SIMULATION OF VARIOUS MODULATION STRATEGIES FOR INDUCTION MOTOR DRIVE

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In

Electrical Engineering, Power Engineering and Management

By

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CERTIFICATE

This is to certify that research work embodied in this project report entitled **"Simulation of various modulation strategies for induction motor drive"** was carried out by **Mr. Jigar Mehta, at Czech Technical University** for the fulfilment of Master's Degree to be awarded by Czech Technical University. This research work has been carried out under my supervision and is to my satisfaction.

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I declare that this is a true copy of my report, including any final revision, as approved by my report review committee.

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ACKNOWLEDGMENT

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ABSTRACT

Developments in power electronics and semiconductor technology have lead improvements in power electronic systems. PWM inverter-powered motor drives are more variable and offer in a wide range better efficiency compared to fixed frequency motor drives. The lower order harmonics can be eliminated and filtering out higher order harmonics are not much to worry about. Thus, it reduces losses and increase performance and accuracy of the system.

In this thesis work, I am presenting Simulink models in Matlab simulation and comparing the performance of a saturated induction motor drive for the basic three phase voltage source inverter and for different PWM strategies such as Space Vector PWM and Sinusoidal PWM. The complete system taken for simulation is a three-phase system, inverter based saturated induction motor drive employing PWM techniques for inverter control. All the components of the system are modelled as functionally decoupled Matlab-Simulink blocks, so that any modifications for a new configuration of the system can be readily incorporated.

Main reason to pick this topic as a thesis work is, because of my field of interest, want to learn more about Matlab simulation and use of the components such as comparators, goto-from etc. Also Deeply getting knowledge about all modulation strategies and their interfacing with an Induction motor used in today's era is one the most interesting thing, to neglect most of the lower order harmonics from any operating system. At the end of the thesis, compare the outcomes of these modulation strategies to decide which PWM technique is most preferable among them.

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1. INTRODUCTION

Induction machines are the most widely used motors in industry. About 60% of the industrial electric energy is converted into mechanical energy by means of pumps, fans, adjustable speed drives and machine tools equipped with induction motors. Thus, considerable research efforts have been focused on topics like modelling and parameter estimation of induction motors.

The machine parameters are not constant and depend on saturation and temperature. The magnetic saturation effect is significant at motor start-up and near rated operating conditions. Under saturated operation the voltage and/or current harmonics generated by the induction motors become non negligible. These alter the static and dynamic performance of induction motor drives, the efficiency as and the harmonic content of the supply mains for the applications where the motors are directly connected to the power network.

For simulation study, different nonlinear models for saturated induction motors have been elaborated based on the equivalent electric circuit approach. One of the first notable attempts to model the saturated induction motors is represented by where an analog computer based model has been developed. The model is built in d-q-0 reference frame and takes into account the magnetic saturation of leakage flux path. The stator and rotor leakage inductances are both separated into a saturable slot inductance and an end-winding inductance, whereas the end winding portions are considered constants, the slot portions of leakage inductances are considered saturable according to saturation factors. These saturation factors are previously determined by experimental measurements on the motor which is to be modelled. The model is quite complex and does not predict the current and/or voltage harmonics generated by the motor under saturated operating conditions. Moreover, because the model structure contains multiple closed loops, numerical convergence problems occur when digital computer implementation is attempted.

In reference another model for saturated induction motors is proposed that accounts for saturation in stator and rotor cores as well as in teeth. The model is built as an equivalent circuit in d-q reference frame with variable reactance depending on saturation factors, previously determined by finite-element methods or experimental measurements. Although the model is quite simple, search coils have to be mounted in the motor air gap, stator slots and around the stator core in order to determine proper values of model parameters. In addition, since the model is in d-q frame (without using the 0 component) it is not possible to simulate the zero-sequence components produced by saturation.

The model is built in a d-q-0 frame and uses variable stator and rotor inductances. These are computed as functions of the variable air gap length and trigonometric functions taking into account the fundamental and 3rd harmonic of the air gap flux. The model requires a large number of parameters such as: geometrical dimensions of motor (air gap length, number of rotor and stator slots, and the rotor stack length), equivalent turns ratio of stator and rotor windings for the 3rd harmonic as well as air gap flux fundamental. Consequently, intensive and time consuming measurements are required to build the model for a given motor.

In recent years, finite-element methods have been developed for magnetic analysis of motors, but their main drawback is the inability to simulate the global system consisting of motor, power converter and control system. Unlike mentioned models, the parameter values of nonlinear model for delta connected saturated induction motors derived from the conventional equations of the non-saturated induction machine can be tuned more easily. All the necessary measurements are performed at the motor terminals. The proposed model gives good prediction of line and stator winding currents under saturated conditions even for overvoltage operation of the motor. [1]

Over the last decades, Power converters have become an enabling technology for a wide range of industrial applications mainly due to higher efficiency and performance. Converter topologies, such as the ac/ac matrix converter, cycloconverters, current-source inverters, load-commutated inverters, dc/dc converters, dc/ac converters, and diode or thyristor based rectifiers, cover a wide range of different nominal power applications. In particular, dc/ac converters, commonly known as voltage-source inverters (VSIs), are used to power a wide variety of applications in the nonstop energy-demanding society with high efficiency, robustness, and economical cost and possibility to reach high nominal power with reduced passive filters.

The rich diversity of industrial applications requires inverters that have very different power ratings, output frequencies, semiconductor devices, number of phases, operate at different voltage/current levels, and even have different types and number of dc-input sources (current or voltage). Therefore, a wide range of different topologies have been developed over the years, particularly in the last decade for medium-voltage applications, to cater the needs and fulfil the specifications

 Apart from well-known multilevel converter topologies, such as neutral-point-clamped (NPC), flying-capacitor (FC), and cascaded H-bridge (CHB), in the last years, a great deal of new inverter topologies have been introduced in industry, particularly in medium-voltage multilevel converters, such as modular multilevel converter (MMC), five-level active NPC (5L-ANPC), transistor-clamped converter (TCC), and stacked multicell. In addition, multiphase applications have been gaining more and more attention due to a series of advantages, such as higher power density, lower torque ripples, and fault-tolerant operation. As another example, open-end-winding-fed drives also have different voltage-space vector distribution, and extension of classic modulation methods is not straight forward. All these new power converters come along with modulation challenges, which include additional voltage-space vectors and different switching harmonics. [2]

A modulation technique generates the gate signals of power semiconductors of a power converter obtaining a switched output waveform in such a way that the fundamental component can be adjusted with an arbitrary magnitude, frequency, and phase, which are essential for the proper control of the process fed by the inverter. Taking this fact into account, the pulse-width modulation (PWM) is the modulation concept that has been the mainstream solution for inverters. [2]

2. MODULATION

In power electronics, modulation is the process of varying one or more properties of a periodic waveform, called the carrier signal, with a modulating signal that typically contains information to be transmitted. [3]

Modulation is a technique in which message signal is transmitted to the receiver with the help of carrier signal. Here in modulation, we combine both carrier signal and message signal. You may get the doubt that what is the need of modulation. Just imagine that you have a paper which contains the message and you would like to send it to your friend standing 40 feet from your place. You can't just through the paper to your friend because paper will not travel that much distance but if you take small stone and cover the paper with it and through it to your friend, it will definitely reach the target. In the same way, we need a carrier signal to transmit our message. Sometimes, message signal is also called as modulating signal. The exact definition of modulation is given below:

"Modulation is a process of message signal and modulating is varied according to the carrier signal for transmission purpose. The message signal can varied in accordance to the carrier signal that is in terms of angular or amplitude. So we are modulating the signal."

Modulation Signal = Original Signal + Carrier Signal [3]

2.1 CARRIER SIGNAL

A method of generating a triangle waveform is to first use a clock oscillator to produce a square wave and then use an integrator (low pass filter) to integrate the square wave into a triangle wave it is called carrier signal which has been shown below in Figure 2.1. [3]
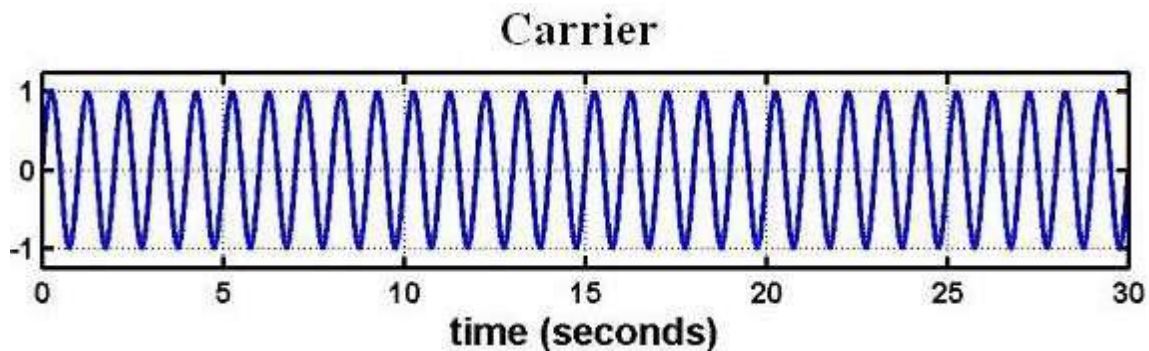

FIGURE 2.1   CARRIER SIGNAL

2.1.1   CLOCK OSCILLATOR

At the core of almost all modern digital systems is a high accuracy time base based on a crystal oscillator. Crystal oscillators use the property of piezoelectricity to create waveforms with excellent frequency accuracy based on the mechanical vibration of a precision machined crystal.

Certain crystals, most notably quartz, exhibit the property of piezoelectricity. If force is applied to the faces of a piece of crystal it causes a voltage to be generated from the crystal. Conversely, if an electrical voltage is applied to a crystal it causes the crystal to deform mechanically, [5] Thus Piezoelectricity converts a force applied to a crystal into an electric voltage and an applied voltage into a mechanical deformation. This process is illustrated in figure 2.2.

APPLIED VOLTAGE
CAUSES PHYSICAL
CONTRACTION

APPLIED FORCE
PRODUCES
VOLTAGE
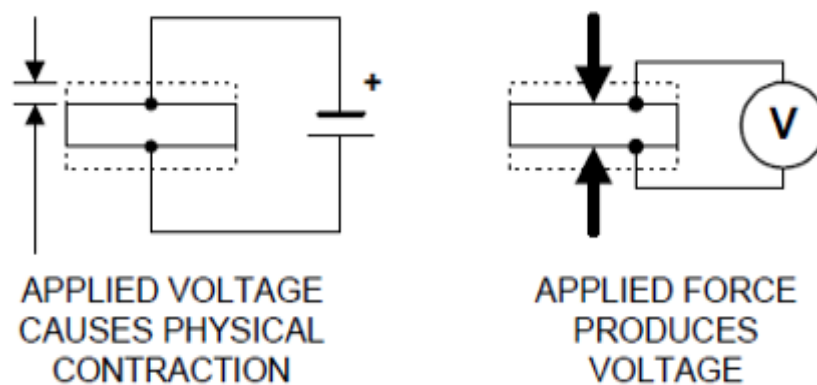
FIGURE 2.2   CONFIGURATIONS OF PIEZOELECTRICITY PROCESS

If a crystal is placed into the feedback path of an amplifier circuit it begins to oscillate at a frequency dependent primarily on the dimensions of the crystal. Figure 2.3 shows the basic crystal oscillator configurations. [4]

CRYSTAL

CONTROL
VOLTAGE

SERIES RESONANT
OSCILLATOR

CONTROL
VOLTAGE

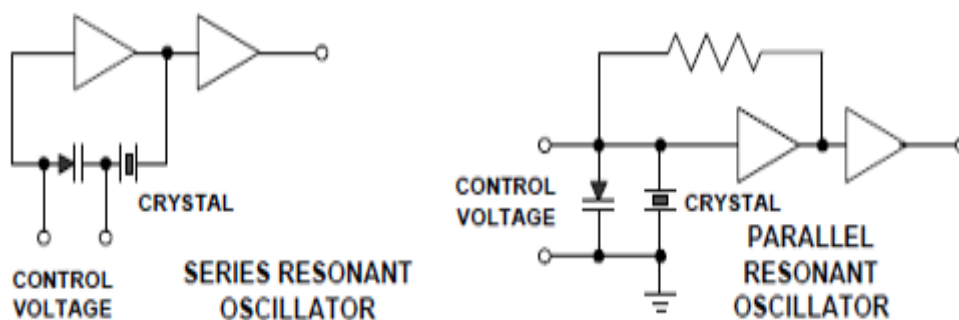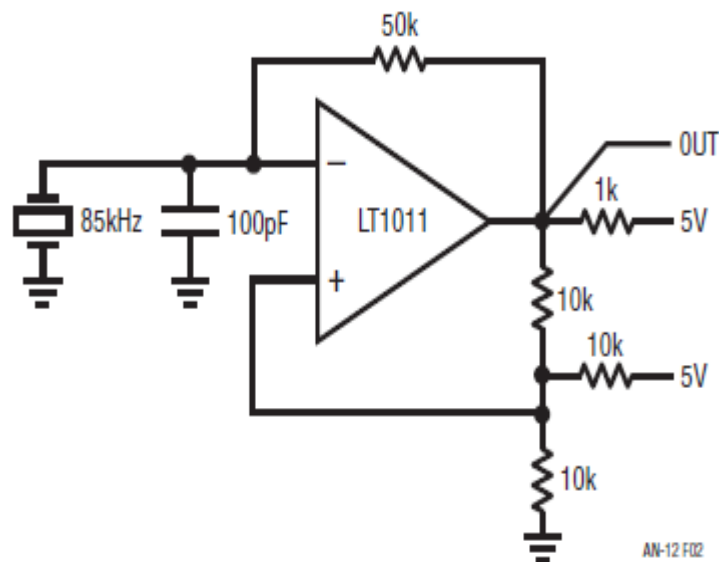CRYSTAL

PARALLEL
RESONANT
OSCILLATOR

FIGURE 2.3   A BASIC CRYSTAL OSCILLATOR (XO) CONFIGURATIONS

There are, basically, two categories of oscillators that are of interest to the electronics engineers: Harmonic and relaxation. The former produce sinusoidal waveforms and contains at least one active component that supplies power constantly to the passive components, whereas relaxation oscillators produce non-sinusoidal waveform, such as rectangular pulses. An oscillator is generally an amplifier operating with positive feedback in a manner whereby an output is produced without any input signal. To achieve the desired frequency every oscillator contains a frequency determining part, which may be an *LC* circuit, a phase shifting *RC* network or a quartz crystal.

Figure 2.4 shows another approach. This circuit uses a standard RC-comparator multi vibrator circuit with the crystal connected directly across the timing capacitor. Because the free running frequency of the circuit is close to the crystal's resonance, the crystal "steals" energy from the RC, forcing it to run at the crystal's frequency. It is important to ensure that enough current is available to quickly start the crystal resonating while simultaneously maintaining an RC time constant of appropriate frequency. Typically, the free running frequency should be set 5% to 10% above crystal resonance with a resistor feedback value calculated to allow about 100μA into the capacitor-crystal network. This type of circuit is not recommended for use above a few hundred kHz because of comparator delays. [5]

[5]

FIGURE 2.4   CRYSTAL STABILIZED RELAXATION OSCILLATOR

2.1.1.1   REQUIREMENTS OF A CLOCK OSCILLATOR

Clock oscillators must be reliable, easily reproducible and simple.

3. TYPES OF MODULATION

There are three types of modulation.

