Comparative Analysis of Different PWM Techniques on Three-Phase Voltage Source Inverter Fed Induction Motor Drive

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A project report submitted to the Department of Electrical and Electronic Engineering in partial fulfillment of the requirements for the degree of
Master of Engineering in Electrical & Electronic Engineering

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Brac University
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Declaration

It is hereby declared that

1. The project submitted is my original work while completing a degree at Brac University.

2. The project does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.

3. The project does not contain material that has been accepted or submitted, for any other degree or diploma at a university or other institution.

4. I have acknowledged all of the main sources of help.

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Approval

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has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Engineering in Electrical & Electronic Engineering on 17-11-2020

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Abstract

The demand for the induction motor is ever-growing day by day because of its robustness, high efficiency, and low cost over other motors. With the increasing demand for speed control of induction motor, a necessity arises to find an efficient motor controlling method. PWM techniques are an efficient method used to vary both the voltage and frequency within an inverter. A comparative study of five different PWM techniques of a three-phase voltage source inverter for the best induction motor drive performance is presented in this paper using MATLAB/Simulink software simulation. Sinusoidal PWM, Sixty-Degree PWM, Trapezoidal PWM, Third Harmonic Injected PWM, Space Vector PWM etc. techniques are demonstrated here. Induction motor characteristics like rotor speed, rotor steady speed obtaining time, rotor current, stator current & electromagnetic torque etc. along with inverter output characteristics like voltage THD%, current THD% etc. were observed by varying modulation index, carrier frequency, and loading condition of the induction motor drive. The simulation result shows that the Third Harmonic Injected PWM (THIPWM) technique exhibits the best induction motor drive performance compared to other PWM techniques.

Keyword- Three phase inverter, SPWM, THIPWM, SDPWM, SVPWM, TPWM

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Chapter 1 Introduction

1.1 Background and Motivation

Most of the machines used in industries nowadays are three-phase induction motors due to their robustness, less maintenance, high efficiency, and low cost. Previously they were mainly used for essentially constant speed applications. But with the advancement of power electronics, the use of induction motor in variable speed drive applications is increased. Speed control of the motor is necessary for the manufacturing and production companies to ensure precise operation and achieve energy saving. Motor speed can be controlled in various ways like controlling supply voltage, changing the number of stator poles, adding rheostat in the stator circuit and constant voltage/frequency control of motor etc.

The pulse width modulation (PWM) is the most efficient method used to vary both the voltage and frequency within a three-phase inverter. PWM delivers full power to the motor, which allows the motor to generate full torque even at lower speeds. In this method, a dc input voltage is converted to ac output voltage using an inverter which is obtained by adjusting the on and off periods of the inverter components**.** When DC is converted to AC, it contains some harmonic content, which affects the performance. The performance parameter of an inverter is total harmonic distortion (THD), lower-order harmonic (LOH), etc. The THD measurement process shows the closeness between a waveform and its fundamental component. Efficiency, power factor etc. of a system can be understood from THD [1-2]. A lower THD value of an inverter output means better efficiency, high power factor, etc. Therefore, THD plays an important role in power electronic systems.

There are various PWM techniques [1]. The most popular PWM technique is Sinusoidal PWM (SPWM) but it has low fundamental output voltage. So other PWM techniques like Sixty-Degree PWM (SDPWM), Trapezoidal PWM (TPWM), Third Harmonic Injected PWM (THIPWM), Space Vector PWM (SVPWM) etc. which provide better performance and has low harmonic content was invented.

Many researchers have been working on PWM techniques as well as induction motor drives for household and industrial applications. PWM techniques are used to vary both the voltage and frequency within an inverter. A comparative study of various PWM techniques is presented by a few researchers where it shows which PWM method provides the lowest THD and switching loss. Hence the efficiency of the inverter will be maximized [2-6].

Induction motor drive performance control is another area where researchers have been focusing on. Research shows that the PWM control scheme induction motor draws a comparatively lesser current than conventional phase angle controlled drive [7]. There are many methods to control the speed of the induction motor. Motor speed control has been done using field-oriented control [8-13] and direct torque control [14-19]. By keeping the voltage/frequency ratio constant we can attain a maximum torque at a wide range of speeds in scalar control. Vector control provides highly desirable performance and they are mostly used for IM control. Closed-loop voltage/frequency control for motor performance has been reported in a few papers as well [20-22].

Induction motor performance can be enhanced by changing inverter characteristics as well. Comparative analysis between different PWM fed inverters like CSI, VSI, ZSI etc. are reported in several papers and show that ZSI inverter provides better induction motor performance than VSI, CSI inverter [23-27]. Another research shows complex converter fed induction motor drive is superior to PWM-VSI fed induction motor drive [28].

Sayeeda-Farzana et al. [29] investigated multilevel inverter and found it can enhance induction motor performance to a certain extent. Multilevel VSI with SVPWM strategy gained importance in high power high-performance industrial drive applications [30].

SVPWM technique eliminates harmonics and reduces THD. Dara-Sandeep et al. [31] investigated SVPWM fed VSI and analyzed it in terms of THD, steady-state and transient performance operated under no-load conditions. Other research works show that SVPWM-VSI fed induction motor drive reduces common-mode voltage, the delay in speed and flux responses and gives better dynamic response [13, 32]. Artificial-neural-network (ANN)-based SVPWM can give higher switching frequency, which is not possible by conventional DSP-based SVM [33]. Synchronized PWM strategies that combine conventional space vector strategy and basic bus clamping strategy eliminates certain harmonics and reduces harmonic distortion in the stator current [8]. Another report analyzed SPWM-VSI fed induction motor drive in terms of frequency, voltage and voltage/frequency ratio variations to observe the change in output quantities [34]. Comparative evaluation of SPWM THIPWM, SVPWM, Discontinuous PWM strategies VSI fed induction motor drives under an open-loop scalar control strategy is reported in [35].

It can be seen that lots of work has been done using SPWM and SVPWM fed voltage source inverter for induction motor drive control. Research focus has not been given to THIPWM, SDPWM and TPWM fed voltage source inverter for motor control. In this paper, we have analyzed different PWM techniques like

SPWM THIPWM, SVPWM, SDPWM, TPWM etc. of a three-phase voltage source inverter (VSI) fed induction motor drive. The analysis was done by varying modulation index, carrier frequency, and a load torque of induction motor drive to see motor characteristics like rotor current, stator current, rotor speed, rotor steady speed obtaining time etc. and also see inverter parameters like voltage THD, current THD as well. All the data were taken from the software simulation. The main objective of this study is to find a PWM technique that will give the optimum induction motor drive performance.

1.2 Scope of the Work

A comparative study of five different PWM techniques on voltage source inverter fed induction motor drive is presented in this paper. Five popular PWM techniques like Sinusoidal PWM (SPWM), Sixty-Degree PWM (SDPWM), Trapezoidal PWM (TPWM), Third Harmonic Injected PWM (THIPWM), Space Vector PWM (SVPWM) etc. were designed in MATLAB/Simulink simulation software. The voltage source inverter is also designed here. Various parameters were changed to see motor performance variation. The performance analysis was done by varying modulation index, carrier frequency and a load torque of the motor drive to see motor characteristics like rotor speed, rotor steady speed obtaining time, rotor current, stator current & electromagnetic torque etc. as well as inverter characteristics like voltage THD, current THD. From the motor drive in Simulink software, rotor speed, rotor steady speed obtaining time, rotor current, stator current and electromagnetic torque etc. was found. Inverter output Total Harmonic Distortion (THD) was found using Fast Fourier Transform (FFT) analysis in Simulink software as well. All the data are taken from simulation software presented in a tabular format. Each PWM technique data were presented first then a comparative analysis was done at the end. This study can help the concerns to understand various PWM technique fed induction motor drive performance and select a PWM technique that gave optimal induction motor performance. High carrier frequency's effect on the induction motor output like rotor current, stator current and electromagnetic torque is also found here.

1.3 Thesis Outline

The book is organized in such an order to make it easy to understand for a reader. The book is structured as follows: Chapter 1 presents Introduction; Chapter 2 presents the PWM techniques used for three-phase voltage source inverter; Results and analysis are discussed in Chapter 3. Finally, Chapter 4 provides conclusion remarks. The contents of the chapters are explained in brief below:

Chapter 1 gives the background and motivation of this research along with the scope of the work.

Chapter 2 demonstrates all the five PWM techniques theoretically. Their gate pulse generation process is also presented here.

Chapter 3 covers the results related analysis and the findings. Individual PWM technique fed motor drive performance is presented here then a comparative analysis is given at the end.

Chapter 4 ends the thesis and presents the main findings and concluding remarks.

Chapter 2 PWM Techniques Used for Three-Phase Voltage Source Inverter

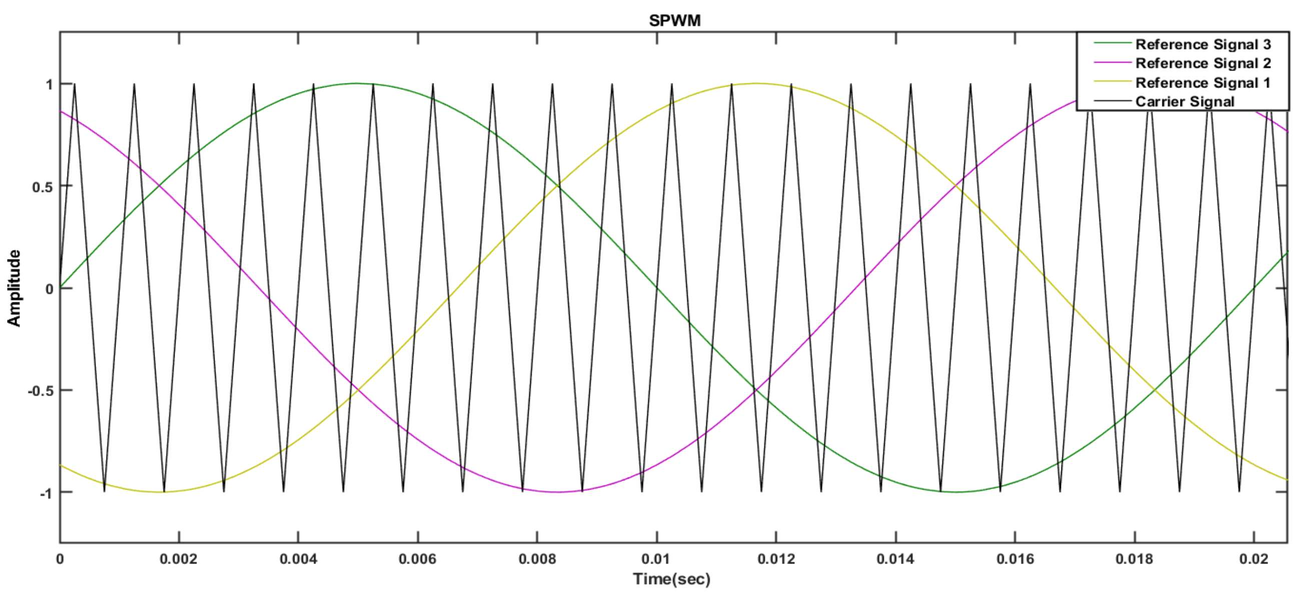
2.1 Sinusoidal PWM (SPWM) Technique:

This is one of the most popular PWM techniques used for its various advantages. To create a three-phase signal, three sinusoidal waves (v_a, v_b, v_c) were taken as a reference signal each shifted by 120 degrees. The Carrier signal is compared with the reference signals to generate switching signals [3-4]. The drawback of this modulation process is the fundamental output voltage is low. Fig. 2.1 shows carrier and reference signals along with the generated gate pulse signal.

