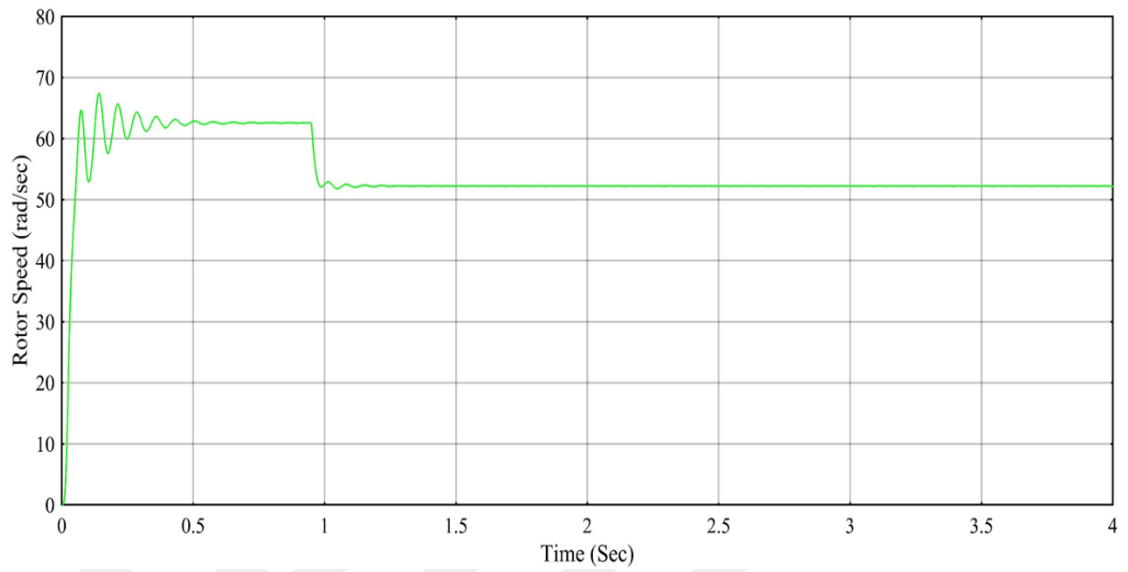
4.7.3.3 System Performance under Load Condition

The following tests show the performance and the response of the system when a set value of (11.9 N.m) load is applied after passing starting time, due to the thermal or dynamic effects or an inaccurate measurement.

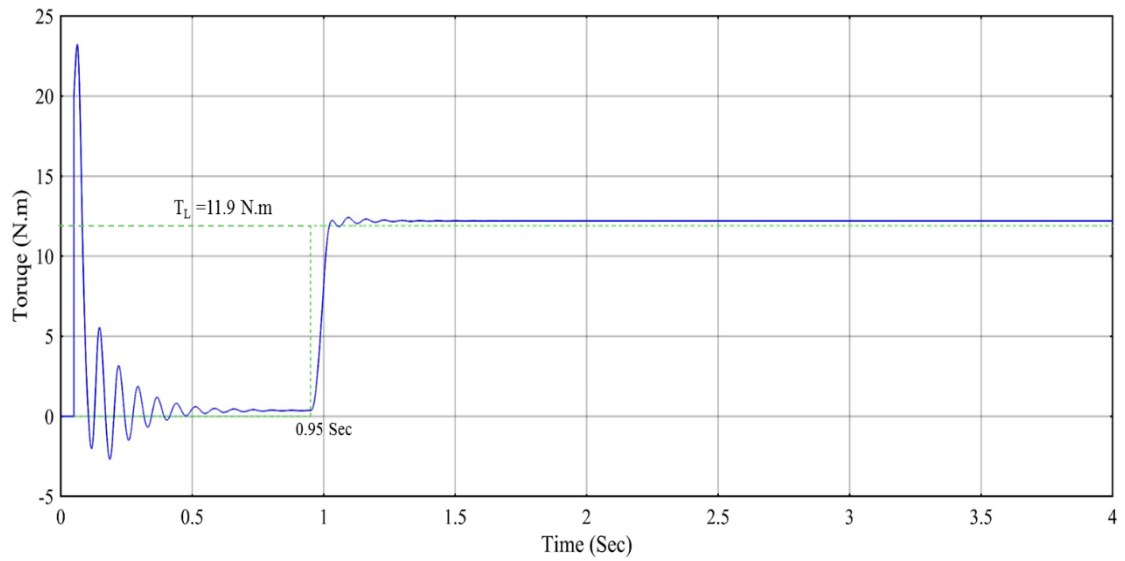
The performance parameter results under load condition can be obtained below:

(See Appendix C):

1. The motor speed (ω_m) and electromagnetic torque (T_e). When applying a mechanical load into induction motor and SPWM inverter technique can be shown in Figures (4.31...4.33) and two other PWM techniques THIPWM, SVPWM can be shown in Figures (4.34...4.36) and Figures (4.37 ...4.39) respectively.
2. The Total Harmonic Distortion (THD) for voltage and current are analyzed and the results include the first 20 harmonics. The FFT analysis of voltage waveform and sidebands of Total Harmonic Distortion for three PWM techniques SPWM, THIPWM, and SVPWM are shown in Figures (4.40....4.42), (4.43.....4.45) and (4.46 4.48) respectively and. The results corresponding to FFT analyses for current waveform and sideband of Total Harmonic Distortion these are shown in Figures (4.49 4.51), (4.52....4.54) and (4.55 ...4.57).

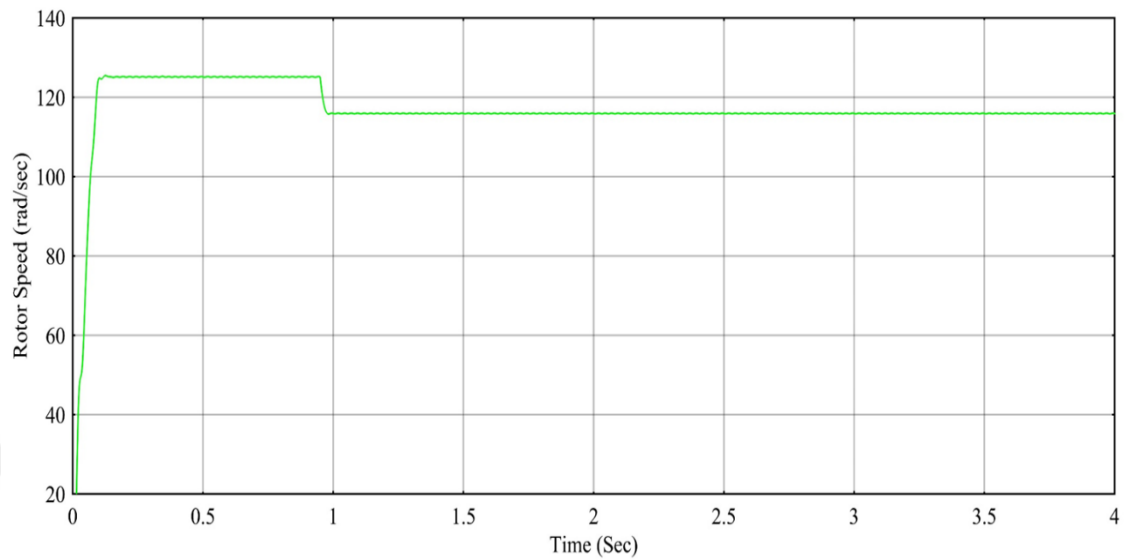


a. Rotor speed (ω_m) response

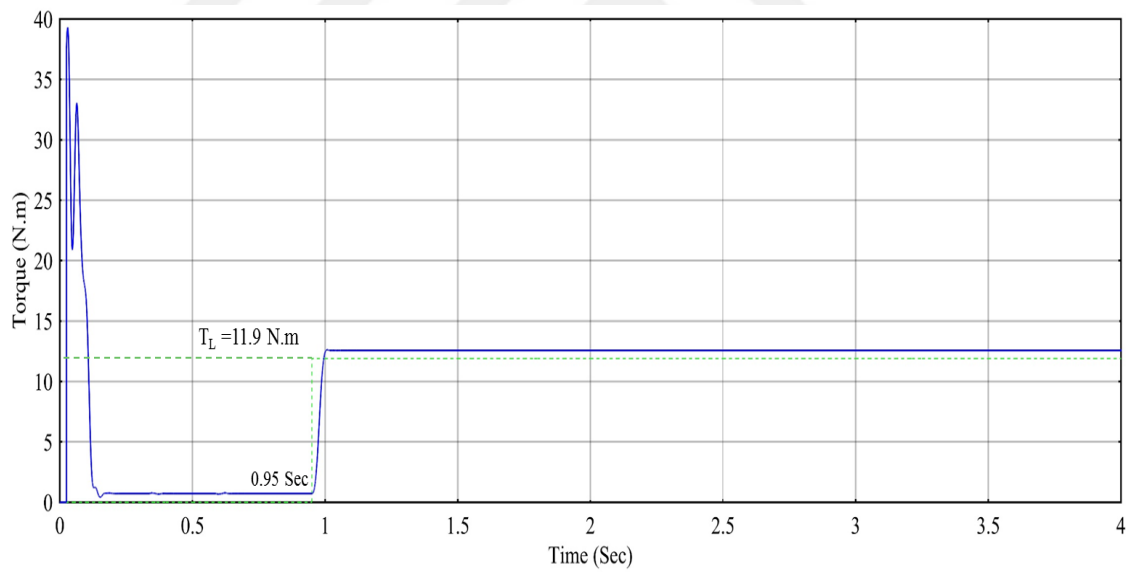


b. Electromagnetic torque (T_e) response

Figure 3.31 Speed and Electromagnetic torque response under load condition of SPWM inverter at 40% of rated frequency.

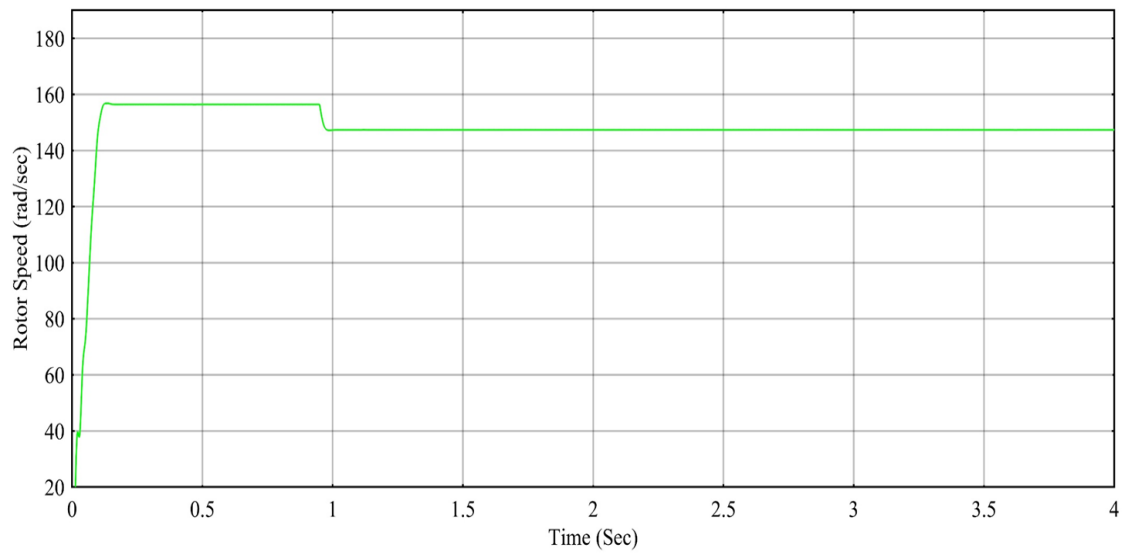


a. Rotor speed (ω_m) response

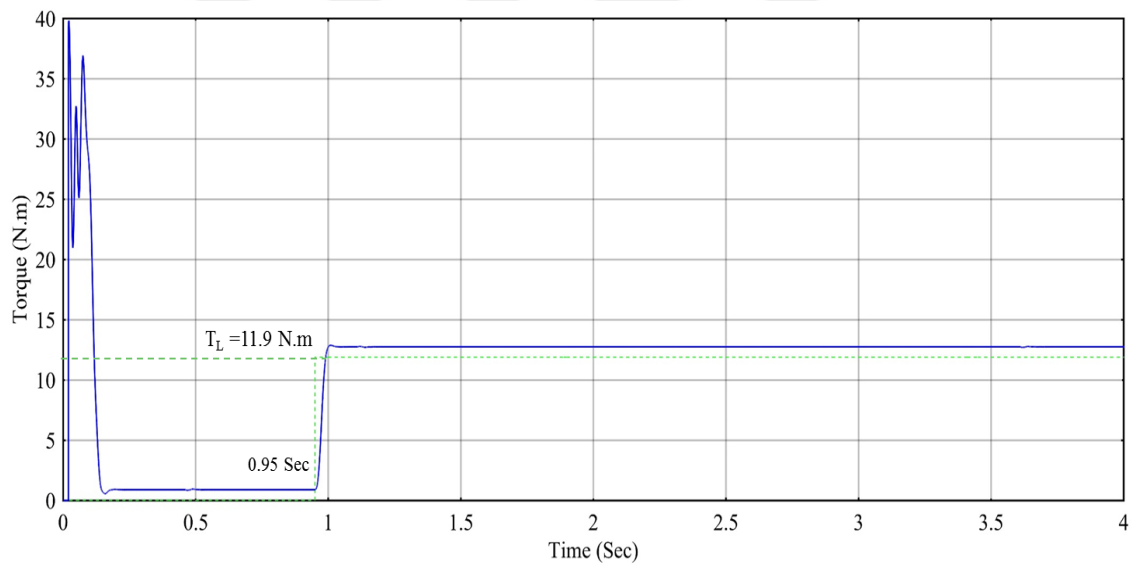


b. Electromagnetic torque (T_e) response

Figure 3.32 Speed and Electromagnetic torque response under load condition of SPWM inverter at 80% of rated frequency.

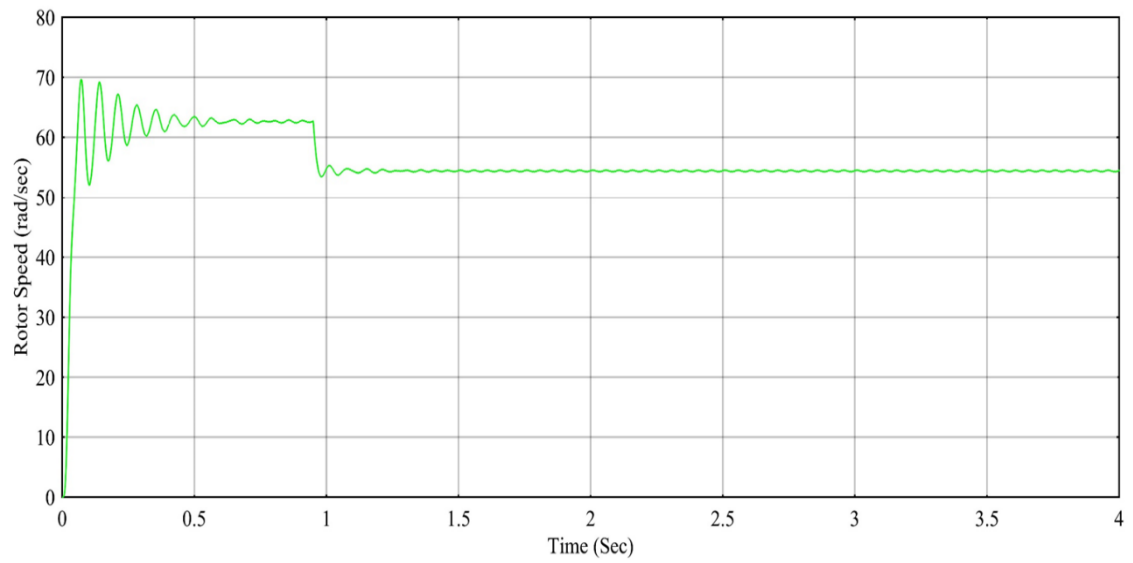


a. Rotor speed (ω_m) response

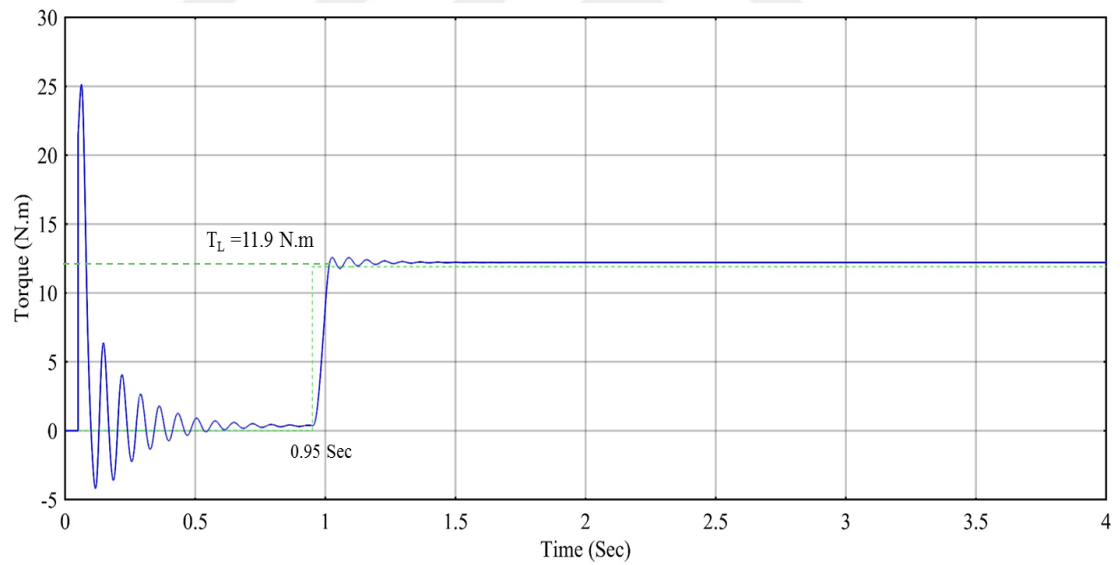


b. Electromagnetic torque (T_e) response

Figure 3.33 Speed and Electromagnetic torque response under load condition of SPWM inverter at 100% of rated frequency.

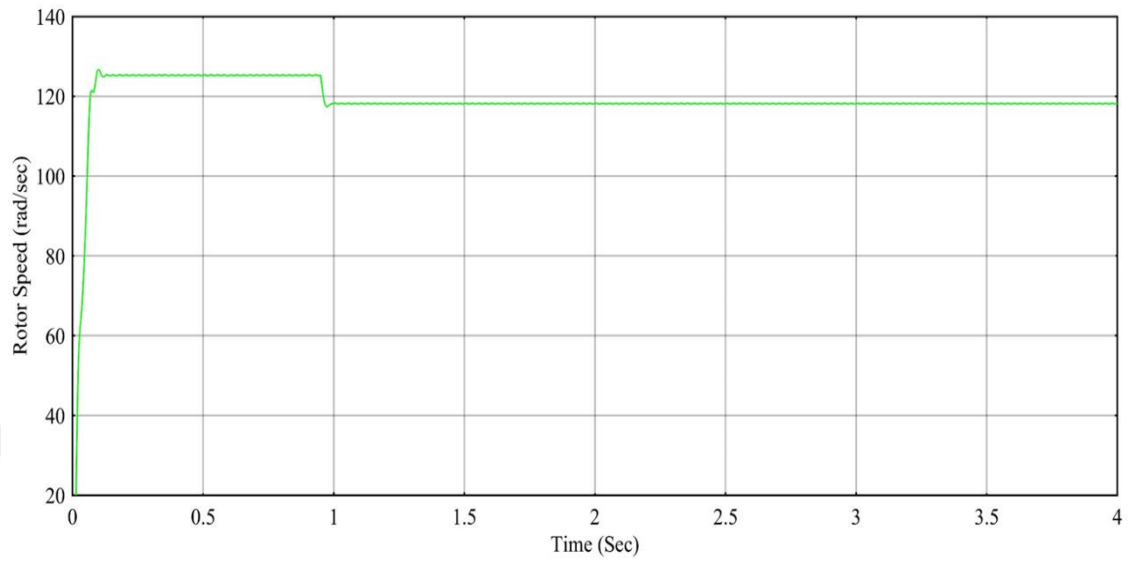


a. Rotor speed (ω_m) response

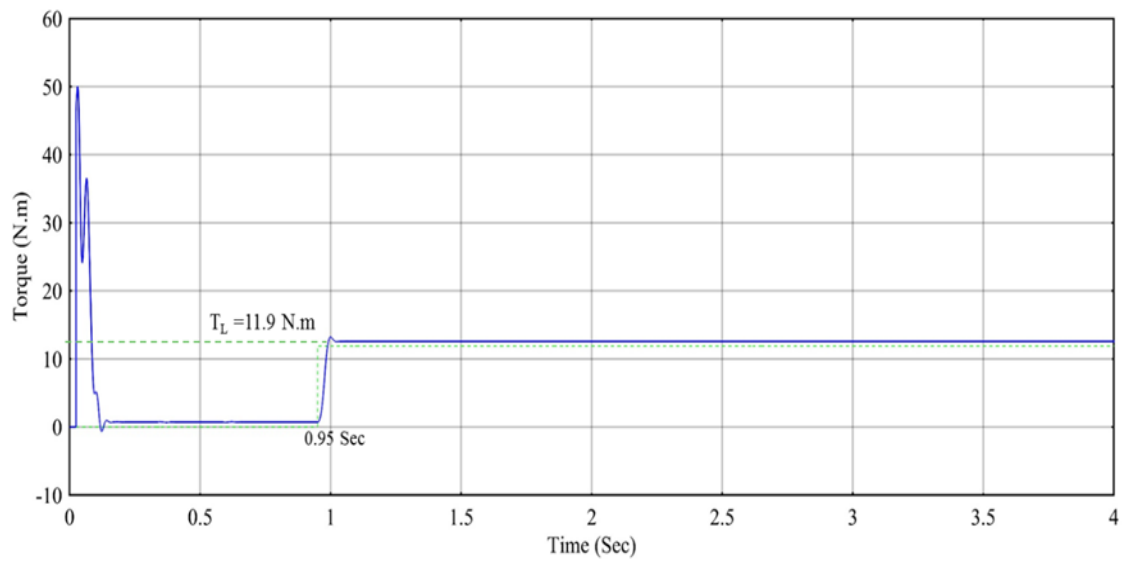


b. Electromagnetic torque (T_e) response

Figure 3.34 Speed and Electromagnetic torque response under load condition of THIPWM inverter at 40% of rated frequency.

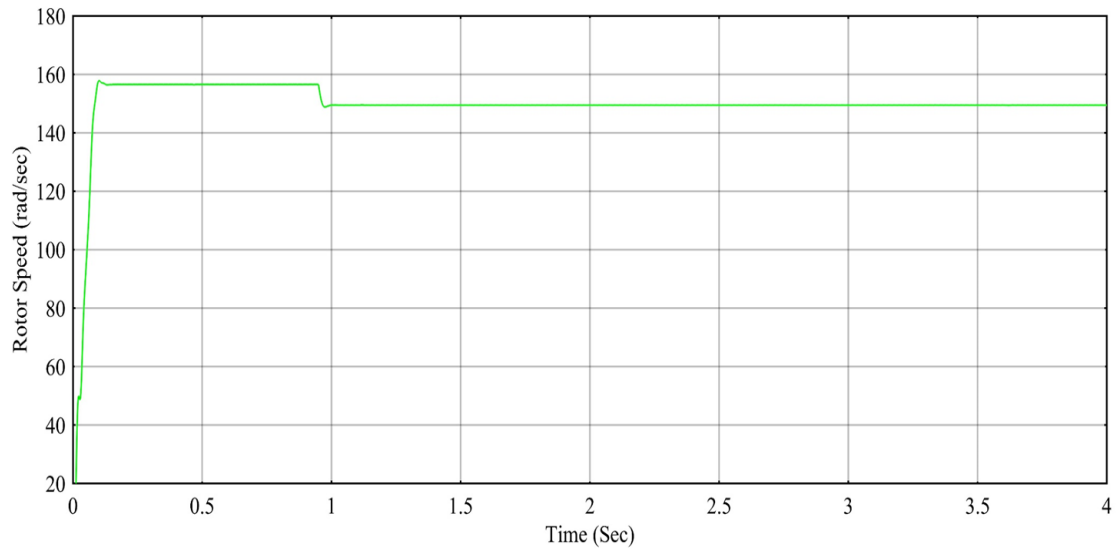


a. Rotor speed (ω_m) response

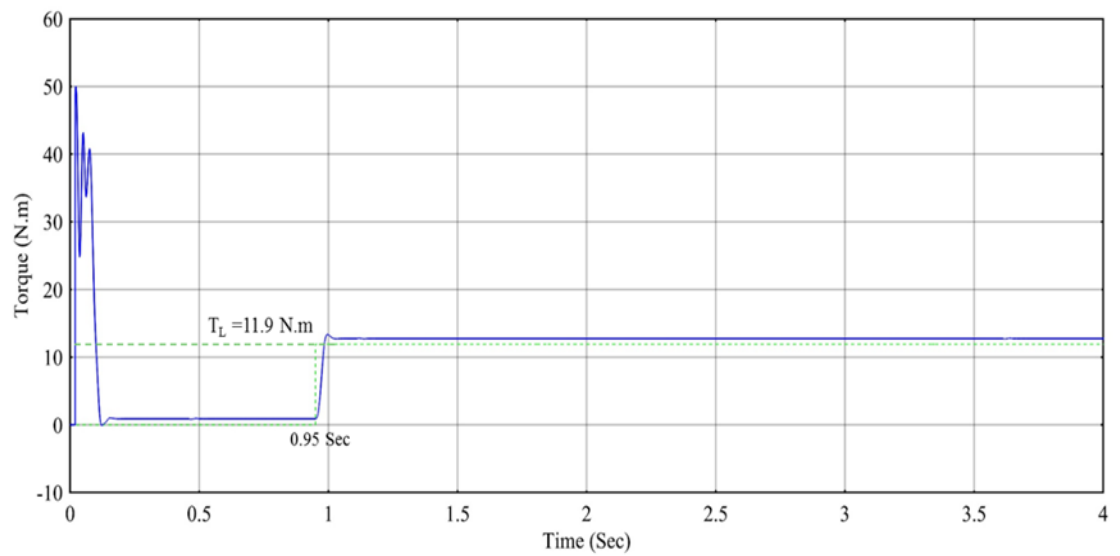


b. Electromagnetic torque (T_e) response

Figure 4.35 Speed and Electromagnetic torque response under load condition of THIPWM inverter at 80% of rated frequency

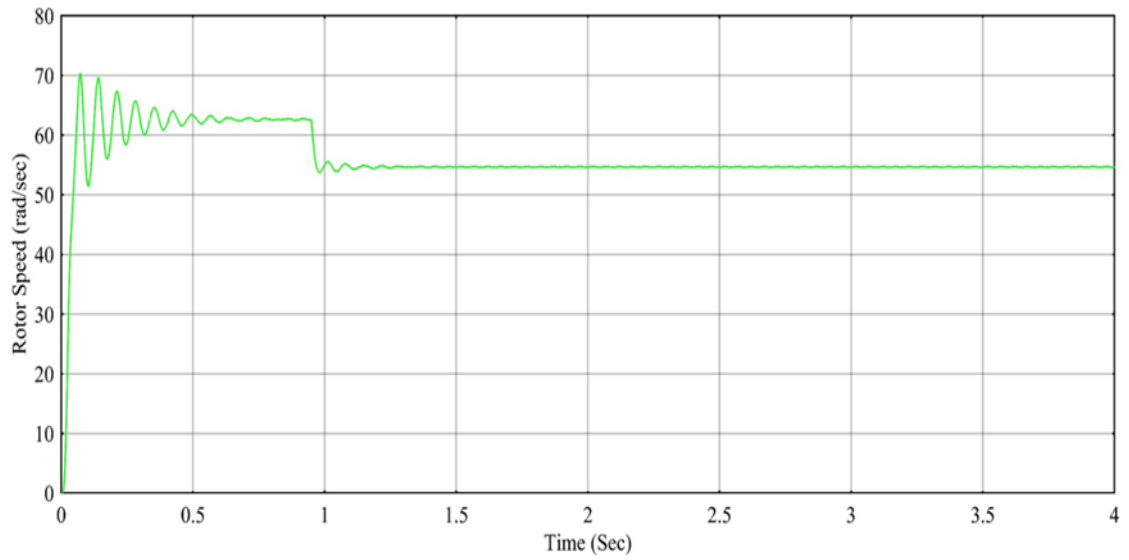


a. Rotor speed (ω_m) response

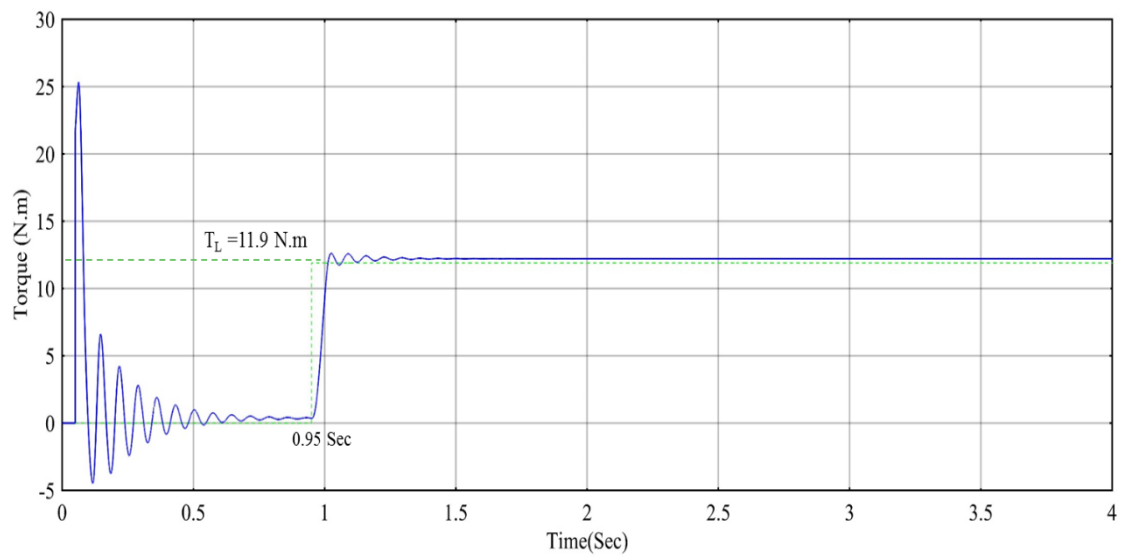


b. Electromagnetic torque (T_e) response

Figure 4.36 Speed and Electromagnetic torque response under load condition of THIPWM inverter at 100% of rated frequency.

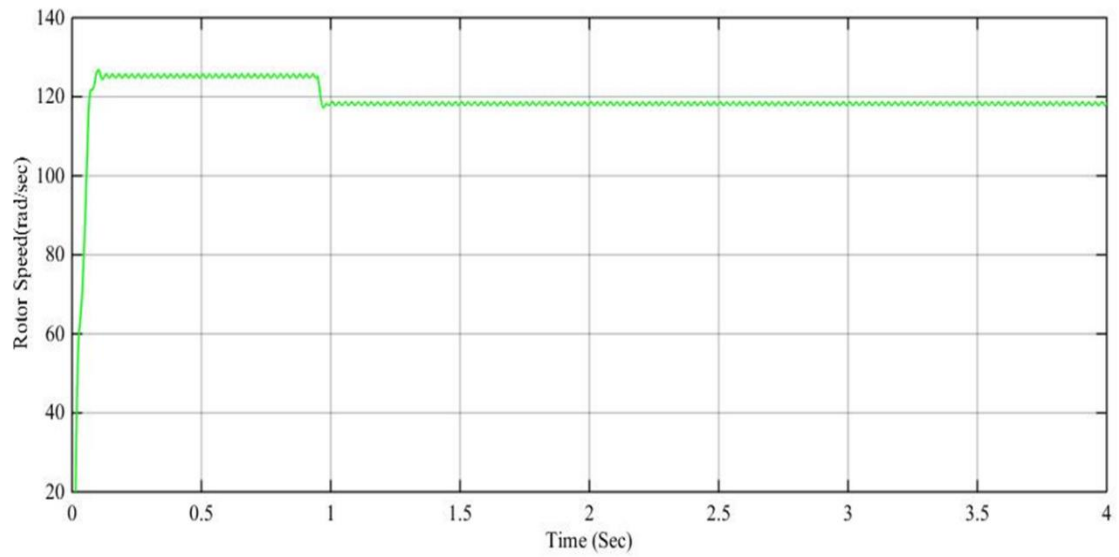


a. Rotor speed (ω_m) response

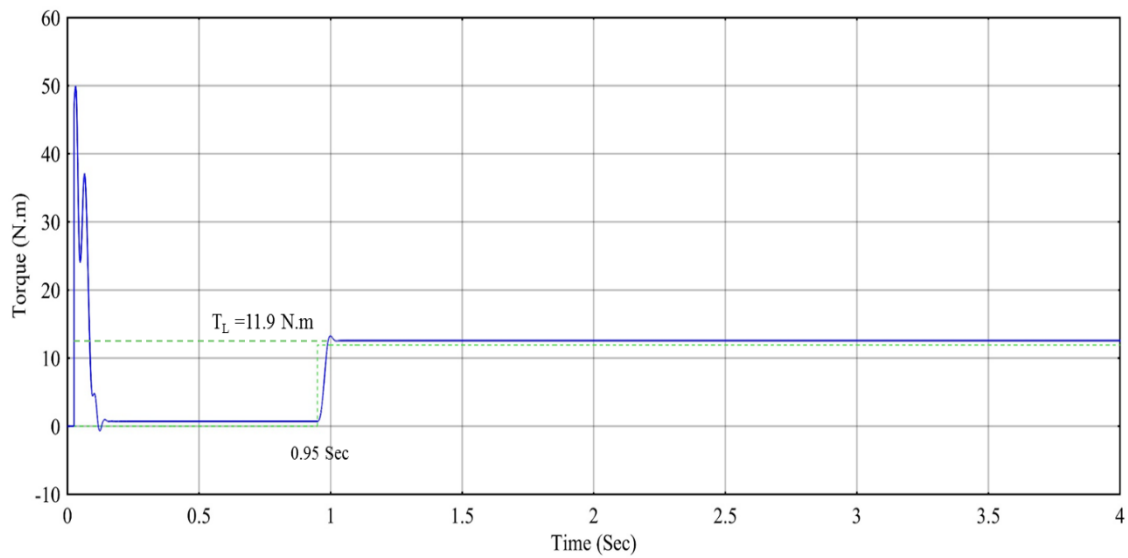


b. Electromagnetic torque (T_e) response

Figure 4.37 Speed and Electromagnetic torque response under load condition of SVPWM inverter at 40% of rated frequency.

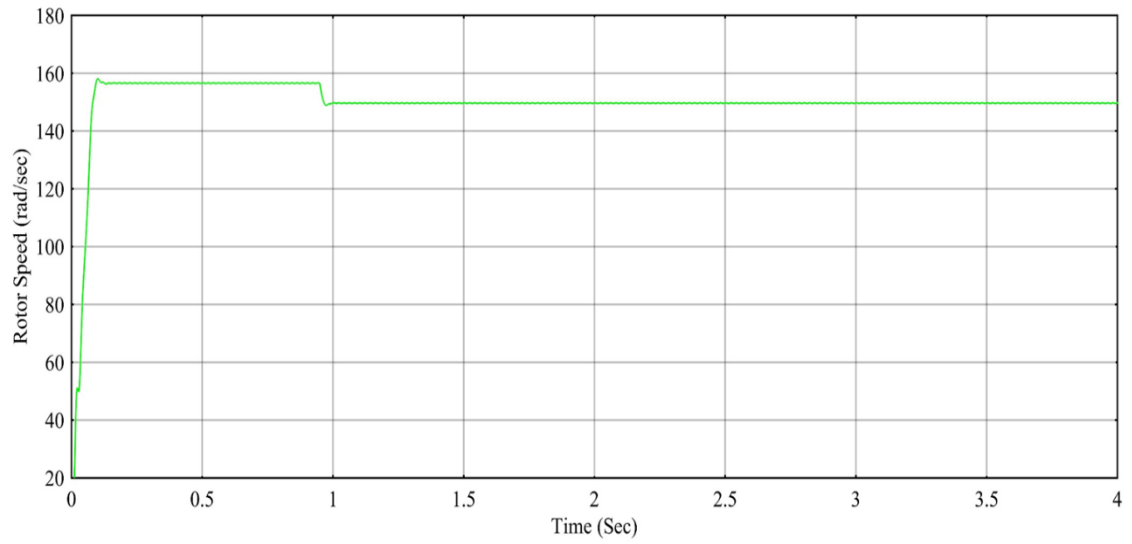


a. Rotor speed (ω_m) response

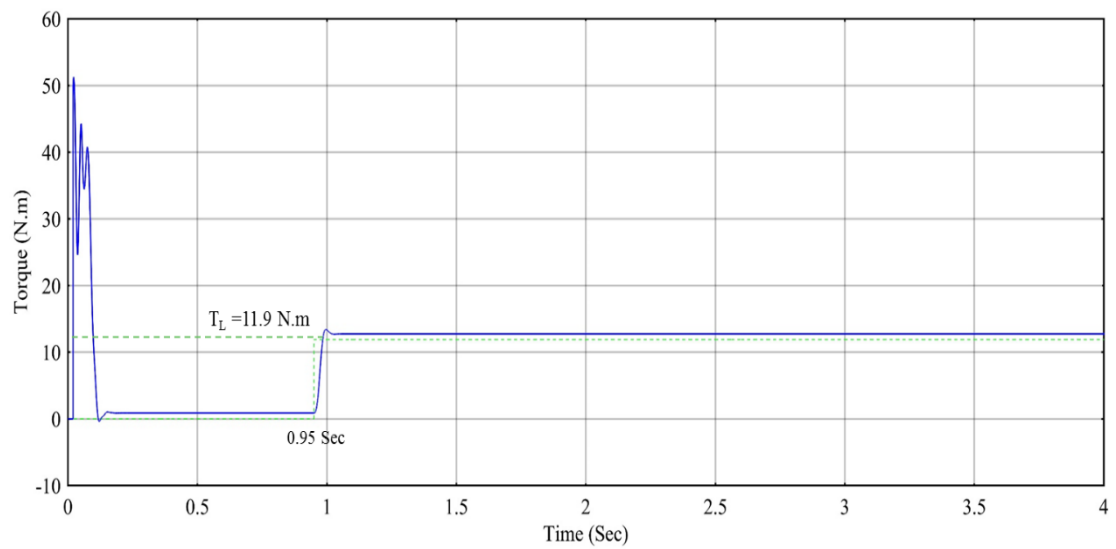


b. Electromagnetic torque (T_e) response

Figure 4.38 Speed and Electromagnetic torque response under load condition of SVPWM inverter at 80% of rated frequency.

