TALLINN UNIVERSITY OF TECHNOLOGY

SCHOOL OF ENGINEERING
Electrical Power Engineering and Mechatronics

THE IMPACT ANALYSIS OF MOTORS CURRENT GAIN ON HIGH FREQUENCY HARMONICS FED FROM INVERTER

KÕRGESAGEDUSLIKE INVERTERIHARMOONIKUTE MÕJU ANALÜÜS ELEKTRIMASINA ANKRUVOOLULE

MASTER THESIS

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Tallinn 2021

AUTHOR'S DECLARATION

Hereby I declare that I have written this thesis independently.

No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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Department of Electrical Power Engineering and Mechatronics

THESIS TASK

Student: Ankurkumar Patel, 184513MAHM

Study programme, MAHM02/18 - Mechatronics main speciality:

Supervisor: Dr. Toomas Vaimann, Senior Researcher

Co-supervisor: Mr. Bilal Asad, Ph.D. Student

Thesis topic:

(In English): The Impact Analysis of Motors Current Gain on High Frequency Harmonics Fed from Inverter.

(In Estonian): Kõrgesageduslike Inverteriharmoonikute mõju analüüs elektrimasina ankruvoolule

Thesis main objectives:

1. Analysis motors characteristics and inverter output current harmonics are investigated for different PWM techniques.

2. Motor current harmonic analysis of the system is by Fast Fourier transform.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Understanding of the technical requirement	01/02/2020
2.	Modelling and simulation of Motor	25/09/2020
3.	Results analysis and writing	25/11/2020

Language: English **Deadline for submission of thesis:** 18/05/2021

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ABSTRACT

The impact of inverter-based analysis of the harmonic content present in 3-phase induction motor (IM) current when driven by a sinusoidal pulse-width modulated (SPWM) and space vector pulse-width modulated (SVPWM) is presented in this study. First, the IM drive's topology and circuit are presented, as well as its operational fundamentals and waveform appearance. Additionally, when adjusting the load, the grid-fed 3-phase IM model and operational characteristics are discussed.

In this thesis work, the MATLAB/Simulink package was used to design a simulation of a 3-phase IM fed from a PWM inverter. In a performance comparison analysis, the IM stator current is measured using SPWM and SVPWM inverters for various modulation indexes. The harmonic content of the IM current is determined by performing a spectrum analysis of the current using the Fast Fourier transform (FFT).

As total harmonic distortion (THD) is reduced at the inverter's output terminal, rotor current, stator current, rotor speed, and torque efficiency improve, resulting in smooth operation. The simulation results demonstrate that the SVPWM converter can enhance stator current output, use better DC voltage, increase rotor speed and minimize torque ripple while maintaining IM performance characteristics.

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Ankurkumar Patel
June 2021

CONTENTS

LIST OF ABBREVIATIONS AND SYMBOLS

IM: Induction Motors

PWM: Pulse Width Modulation

FFT: Fast Fourier Transform

DC: Direct Current

AC: Alternating Current

FT: Fourier Transform

SPWM: Sinusoidal Pulse Width Modulation

SVPWM: Space Vector Pulse Width Modulation

V/F: Voltage Frequency

VFD: Variable Frequency Drives

VSI: Voltage Source Inverter

CSI: Current Source Inverter

THD: Total Harmonic Distortion

IGBT: Insulated-Gate Bipolar Transistor

MOSFET: Metal Oxide Semiconductor Field-Effect Transistors

DTC: Direct Torque Control

FOC: Field-Oriented Control

SIC: Silicon Carbide Devices

RMS: Root Mean Square

RPM: Revolutions per minute

D-Q: Direct axis and Quadrature axis

MMF: Magneto Motive Force

HP: Horse Power

Ma: Modulation Index

Mf: Modulation Frequency

HZ: Hertz

LIST OF FIGURES

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1 INDUCTION MOTOR

1.1 Induction Motor

Electrical motors, particularly industrial usage, represent a large portion of electrical energy consumption. I have chosen 3-phase IM for my analysis, as they are reliable and necessitates low maintenance, hence often called the workhouse of motion industries [1, 2]. When power is supplied to an IM with specified frequency and voltage, it runs at its rated speed [3]. Electrical motors find various applications in the mining industry, avionics industry, machinery buildings, and mechatronics.

Furthermore, several industrial applications use IM, which is fed by static frequency inverters. The 3-phase voltage inverter used at the source converts DC into AC using the PWM method based on which we evaluate the performance of the IM [3]. It is possible to control the functional voltage and current using the voltage source inverter (VSI).Therefore, PWM controlled inverter powered IM motor drives are highly versa-tile, reliable and can operate a wide range of speeds [4]. It is also highly efficient compared to a fixed frequency IM.

The use of power electronic drives in circuits generates harmonics in output voltages, which need to be accounted [5]. Harmonic losses are the sum of voltage losses produced by each existing order of harmonic current due to non-sinusoidal current supplied by inverters. Each harmonic produces corresponding harmonic losses, which consist of iron losses, winding losses. With more, the component includes skin effect losses and internal proximity effect losses, in which the eddy currents are caused by the harmonic stator currents. [6]. these harmonics generate noise in the power supplied to the IM, which is undesirable as it caused pulsations in torque during operation [5].

The following are the important parameters that measure the quality of the inverter output voltage [7].

- Harmonic Factor (HF)
- Total Harmonic Distortion (THD)
- Distortion Factor (DF)
- Lowest order Harmonic (LOH)

1.1.1 Pulse Width Modulation (PWM)

In PWM techniques, a controlled AC output voltage can be achieved by turning on and off a fixed DC input voltage. It is a common methodology wherever triggering the inverter provides constant V/F (voltage/frequency) control. Among the assorted PWM techniques, the SPWM is nice enough and most well-liked that gives smooth conversion of V/F, four quadrant operation, harmonic elimination, etc. in each closed and open loop application [8].

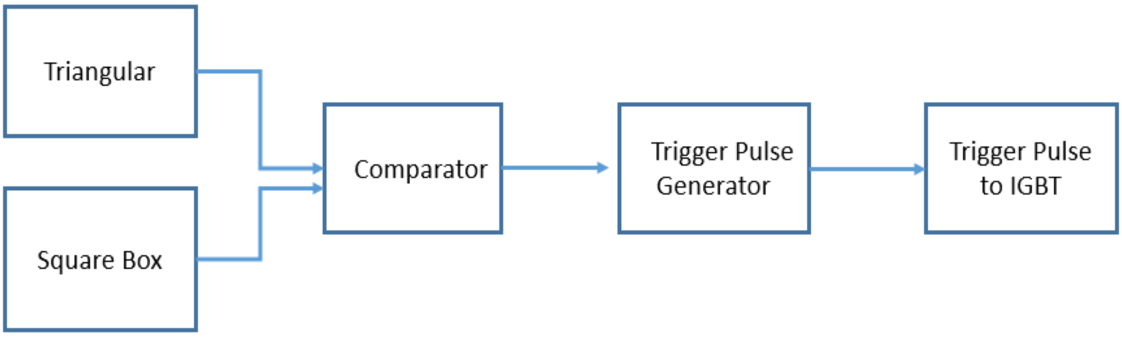


Figure 1 Block Diagram of PWM Signal Generation [8]

- Types of P.W.M Technique’s

1. Single Pulse Width Modulation
2. Multiple-Pulse Modulation
3. Selected Harmonic Elimination PWM (SHEPWM)
4. Minimum Ripple Current PWM
5. Sinusoidal PWM (SPWM)
6. Modified sinusoidal PWM (MSPWM)
7. Space Vector PWM (SVPWM)

1.1.2 Sinusoidal PWM (SPWM)

To obtain gate pulses, a 3-phase sine wave is compared to a triangular wave. For industrial converters, the SPWM technique is widely used. The sinusoidal output waveform is best regulated when the switching frequency is high. Amplitude modulation can regulate the fundamental frequency component of the inverter output voltage. [3].

It creates a sinusoidal waveform by filtering a varying-width output pulse waveform. A sinusoidal output waveform with a high switching frequency is better filtered. Variations in the reference voltage's amplitude and frequency alter the output voltage's pulse-width patterns while maintaining sinusoidal modulation [8].

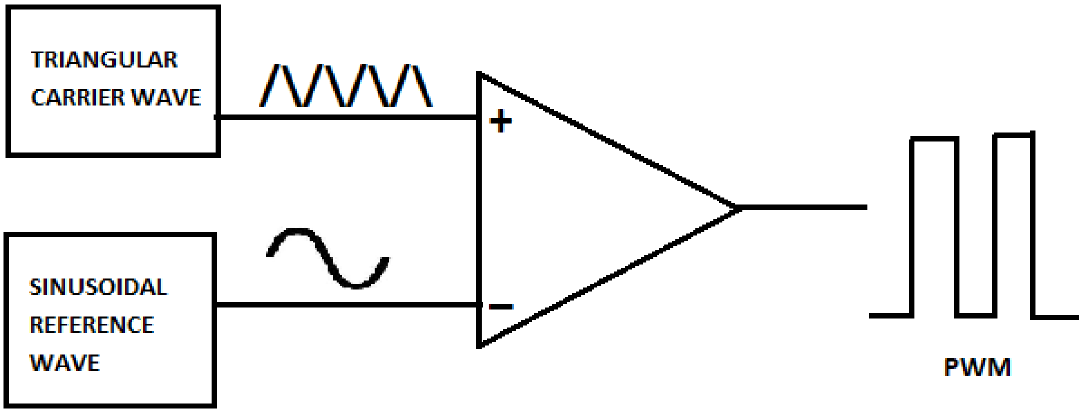


Figure 2 Sinusoidal pulse width modulation [2]

The sinusoidal signal peak magnitude is equal or less compared to the carrier signal peak magnitude. The modulating signal magnitude always needs to be lower than the magnitude of the carrier signal. A Sine-PWM inverter needs a set of 3-phase sinusoidal modulating signals with a high-frequency triangular carrier signal [2].

1.1.3 Space Vector PWM (SVPWM)

SVPWM is a sophisticated computation-intensive PWM technique that is likely the best for variable frequency drive (VFD) applications. It has recently found widespread use due to its superior performance characteristics [8]. Generating lower THD in the sine wave and a higher voltage to the motor is the best-advanced technique. The aim of all techniques is to get a variable output and having the most fundamental element with the minimum harmonics [10].

In a 3-phase inverter, the SVPWM technique used to produce the switching control signal. Compared to the SPWM inverter, the SVPWM inverter had a 15% higher dc-link voltage utilization and lower output harmonic distortions. The SVPWM inverter is operated using V/f control methods. Which is based on the technique of space-vector modulation. The difference between SVPWM and SPWM is there are two additional zero voltage states V0 (000), and V7 (111) in SVPWM. [3].

Space vector modulation is a PWM regulator algorithm for multi-phase AC generation. The reference signal is sampled frequently, for every 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 to integrate the reference signal as the average of the used vectors [8]. To implement SVPWM, the voltage equations within the abc reference frame transformed into the stationary reference frame that includes the horizontal (d) and vertical (q) axes, as depicted in figure 3 [4].

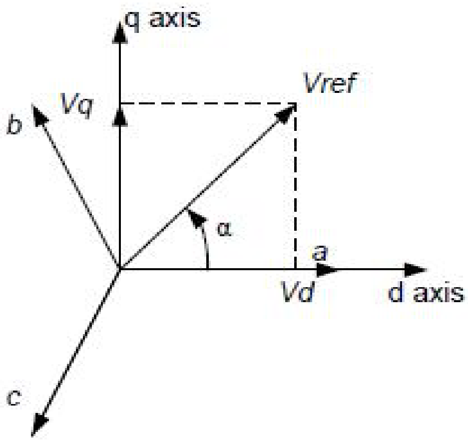


Figure 3 Voltage Space Vector and its d, q axis [4]

1.1.4 Modulation Index (Ma)

The Fourier series Expansion of a symmetrical square wave voltage with a peak magnitude of $V_{cr}/2$ has a fundamental of magnitude $2V_{cr}/\pi$. The maximum of the output voltage generated by the SPWM method is $V_{cr}/2$. The modulation index is defined by the ratio of maximum square wave. The output voltage magnitude depends on the modulation index, which is defined as, “The ratio V_m/V_{cr} is called Modulation Index” [8].

The output voltage waveform harmonic content control by the modulation index. Thus, the maximum modulation index is

$$m_a = \frac{V_m}{V_{cr}} \tag{1.1}$$

Where V_m and V_{cr} are the peak values of the modulating and carrier wave, respectively.

1.2 Motivation

In any drive, it is important to study both the variable frequency source and the motor. With the increased usage of PWM inverters as power, sources for 3-phase IM. High frequency current components based on inverters have a major effect on machine output parameters such as torque pulsations in the motor shaft, higher power loss, rotor heating, and a decrease in efficiency, and thus affect the motor's operation. There have been extensive works published on IM, several of these giving an excellent analysis to help reduce the harmonic content when connected to PWM inverter supplies. Factors utilised in the PWM variable speed drive that impact the extent to which these harmonics exist if an IM is a load. For this purpose, a better understanding of the impacts of voltage, and current harmonics need to be further investigated.

1.3 Research Objective

My research focuses on analyzing motor characteristics in both grid-fed and inverter-fed applications using a dynamic quadrature axis (D-Q) model of 3-phase IM in state-space form and computer simulation in MATLAB/Simulink. IM current harmonic analysis is conducted by changing the modulation index of SPWM and SVPWM inverter. Output current of the inverter system, which controlled by using different PWM techniques. For this purpose, a comparative study is obtained regarding the stator current THD and fundamental component determine through FFT analysis.

1.4 Thesis Structure

This work is organized as follows: Chapter 2 is a summary of previous research on motor harmonics, harmonic effects, and motor losses due to high-frequency harmonics in IM. Chapter 3 covers the method used to conduct this research, and the computer model used to implement this investigation. Chapter 4 contains the results and discussions. The conclusions of this investigation are presented in chapter 5. Each case consists of the analysis of three-phase voltage, current, torque, and speed.

2 BACKGROUND

2.1 Parameters of 3-Phase IM

2.1.1 Voltage and Current

An IM is supplied by a three-phase AC system in which the 3-phase currents are phase-shifted by 120ºe or 2п/3 electrical radians. The 3-phase currents are, thus, defined as [11],

$$i_a = I_m \cos(\omega t - \phi) \tag{2.1}$$

$$i_b = I_m cos(\omega t - \phi - \frac{2\pi}{3}) \tag{2.2}$$

$$i_C = I_m cos(\omega t - \phi + \frac{2\pi}{3}) \tag{2.3}$$

Where; ia- current in phase A in (Amp), ib - current in phase B in (Amp), i_C - current in phase C in (Amp), I_m –peak fundamental frequency value of each phase current, ω-fundamental electrical angular frequency in (Rad/s), ϕ - lag power factor angle in (electrical rad), and t – time in (sec).

The phase voltages are also phase-shifted by 120ºe or 2п/3 electrical rad. Considering the phase voltage, v_a, as a reference, the three-phase voltages are defined as [11],

$$v_a = V_m cos(\omega t) \tag{2.4}$$

$$v_b = V_m cos(\omega t - \frac{2\pi}{3}) \tag{2.5}$$

$$v_C \ = V_m cos(\omega t + \frac{2\pi}{3}) = V_m cos(\omega t - \frac{4\pi}{3}) \tag{2.6}$$

Where, v_a - phase voltage A in (V), v_b- phase voltage B in (V), v_C - phase voltage C in (V), and V_m- peak fundamental frequency value of the phase voltage.