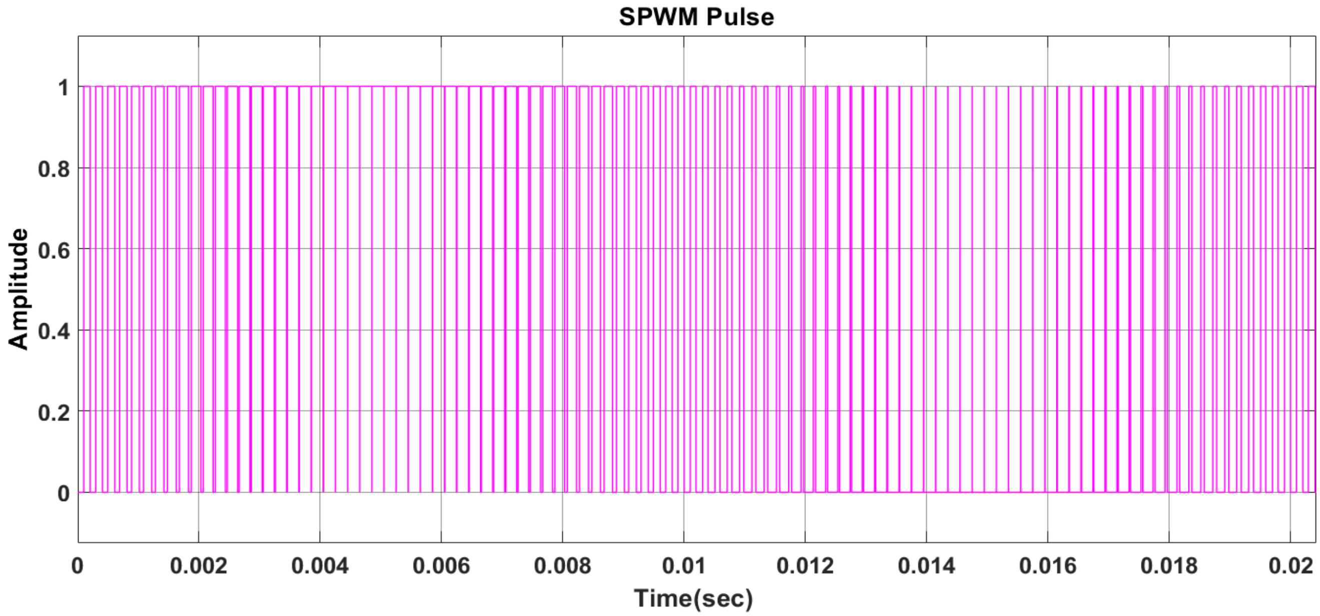
$$v_a = V_m \, sin(\theta); \quad (1)$$

$$v_b = V_m \, sin(\theta - 120°); \quad (2)$$

$$v_c = V_m \, sin(\theta + 120°); \quad (3)$$



2.1(a) Reference and carrier signal of SPWM.

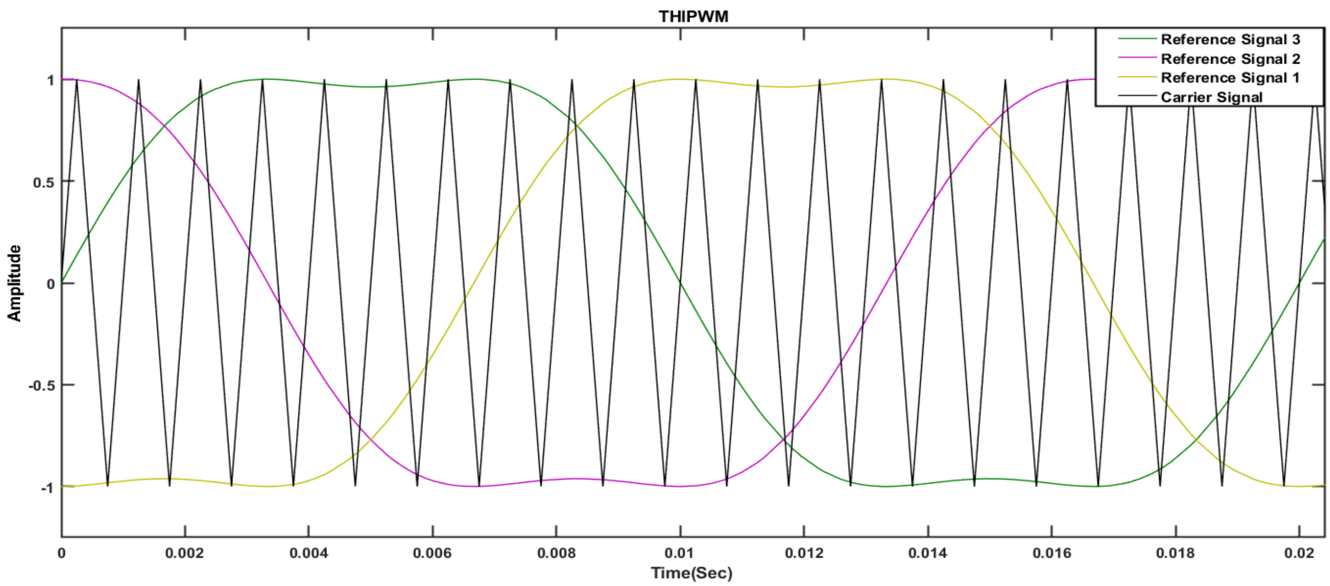


2.1(b) Generated gate pulse

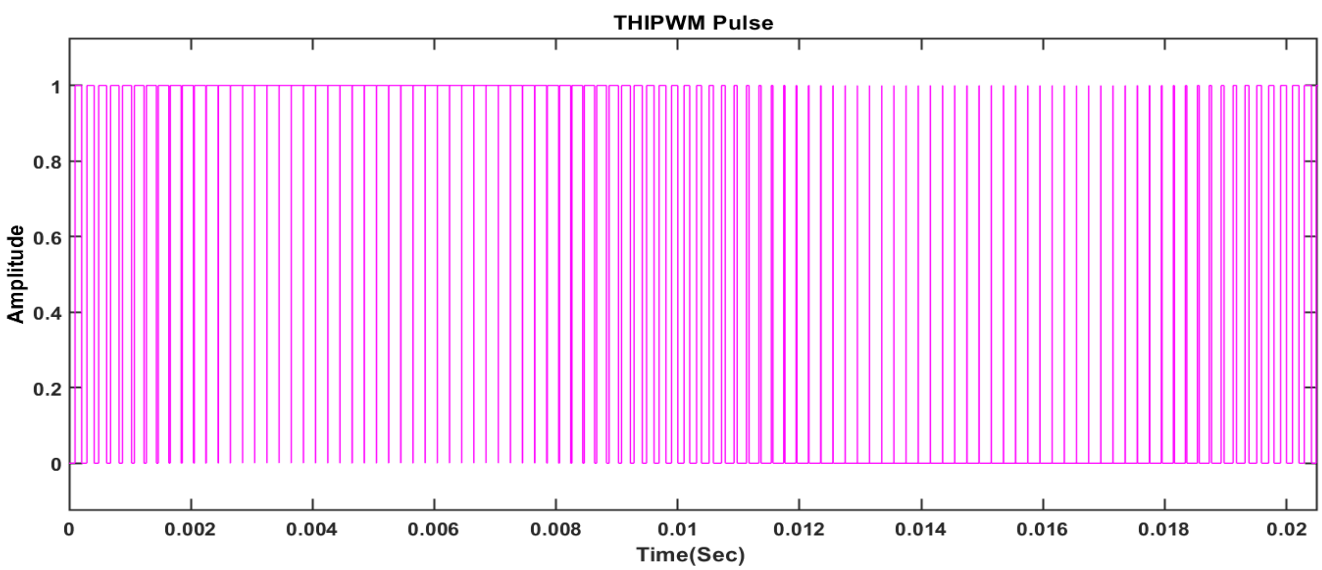
Figure 2.1 Gate pulse generation process of SPWM.

2.2 Third-Harmonic Injected PWM (THIPWM) Technique:

In this method, Switching signals are created superimposing original reference voltages (v_a, v_b, v_c) with third-harmonics signals [1, 3-4]. This technique cancels third harmonic components and creates a sinusoidal line to neutral voltages. Fig. 2.2 shows carrier and reference signals along with the generated gate pulse signal.



2.2(a) Reference and carrier signal of THIPWM.