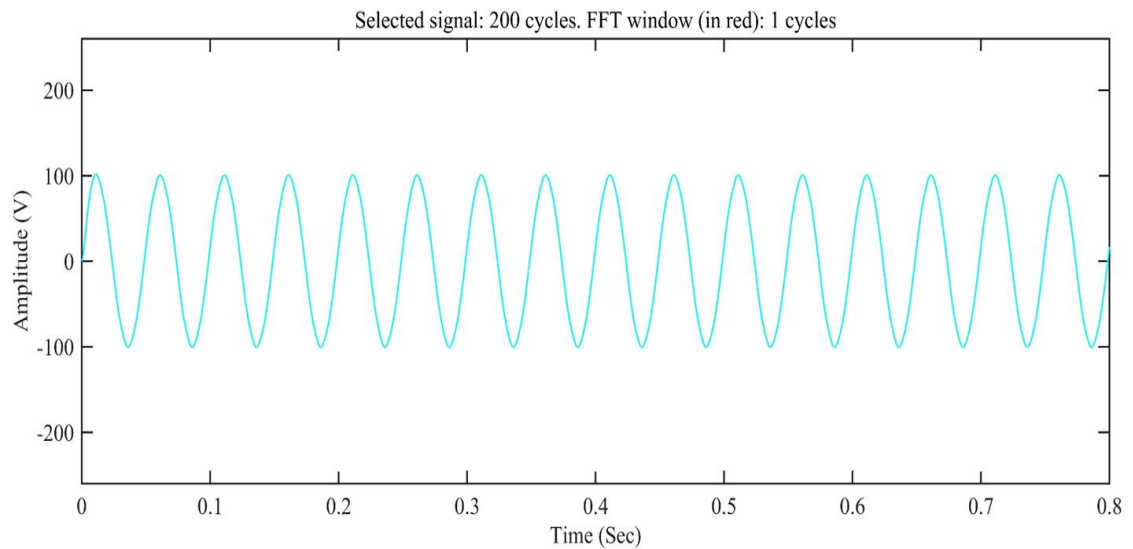


a. Rotor speed (ω_m) response

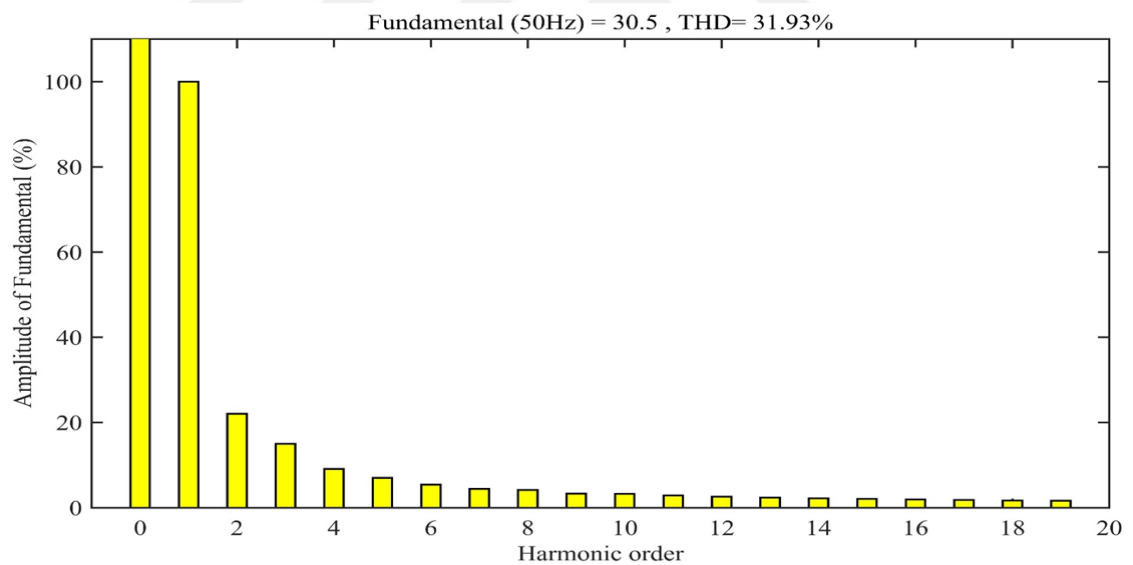


b. Electromagnetic torque (T_e) response

Figure 4.39 Speed and Electromagnetic torque response under load condition of SVPWM inverter at 100% of rated frequency.

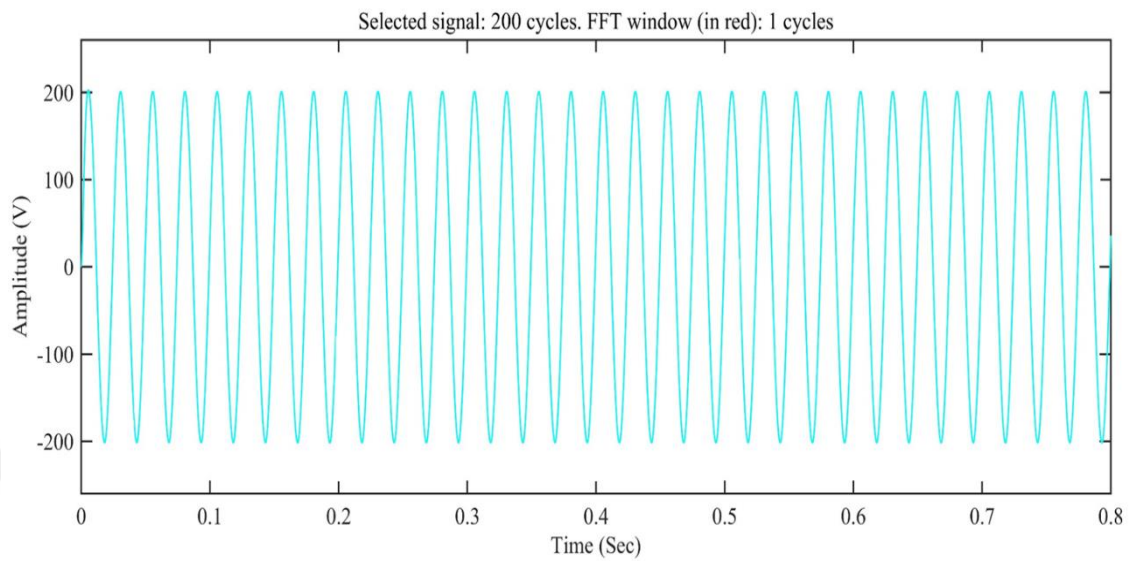


a. FFT analysis of phase voltage waveform after Second order low pass filter

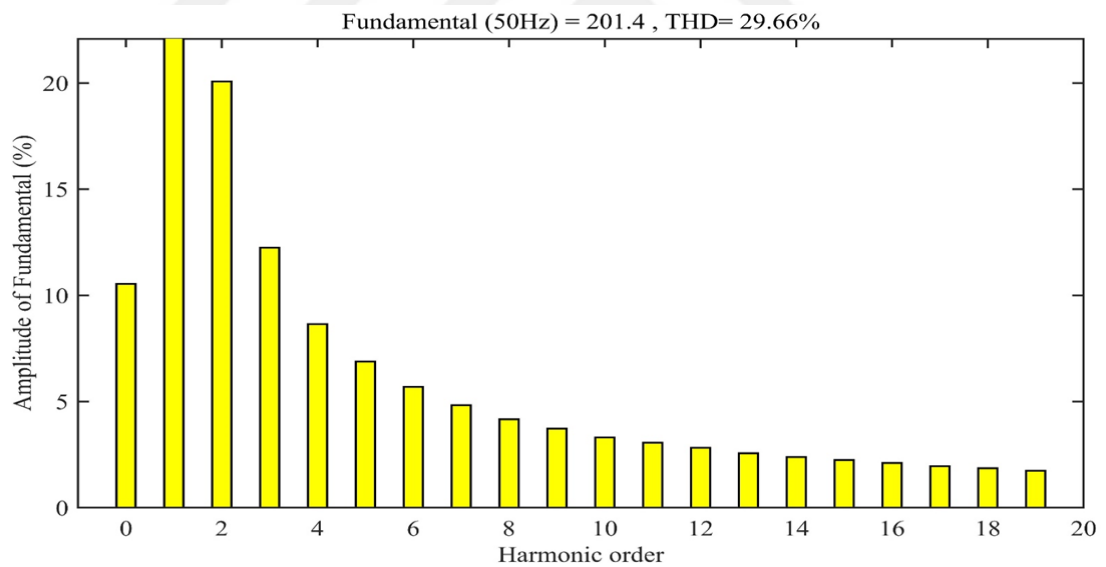


b. THD V (%)

Figure 4.40 SPWM Inverter performance parameter under load condition. THD% and FFT analysis of phase voltage waveform after second order low pass filter at 40% of rated frequency.

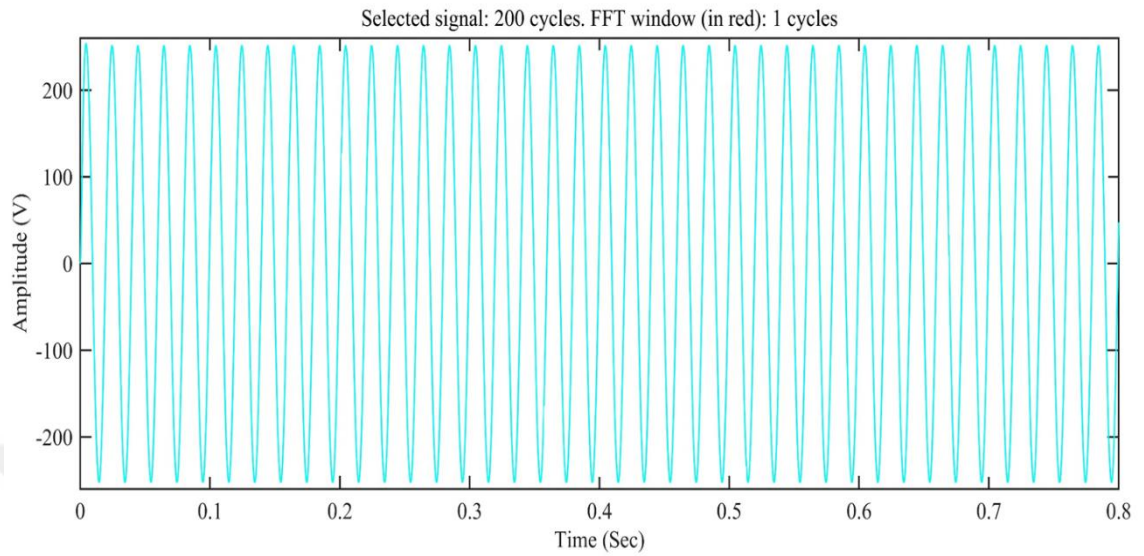


s. FFT analysis of phase voltage waveform after Second order low pass filter

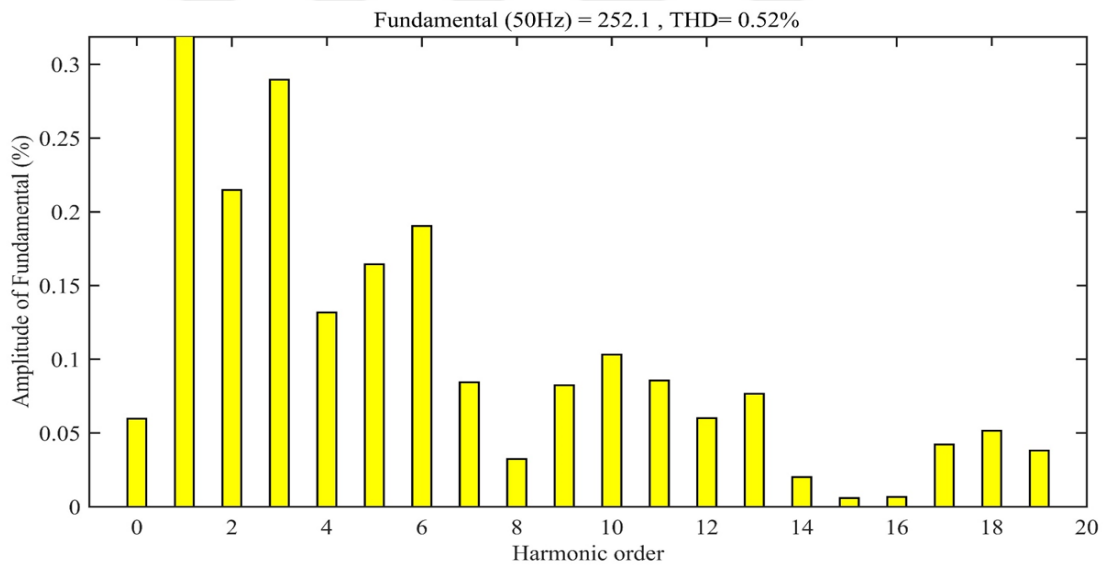


b. THD V (%)

Figure 4.41 SPWM Inverter performance parameter under load condition. THD% and FFT analysis of phase voltage waveform after second order low pass filter at 80% of rated frequency.

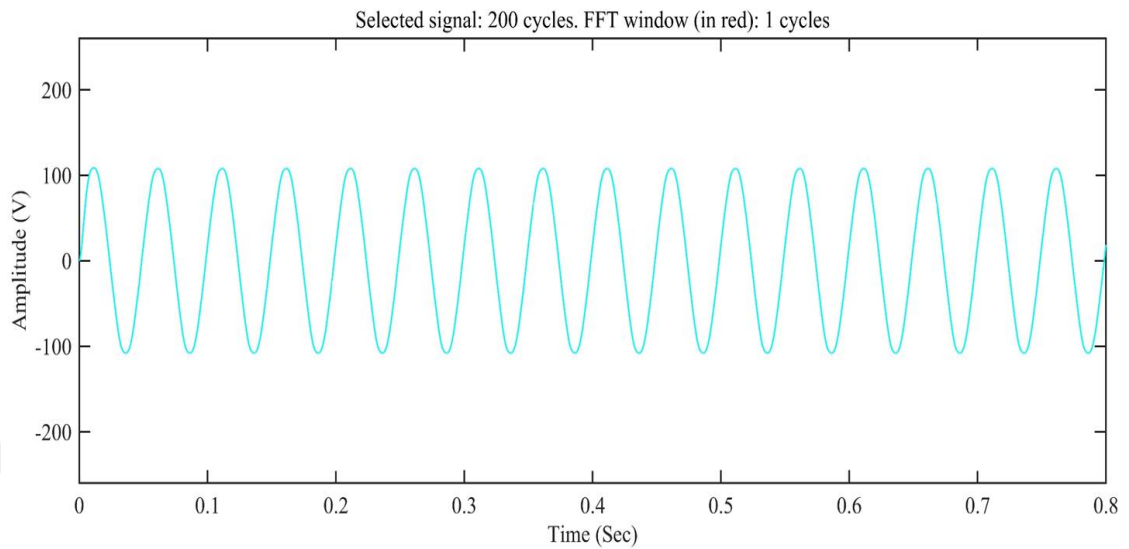


a. FFT analysis of phase voltage waveform after Second order low pass filter

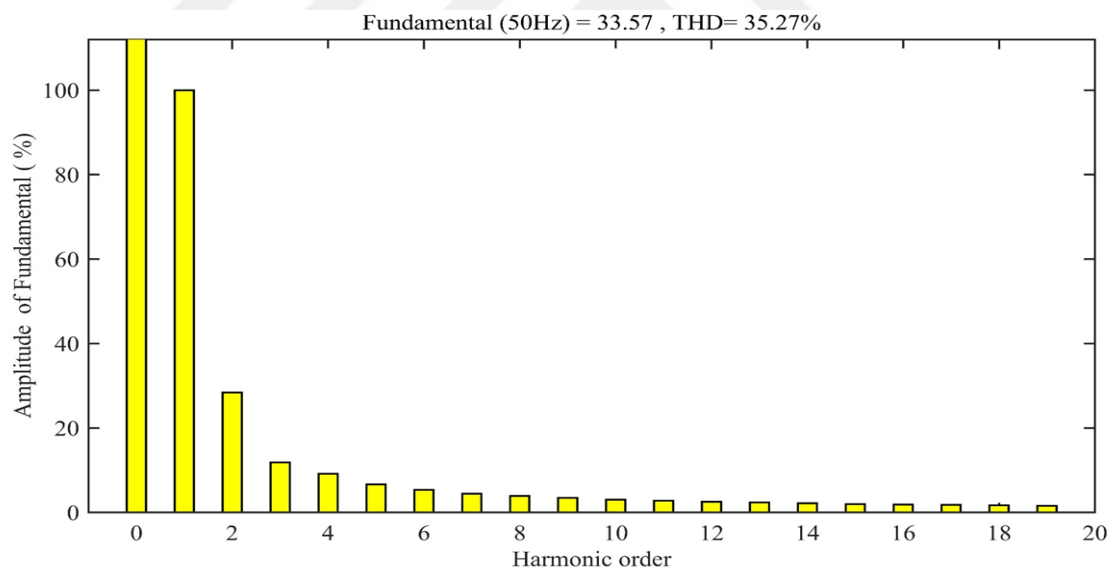


b. THD V (%)

Figure 4.42 SPWM Inverter performance parameter under load condition. THD% and FFT analysis of phase voltage waveform after second order low pass filter at 100% of rated frequency.

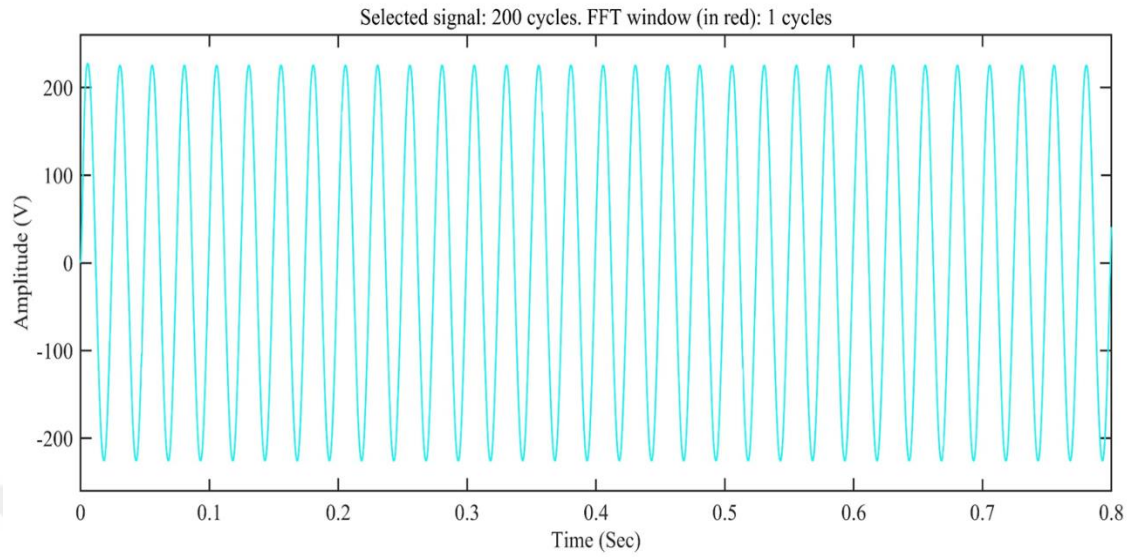


a. FFT analysis of phase voltage waveform after Second order low pass filter.

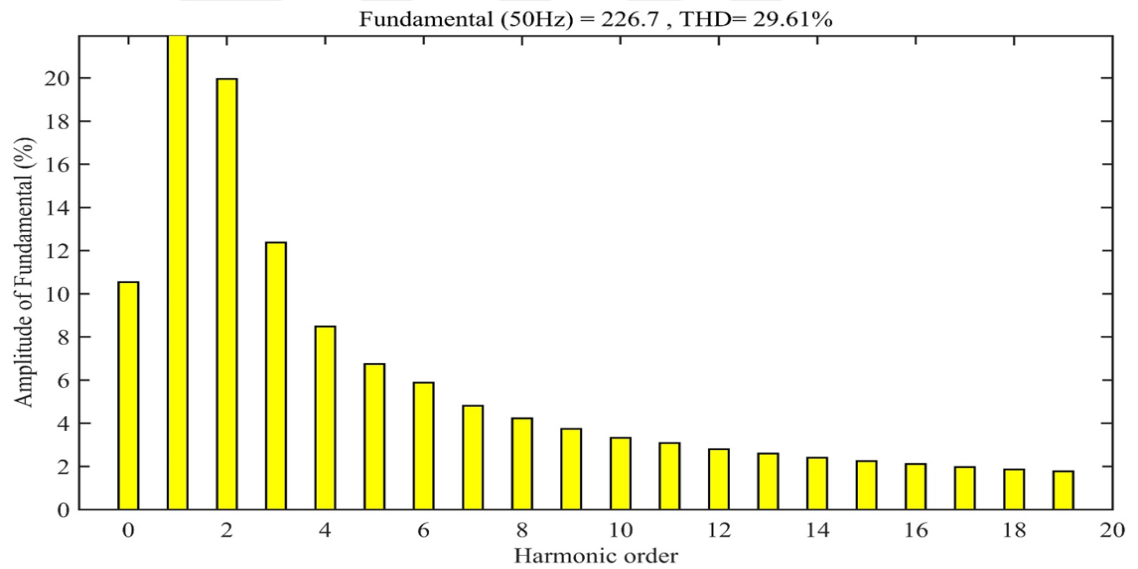


b. THD V (%)

Figure 4.43 THIPWM Inverter performance parameter under load condition. THD% and FFT analysis of phase voltage waveform after second order low pass filter and applied 40% of rated frequency.

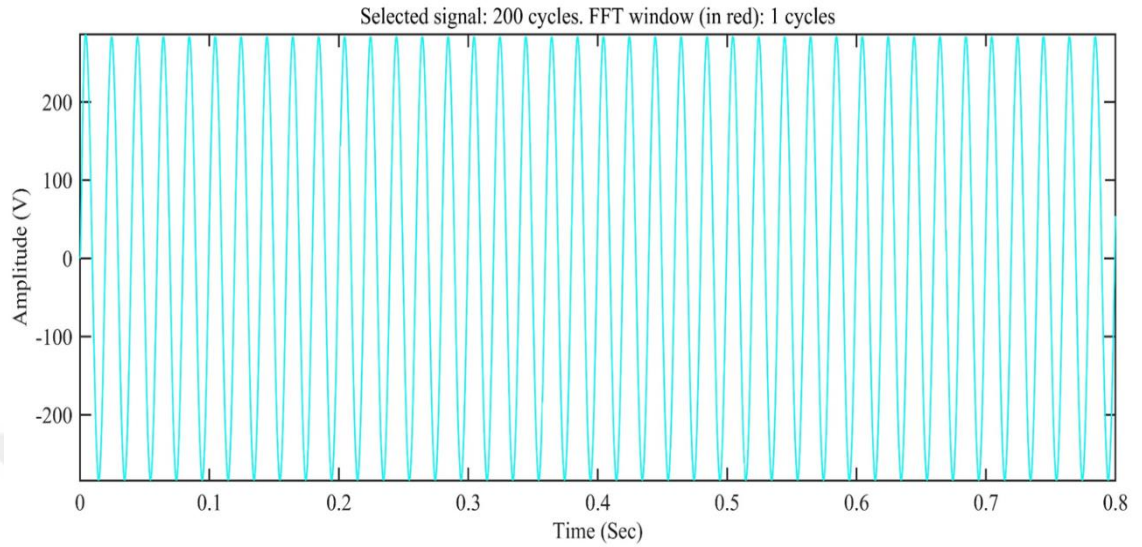


a. FFT analysis of phase voltage waveform after Second order low pass filter.

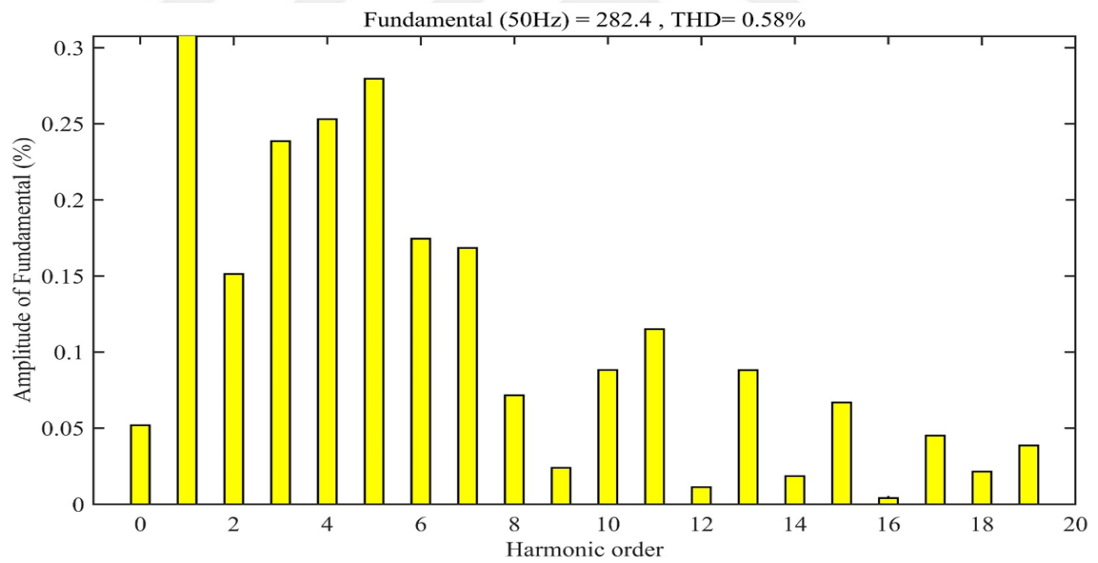


b. THD V (%)

Figure 4.44 THIPWM Inverter performance parameter under load condition. THD% and FFT analysis of phase voltage waveform after second order low pass filter and applied 80% of rated frequency.

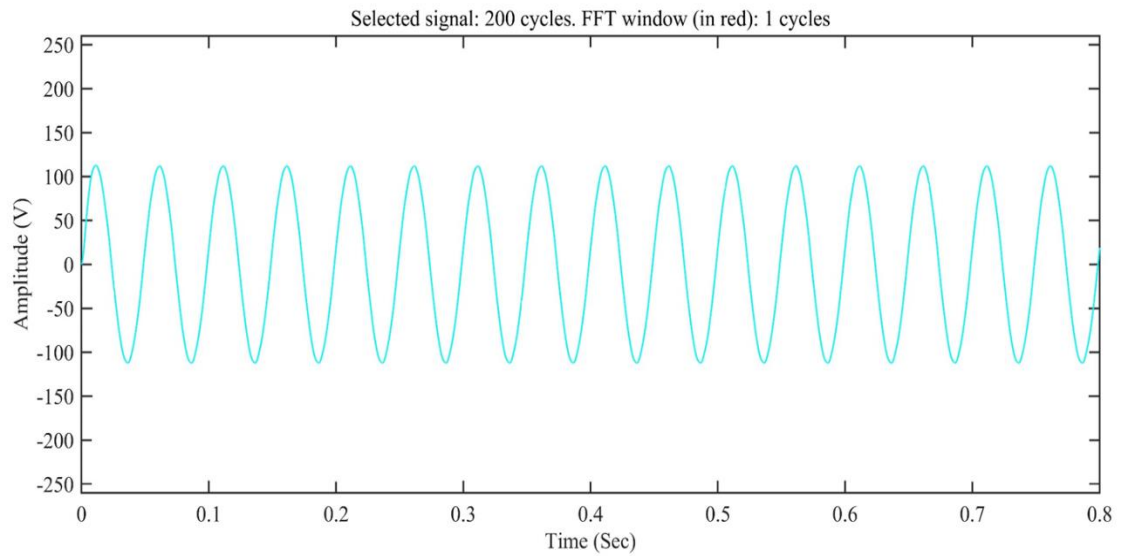


a. FFT analysis of phase voltage waveform after Second order low pass filter.

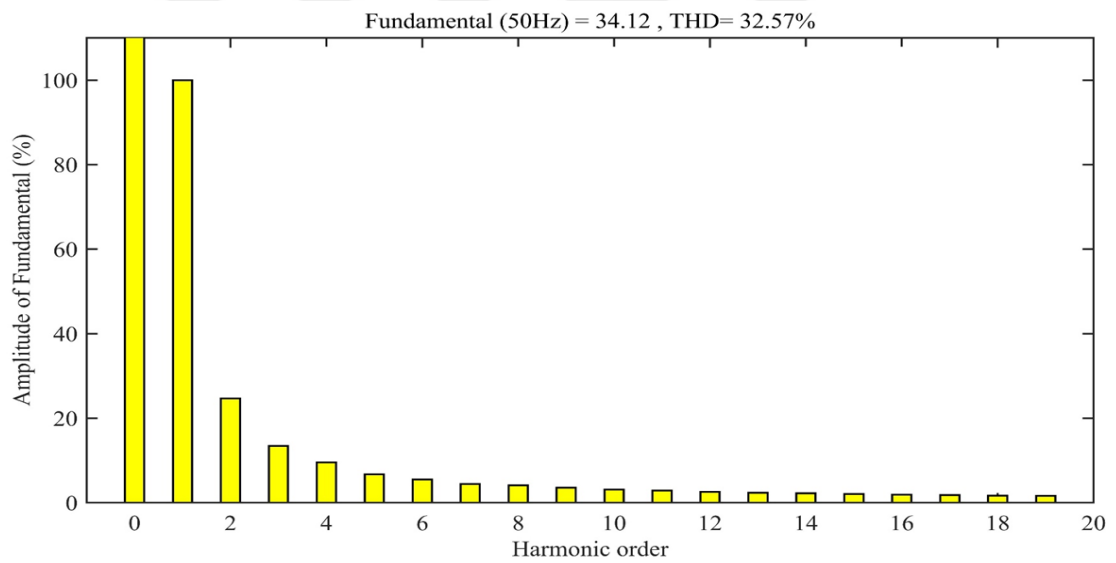


b. THDV (%)

Figure 4.45 THIPWM Inverter performance parameter under load condition. THD% and FFT analysis of phase voltage waveform after second order low pass filter and applied 100% of rated frequency.

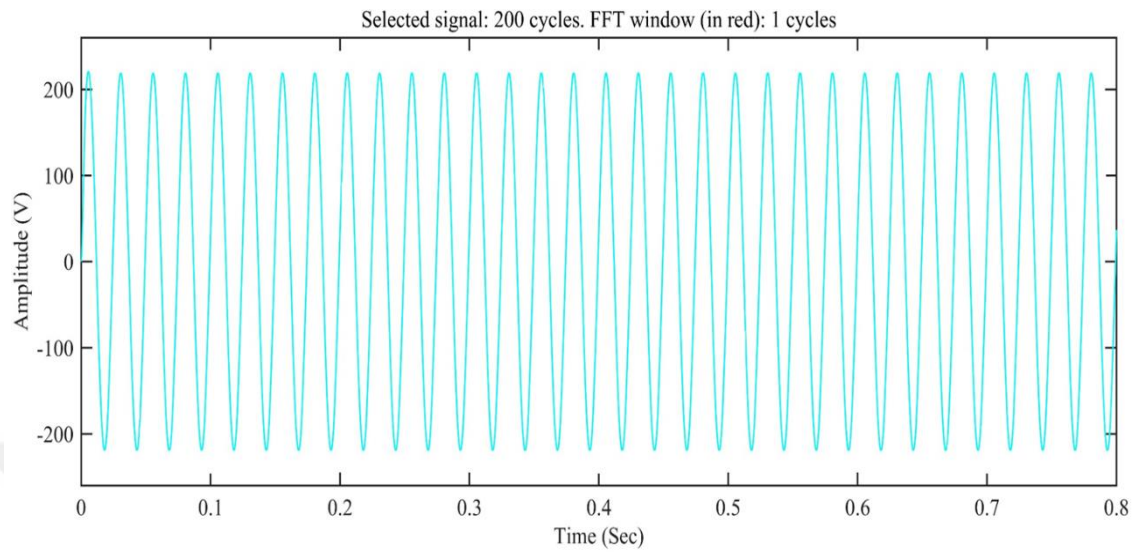


a. FFT analysis of Phase voltage waveform after Second order low pass filter.

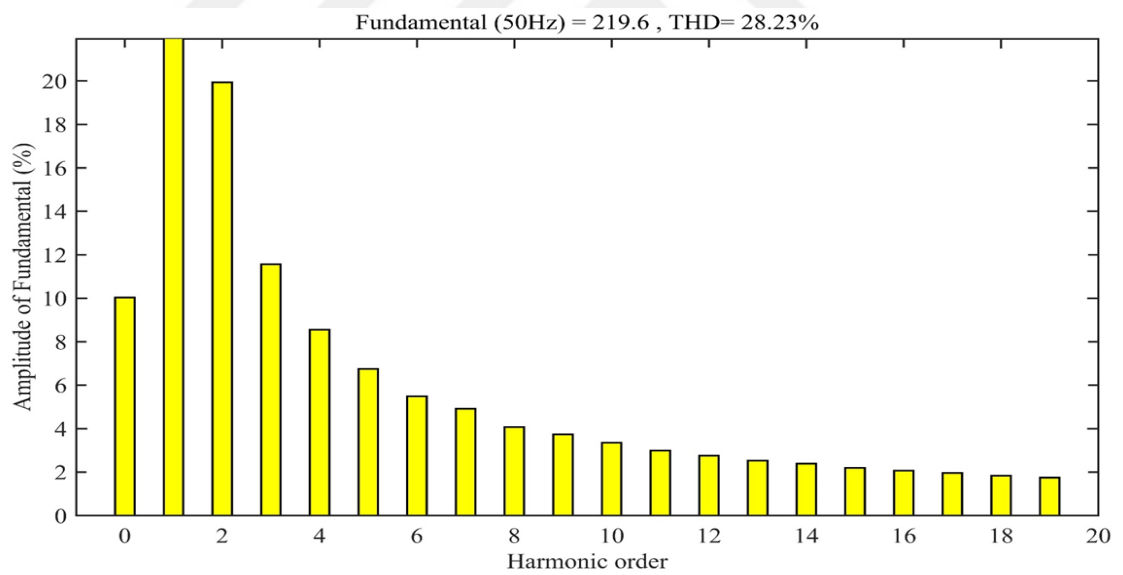


b. THD V (%)

Figure 4.46 SVPWM Inverter performance parameter under load condition. THD% and FFT analysis of phase voltage waveform after second order low pass filter and applied 40% of rated frequency.

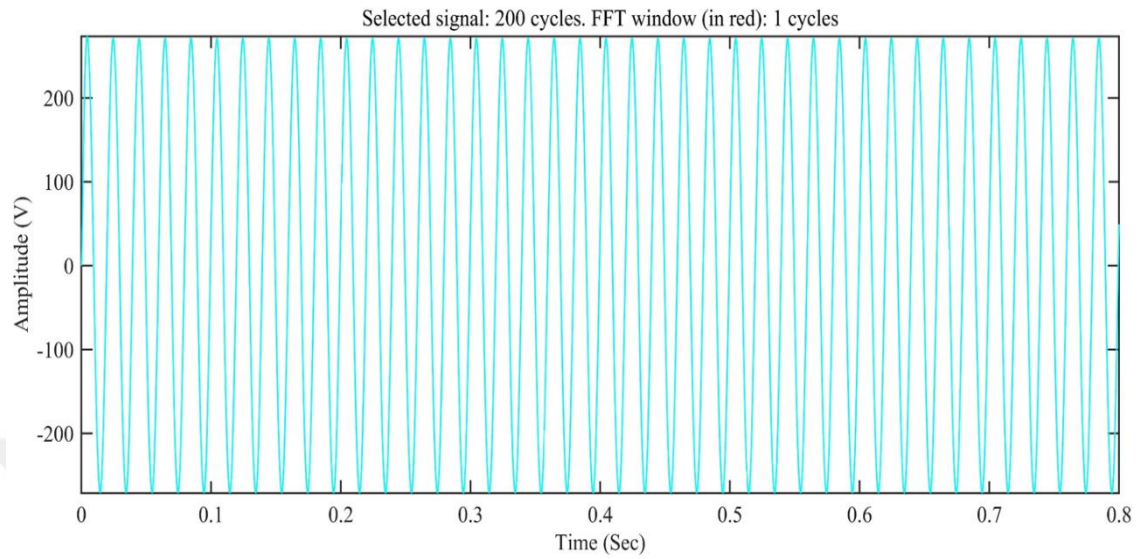


a. FFT analysis of phase voltage waveform after Second order low pass filter.