The 3-phase voltage system is defined in terms of the phase voltage (Vp) or the line voltage (v_L). The relation between Vp and $v_L$is defined as [11],

$$v_L = Vp\sqrt{3} \tag{2.7}$$

2.1.2 Synchronous Speed

For an IM, rotor speed, frequency of the voltage source and number of poles are interrelated according to the following equation:

$$n_{syn} = \frac{120f}{p} \tag{2.8}$$

Where, n_{syn}- Synchronous speed (RPM),f –stator frequency (Hz),P-Number of poles, The synchronous speed of IM is the function of three parameters that derived on the above formula [9].

2.1.3 Torque

Torque is the force needed to turn a shaft times it is arms-length to the axis of rotation. Thus, torque (T) is given by [11].

$$T=F * r \tag{2.9}$$

Where F- force in Newton’s (N) applied to a shaft and r- is the arm length of the force. The torque in an IM is produced from the interaction of the resultant air-gap flux, and magneto motive force (MMF) of either the stator winding or the rotor cage. Torque is produced on the shaft of the motor only if the rotor is running at a speed lower than the synchronous speed, i.e., if the slip speed is a nonzero value.

2.1.4 Torque - Speed Characteristics of IM

The X-axis shows speed and slip. The Y-axis shows the torque and current. The characteristics are drawn with rated voltage and frequency supplied to the stator. The base speed of the IM is directly proportional to the supply frequency and the number of poles of the motor. Since the number of poles is fixed by design, controlling the speed of an IM by varying the supply frequency.

During start-up, high current is a result of stator and rotor flux, the losses in the stator and rotor windings, and losses in the bearings due to friction. As the speed increases, the current drawn by the motor reduces in figure 4 [25].

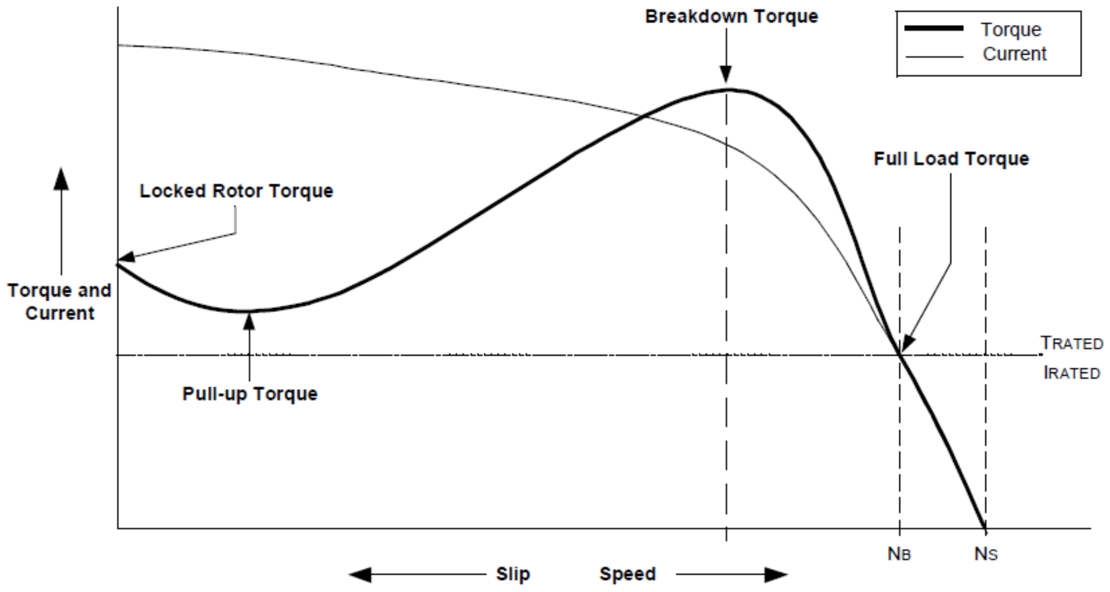


Figure 4 Torque-speed characteristics of IM [12]

2.1.5 V/F Control Strategy

The magnetic field created by the stator is directly proportional to the torque generated by the motor. As a result, the voltage applied to the stator is proportional to the product of the flux and the angular velocity of the stator. Therefore, the flux generated by the stator is proportional to the applied voltage and supply frequency. The motor's speed can be adjusted by changing the frequency. Flux, and hence torque, can be held constant throughout the speed range by varying the voltage and frequency by the same ratio [26].

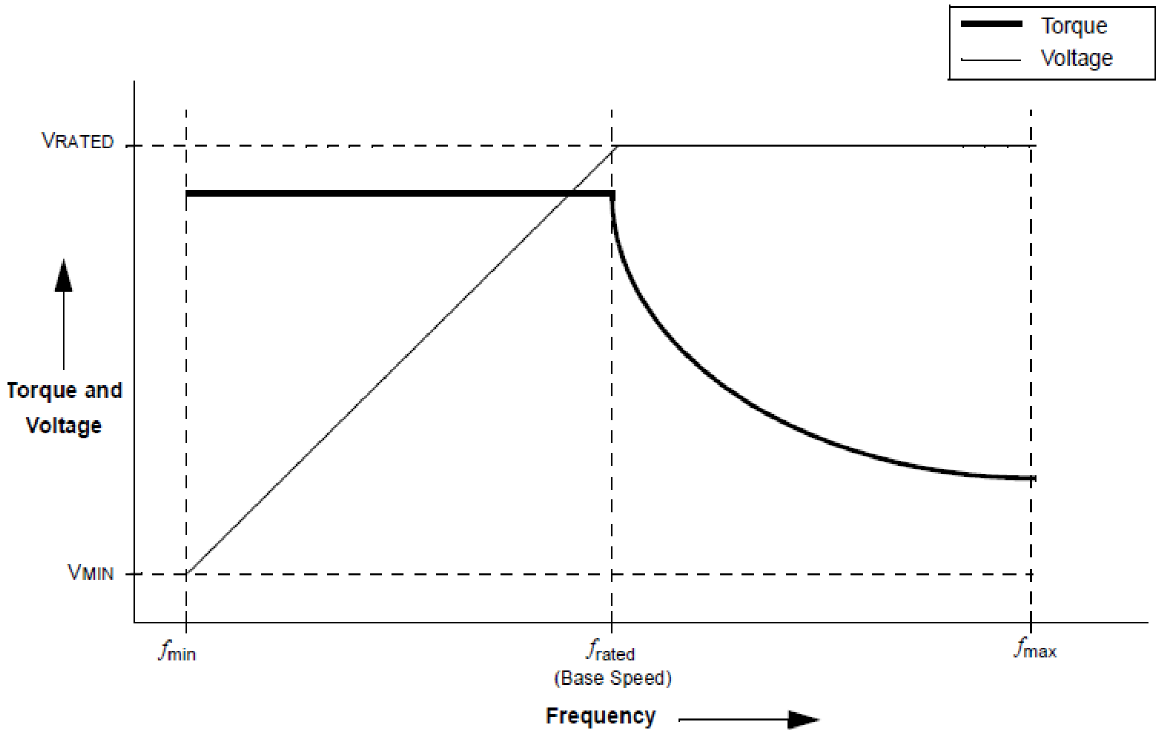


Figure 5 torque-speed characteristics of IM V/F control [26]

2.1.6 Space-Vector

A common three-phase electrical system comprises a set of three voltages and currents interacting with each other to deliver electrical power. A practical 3-phase system cannot be considered the simple addition of three independent single-phase subsystems. Particular relations exist between the phase variables of a 3-phase system, such as those resulting from the Kirchhoff laws or regarding phase sequences, which invite the application of certain space vector transformations to obtain a more elegant and meaningful representation of its variables.

The space-vector analysis is based on the transformation of a set of 3-phase variables into a space vector (complex variable). In steady-state conditions, such transformation is related to the traditional symmetrical component. When a space-vector theory is applied, various transformation models can be obtained without performing matrix transformation [5]. The space-vectors for balanced 3-phase sinusoidal signal are described as [6],

$$I_A = cos(\omega t),\ I_B = \cos(\omega t - \alpha), I_C = \cos(\omega t + \alpha) \tag{2.10}$$

Where $\alpha = \frac{2\pi}{3}$

The corresponding space-vector is,

$$I_R = (I_A + \gamma I_B + \gamma^2 I_C) = 1.5e^{j\omega t} \tag{2.11}$$

Where $\gamma = e^{j\alpha}$

2.1.7 High Frequency Harmonics

An ideal IM built with field-distributed stator operating in a uniform magnetic field will produce a true sinusoidal voltage. However, since an ideal situation cannot be realised in a real-life situation, the distortion of the voltage waveform is created and causes the voltage-time relationship to deviate from the pure sine function. This distortion is the form of periodic functions known as harmonics.

The system of nonlinear load (frequency inverter) current includes harmonics in the AC power line (Frequency component multiples of the power line frequency). A harmonic is the component frequency of the wave signal that is an integral multiple of the fundamental (60Hz is the USA) frequency; 120Hz, 180Hz, 240Hz, etc. Harmonics are designated by their harmonic number or multiples of the fundamental frequency. For example, the 3rd harmonic are three times the fundamental frequency (180Hz) and the 5th harmonic are five times the fundamental frequency (300Hz) [1].

Harmonics are readily generated in an IM with the inverse use of variable frequency drives (VFD) [9]. These harmonics are generated by inverters by the order below:

$$\mathrm{Kp} \pm 1 \tag{2.12}$$

Where, n -order of harmonics, k-integer 1, 2, 3,….., p-number of pulses of the inverters. For example, a six pulse/pole inverter will generate the following characteristic harmonics, 5th, 7th, 11th, 13th, and so forth. In an ideal and normal operational condition, the slip, s of an IM is insignificant in such that the slip associated with each harmonic for any harmonic frequency is a given by:

$$\mathrm{S_n} = \frac{\mathrm{Kp + s}}{\mathrm{Kp} \pm 1} \tag{2.13}$$

Where $\mathrm{S_n}$-harmonic slip, s-rated slip of the motor, K-integer 1, 2, 3, p-number of poles of the inverter.

2.1.8 Total Harmonic Distortion

THD check the presence of the harmonics the waveforms and determine the order of those harmonics. Also useful for analysing the standard of voltage and current. Quality of non-Sinusoidal waveforms observed through THD. Measurement of the THD is described as the ratio of the RMS (Root Mean Square) value of all harmonic components to the RMS value of the fundamental component. Calculating the THD percentage is the summation of the harmonic content of the current to the fundamental component of the current [3].

$$\mathrm{THD}_V\% = \frac{\sqrt{\sum_{\mathrm{n=2}}^{\infty}(\mathrm{V_{oh\,rms}})^2}}{\mathrm{V_{or\,rms}}} \tag{2.14}$$

$$\mathrm{THD} = \frac{\mathrm{V_{oh}}}{\mathrm{V_{or}}} \quad \text{(Voltage THD)} \tag{2.15}$$

$\mathrm{V_{oh}}$-harmonic components in the output of inverter (RMS value),$\mathrm{V_{or}}$ = fundamental component of output voltage (RMS value).

$$\mathrm{THD_I}\% = \frac{\sqrt{\sum_{\mathrm{n=2}}^{\infty}(\mathrm{I_{oh\,rms}})^2}}{\mathrm{I_{or\,rms}}} \tag{2.16}$$

$$\mathrm{THD} = \frac{\mathrm{I_{oh}}}{\mathrm{I_{sr}}} \quad \text{(Current THD)} \tag{2.17}$$

Ioh = harmonic components (RMS value), Isr = fundamental component of supply current (RMS value).The Harmonic distortion signal depends on the percentage of THD [5].

2.2 Literature Survey

Research conducted on IM current, nonlinear loads, harmonic orders, motor and losses and unbalanced voltages is efficiency, well documented. Previously done research is useful in identifying the limitations of existing literature, and the scope of research to be conducted to achieve our desired results.

2.2.1 Interaction Between Inverter and Motor

The existence of harmonics in IM is understood from the corruption of current and voltage waveforms that have sinusoidal form. One of the known harmonic sources is inverter too. Effects of the inverter output current harmonics cause that the increment of voltage droop because of current harmonic components, overheating at IM because of occurred oscillations, faulty measurements and decrement of the life of equipment's which is connected to out of inverter. Therefore, the decrement of harmonics is desired [31].

Variable voltage and frequency supply to ac drives is invariably obtained from a 3-phase VSI. Here in this paper used 3-phase VSI, which is carrier-based sinusoidal PWM with power Insulated-Gate Bipolar Transistors (IGBT), is described. In ac motor drives, SPWM inverters make it possible to control both frequency and magnitude of the voltage and current applied to a motor. As a result, PWM inverter-powered motor drives are more variable and offer in a wide range better efficiency and higher performance compared to fixed frequency motor drives [2].

2.2.2 Voltage and Current Harmonics

In a literature, several methods were mentioned in literature to control the current of VSI- PWM inverter. The controller uses the feedback signal of torque, angular speed, calculated flux to create sinusoidal current reference for comparing with the real current in current controller block. The deviation of reference and real current is limited by a mechanism such as hysteresis or ramp comparison band so that the actual current always in shape with current reference. Simulation was done by two current controller's mode, hysteresis and ramp comparison current controller. For each method, load and speed are varied, harmonics created, and power factor on ac side then monitored [13].

Considering this critical issue, it is needed to study VSD fed drives in terms of harmonics and their effects on IM motors. In inverter-fed drive system, currents are distorted and the shapes of input currents are not sinusoidal. The most significant harmonics are the fifth and seventh harmonics, which are injected into the grid. The even harmonics have negligible magnitude [16].

This paper has two important contributions. First, the work was presenting a new method that consists of synchronizing the modulation control of the voltage-current (V-I) and Current source inverter (CSI) converters based on Silicon Carbide Devices (SIC) devices. Due to the controls being based on PWM techniques, two carriers are used to generate the pulses of the transistors. The method was including the search of the optimal operating frequency and a better shift angle between carries as well. The main purpose was improving the THD in the CSI outputs current at high frequencies. Second, the paper was demonstrating a coordinated modulation improvement and the consequent reduction of harmonics, allowing for a better efficiency in the motor and inverter system to be obtained [18].

2.2.3 Inverter with LC Passive Filters

This paper includes the performance analysis of 3-phase IM with 3-phase Alternating Current (AC) direct and variable frequency drives (VFD). As an extensive solution for AC drives' harmonics distortion, some harmonics were eliminated using passive or active filters**.** Using passive filters on the grid-side before the frequency converter decreases the currents harmonics notably. The structure for this method is simple and affordable to implement. The comparison has been concluded with respect to various parameters. MATLAB/Simulink is used for the analysis. When an appropriate LC filter is added after the VFD converter the waveforms of the rotor current improve, torque oscillations are damped after initial transients and converter output waveform becomes more sinusoidal. [28].

2.2.4 Space Vector Based Random PWM Techniques

This work provides analytical and graphical methods for the study, performance evaluation, and the design of the modern carrier-based PWM, which are widely employed in PWM VSI drives presented in this literature. The effects of random signal are analysed intuitively and then accordingly, the quantitative designs, the Simulink simulations of the proposed RPWM inverter are introduced in detail. Based on the results presented in this work it is concluded that the Random PWM methods employed for AC drive resulted in reduced harmonic distortion and confirms the superiority compared to SVPWM algorithm in the form of distributed spectra that resulted in reduced acoustic noise [14].