3.1 A.M (AMPLITUDE MODULATION)

In amplitude modulation, the amplitude (signal strength) of the carrier wave is varied in proportion to the waveform being transmitted.
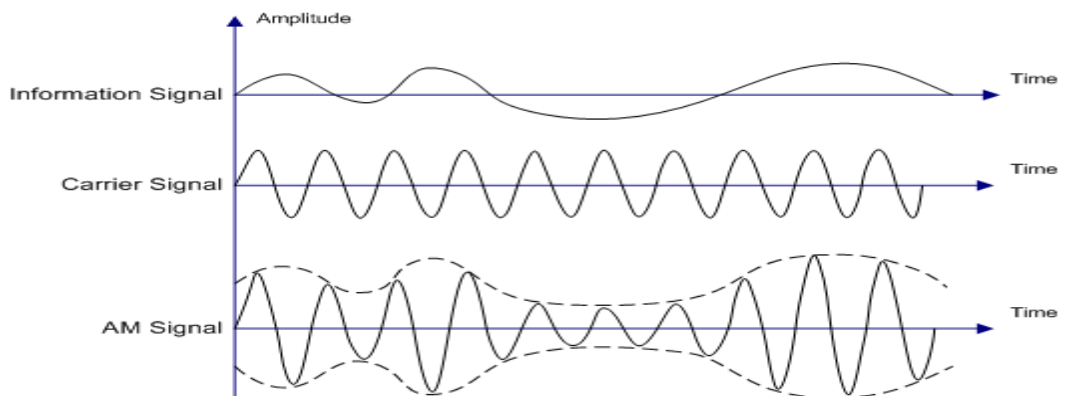

FIGURE 3.1 AMPLITUDE MODULATION SIGNALS

3.2 F.M (FREQUENCY MODULATION)

Frequency modulation (FM) is a modulation technique used in electronic communication, most commonly for transmitting information via a radio carrier wave. [3]
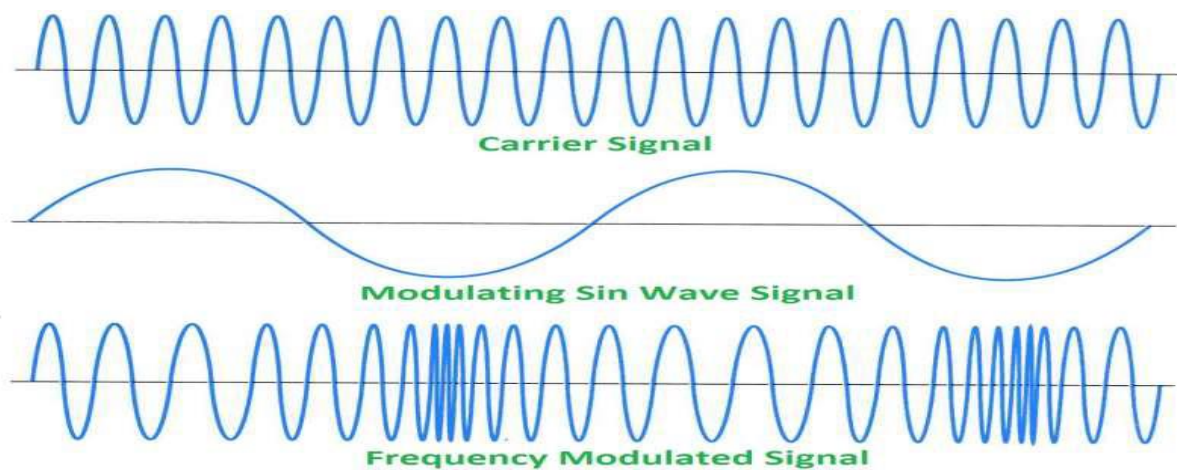

FIGURE 3.2 FREQUENCY MODULATION SIGNALS

3.3   P.W.M (PULSE WIDTH MODULATION)

Pulse-width modulation (PWM) is a digital modulation technique in which the width of a pulse carrier is changed according to the instantaneous value of the information signal. [3]

Pulse Width Modulation method is a fixed dc input voltage is given to the inverters and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components. This is the most popular method of controlling the output voltage and in this method is known as pulse width modulation (PWM CONTROL).

converters and motors, the PWM technique is mostly used to supply AC current to the load by converting the DC current and it appears as a AC signal at load or can control the speed of motors that run at high speed or low. The duty cycle of a PWM signal varies through analog components, a digital microcontroller or PWM integrated circuits.
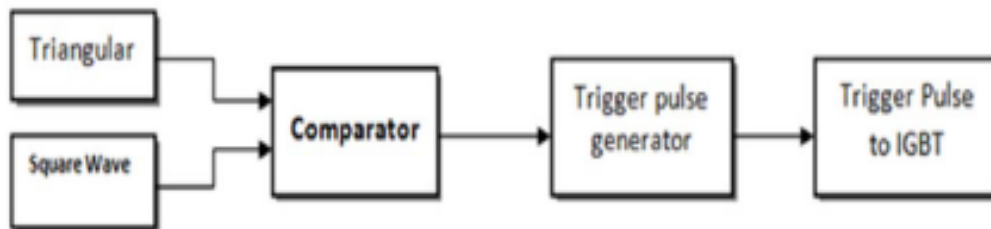
FIGURE 3.3   BLOCK DIAGRAM OF PWM SIGNAL GENERATION

Figure 3.3 shows the comparator gets the inputs as reference waveform (square wave) and a carrier wave (triangular wave) is supply to the comparator to obtained PWM waveform. Triangular wave is formed by op-amp driver. Triggering pulses are produced at the instant of the carrier signal magnitude is greater than the reference signal magnitude. To turn-on the IGBT switches, firing pulses are produced, the output voltage during the interval triangular voltage wave stipulated the square modulating wave.

ADVANTAGES OF PWM TECHNIQUE:

• Output voltage can be controlled without other components.
• Output voltage can be controlled, lower order harmonics can be eliminated and filtering out higher order harmonics by this filter requirements is minimized.

DISADVANTAGES OF PWM TECHNIQUE:

• The inverter switches are costly as they must have low turn off and turn on times. [6]

4.   TYPES OF P.W.M TECHNIQUE

A number of PWM techniques are there to obtain variable voltage and frequency supply such as,

(I)   Single-Pulse Modulation
(II) Multiple-Pulse Modulation
(III) Selected Harmonic Elimination PWM (SHEPWM)
(IV) Minimum Ripple Current PWM
(V) Sinusoidal-Pulse PWM (SPWM)
(VI) Space Vector-Pulse PWM (SVPWM) [6]

4.1   SINGLE PULSE WIDTH MODULATION (SINGLE PWM)

In single pulse width modulation control technique only one pulse is present in every half cycle. By adjusting the width of the single pulse we can control the output voltage of the inverter. The gating signals are generated by comparing rectangular reference signal of amplitude (A_r) and a triangular carrier wave (Ac), which has been shown in Figure 4.1.

This generated gating signal can be used to control the output of single phase full bridge inverter. The fundamental frequency of the output voltage can be obtained by the frequency of the reference signal.

For this technique the amplitude modulation index (M) can be defined as $M=A_cA_r$, whereas the instantaneous output voltage of the inverter can be given as $V_0= V_1 (S_1 - S_4)$.
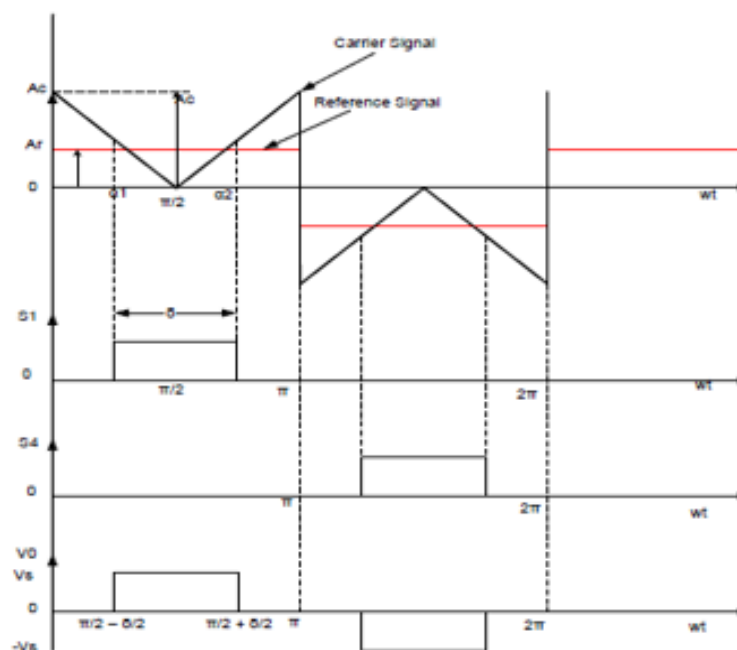

FIGURE 4.1   GENERATION OF SINGLE PULSE WIDTH MODULATION

The single pulse-width modulation converts the reference signal to the square wave signal. This process is obtained by inter the reference signal to the zero-crossing circuit which consider the positive part of the input signal is positive part of the output signal (square wave) and the negative part of the input signal is negative part of the output signal as shown in Figure 4.1. [7]

4.2 MULTIPLE PULSE WIDTH MODULATION (MPWM)

The main drawback of single PWM technique is high harmonic content. The multiple PWM technique is used in order to reduce the harmonic content. In this technique, a number of pulses are given in each half cycle of output voltage. The gating signal are generated by comparing the reference signal of the amplitude (A_r) with a triangular carrier wave (A_c) as shown Figure 4.2.
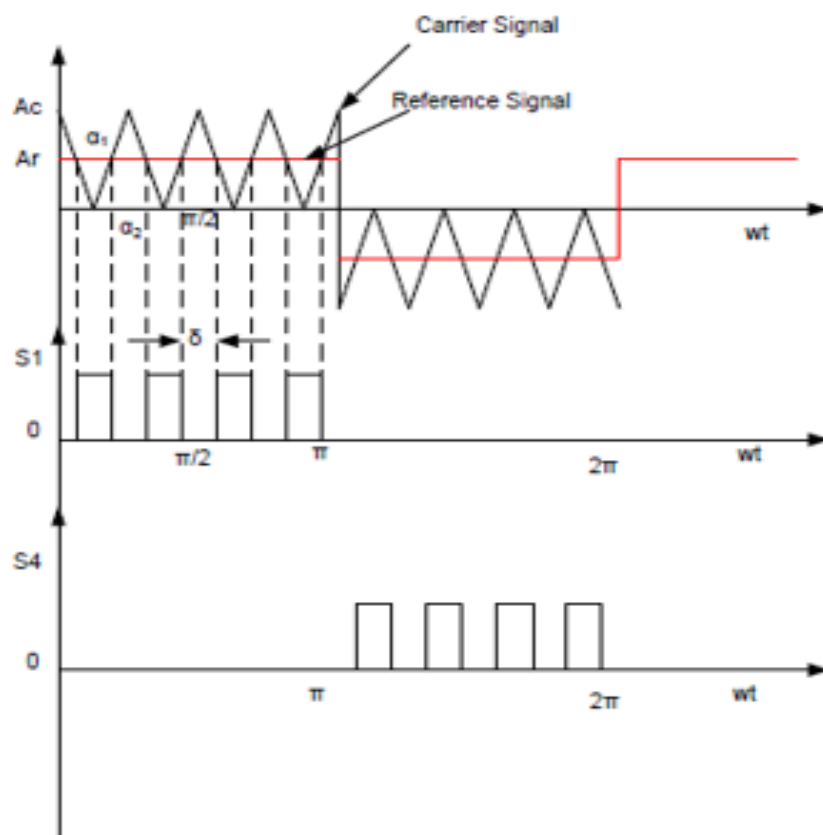

FIGURE 4.2   GENERATION OF MULTIPLE PULSE WIDTH MODULATION

The frequency (f_0) of the output can be determined by the frequency of the reference signal. By varying the modulation index the output voltage can be controlled. The number of pulses 'P' per half cycle is calculated by the carrier frequency (f_c).

Number of pulses per half cycle is found by

$$P = \frac{f_c}{2f_0}$$

$$= \frac{M_f}{2}$$

Where

$M_f = \frac{f_c}{f_0}$, called as frequency modulation ratio.

The instantaneous output voltage of the inverter can be given as $V_0 = V_1 (S_1 - S_4)$. [8]

The variation of modulation index (M) from 0 to 1 varies the pulse from 0 to π/p and the output voltage from 0 to A_r (V_r). [7]

4.3   SELECTED HARMONIC ELIMINATION PWM

There are many popular methods are used to reduce the harmonics in order to get an effective results. The popular methods for high switching frequency are Sinusoidal PWM and Space Vector PWM. For low switching frequency methods are space vector modulation and selective harmonic elimination. The SPWM technique has disadvantage that it cannot completely eliminate the low order harmonics. Due to this it cause loss and high filter requirement is needed. In Space Vector Modulation technique cannot be applied for unbalanced DC voltages. SHE PWM technique uses many mathematical methods to eliminate specific harmonics such as 5th, 7th, 11th, and 13th harmonics. The popular Selective Harmonic Elimination method is also called fundamental switching frequency based on harmonic elimination Theory.

4.3.1   HARMONIC ELIMINATION THEORY

By applying Fourier series analysis, the output voltage can be obtained. Fourier series is an infinite sum of trigonometric functions that are economically related. [6]

$$f(t) = a_0 + \sum_{n=0}^{\infty} C_n Cos(2\pi n f_0 + \phi_n) \qquad (1)$$

Where,
n = Integer Multiple,
ϕ_0 = Initial Phase for nth Harmonic,
a_0 and C_n = Fourier Co-efficients,

The output voltage equation derived for different voltage sources is given below:

$$v(t) = \sum_{n=1,3,5}^{\infty} \frac{4V_{dc}}{n\pi} ((v_1 Cos(n\phi_1) + v_2 Cos(n\phi_1) \dots v_s Cos(n\phi_2)) Sin(n\omega t)) \qquad (2)$$

Where,
S = No. of dc sources connected per phase,
v_1, v_2, v_3 = level of dc voltage $0 < \theta_1 < \theta_2 < \theta_3 \dots \dots < \theta_s < \frac{\pi}{2}$ = Switching angles

For the above Fundamental peak voltage v (t), it is required to determine the switching angles and some lower order harmonics of phase voltage are zero. Among no of switching angles one is used for fundamental voltage selection and remaining (s-1) switching angles are needed to eliminate lower order harmonics. For a balanced three phase system, triplen harmonics are eliminated automatically by using line-line voltages so only non triplen odd harmonics are present. To minimize harmonic distortion and to achieve adjustable amplitude of the fundamental component, up to *s*-1 harmonic contents can be removed from the voltage waveform. To keep the number of eliminated harmonics at a constant level, all switching angles must satisfy the condition otherwise the total harmonic distortion (THD) increases dramatically.

In order to achieve a wide range of modulation indexes with minimized THD for the synthesized waveforms, a generalized selective harmonic modulation method is proposed, which is called virtual stage PWM. An output waveform is shown in Figure 4.3. [8]
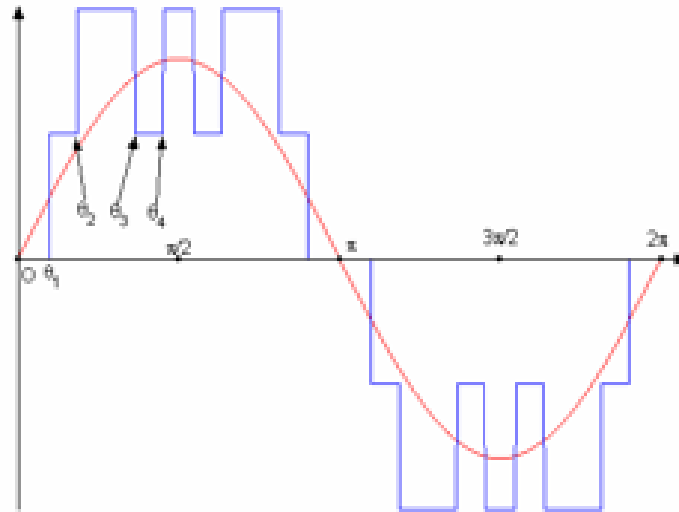

FIGURE 4.3   OUTPUT WAVEFORM OF VIRTUAL STAGE PWM CONTROL

Hence the relation between the fundamental voltage and maximum voltage is given by modulation Index. It is given by m1, is the ratio of fundamental voltage v1 to the maximum voltage.

The maximum voltage is given by

$$v_{1max} = \frac{4}{\pi}sV_{dc}$$

$$\text{m} = \frac{\pi v_1}{4sV_{dc}} \qquad (3)$$

Selective harmonic elimination control has been a widely researched alternative to traditional pulse-width modulation technique. The elimination of specific low-order harmonics from a given voltage/current waveform achieved by Selective Harmonic Elimination (SHE) technique.

In this method there is no need to calculate the firing angles for placing notches. Here, the lower order harmonics will be reduced by the dominant harmonics of same order generated in opposite phase by sine PWM inverter. This is achieved by varying the phase angle of the carrier wave of the sinusoidal Pulse Width Modulation (PWM) inverter, which generates the dominant harmonics with sidebands very close to the amplitude of prominent voltage harmonics present in the system but in opposite polarity.

In this method first, calculate the Total Harmonic Distortion (THD) for 3rd, 5th, 7th and 9th order harmonics. Then calculate the amplitude of these order (3rd, 5th, 7th, and 9th) harmonics with help of Total Harmonic Distortion (THD). After calculating amplitude, injecting the same order of harmonics in opposite amplitude Thus the resultant disorder sine wave is compared with triangular waveform and results in pulse are produced and will give to the switches. This method is simple and easy implementation method for reducing the Total Harmonic Distortion (THD).

4.3.2 LC-SECTION

Generally In inductor filter; the ripple feature is unswervingly comparative to the load resistance (RL). On the other hand in a capacitor filter, it is unreliable inversely through the load. Thus if we unite the inductor filter with the capacitor the ripple aspect will turn out to be more or less autonomous of the load filter. It is also said to be as LC-section. In LC filter an Inductor is connected in series with the load (RL). It offers high resistance path to the AC mechanism and allows DC component to flow through the load (RL). The capacitor transverse the load associated parallel and filter out if any AC constituent flowing through the inductance, In this manner the AC component are filtered and a flat DC is supplied all the way through the load. Here the distorted harmonics are removed and the smooth wave forms are obtained. [9]

4.4 MINIMUM RIPPLE CURRENT PWM

One disadvantage of the SHE PWM method is that the elimination of lower order harmonics considerably boosts the next higher level of harmonics. Since the harmonic loss in a machine is dictated by the RMS ripple current, it is the parameter that should be minimized instead of emphasizing the individual harmonics.