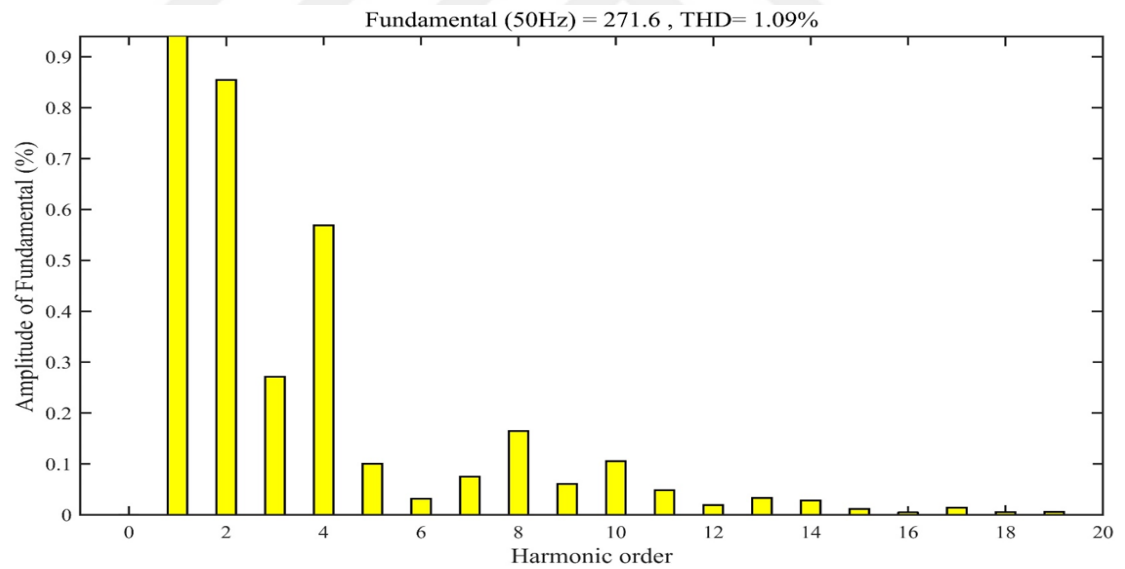


b. THD V (%)

Figure 4. 47 SVPWM Inverter performance parameter under load condition. THD% and FFT analysis of phase voltage waveform after second order low pass filter and applied 80% of rated frequency.

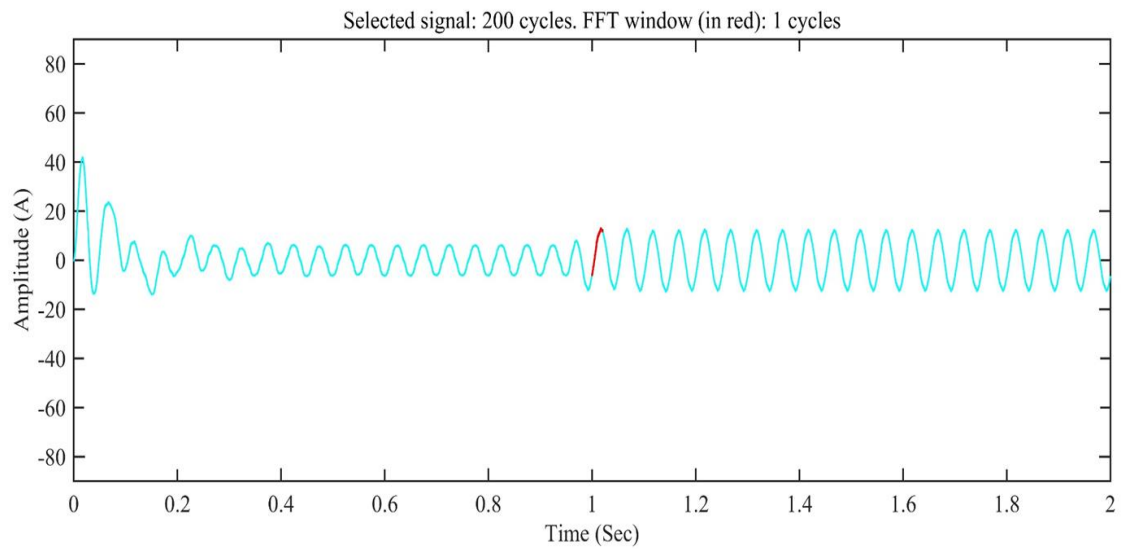


a. FFT analysis of Phase voltage waveform after Second order low pass filter.

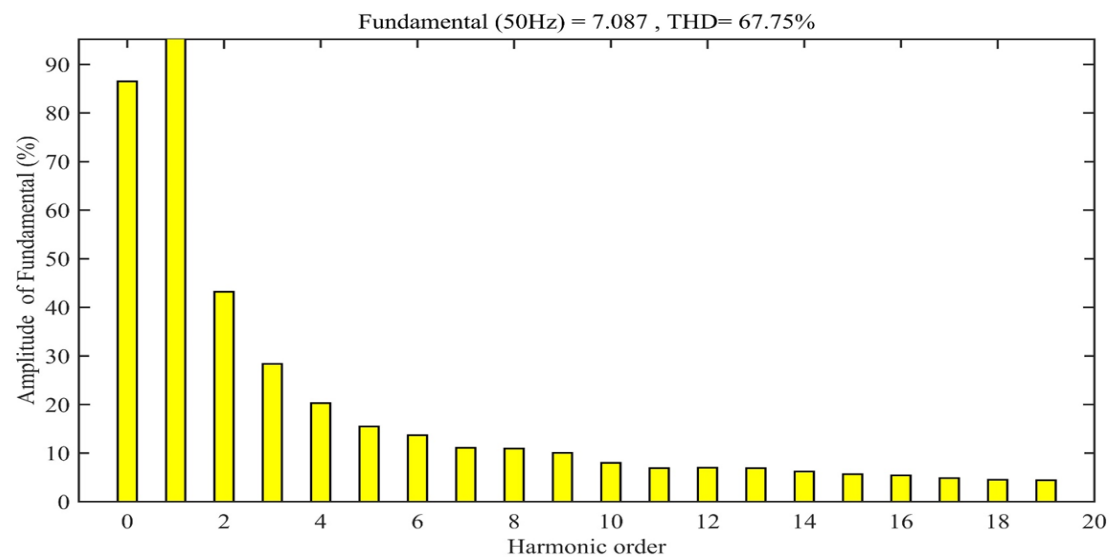


b. THD V (%)

Figure 4.48 SVPWM Inverter performance parameter under load condition. THD% and FFT analysis of phase voltage waveform after second order low pass filter and applied 100% of rated frequency.

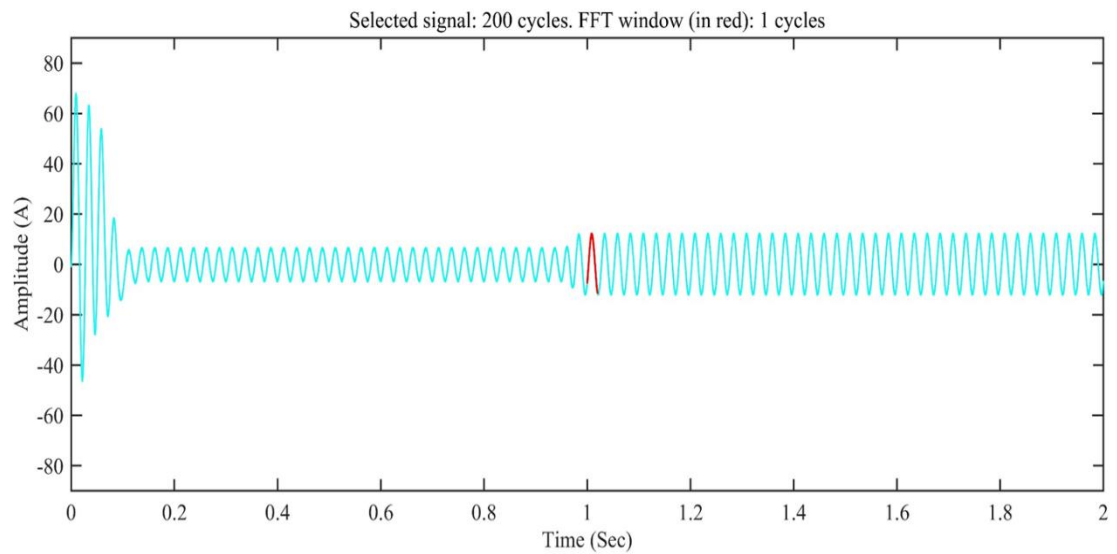


a. FFT analysis of current waveform per phase

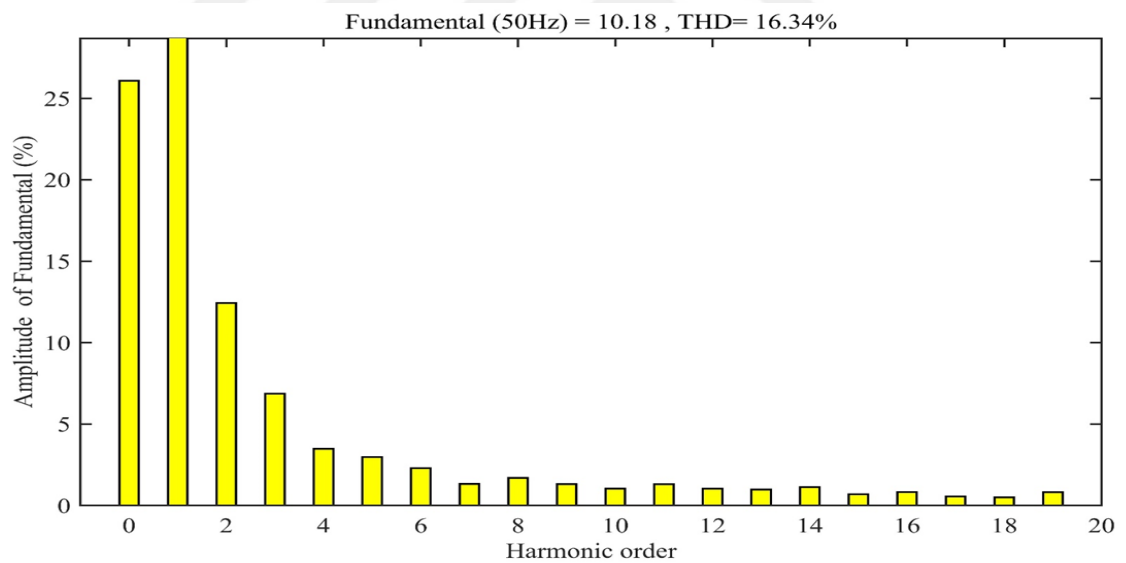


b. THD I (%)

Figure 4.49 SPWM Inverter performance parameter under load condition. THD% and FFT analysis of current waveform per phase during work of the motor and applied 40% of rated frequency.

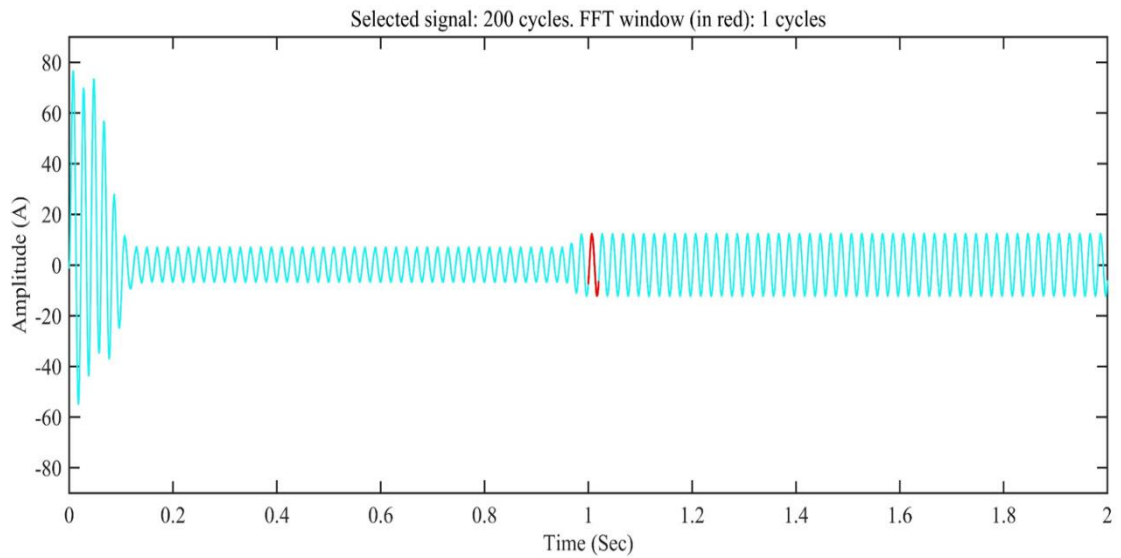


a. FFT analysis of current waveform per phase

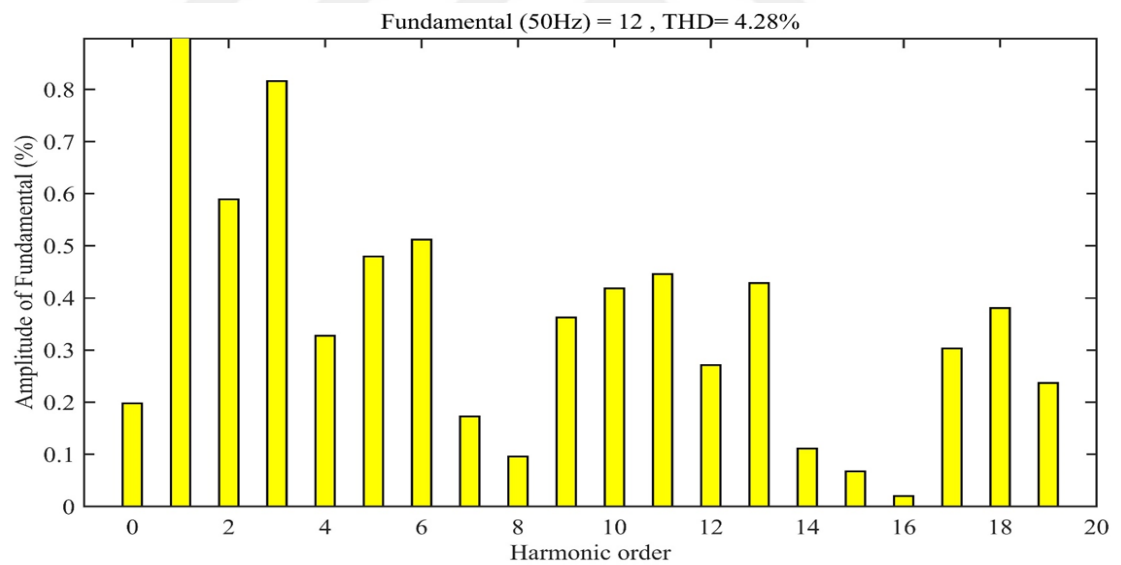


b. THD I (%)

Figure 4.50 SPWM Inverter performance parameter under load condition. THD% and FFT analysis of current waveform per phase during work of the motor and applied 80% of rated frequency.

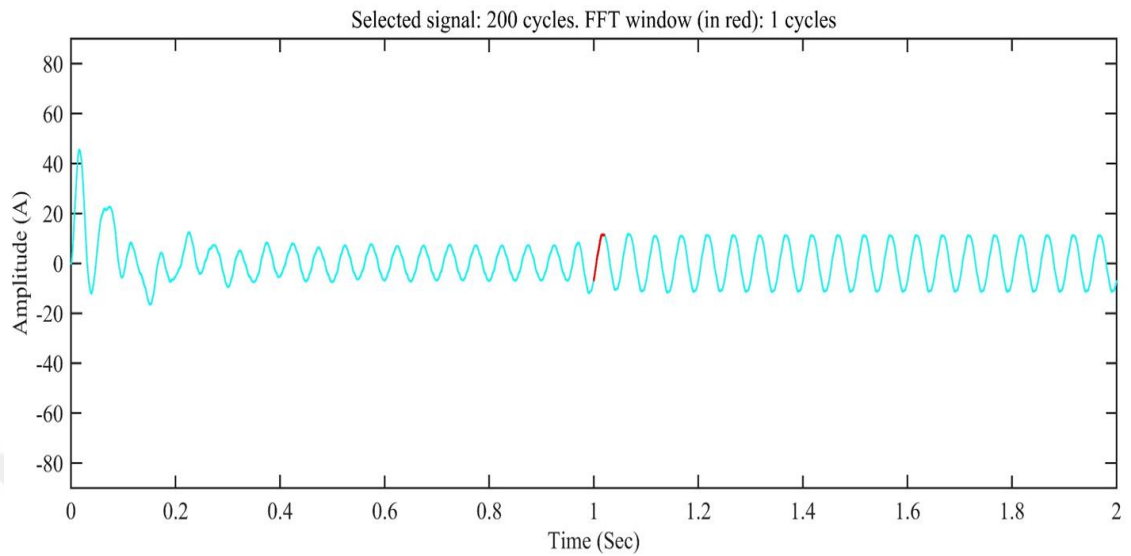


a. FFT analysis of current waveform per phase

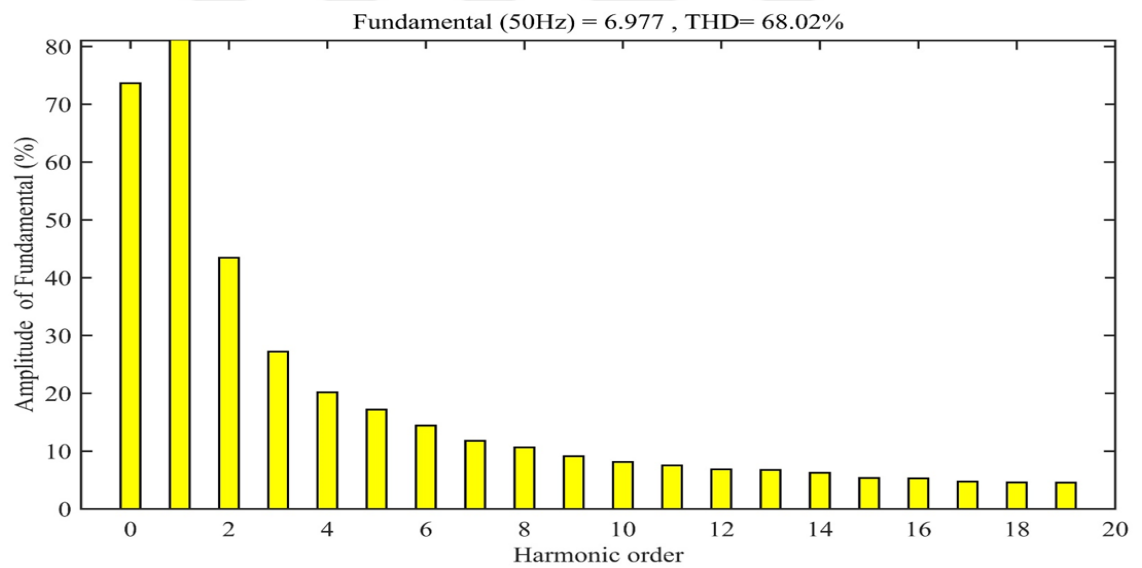


b. THD I (%)

Figure 4.51 SPWM Inverter performance parameter under load condition. THD% and FFT analysis of current waveform per phase during work of the motor and applied 100% of rated frequency.

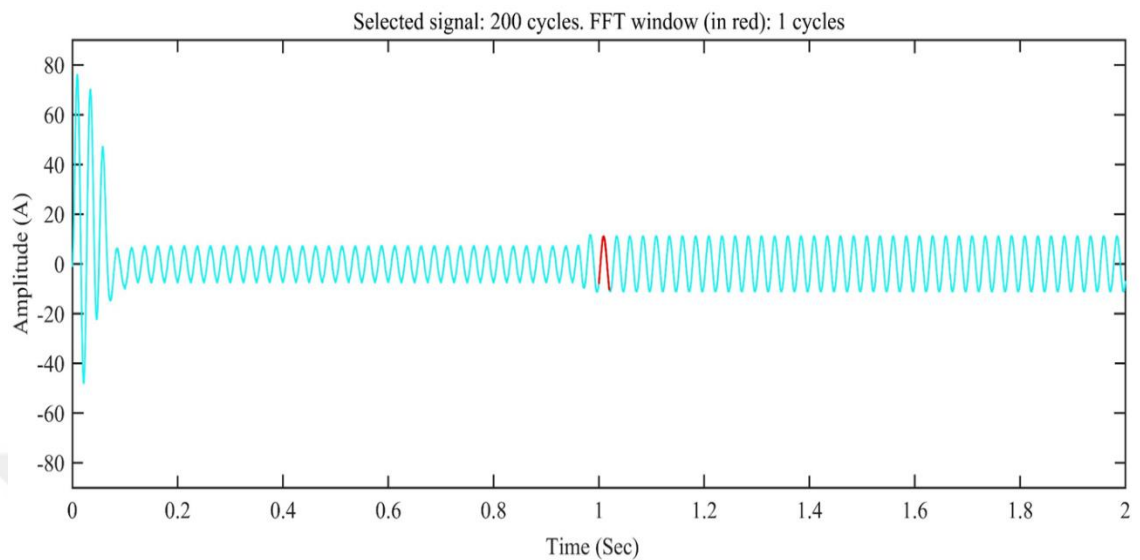


a. FFT analysis of current waveform per phase

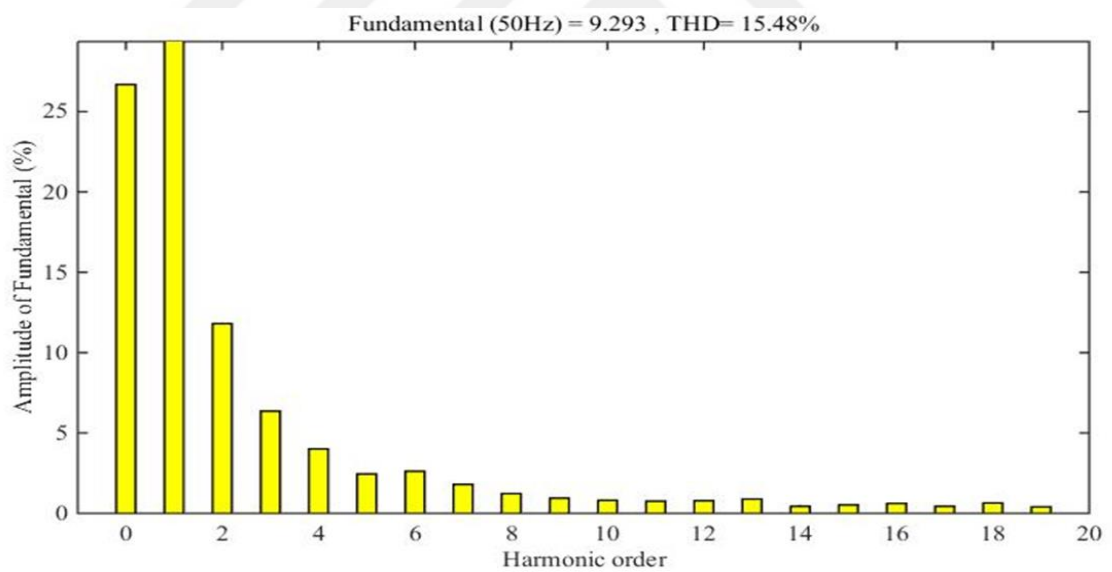


b. THD I (%)

Figure 4.52 THIPWM Inverter performance parameter under load condition. THD% and FFT analysis of current waveform per phase during work of the motor and applied 40% of rated frequency.

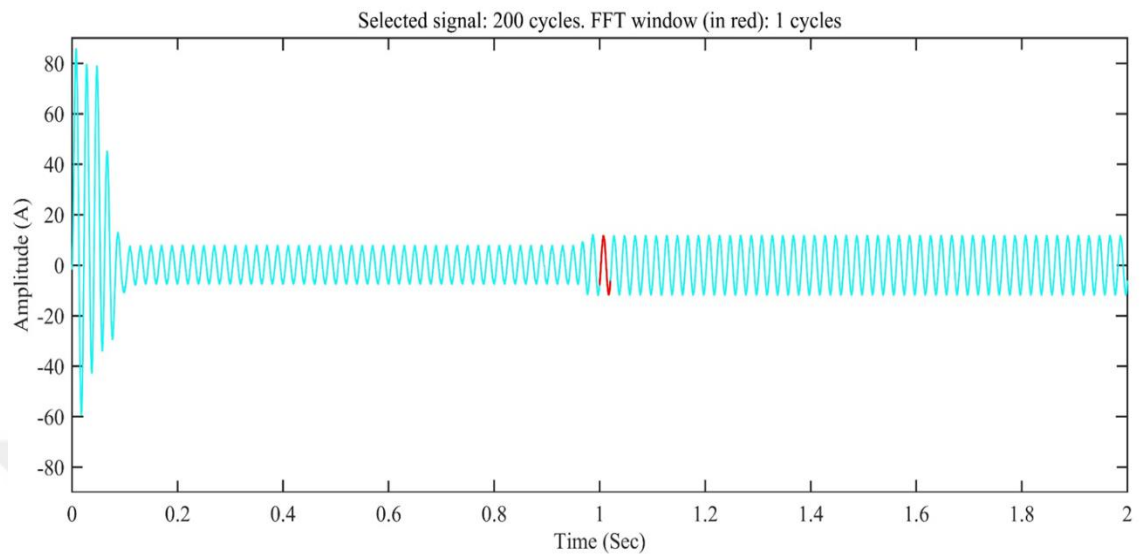


a. FFT analysis of current waveform per phase

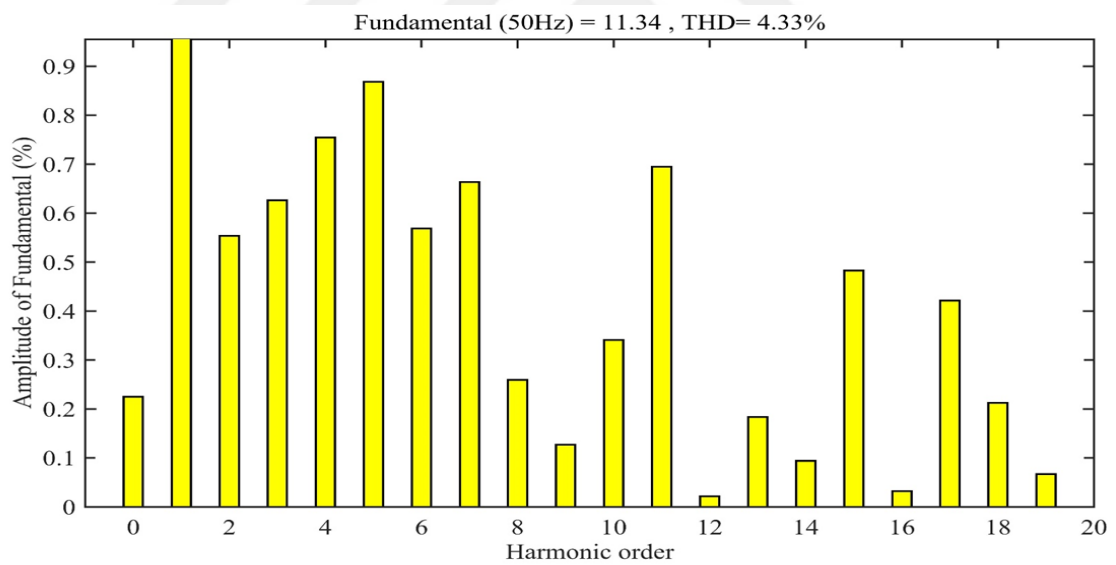


b. THD I (%)

Figure 4.53 THIPWM Inverter performance parameter under load condition. THD% and FFT analysis of current waveform per phase during work of the motor and applied 80% of rated frequency.

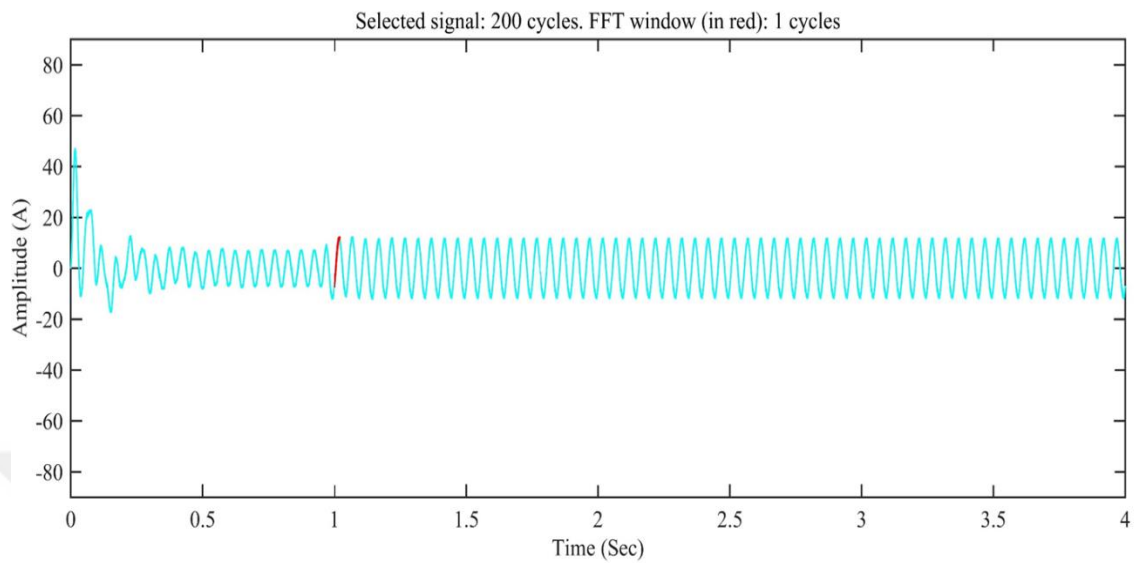


a. FFT analysis of current waveform per phase

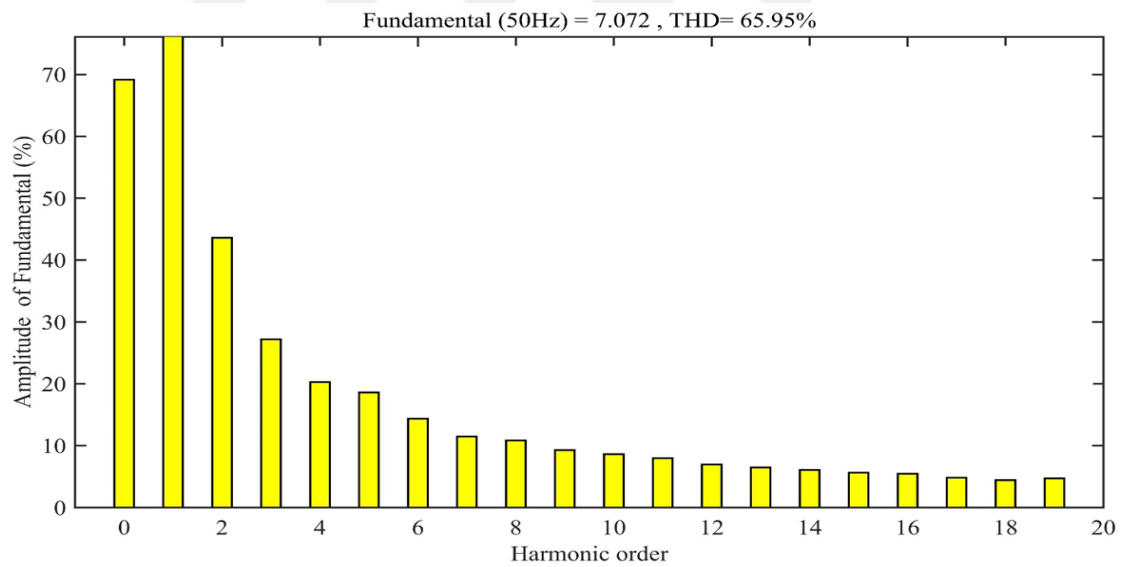


b. THD I (%)

Figure 4.54 THIPWM Inverter performance parameter under load condition. THD% and FFT analysis of current waveform per phase during work of the motor and applied 100% of rated frequency.

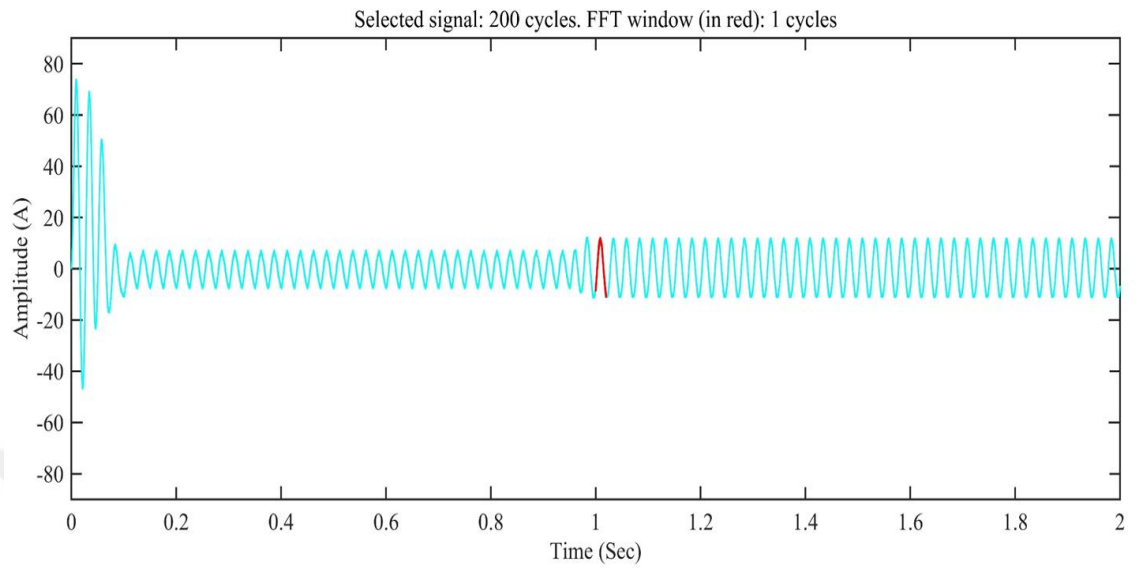


a. FFT analysis of current waveform per phase

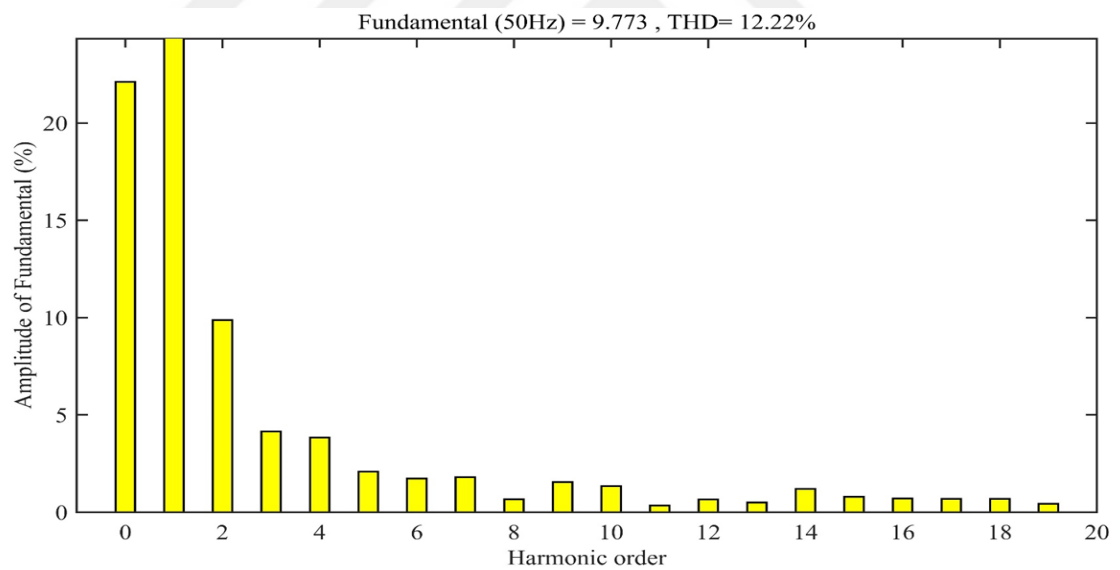


b. THD I (%)

Figure 4.55 SVPWM Inverter performance parameter under load condition. THD% and FFT analysis of current waveform per phase during work of the motor and applied 40 % of rated frequency.