2.2.5 SVPWM and Hysteresis Current Controlled

The hysteresis current controller is built in with PI speed controller and three hysteresis current bands, while the SVPWM system is embedded with the two control loops, the inner current control loop and the outer speed control loop using PI controller. Both systems were run and tested using MATLAB/Simulink software. The simulation results demonstrate that the SVPWM can improve the quality of the stator current and reduce the torque ripple while maintaining the other performance characteristics of the system [31].

The SPWM and SVPWM inverter technique used for analysing “The Impact Analysis of Motors Current Gain on High Frequency Harmonics Fed from Inverter”. For this research work initially, MATLAB/Simulink modeled for grid fed and both PWM inverter techniques. Then, the current, voltage, torque, and speed results were recorded under modulation range. These results were processed in MATLAB programme to get THD using FFT. Analyse the stator current THD and the rotor speed and torque performance under modulation range to get the result.

3 MODELING AND SIMULATION

3.1 Dynamics of IM

The mathematical modelling and simulations of IM are essential, as it is a fundamental milestone for design and control procedures. The more accurate the mathematical model of the machine is, the more precise its practical design and control would be. The dynamic model is used to obtain the transient and steady state behavior of IM. Analysis of the dynamic behavior of IM is described the equation of IM. The Squirrel cage IM using the direct axis and d-q theory in the stationary reference frame shown in the figures 6 below needs less variables and analysis becomes easy [21].

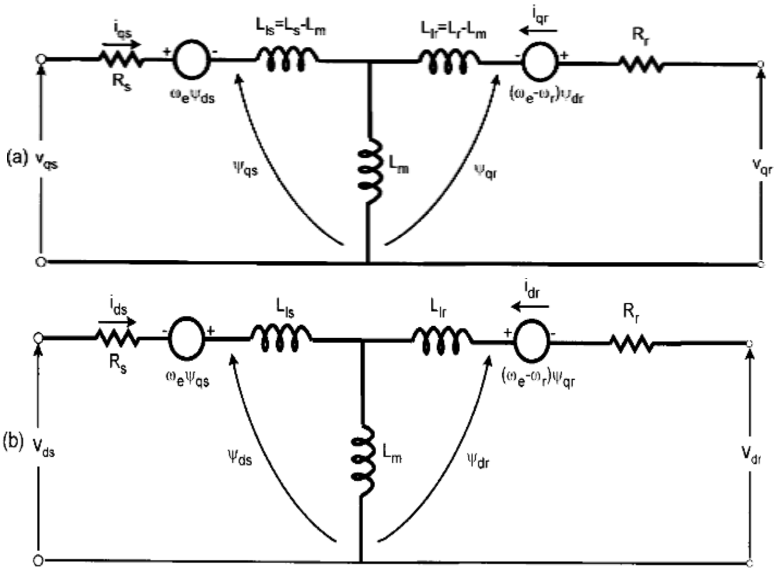


Figure 6 stator and rotor axis in two axis reference frame (a) q-axis and (b) d-axis [21]

The IM model is established using a rotating (d, q) field reference (without saturation) concept. An IM model is then used to predict the voltage required to drive the flux and torque to the demanded values within a fixed period. This calculated voltage is then synthesized using the dynamic model of the motor in Simulink [22].

The dynamic model is used to obtain the transient and steady state behavior of IM. Equation Analysis of the dynamic behavior of IM is described as [23]. The stator and rotor voltage equation of motor is described as:

$$v_{ds} = R_s i_{ds} - \omega_s \psi_{qs} + p\psi_{ds} \qquad (3.1)$$

$$v_{qs} = R_s i_{qs} - \omega_s \psi_{ds} + p\psi_{qs} \qquad (3.2)$$

Where $R_s i_{ds}$ stator-winding voltage drop are $R_s i_{ds}$, speed voltage term and $p\psi_{qs}$ transient term.

$$v_{dr} = R_r i_{dr} - S\omega_s \psi_{qr} + p\psi_{dr} \qquad (3.3)$$

$$v_{qr} = R_r i_{qr} - S\omega_s \psi_{dr} + p\psi_{qr} \tag{3.4}$$

Where, $S\omega_s\psi_{qr}$ is rotor speed voltage created in the Rotor windings moving at slip speed with respect to the synchronously rotating flux wave. Power input to the stator and rotor equations described as:

$$P_s = v_{ds}i_{ds} - v_{qs}i_{qs} \tag{3.5}$$

$$P_r = v_{dr}i_{dr} - v_{qr}i_{qr} \tag{3.6}$$

The torque and Speed equation is described as:

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_{qr}I_{dr} - \lambda_{dr}I_{qr}) \tag{3.7}$$

$$\Omega_r = \int \frac{P}{2 * J}(T_e - T_L) \tag{3.8}$$

Where, P denote the no. Of poles; J: moment of inertia , The d-q axis transformation can now be applied to the system input (stator) voltage after driving the torque and speed equation in terms of d-q flux linkage and current of the stator.

3.1.1 Spectrum Analysis Using FFT

In IM, it must know the frequency content of the current signal rather than the amplitudes of the individual samples. The representation of the signal in terms of its individual frequency components is known as the frequency domain representation of the signal. The frequency domain representation could give more insight about the signal and system. The algorithm used to transform samples of the data from the time domain into the frequency domain is known as the FFT. The FFT establishes the relationship between the samples of a signal in the time domain and their representation in the frequency domain. The FFT is widely used in the fields of spectral analysis [24].

3.1.2 Torque Calculation

The Torque calculation using the motor rated parameters of voltage $V_{rms} = 400V$.

$$V_{max} = \frac{\sqrt{2 *} V_{rms}}{\sqrt{3}} \tag{3.9}$$

$$= \frac{\sqrt{2 *} 400}{\sqrt{3}} = 326.54 \text{ V}$$

Types of torque in IM [11]

T_a- Gross mechanical torque (or) motor torque T_{lost}- loss torque due to friction, windage and iron losses, T_{sh} (Or) T_L - load torque

$$T_a = T_{lost} + T_{sh} \tag{3.10}$$

$$P_{out} = T_{sh} * \omega \tag{3.11}$$

$$T_{sh} = \frac{P_{out}}{\omega} \tag{3.12}$$

P_{out}=4000 watts

$$\omega = \frac{2\pi N}{60} \tag{3.13}$$

$$\omega = \frac{2\pi * 1430}{60}$$

ω = 149.67 rad/sec.

$$T_{sh} = \frac{4000}{149.67}$$

T_{sh} (Or) T_L = 26.72 N.M

$\frac{TL}{2}$ = 13.36 N.M

$\frac{TL}{4}$ = 6.68 N.M

3.2 Modelling of Grid Fed 3-Phase IM

3.2.1 Simulink Model

To perform a computer simulation, a library of models was developed to investigate the adjustable IM drives in MATLAB/Simulink. The models designed in the simulation environment were equipped with an IM, loading device and 3-phase AC supply with 120° directly from the grid. Here in, a model of 5.5 HP rated 3-phase IM driving step input loads at different levels was demonstrated. Motor parameters were varied to study the effects of such variations on transient response and general performance of the motor. Motor torque, speed, stator current, rotor current responses were examined while changing the load torque [28].The simulation motor parameters have shown in table 1.

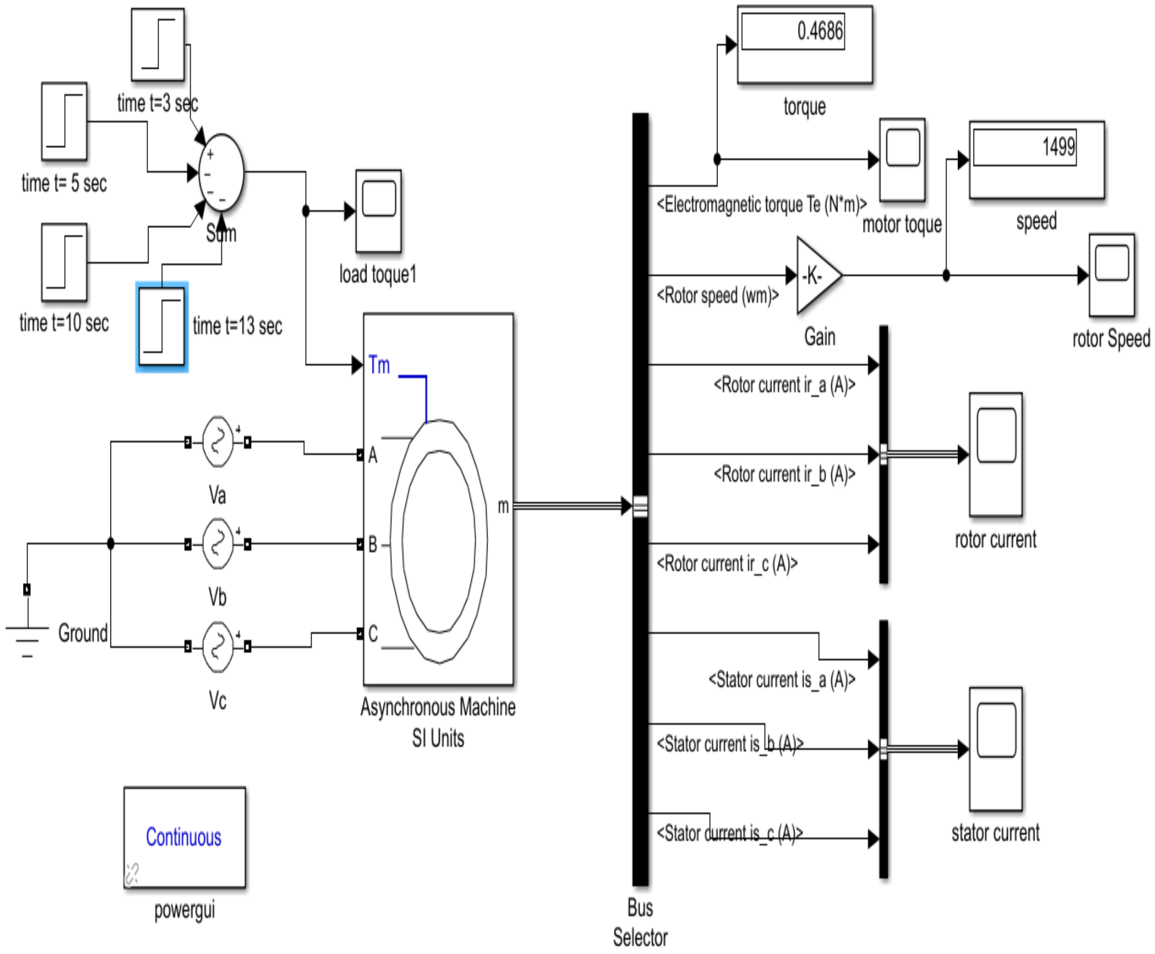


Figure 7 Simulation of 3-Phase IM at Different Load Conditions

Table 1 3-Phase IM parameters

Motor Parameters	**Value**
Horse Power	5.4 HP (4KW)
Number of poles	4
A.C. motor input voltage	400 V
Synchronous speed	1430 RPM
Supply Frequency	50 Hz
Stator resistance	1.405 Rs (Ω)
Rotor resistance	1.395 Rr'(Ω)
Inertia	0.0131 kg·m^2
Mutual inductance Lm (H)	0.1722 H

Table 2 speed and motor torque values for different load conditions

Load torque (TL) N.M		Motor torque T (N.M)	Speed N (rpm)
T_L at 3 sec	T_L	26.72	1435
T_L at 5 sec	$\frac{TL}{2}$	13.36	1469
T_L at 10 sec	$\frac{TL}{4}$	6.68	1484
T_L at 13 sec	0	0.4686	1499

3.3 Modelling of PWM Inverter Fed IM in Matlab/ Simulink

3.3.1 Inverter Circuit Topology and Specification

As with the single-phase inverter, the output voltage magnitude and frequency of 3-phase configuration shapes and controls with a constant DC input voltage V_d. This is accomplished by varying the magnitude of the control voltage and the switching frequency. Again, due to harmonics created, proper selection of modulation ratio (*ma*) and frequency modulation (mf) is important.

A 3-phase inverter does offer benefits regarding harmonic component reduction that the single-phase inverter does not. Due to the 120° phase shift between the inverter 3-phase outputs, only line-to-line voltage harmonics are of concern. By selecting mf as an odd multiple of three, the substantial harmonics are the ones known as sidebands around mf*,* where due to the 120°phase shift; the resulting harmonics at mf are zero [31].

The power semiconductor components used can be in the form of Silicon controlled rectifier (SCR), transistors, and Metal Oxide Semiconductor Field-Effect Transistors (MOSFET) that operate as switches and converters. 3-phase inverter can be shown in figure 10 [31].

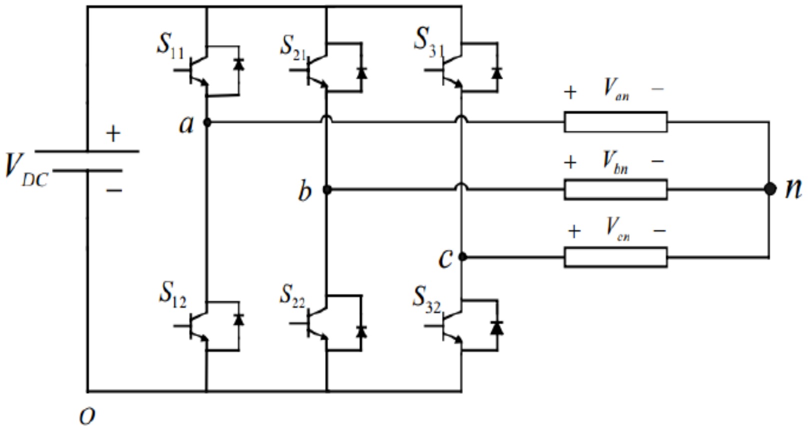


Figure 8 3-phase inverter circuit [31]

3.3.2 Operation Regions for 3-Phase PWM Inverter

There are two primary regions of operation regarding modulation, linear (ma<=1.0) and over-modulation (m > 1.0). Both of these are discussed in some detail to help understand their influence on harmonic content and its potential effect on motor performance.

- Linear Modulation (m_a <= 1.0)

In this mode operation, the component of fundamental frequency in the O/P varies linearly with the modulation ratio m_a.

- Over Modulation_($m_{a.}$ > 1.0)

In this mode of operation, there is a non-linear increase in the fundamental component. The peak control voltages are allowed to exceed the peak of the triangle waveform, and as the ratio increases (large values of m_a), the PWM waveform degrades into a square wave resulting in a maximum value of V_{LL} of $0.78V_d$ [31].

3.3.3 SPWM Inverter Fed IM

The voltage and current harmonics present in 3-phase IM drive systems using 3-phase 3-level inverter are due to the presence of Non-sinusoidal voltage at the output of the inverter. Depending on the type of PWM strategy, the switching frequency and other peculiarities of the control, the motor may present efficiency decreases and losses, temperature, noise and vibration levels increase [9]. Furthermore, in SPWM inverter fed 3-phase IM 3-level 12-bridge and 3-level PWM generator block used for analysis.