4.5   SINUSOIDAL PULSE WIDTH MODULATION (SPWM)

The Sinusoidal PWM is a modulation technique in which a sinusoidal signal is compared with the triangular signal, in which the frequency of triangular signal (f_{tri}) is equals to the desired sinusoidal output and the frequency of triangular signal gives the switching frequency of the switches. [6]

It produces a sinusoidal waveform by filtering an output pulse waveform with varying width. A high switching frequency leads to a better filtered sinusoidal output waveform. The variations in the amplitude and frequency of the reference voltage change the pulse-width patterns of the output voltage but keep the sinusoidal modulation.[10]

In three-phase SPWM, a triangular voltage waveform (V_T) is compared with three sinusoidal control voltages (V_a, V_b, and V_c), which are 120^0 out of phase with each other and the relative levels of the waveforms are used to control the switching of the devices in each phase leg of the inverter.[10]

A six-step inverter is composed of six switches S1 through S6 with each phase output connected to the middle of each inverter leg as shown in Figure 2.2. The output of the comparators in Figure 2.1 form the control signals for the three legs of the inverter. Two switches in each phase make up one leg and open and close in a complementary fashion.
That is, when one switch is open, the other is closed and vice-versa. The output pole voltages V_{ao}, V_{bo}, and V_{co} of the inverter switch between $-V_{dc}/2$ and $+V_{dc}/2$ voltage levels where V_{dc} is the total DC voltage.

The peak of the sine modulating waveform is always less than the peak of the triangle carrier voltage waveform. When the sinusoidal waveform is greater than the triangular waveform, the upper switch is turned on and the lower switch is turned off. Similarly, when the sinusoidal waveform is less than the triangular waveform, the upper switch is off and the lower switch is on. Depending on the switching states, either the positive or negative half DC bus voltage is applied to each phase. The switches are controlled in pairs ((S_1; S_4), (S_3; S_6), and (S_5; S_2)) and the logic for the switch control signals is:

S_1 is ON when $V_a > V_T$ S_4 is ON when $V_a < V_T$

S_3 is ON when $V_b > V_T$ S_6 is ON when $V_b < V_T$

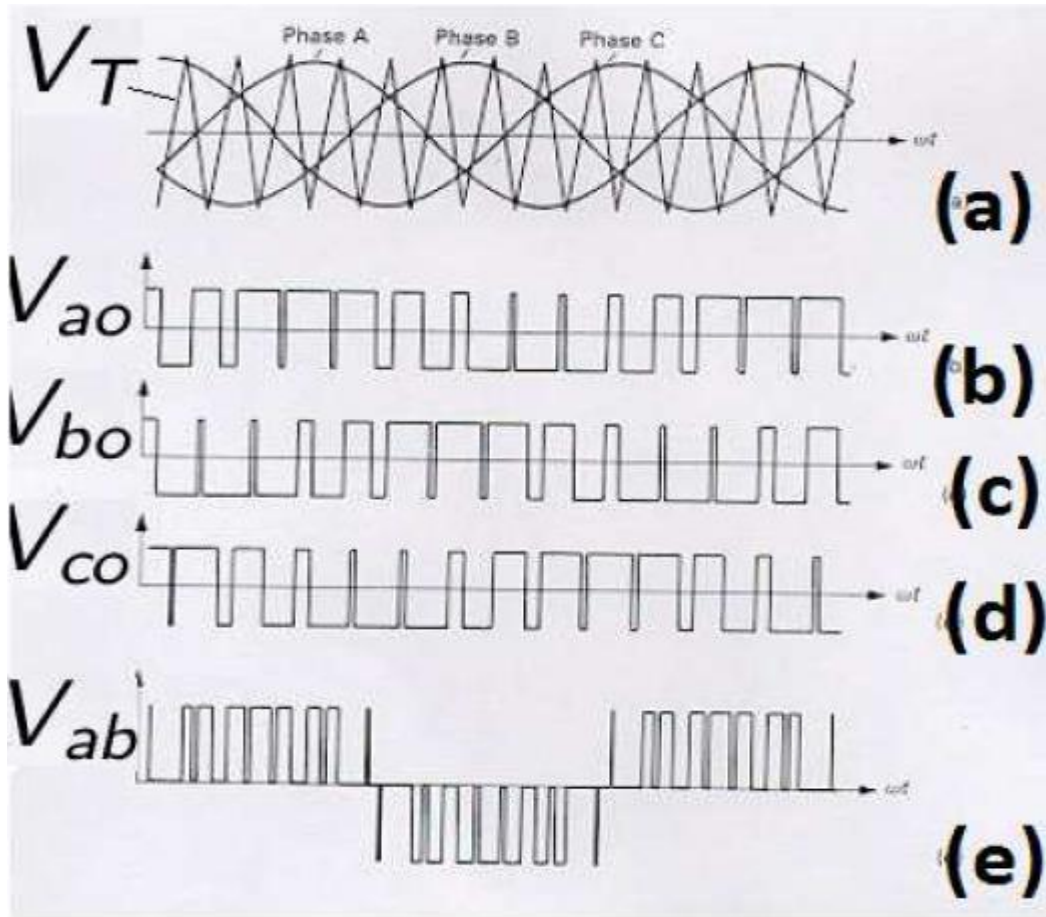S_5 is ON when $V_c > V_T$ S_2 is ON when $V_c < V_T$

FIGURE 4.4   THREE-PHASE SINUSOIDAL PWM: A) REFERENCE VOLTAGES (A, B, C) AND TRIANGULAR WAVE, B) V_{AO}, C) V_{BO}, D) V_{CO}, E)   LINE-TO-LINE VOLTAGES

As seen in Figure 4.4, the pulse widths depend on the intersection of the triangular and sinusoidal waveforms. The inverter output voltages are determined as follows:

$$\text{If} \quad V_a > V_T \text{ then } V_{ao} = 0:5V_{dc}$$
$$V_b > V_T \text{ then } V_{bo} = 0:5V_{dc}$$
$$V_c > V_T \text{ then } V_{co} = 0:5V_{dc}$$

And

$$\text{If} \quad V_a < V_T \text{ then } V_{ao} = -0:5V_{dc}$$
$$V_b < V_T \text{ then } V_{bo} = -0:5V_{dc}$$
$$V_c < V_T \text{ then } V_{co} = -0:5V_{dc}$$

The inverter line-to-line voltages are obtained from the pole voltages as:

$$V_{ab} = V_{ao} - V_{bo}$$
$$V_{bc} = V_{bo} - V_{co}$$
$$V_{ca} = V_{co} - V_{ao}$$

[10]

5.4.1   MODULATION INDEX OF SINUSOIDAL PWM

The Fourier Series Expansion of a symmetrical square wave voltage with a peak magnitude of $V_{dc}/2$ has a fundamental of magnitude $2V_{dc}/\pi$. The maximum of the output voltage generated by the SPWM method is $V_{dc}/2$. The modulation index is defined as the ratio of the magnitude of output voltage generated by SPWM to the fundamental peak value of the maximum square wave. The magnitude of o/p voltage depends on modulation index which is defined as,

"The ratio V_T/V_{DC} is called Modulation Index (M_a)"

It controls the harmonic content of the output voltage waveform. Thus, the maximum modulation index of the SPWM technique is:

$$\text{Modulation Index } (M_a) = \frac{\text{Amplitude of Sinusoidal Signal}}{\text{Amplitude of Triangular signal}}$$

$$= \frac{Vpwm}{Vmax - Six\ Step}$$

$$= \frac{\frac{VDC}{2}}{\frac{2VDC}{\pi}}$$

$$= \frac{\pi}{4}$$

$$= 0.7855 = 78.55\%$$

Where V_{PWM} is the maximum output voltage generated by a SPWM
          $V_{max\text{-}Six\ Step}$ is the fundamental peak value of a square wave. [10]

ADVANTAGES

Controlled inverter output voltage
Reduction of harmonics

DISADVANTAGES

Increase of switching losses due to high PWM frequency
Reduction of available voltage
EMI problems due to high-order harmonics [6]

4.5.2 MODIFIED SINUSOIDAL PULSE WIDTH MODULATION

When considering sinusoidal PWM waveform, the pulse width does not change significantly with the variation of modulation index. The reason is due to the characteristics of the sine wave. Hence this sinusoidal PWM technique is modified so that the carrier signal is applied during the first and last 600 intervals per half cycle as shown in Figure 4.5.
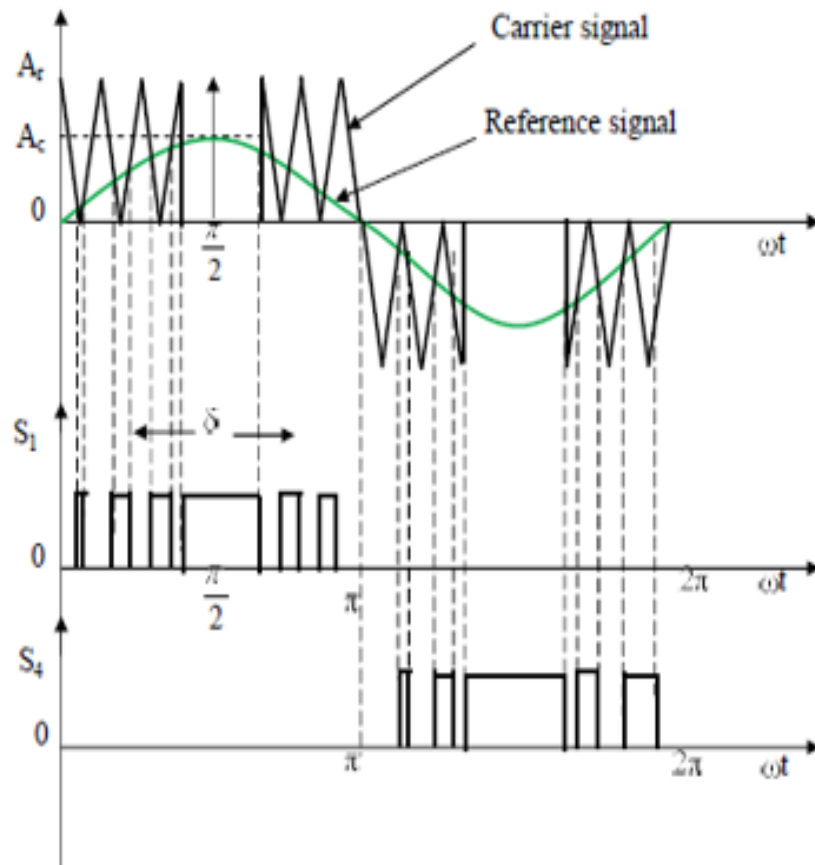
FIGURE 4.5   GENERATION OF MODIFIED SINUSOIDAL PULSE WIDTH MODULATION

The fundamental component is increased and its harmonic characteristics are improved. The main advantages of this technique is increased fundamental component, improved harmonic characteristics, reduced number of switching power devices and decreased switching losses.

ADVANTAGES OF PWM

1. The output voltage control with method can be obtained without any additional components
2. With this method, lower order harmonic can be eliminated or minimized along with its output voltage control.
3. It reduces the filtering requirements [11]

4.6 SPACE VECTOR PULSE WIDTH MODULATION

The space vector PWM (SVM) method is an advanced computation-intensive PWM method and is possibly the best method among the all PWM techniques for variable frequency drive application. Because of its superior performance characteristics, it has been finding wide spread application in recent years.

There are various variations of SVM that result in different quality and computational requirements. One major benefit is in the reduction of total harmonic distortion (THD) created by the rapid switching inherent to this PWM algorithm. [13]

It is an algorithm for the control of pulse width modulation (PWM). SVPWM is used for producing of alternating current (AC) waveforms. It is frequently used to drive 3-phase AC powered motors at variable speed from DC power. Various variations of SVPWM that result in different quality and computational requirements. The development is in the reduction of total harmonic distortion (THD) created by the rapid switching inherent to these algorithms.

Space vector modulation is a PWM regulator algorithm for multi-phase AC generation. The reference signal is sampled frequently, after each sample, non-zero active switching vectors adjacent to the reference vector and one or more of the zero switching vectors are preferred for the suitable fraction of the sampling period in order to integrate the reference signal as the average of the used vectors.

PRINCIPLE OF SPACE VECTOR PWM:

The circuit model of a typical three-phase voltage source PWM inverter is shown in Fig. 4.6, S_1 to S_6 are the six power switches that shape the output, which are controlled by the switching variables a, a', b, b', c and c'. When an upper IGBT is switched on, i.e., when a, b or c is 1, the corresponding lower IGBT is switched off, i.e., the corresponding a', b' or c' is 0.
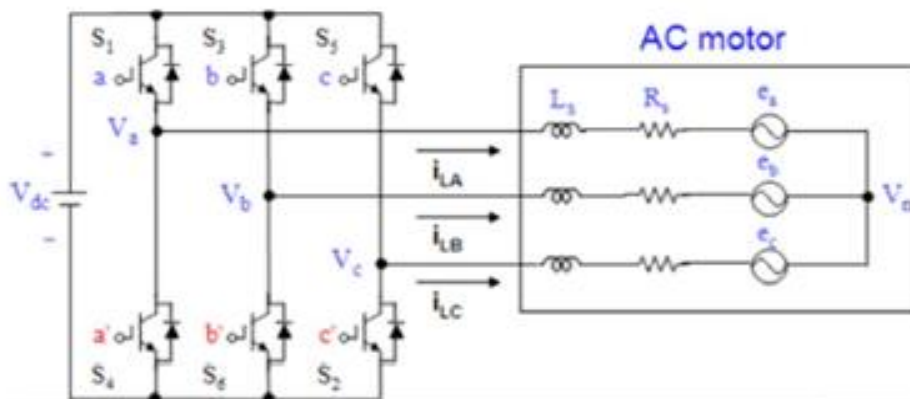
FIGURE 4.6   THREE-PHASE VOLTAGE SOURCE PWM INVERTER

Space vector representation of the three-phase inverter output voltages is introduced next. Space vector is defined as

$$V_s = (2/3)(V_a + a\, V_b + a^2\, V_c) \qquad (1)$$

Where,

$$A = \exp(j\, 2\pi/3)$$

The space vector is a simultaneous representation of all the three-phase quantities. It is a complex variable and is function of time in contrast to the phasors. Phase-to-neutral voltages of a star-connected load are most easily found by defining a voltage difference between the star point n of the load and the negative rail of the dc bus N. The following correlation then holds true,

$$V_A = V_a + V_{nN}$$
$$V_B = V_b + V_{nN} \qquad (2)$$
$$V_C = V_c + V_{nN}$$

Since the phase voltages in a start connected load sum to zero, summation of equation (2) yields

$$V_{nN} = (1/3)(V_A + V_B + V_C) \qquad (3)$$

Substitution of (3) into (2) yields phase -to-neutral voltages of the load in the following form:

$$V_a = (2/3)\, V_A - (1/3)(V_B + V_C)$$

$$V_b = (2/3)\, V_B - (1/3)(V_A + V_C)$$

$$V_c = (2/3)\, V_C - (1/3)(V_B + V_A)$$

Phase voltages are summarized in Table 1 and their corresponding space vectors are listed in Table 2.

TABLE 1 PHASE VOLTAGE VALUES FOR DIFFERENT SWITCHING STATE

STATE	SWITCH ON	V_A	V_B	V_C
1	1,4,6	(2/3)Vdc	-(1/3) Vdc	-(1/3) Vdc
2	1,3,6	(1/3) Vdc	(1/3) Vdc	-(2/3)Vdc
3	2,3,6	-(1/3) Vdc	(2/3)Vdc	-(1/3) Vdc
4	2,3,5	-(2/3)Vdc	(1/3) Vdc	(1/3) Vdc
5	2,4,5	-(1/3) Vdc	-(1/3) Vdc	(2/3)Vdc
6	1,4,5	(1/3) Vdc	-(2/3)Vdc	(1/3) Vdc
7 & 0	1,3, 5 & 2,4,6	0	0	0

And we have space vectors corresponding to above Phase voltages are as follows.

TABLE 2 PHASE VOLTAGE SPACE VECTORS.