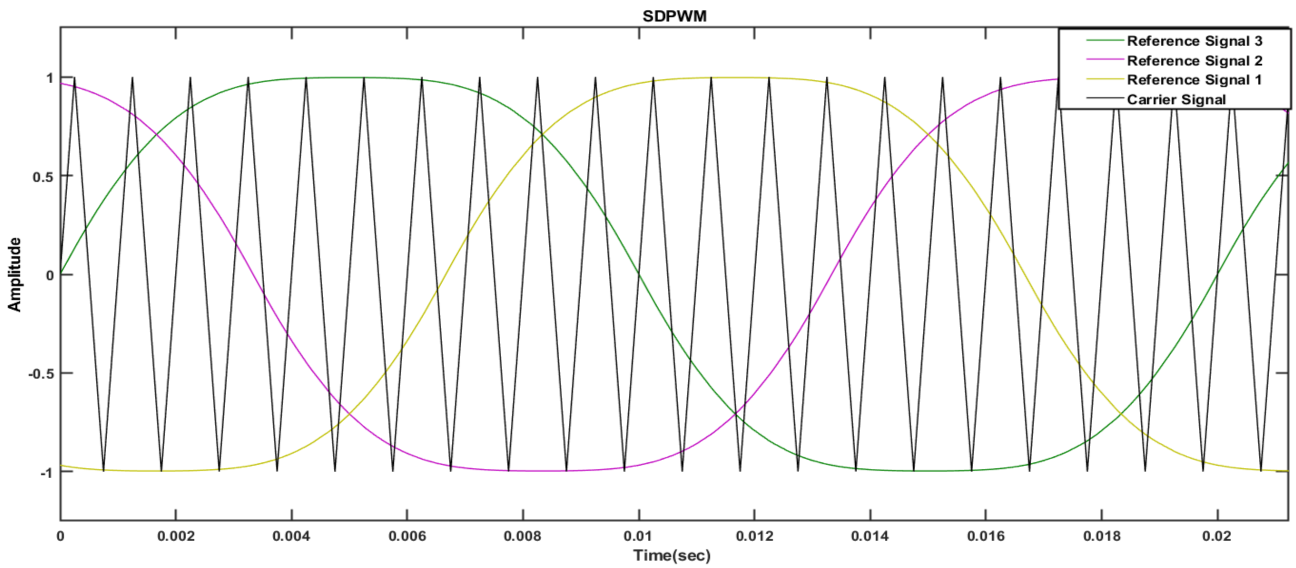


2.2(b) Generated gate pulse

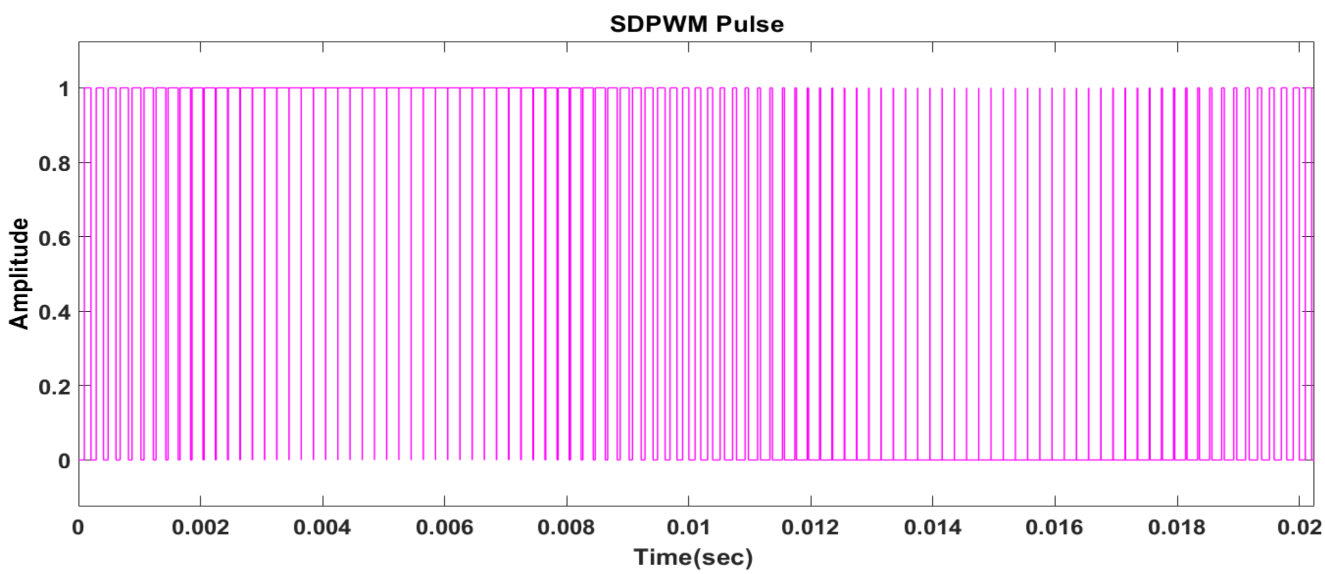
Figure 2.2 Gate pulse generation process of THIPWM.

2.3 Sixty-Degree PWM (SDPWM) Technique:

In the sixty-degree PWM technique, switches are held high or low for the sixty degrees of every half cycle of fundamental. The advantages of this technique compared to SPWM are switching losses reduced and creates larger fundamental voltage components [1, 5]. In addition, all triple harmonics are gone in three-phase voltages. Carrier and reference signals along with the generated gate pulse signal are shown in Fig. 2.3.



2.3(a) Reference and carrier signal of SDPWM.

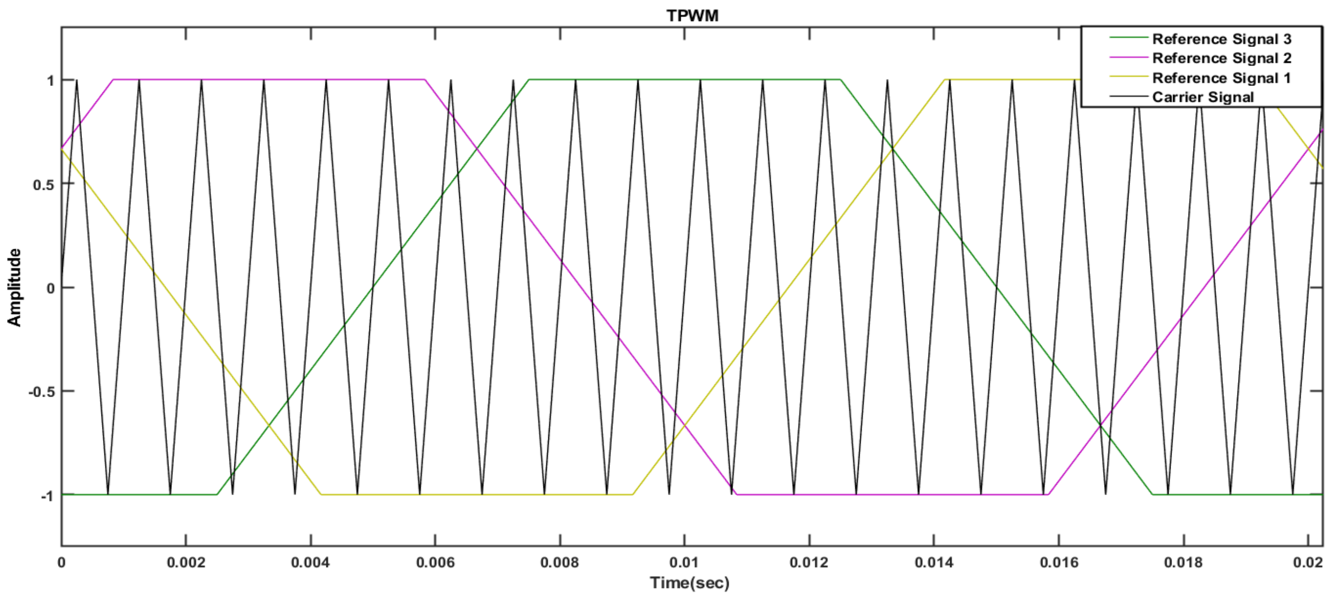


2.3(b) Generated gate pulse

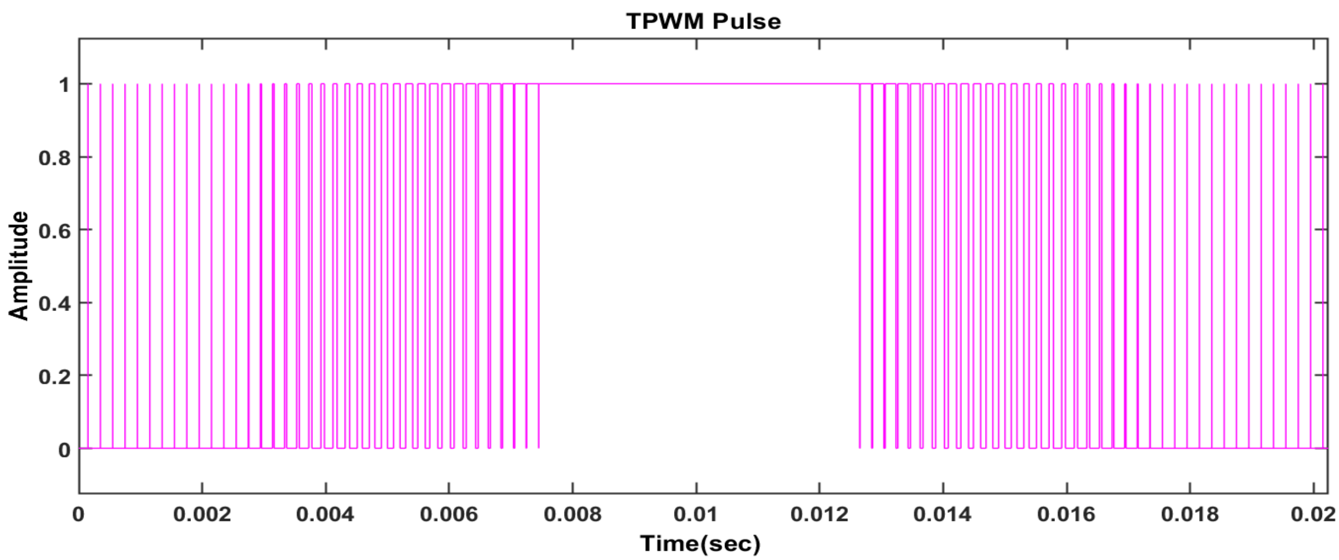
Figure 2.3 Gate pulse generation process of SDPWM.

2.4 Trapezoidal PWM (TPWM) Technique:

Trapezoidal signals were compared with the triangular signal to generate switching signals of the inverter [1, 36]. The magnitude of the triangular wave is limited to create a trapezoidal signal for this method. This advanced modulation technique increases the peak fundamental output voltage. One drawback of this technique is that it contains low order harmonics in the inverter output. The Gate pulse generation process is shown in Fig. 2.4.



2.4(a) Reference and carrier signal of TPWM.



2.4(b) Generated gate pulse

Figure 2.4 Gate pulse generation process of TPWM.

2.5 Space Vector PWM (SVPWM) Technique:

Another one of the most popular techniques is SVPWM. For the three-phase SVPWM technique, there are eight switching states in which six are non-zero and two are zero switching states. The eight switching states correspond to eight stationary voltage vectors in space and these vectors divide it into six sectors which are shown in Fig. 2.5. Gate signals of the inverter were generated by switching to these eight states [1, 37-38]. The advantages of this technique are efficient utilization of DC bus voltage, lower-order harmonic distortion in the inverter output. Fig. 2.6 shows the generated switching signal of the SVPWM technique. The normalized peak value of the nth line voltage vector can be found from

$$V_n = \frac{2}{\sqrt{3}}\left[\cos\left(\frac{(2n-1)\pi}{6}\right) + j\sin\left(\frac{(2n-1)\pi}{6}\right)\right] \quad (4)$$

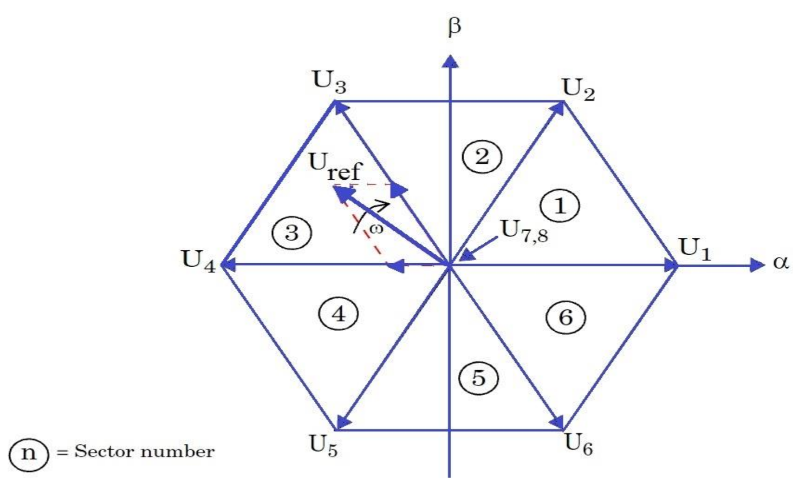


Figure 2.5 Space Vector Representation [39]