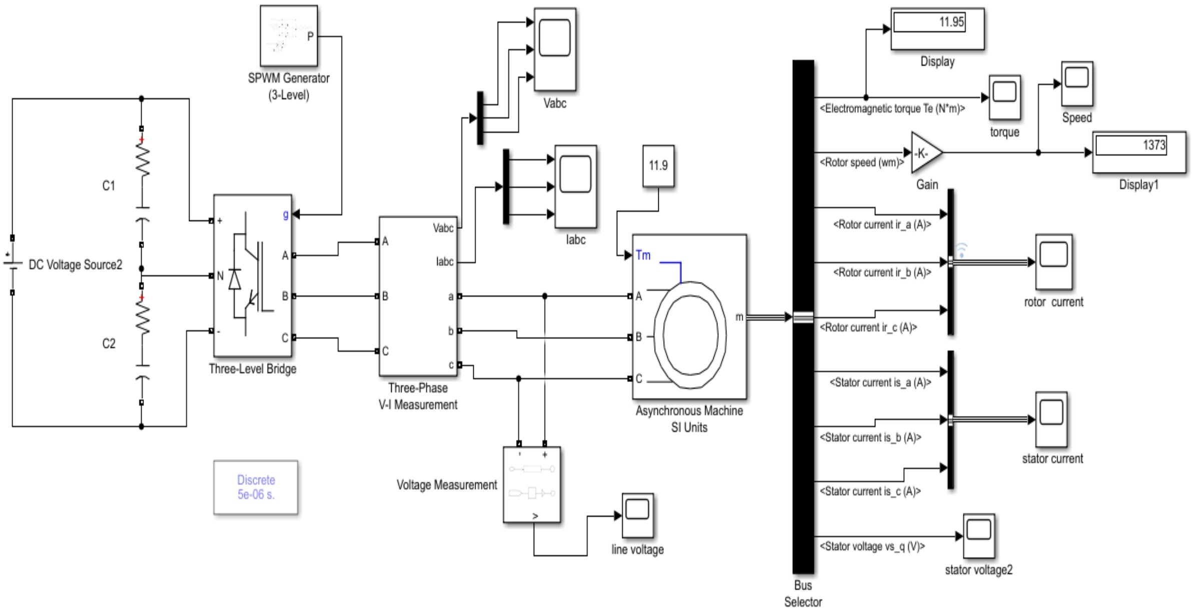


Figure 9 Simulink Model for SPWM Inverter fed IM

In the switching frequency, harmonics appear as sidebands in the output voltage then multiples in a PWM inverter. Therefore, the result of a high switching frequency get a necessary sinusoidal current (also a superimposed small ripple at a high frequency) in the motor. 3-phase 3-level inverter connected to a DC voltage source of 400 V. The applied load torque nominal value is 11.9 N.M and its machine’s shaft is constant [20, 29].

3.3.4 SVPWM Inverter Fed IM

For VFD applications, SVPWM advanced technique is used. The SVPWM technique utilizes dc bus voltage effectively and generates lower THD in the 3-Phase VSI. For reducing peak harmonics SVPWM utilize a chaotic changing switching frequency for continuously spreading harmonics to a wide band area. In the Simulation, different modulation index has been used. For the analysis of SVPWM fed IM 2-level PWM generator and universal bridge blocks have been used. Finally, the performance of SVPWM has been compared with conventional SPWM [30].

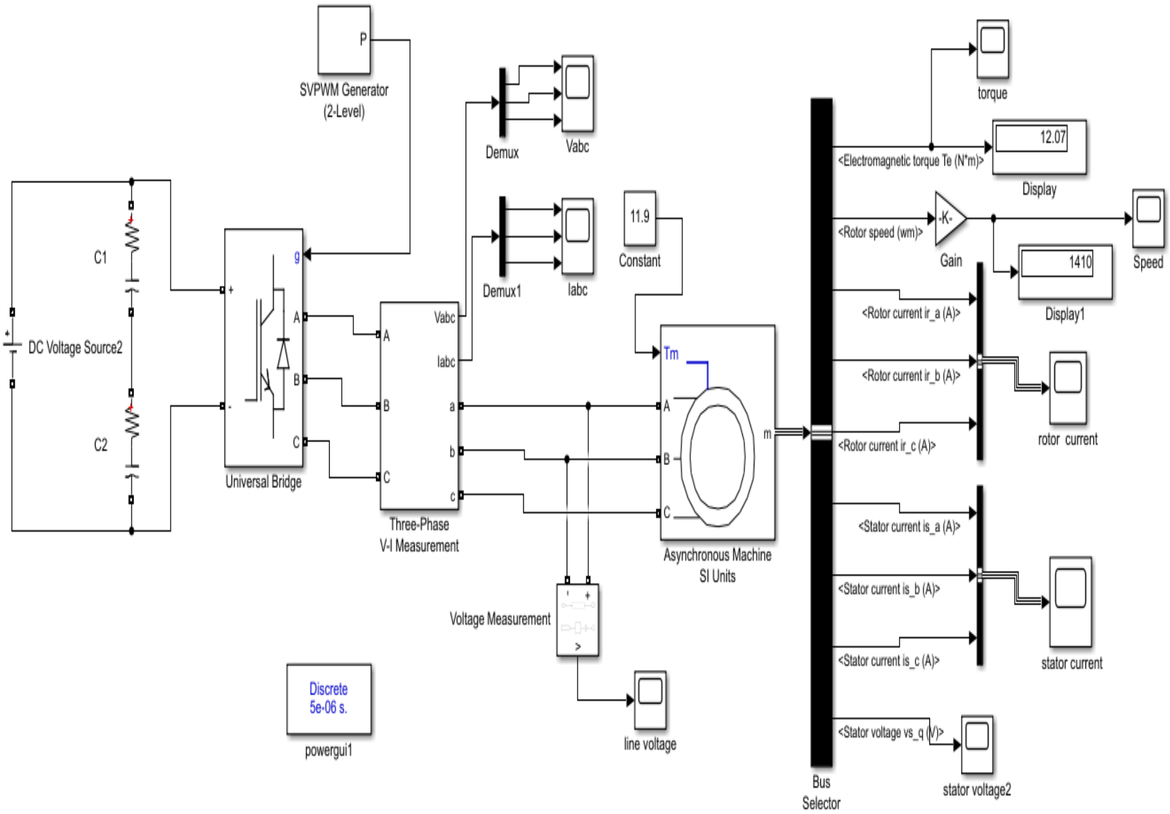


Figure 10 Simulink Model for SVPWM Inverter fed IM

The following parameters were passed for the PWM Generator and universal bridge block:

PWM Generator- This block generates pulses for PWM for firing the bridges of forced commutation devices. The pulses are generated by comparing a triangular carrier waveform to a reference signal.

Table 3 Parameters passed for PWM Generator block

PWM Generator Parameters	Value
Generator mode-	3-arm bridge (12 pulses)
Carrier frequency	1350 HZ
Modulation Index	0.8, 0.9, 0.95
Frequency of output voltage	50 Hz
Phase of output voltage	120

Universal Bridge: The universal bridge block component represents a universal voltage converter for 3-phase power system. This block contains six switches, which connected in bridge arrangements. The universal bridge can be power electronic device component [5].

Table 4 Parameters for Universal Bridge block

Universal Bridge Parameters	Value
No. of bridge arms	3-arm bridge
Snubber resistance	1e5
Snubber capacitance	inf
Internal resistance Ron (Ohms)	1e-3
Forward Voltages [Device Vf(V) , Diode Vfd(V)]	[0 0]

4 RESULTS AND DISCUSSION

4.1 Simulation Result of Grid Fed 3-Phase IM

From the simulation results, overshoot in the electromagnetic torque, speed, stator and rotor current was observed while changing the load from its rated value to zero. Precisely, a high overshoot was observed in motor parameters in both starting and load step inputs at when the load is changing. The starting overshoot is about four times its rated value. In addition, the motor experienced jerky start with no load value. A low overshoot was also observed while the load was changed.

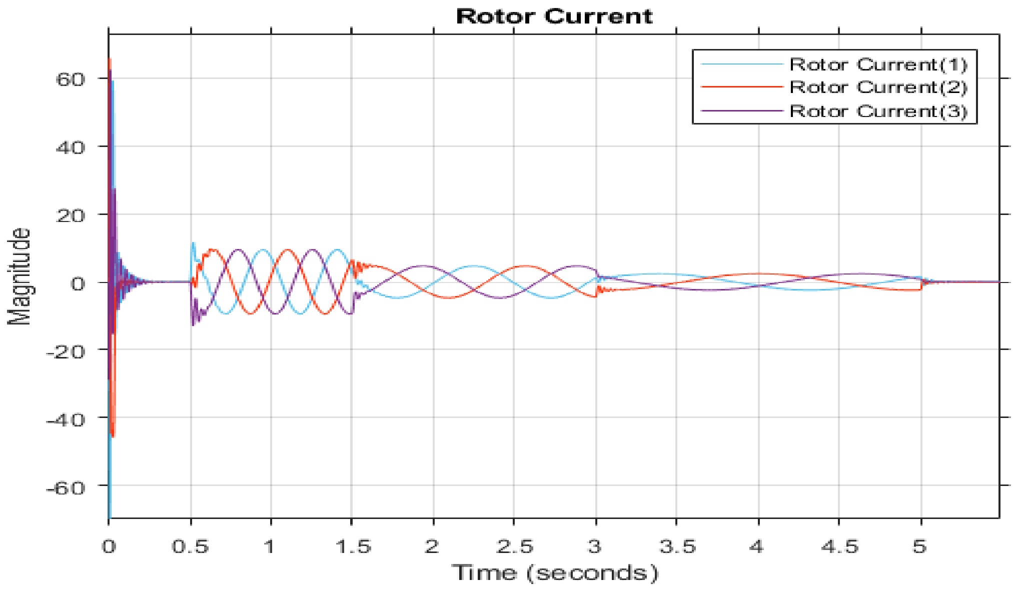


Figure 11 Rotor current of grid fed IM

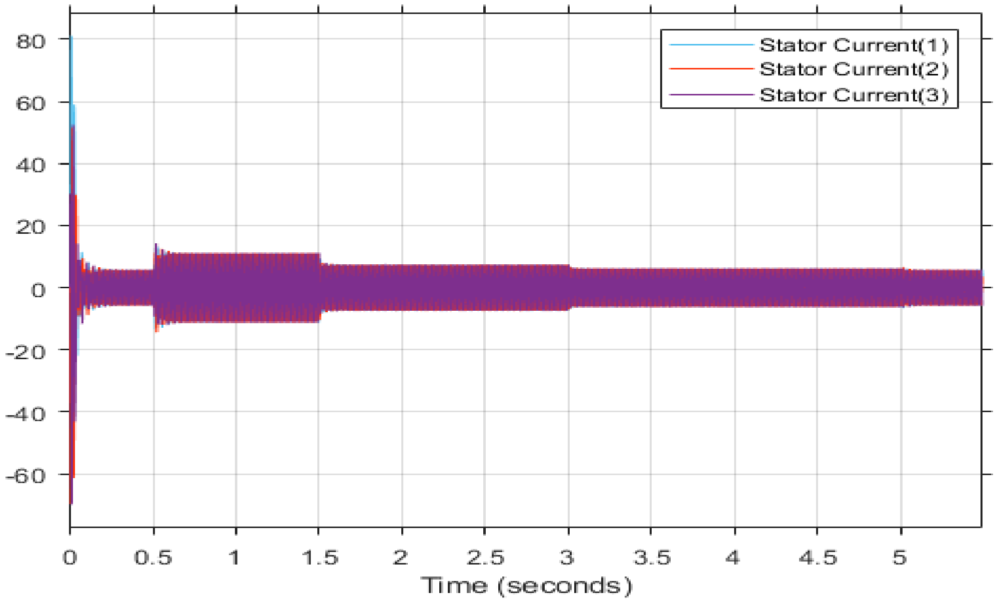


Figure 12 Stator current of grid fed IM

Figure 13 shows the waveform of speed. It is clearly shown that when the load torque decreases speed increases. Figure 14 shows the result of load torque of grid fed IM.