State	Phase voltage space vectors
1	(2/3)Vdc
2	(2/3)Vdc exp (j π/3)
3	(2/3)Vdc exp (j2π/3)
4	(2/3)Vdc exp (j π)
5	(2/3)Vdc exp (j4π/3)
6	(2/3)Vdc exp (j5π/3)
7 & 0	0

The discrete phase voltage space vector positions are shown in Figure 4.7 [12]
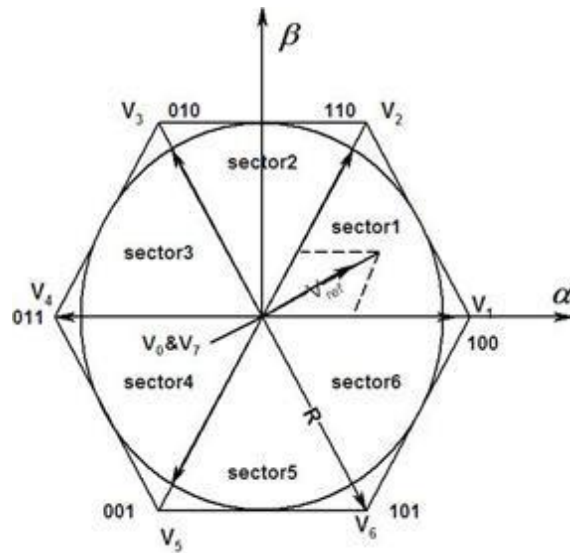
FIGURE 4.7   PHASE VOLTAGE SPACE VECTORS

The major advantage of SVPWM method is from the fact that there is a degree of freedom of space vector placement in a switching cycle. This improves the harmonic performance of this method. [7]

5. INDUCTION MACHINE

Three-phase squirrel-cage type induction motors (IM) have been favoured because of their good self-starting capability, simple and rugged structure, low cost and reliability, etc. These motors are commonly utilized in the industries from the capacity of several kilowatts to thousands of kilowatt as the driving units for fans, pumps, and compressors.

Usually, the motors are maintained periodically. However, when the ground fault occurs at the motor terminal, a serious damage may be brought to the motor. In the worst case, the motor is unable to start after the restoration of the power supply. Also it has been known that re-switching the supply onto a squirrel cage induction motor can result in the production of large negative torque transients. Therefore, it is significant to understand the transient phenomena under abnormal conditions for the optimal design of induction motors.

In this method of analysis, it is assumed that the effect of saturation due to either the magnetizing inductance or the leakage inductances is negligible. Using this assumption, the values of the magnetizing inductance, stator leakage, and rotor leakage inductances are constant and thus do not vary with the magnetizing current. Also several methods have been developed for the modelling of saturation effects in induction machines. For example in induction motor with saturable leakage reactance is modelled. [14]

SYSTEM OF EQUATIONS

The voltage equation can be written for each winding i:

$$u_i = R_i * i_i + \frac{d\psi_i}{dt}$$

Magnetic flux ψ_i can be expressed:

$$\psi_i = L_{ii} * i_i + \sum_{i,j=a}^{c} M_{ij(j \neq 1)} * i_{j(j \neq i)}$$

Angle q - mutual position between stator and rotor depends on mutual angular velocity between them

$$\Theta = \int \omega dt$$

Usually, three stator voltages, three rotor voltages and angular velocity are chosen. In order to reduce the number of electrical equations, the Clarke and Park transformations are established.

CLARKE TRANSFORMATION

It is assumed for the stator and rotor currents:

$$i_{Sa} + i_{Sb} + i_{Sc} = 0 \qquad i_{Ra} + i_{Rb} + i_{Rc} = 0$$

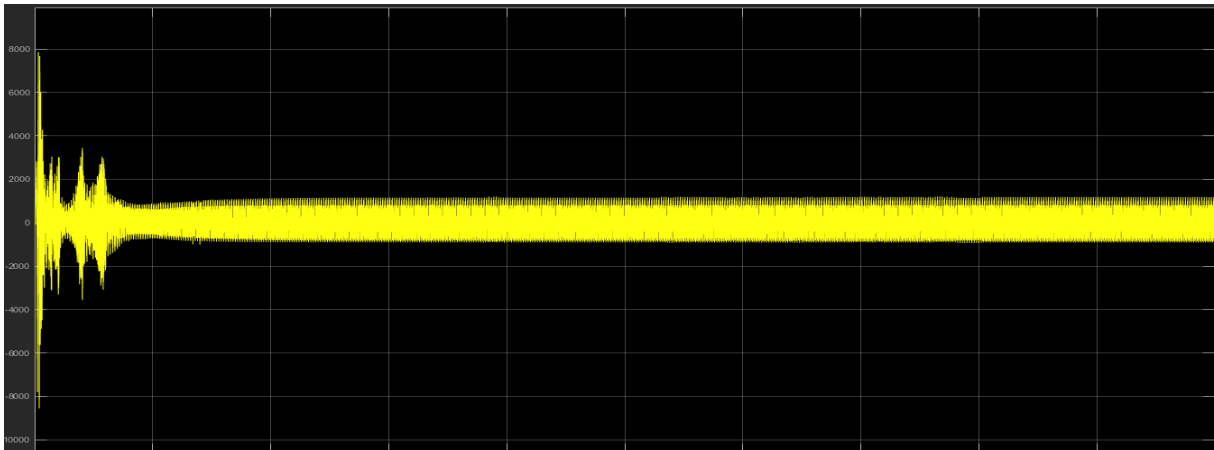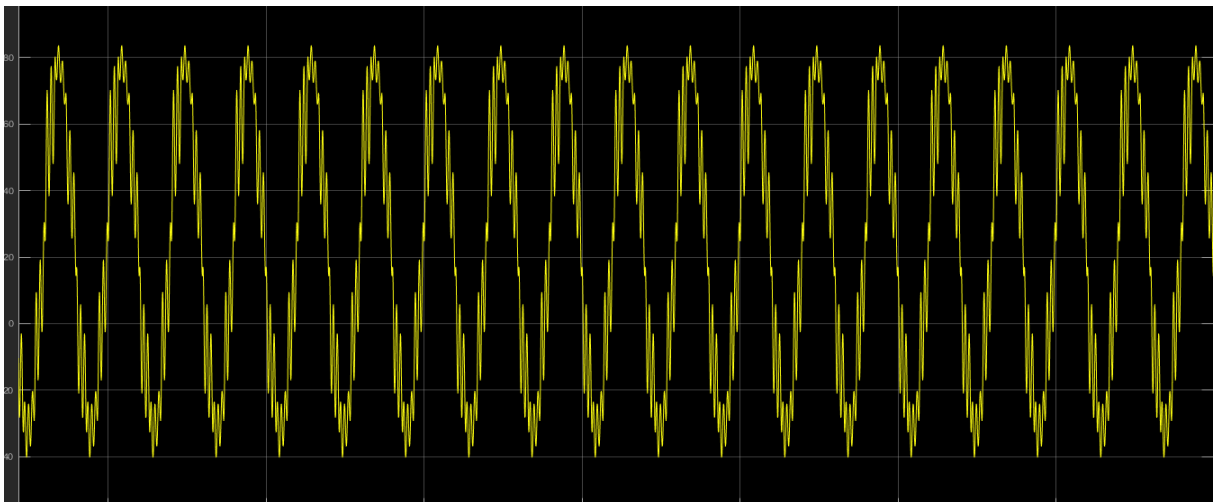The three-phase windings system abc is transformed into the system αβ of two windings that are perpendicular, so that the mutual inductance is zero. This transformation is called the 3/2 transformation or Clarke transformation.

$$i_{S\alpha} = i_{Sa} \quad , \quad i_{S\beta} = \frac{1}{\sqrt{3}}*i_{Sa} + \frac{2}{\sqrt{3}}*i_{Sb}$$
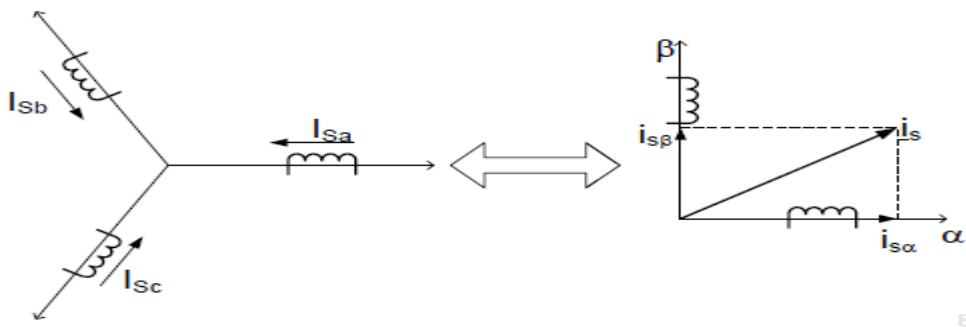
FIGURE 5.1   CLARKE TRANSFORMATION

PARK TRANSFORMATION

The two windings system αβ is transformed into another system UV that rotates with angular speed ω_k.

$$i_{Su} = i_\alpha*\text{Cos } \theta_k + i_\beta*\text{Sin}\theta_k \qquad i_{Sv} = -i_\alpha*\text{Sin}\theta_k + i_\beta*\text{Cos}\theta_k$$
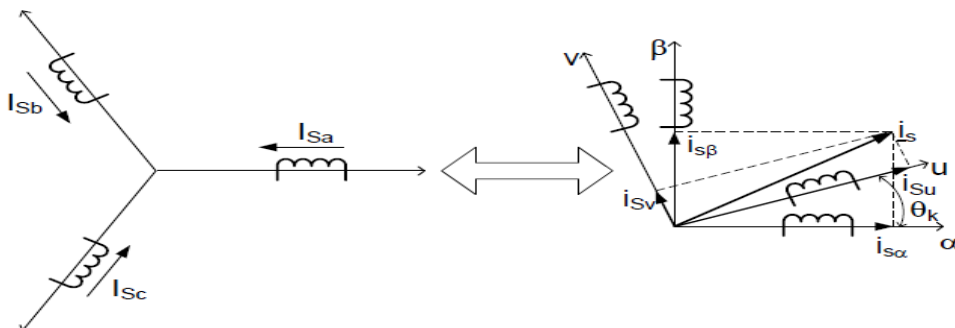
FIGURE 5.2   PARK TRANSFORMATION

TRANFORMED VOLTAGE EQUATION

The set of voltage equations after the Park transformation into the general system uv that rotates with angular speed ω_k:

$$u_{Su} = R_S * i_{Su} + \frac{d\psi_{Su}}{dt} - \omega_{k}*\psi_{Sv}$$

$$u_{Sv} = R_S * i_{Sv} + \frac{d\psi_{Sv}}{dt} - \omega_{k}*\psi_{Su}$$

$$u_{Ru} = R_R * i_{Ru} + \frac{d\psi_{Ru}}{dt} - (\omega_k - \omega)*\psi_{Rv}$$

$$u_{Rv} = R_R * i_{Rv} + \frac{d\psi_{Rv}}{dt} + (\omega_k - \omega)*\psi_{Ru}$$

The rotor voltages u_{Su} and u_{Sv} are zeros for a squirrel cage induction machine.

TRANSFORMED FLUX EQUATIONS

The imagination of the flux in an induction machine can be as depicted in the picture. Then, the flux equations can be written:

$$\psi_{Su} = L_S * i_{Su} + L_h * i_{Ru} \qquad \psi_{Sv} = L_S * i_{Sv} + L_h * i_{Rv}$$

$$\psi_{Ru} = L_S * i_{Ru} + L_h * i_{Su} \qquad \psi_{Rv} = L_S * i_{Rv} + L_h * i_{Sv}$$
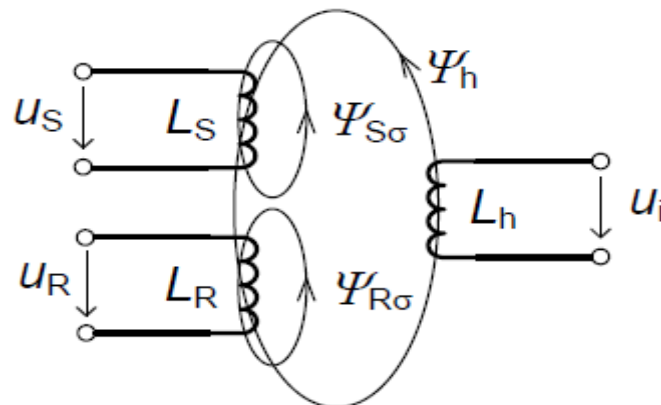
FIGURE 5.3 TRANSFORMED FLUX

The electromagnetic torque T_e can be expressed as:

$$T_e = \frac{3}{2} * p_p * \frac{L_h}{L_R} * (\psi_{Ru} * i_{Sv} + \psi_{Rv} * i_{Su})$$

p_p ... number of pole-pairs

The motion equation is usually written as:

$$T_e - T_L = J * \frac{d\omega_m}{dt}$$

$$\omega = p_p * \omega_m$$

Where, T_L is the load torque, J is the moment of inertia, ω_m is the mechanical angular speed and ω is the electrical angular frequency.

There are several ways, how to form the system of equations that describes the model of an induction machine. It depends on a selection on state quantities. Let's select the stator current i_s, the rotor flux ψ_R and mechanical rotational speed ω_m.

The state quantities have to be in the simulation equations in form of differential coefficient – they will be integrated and therefore the system of equations will be stable.