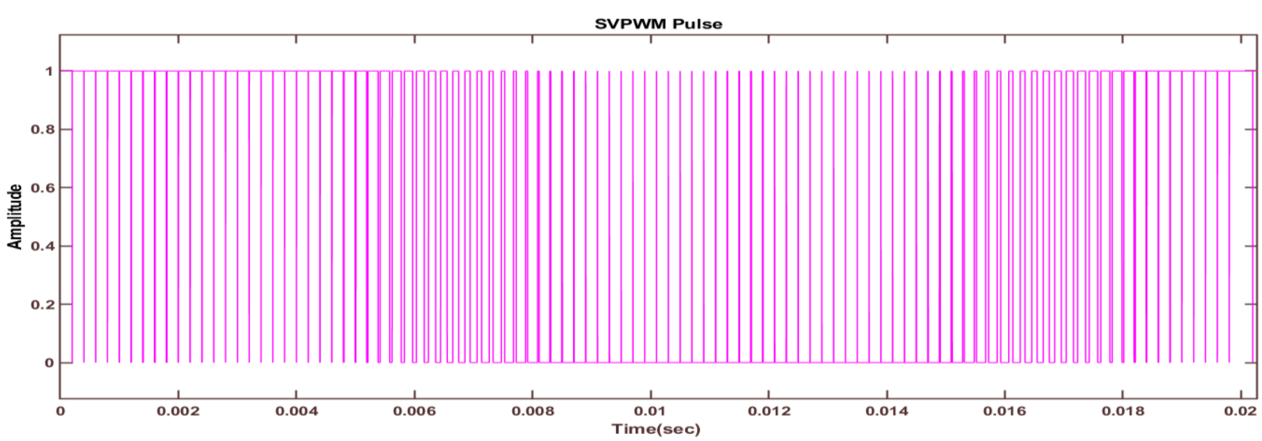
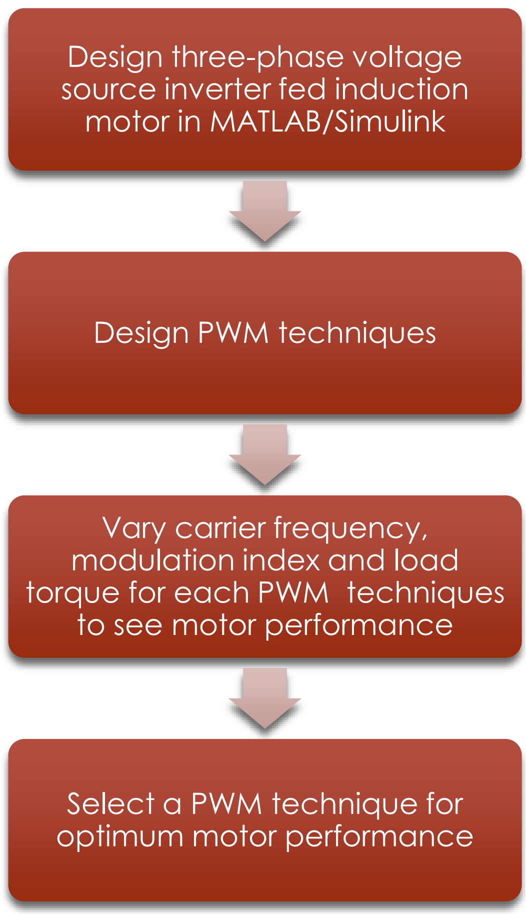


Figure 2.6 Generated gate pulse of SVPWM.

Chapter 3 Result and Analysis

3.1 Methodology

A three-phase voltage source inverter fed induction motor drive is designed in Matlab/Simulink software. Different types of PWM techniques like-Sinusoidal PWM, Sixty Degree PWM, Space Vector PWM, Third Harmonic Injected PWM, and Trapezoidal PWM, etc. is also designed on that software as well. These PWM techniques is used to run voltage source inverter. Each PWM technique gave different rotor speed settling time, motor torque, rotor current and stator current etc. The best PWM technique is selected based on motor performance.



3.2 Simulation Results

The simulation was done on Matlab/Simulink software and these data were presented in tables. The DC input voltage=200V, fundamental frequency=50Hz, the carrier frequency=1kHz were taken for the simulation. The modulation index value was varied from 0.3 to 1.0 to see the variation in inverter output THD value and motor characteristics. To see the inverter and induction motor performance carrier frequency was varied from 1kHz to 30kHz as well. Section 3.1.1 to 3.1.5 shows each of the five PWM methods fed induction motor drive performance individually.

3.2.1 SPWM technique fed induction motor drive performance:

Simulation schematic diagram of SPWM technique fed Induction motor drive is shown below in Fig. 3.1 from which inverter output THD value and motor parameters like rotor current, stator current, electromagnetic torque, rotor speed and rotor steady-speed obtaining time are found.

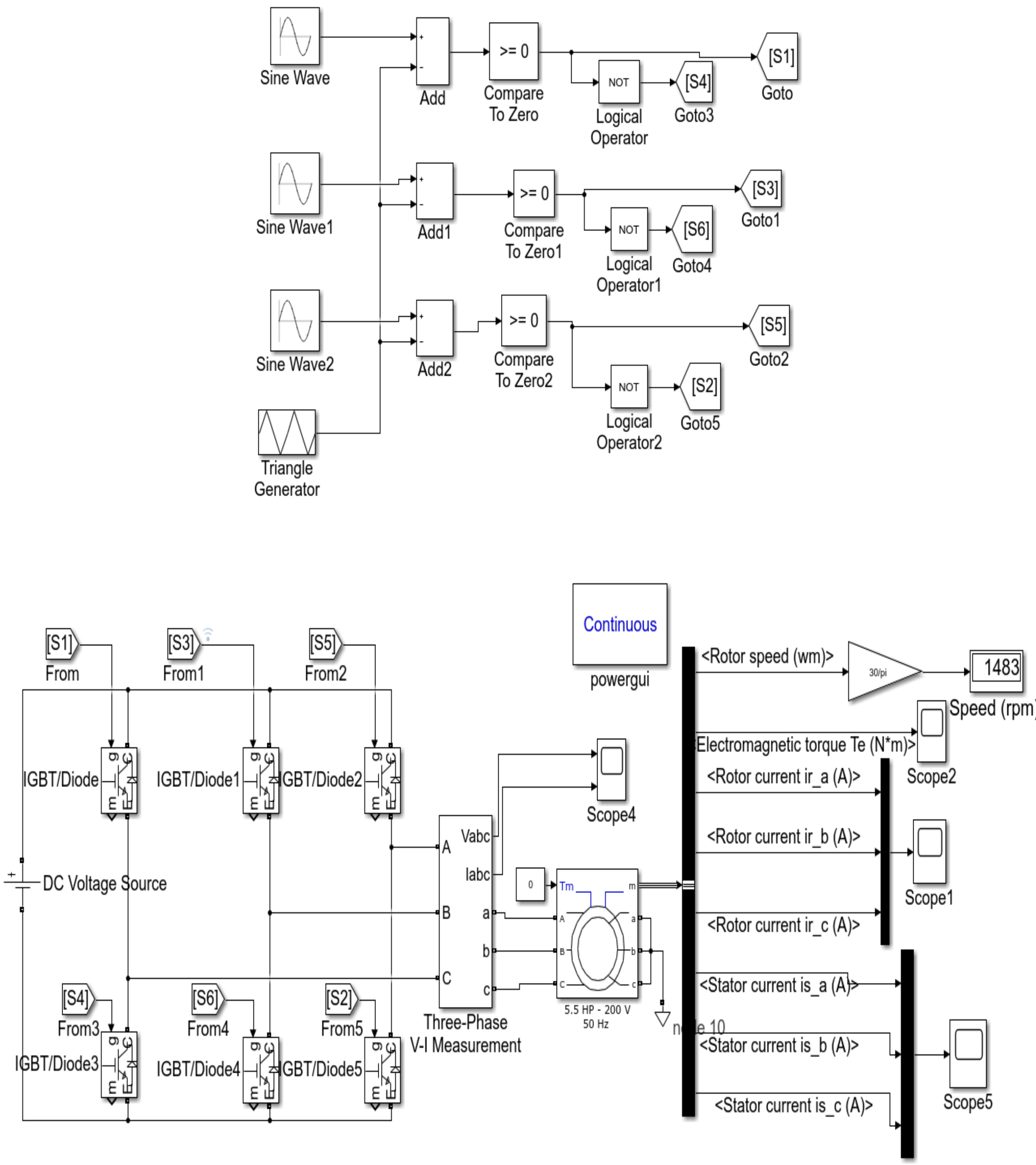


Figure 3.1 Simulation Schematic diagram of SPWM technique fed Induction motor drive.

Table 3.1 Inverter output and motor performance at SPWM technique for variable carrier frequency (Tm= 0 Nm, M=1)

Carrier Frequency F (Hz)	**Inverter Output**		**Motor Performance**	
	Voltage THD (%)	**Current THD (%)**	**Steady speed obtaining time (sec)**	**Rotor Speed (rpm)**
1000	68.83	35.86	0.392	1488
5000	68.84	7.11	0.392	1488
10000	68.56	3.58	0.392	1488
20000	68.48	1.85	0.392	1488
30000	68.59	1.29	0.392	1488

From Table 3.1, it can be seen that the current THD value decreases significantly from 35.86% to 1.29% with the increase in carrier frequency. Insignificant change occurs in output voltage THD value with the carrier frequency. Rotor steady speed obtaining time and rotor speed don't change with the carrier frequency variation.

Table 3.2 Inverter output and motor performance at SPWM technique for variable modulation index (Tm= 0 Nm, f=1 kHz)

Modulation index, M	**Inverter Output**		**Motor Performance**	
	Voltage THD (%)	**Current THD (%)**	**Steady speed obtaining time (sec)**	**Rotor Speed (rpm)**
0.3	201.38	16.25	6.05	1362
0.6	119.46	34.48	1.2	1468
0.8	91.98	35.88	0.65	1482
1	69.06	36.03	0.392	1488

With the increase in modulation index in Table 3.2, voltage THD decreases from 201.38% to 69.06% and current THD increases from 16.25% to 36.03%. The motor performance also varies with modulation index variation. Rotor steady speed obtaining time decreases from 6.05 sec to 0.392 sec and rotor speed increases from 1362 rpm to 1488 rpm with increasing modulation index.

Table 3.3 Induction motor performance at SPWM technique for variable torque Tm (M=1, f=1 kHz)

Load Torque Tm (Nm)	**Induction Motor Performance**	
	Steady speed obtaining time (sec)	**Rotor Speed (rpm)**
0	0.392	1488
5	1.075	1334
7	Failed	N/A
8	Failed	N/A
9	Failed	N/A

Table 3.3 shows that rotor steady speed obtaining time increases and rotor speed decreases with increasing torque Tm. When the load torque applied above 5 Nm, the induction motor failed to reach steady-state rotor speed using the SPWM technique.

3.2.1.1 Effect of carrier frequency on stator current, rotor current and electromagnetic torque

The effect of carrier frequency on rotor current, stator current & electromagnetic torque is presented in Fig. 3.2 to Fig. 3.7 using the SPWM method at load torque, Tm=0Nm and modulation index, M=1.