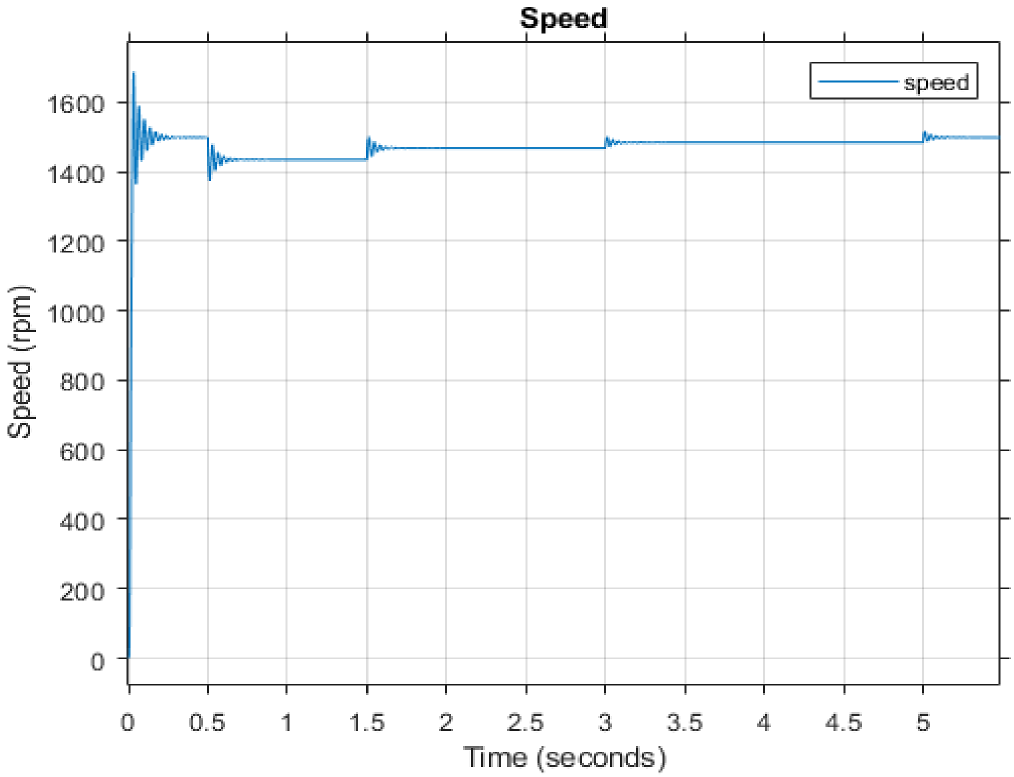


Figure 13 Speed of grid fed IM

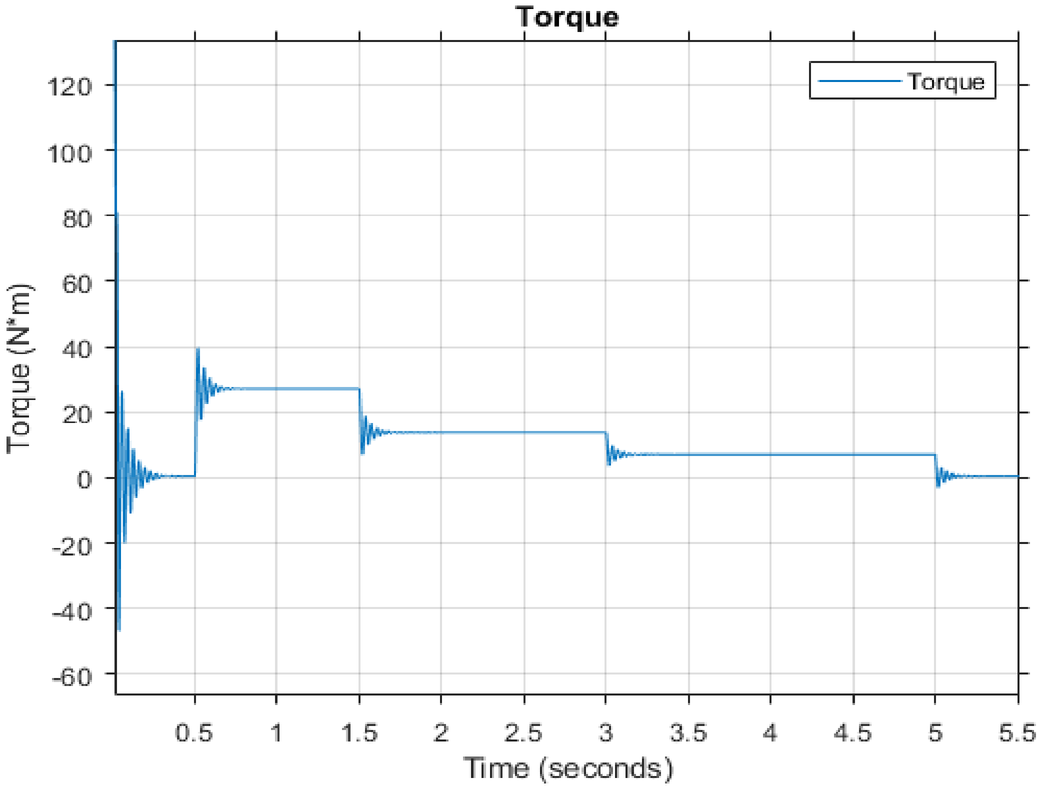


Figure 14 Load torque of grid fed IM

4.1.1 IM Simulation Results Using SPWM and SVPWM Inverter Control Strategy.

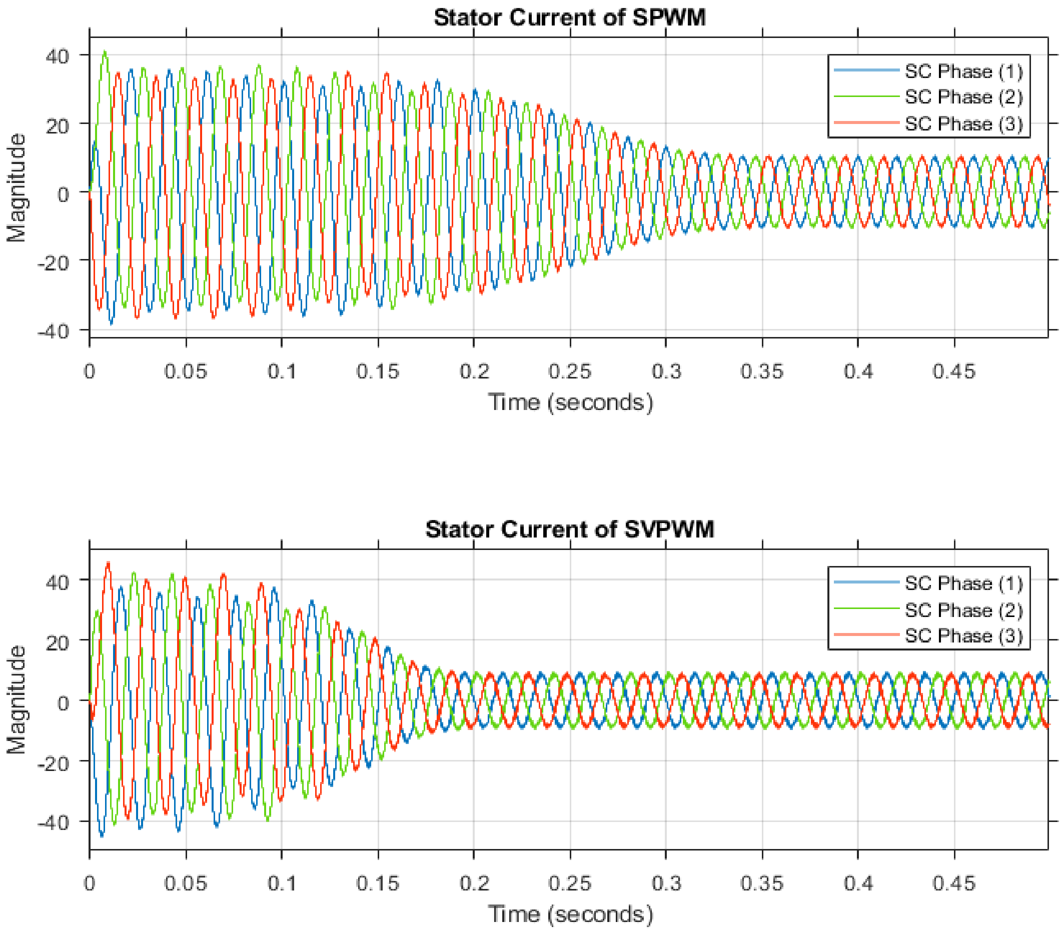


Figure 15 Stator current for 0.8 m_a

It is also an important factor to decide the performance of the motor. The comparison analysis of stator current for SPWM and SVPWM inverter for 0.8 modulation index with respect to time is shown in figure 15. IM stator current transient time is so less in SVPWM inverter compared to SPWM inverter for the same modulation index. In addition, in figure 16 the motor speed OF SVPWM inverter start increasing from zero to its maximum value faster and than SPWM inverter.

A lot of vibration in the SPWM inverter fed IM rotor speed, which results in the heating effect and the mechanical parts like bearing are much effected and thus effect the performance of the motor.

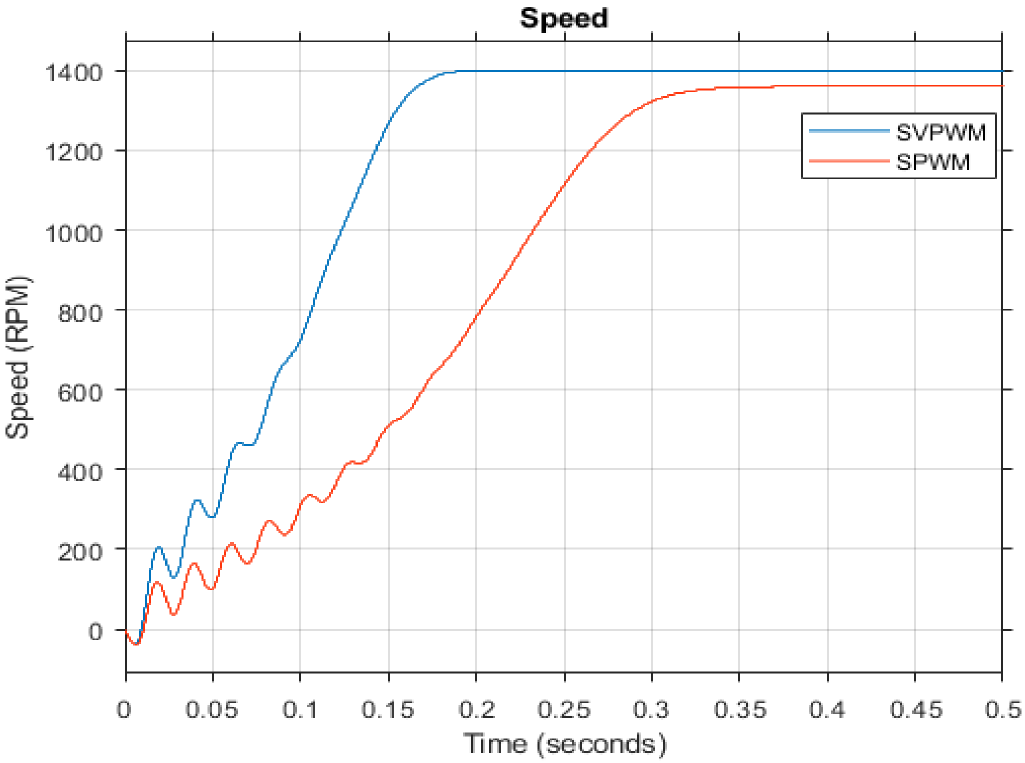


Figure 16 Speed for 0.8 m_a

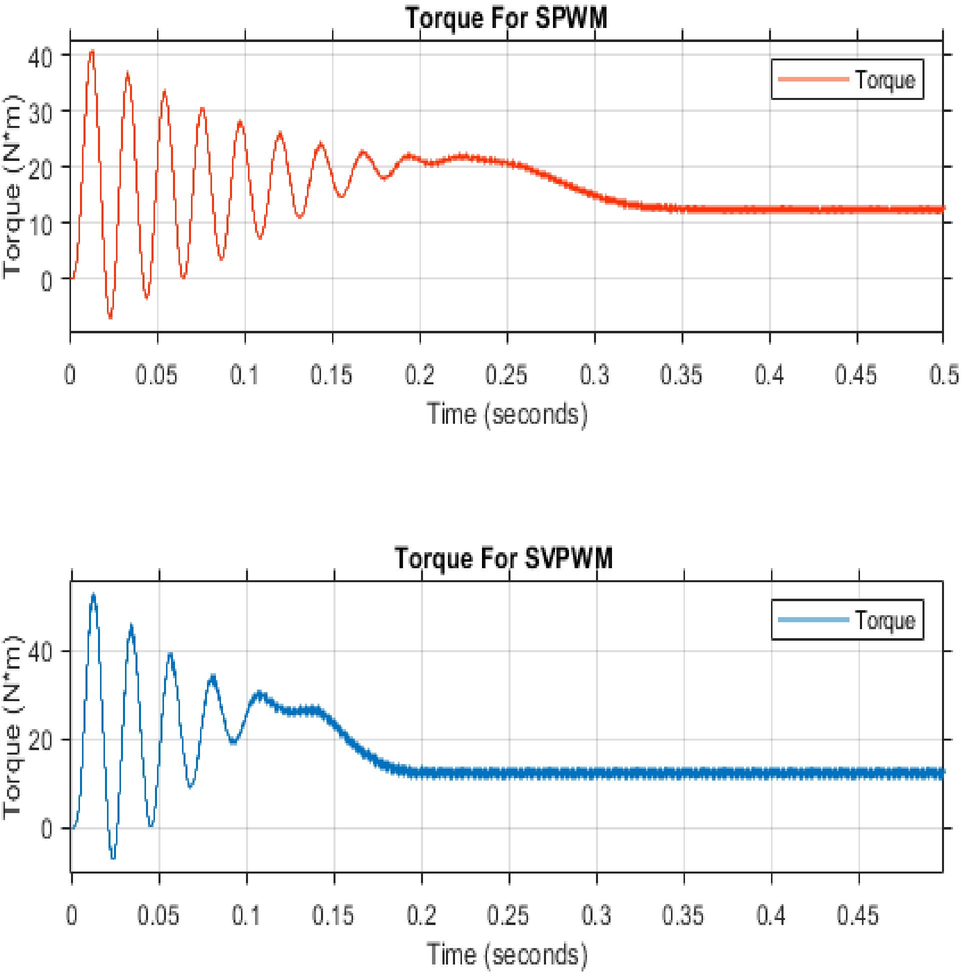


Figure 17 Torque for 0.8 m_a

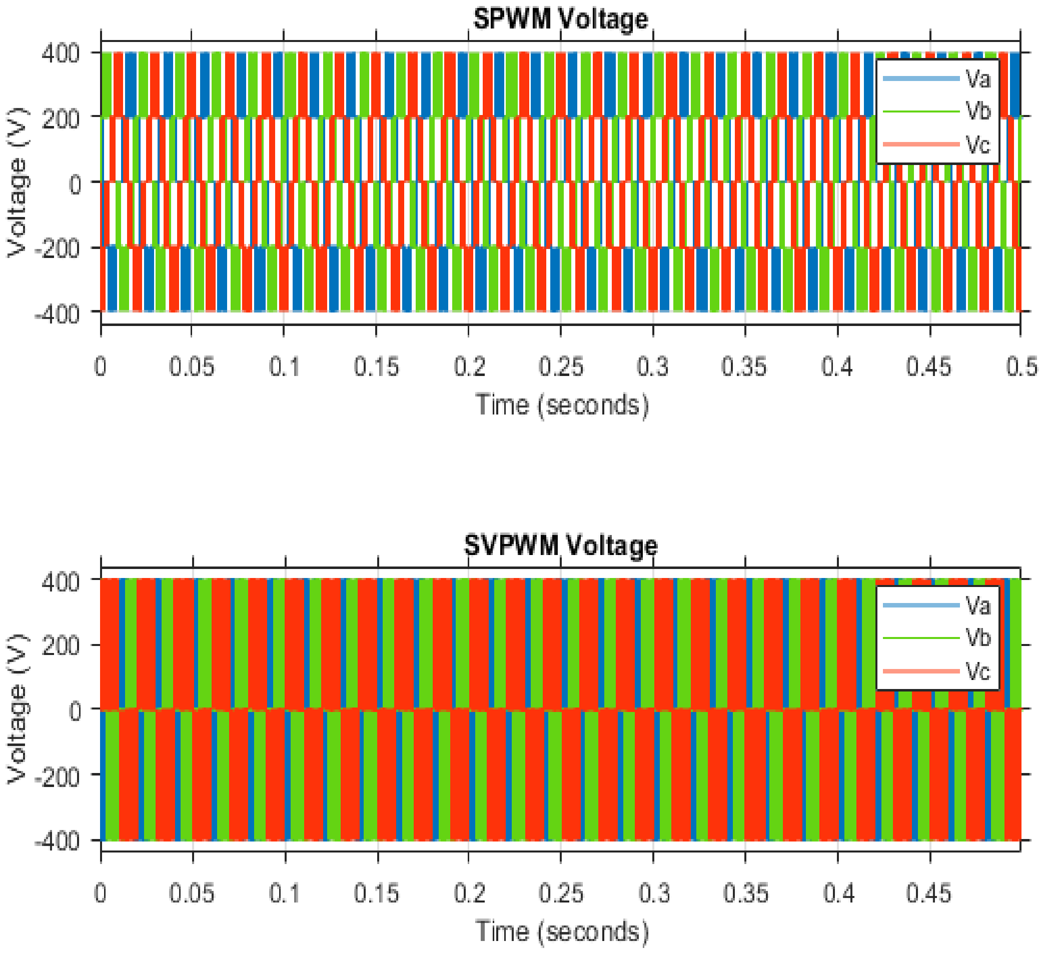


Figure 18 phase voltage for 0.8 m_a

In figure, 17 and 14 an electromagnetic torque shows a different pattern when comparing feeding the 3-phase IM through a sinusoidal source and through an inverter. Fundamental frequency of the induction motor produces forward operating torque and harmonic frequency will generate torque in both forward and in the reverse direction. Hence, in figure 17 IM Torque results are compared with both PWM techniques and in SVPWM inverter fed IM torque steady state response much faster than SPWM inverter fed IM.