6. SIMULINK MODEL

6.1 INDUCTION MOTOR DRIVE
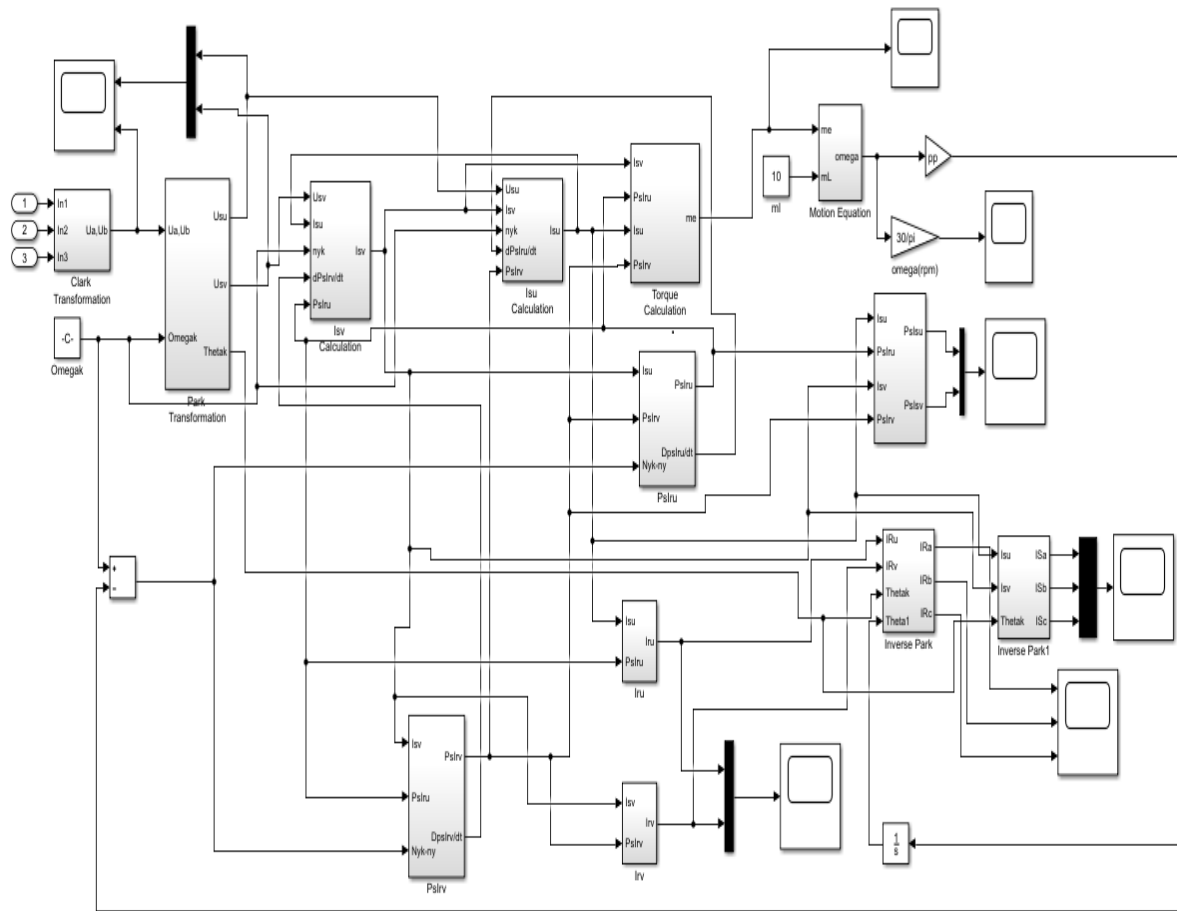
FIGURE 6.1   UNSATURATED INDUCTION MOTOR

6.2 INDUCTION MOTOR FED BY AN INVERTER
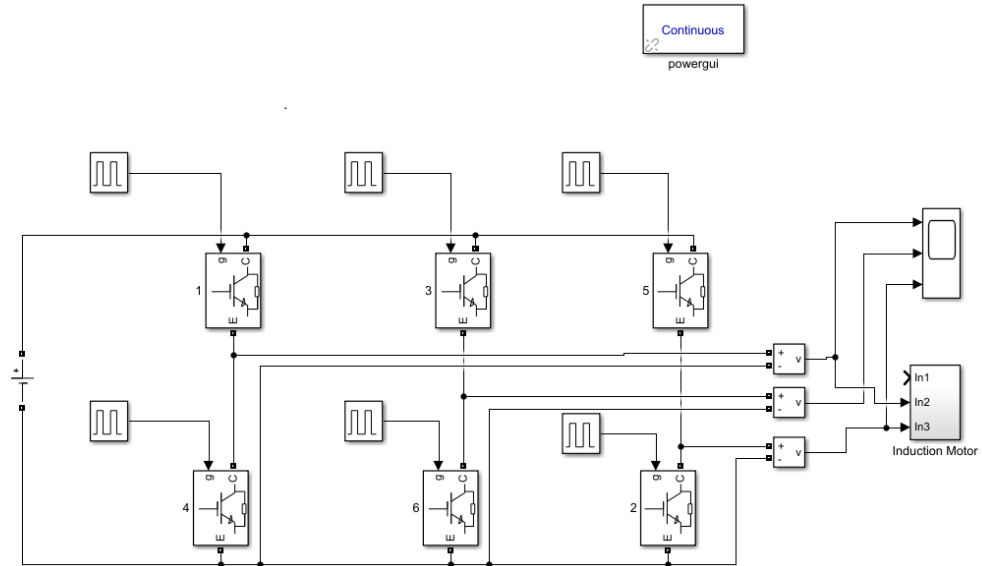
FIGURE 6.2   IM FED BY VSI

FIGURE 6.2.1   INPUT SUPPLY VOLTAGE
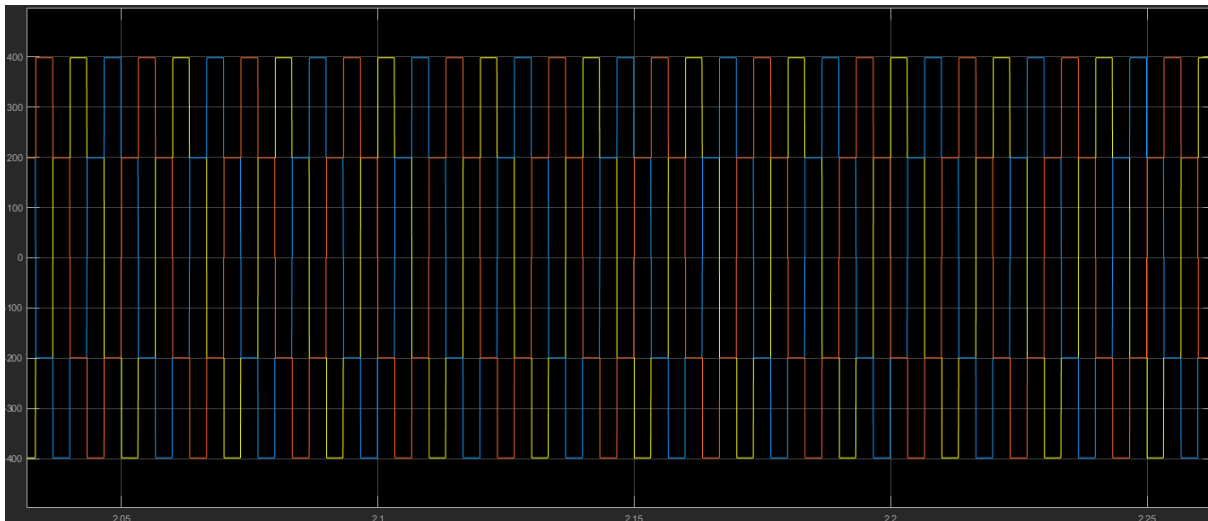
FIGURE 6.2.2 CLARKE TRANSFORMATION
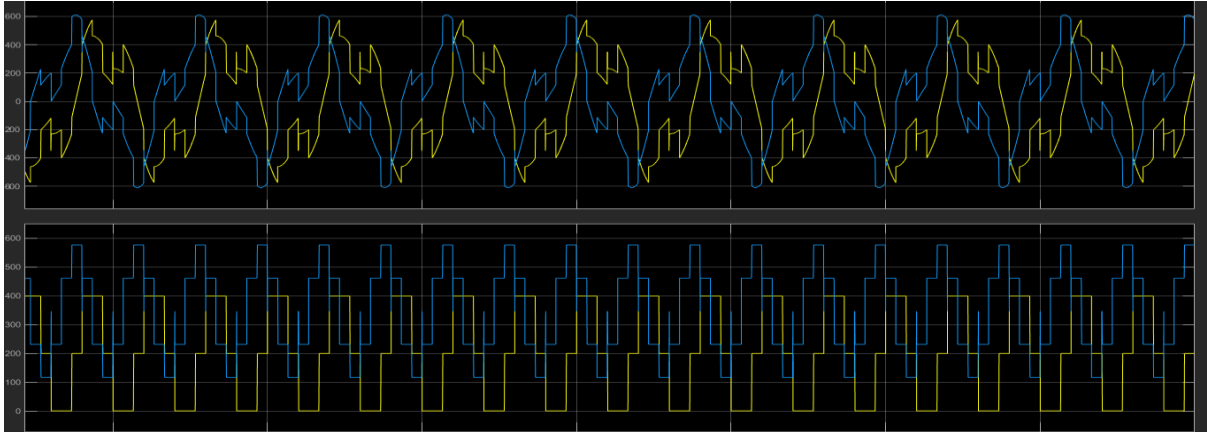
From above graph and Simulink model, we can observe that by using Clark transformation the three-phase windings system is transformed into the system of two windings that are perpendicular, so that the mutual inductance is zero.
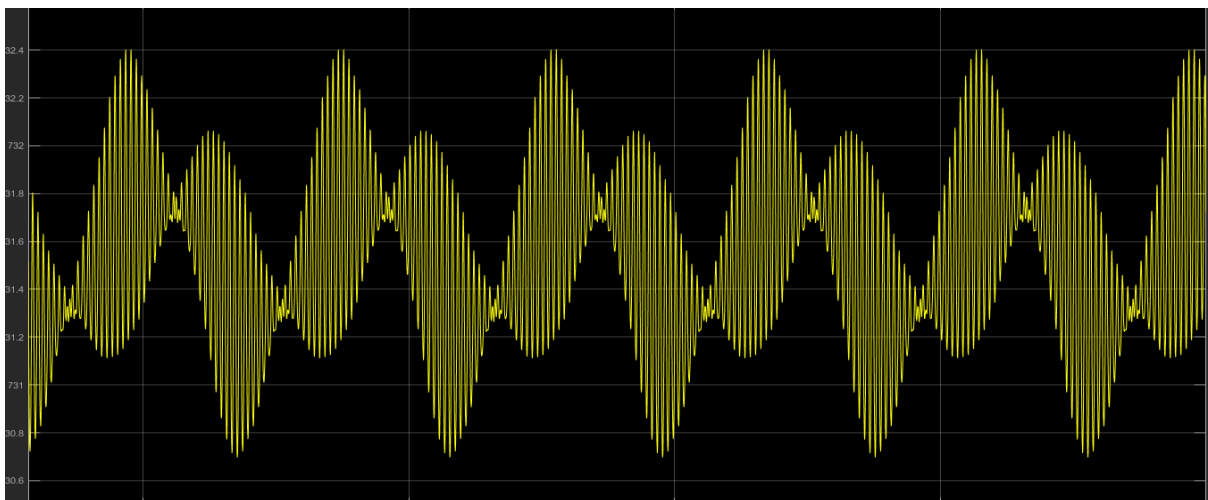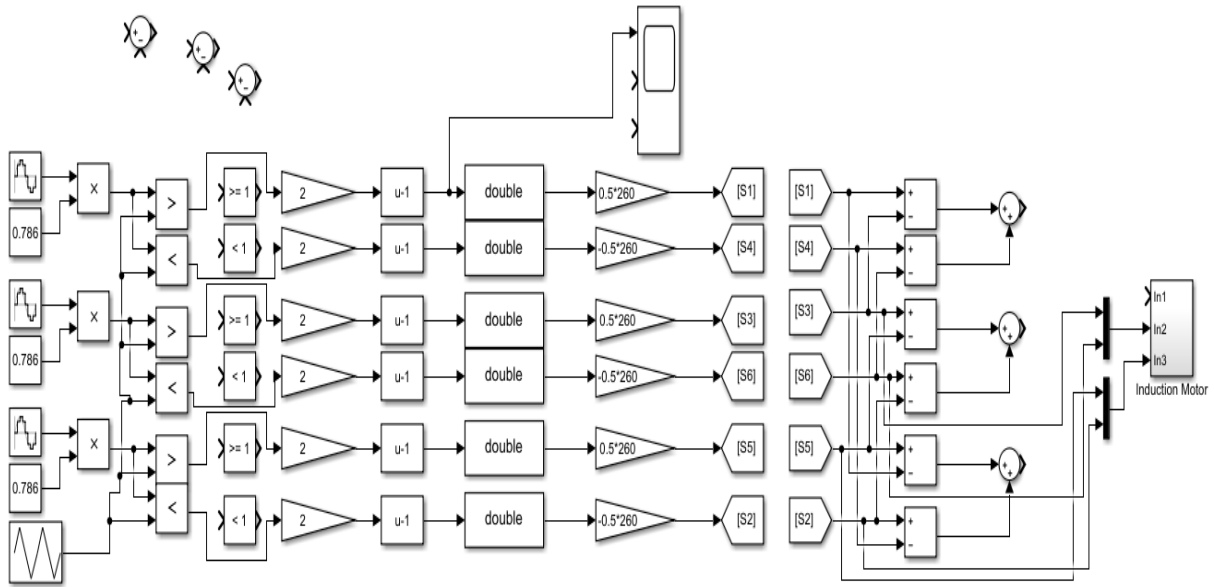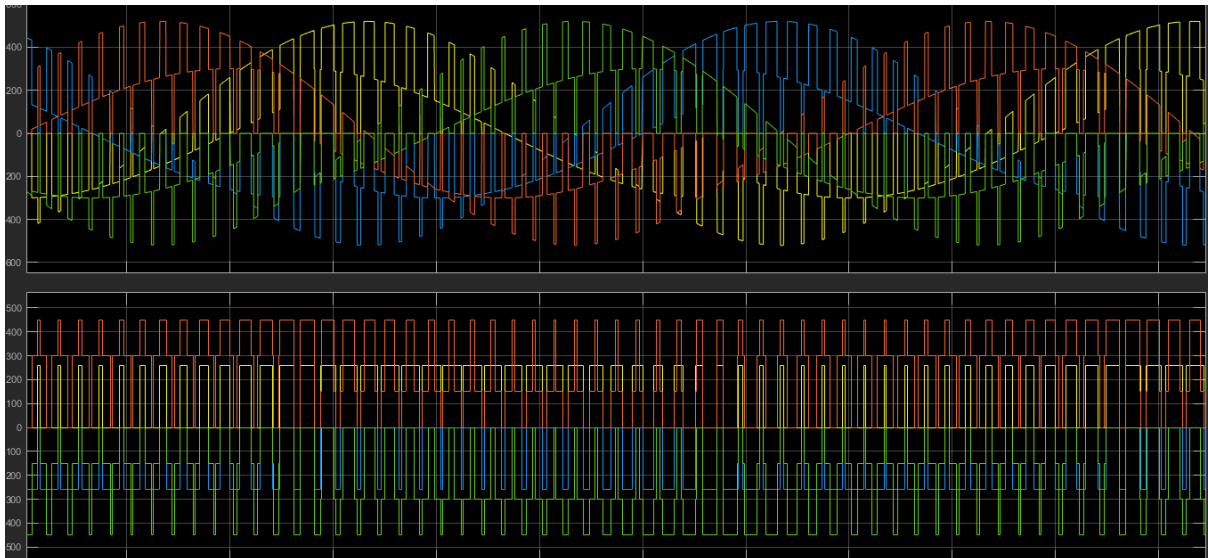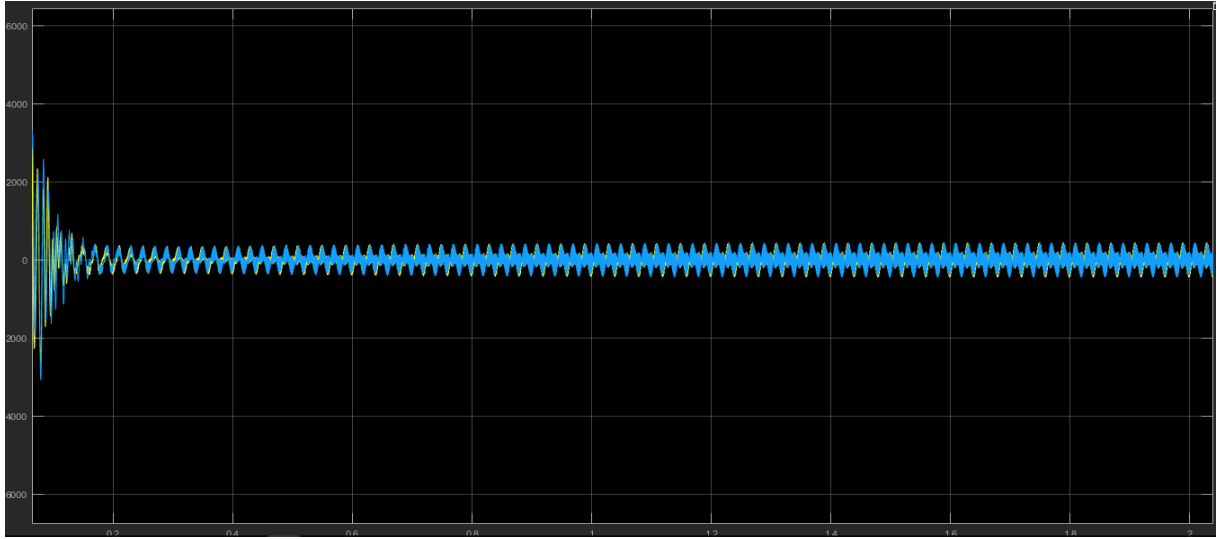
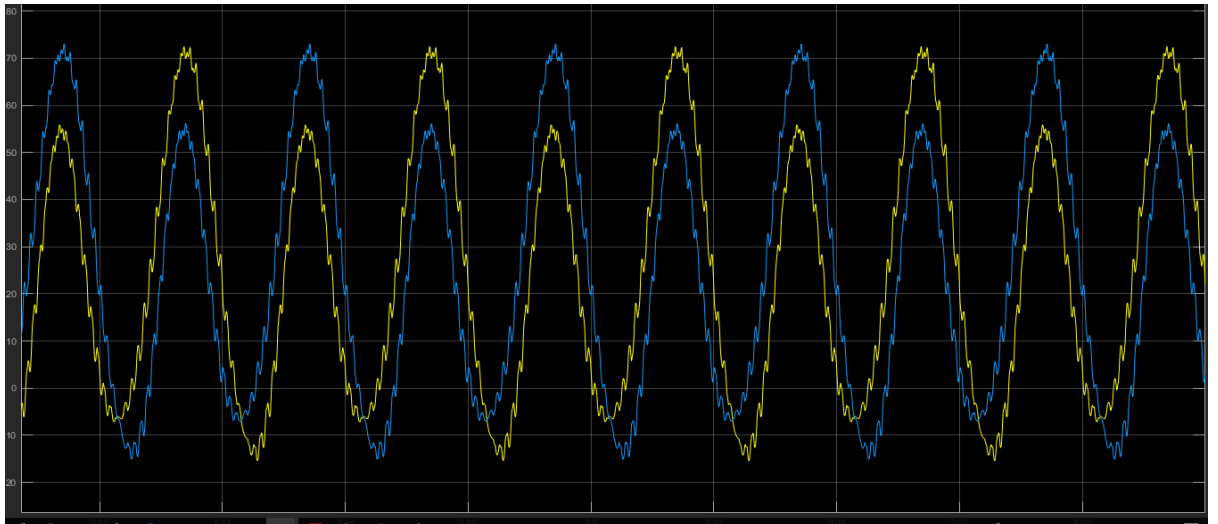FIGURE 6.2.3   TORQUE