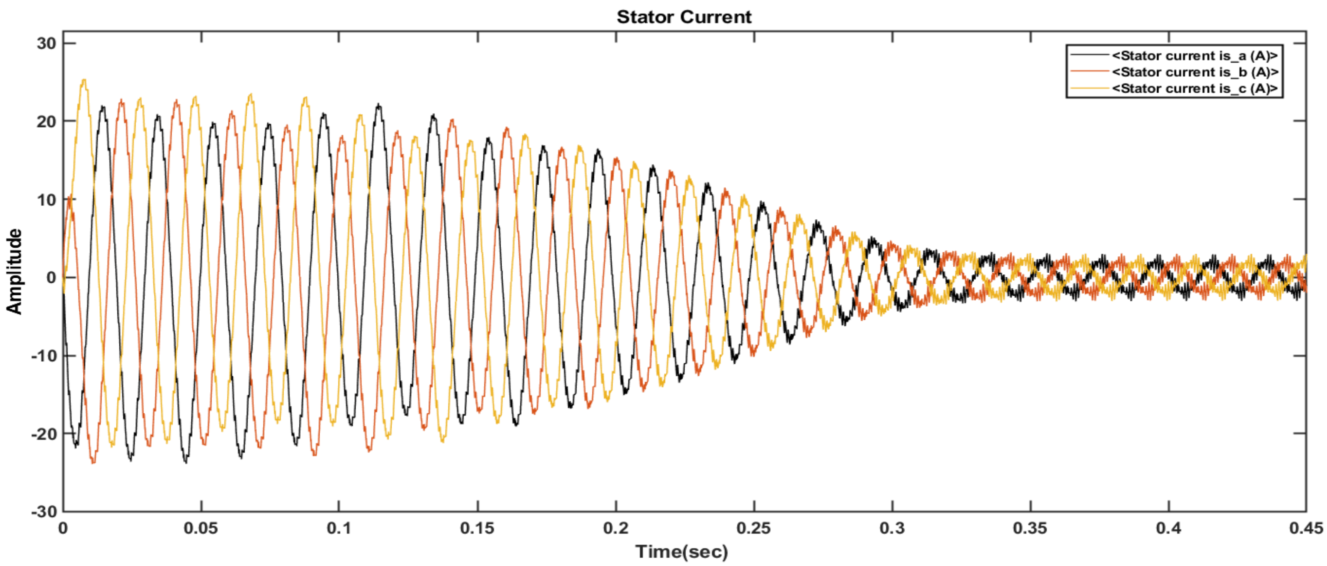


Figure 3.2 Stator current of induction motor drive at 1 kHz carrier frequency.

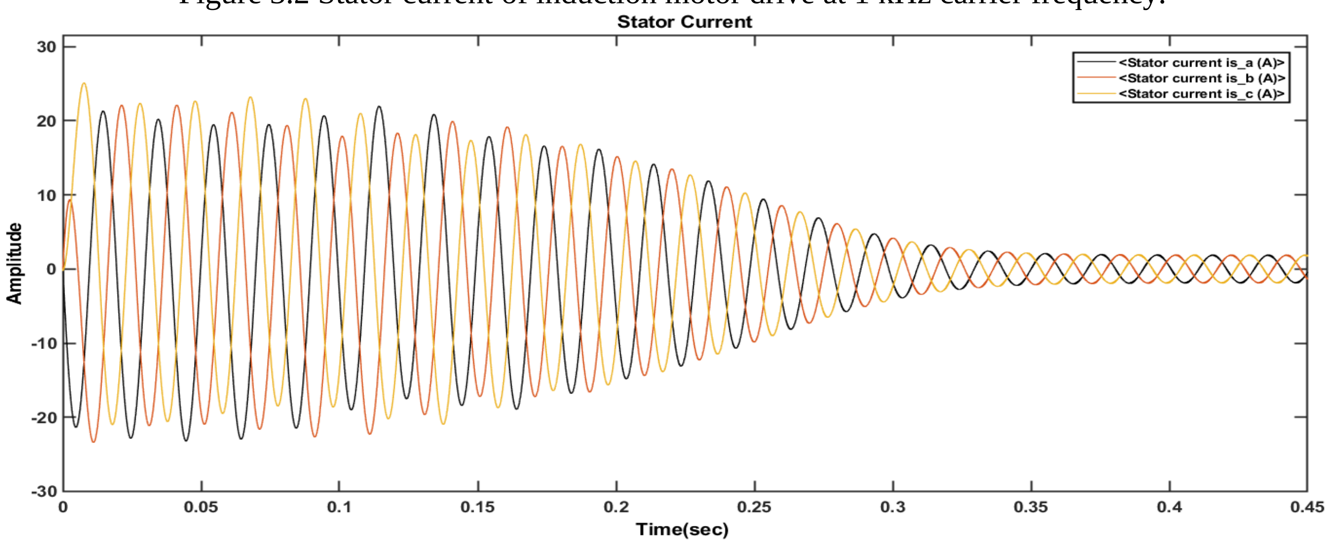


Figure 3.3 Stator current of induction motor drive at 10 kHz carrier frequency.

From Fig. 3.2 & Fig. 3.3 it can be seen that high modulation carrier frequency reduces stator current distortion. Stator current achieves steady state after some time. A more stable stator current is achieved from applying higher carrier frequency. Similar current output is found in [23] as well.

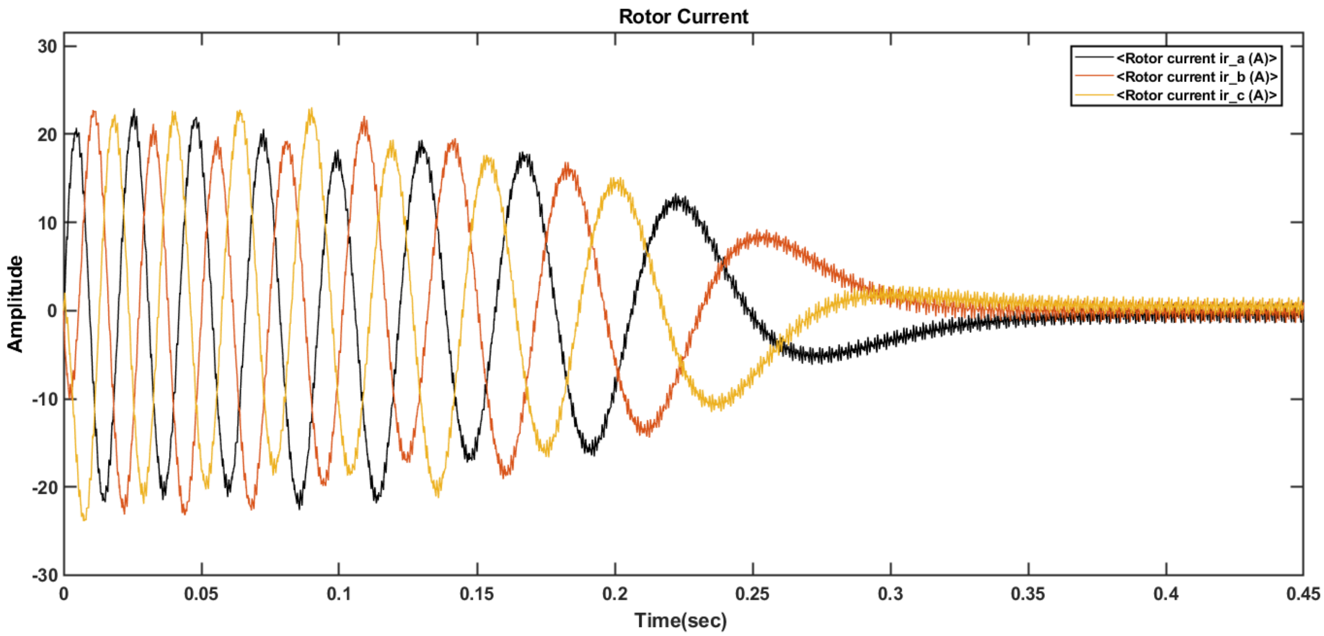


Figure 3.4 Rotor current of induction motor drive at 1 kHz carrier frequency.

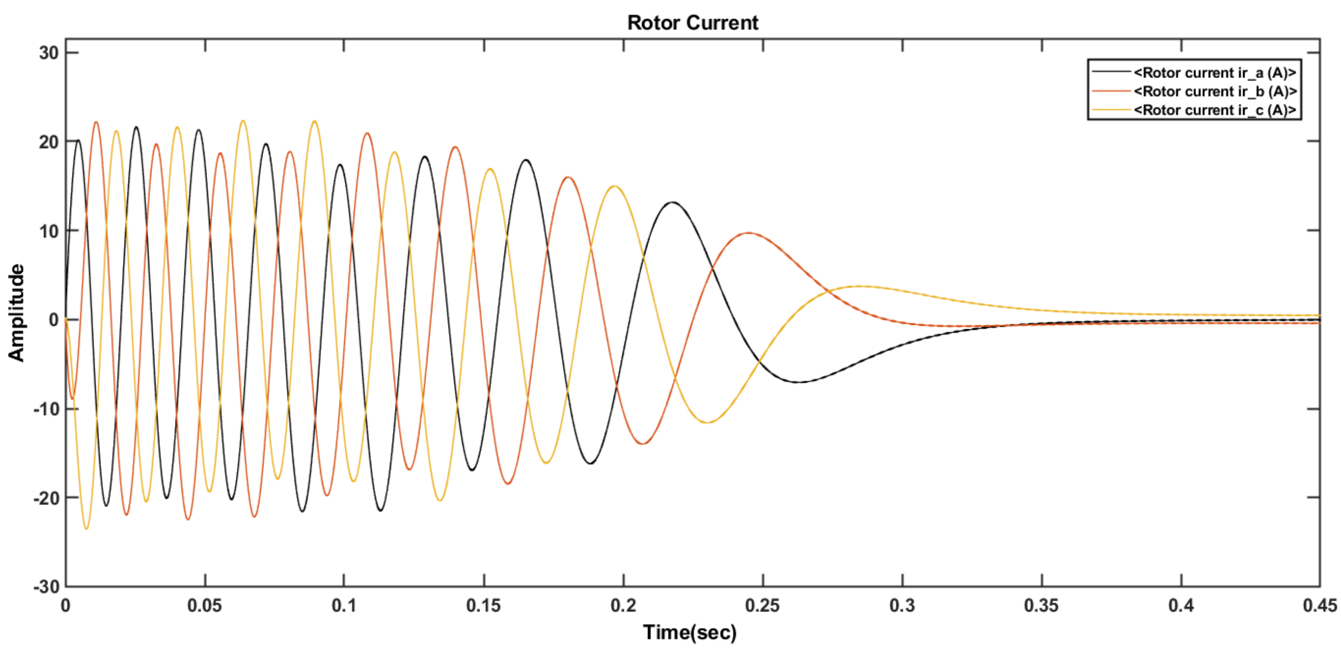


Figure 3.5 Rotor current of induction motor drive at 10 kHz carrier frequency.

Fig. 3.4 & Fig. 3.5 show that high carrier frequency reduces rotor current distortion and produces stable rotor current output than 1 kHz carrier frequency. Rotor current achieves steady state approximately 0.4 sec. Similar current output is found in [23] as well.