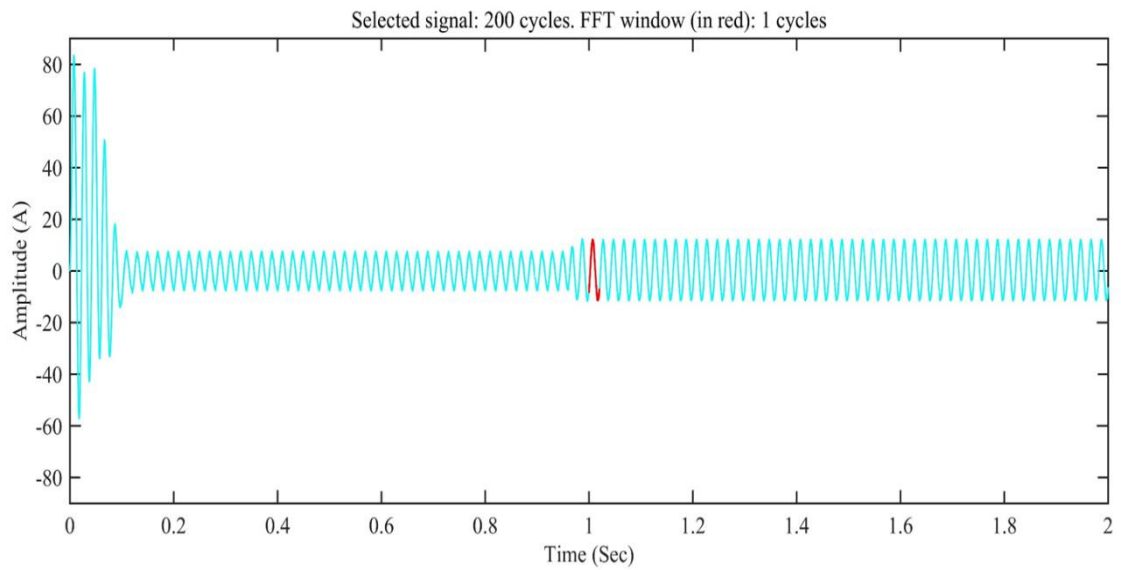


a. FFT analysis of current waveform per phase

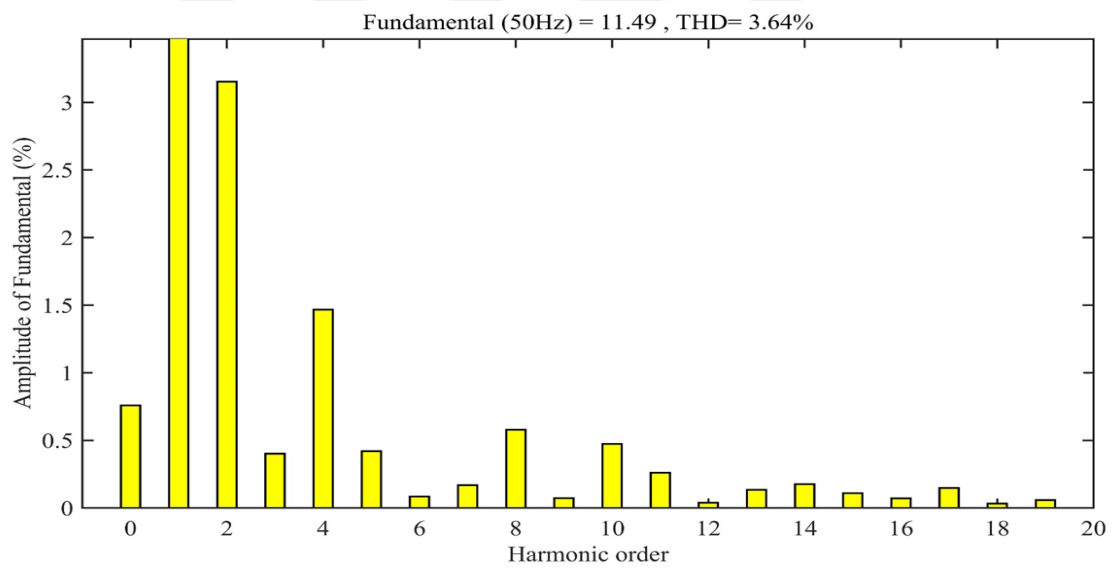


b. THD I (%)

Figure 4.56 SVPWM Inverter performance parameter under load condition. THD% and FFT analysis of current waveform per phase during work of the motor and applied 80 % of rated frequency.



a. FFT analysis of current waveform per phase



b. THD I (%)

Figure 4.57 SVPWM Inverter performance parameter under load condition. THD% and FFT analysis of current waveform per phase during work of the motor and applied 100 % of rated frequency.

4.8 Results analysis and study:

4.8.1 Under no load condition.

The Figure 4.19 draws according to Table 4.5, in three cases of PWM inverter techniques, the output voltage equals to the rated voltage of motor when applied a frequency greater than the rated value. This can be seen clearly in Table 4.5 when the frequency ratio is 120% of rated voltage. However the region between (100%, 160%) is called a constant power region, it can be seen clearly in figure 4.19. In this region the electromagnetic torque is weak. Because the (volt/hertz) ratio is not equal to rated value. In case (20%, 100%) the output speed is varied with respect to frequency. The (Volt/hertz) control systems can estimate the modulation index for PWM inverter with respect to frequency applied by the user. In the same table it can clearly be seen that there are increases in output inverter voltage when using SVPWM and THIPWM techniques compared with SPWM. This one is of advanced of using SVPWM

Figures (4.20(a, b, c)) (4.21(a, b, c)) are drawn according to Table (C1 and C2)) (See in Appendix C). The THIPWM technique has clearly increased the (5th, 7th and 11th) compared with SPWM. Thus, produced a better electromagnetic torque the SVPWM technique the (5th, 7th and 11th) Harmonics magnitude are very high totally, which gives more stable operation and low pulsating in output torque.

The (Volt/hertz) control system performance is described in Figures (4.22..... 4.24) (4.25..... 4.27) and (4.28..... 4.30) for SPWM, THIPWM and SVPWM respectively (See Appendix C)

It can be seen clearly in all cases of voltage waveforms, that the (Volt/hertz) control system successfully to change the peak value of the voltage when varying frequency ratio. The current increased at starting and slightly reduce when the simulation time reach 0.55 Sec, at steady state approximately equal in all cases.

4.8.2 Under load condition.

Figures (4.31...4.33) (4.34...4.36) and (4.37...4.39) show a motor mechanical parameter under load condition. Each figure consists of two parts (a, b). Where "a" refers to a rotor speed ($\omega_m(\text{rad/sec})$) and "b" to electromagnetic torque ($T_e(\text{N.m})$). With respect to increase in frequency ratio (f_{comm}) a mechanical load ($T_e(\text{N.m})$) equals to (11.9N.m) at simulation time (0.95 sec), and all Figures respecting to three PWM inverter cases (See in Appendix C):

- At 40% of rated frequency the electromagnetic torque is high overshoot at starting for THPWM an SVPWM compared with SPWM inverter technique. After (0.95) from starting simulation the set value of load torque. The torque increased to (11.9 N.m), the electromagnetic torque is tracking mechanical torque. The overshoot and the amount of torque ripple is much less than that of the THIPWM, SVPWM. The initial value of speed is (61 rad/Sec) and after (0.95 Sec) the value is reduced to (54 rad/Sec).The open loop control system Volt/Hertz can't correct this error and that is one disadvantage of the system
- At 60% of rated frequency the control system is unstable. After (0.95) from starting simulation the set value of load torque .The torque increased and the speed is reduced. The system is high ripple for both speed and torque. However. The open loop Volt/Hertz system is not suitable for variable torque application
- At 80% of rated frequency the ripple in speed after applying load is still high But the amount of torque ripple is much less than that of the (60%).
- At 100% of rated frequency the system is more stable also after applying a load

The SVPWM technique is better overshoot and the amount of torque ripple is much less than that of the SPWM and the speed response, for the (THIPWM, SPWM) is smoother and faster than the (SVPWM) technique.

4.8.3 Total Harmonic Distortion (THD) Results

The calculation of the THD for three- phase (Voltage and Current) in stator side are shows in Figures (4.40....4.42) (4.43... 4.45) (4.46..... 4.48) and (4.49.....4.51), (4.52....4.54) (4.55 ...4.57) and can be summarized in Table 4.8 the FFT analyses for current waveform and voltage after (1sec) from starting

Table 4.6 Shows the percentage ratio of Total Harmonic Distortion for voltage and current (THD_v THD_i) under load condition.

Modulation Techniques	SPWM		THIPWM		SVPWM	
f_{comm} (%)	THD_v (%)	THD_i (%)	THD_v (%)	THD_i (%)	THD_v (%)	THD_i (%)
40	31.93	67.75	35.27	68	32.57	65.95
60	37.78	36.63	38.30	37	36.48	36.55
80	29.66	16.34	29.61	15.48	28.33	12.22
100	0.52	4.28	0.58	4.33	1	3.64

From the above table the following notices can be recorded:

The Total Harmonic Distortion of SVPWM at low frequency ratio (40 %, 60%) is clearly slightly less than SPWM, with keeping the magnitude of the fundamental components approximately constant. Also the SVPWM is less Total harmonic for current waveform compared with SPWM. In the other words the variation of the Total Harmonic Distortion parameters in all cases of current is higher, when a common frequency percentage ratio approaching to (40%).

However, this appears in the higher value of modulation index of the under modulation region (i.e. 0.9), with respect to frequency percentage ratio (100%), whereas, the maximum value of Total Harmonic Distortion appears in the lower values of modulation index (i.e. 0.5). with respect to frequency percentage ratio (40%). The FFT analysis of harmonic order for current waveform is given in Figures (4.49(b)...4.51(b)) for SPWM, (4.52(b).....4.54(b)) for THIPWM, and (4.55(b).....4.57 (b)) for SVPWM.

To study the comparisons between three PWM techniques in case of current distortion and the comparison of the same modulation index, the THIPWM technique operates by adding a Third Harmonic component to the waveforms .It can be seen clearly that in all cases of frequency ratio the magnitude of 3Th component is higher than SPWM and SVPWM that is gives batter inverter operation at rated frequency the SVPWM. Allow a better utilization of the DC voltage. Therefore, the THD for current waveform under load condition is low. Thus, possible to reduce the amount of torque ripple, and increases the overall system efficiency.



CHAPTER 5

EXPERIMENTAL STUDY

5.1 Introduction

The practical design of inverter fed induction motor is very important to examine the behavior and the performance of the whole system, which gives a real operation features and results. Then it's very useful to make comparisons between the theoretical simulation and the practical testing results.

Designing traditional AC drives and PWM inverter is simple, because it depends on some ordinary analogue electronic circuits, like triangle carrier wave generation and operational amplifiers, which are available components. Whereas, the new technology for designing variable frequency drives, has made them even more efficient. This design is fully based on interconnection module technology, which is available in markets at the present time; therefore, in order to achieve our goal, first we must understand the operation of each module used in AC drive model, and then imitate this operation. In general, the outlines of the system depend on the concepts of SPWM inverter theory, which can briefly be described in the block diagram shown in Figure. 5.1:

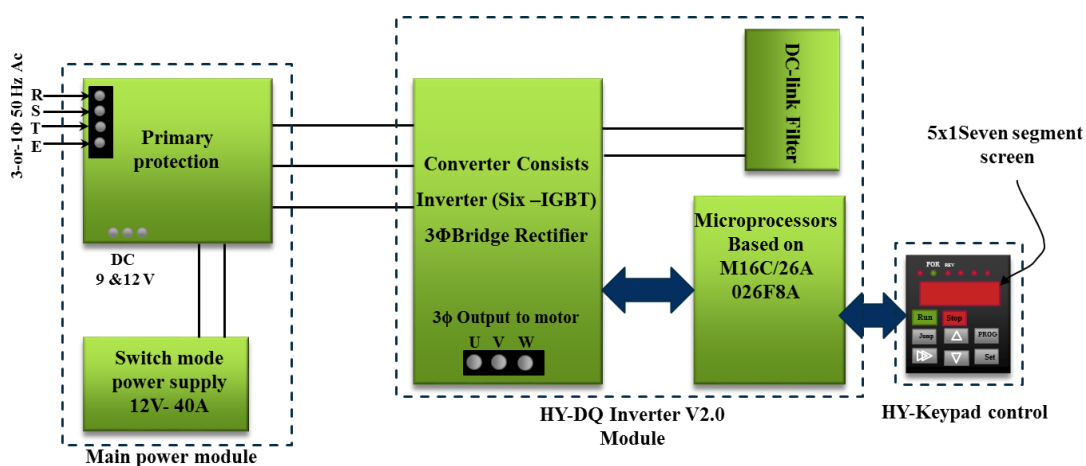


Figure 5.1 Block diagram of proposed AC Drive system.

5.2 Main Power module:

5.2.1 Power supply of Ventilation System

Because of the high switching frequency in the power circuit, the increase in temperature leads to disturb operation of electronic devices and causing unstable performance; therefore, ventilation system keeps the system temperature at normal limit and protect overheating. The switch mode power supply module can be used to supply cooling system. The module obtains pure and stable (+9, +12volt) DC supply and is not affected by interferences. A practical power supply module based on the PWM technique used for this reason as shown in Figure 5.2

5.2.2 Primary protection System:

In order to improve the diagnostic system technique, under fault conditions, the fuse protection module is used in order to protect the drive system under fault “short circuit”. This module design is based on (2A&10A) fuse for power supply and converter respectively. A practical protraction circuit is shown in Figure 5.2

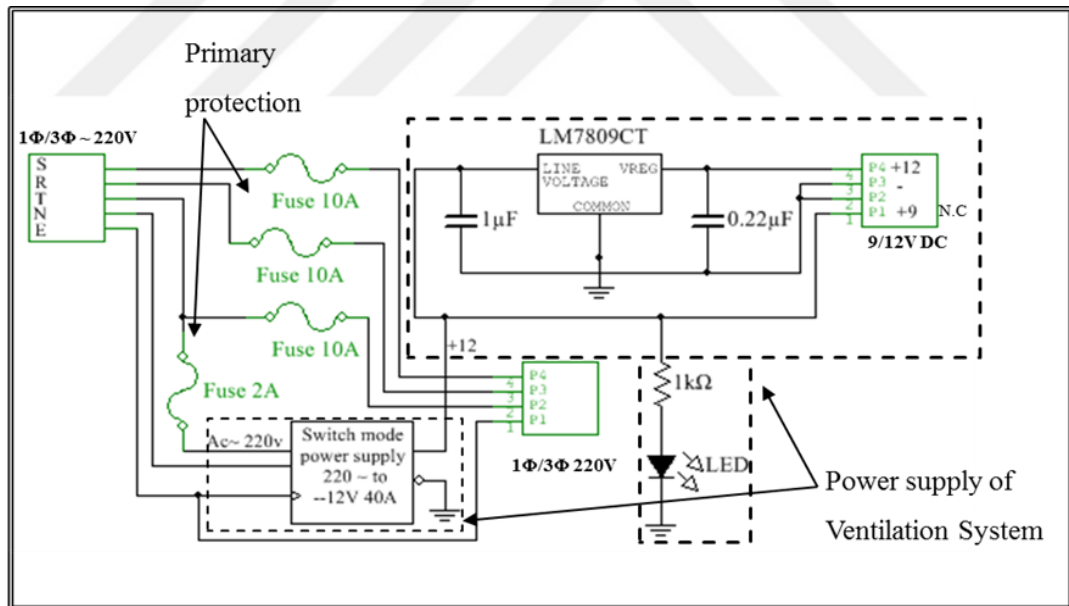


Figure 5.2 Practical scheme of the primary protection and Ventilation power supply module.

5.3 Converter module:

5.3.1 Bridge rectifier Power Modules

A three phase bridge rectifier Power Modules (26MT40) series (see Appendix B), is used to convert three or single phase alternating voltage supply to DC direct voltage. The output voltage is not obtained as same as the normal level of battery. The direct voltage contains a ripple component superimposed on the mean of output voltage.

To eliminate ripple, a capacitor is connected in series with a load, and a capacitor is in parallel with the load. The capacitor exhibits reactance, and blocks low-frequency signals, causing them to go through the load instead. This topology is called a low-pass filter as shown in Figure 5.3.

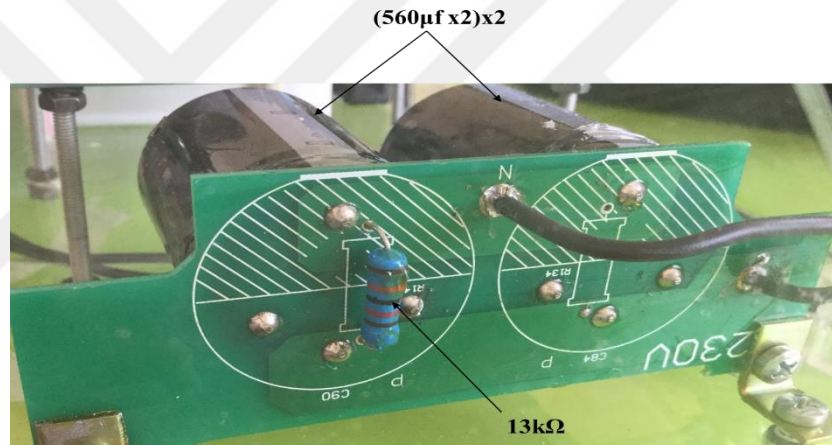


Figure 5.3 DC-Link Filter module.

5.3.2 IGBT Inverter

Because of advances in solid state devices and microprocessor electronics, high speed switch IGBT and SPWM inverters, are becoming more and more popular in today's motor drives, which makes it possible to control both frequency and magnitude of the output voltage and current. As a result, SPWM inverter powered motor drives offer acceptable efficiency and higher performance compared to other types of PWM.

Six IGBT transistors were used to construct a three-phase bridge as shown in Figure (5.4)

The (FGA25N120A) IGBT with certain specifications (see Appendix B) will be suitable for such requirements. The 6-IGBT transistors are fitted into suitable heat sink each in order to dissipate the heat resulting from the conduction losses.

To turn-on the power IGBT, a gate voltage signal must be applied between the gate and source terminals to push the IGBT into saturation region. The logical signal generated by the electronic circuit has a peak value of (5 volt) with respect to its own ground. Therefore, to use this signal the gate signal must be connected to the IGBT gate terminal and the ground of the logic circuit to the IGBT source terminal. This connection leads to short circuit between the source terminals of the six power switches.

Therefore, the IGBT gating circuit must be isolated from logic circuit and from other transistor gating circuits. The main types of isolating gating circuits are:

- Pulse transformer isolation, or
- photo-couplers isolation

In this module six-TLP351 photo-coupler isolation circuits are used. It consists of an infrared transmitter diode and silicon photo transistor receiver. Figure 5.4 shows gating signal transfers from the logic circuit to the power circuit by means of infrared which light provides an electrical isolation gap [55]

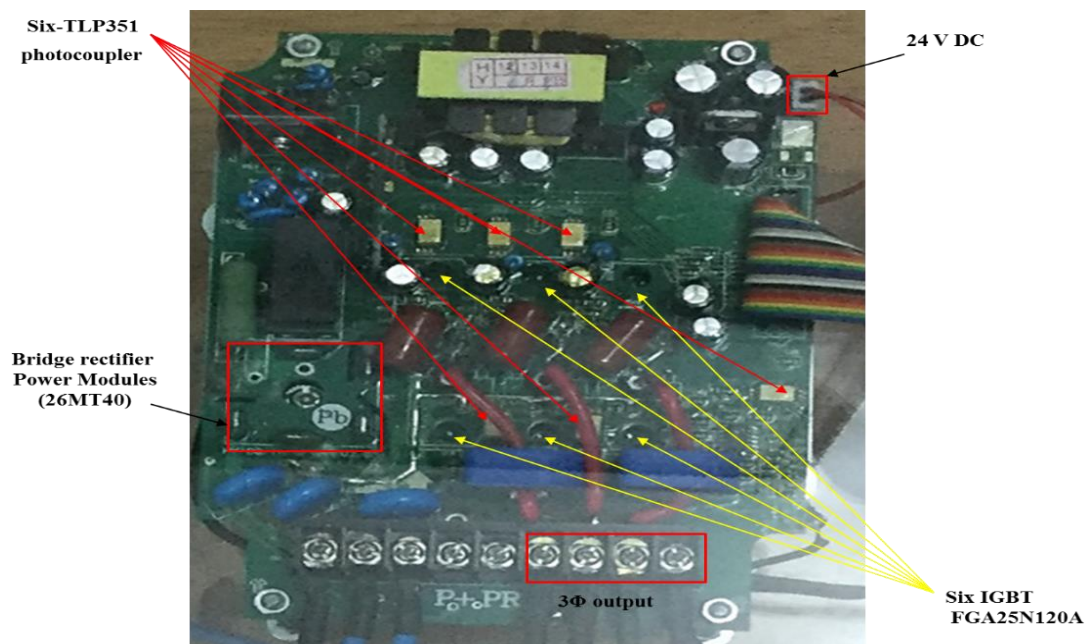


Figure 5.4 Top –view of power inverter module "HY-DQ inverter v2.0".

5.3.3 Microprocessor conception [53]:

In this power inverter module using a high performance silicon gate CMOS Complementary metal–oxide–semiconductor technology. A (M16C/26A026F8A) is a single chip MCU Multipoint control unit used for managing the inverter. The main feature of the M16C/26A026F8A processor executes a complex instructions at high speed; therefore it is widely used in industrial applications such as air-conditioning equipment. The Figure 5.5 illustrated (M16C/26A026F8A) Microprocessor module based on (HY-DQ inverter v2.0).

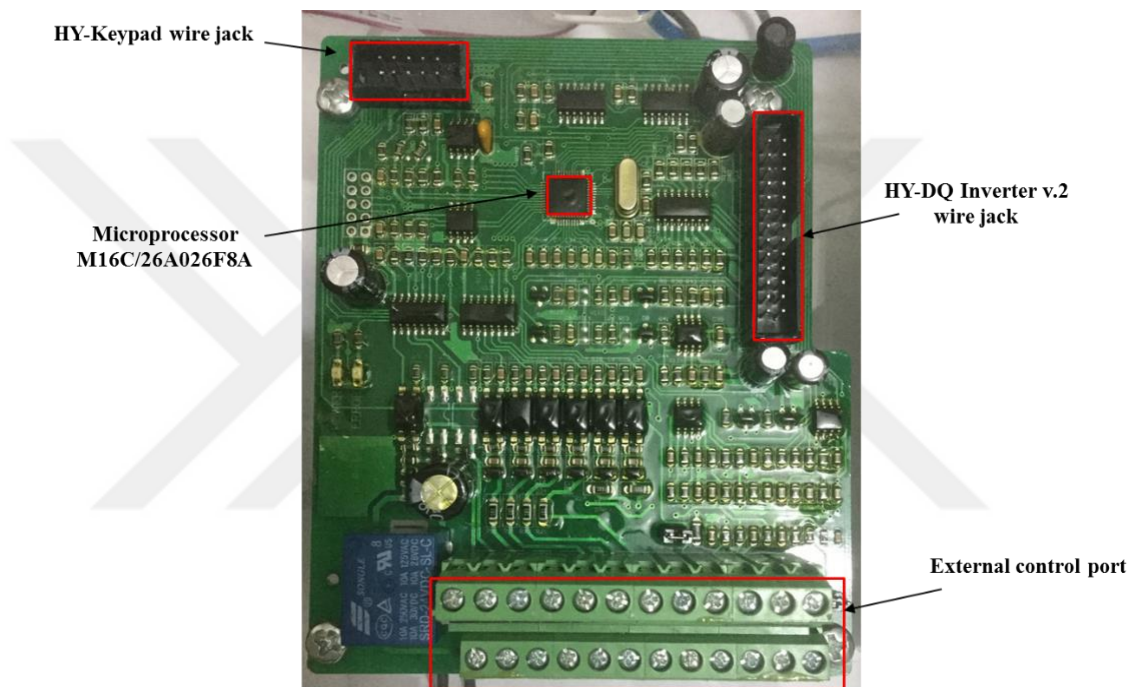


Figure 5.5 Illustrated (M16C/26A026F8A) Microprocessor module based on "HY-DQ inverter v2.0".

5.4 Experimental testing and results:

By applying single phase AC 220V 50Hz to the input power bridge of the designed SPWM drive with set 8KHz carrier frequency (see Appendix B), a D.C voltage source equals to (300 volt) is gotten, and by using the same practical induction motor which was used in the simulation tests, then repeating the no-load test steps of different Frequency ratio $f_{comm} \%$, we obtained system performance as shown in Tables 5.1, and Figures (5.6.....22). The results obtained by using UNI-T “digital voltmeter” “-oscilloscope”, “speed meter (R.p.m).

- Motor name plate: 3-Phase I.M, 380 volt (star connection), squirrel cage, 50 Hz, 4-Poles, 750 watt, and 1420 r.p.m.

Table 5.1 No- load test (V_{Phase} & N_r).

PWM	SPWM	
$f_{comm}(\%)$	$N_r(\text{r. p. m})$	$V_{\text{phase}}(\text{V})$
20	284	104.6
40	568	147.55
60	852	190
80	1136	210.59
100	1423	225.67
120	1704	226.8
140	1988	226.78
160	2270	226.83

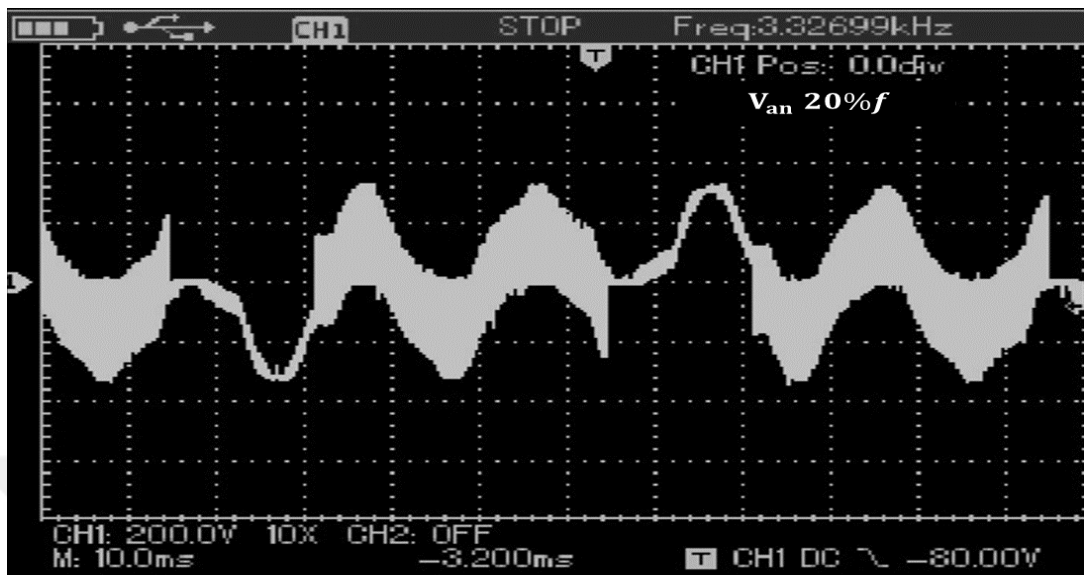


Figure 5.6 Phase voltage of $f_{comn}(\%) = 20\%$ under-no load.

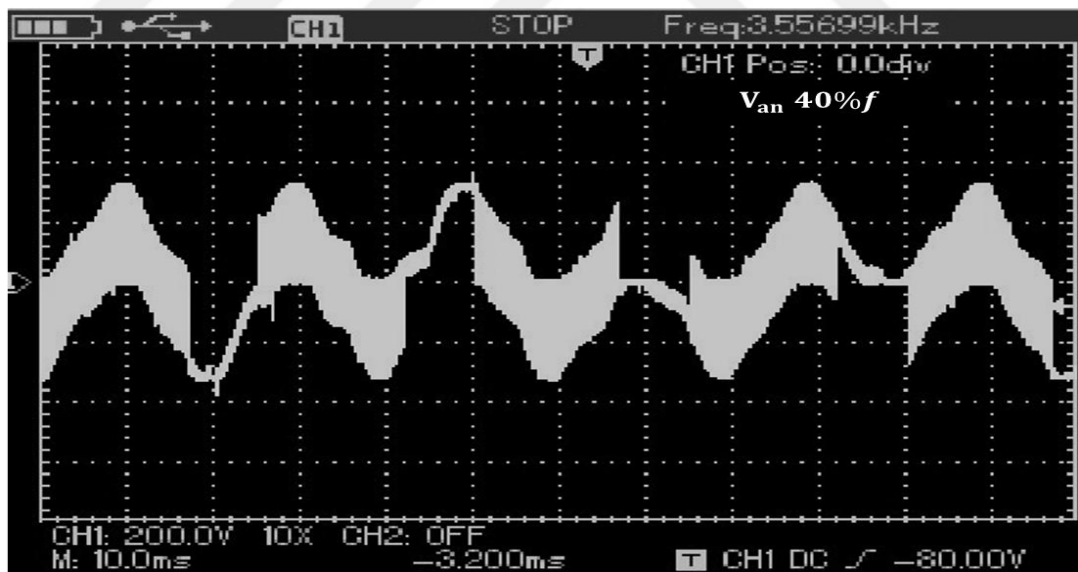


Figure 5.7 Phase voltage of $f_{comn}(\%) = 40\%$ under-no load.

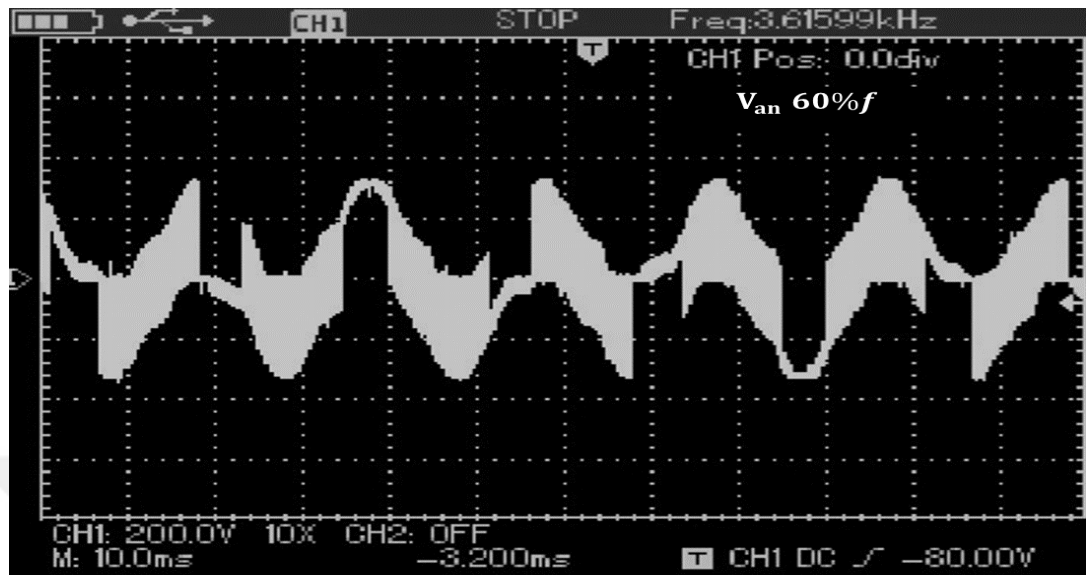


Figure 5.8 Phase voltage of $f_{comn}(\%) = 60\%$ under-no load.

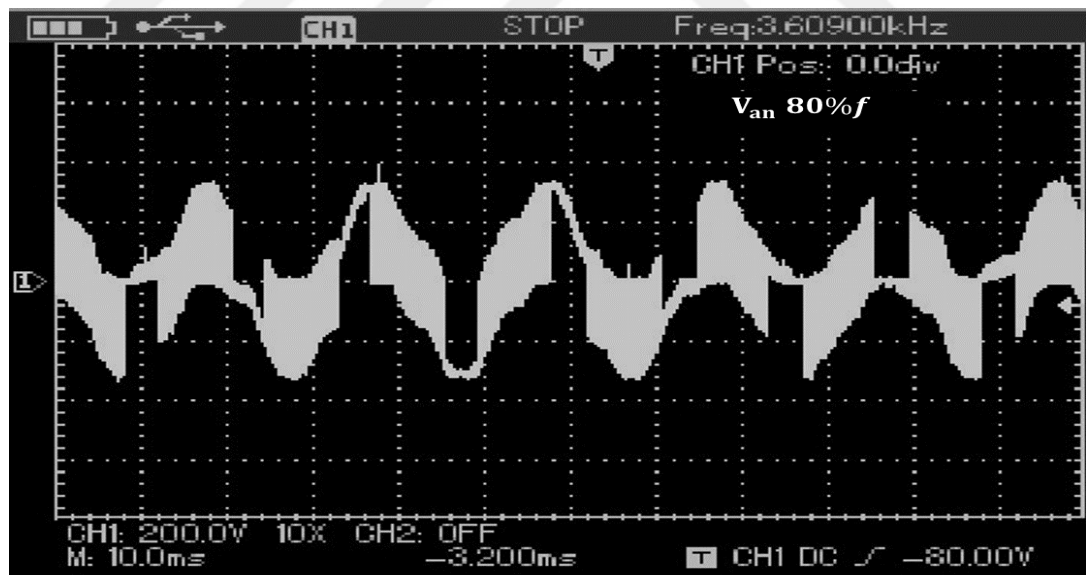


Figure 5.9 Phase voltage of $f_{comn}(\%) = 80\%$ under-no load.

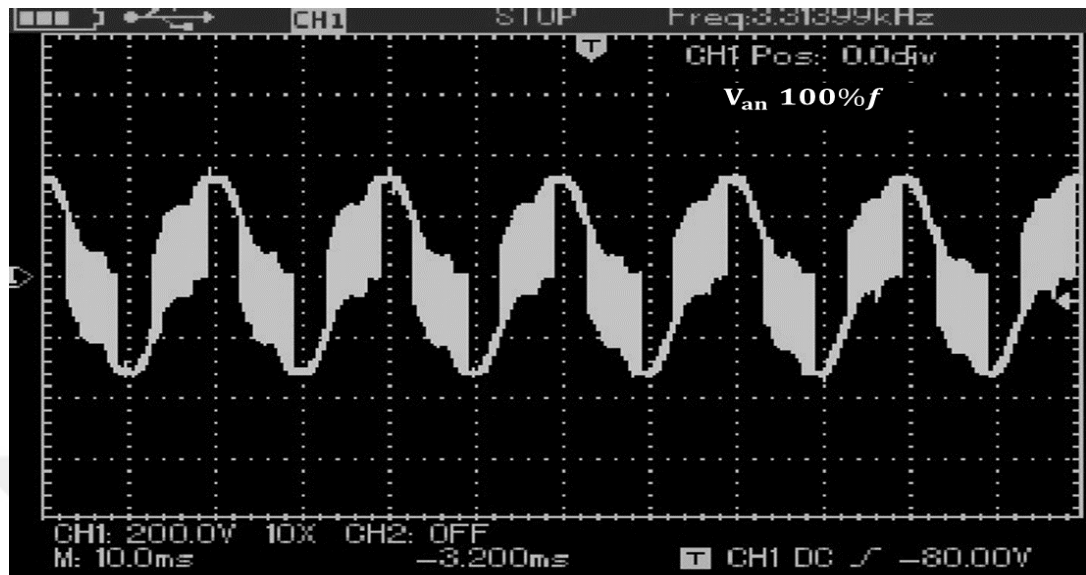


Figure 5.10 Phase voltage of $f_{comn}(\%) = 100\%$ under-no load.

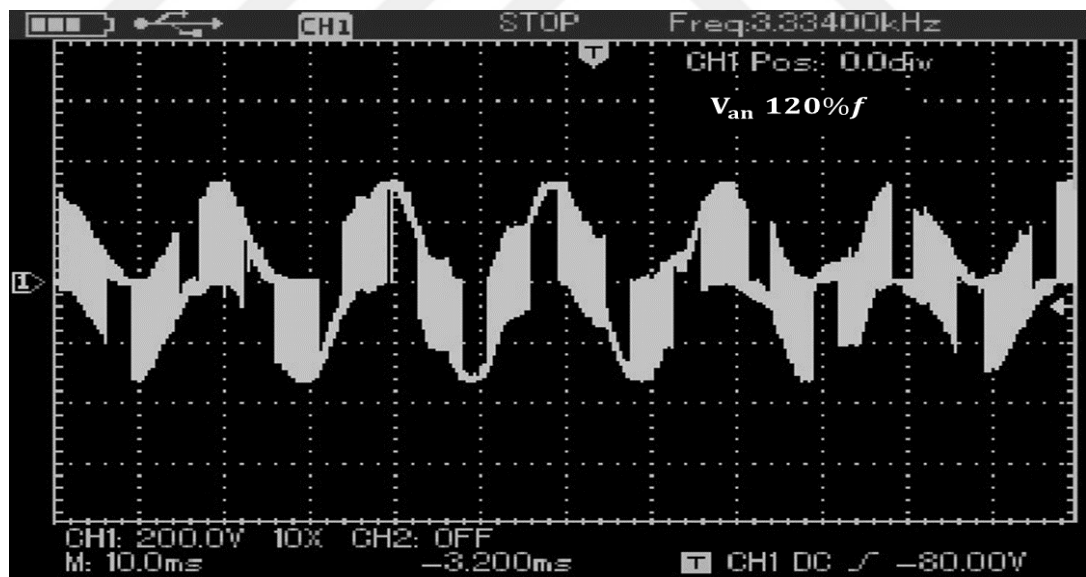


Figure 5.11 Phase voltage of $f_{comn}(\%) = 120\%$ under-no load.

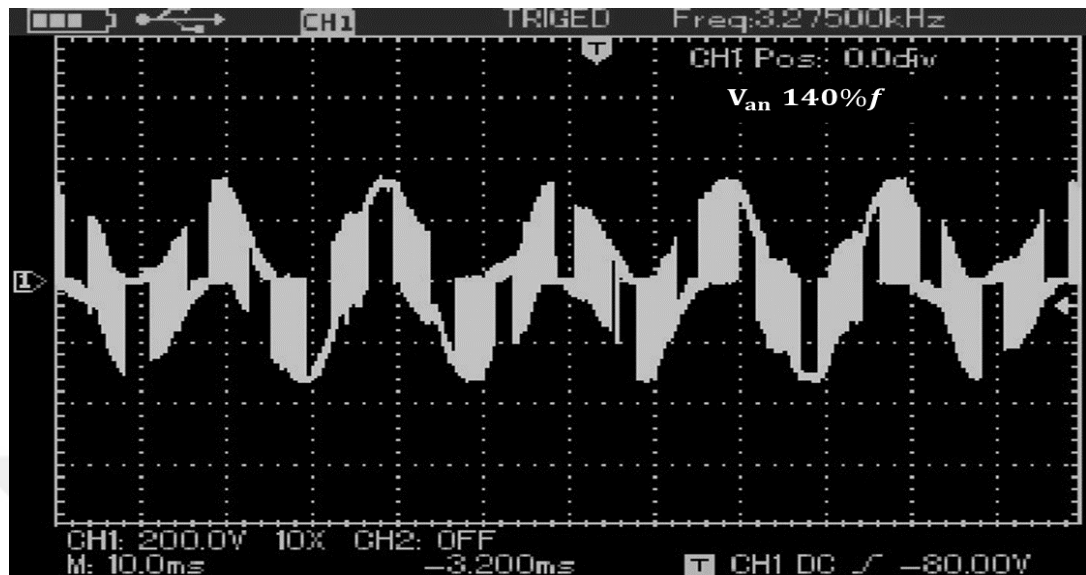


Figure 5.12 Phase voltage of $f_{comn}(\%) = 140\%$ under-no load.