In SPWM inverter fed IM, torque pulsation is more compared to SVPMW inverter. Although, with increasing the modulation index of PWM inverter fed IM current, harmonics are decreasing and speed of the IM increasing. In addition, the rotor speed vibration is decreases and torque transient time decreasing for SVPWM inverter fed IM. There is more result for 0.9 m_a and 0.95 m_a.

4.1.2 Simulation Results for 0.9 ma

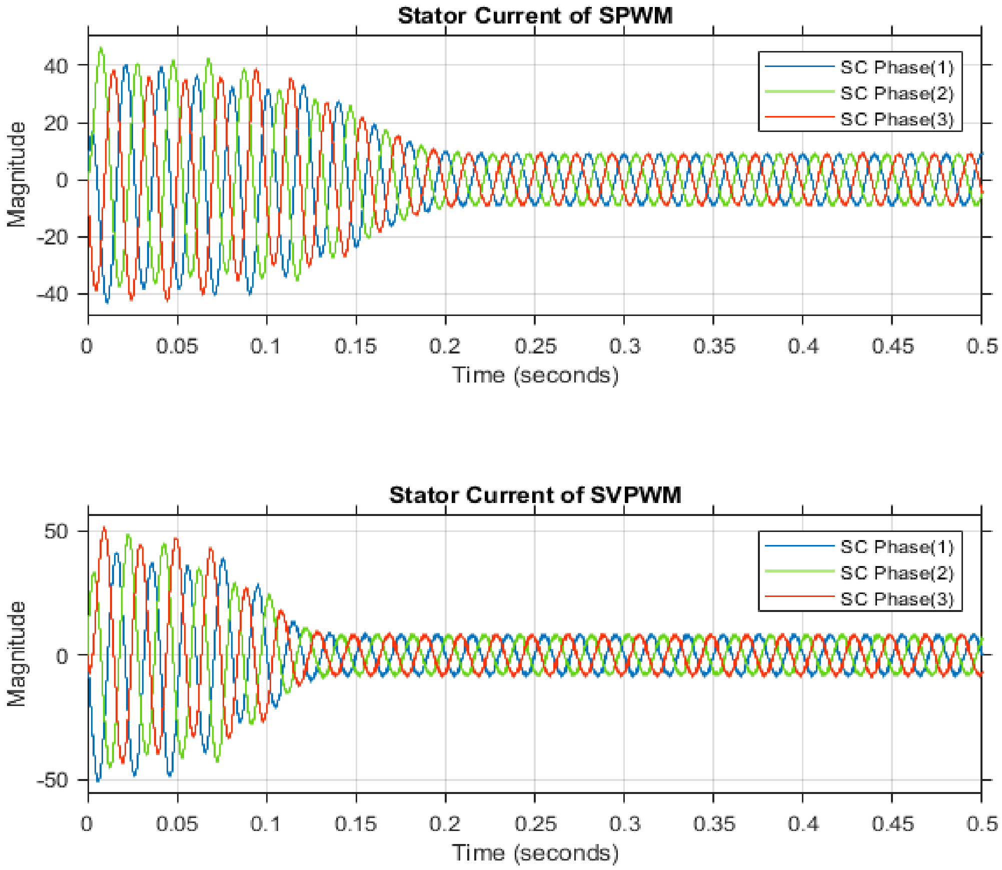


Figure 19 stator current for 0.9 m_a

The IM stator current (I_s) with respect to time is compared with both PWM inverter techniques is shown in figure 19.So for 0.9 m_a a stator current transient time is approximately 0.13 Sec for SVPWM inverter fed IM while in SPWM inverter is approximately 0.20 sec. Although, stator current magnitude is higher in SVPWM inverter fed IM compared to SPWM inverter fed IM.

The comparison analysis of variation in torque and speed of motor with respect to time is shown in figure 20 and 21.

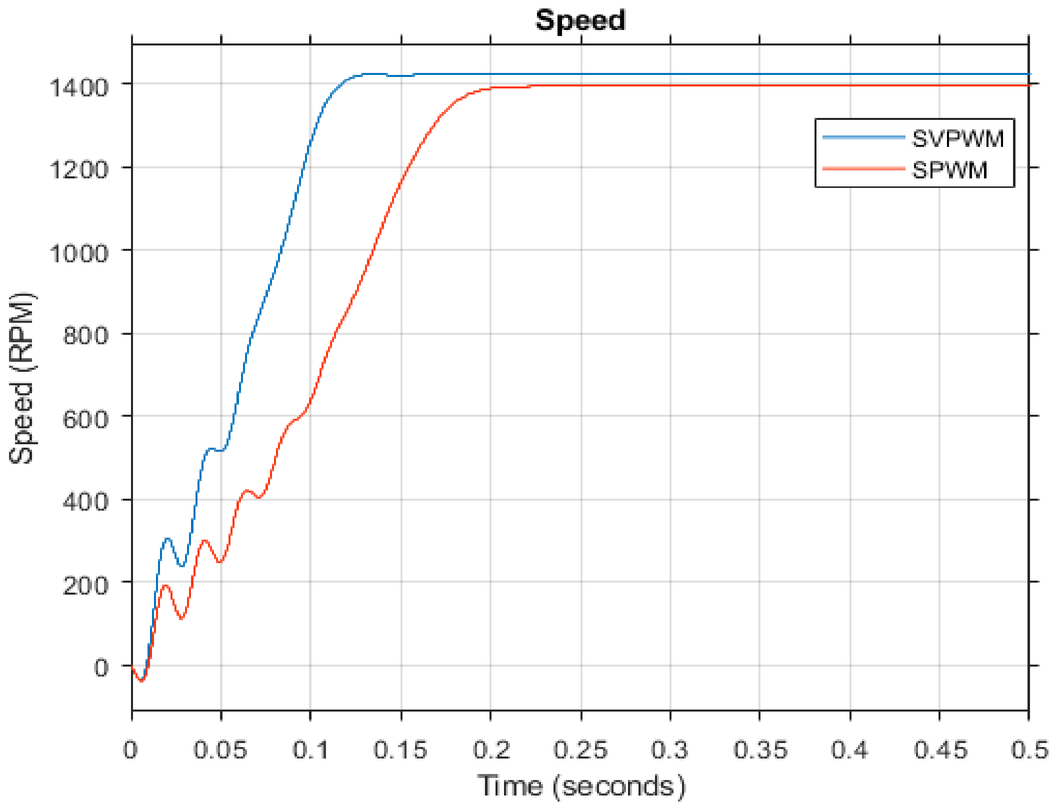
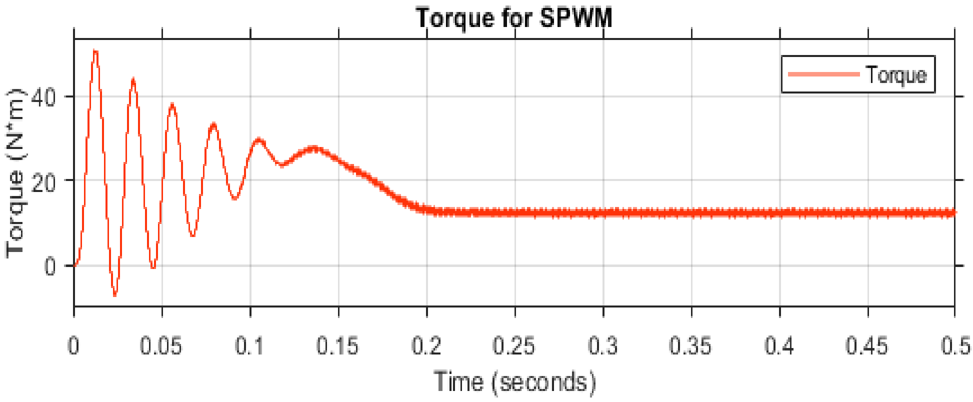