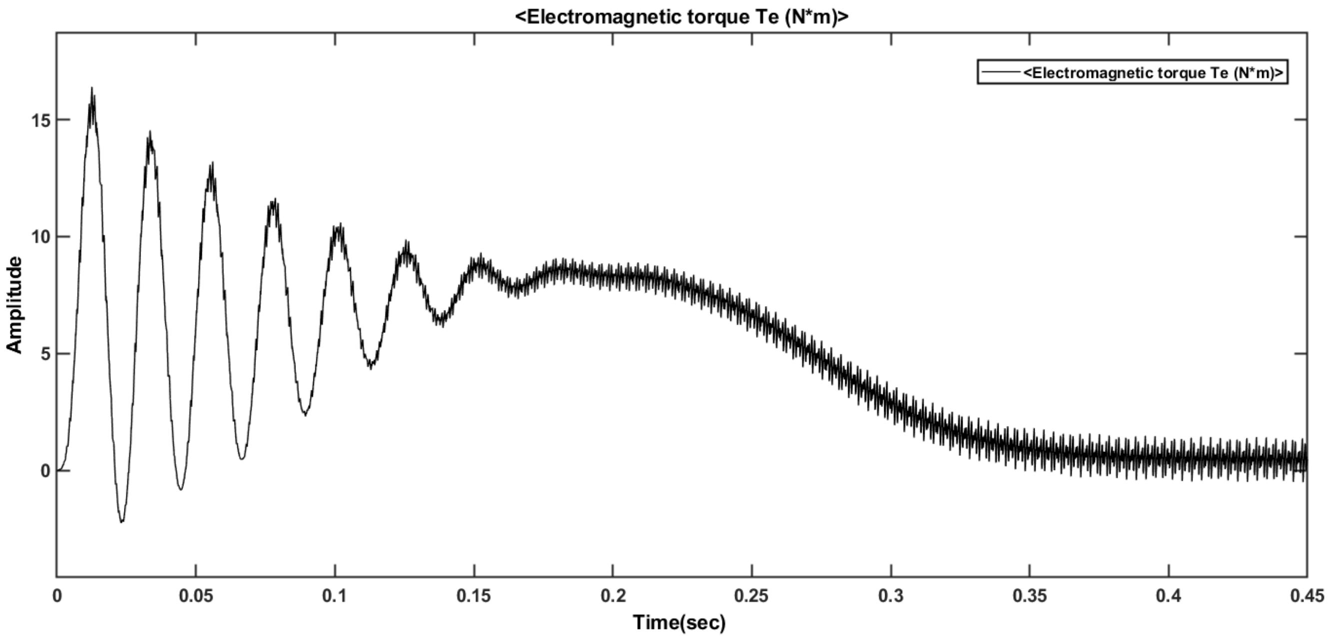


Figure 3.6 Electromagnetic torque of induction motor at 1 kHz carrier frequency.

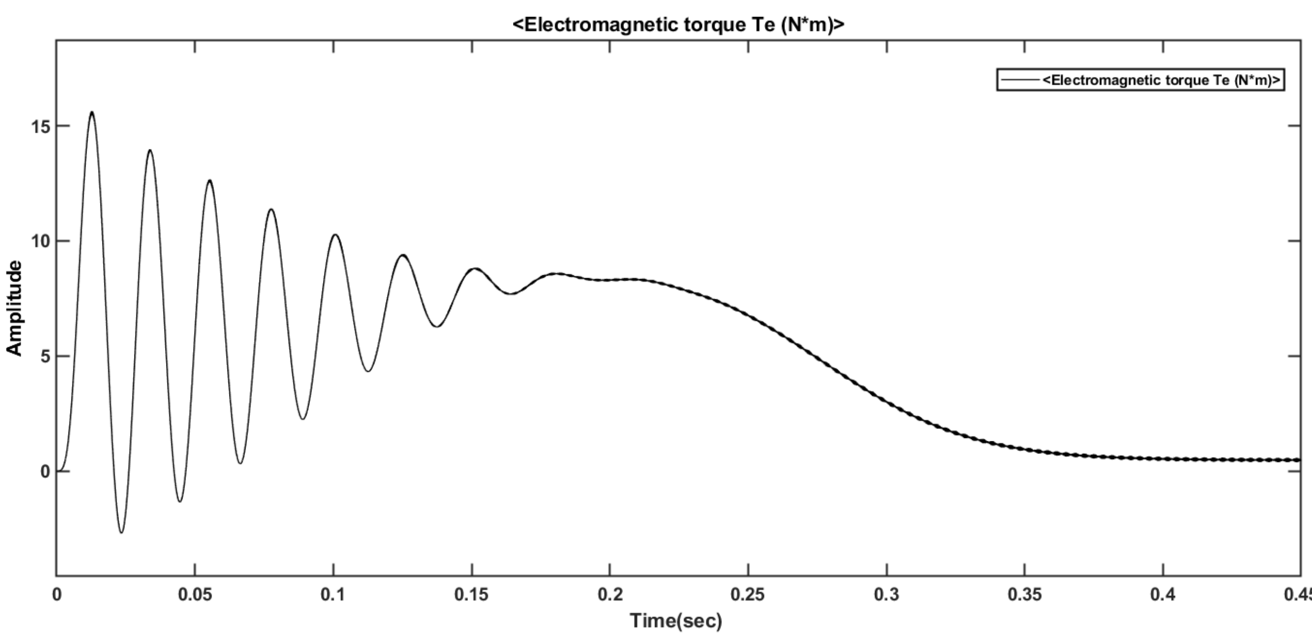


Figure 3.7 Electromagnetic torque of induction motor at 10 kHz carrier frequency.

From Fig. 3.6 & Fig. 3.7 it can be seen that electromagnetic torque distortion reduces with an increase in carrier frequency. More stable electromagnetic torque is achieved from the higher carrier frequency.

3.2.2 SDPWM technique fed induction motor drive performance:

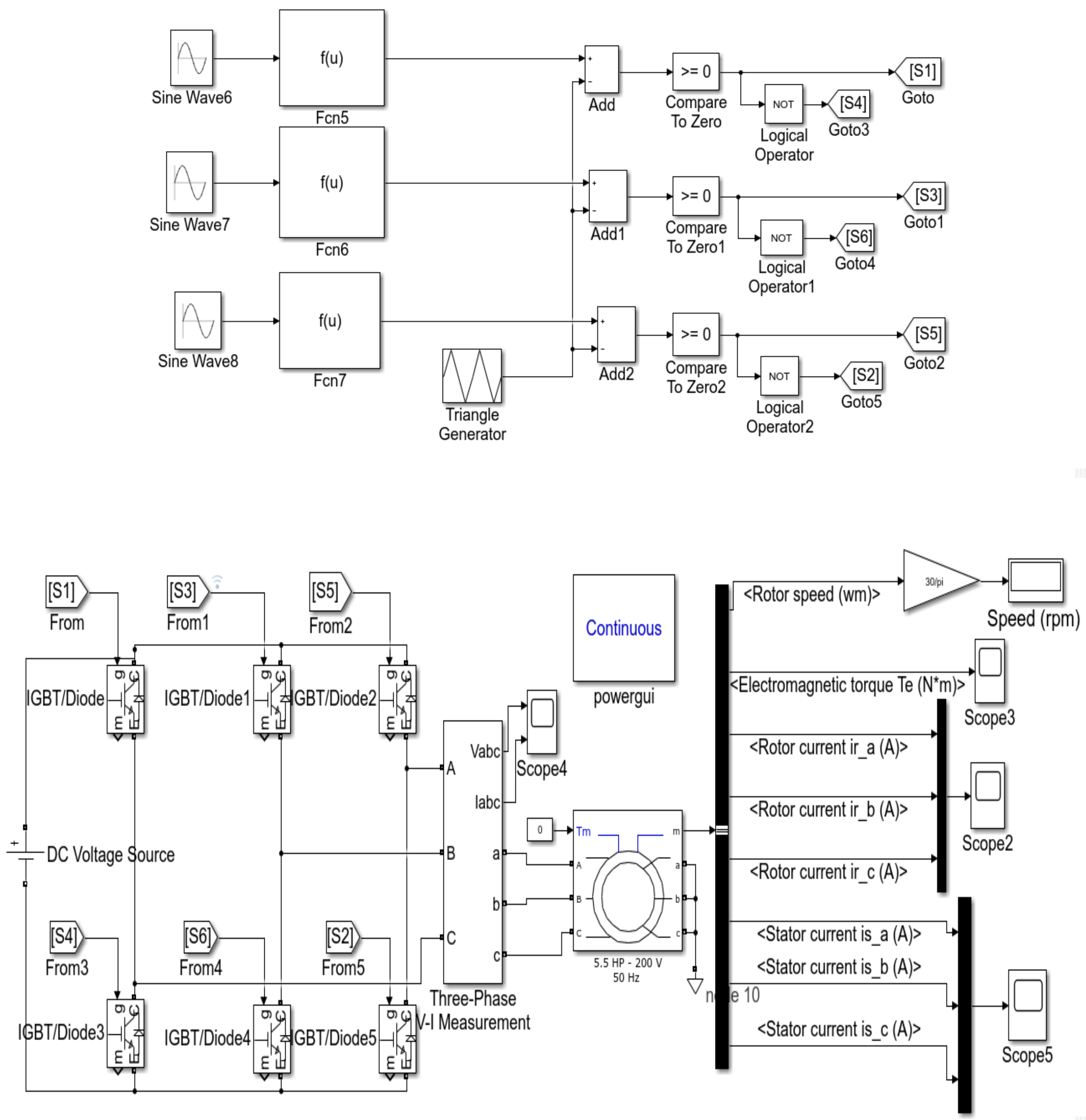


Figure 3.8 Simulation Schematic diagram of SDPWM technique fed Induction motor drive.

Fig. 3.8 shows a simulation schematic diagram of SDPWM technique fed Induction motor drive from which inverter output THD value and motor parameters like rotor current, stator current, electromagnetic torque and rotor speed is found.

Table 3.4 Inverter output and induction motor performance at SDPWM technique for variable carrier frequency (T= 0 Nm, M=1)

Carrier Frequency F (Hz)	Inverter Output		Motor Performance	
	Voltage THD (%)	Current THD (%)	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)
1000	55.75	31.64	0.306	1491
5000	55.1	7.26	0.306	1491
10000	54.83	4.98	0.306	1491
20000	54.74	4.23	0.306	1491
30000	54.89	4.07	0.306	1491

From Table 3.4, it can be seen that the current THD value decreases significantly from 31.64% to 4.07% with the increase in carrier frequency. Insignificant change occurs in output voltage THD value with the carrier frequency. Rotor steady speed obtaining time and rotor speed don't change with the carrier frequency variation.

Table 3.5 Inverter output and induction motor performance at SDPWM technique for variable modulation index (Tm= 0 Nm, f=1 kHz)

Modulation index, M	Inverter Output		Motor Performance	
	Voltage THD (%)	Current THD (%)	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)
0.3	142.82	29.35	1.9	1448
0.6	86.48	34.29	0.56	1483
0.8	65.41	32.78	0.37	1488
1	55.75	31.64	0.306	1491

With the increase in modulation index, voltage THD decreases from 142.82% to 55.75% and current THD increases from 29.35% to 31.64%. The motor performance also varies with modulation index variation. Rotor steady speed obtaining time decreases from 1.9 sec to 0.306 sec and rotor speed increases from 1448 rpm to 1491 rpm with increasing modulation index.

Table 3.6 Induction motor performance at SDPWM technique for variable torque Tm (M=1, f=1 kHz)

Load Torque Tm (Nm)	Induction Motor Performance	
	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)
0	0.306	1491
5	0.61	1379
7	1.10	1315
8	Failed	N/A
9	Failed	N/A

Table 3.6 shows that rotor steady speed obtaining time increases and rotor speed decreases with increasing torque Tm. When the load torque applied above 7 Nm, the induction motor failed to reach steady-state rotor speed using the SDPWM technique.

3.2.2.1 Effect of carrier frequency on stator current, rotor current and electromagnetic torque

The effect of high carrier frequency on rotor current, stator current & electromagnetic torque is presented in Fig. 3.9 to Fig. 3.14 using the SDPWM method at load torque, Tm=0Nm and modulation index, M=1.