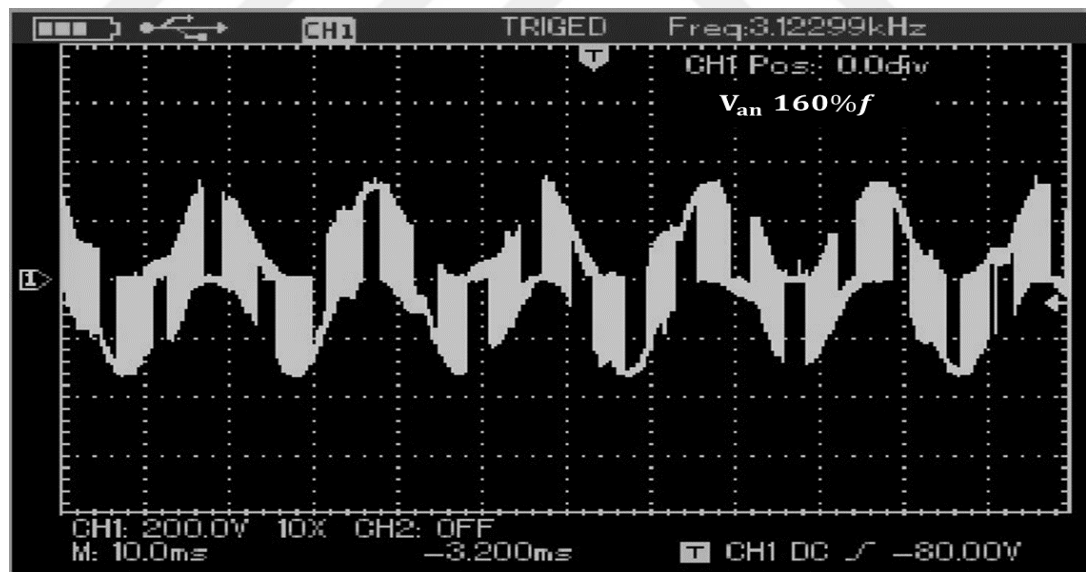


Figure 5.13 Phase voltage of $f_{comn}(\%) = 160\%$ under-no load.

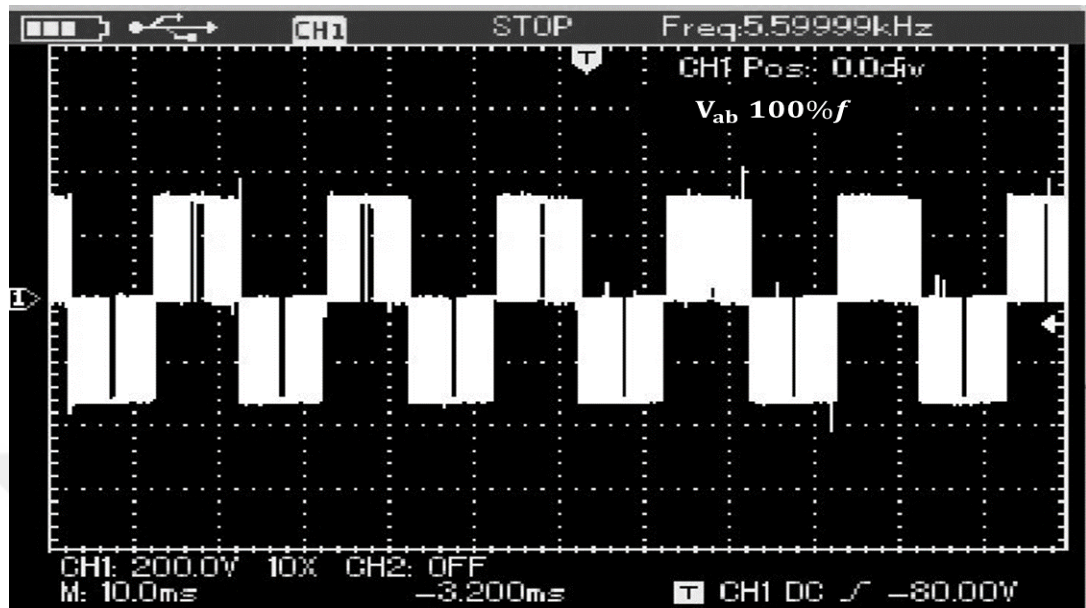
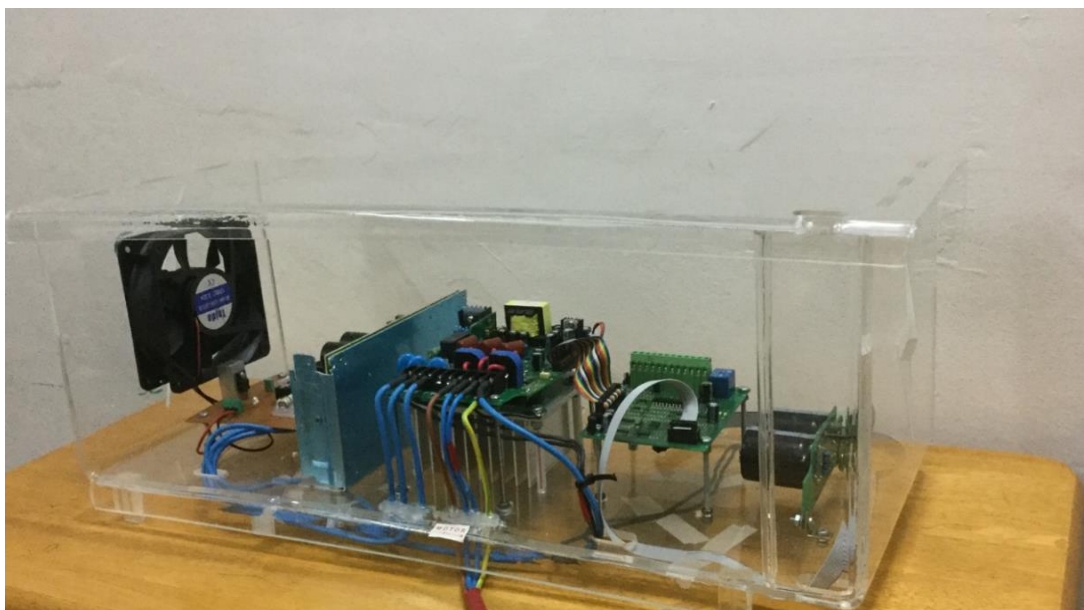
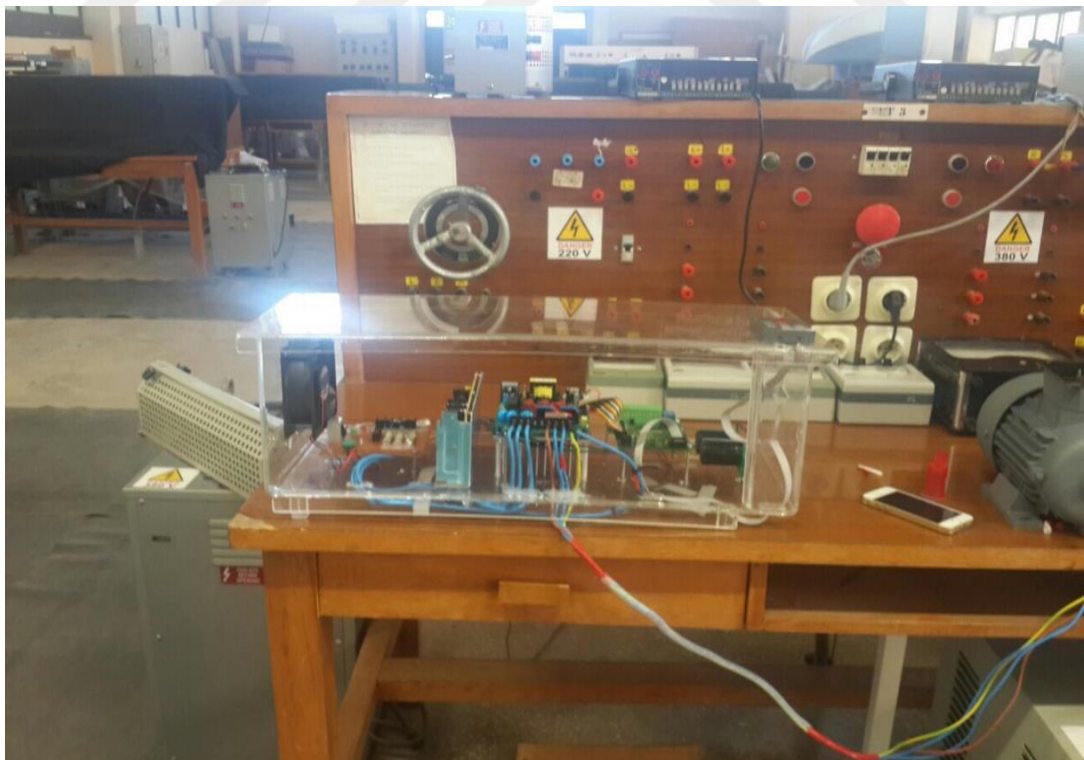
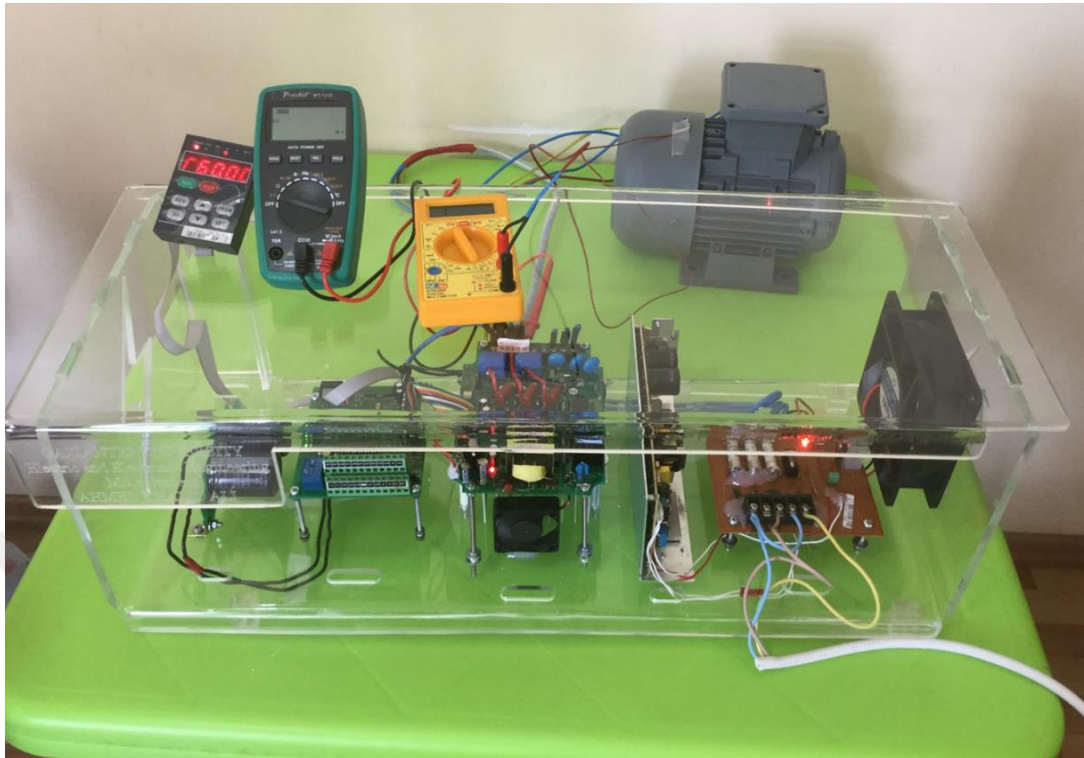


Figure 5.14 Line voltage of $f_{conn}(\%) = 100\%$ under-no load.

The practical experimental tests have excellent performance parameters with respect to the theoretical results, and it can be seen clearly in the, phase voltage waveforms. The minimum value of overshoot appears in the higher value of frequency ratio (i.e. 80% of rated) the line voltage at (100%) of rated frequency is a square waveform under no- load condition, because the mechanical load effectively as same as an L-C filter.





Pictures of SPWM drive system and workbench

5.5 Comparison between simulation and experimental results.

5.5.1 Phase voltage &Speed comparison:

The comparison between, simulation and experimental in the same PWM inverter type Table 5.2 and Figure 5.15 show the difference between the simulation and experimental results for the SPWM inverter at no load condition:

Table 5.2 Comparison between simulation and experiment results.

PWM	SPWM(Simulation)		SPWM(Experiment)	
$f_{comn}(\%)$	$N_r(r. p. m)$	$V_{phase}(V)$	$N_r(r. p. m)$	$V_{phase}(V)$
20	294	100	284	104.6
40	584	138	568	147.55
60	870	171	852	190
80	1147	196	1136	210.59
100	1418	220	1423	225.67
120	1698	220	1704	226.8
140	1910	220	1988	226.78
160	2075	220	2270	226.83

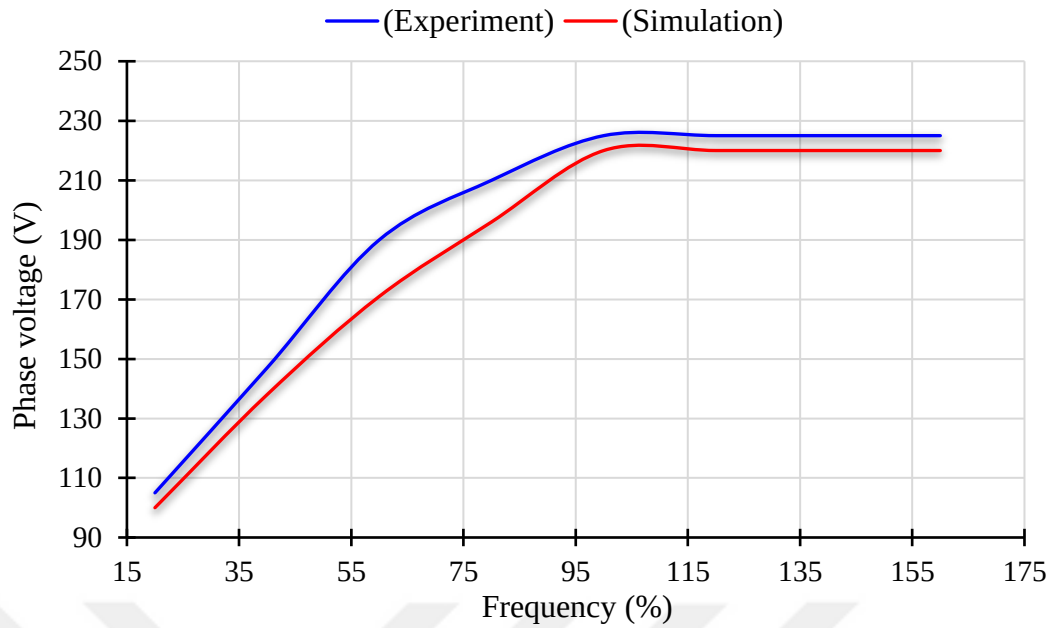


Figure 5.15 Comparison between simulation and experiment results.

By examining the above results the following notices can be recorded:

- The practical experiment has excellent performance parameters with respect to the simulation results, and it can be seen clearly in the Figure. A phase voltage parameter has excellent values with respect to simulation results. The value of RMS phase voltage is very smaller than that of the simulation.
- The motor speed (N_r) of different frequency steps ratio are approximately equals. Which gives a wide range at constant electromagnetic torque region, because the torque is approximately directly proportional to the square stator voltage.
- Practically, the speed in the region above the rated frequency, is greater than the simulation speed components that is because of the effect of the moment of inertia on rotor speed.

CHAPTER 6

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

6.1 Conclusion.

The object of this study is to simulate design and discuss, a three popular PWM inverter (SPWM, THIPWM, SVPWM) based open loop (Volt/Hertz) controller, to control the speed of three phase induction motor. The thesis focuses on the linear modulation region, for all three PWM techniques. The system is designed and analyzed by Simulink software environment. The results of the simulation of (PWM inverter based on open loop Volt/Hertz controller) system are compared with respect to the speed and torque response, total harmonic distortion, and inverter parameters when changing the frequency. The simulation models for all three PWM techniques (SPWM, THIPWM, SVPWM), and open loop (Volt/Hertz) controller, has been presented step by step model development is reported. A Sim-power system in simulation computer program has been extremely helpful in reducing the data preparation time. The simulation method has been found to be simple and flexible. The developed model enables the researcher and designer to change any parameter of the drive system in the software, which can provide convenience for future analysis and design. Finally A simple, practical design model of SPWM inverter is presented. This practical model is completely implemented with exact results. Due to simulation and experimental results the following general notes are concluded:

1. This thesis provided a review to each one of the PWM techniques in the under-modulation region and investigation of the advantages and drawbacks of each PWM technique, by comparing and plotting the output inverter parameters. As seen from the simulation results, SVPWM based on open loop (Volt/Hertz) drive treats the inverter as a single unit with eight possible switching states. Each state can be represented by a state vector in the two-axis space, the eight state vectors formed a hexagon shape with six sectors. The modulation procedure is accomplished by switching the state vectors in

Each sector by appropriate time intervals which are calculated in a certain sampling time (T_s).

2. The linear region in SVPWM is larger than the DC bus voltage of other types of PWM technique, where the modulation index approaches to (90.7%) and the maximum output fundamental is ($0.577V_{DC}$). Whereas, in the SPWM the maximum linear modulation index is (78.54%) and the maximum output fundamental is ($0.5V_{dc}$).which is for the same DC bus voltage a SVPWM allow better utilization of the DC power supply .There are several types of switching pattern schemes, the symmetrical switching pattern gives minimal output harmonics.
3. The SPWM is simple and easier modulation scheme. It is possible to be used in single or three phase inverters
4. The THIPWM strategy is by adding a third harmonic component to the three reference sinusoidal waves, it allows a better utilization of the DC-link. which makes the performance of inverter equal to SVPWM technique
5. The Harmonic analysis of different output voltage and current, with respect to frequency ratio. In SVPWM simulation, gives excellent harmonic reduction and harmonic parameters with respect to THIPWM and SPWM
6. The Harmonic analysis of the motor current in load and no-load operation shows that, the SVPWM and THIPWM have a superior performance compared to SPWM under load condition the waveform current is very close to a sine wave and the three phase voltage is pure sinusoidal after adding second order low pass –filter, also in SPWM the total harmonic distortion is very small.
7. For all three techniques, the Total losses of low order harmonics can be minimized by increasing the switching frequency, but on the other hand it may increase the switching losses. Therefore, switching frequency must be selected to get minimum total harmonic and switching losses. According to simulation results the SVPWM can be considered as the best and the optimum of all PWM technique.
8. The results of the speed response of the (Volt/Hertz) simulation system after steady state error are faster with no overshoot for different speeds, without tuning.

9. The (Volt/Hertz) system is more robust system when applying a constant load to the motor. However, these control techniques are very suitable for real time implementation due to their simplicity, robustness and ease of tuning.
10. According to the experimental results of the SPWM inverter which used variable-speed induction motor operation, the SPWM technique gives acceptable performance with low disturbance and overshoot in voltage waveform. From the above conclusion and due to simulation and experimental results, the SPWM inverter can be considered as the best and the optimum a variable-speed drive in applications with constant load such as fan, pump ie.

6.2 Suggestions of future work.

The work presented in this thesis may have several additional works to be continued in the future to improve the drive performance or to give it additional features as stated below:

- 1- Analysis of the three PWM technique with low modulation index (0.1 -0.4) and different loads.
- 2- Designing three-phase (LC) filter to improve the harmonic contents of the inverter output parameter voltage, current.
- 3- Try to improve the linear under-modulation region.
- 4- Increasing the voltage/frequency variation range in the practical model.
- 5- Using IGBTs Power Bridge Instead Of MOSFETs Power Bridge and investigating the difference between them.
- 6- Try to reduce the dead time interval and investigate its effect on harmonic contents.

Implementing the system using either DSP TMS processor or state-of-the-art FPGA

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APPENDIXES

APPENDIX A

Open loop Volt/hertz controller:

The (Volt/Hertz) controller in Figure **A.1** has one input, reference (or command) frequency “ f_r^* ” and three outputs (V_a^* , V_b^* , and V_c^*) S-function code

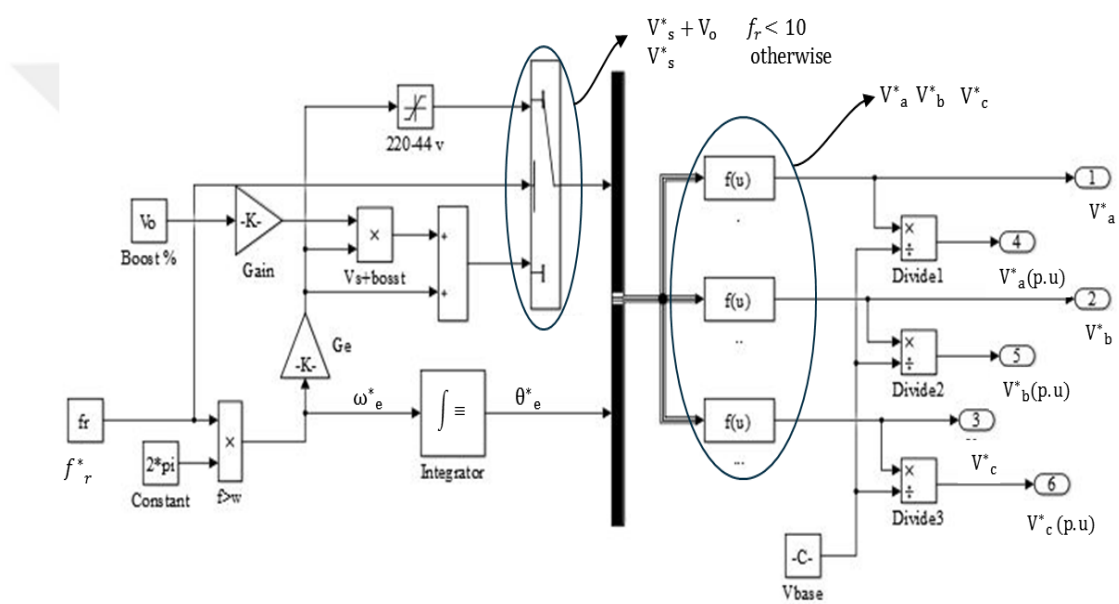


Figure A.1

$$V_a^* = u[1] * \sin(u[2])$$

$$V_b^* = u[1] * \sin(u[2] - 2 * \pi / 3)$$

$$V_c^* = u[1] * \sin(u[2] + 2 * \pi / 3)$$

Why using discrete integral? The discrete integral operates at fixed steps, which makes the program able to calculate all variables in the same time of each step. Whereas, the continuous integral calculates the variables at random steps. Also to set θ_e^* “at fix steps in each sector and sub-sector.

Sinusoidal Pulse Width Modulation SPWM:

Triangular "ramp function" option and triangular wave generator blocks setting are shown in figure A.2 .Where f_s : refer to the carrier frequency

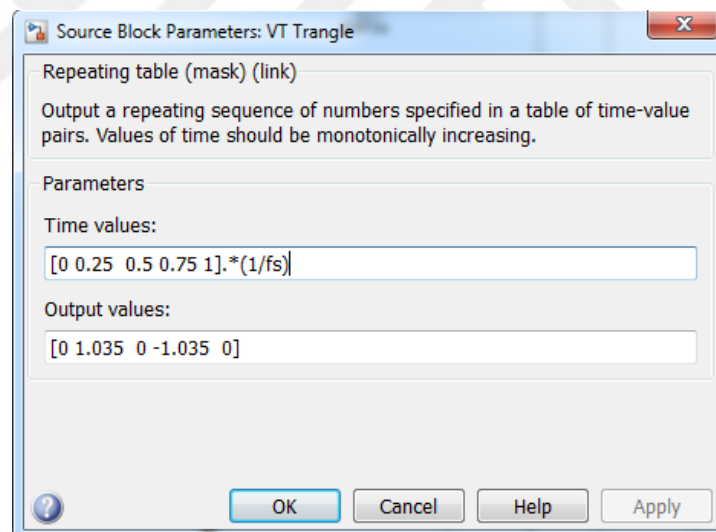
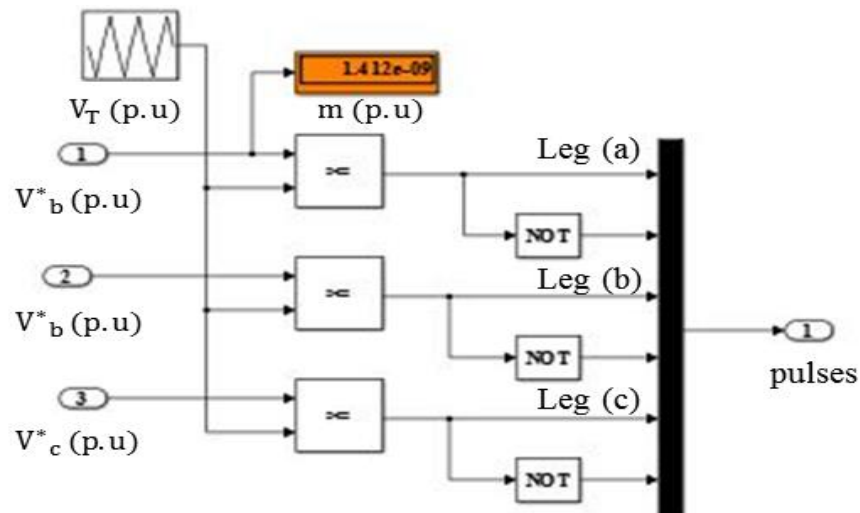


Figure A.2

Third Harmonic Injection Pulse Width Modulation (THIPWM):

The same SPWM but the three reference voltage signals (V_a^* , V_b^* , and V_c^*), are obtained by;

$$\begin{bmatrix} V_{\text{mod}(a)} \\ V_{\text{mod}(b)} \\ V_{\text{mod}(c)} \end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix} \sin(\omega t) & \frac{\sin(3\omega t)}{6} \\ \sin\left(\omega t + \frac{2\pi}{3}\right) & \frac{\sin(3\omega t)}{6} \\ \sin\left(\omega t - \frac{2\pi}{3}\right) & \frac{\sin(3\omega t)}{6} \end{bmatrix}$$

Space Vector Pulse Width Modulation (SVPWM):

1 Space Vector voltage Calculation and vector Location

A Simulink block diagram in the figure A.3 shown to generate this parameter

$V_\psi, V_\beta, \theta, \vec{V}_{\text{ref}}$

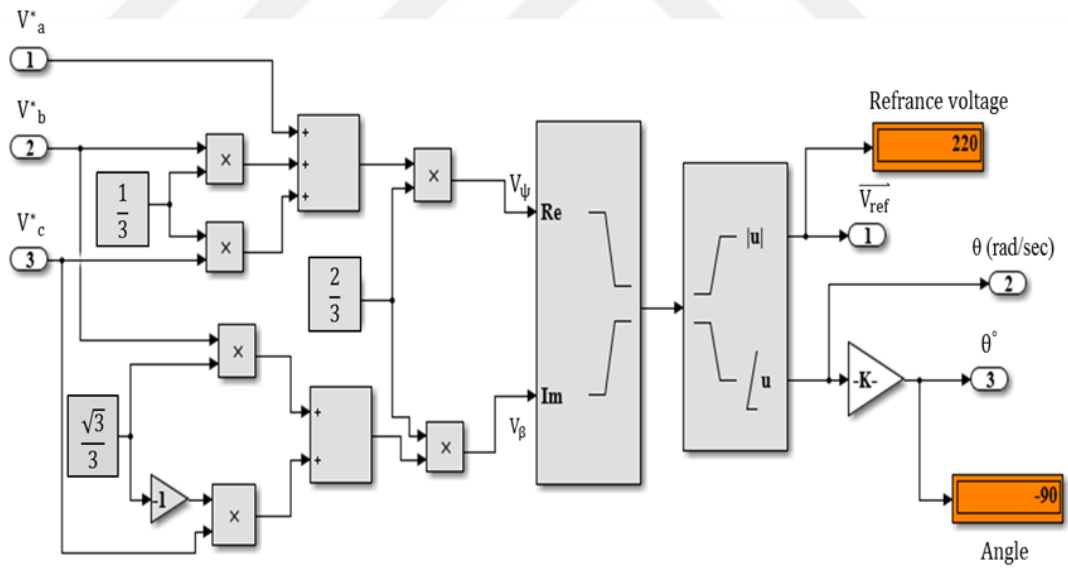


Figure A.3

$$V_{\psi} = V_{an} - \frac{1}{2} V_{bn} - \frac{1}{2} V_{cn}$$

$$V_{\beta} = V_{an} + \frac{\sqrt{3}}{2} V_{bn} - \frac{\sqrt{3}}{2} V_{cn}$$

$$|\vec{V}_{ref}| = \sqrt{V_{\psi}^2 + V_{\beta}^2}$$

2. Time Interval Calculation: S-function code see calculate the time periods“ T_a , T_b , T_o ,”

$$M_i = \sqrt{3} \frac{|\vec{V}_{ref}|}{V_{DC}}$$

$$M_i.T_z = \text{sqrt}(3)*u(3)*u(1)/u(2)$$

$$T_a = u(1)*(\sin((u(3)*\pi/3)-(u(2))))$$

$$T_b = u(1)*(\sin((u(2))-((u(3)-1)*\pi/3)))$$

$$T_o = 0.5(T_a - T_b)$$

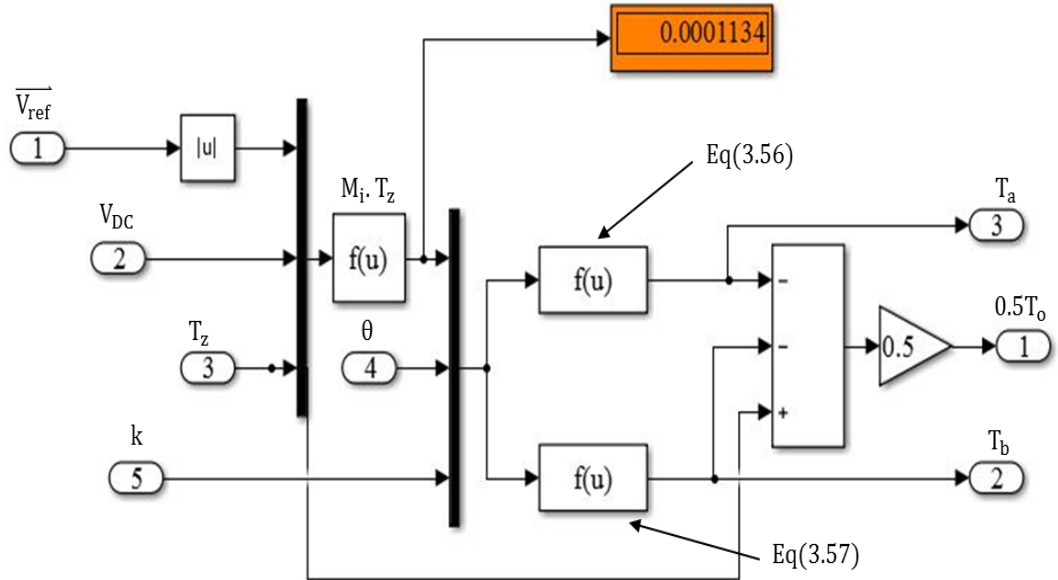


Figure A.4

3. Switching time pattern of each transistor: The S-function code to calculate “ $Q_1, Q_3, Q_5,$ ” & PWM as shown in figure A.5

$$Q_1 = (u[4] == 1) * (u[1] + u[2] + u[3]) + (u[4] == 2) * (u[1] + u[3]) + (u[4] == 3) * (u[1]) + (u[4] == 4) * (u[1]) + (u[4] == 5) * (u[1] + u[2]) + (u[4] == 6) * (u[1] + u[2] + u[3]).$$

$$Q_3 = (u[4] == 6) * (u[1]) + (u[4] == 1) * (u[1] + u[2]) + (u[4] == 2) * (u[1] + u[2] + u[3]) + (u[4] == 3) * (u[1] + u[2] + u[3]) + (u[4] == 4) * (u[1] + u[3]) + (u[4] == 5) * (u[1]).$$

$$Q_5 = (u[4] == 6) * (u[1] + u[3]) + (u[4] == 1) * (u[1]) + (u[4] == 2) * (u[1]) + (u[4] == 3) * (u[1] + u[2]) + (u[4] == 4) * (u[1] + u[2] + u[3]) + (u[4] == 5) * (u[1] + u[2] + u[3]).$$

PWM: Ramping sequence option as shown in figure A.6

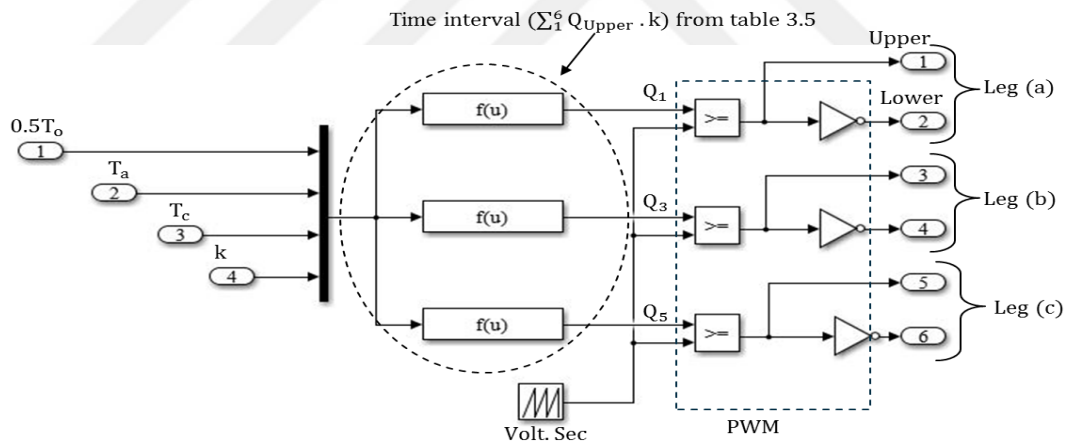


Figure A.5

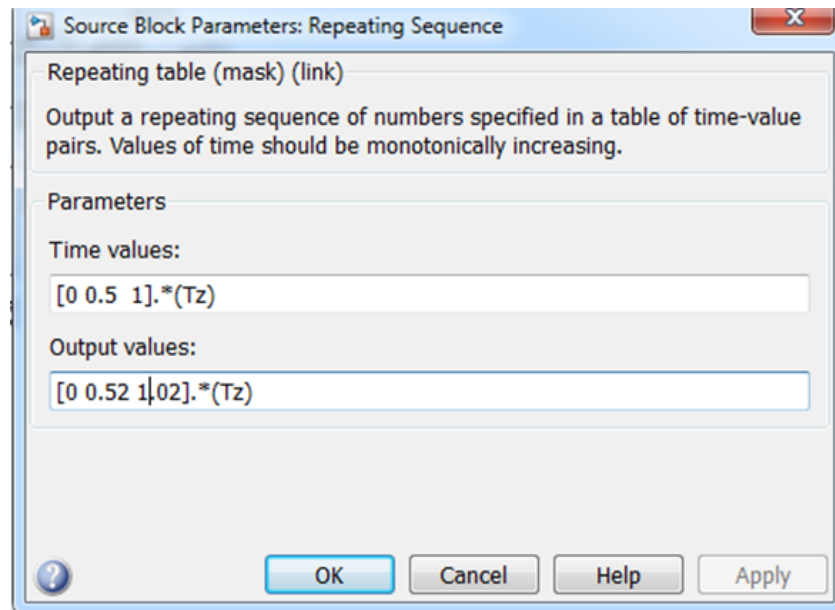


Figure A.6

Induction motor model: assume efficiency; 79%

$$\ell_T = K (\omega_m)^2 0.2$$

Fixed losses = (K)*u²

Measurements output parameter model:

The sub-system block of simulation software environment. Measurement three phase voltage of “VSI “ [1,2]

$$V_{an} = \frac{1}{3}(V_{ab} - V_{ca})$$

$$V_{bn} = \frac{1}{3}(-V_{ab} + V_{bc})$$

$$V_{cn} = \frac{1}{3}(-V_{bc} + V_{ca})$$

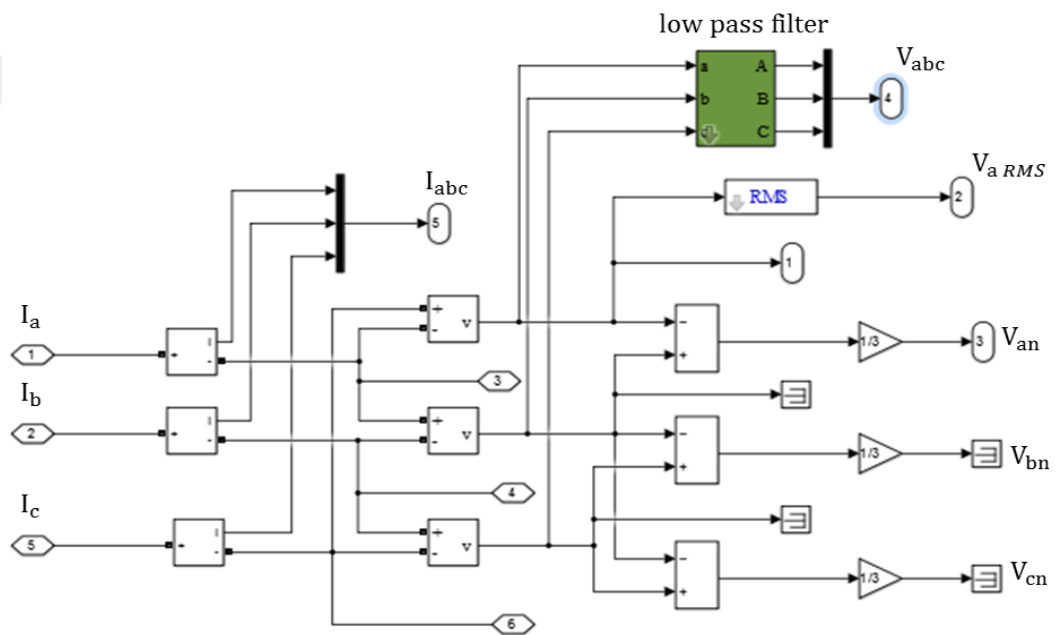
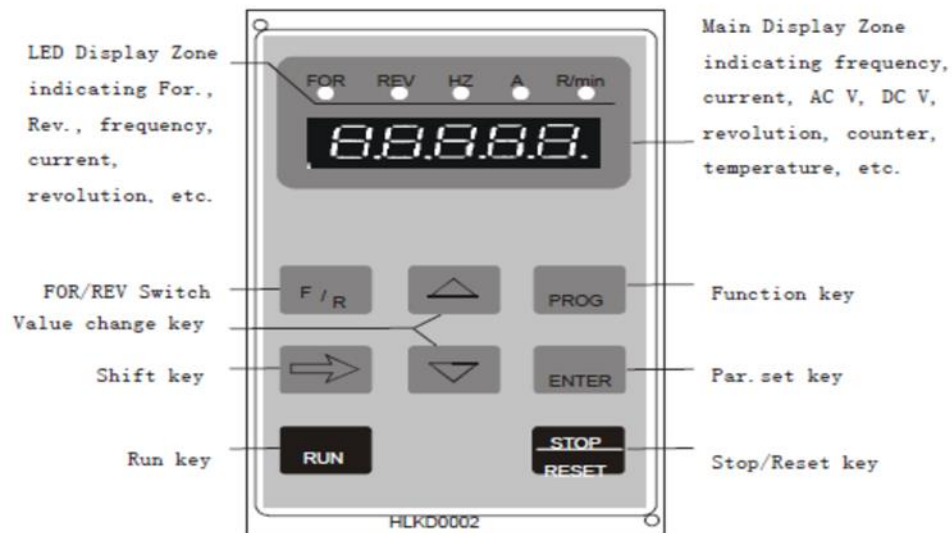


Figure A.8

APPENDIX B

HY-HY02D223B Keypad:



General specifications of HY-inverter:

Inverter Series		HY-A
Control Mode		SPWM
Input Power		330~440V for 380V power; 170~240 for 220V power
5-Digits Display & Status Indicator Lamp		Displaying frequency, current, revolution, voltage, counter, temperature, forward or reserve running, and fault, etc.
Communication Control		RS-485
Operation Temperature		-10~40℃
Humidity		0-95% Relative Humidity (without dew)
Vibration		Below 0.5G
Frequency Control	Range	0.10~400.00Hz
	Accuracy	Digital: 0.01% (-10~40℃), Analog: 0.1% (25±10℃)
	Setting Resolution	Digital: 0.01Hz, Analog: 1% of Max. Operating Frequency
	Output Resolution	0.01Hz
	Operator Setting Method	Press directly $\square$ $\triangle$ ∇ to set.
	Analog Setting Method	External Voltage 0-5V, 0-10V, 4-20mA, 0-20mA.
	Other Functions	Frequency lower limit, starting frequency, stopping frequency, three skip frequencies can be respectively set.
General Control	Ramp Control	Selectable 4-speed steps ramp-up and -down time (0.1-6500s).
	V/F Curve	Set V/F curve at will

Carrier frequency setting:

PD041	Carrier Frequency	(Note: 0—15 corresponds to 0—20K Hz)		
	Set Range: 0—15	Unit: 1	Factory Setting: 5	

The carrier frequency has some relation with the electromagnetic noise of the motor, and meanwhile the level of the carrier frequency has certain relation with the heating capacity of the inverter and the interference to the environment. See the following table:

Carrier Frequency	Electromagnetic Noise	Heating Capacity	Interference to the Environment
Low ↓ High	High ↓ Low	Small ↓ Large	Little ↓ Great

Carrier Frequency Corresponding Table

Set Value	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Carrier Frequency KHz	0.7	1	1.5	2	3	4	5	7	8	9	10	11	13	15	17	20

As shown in the table above, the higher the carrier is, the lower the electromagnetic noise of the motor will be, but the stronger its interference to other systems will be and the greater the heating capacity of the inverter will have. Under higher ambient temperature and heavier load of the motor the carrier frequency should be decreased properly to improve the heat characteristics of the inverter.