FIGURE 6.2.4   MOTION

FIGURE 6.2.5   STATOR CURRENTS
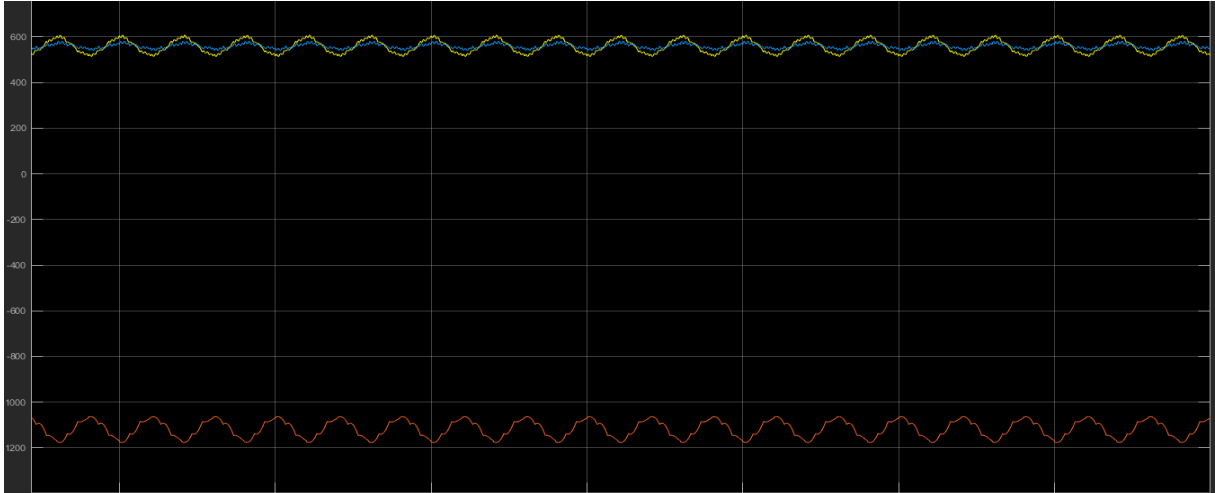
FIGURE 6.2.6   ROTOR CURRENTS
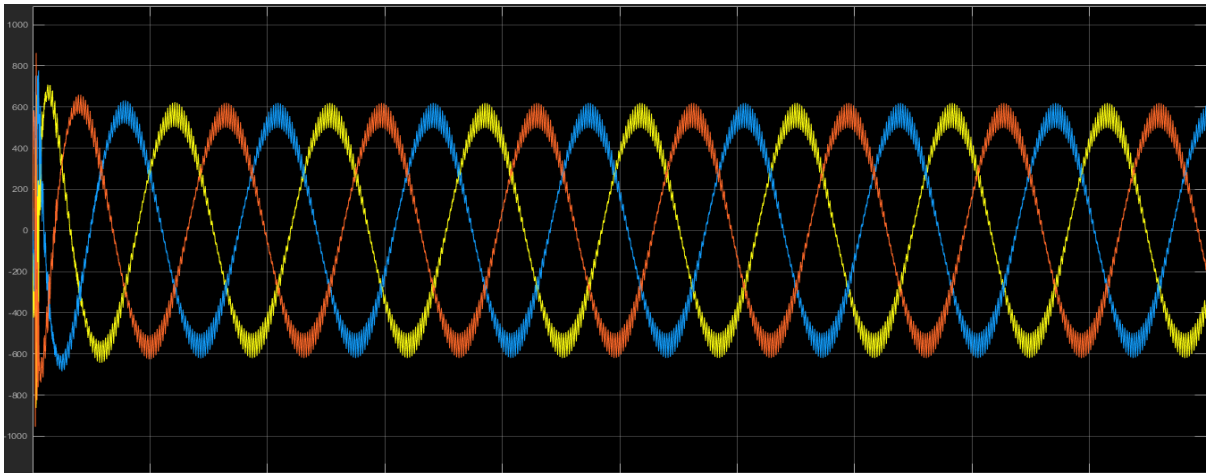
FIGURE 6.2.7   U,V COMPONENTS OF ROTOR CURRENTS
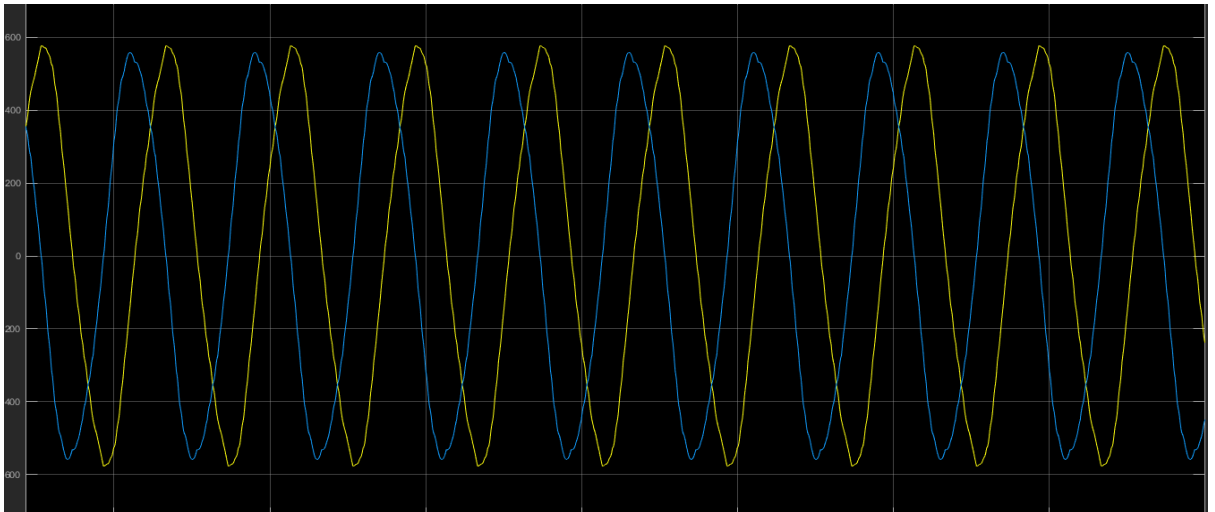
6.3   INDUCTION MOTOR FED BY PWM
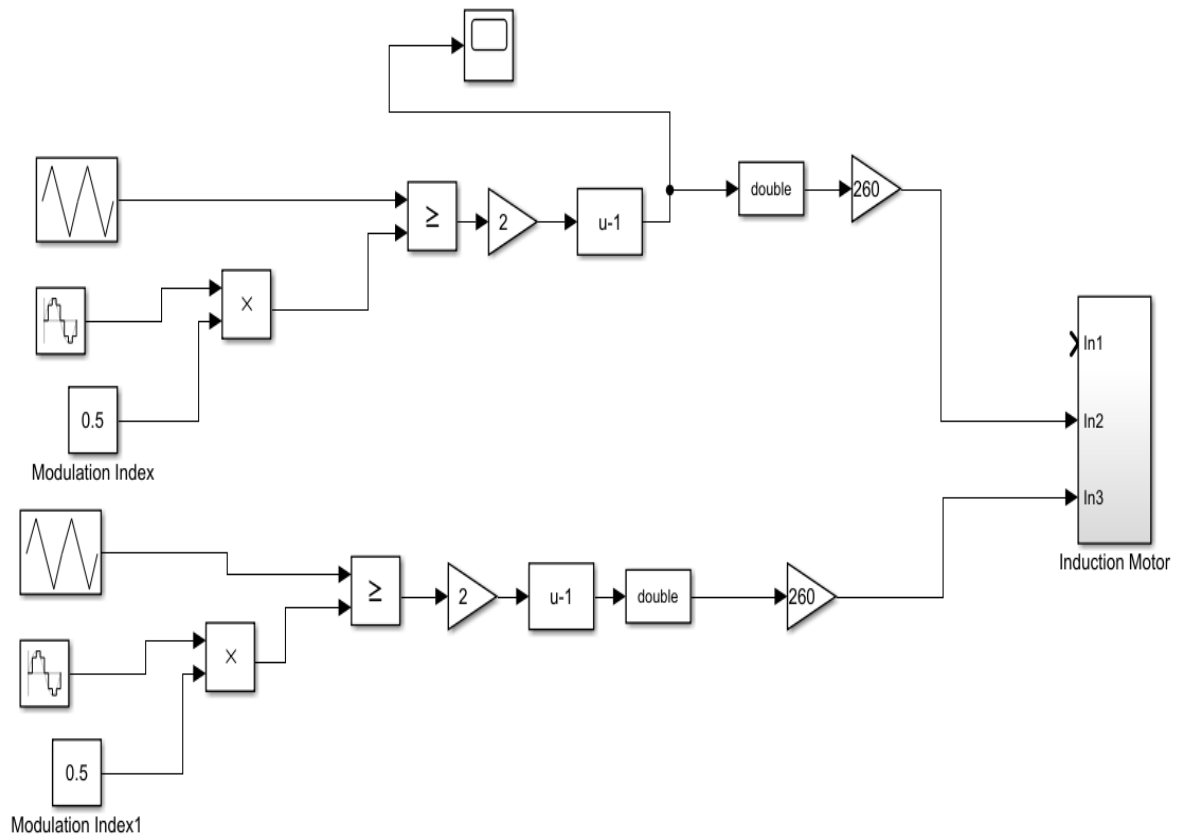
FIGURE 6.3 IM FED BY PWM INVERTER

FIGURE 6.3.1   INPUT SUPPLY VOLTAGE
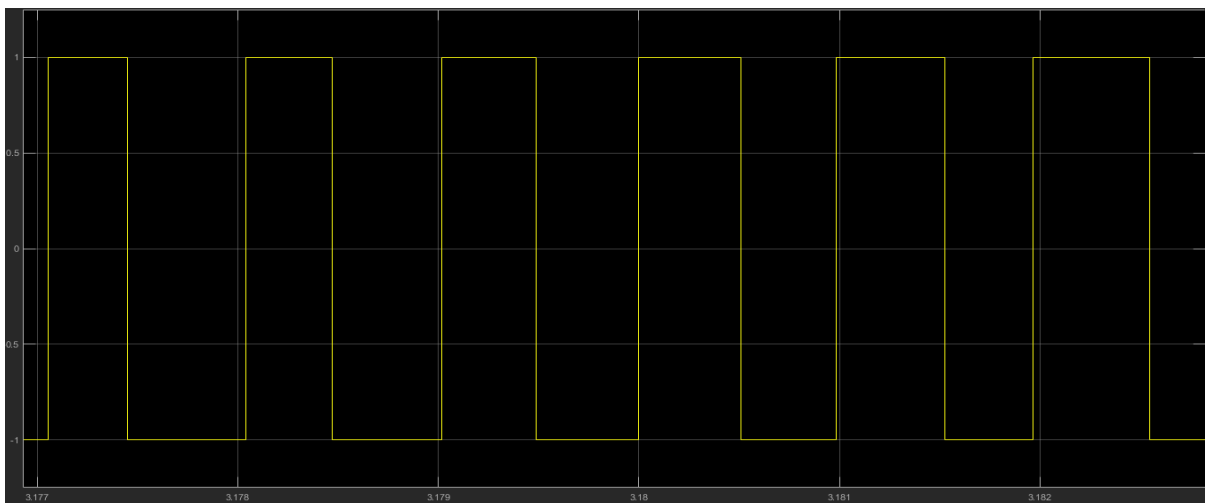
FIGURE 6.3.2   CLARKE TRANSFORMATION
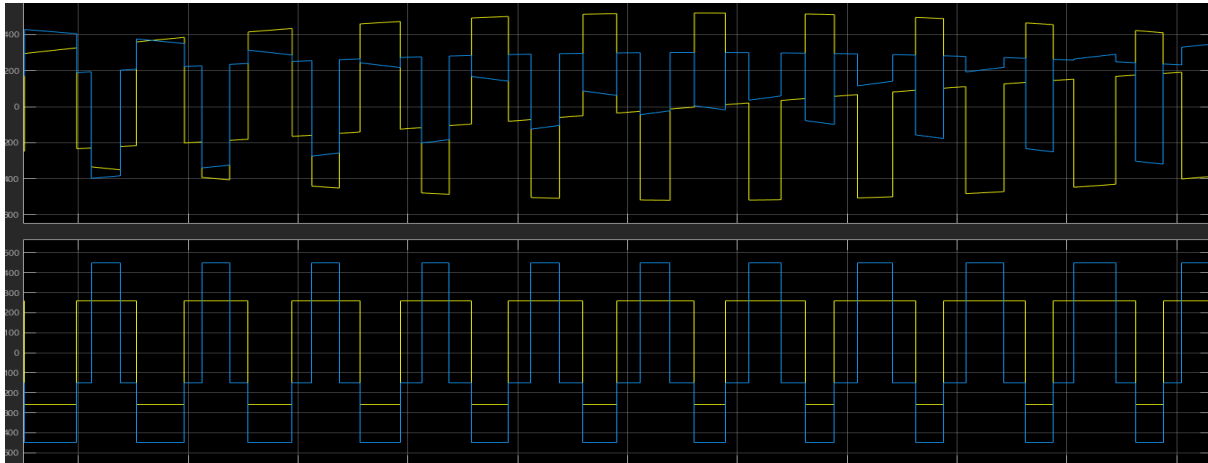
FIGURE 6.3.2   CLARKE TRANSFORMATION

From above graph and Simulink model, we can observe that by using Clark transformation the three-phase windings system is transformed into the system of two windings that are perpendicular, so that the mutual inductance is zero.

FIGURE 6.3.3   TORQUE
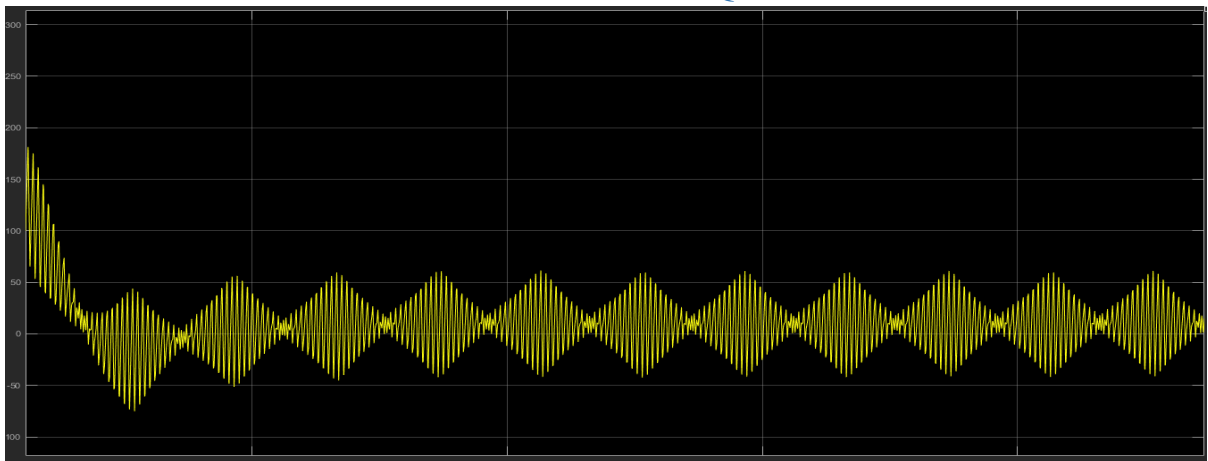
FIGURE 6.3.4   MOTION