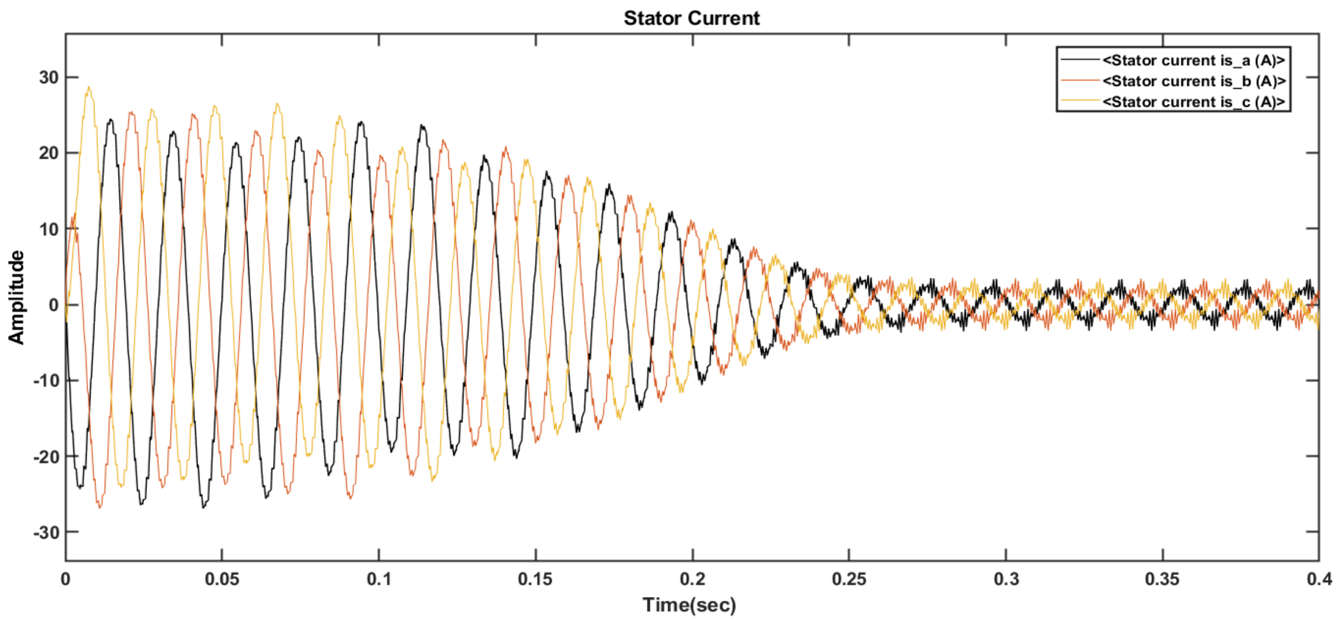


Figure 3.9 Stator currents of induction motor drive at 1 kHz carrier frequency.

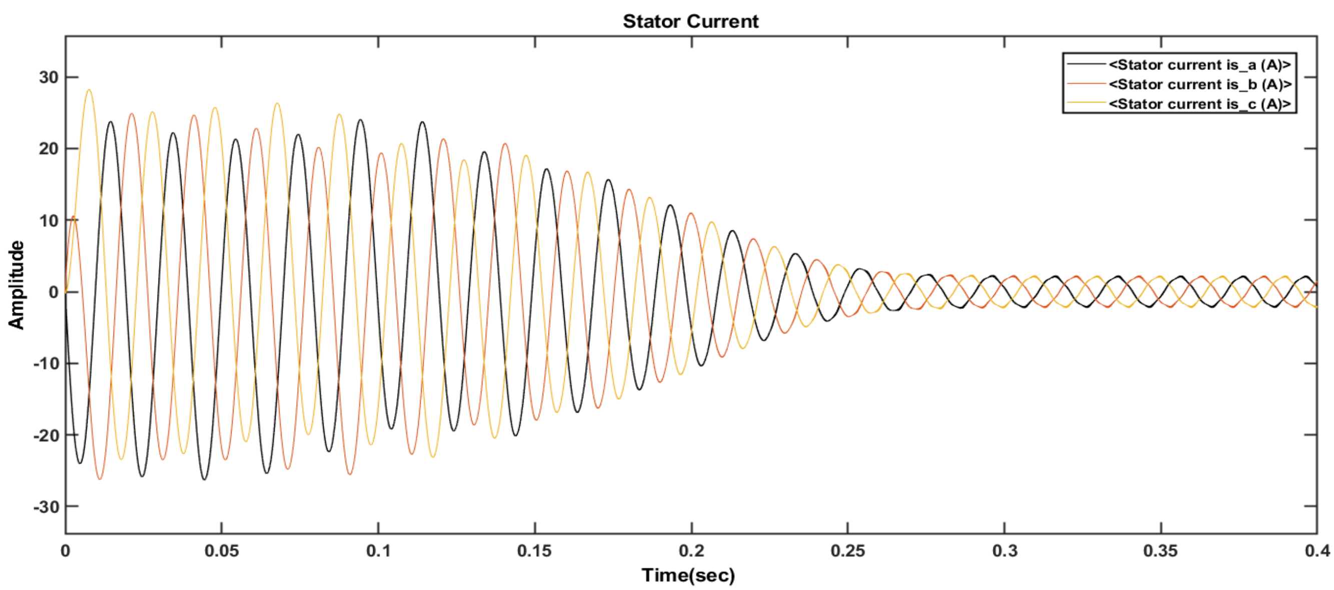


Figure 3.10 Stator currents of induction motor drive at 10 kHz carrier frequency.

From Fig. 3.9 & Fig. 3.10 it can be seen that high modulation carrier frequency reduces stator current distortion. Stator current achieves steady state after some time. A more stable stator current is achieved from applying higher carrier frequency. Similar current output is found in [23] as well.

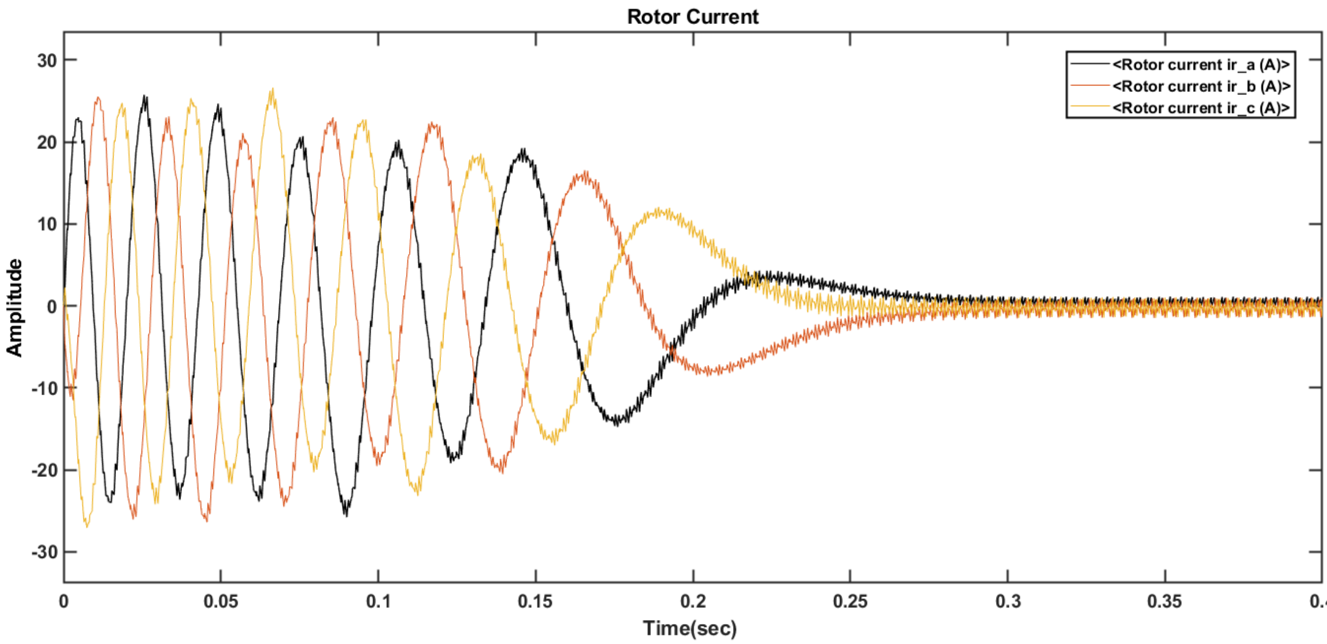


Figure 3.11 Rotor currents of induction motor drive at 1 kHz carrier frequency.

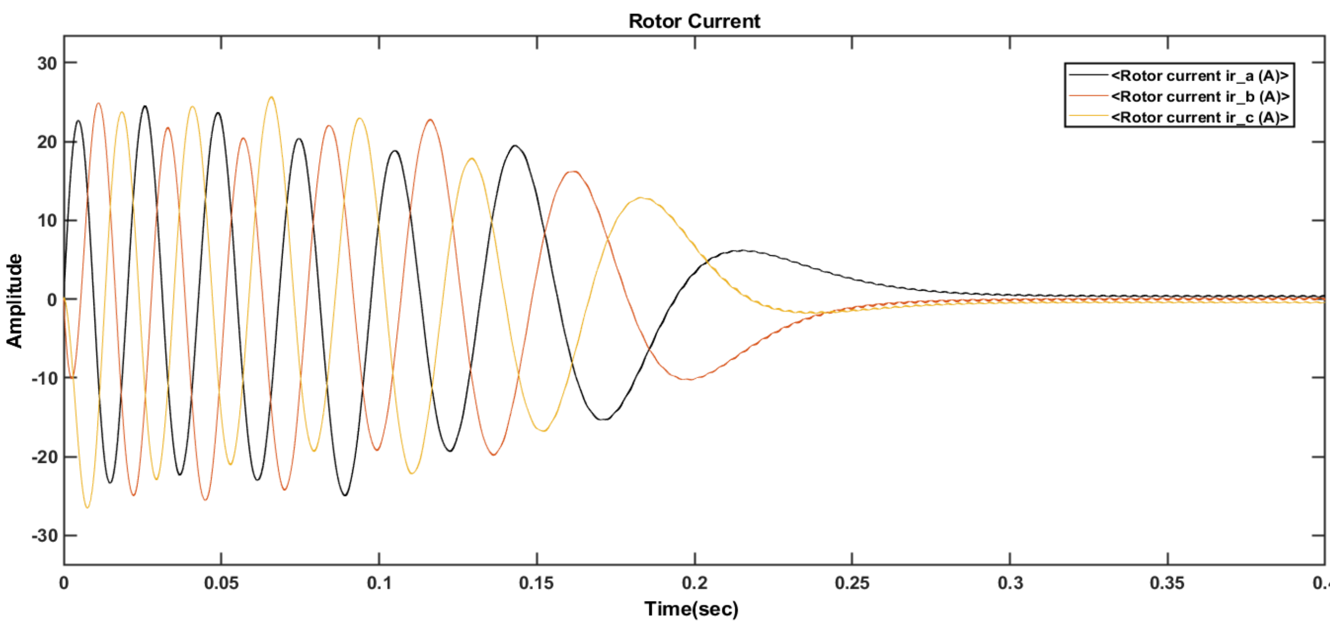


Figure 3.12 Rotor currents of induction motor drive at 10 kHz carrier frequency.