The factory setting of carrier frequency is depending on the model. For specific data refer to the table in the description of PD007.

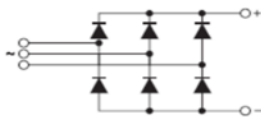
More information see the datasheet [54]

Bridge rectifier Power Modules:

Three Phase Bridge
Power Modules



D-34A



FEATURES

- Universal, 3 way terminals: push-on, wrap around or solder
- High thermal conductivity package, electrically insulated case
- Center hole fixing
- Excellent power/volume ratio
- UL E300359 approved 
- Gold plated terminals solderable using lead (Pb)-free solder; solder alloy Sn/Ag/Cu (SAC305); solder temperature 260 to 275 °C
- RoHS compliant
- Designed and qualified for industrial and consumer level



DESCRIPTION

A range of extremely compact, encapsulated three phase bridge rectifiers offering efficient and reliable operation. They are intended for use in general purpose and instrumentation applications.

MAJOR RATINGS AND CHARACTERISTICS				
PARAMETER		26MT	36MT	UNITS
I_O		25	35	A
	at T_C	70	60	°C
I_{RSM}	at 50 Hz	360	475	A
	at 60 Hz	375	500	
i^2t	at 50 Hz	635	1130	A ² s
	at 60 Hz	580	1030	
V_{RRM}		100 to 1600		V
T_J		- 55 to 150		°C

ELECTRICAL SPECIFICATIONS

VOLTAGE RATINGS				
TYPE NUMBER	VOLTAGE CODE	V_{RRM} , MAXIMUM REPETITIVE PEAK REVERSE VOLTAGE V	V_{RSM} , MAXIMUM NON-REPETITIVE PEAK REVERSE VOLTAGE V	I_{RRM} MAXIMUM AT T_J MAXIMUM mA
26MT../36MT..	10	100	150	2
	20	200	275	
	40	400	500	
	60	600	725	
	80	800	900	
	100	1000	1100	
	120	1200	1300	
	140	1400	1500	
	160	1600	1700	

See in the datasheet:[52]

(FGA25N120A) IGBT:



November 2013

FGA25N120ANTD 1200 V, 25 A NPT Trench IGBT

Features

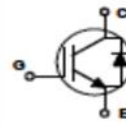
- NPT Trench Technology, Positive Temperature Coefficient
- Low Saturation Voltage: $V_{CE(sat)}$, typ = 2.0 V
@ $I_C = 25$ A and $T_C = 25^\circ\text{C}$
- Low Switching Loss: E_{sw} , typ = 0.96 mJ
@ $I_C = 25$ A and $T_C = 25^\circ\text{C}$
- Extremely Enhanced Avalanche Capability

Description

Using Fairchild's proprietary trench design and advanced NPT technology, the 1200V NPT IGBT offers superior conduction and switching performances, high avalanche ruggedness and easy parallel operation. This device is well suited for the resonant or soft switching application such as induction heating, microwave oven.

Applications

- Induction Heating, Microwave Oven



Absolute Maximum Ratings

Symbol	Description		Ratings	Unit
V _{CES}	Collector-Emitter Voltage		1200	V
V _{GES}	Gate-Emitter Voltage		± 20	V
I _C	Collector Current	④ T _C = 25°C	50	A
	Collector Current	④ T _C = 100°C	25	A
I _{CM (1)}	Pulsed Collector Current		90	A
I _F	Diode Continuous Forward Current	④ T _C = 25°C	50	A
	Diode Continuous Forward Current	④ T _C = 100°C	25	A
I _{FM}	Diode Maximum Forward Current		150	A
P _D	Maximum Power Dissipation	④ T _C = 25°C	312	W
	Maximum Power Dissipation	④ T _C = 100°C	125	W
T _J	Operating Junction Temperature		-55 to +150	°C
T _{stg}	Storage Temperature Range		-55 to +150	°C
T _L	Maximum Lead Temp. for soldering Purposes, 1/8" from case for 5 seconds		300	°C

Notes:

(1) Repetitive rating; Pulse width limited by max. junction temperature

Thermal Characteristics

Symbol	Parameter	Typ.	Max.	Unit
$R_{\theta JC}(\text{IGBT})$	Thermal Resistance, Junction-to-Case	—	0.4	$^\circ\text{C/W}$
$R_{\theta JC}(\text{DIODE})$	Thermal Resistance, Junction-to-Case	—	2.0	$^\circ\text{C/W}$
$R_{\theta JA}$	Thermal Resistance, Junction-to-Ambient	—	40	$^\circ\text{C/W}$

TLP351 photo coupler:

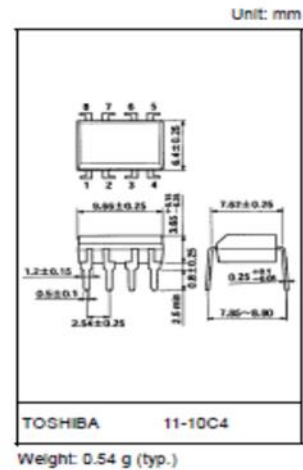
TOSHIBA Photocoupler GaAs IRED + Photo IC

TLP351

Inverter for Air Conditioner
IGBT/Power MOS FET Gate Drive
Industrial Inverter

The TOSHIBA TLP351 consists of a GaAs light emitting diode and a integrated photodetector.
This unit is 8-lead DIP package.
TLP351 is suitable for gate driving circuit of IGBT or power MOS FET.
Especially TLP351 is capable of "direct" gate drive of lower Power IGBTs.

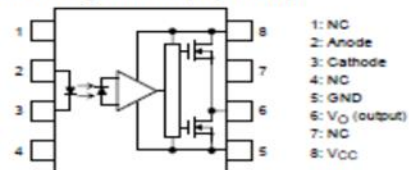
- Peak output current: ± 0.6 A (max)
 - Guaranteed performance over temperature: -40 to 100°C
 - Supply current: 2 mA (max)
 - Power supply voltage: 10 to 30 V
 - Threshold input current: $I_T = 5$ mA (max)
 - Switching time (t_{pLH}/t_{pHL}): 700 ns (max)
 - Common mode transient immunity: 10 kV/ μs
 - Isolation voltage: 3750 Vrms
 - Option(D4)
 - VDE Approved : DIN EN60747-5-2
 - Maximum Operating Insulation Voltage : 890V_{RM}
 - Highest Permissible Over Voltage : 4000V_{RM}
- (Note):When a EN60747-5-2 approved type is needed,
Please designate "Option(D4)"



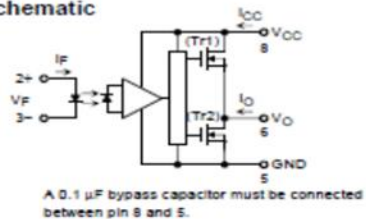
Truth Table

Input	LED	Tr1	Tr2	Output
H	ON	ON	OFF	H
L	OFF	OFF	ON	L

Pin Configuration (top view)

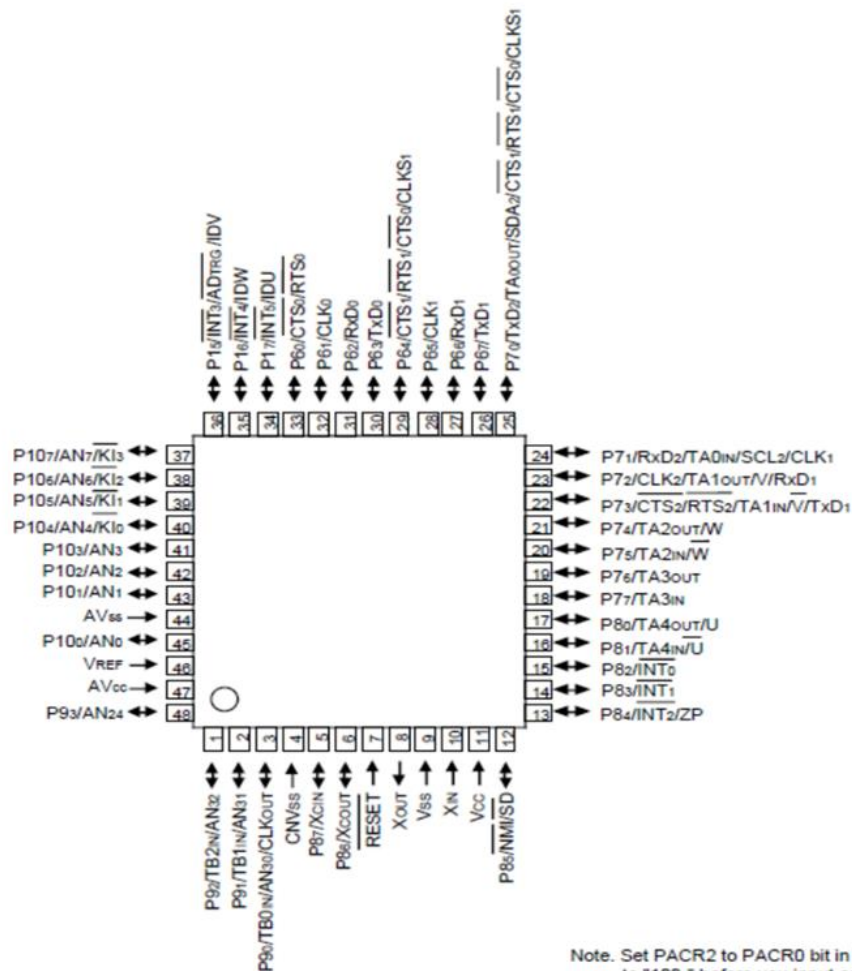


Schematic



For more information and specifications See datasheet:[55]

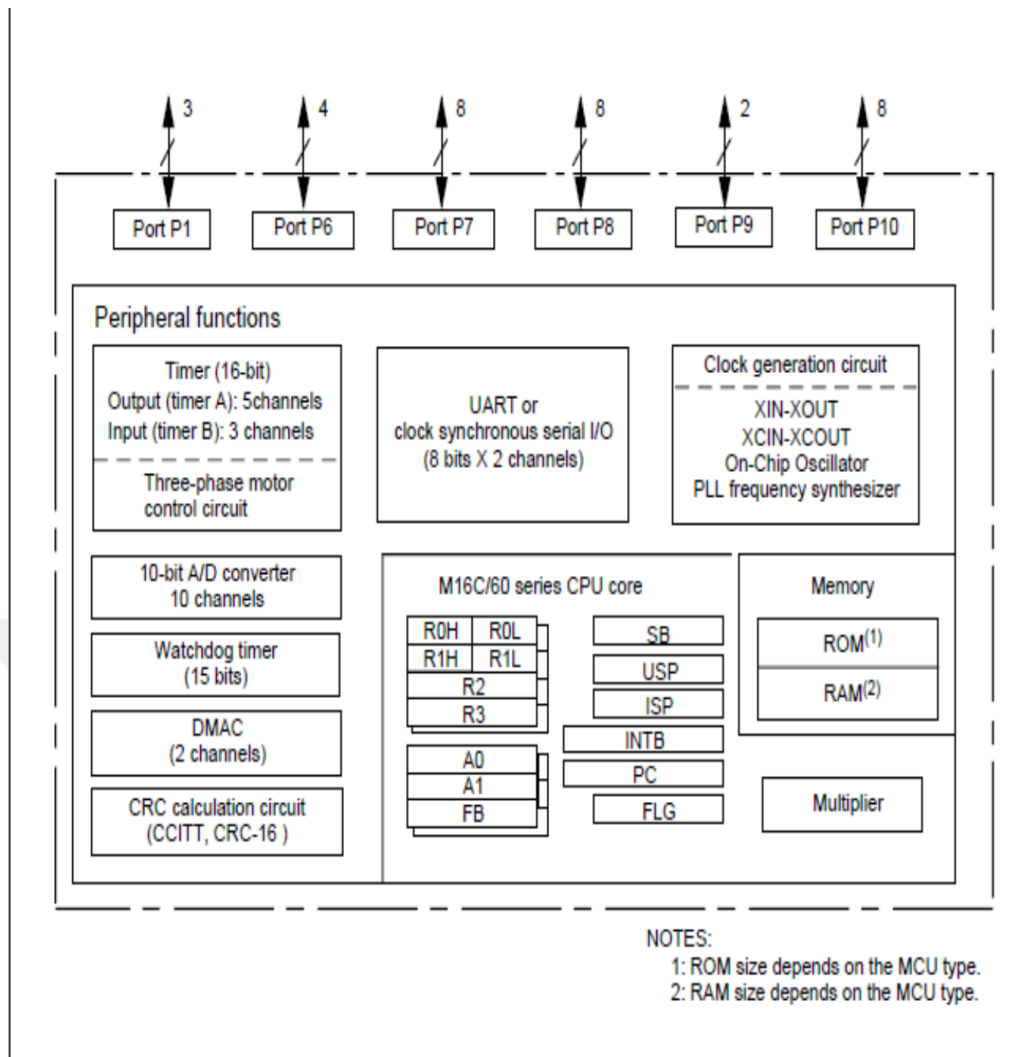
Microprocessor M16C/26A026F8A:



Note. Set PACR2 to PACR0 bit in the PACR register to "100₂" before you input and output it after resetting to each pin. When the PACR register isn't set up, the input and output function of some of the pins are disabled.

Package: PLQP0048KB-A (48P6Q)

Pin Assignment for 48-Pin Package (Top View)



Block Diagram (48-pin Package)

For more information about Microprocessor M16C/26A026F8A [53]

APPENDIX C

System Performance under No Load Conditions:

1. Harmonic order

The Tables C1 (a, b, c) which is refer to voltage Harmonic order, Table C2 (a, b, c) which is referred to current Harmonic order thus results inducts to three PWM techniques SPWM, THIPWM, SVPWM respectively.

$$h_{nth} = \left(\frac{V_{nth}}{V_1} \right) * 100\%$$

Where h_{nth} Harmonic magnitude (%), V_{nth} RMS voltage n^{th} and V_1 fundamental RMS voltage.

Table C1.a Magnitude of 5th, 7th and 11th Harmonics and THD of line voltage waveform for the SPWM inverter technique with different steps of frequency ratio.

Harmonics order	5 th	7 th	11 th	THD (%)
Frequency (Hz)	250	350	550	
$f_{comn}(\%)$	Magnitude (%)	Magnitude (%)	Magnitude (%)	
20	24	9	7.8	26.7
40	12.8	11	5.8	17.8
60	13	9	6.5	17
80	2	1.6	0.8	2.68
100	0.2	0.4	0.5	0.67
120	5	13	3	14
140	7	4	2.7	8.5
160	34	24	12.1	43

Table C1.b Magnitude of 5th, 7th and 11th Harmonics and THD of line voltage waveform for the THIPWM inverter technique with different steps of frequency ratio

Harmonics order	5 th	7 th	11 th	THD (%)
Frequency (Hz)	250	350	550	
$f_{\text{comn}}(\%)$	Magnitude (%)	Magnitude (%)	Magnitude (%)	
20	23.8	14.7	13	30.8
40	14.5	10.6	5	18.6
60	12	8.7	5.9	15.8
80	1.8	1.6	1	2.6
100	0.6	0.65	0.8	1.19
120	6.5	5	2.5	8.5
140	7	3.7	2.6	8
160	33	23.7	15	43

Table C1.c Magnitude of 5th, 7th and 11th Harmonics and THD of line voltage waveform for the SVPWM inverter technique with different steps of frequency ratio.

Harmonics order	5 th	7 th	11 th	THD (%)
Frequency (Hz)	250	350	550	
$f_{\text{comn}}(\%)$	Magnitude (%)	Magnitude (%)	Magnitude (%)	
20	26	10.7	8	29
40	10.7	8.5	5.6	14.7
60	12.1	8.1	5.5	15
80	1.9	2.9	1	3.6
100	0.34	0.2	0.2	0.4
120	5.8	4.9	2.6	8
140	7	5	3.5	9
160	34.7	22.5	13	43

Table C2.a Magnitude of 5th, 7th and 11th Harmonics and THD of motor stator current waveform for the SPWM inverter technique with different steps of frequency ratio.

Harmonics order	5 th	7 th	11 th	THD (%)
Frequency (Hz)	250	350	550	
$f_{comn}(\%)$	Magnitude (%)	Magnitude (%)	Magnitude (%)	
20	20	1.3	3	20
40	17	11.5	7.5	21.7
60	9.9	7	4.7	13
80	5	3.7	2	6.5
100	0.15	0.07	0.16	0.23
120	1.7	1	0.6	2
140	19.7	13.5	8.7	25
160	10.5	3.7	6.5	12.8

Table C2.b Magnitude of 5th, 7th and 11th Harmonics and THD of motor stator current waveform for the THIPWM inverter technique with different steps of frequency ratio.

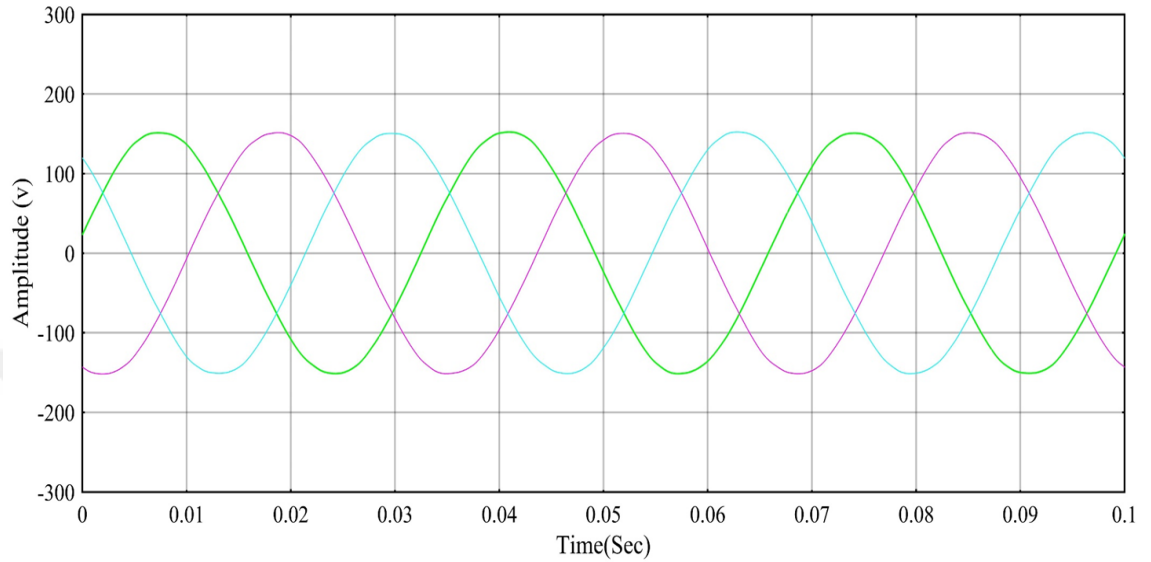
Harmonics order	5 th	7 th	11 th	THD (%)
Frequency (Hz)	250	350	550	
$f_{comn}(\%)$	Magnitude (%)	Magnitude (%)	Magnitude (%)	
20	11	11.5	2.8	16
40	21	12	7.6	25
60	10	7	4	12.84
80	5	3	2.5	6
100	0.35	0.29	0.2	0.49
120	1.8	1	0.5	2.11
140	20	14	7.7	25
160	10.5	6.7	3	12.8

Table C2.c Magnitude of 5th, 7th and 11th Harmonics and THD of motor stator current waveform for the SVPWM inverter technique with different steps of frequency ratio.

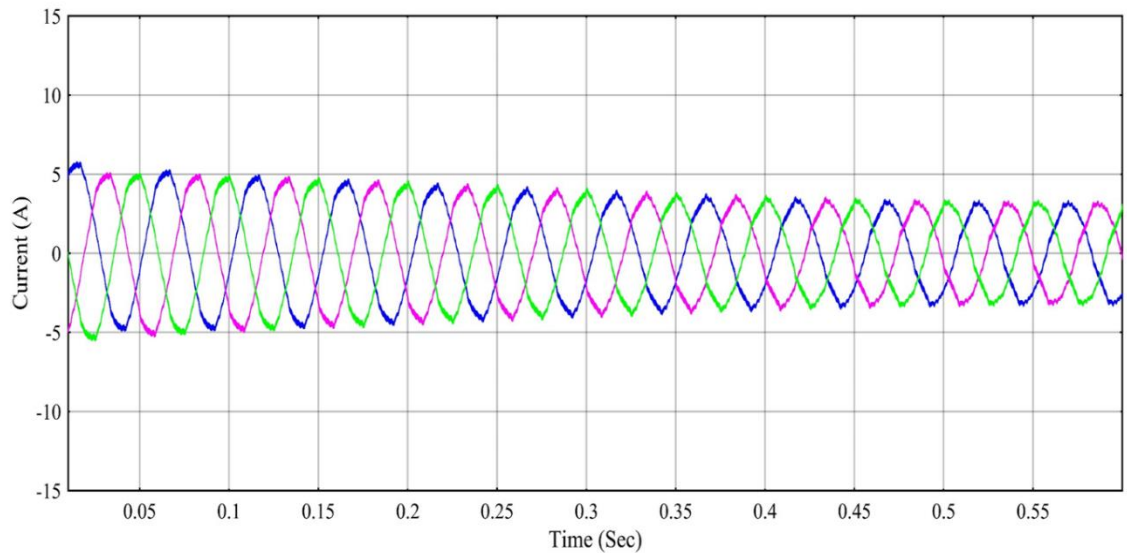
Harmonics order	5 th	7 th	11 th	THD (%)
$f_{\text{Fundamental}}=50\text{Hz}$	250	350	550	
$f_{\text{comn}}(\%)$	Magnitude (%)	Magnitude (%)	Magnitude (%)	
20	13	0.9	2	13
40	16	11	7.5	20.8
60	10	7	4	12.8
80	5	3.5	2	6
100	0.6	0.1	0.04	0.6
120	1.7	1	0.4	2
140	20	14	9	26
160	10.8	6.7	3.6	12.5

2. Performance of (Volt/Hertz) controller and PWM inverter

The three phase voltage after (2nd low pass filter) and current for steps of the frequency ratio (60%, 80%, 120%, and 160 %) at no-load.

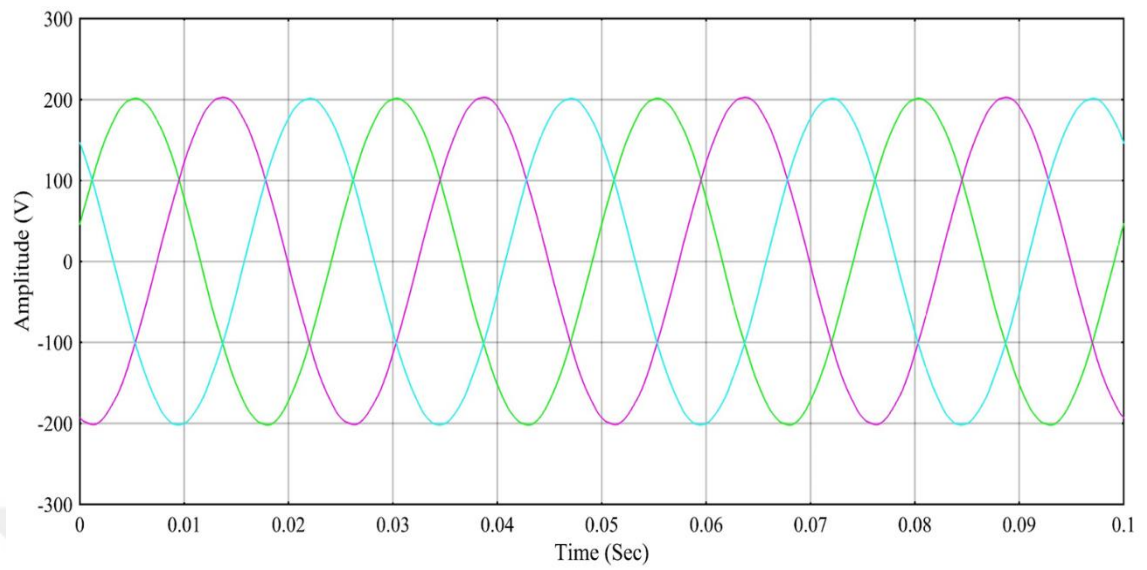


a. Three Phase voltage after second order low-pass filter.

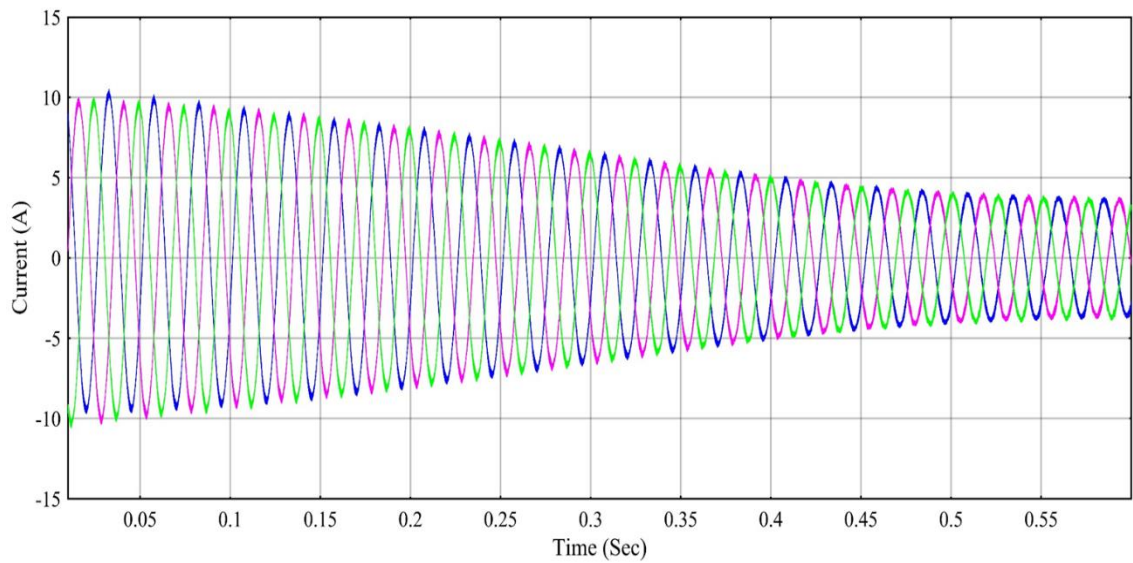


b. Three phase current feeding stator of motor

Figure C.1 Performance parameter (V&I) of SPWM inverter at 60% of rated frequency.

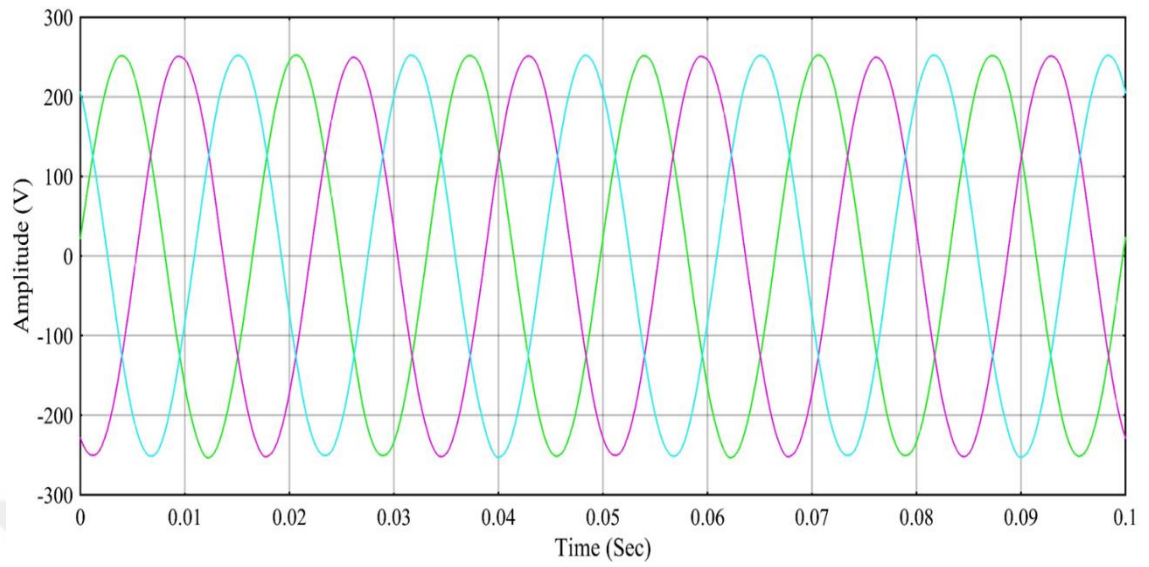


a. Three phase voltage after second order low-pass filter.

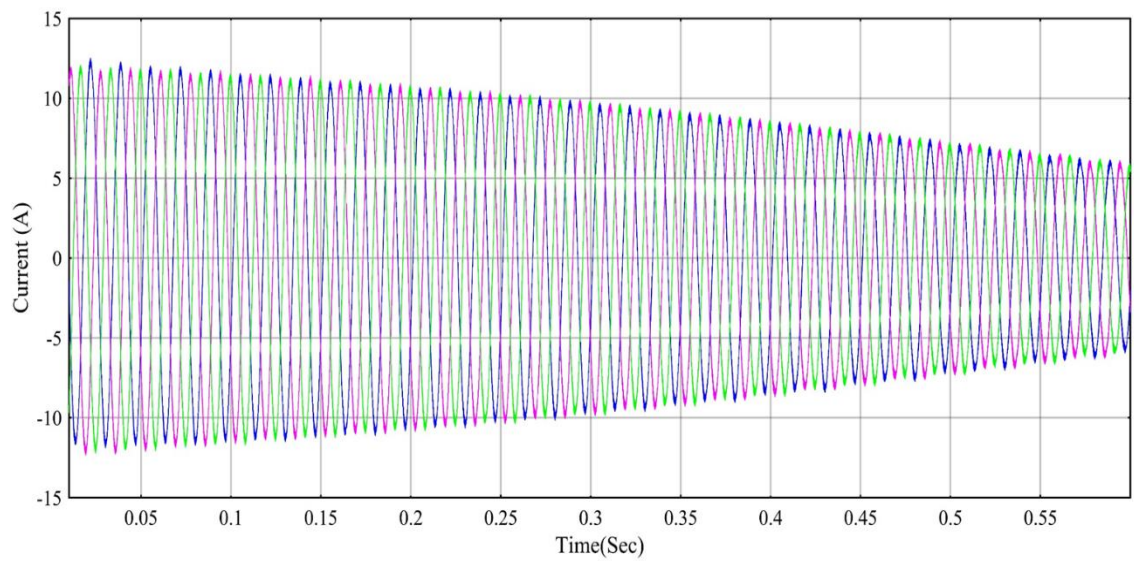


b. Three phase current feeding stator of motor

Figure C.2 Performance parameter (V&I) of SPWM inverter at 80% of rated frequency.