Figure 20 Speed for 0.9 m_a



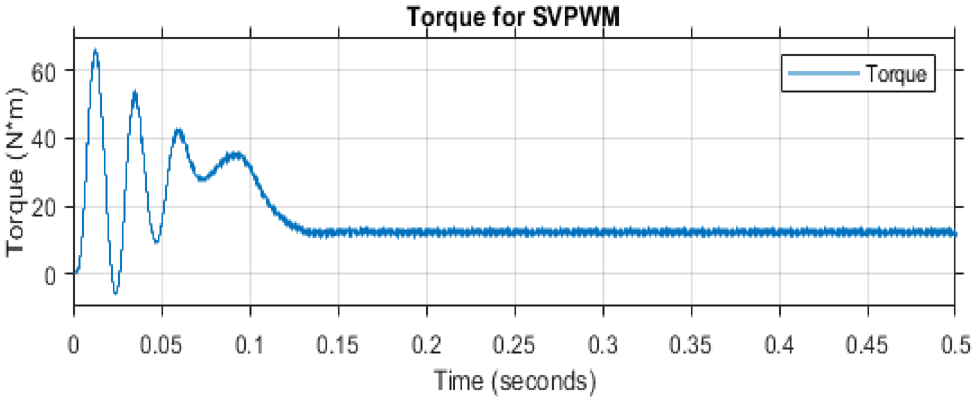


Figure 21 Torque for 0.9 m_a

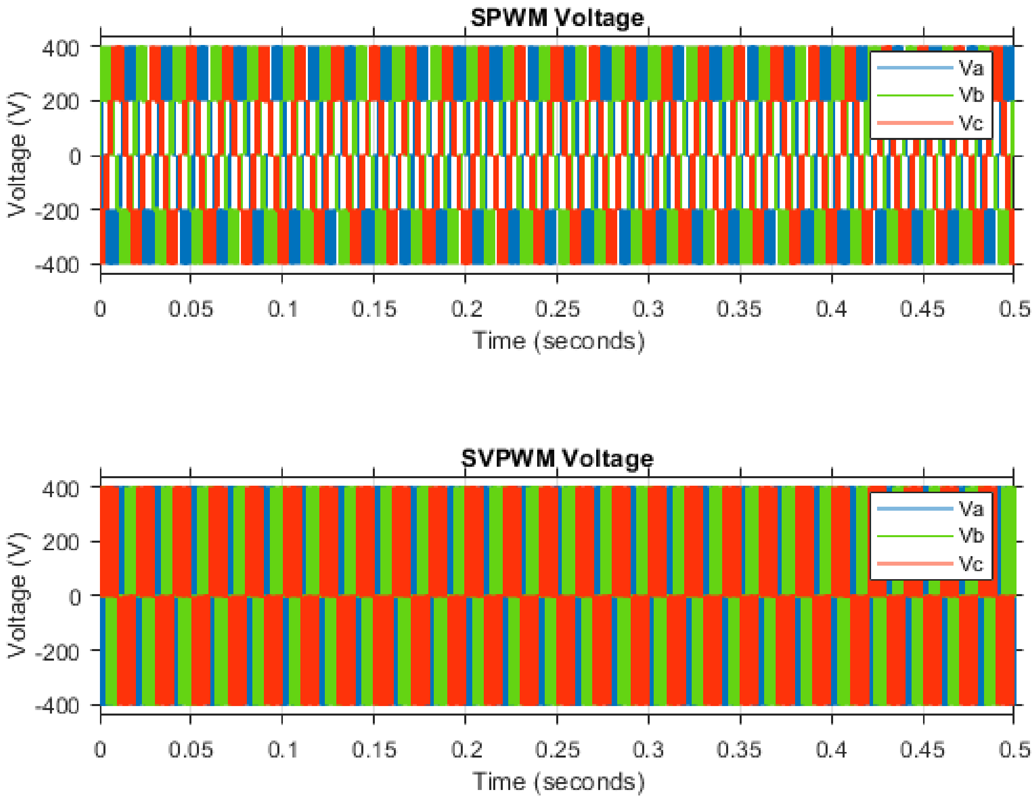


Figure 22 phase voltage for 0.9 m_a

4.1.3 Simulation Results For 0.95 m_a

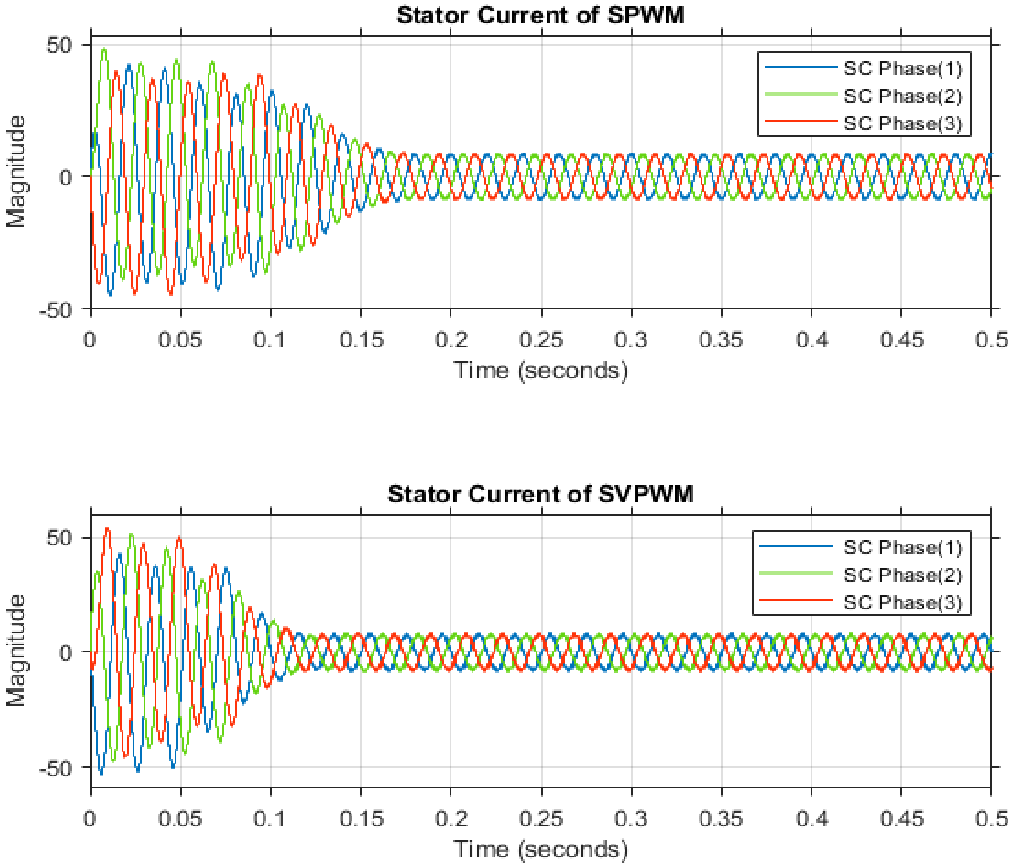


Figure 23 Stator current for 0.95 m_a

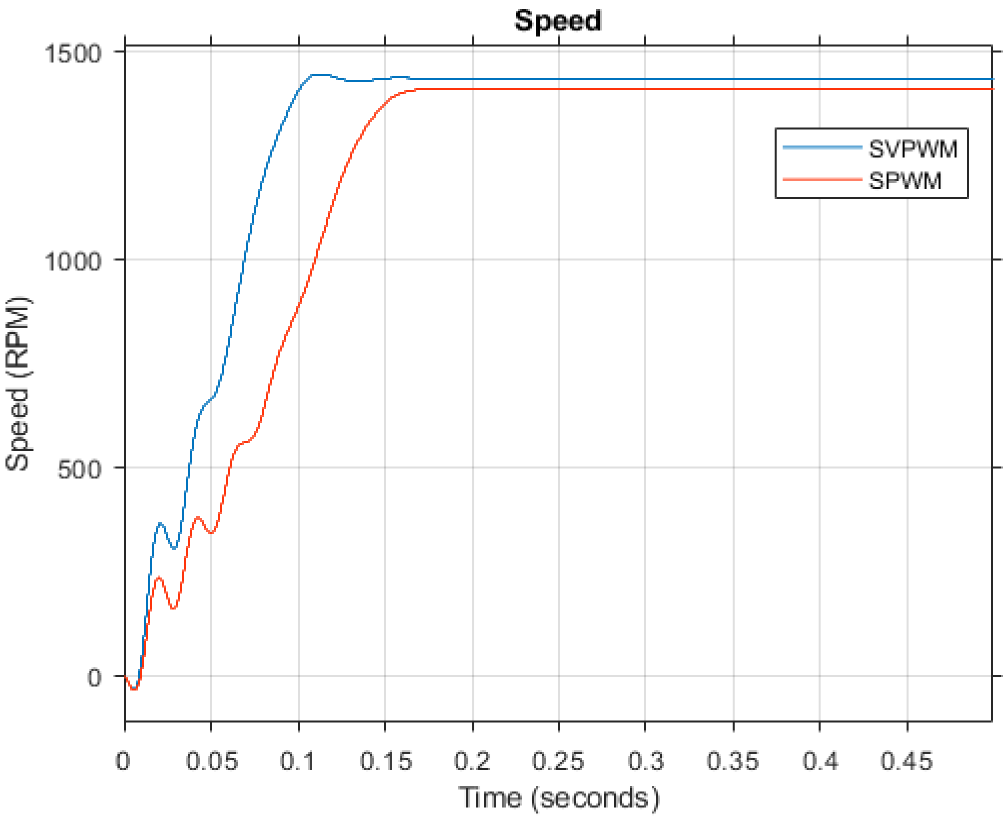


Figure 24 Speed for 0.95 m_a

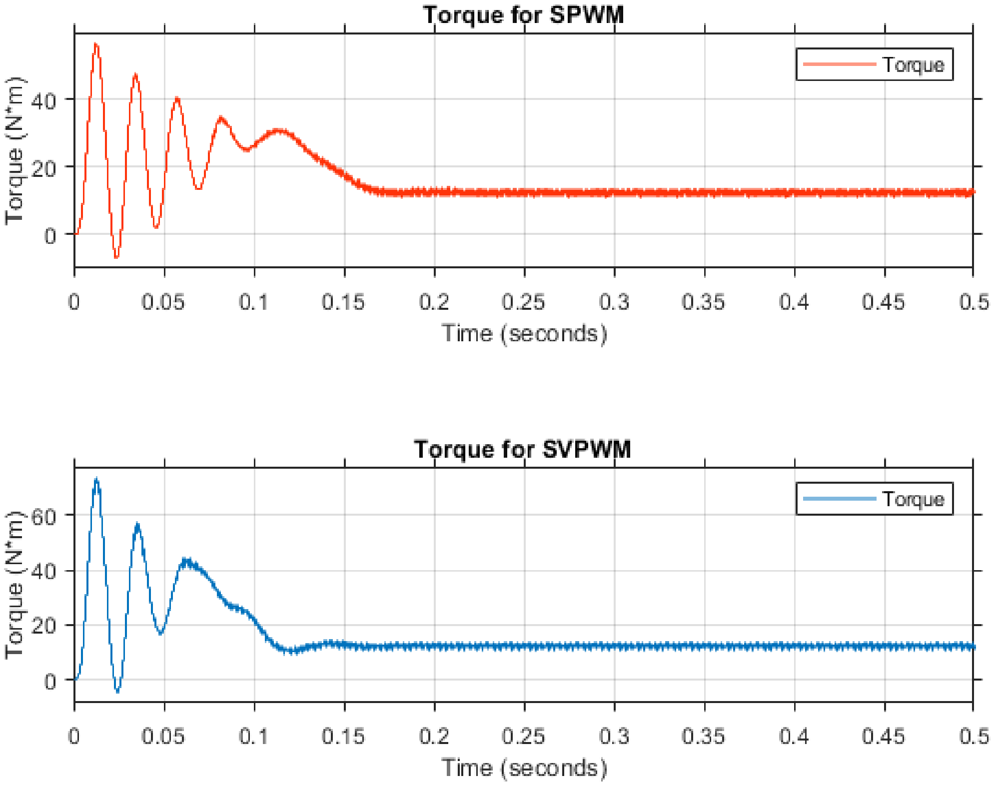


Figure 25 Torque for 0.95 m_a

As by comparing both the curves in figure 24, we conclude that SPWM inverter results in decreases of motor speed along with vibration. However, figure 24 shows that the rotor speed increases and that get constant in a smooth constant periodic formation for SVPWM inverter fed IM.