FIGURE 6.3.5   ROTOR CURRENTS
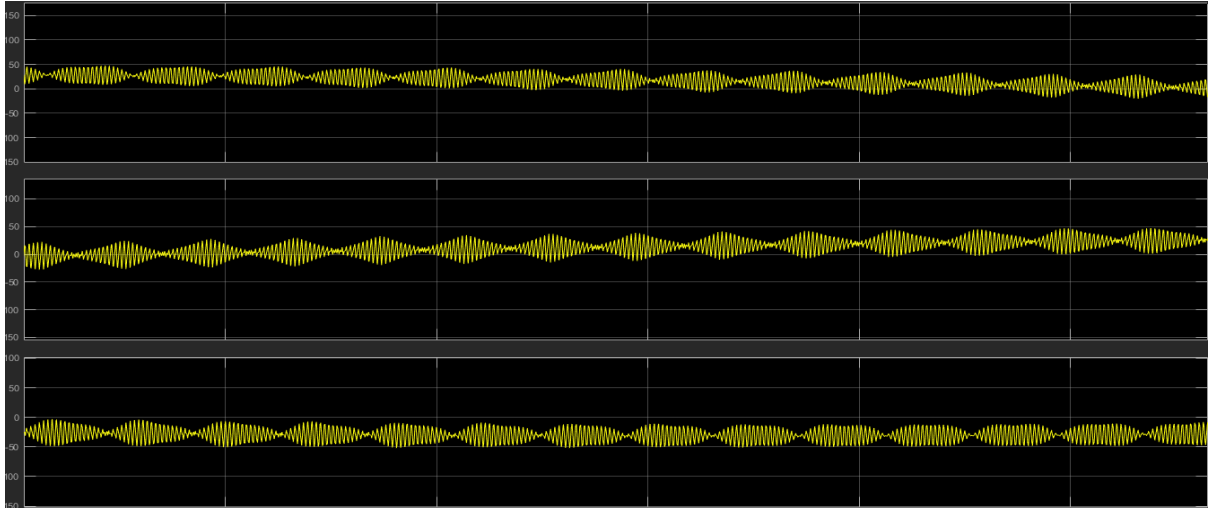
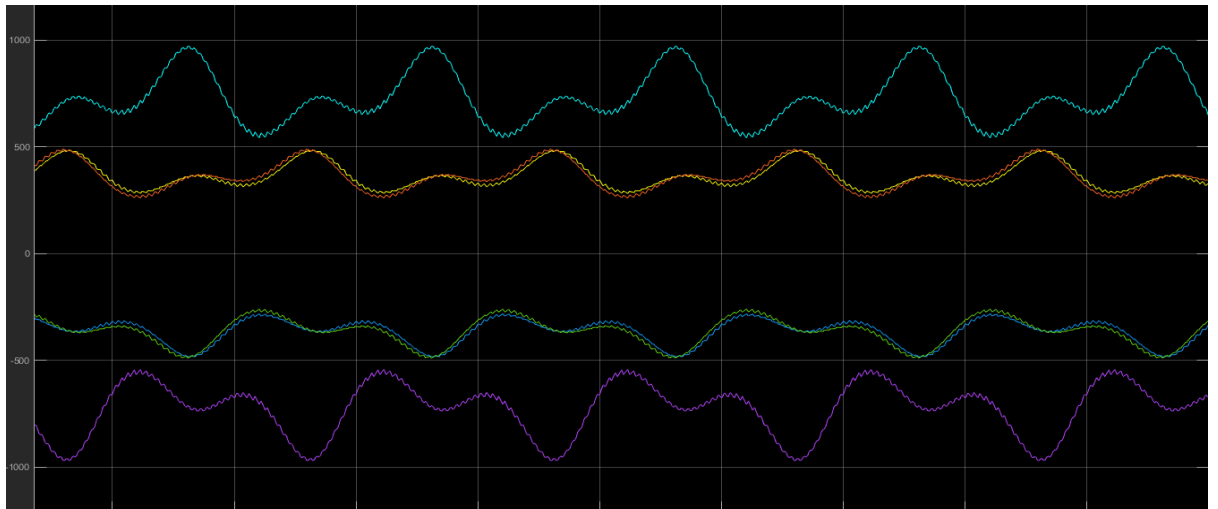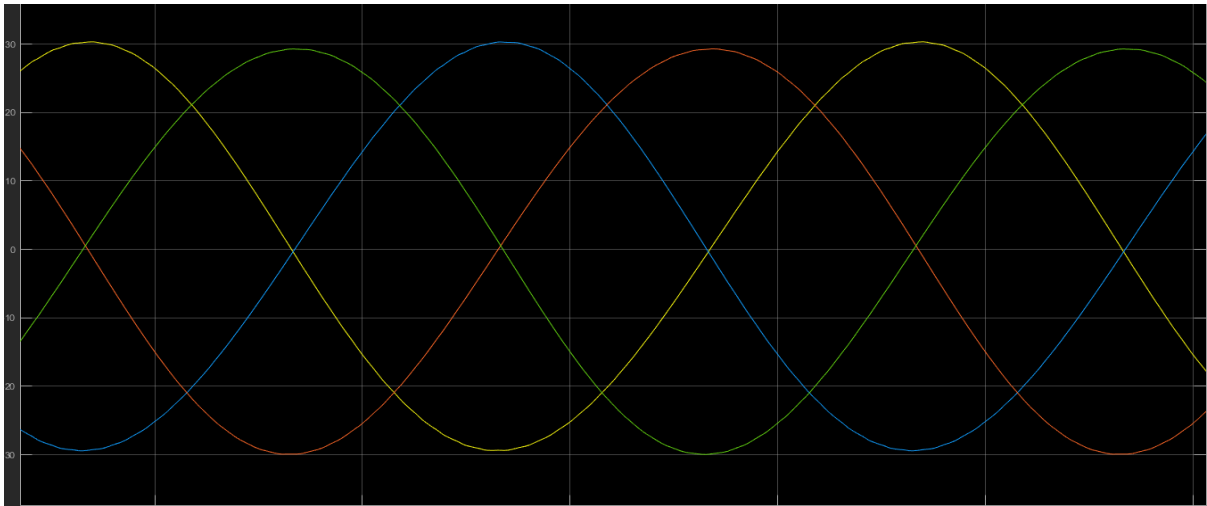
FIGURE 6.3.6   STATOR CURRENTS
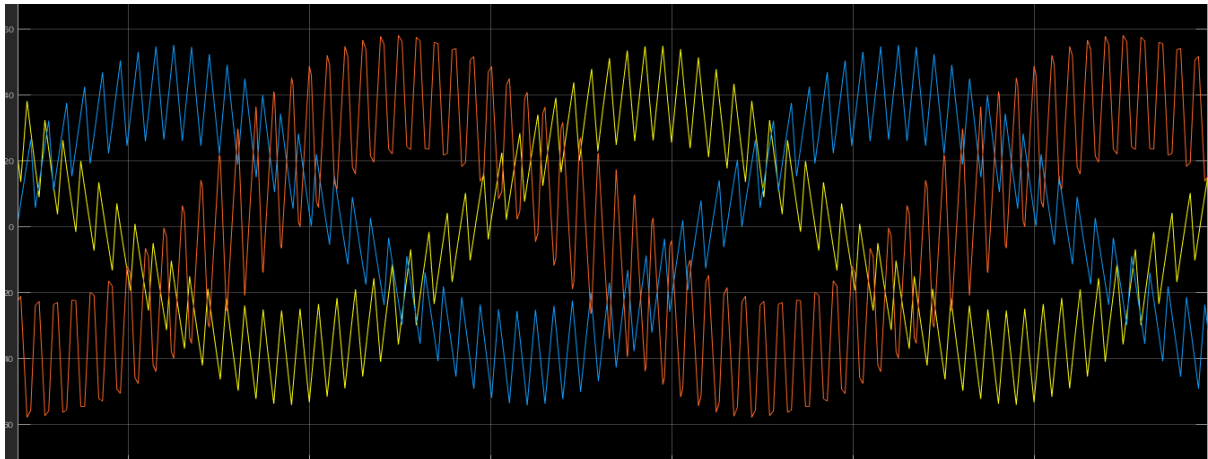
6.4   INDUCTION MOTOR FED BY SINUSOIDAL PULSE WIDTH MODULATION

FIGURE 6.4   IM FED BY SINUSOIDAL PWM INVERTER

FIGURE 6.4.1   CLARKE TRANSFORMATION

From above graph and Simulink model, we can observe that by using Clark transformation the three-phase windings system is transformed into the system of two windings that are perpendicular, so that the mutual inductance is zero.

FIGURE 6.4.2   TORQUE

FIGURE 6.4.3   MOTION

FIGURE 6.4.4   REVERSE PARK TRANSFORMATION

FIGURE 6.4.5   ROTOR CURRENTS
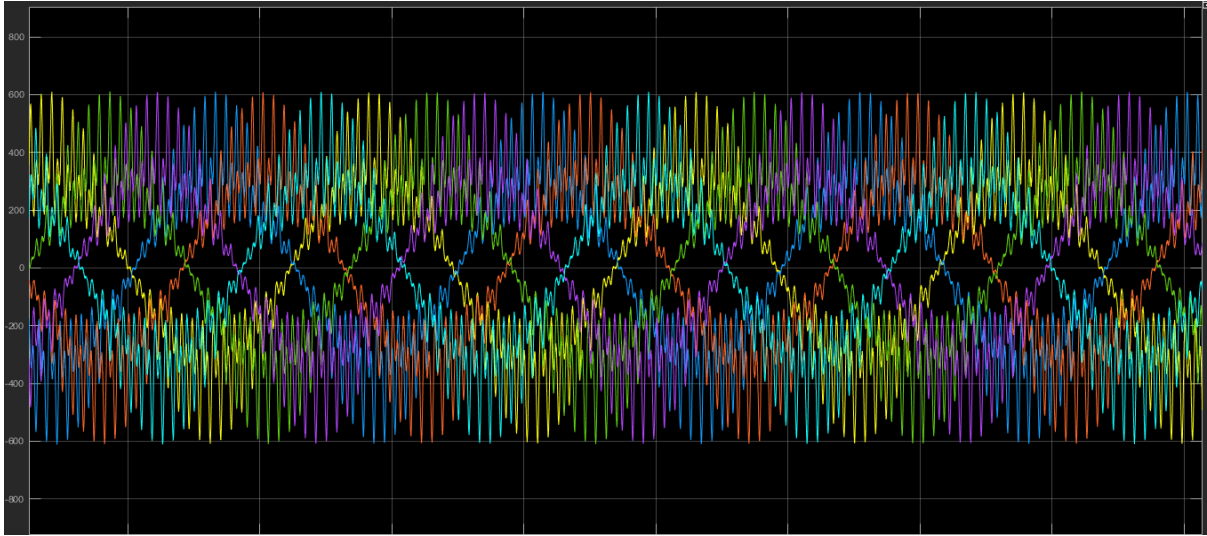
FIGURE 6.4.6   FLUX

FIGURE 6.4.6   U,V COMPONENTS OF ROTOR CURRENTS
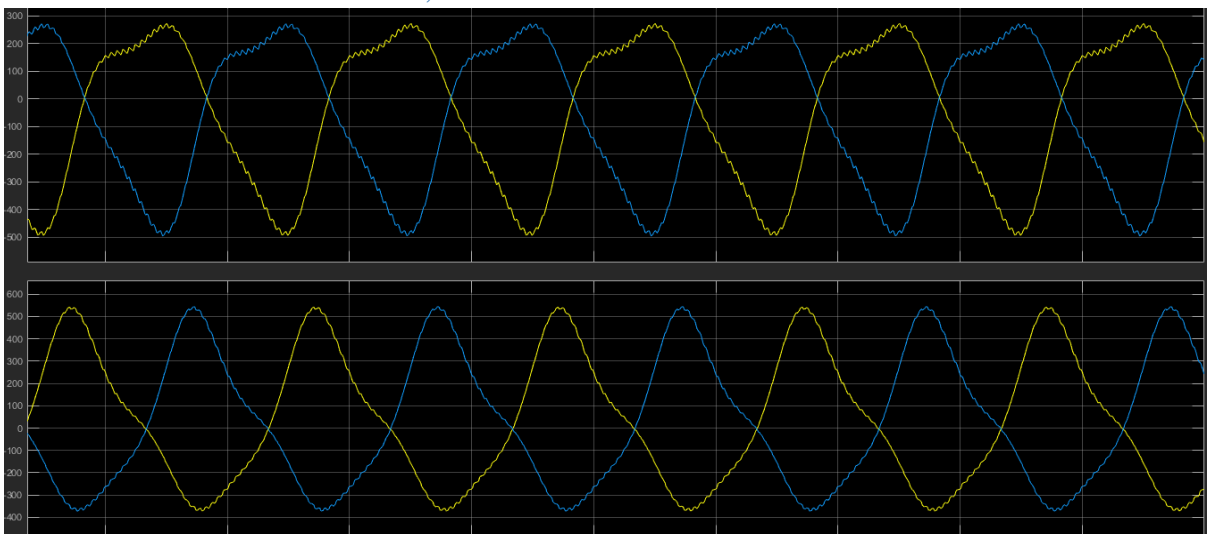
6.5   INDUCTION MOTOR FED BY SPACE VECTOR PWM
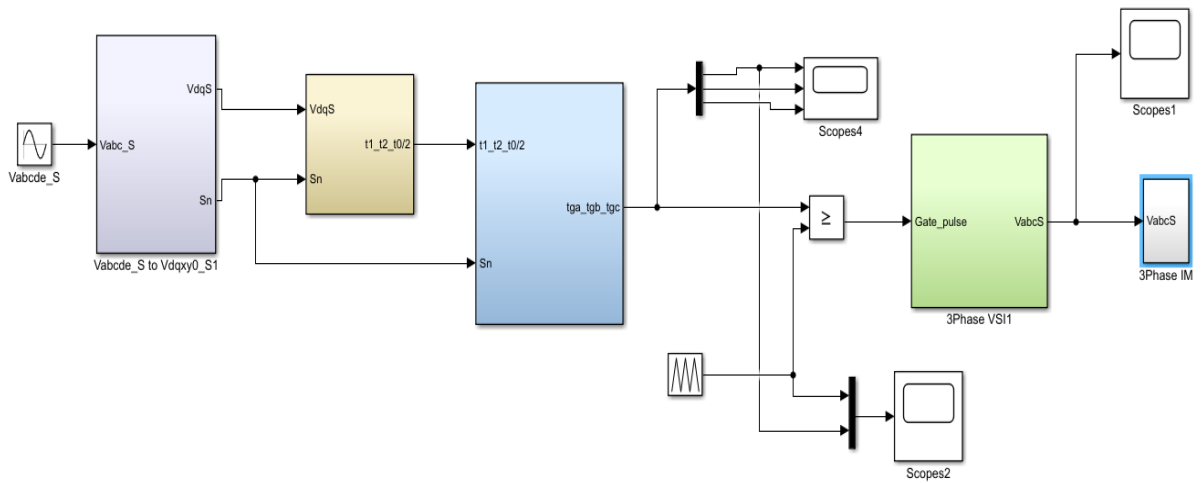

FIGURE 6.5   IM FED BY SPACE VECTOR PWM INVERTER
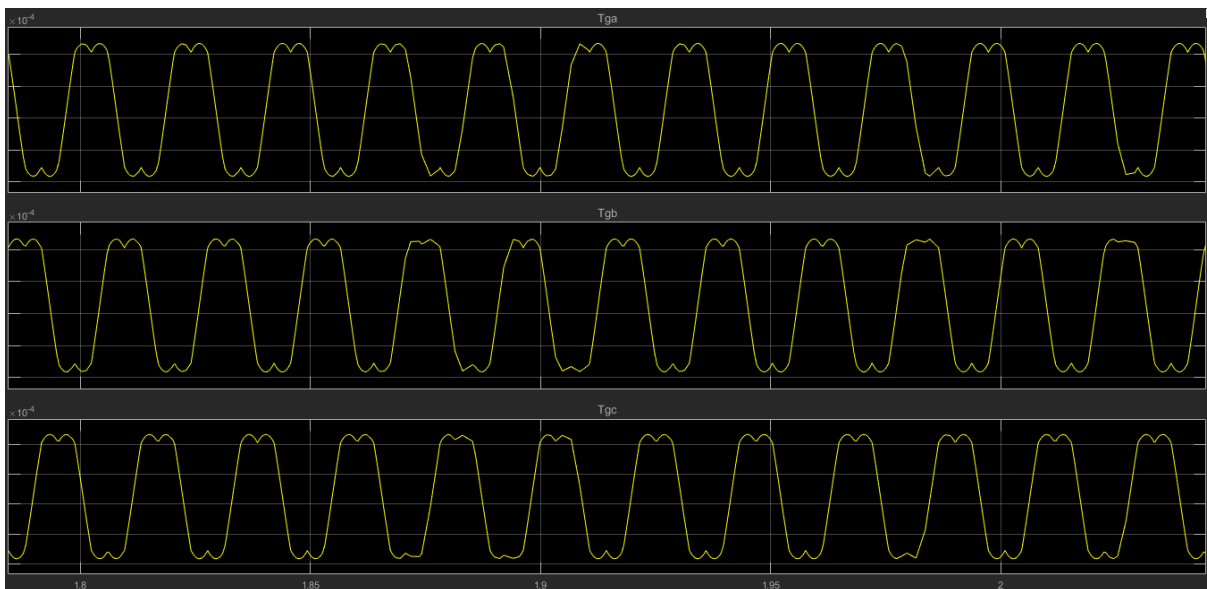
FIGURE 6.5.1   INPUT SUPPLY VOLTAGE

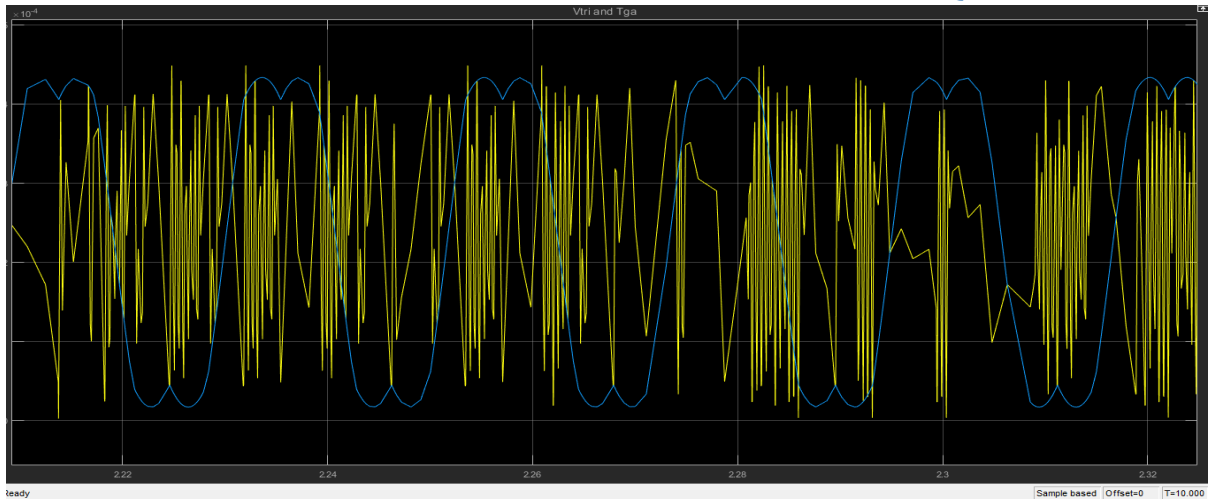## FIGURE 6.5.2   COMPARE SUPPLY WITH REPEATING SEQUENCES