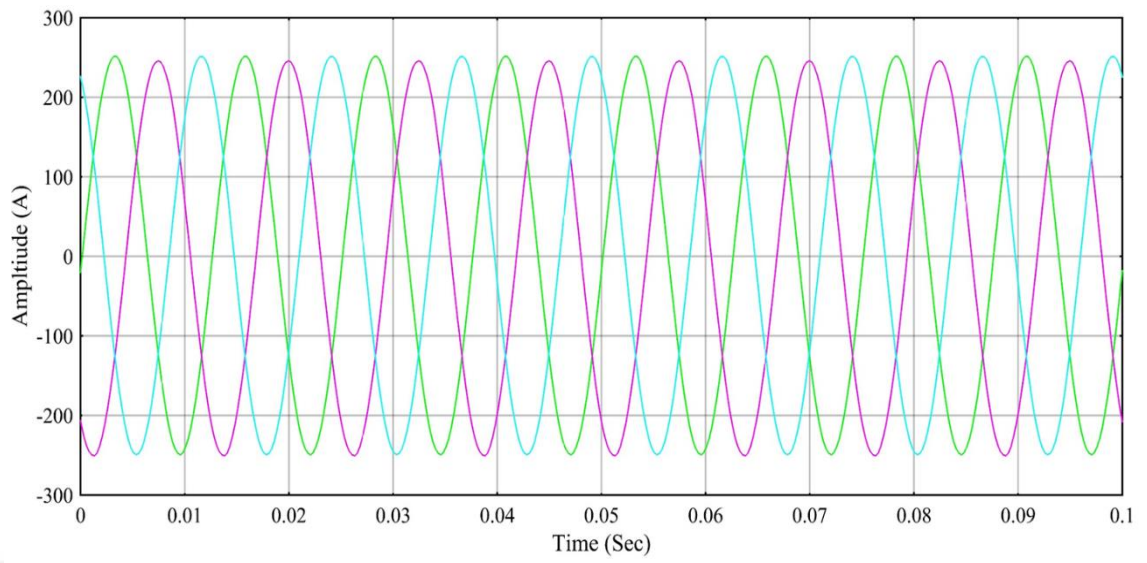


a. Three phase voltage after second order low-pass filter

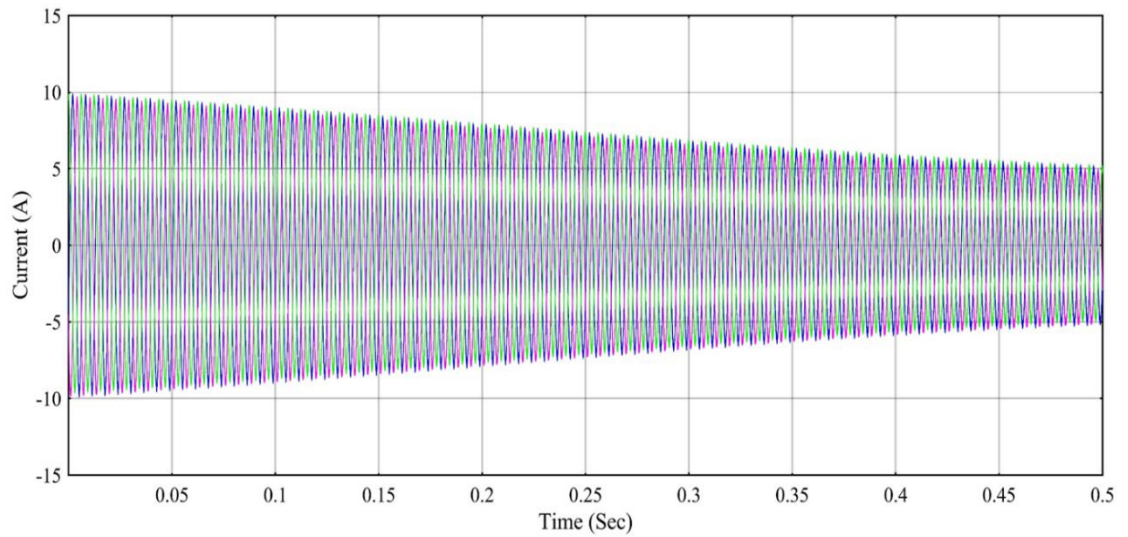


b. Three phase current feeding stator of motor

Figure C.3 Performance parameter (V&I) of SPWM inverter at 120% of rated frequency.

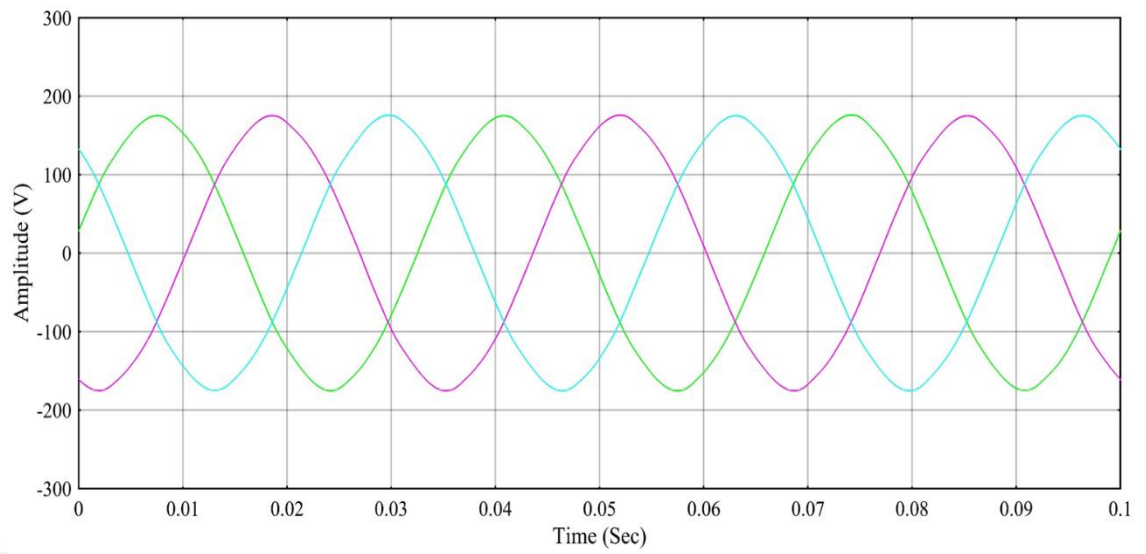


a. Three phase voltage after second order low-pass filter.

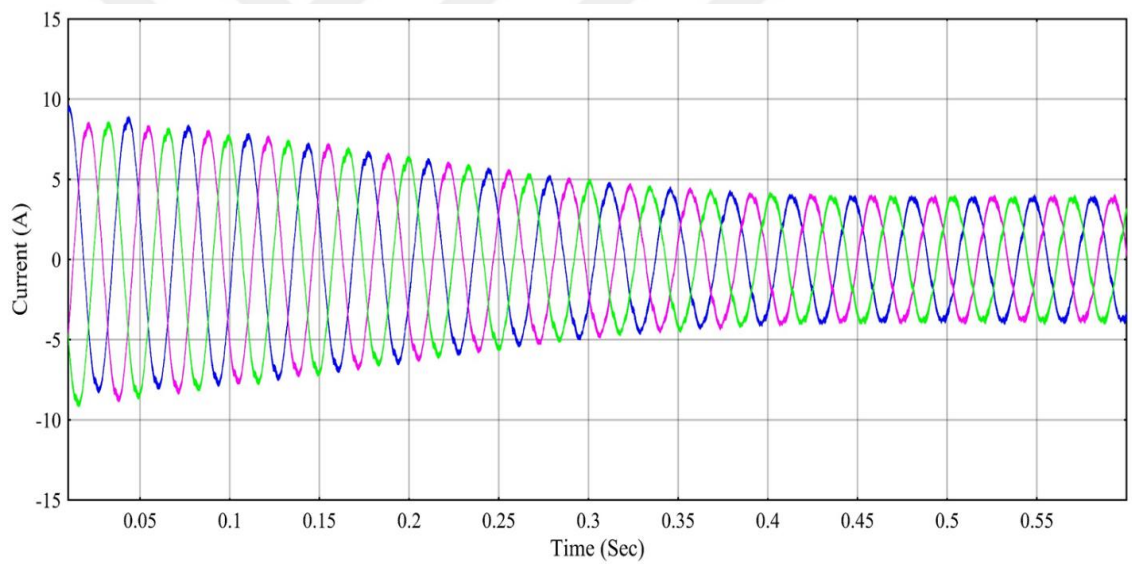


a. Three phase current feeding stator of motor.

Figure C.4 Performance parameter (V&I) of SPWM inverter at 160% of rated frequency.

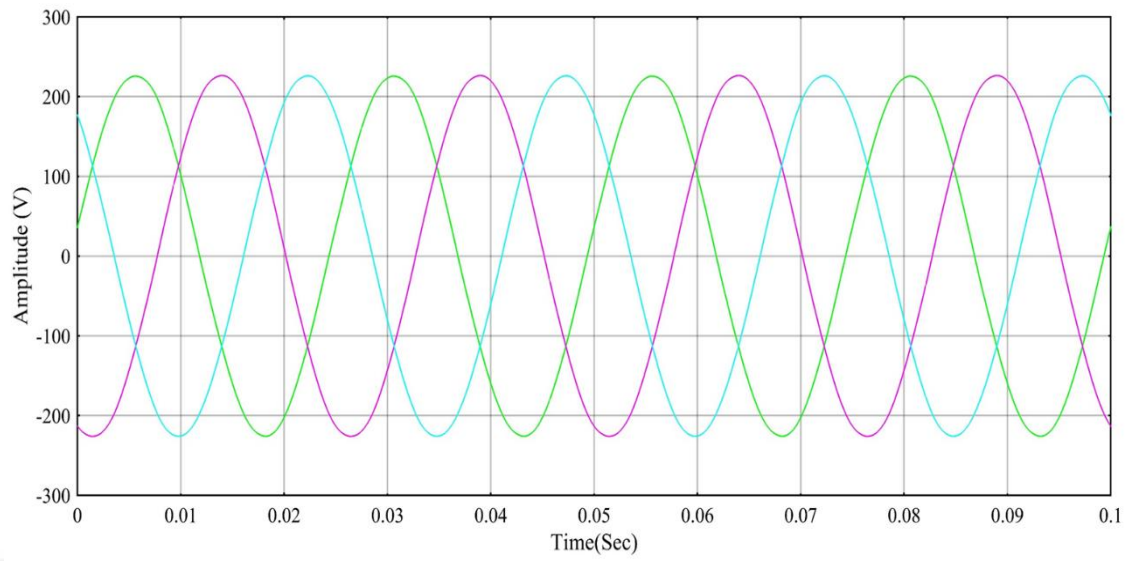


a. Three phase voltage after second order low-pass filter

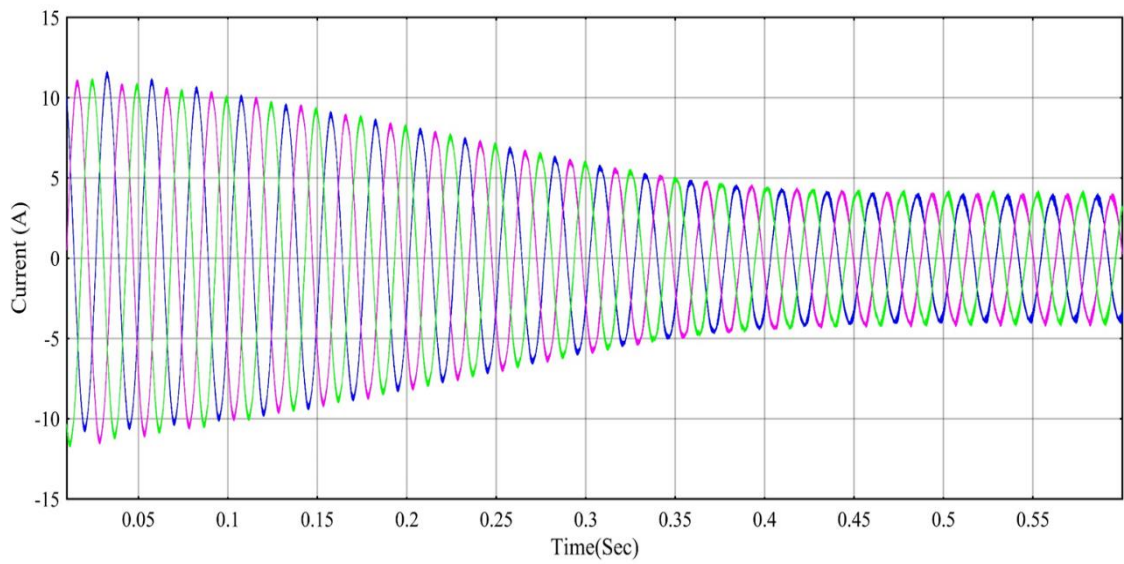


b. Three phase current feeding stator of motor

Figure C.5. Performance parameter (V&I) of THIPWM inverter at 60% of rated frequency.

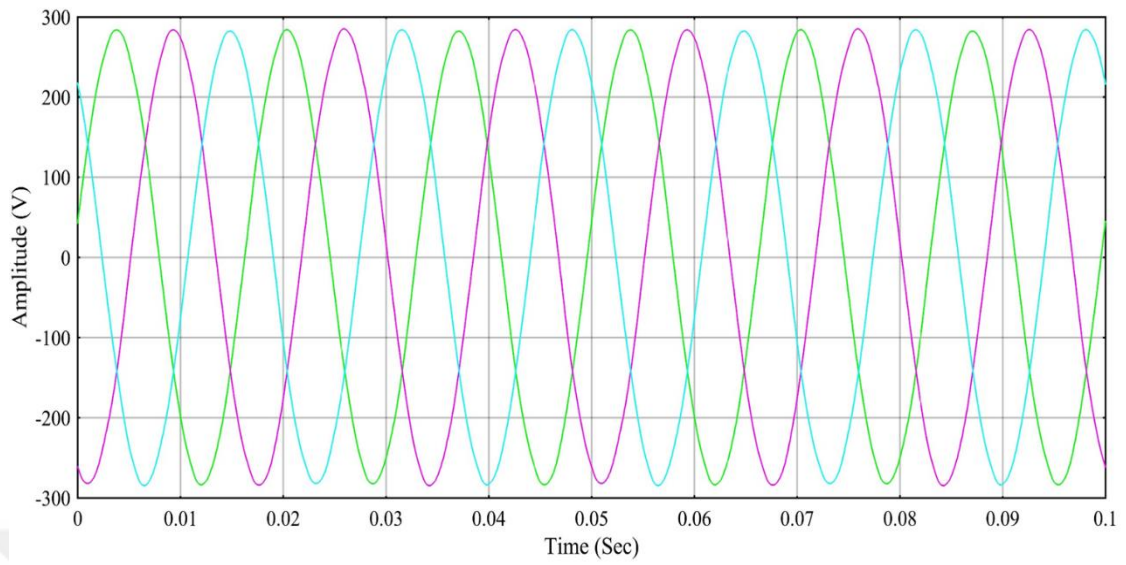


a. Three phase voltage after second order low-pass filter

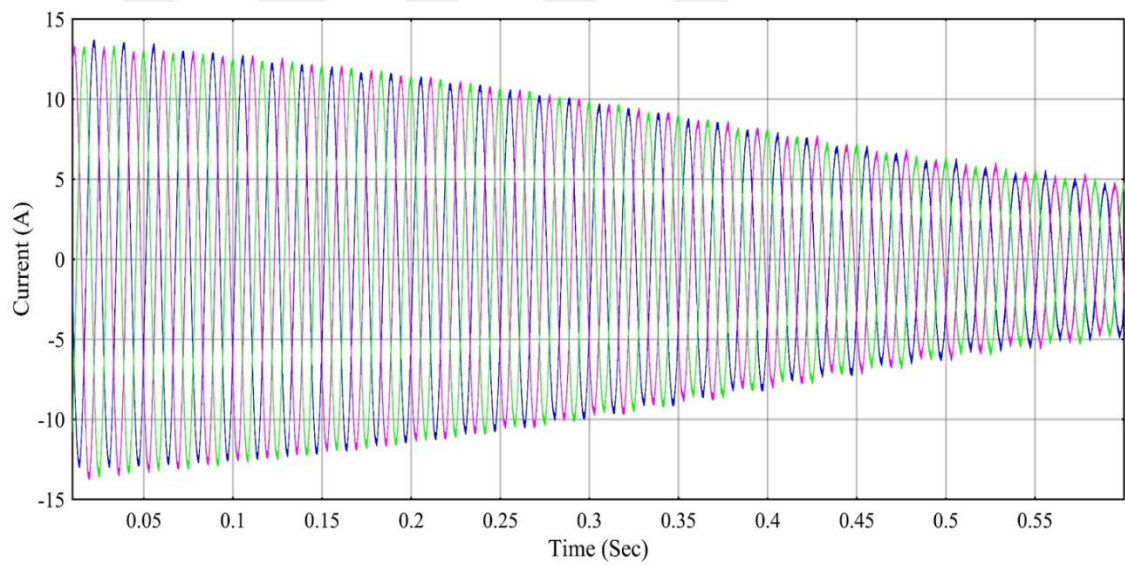


b. Three phase current feeding stator of motor

Figure C.6 Performance parameter (V&I) of THIPWM inverter at 80% of rated frequency.

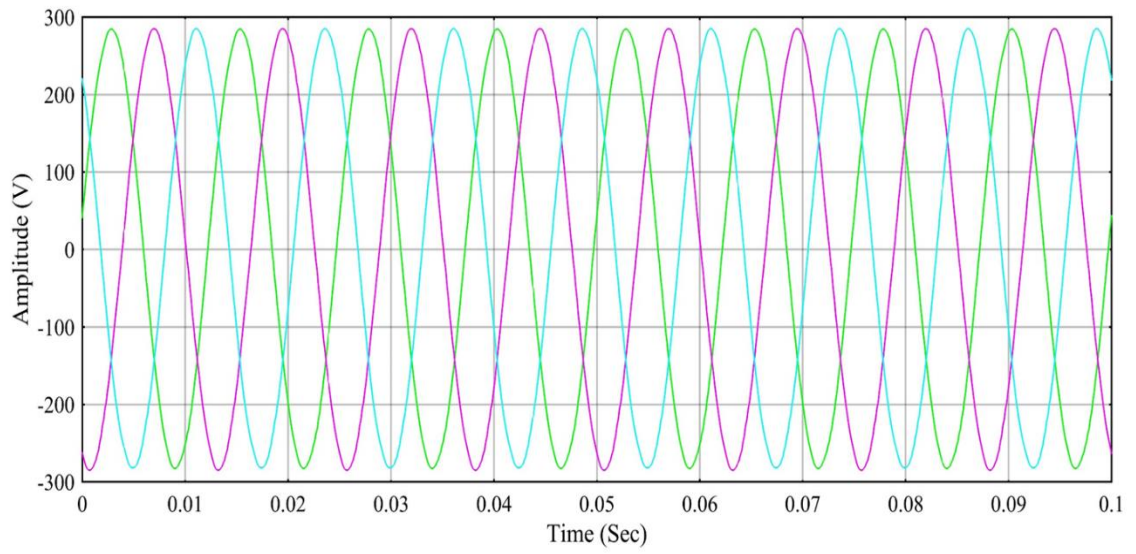


a. Three Phase voltage after second order low-pass filter

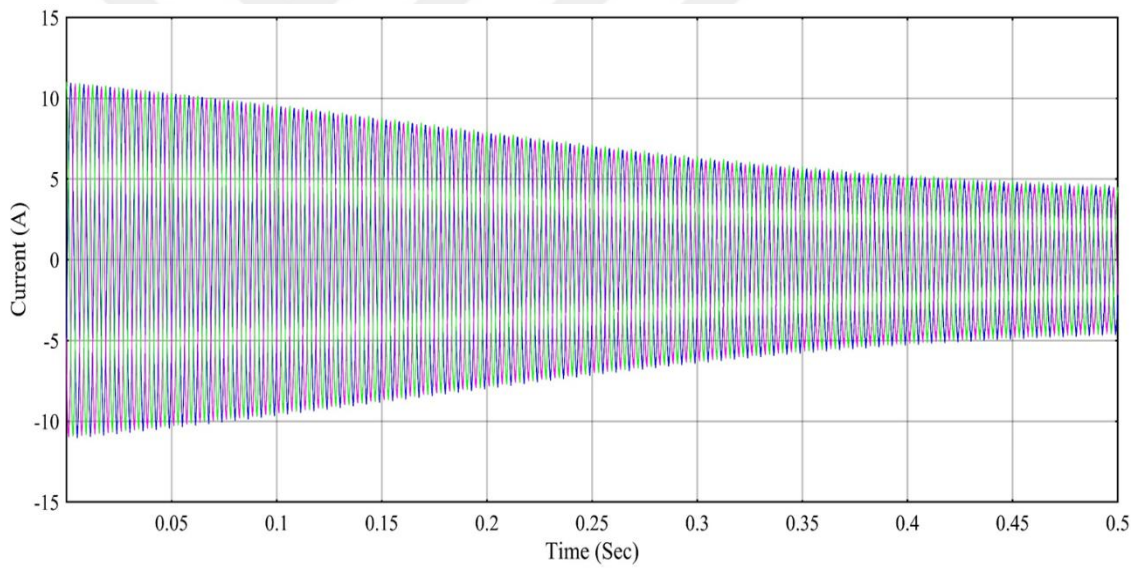


b. Three phase current feeding stator of motor

Figure C.6 Performance parameter (V&I) of THIPWM inverter at 120% of rated frequency.

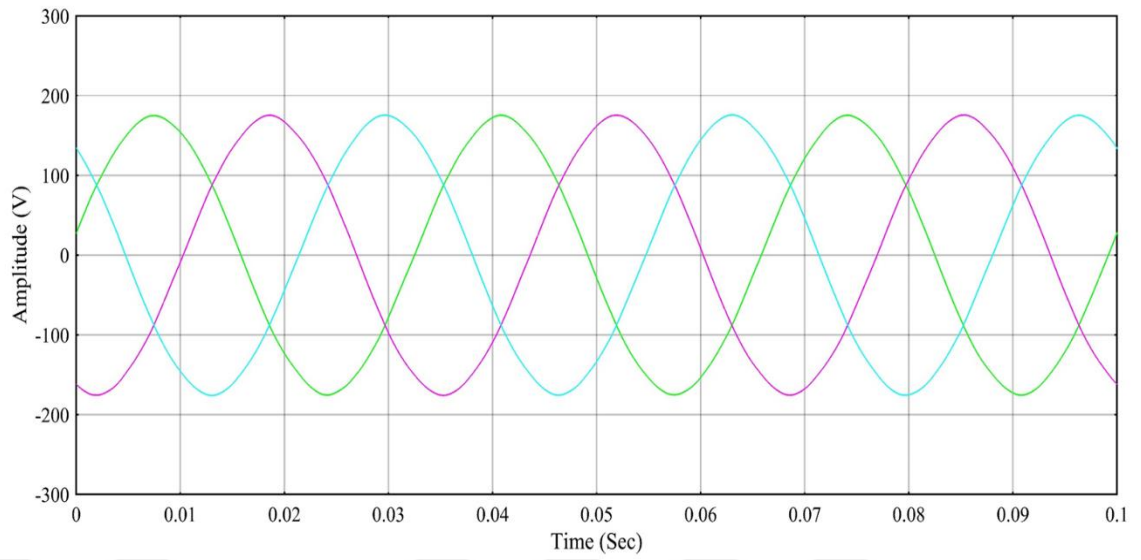


a. Three Phase voltage after second order low-pass filter

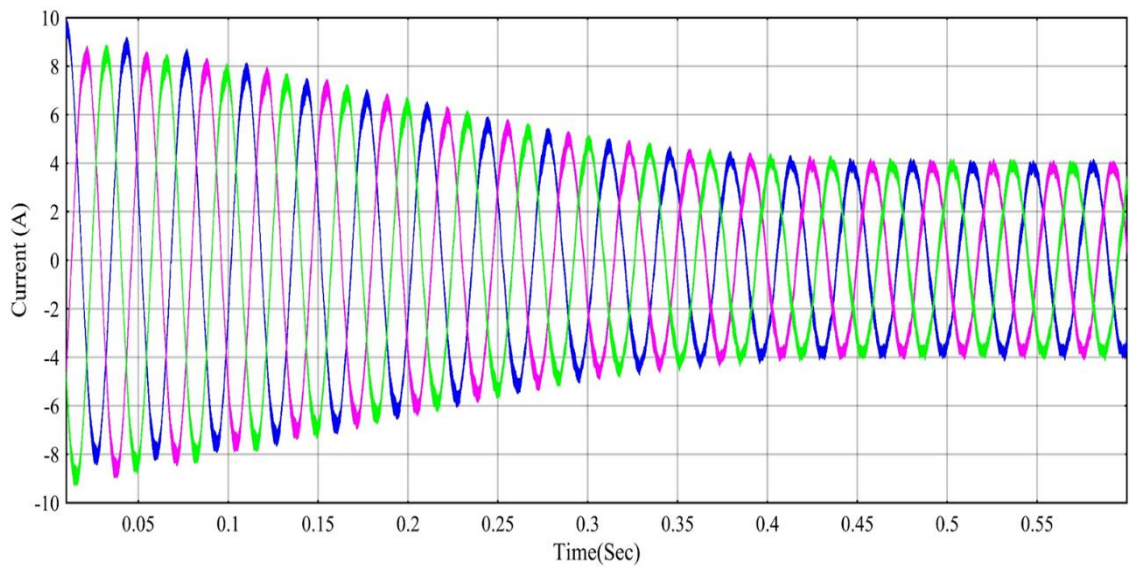


b. Three phase current feeding stator of motor

Figure C.7 Performance parameter (V&I) of THIPWM inverter at 160% of rated frequency.

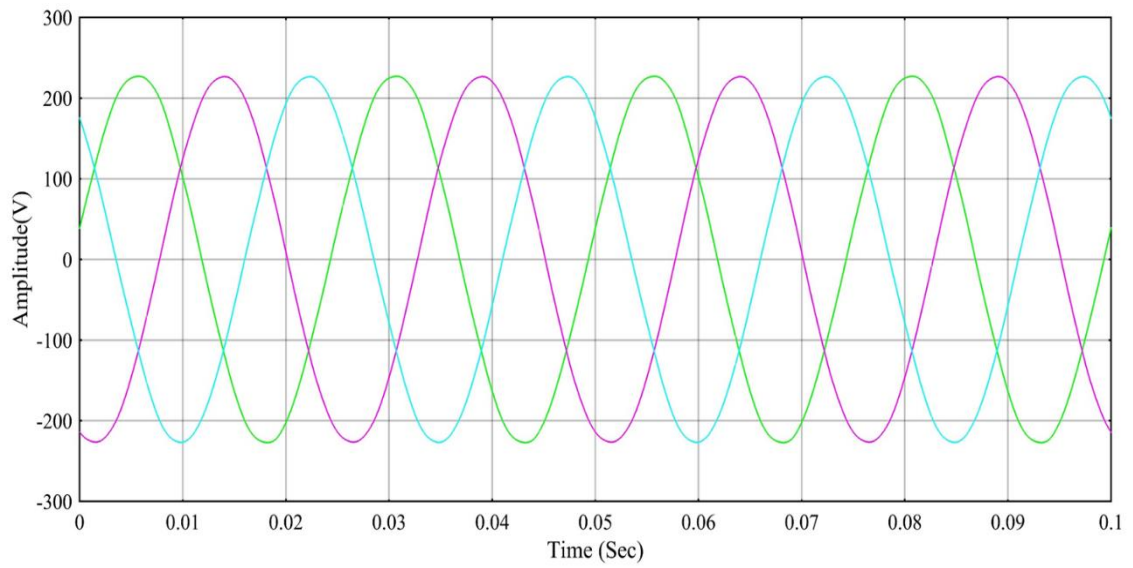


a. Three Phase voltage after second order low-pass filter

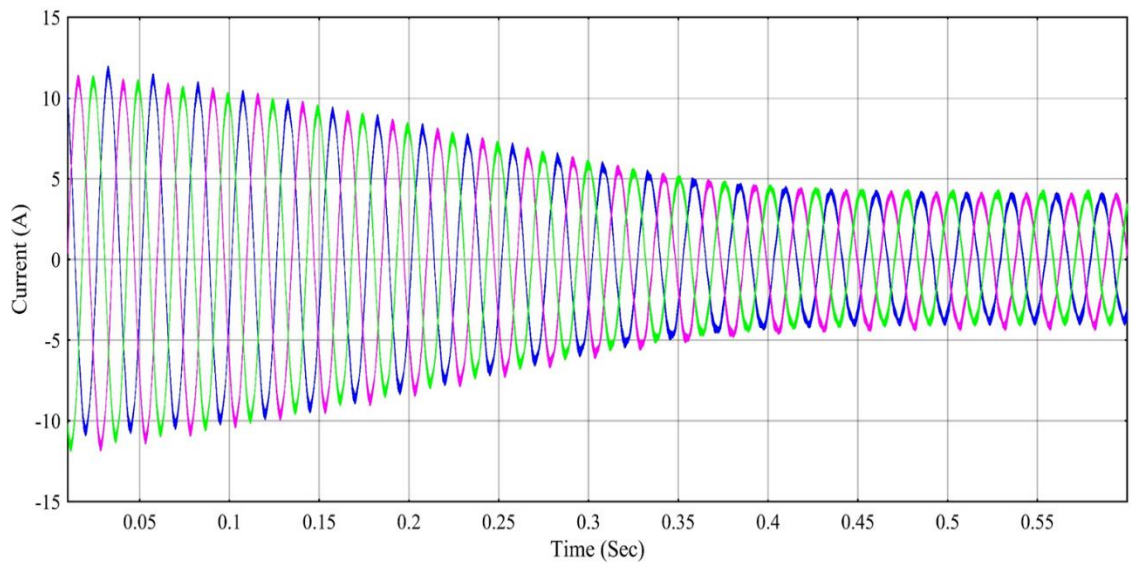


b. Three phase current feeding stator of motor

Figure C.8 Performance parameter (V&I) of SVPWM inverter at 60% of rated frequency.

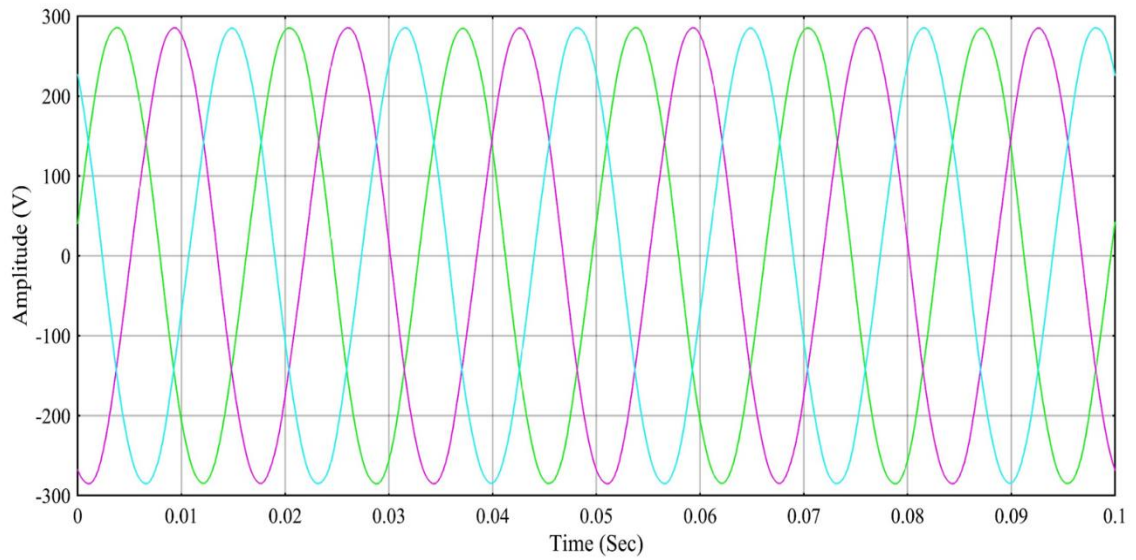


a. Three Phase voltage after second order low-pass filter

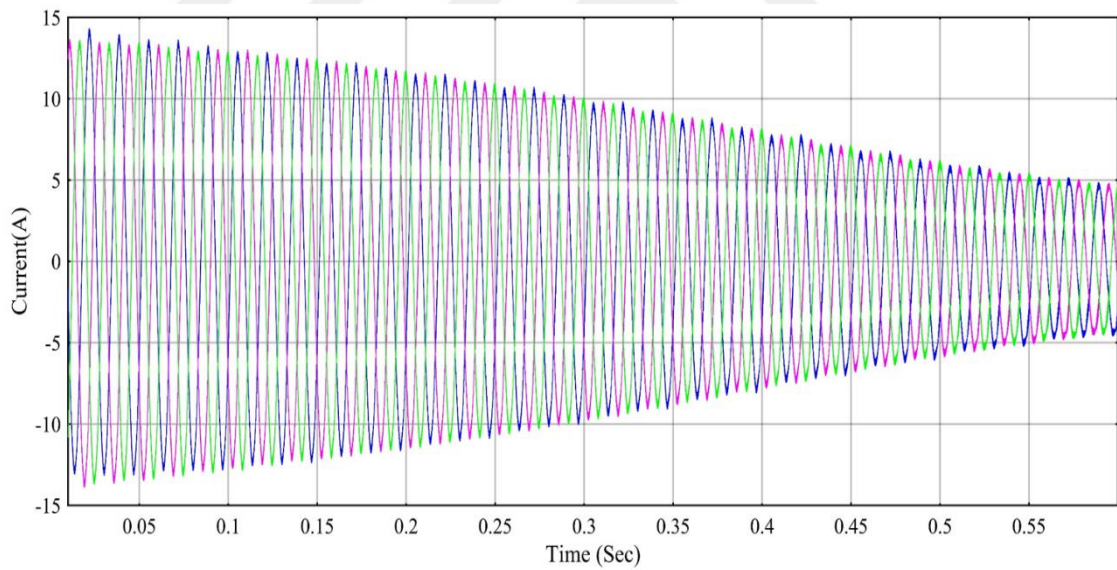


b. Three phase current feeding stator of motor

Figure C.9 Performance parameter (V&I) of SVPWM inverter at 80% of rated frequency.

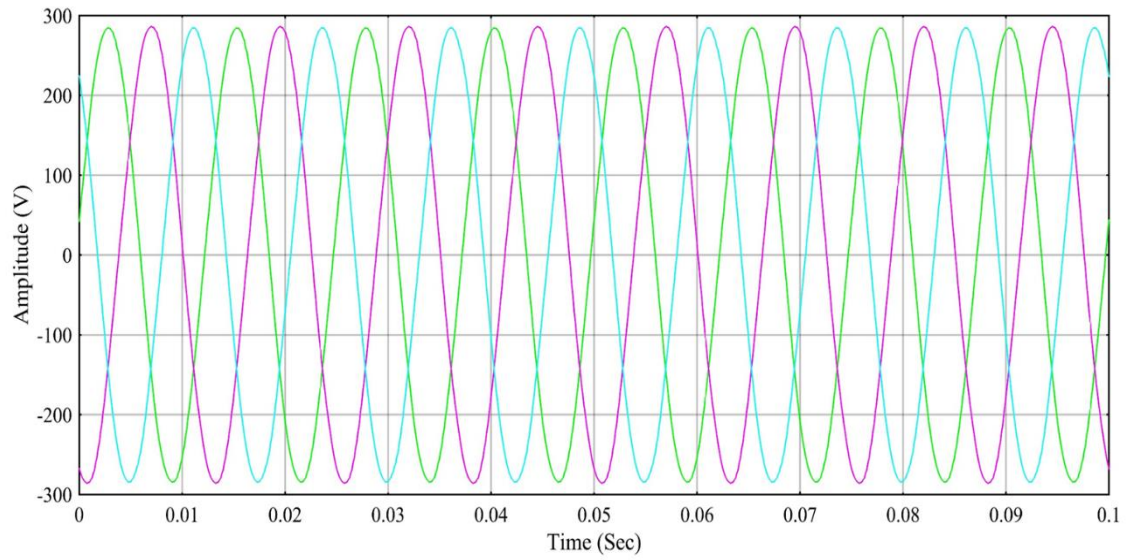


a. Three Phase voltage after second order low-pass filter

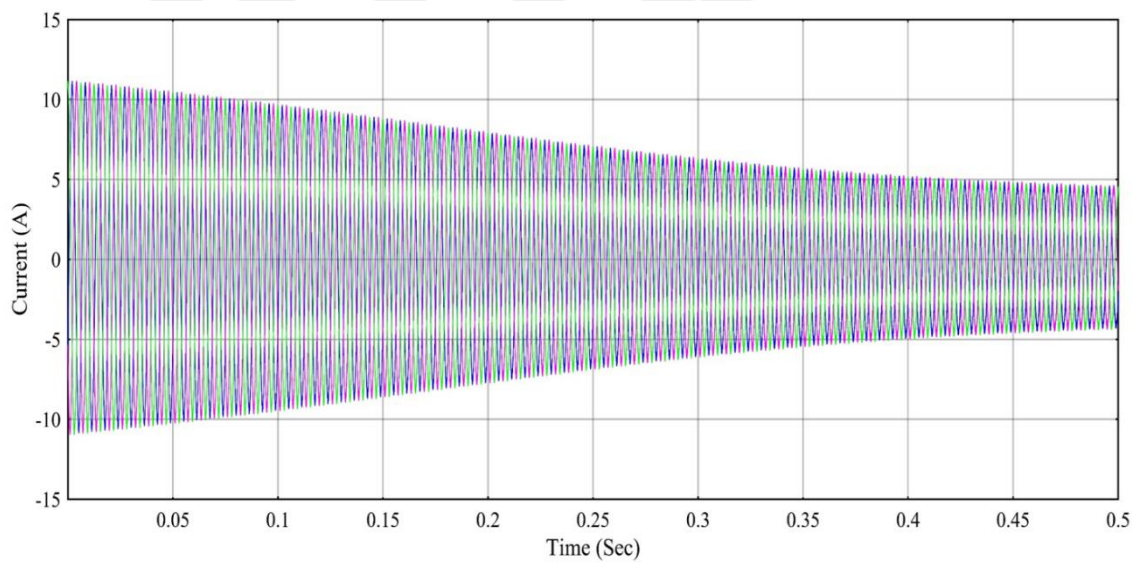


b. Three phase current feeding stator of motor

Figure C.10 Performance parameter (V&I) of SVPWM inverter at 120% of rated frequency.



a. Three Phase voltage after second order low-pass filter

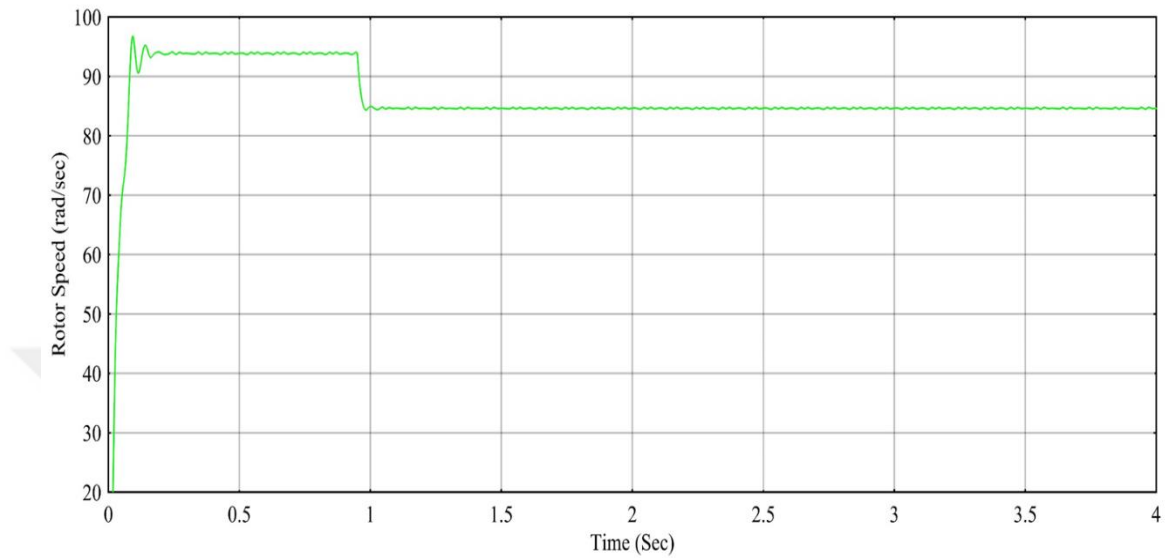


b. Three phase current feeding stator of motor

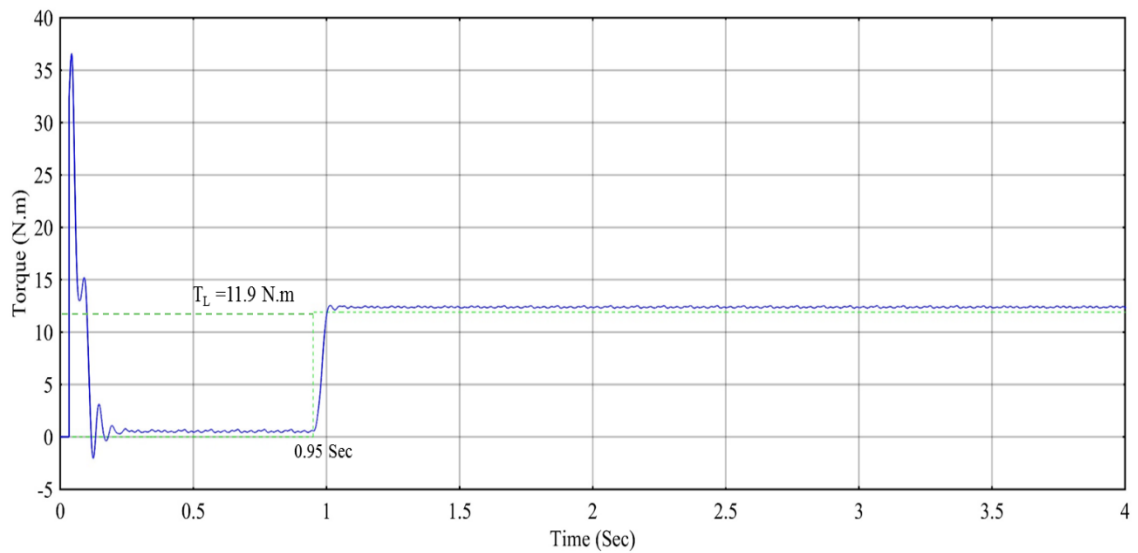
Figure C.11 Performance parameter (V&I) of SVPWM inverter at 160% of rated frequency.