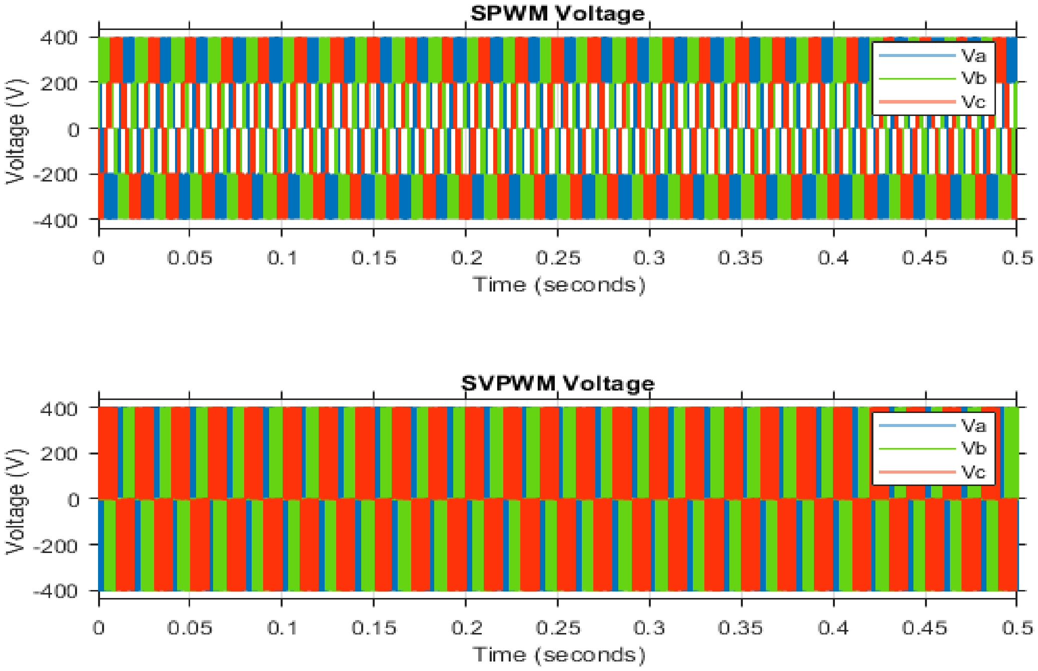


Figure 26 phase voltage for 0.95 m_a

4.2 Stator Current THD Analysis Using SPWM Inverter

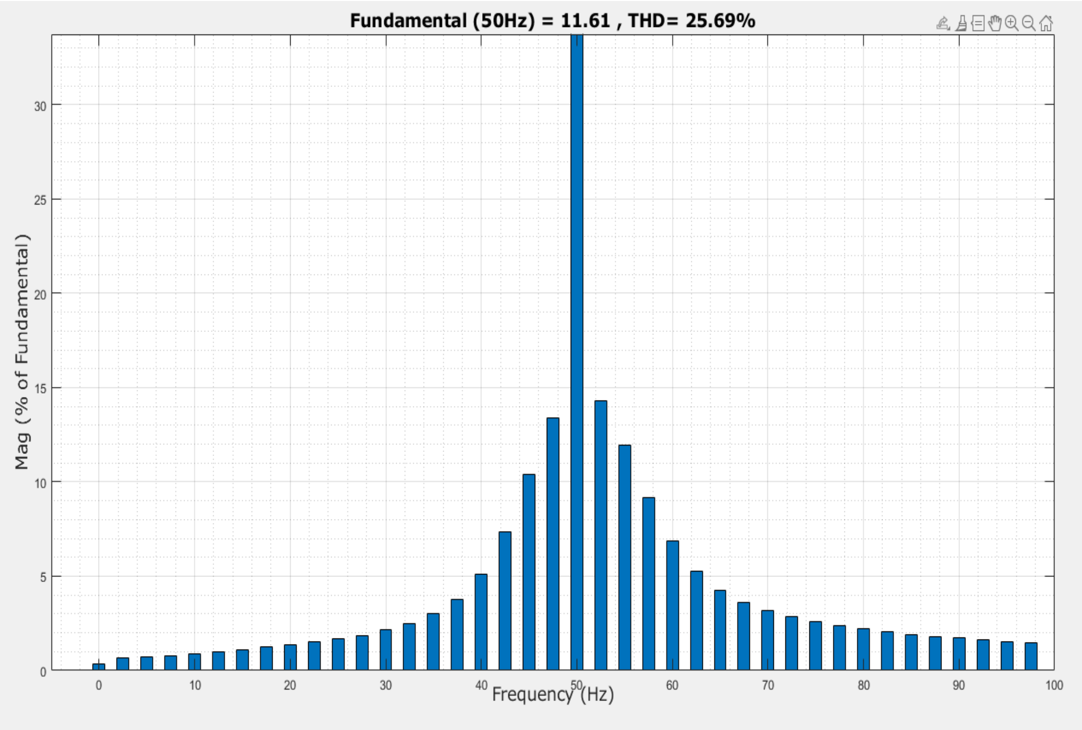


Figure 27 stator Current THD for SPWM inverter at m_a=0.8

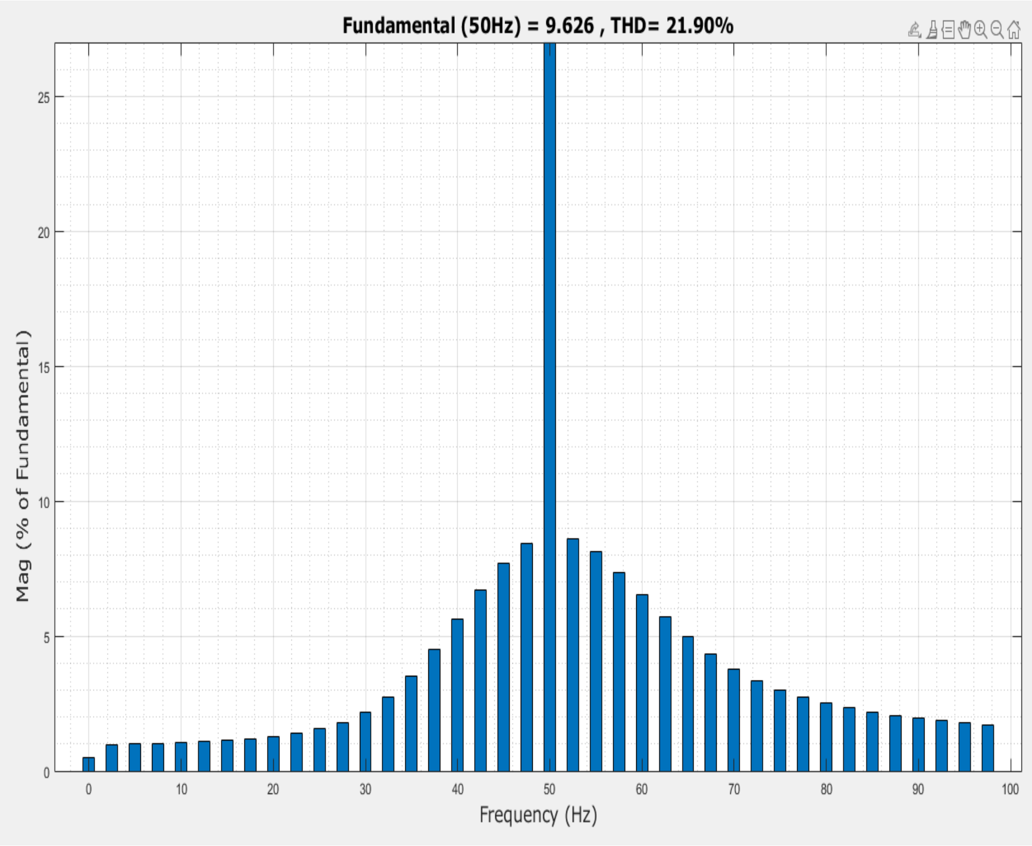


Figure 28 stator Current THD for SPWM inverter at m_a=0.9

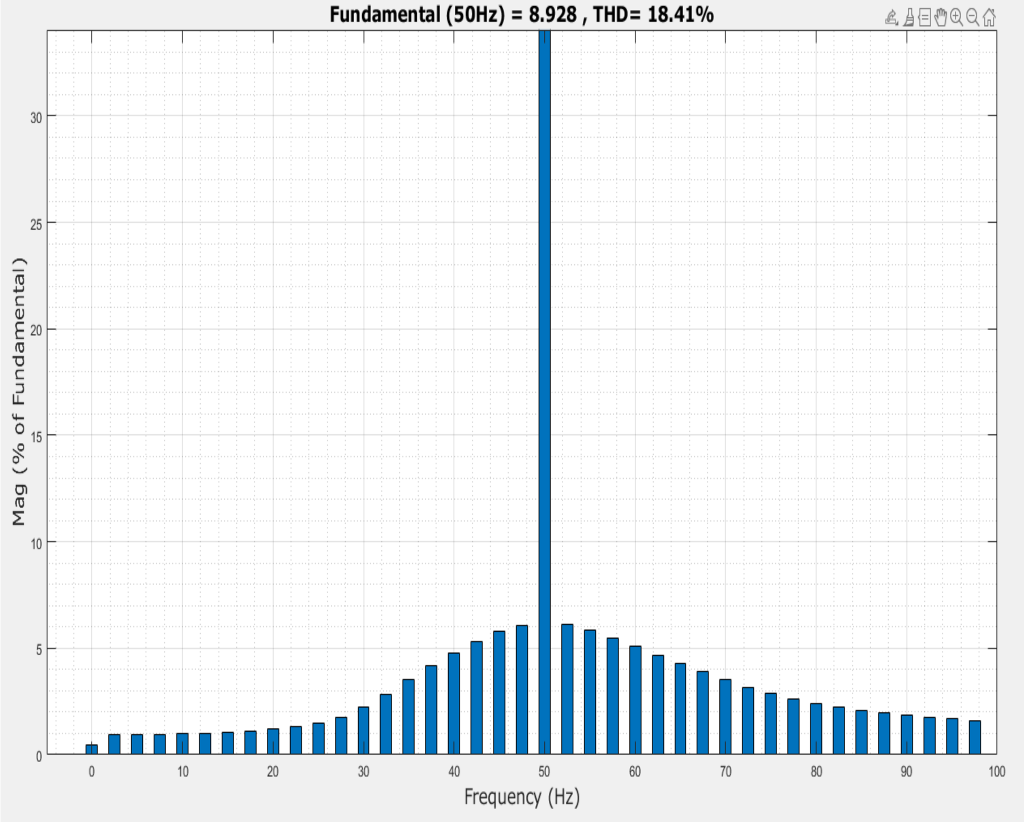


Figure 29 stator Current THD for SPWM inverter at m_a=0.95

4.2.1 Stator Current THD Analysis Using SVPWM Inverter

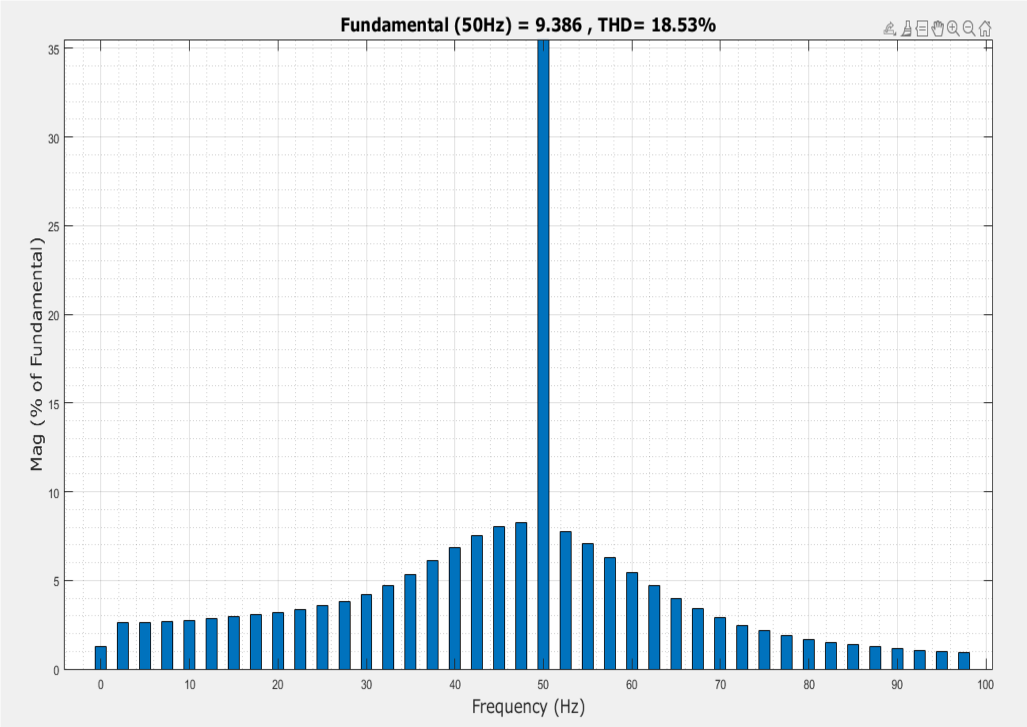


Figure 30 stator Current THD for SVPWM inverter at m_a=0.8

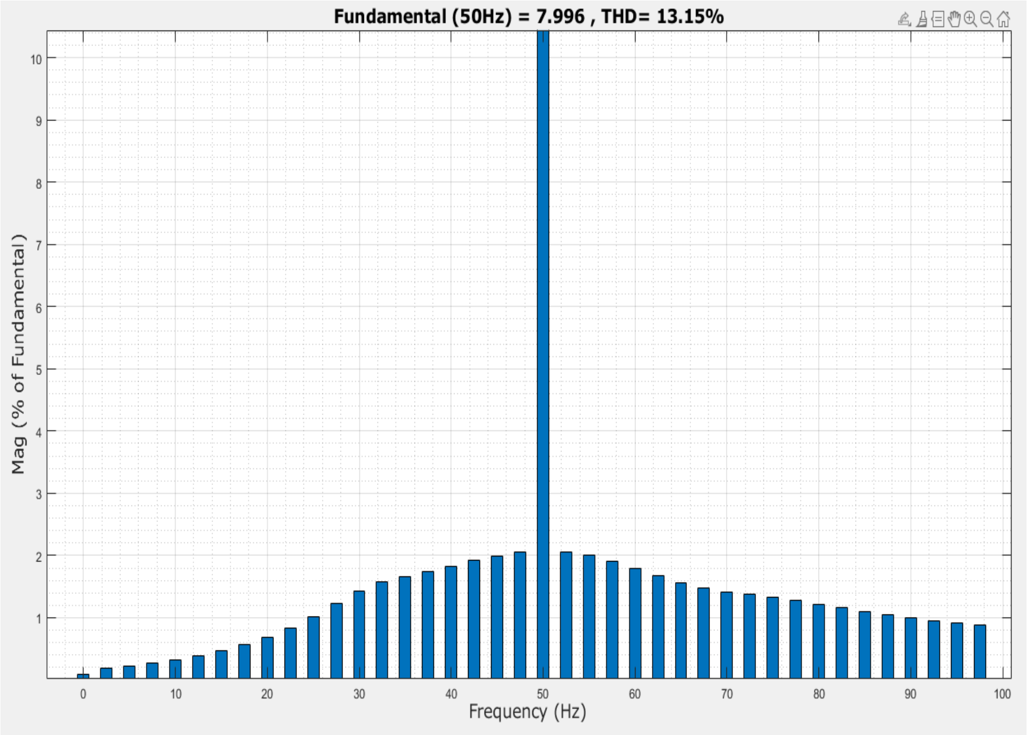


Figure 31 stator Current THD for SVPWM inverter at m_a=0.9

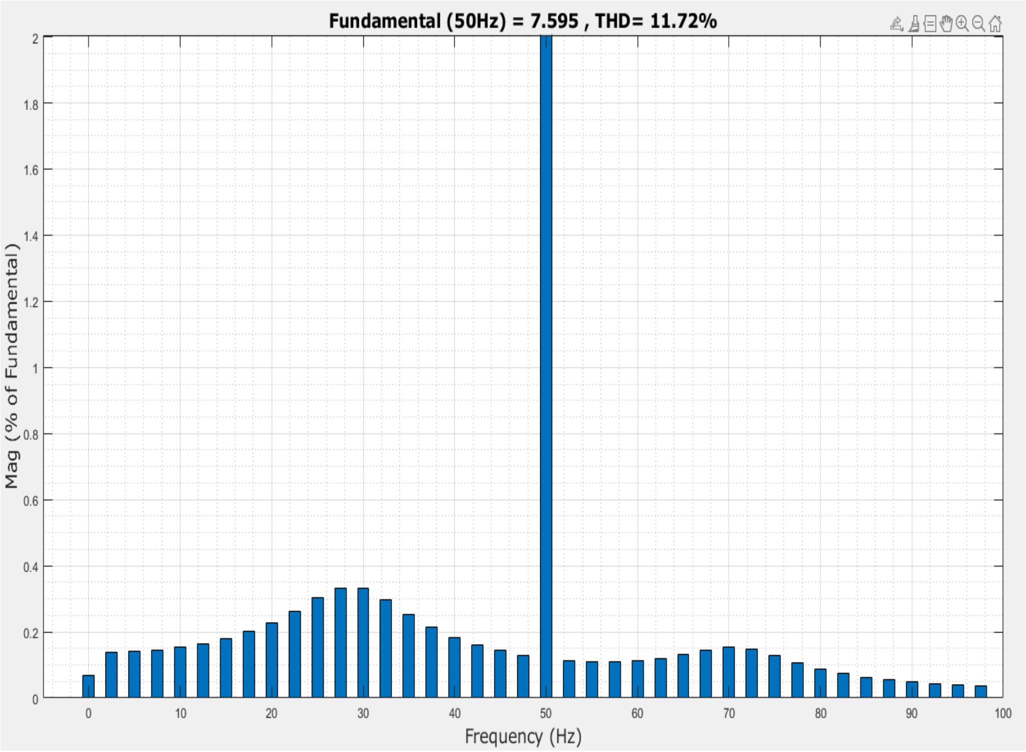


Figure 32 stator Current THD for SVPWM inverter at m_a=0.95

All the THD values have been taken after 0.1sec for 20 cycles of the stator current. The value of the THD and Fundamental component in the stator current significant decreases with the increase of modulation index. Figure 27, 28 and 29 show the SPWM inverter fed IM current THD; there values are 25.69%, 21.90%, and 18.41%, respectively for different modulation index. When it is compared to SVPWM, inverter fed IM then THD results are much lower for the same range of modulation index.

4.2.2 Analysis

The research indicates performance analysis of 3-phase IM current when it is fed by SPWM and SVPWM VSI under-modulation range. The effect of modulation index on the performance of IM parameters such as torque, rotor speed, stator current and phase voltage graphical result has been conducted. It can also be observed that the output with a SVPWM technique has low torque ripple and low current distortion as well as maintained the rest characteristic of the system.

In speed and torque appreciable improvement notice as the modulation index is increased to unity. From the above analysis, we conclude that as the modulation index increased effect of THD on stator current decreased. The performance of the motor in terms of stator current, speed, and torque transients and steady-state response are significantly decreased for SVPWM inverter fed IM compared to SPWM inverter fed IM [3].

Tables 5 and 6 show the THD analysis of 3-phase IM current and speed changes for different modulation index and it is observed that optimum value for SVPWM is obtained at modulation index 0.95 with lower THD in current and improved transient time for speed and torque.

Table 4 stator current SPWM inverter fed IM THD analysis

S.No.	Modulation Index (m_a)	Speed (R.P.M)	Stator Current THD (%)
1	0.8	1361	43.77
2	0.9	1394	36.90
3	0.95	1405	30.53

Table 5 stator current SVPWM inverter fed IM THD analysis

S.No.	Modulation Index	Speed (R.P.M)	Stator Current THD (%)
1	0.8	1404	32.36
2	0.9	1424	14.31
3	0.95	1434	11.92

5 CONCLUSION

The purpose of this research is to present analysis of a 3-phase IM fed by a pure sinusoidal supply from grid and different PWM technologies such as SPWM and SVPWM VSI under different modulation range. In comparison to bipolar switching, the 3-phase inverter uses the unipolar scheme. The generating switching pulses algorithm, which generates a 3-phase balanced output, is used to drive an IM with SPWM and SVPWM. The analysis of 3-phase IM output parameters has been done using FFT. The transients and steady state response of the IM has been shown using the SPWM and SVPWM techniques.

The results show that we can reduce the THD effect on the stator current by varying the modulation index close to unity. The speed of IM is affected by changes in modulation index. There is a fluctuation in the rotor and stator currents and electromagnetic torque at start-up, but due to machine inertia, it is absent in speed. The results of both methods were compared. According to the simulation results, the SVPWM technique performs better in terms of eliminating stator current harmonics and reducing torque ripple while maintaining the other system characteristics.

5.1 Future Work

I would like to work on some hardware practical based on these various techniques fed to an Induction Machine and how they influence all of the machine's parameters such as speed, torque, stator and rotor currents.

6 SUMMARY

6.1 English

Induction motors has a major influence on nearly every area of modern life. Electric motors are the world's largest energy consumers, accounting for roughly 60% of global power consumption. When a motor is started with a voltage source inverter fed drive system, a large number of harmonics appear at the inverter's output terminal. The 3-phase voltage source inverter converts direct current to alternating current using the pulse width modulation process, which we use to evaluate the design's output. Therefore, inverter-powered induction motor drives with pulse width modulation are extremely flexible, dependable, and capable of running at a variety of speeds.

The simulation and testing performance of the induction motor drive for the 3-phase voltage source inverter and various pulse width modulation methods such as space vector pulse width modulation and sinusoidal pulse width modulation were carried out in MATLAB/Simulink. Sinusoidal pulse width modulation and space vector pulse width modulation are switching pulse generation algorithms that generate a three-phase balanced output, which is then used to drive an induction motor. The analysis of 3-phase induction motor output parameters has been done using fast fourier transform.

The analysis has been carried under modulation range. The sinusoidal pulse width modulation and space vector pulse width modulation inverter techniques were used to demonstrate the induction motors transients and steady state response .The effect of the inverter on the stator current, phase voltage, and phase current waveform of the motor has been investigated.

The comparative performances between both techniques were presented. From the simulation results, the space vector pulse width modulation technique gives better performances in elimination of the stator current harmonics and reduction of the torque ripple while maintaining the other characteristic of the system.

6.2 Estonian

Asünkroonmootorid mõjutavad oluliselt peaaegu kõiki tänapäeva elu valdkondi. Elektrimootorid on maailma suurimad energiatarbijad, moodustades ligikaudu 60% maailma energiatarbimisest. Kui mootor käivitatakse pingeallikast inverteriga toidetava ajamiga, tekib vooluspektrisse suur hulk harmoonikuid. Allikas olev kolmefaasiline pingeinverter muundab alalisvoolu vahelduvvooluks, kasutades pulsilaiusmodulatsiooni, mida kasutatakse väljundi hindamiseks. Seetõttu on pulsilaiuse modulatsiooniga juhitavad inverteriga töötava asnkroonmootori ajamid äärmiselt paindlikud, usaldusväärsed ja võimelised töötama erinevatel kiirustel.

Asünkroonmootori ajami simulatsioon ja katsetamine komefaasilise pingeallika inverteri ja erinevate pulsilaiusmodulatsiooni meetoditel, nagu ruumivektori pulsilaius-modulatsioon ja sinusoidne pulsilaiusmodulatsioon, viidi läbi MATLAB/Simulinkis. Sinusoidne pulsilaiusmodulatsioon ja ruumivektori pulsilaiusmodulatsioon on lülitusimpulsside genereerimise algoritmid, mis tekitavad kolmefaasilise tasakaalustatud väljundi, mida kasutatakse induktsioonimootori käitamiseks. Kolmefaasilise asünkroonmootori väljundparameetrite analüüs on tehtud kiire Fourier' teisenduse abil.

Analüüs on teostatud modulatsioonivahemikus. Asünkroonmootorite siirete ja püsitalitluse demonstreerimiseks kasutati sinusoidaalse pulsilaiusmodulatsiooni ja ruumivektori pulsilaiusmodulatsiooni. Uuriti inverteri mõju mootori jõudlusele seoseid staatorivoolu, faasipinge ja faasivoolu lainekujuga.

Esitati mõlema tehnika võrdlevad tulemused. Simulatsioonitulemuste kohaselt annab ruumivektori pulsilaiusmodulatsiooni tehnika parema tulemuse staatori voolu harmoonikute kõrvaldamisel ja pöördemomendi kõikumise vähendamisel, säilitades samal ajal süsteemi muud omadused.

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APPENDIX

- State vector formulation

Rs, Lls: Resistance and leakage inductance of stator

Rr, Llr: Resistance and leakage inductance of rotor

Lm: The magnetizing Inductance

Ls, Lr: Stator and rotor inductances

Vqs, iqs: q axis component of stator voltage an current

Vqr, iqr: q axis component of rotor voltage and current

Vds, ids: d axis component of stator voltage and current

Vdr, idr: d axis component of rotor voltage and current

ϕqs, φds: q and d axis components of stator fluxϕ

ϕqr, φdr: q and d axis components of rotor flux

ωm: Angular velocity of rotor

θm: Angular position of rotor

P : Number of poles

p : Pairs of Poles ($\frac{P}{2}$)

ωr: Electrical angular velocity (ωr, p)

θr: Electrical rotor angular position (θm, p)

Te: Electromagnetic Torque

Tm: Mechanical Torque on Shaft

J: Load Inertia Constant

F: Friction Coefficient