FIGURE 6.5.3   OUTPUT VOLTAGE OF VSI
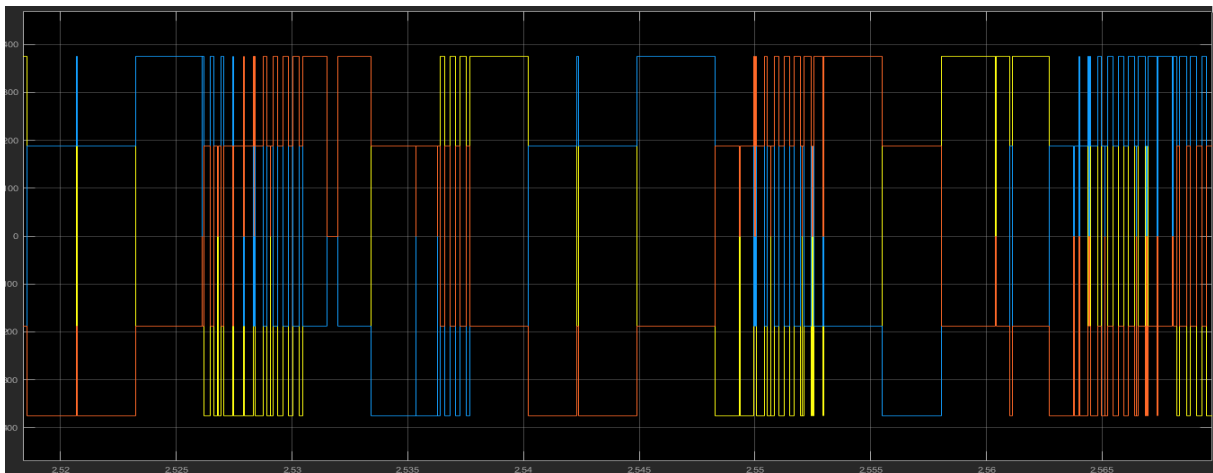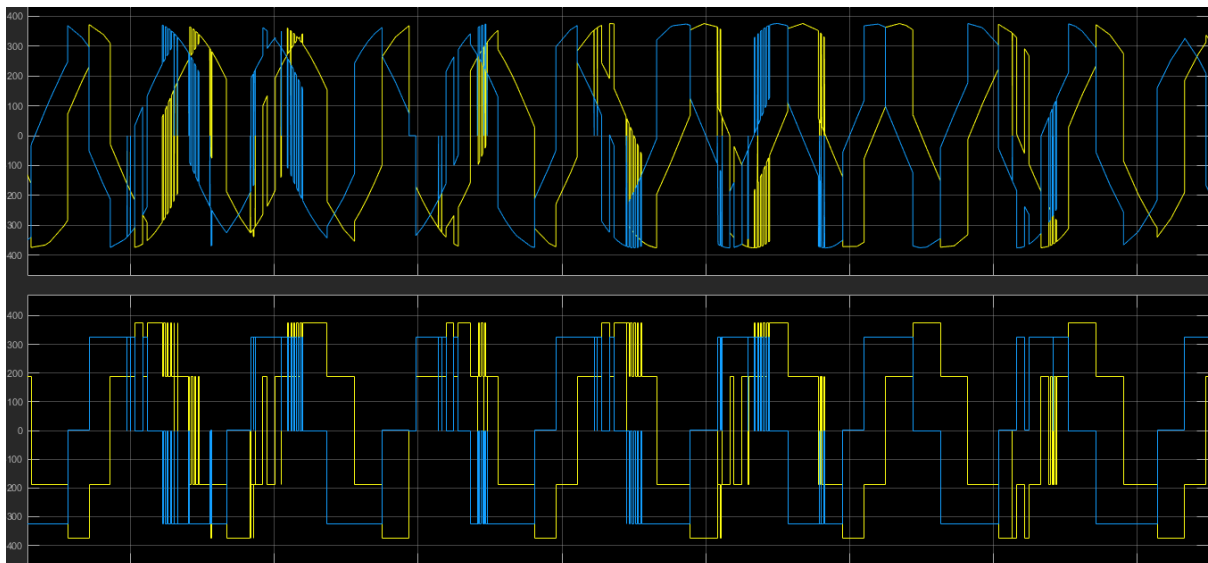

FIGURE 6.5.4   CLARKE TRANSFORMATION

From above graph and Simulink model, we can observe that by using Clark transformation the three-phase windings system is transformed into the system of two windings that are perpendicular, so that the mutual inductance is zero.
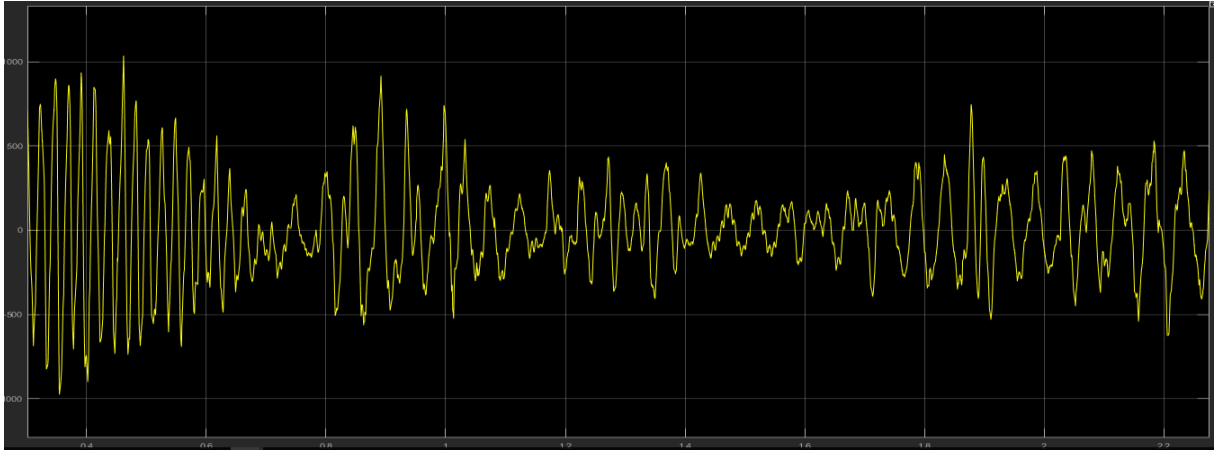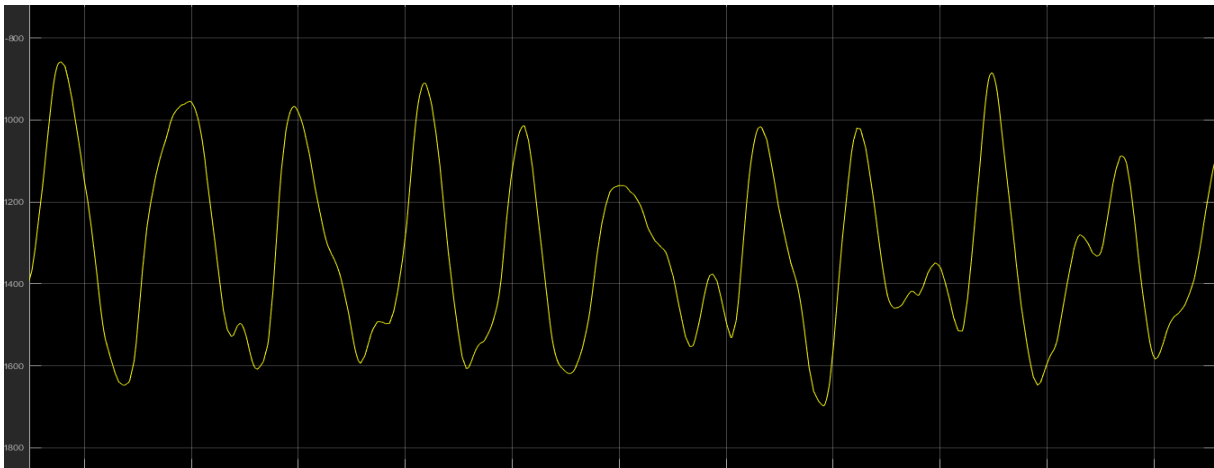
FIGURE 6.5.5   TORQUE
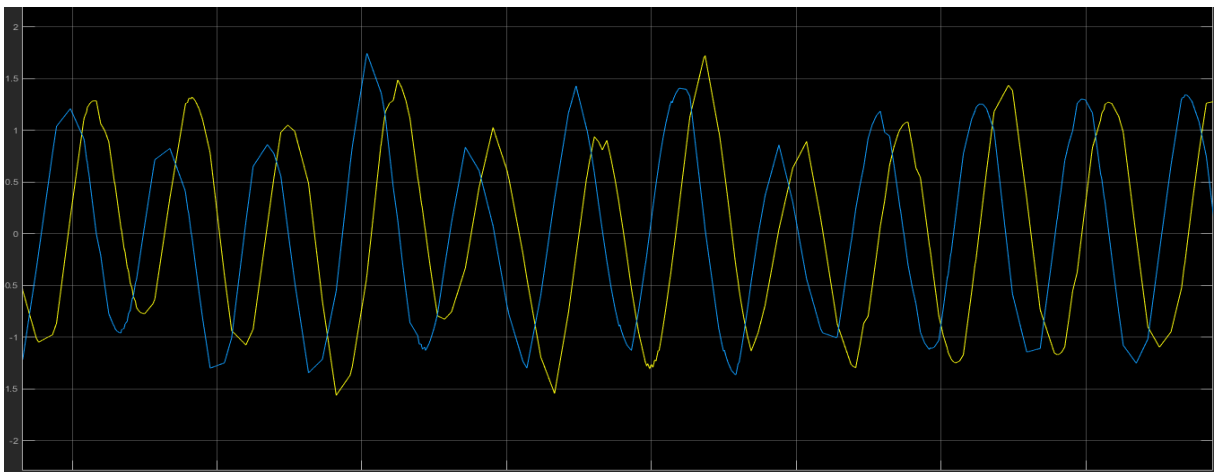

FIGURE 6.5.6   MOTION

FIGURE 6.5.7   FLUX
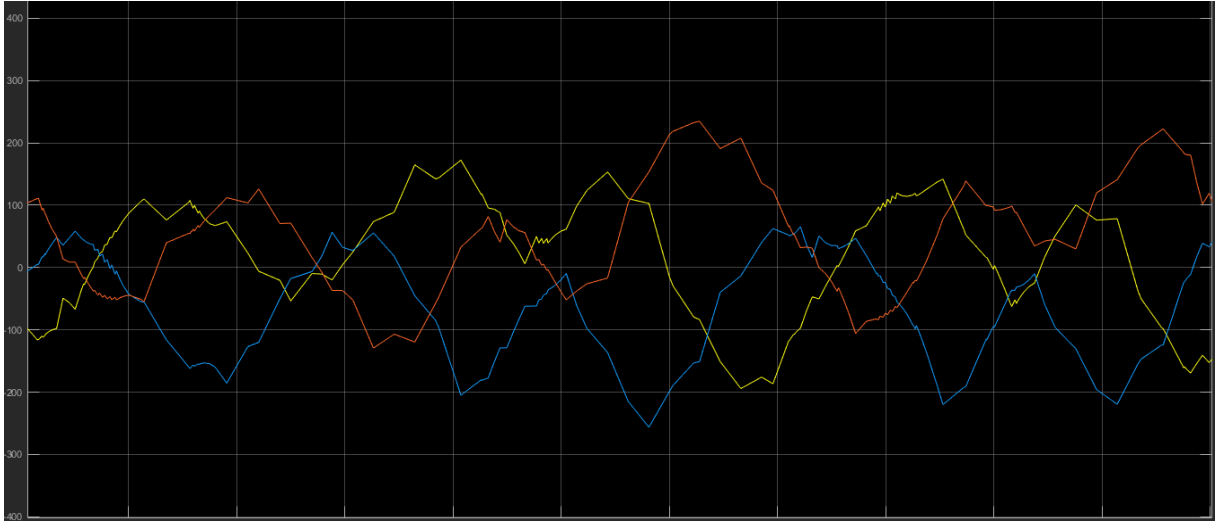
FIGURE 6.5.8   STATOR CURRENTS
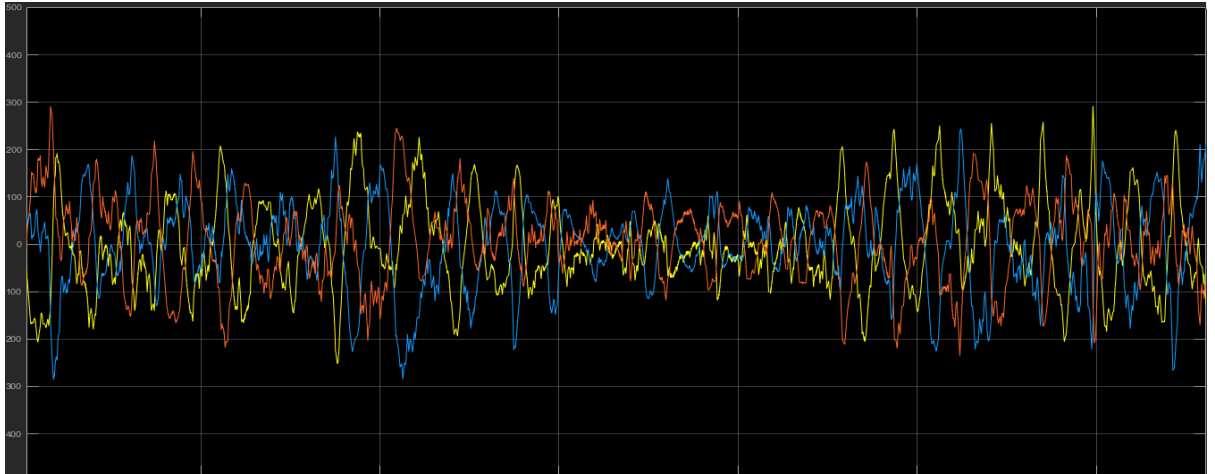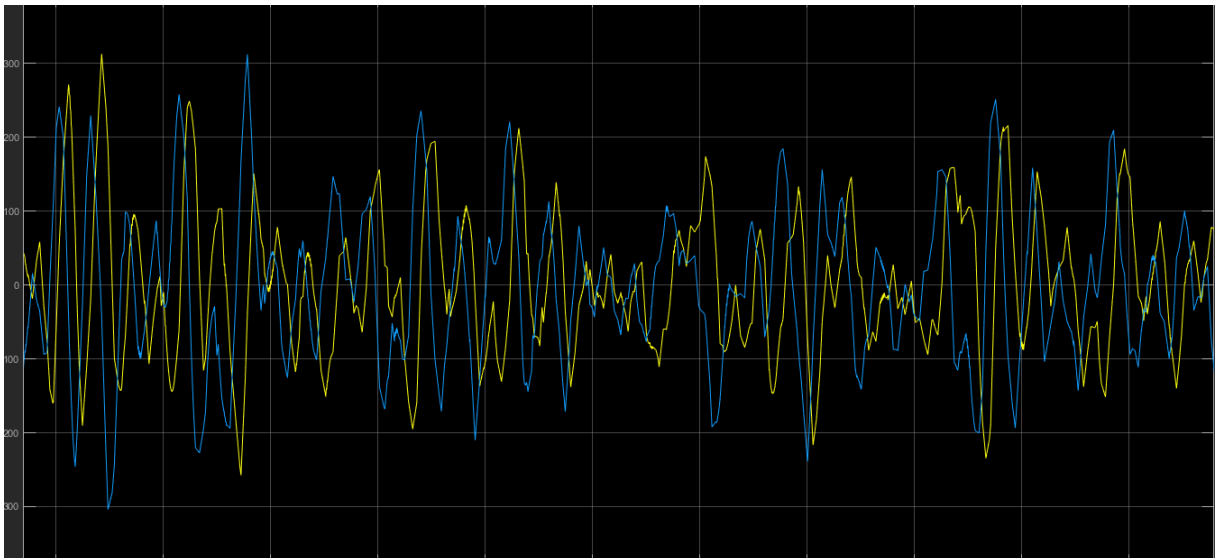

FIGURE 6.5.9   ROTOR CURRENTS

FIGURE 6.5.10   U, V COMPONENTS OF ROTOR CURRENTS

7. CONCLUSION AND DISSCUSSION

Pulse Width Modulation is most preferable strategy used in each and every industrial applications. Different Pulse Width Modulation technologies are accurate and they minimize switching losses. By applying two different kind of Pulse Width Modulation strategies to the Induction machine, we compare results which we got in the Matlab simulation so we can see the pros and cons of both the strategies. At the end, we can choose the best strategy that we can apply and it is beneficial for industrial use.

7.1 FUTURE ASPECTS

I would like to work on some hardware practical based on these different strategies fed to an Induction Machine and how they affect all the parameters of the machine such as speed, torque, stator and rotor currents. I also want to continue my work ahead in Research work.

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APPENDIX

AC: Alternating Current

DC: Direct Current

VSI: Voltage-Source Inverters

NPC: Neutral-Point-Clamped

FC: Flying-Capacitor

CHB: Cascaded H-bridge

MMC: Modular Multilevel Converter

TCC: Transistor-Clamped Converter

A.M: Amplitude Modulation

F.M: Frequency Modulation

PWM: Pulse Width Modulation

SHEPWM: Selected Harmonic Elimination PWM

SPWM: Sinusoidal PWM

SVPWM: Space Vector PWM

THD: Total Harmonic Distortion

IM: Induction Motor