3. System Performance under Load Conditions

The motor speed (ω_m), electromagnetic torque (T_e) and FFT analysis with Total Harmonic Distortion (THD), to voltage and current waveform, for the frequency ratio (60%) at load.

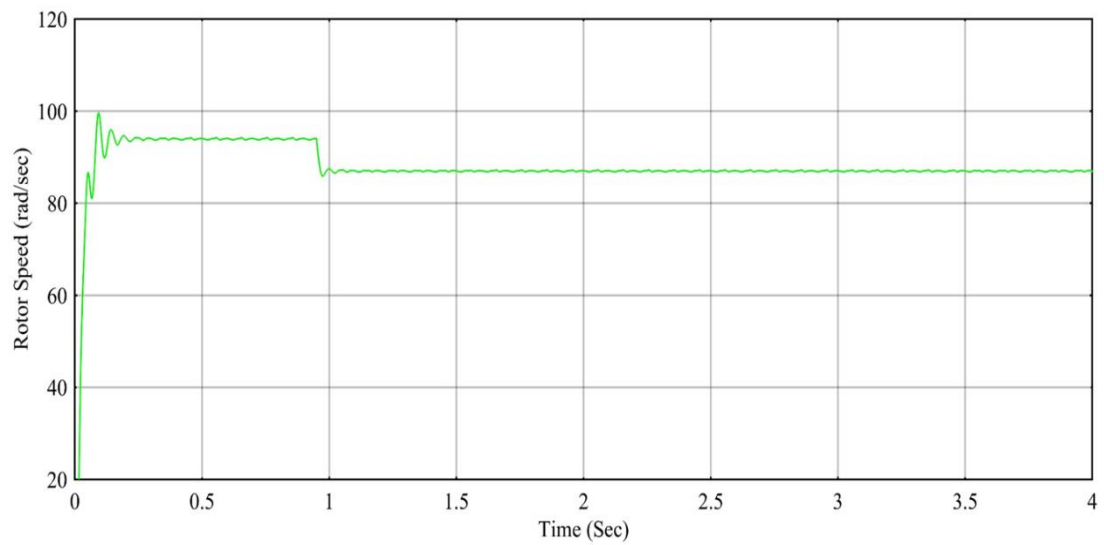


a. Rotor speed (ω_m) response.

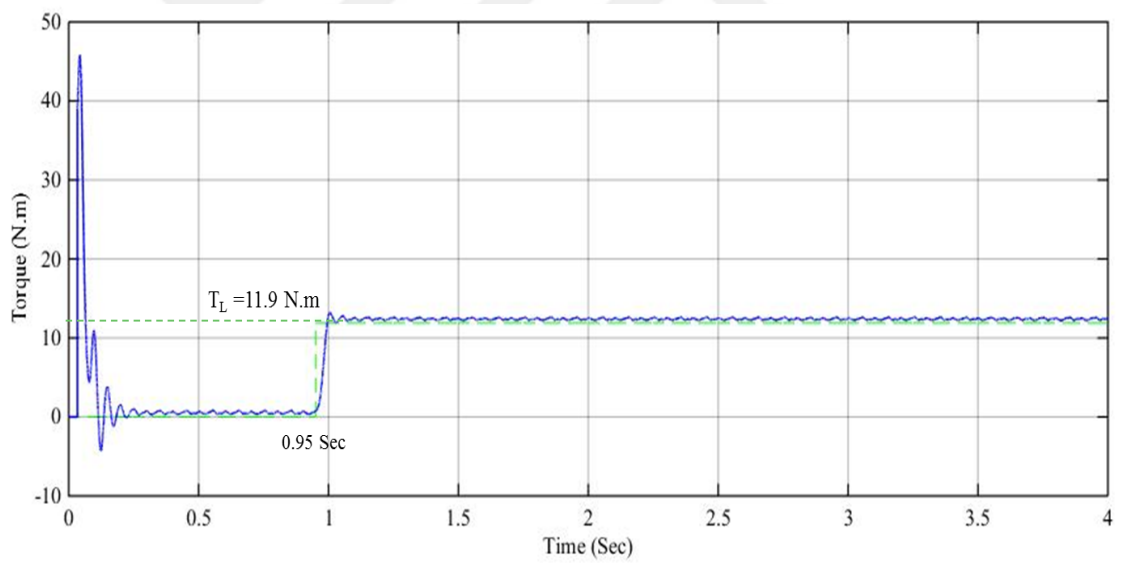


b. Electromagnetic torque (T_e) response

Figure C.12 Speed and Electromagnetic torque response under load condition of SPWM inverter at 60% of rated frequency.

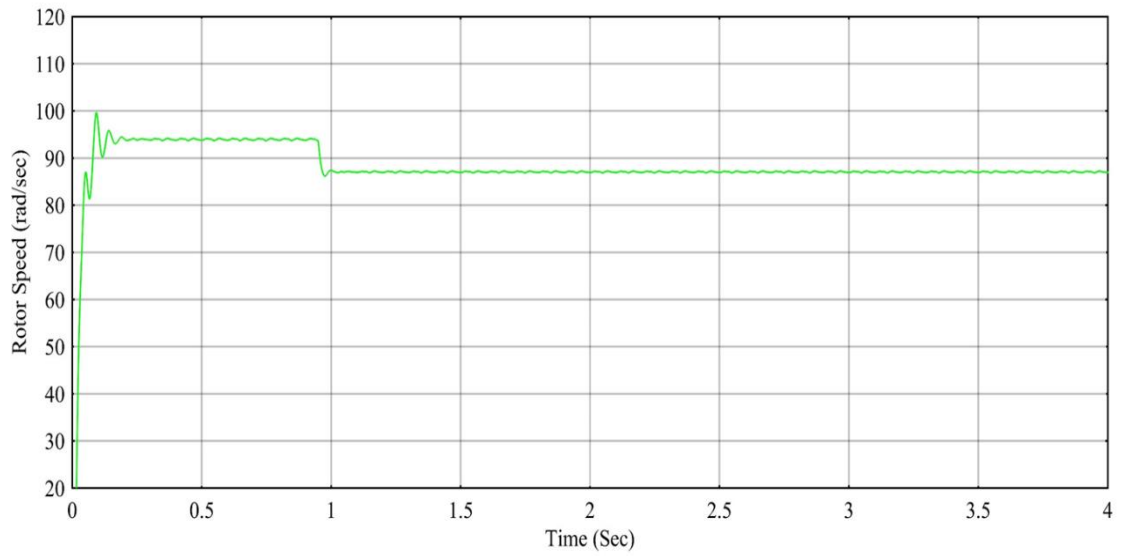


a. Rotor speed (ω_m) response

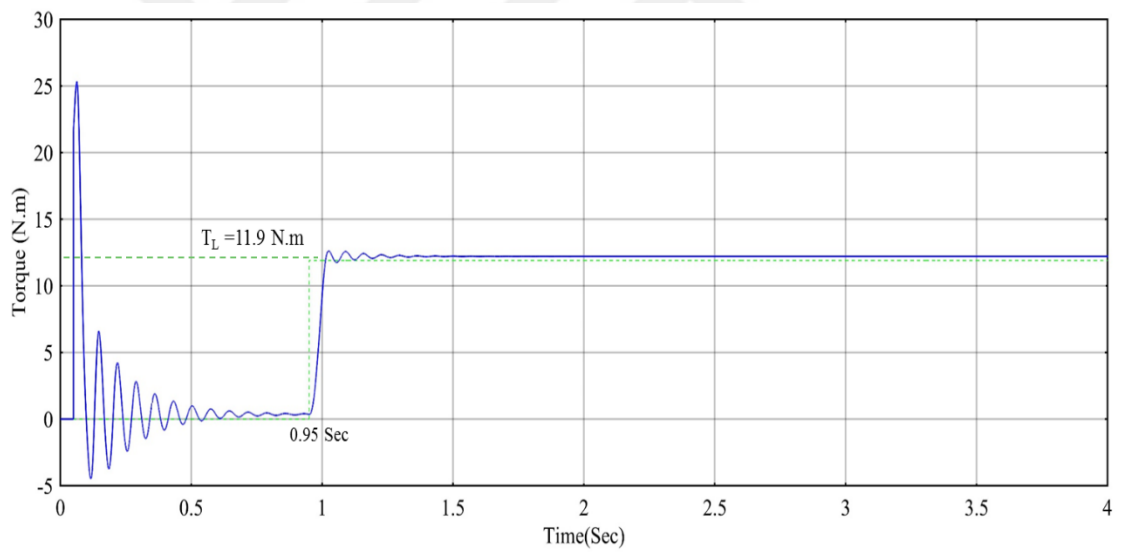


b. Electromagnetic torque (T_e) response

Figure C.13 Speed and Electromagnetic torque response under load condition of THIPWM inverter at 60% of rated frequency

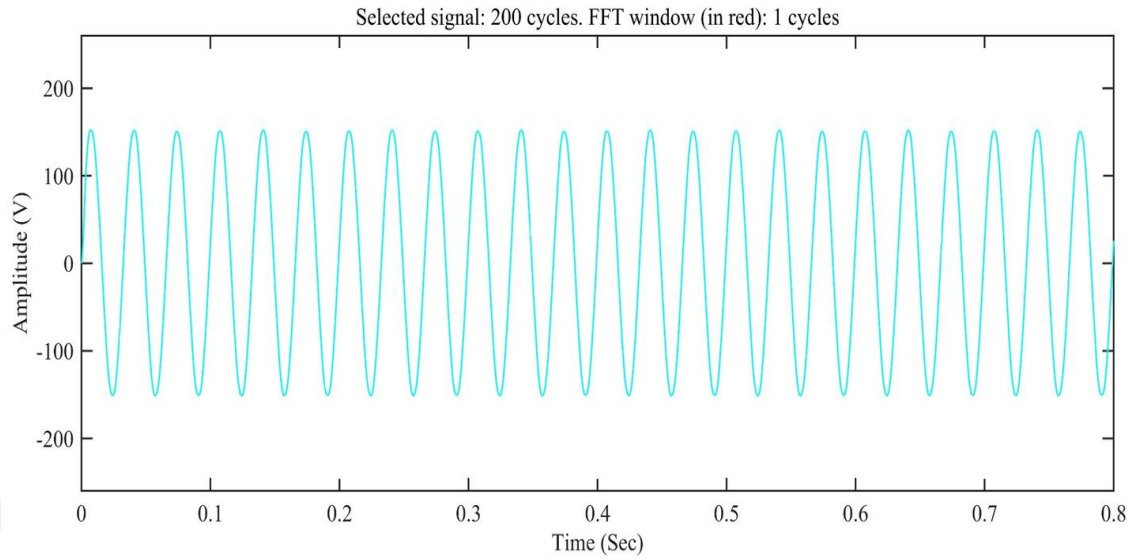


a. Rotor speed (ω_m) response

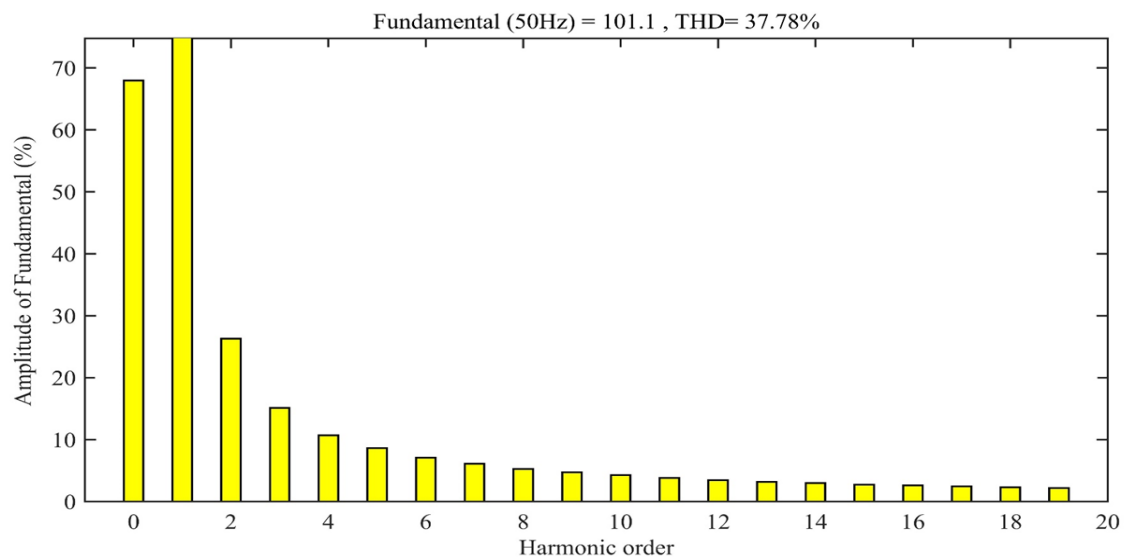


b. Electromagnetic torque (T_e) response

Figure C.14 Speed and Electromagnetic torque response under load condition of SVPWM inverter at 60% of rated frequency.

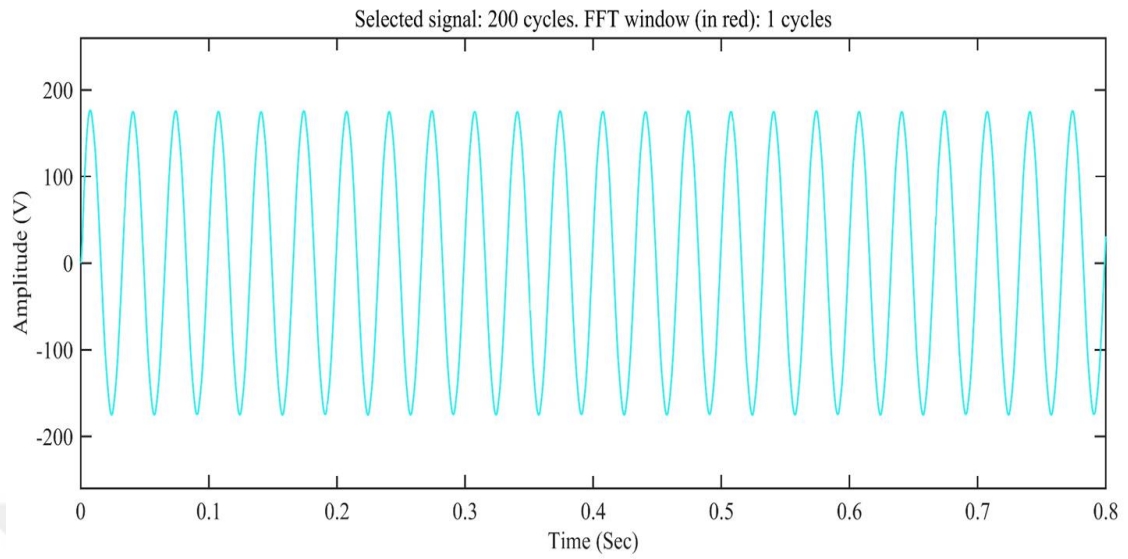


a. FFT analysis phase voltage waveform after Second order low pass filter

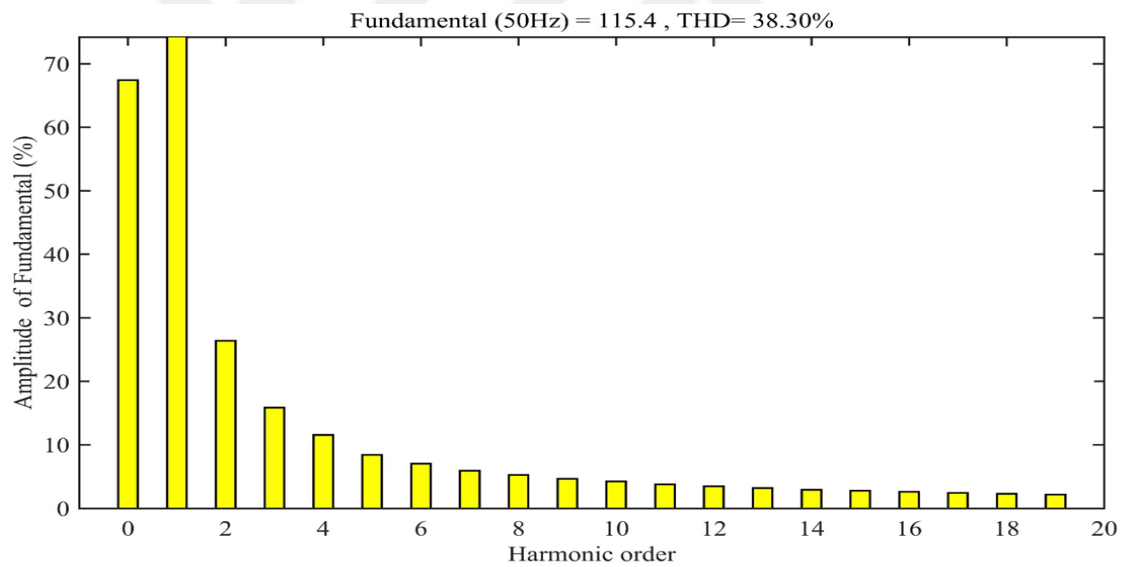


b. THD V (%)

Figure C.15 SPWM Inverter performance parameter under load condition. THD% and FFT analysis for phase voltage waveform after second order low pass filter at 60% of rated frequency.

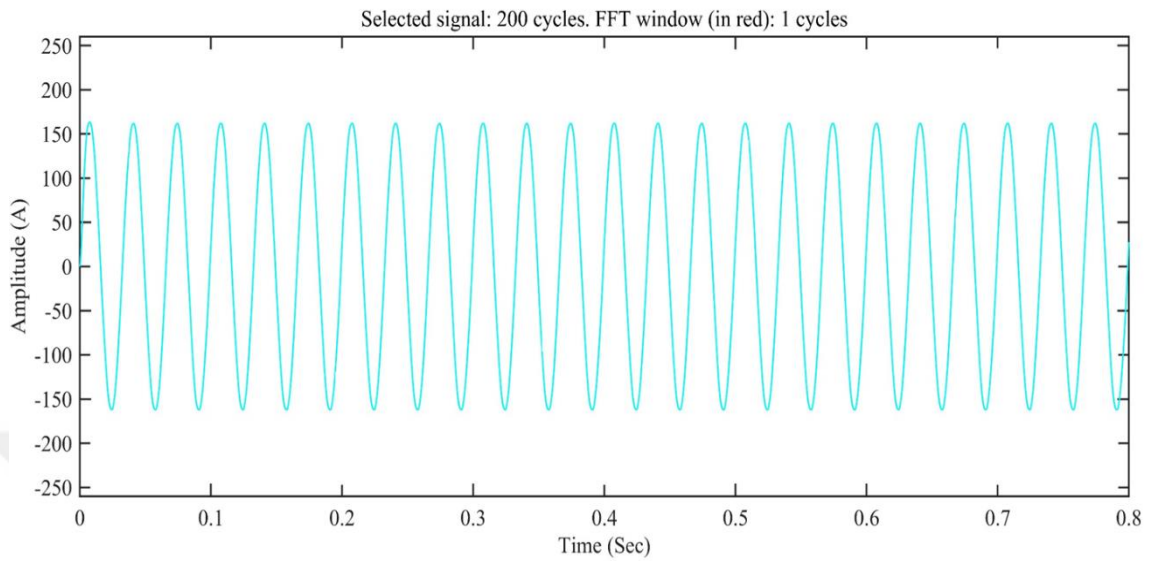


a. FFT analysis Phase voltage waveform after Second order low pass filter.

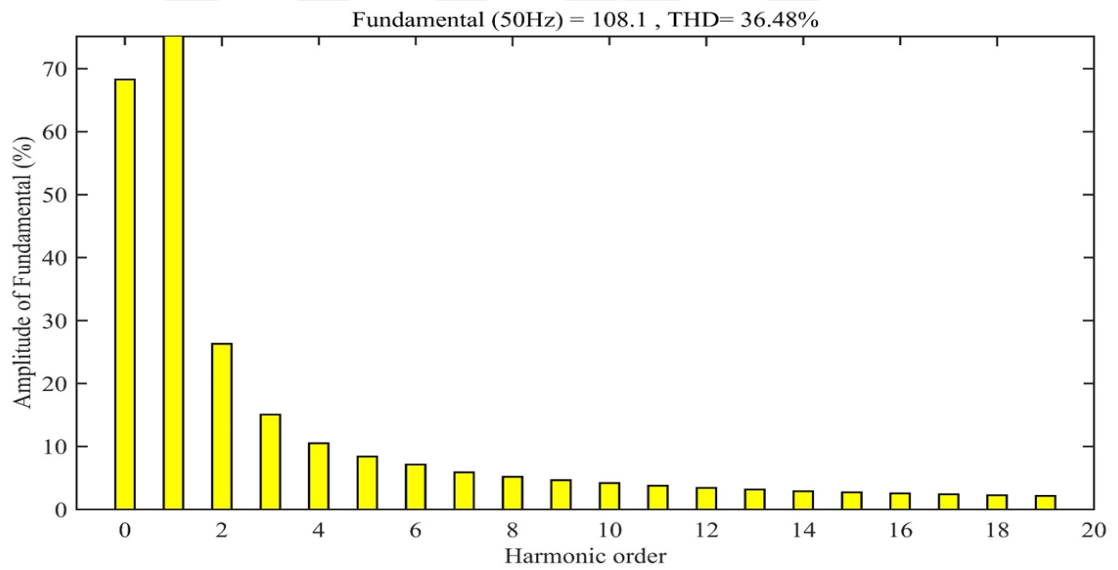


b. THD V (%)

Figure C.16 THIPWM Inverter performance parameter under load condition. THD% and FFT analysis for phase voltage waveform after second order low pass filter and applied 60% of rated frequency

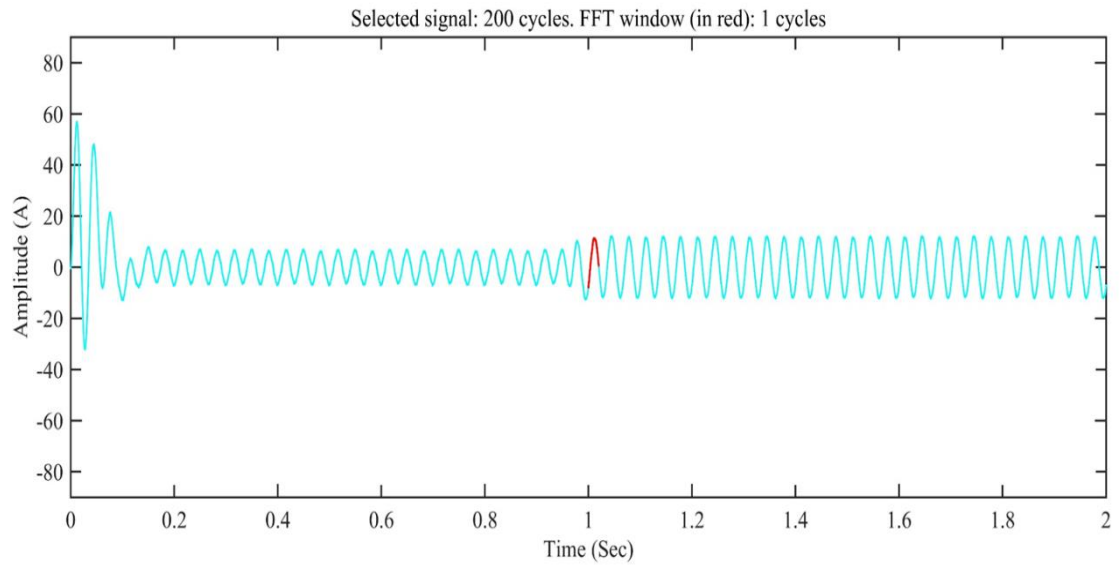


a. FFT analysis Phase voltage waveform after Second order low pass filter.

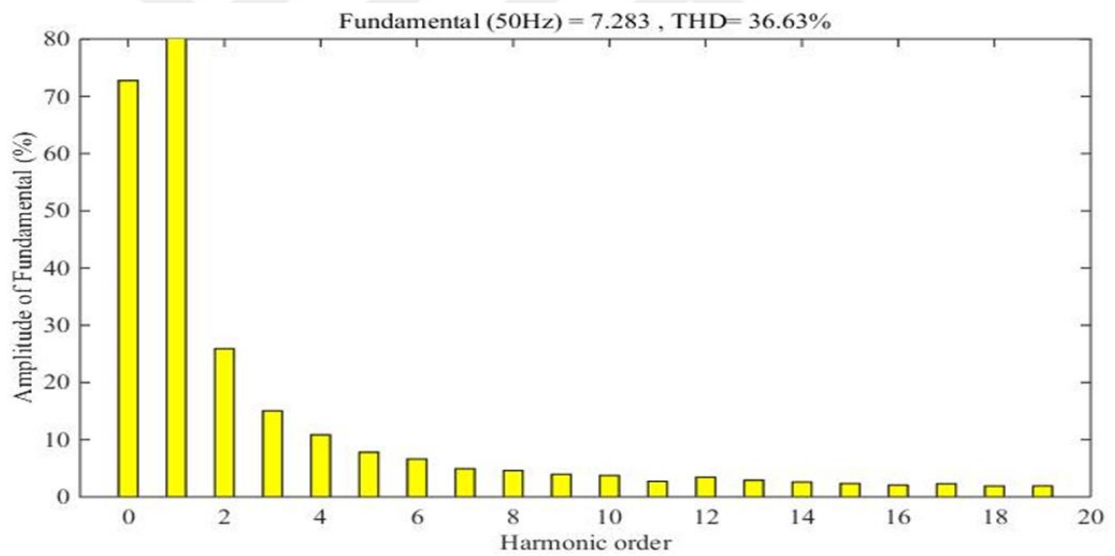


b. THDV (%)

Figure C.17 SVPWM Inverter performance parameter under load condition. THD% and FFT analysis for phase voltage waveform after second order low pass filter and applied 60% of rated frequency.

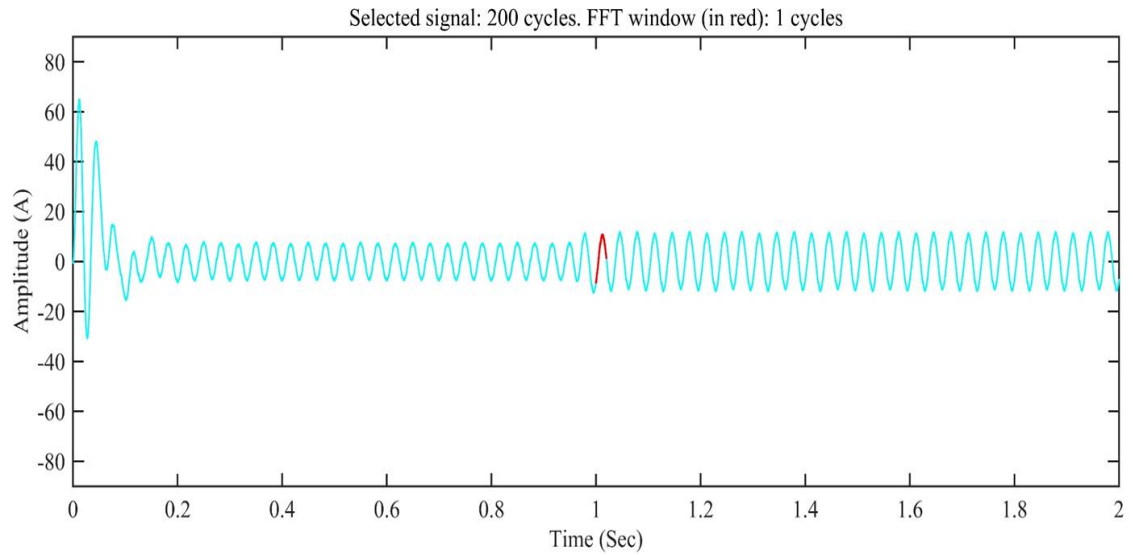


a. FFT analysis for current waveform per phase

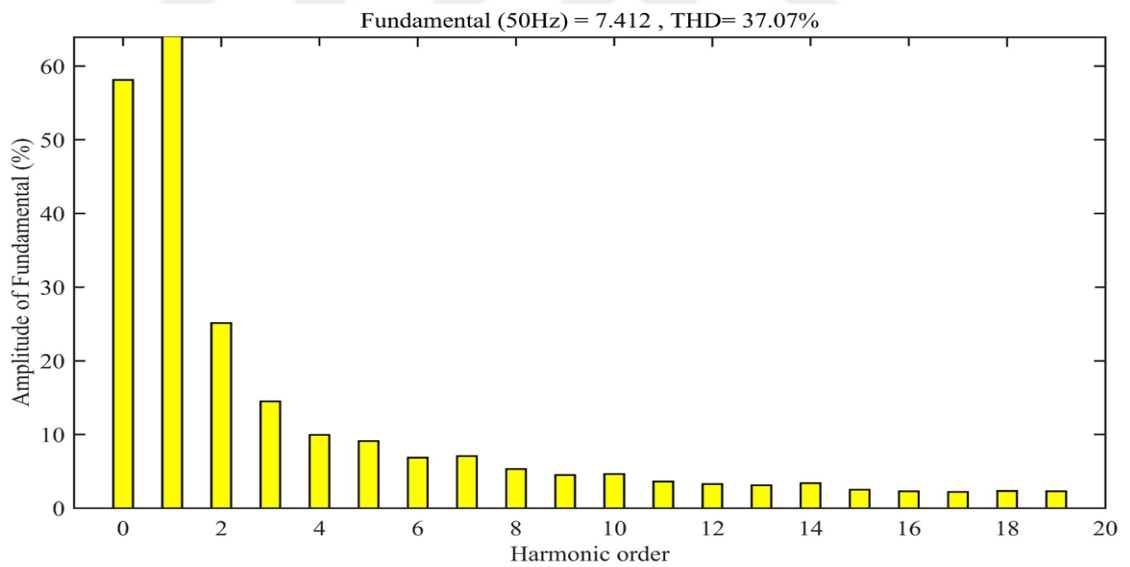


b. THD I (%)

Figure C.18 SPWM Inverter performance parameter under load condition. THD% and FFT analysis for current waveform per phase during work of the motor and applied 60% of rated frequency.

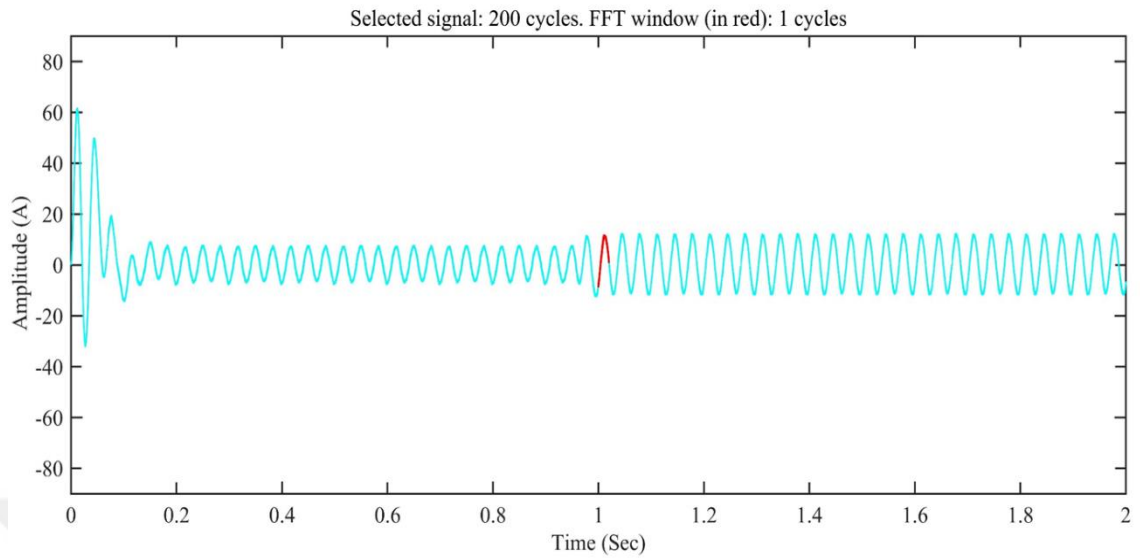


a. FFT analysis for current waveform per phase

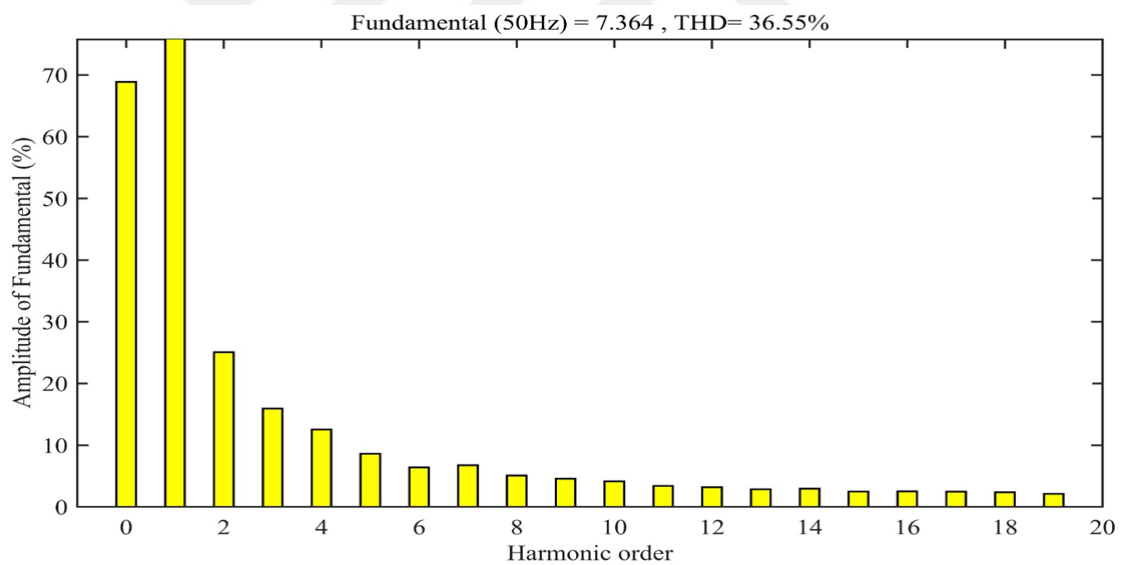


b. THD I (%)

Figure C.19 THIPWM Inverter performance parameter under load condition. THD% and FFT analysis for current waveform per phase during work of the motor and applied 60% of rated frequency.



a. FFT analysis for current waveform per phase



b. THD I (%)

Figure C.20 SVPWM Inverter performance parameter under load condition. THD% and FFT analysis for current waveform per phase during work of the motor and applied 60 % of rated frequency.