Fig. 3.11 & Fig. 3.12 show that high carrier frequency reduces rotor current distortion and produces stable rotor current output than 1 kHz carrier frequency. Rotor current achieves steady state after some time. Similar current output is found in [23] as well.

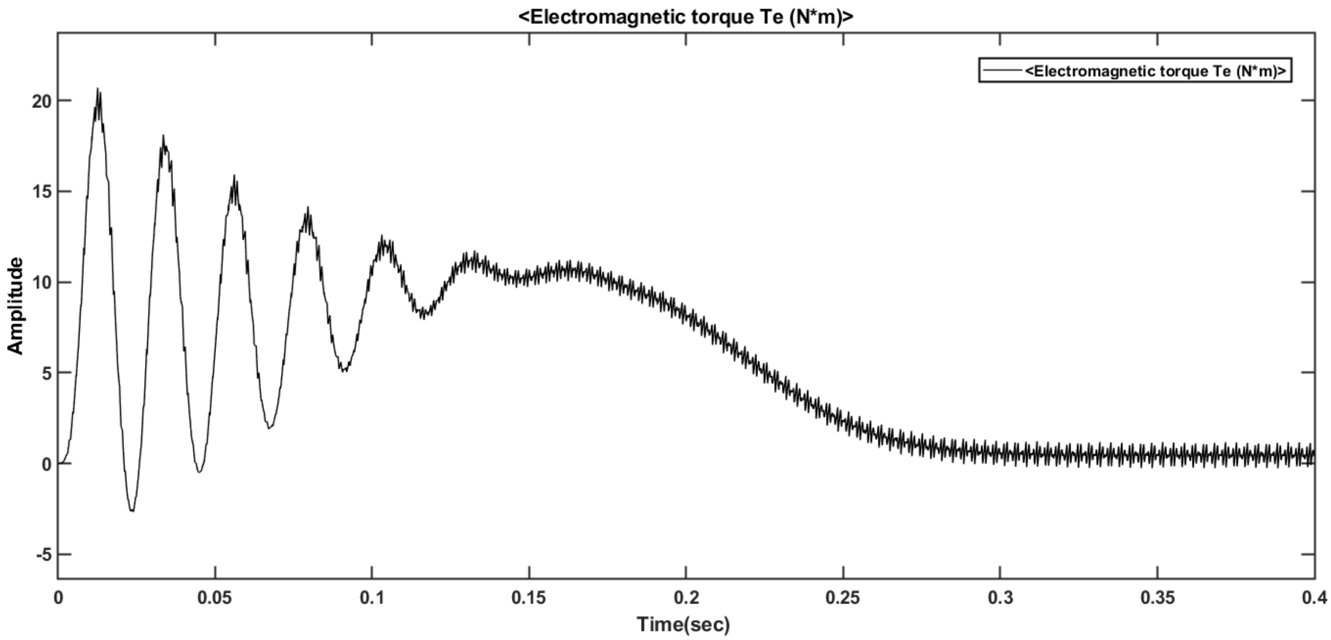


Figure 3.13 Electromagnetic torque of induction motor at 1 kHz carrier frequency.

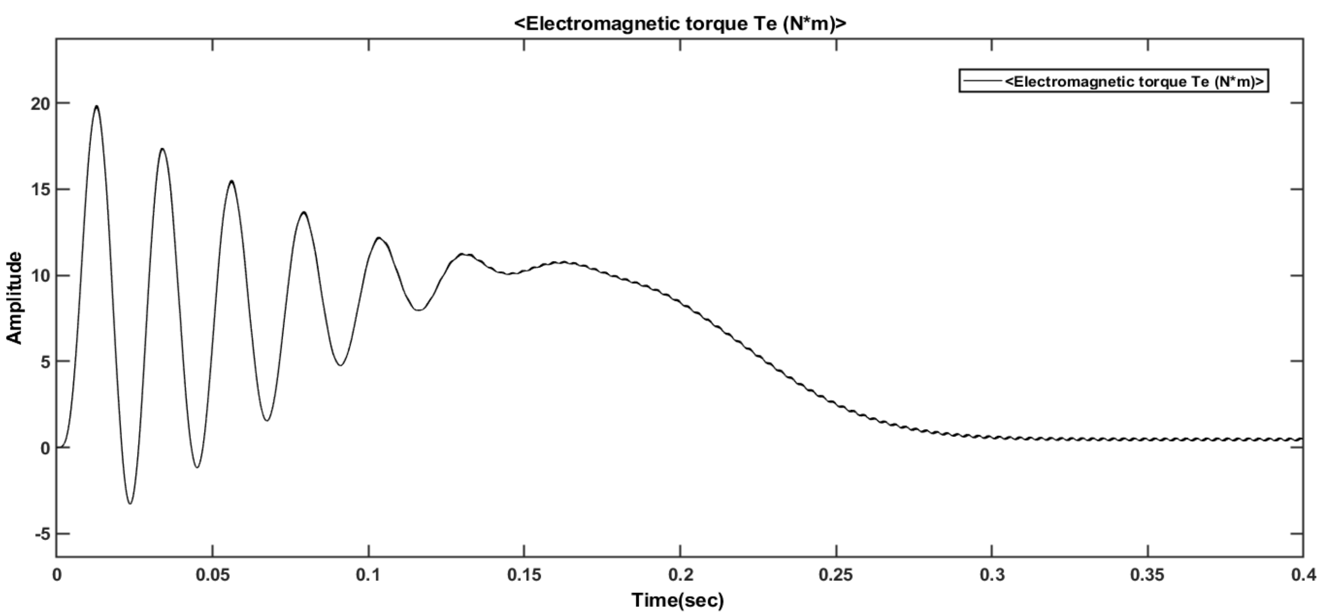


Figure 3.14 Electromagnetic torque of induction motor at 10 kHz carrier frequency.

From Fig. 3.13 & Fig. 3.14 it can be seen that electromagnetic torque distortion reduces with an increase in carrier frequency. More stable electromagnetic torque is achieved from the higher carrier frequency.

3.2.3 THIPWM technique fed induction motor drive performance:

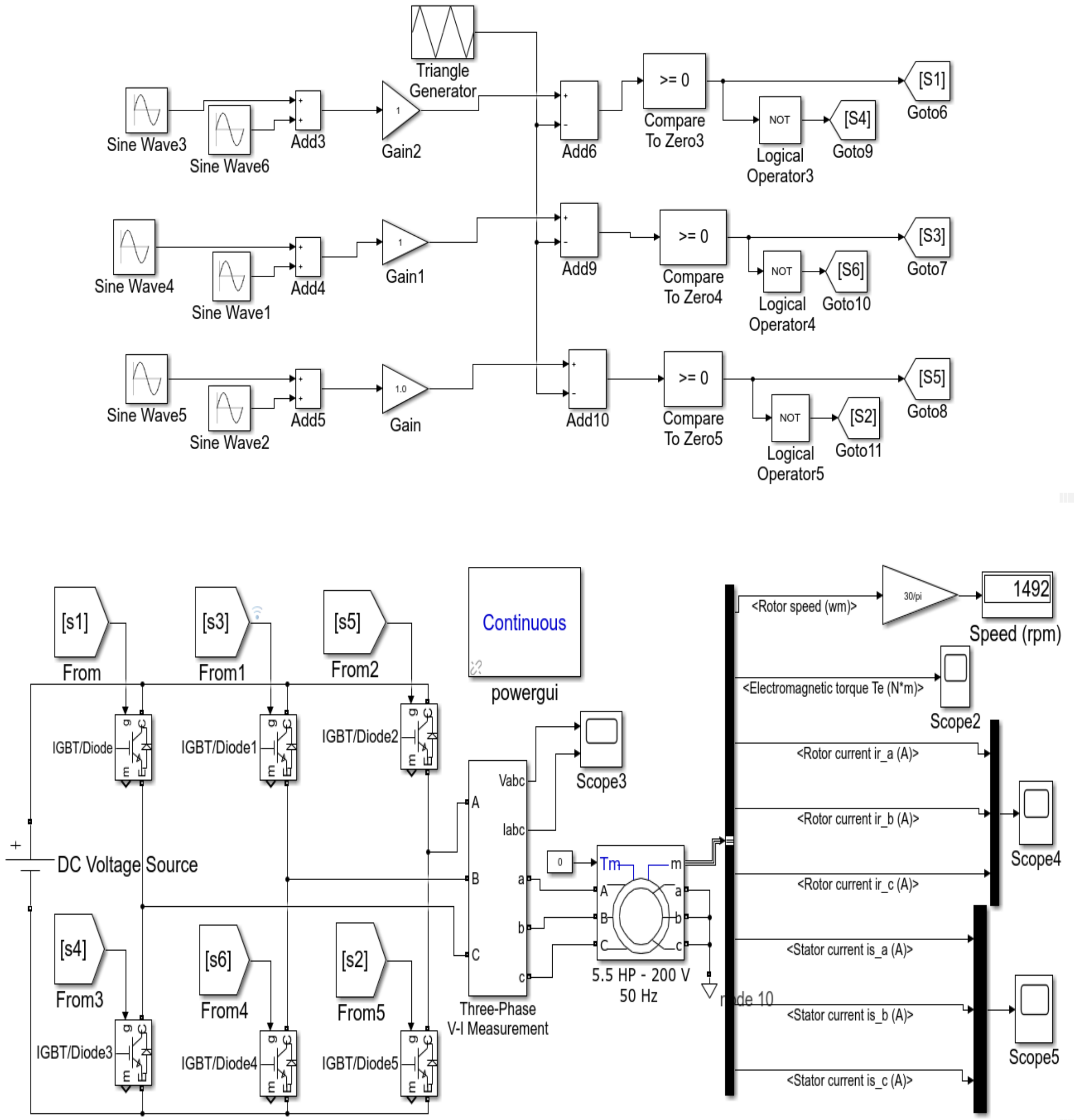


Figure 3.15 Simulation Schematic diagram of THIPWM technique fed Induction motor drive.

Fig. 3.15 shows a simulation schematic diagram of THIPWM technique fed Induction motor drive from which inverter output THD value and motor parameters like rotor current, stator current, electromagnetic torque and rotor speed is found.

Table 3.7 Inverter output and induction motor performance at THIPWM technique for variable carrier frequency (Tm= 0 Nm, M=1)

Carrier Frequency F (Hz)	**Inverter Output**		**Motor Performance**	
	Voltage THD (%)	**Current THD (%)**	**Rotor steady speed obtaining time (sec)**	**Rotor Speed (rpm)**
1000	52.40	30.28	0.281	1491
5000	52.31	6.01	0.281	1491
10000	52.16	3.02	0.281	1491
20000	52.14	1.51	0.281	1491
30000	52.31	1.01	0.281	1491

From Table 3.7, it can be seen that the current THD value decreases significantly from 30.28% to 1.01% with the increase in carrier frequency. Insignificant change occurs in output voltage THD value with the carrier frequency. Rotor steady speed obtaining time and rotor speed don't change with the carrier frequency variation.

Table 3.8 Inverter output and motor performance at THIPWM technique for variable modulation index (Tm= 0 Nm, f=1 KHz)

Modulation index, M	**Inverter Output**		**Motor Performance**	
	Voltage THD (%)	**Current THD (%)**	**Rotor steady speed obtaining time (sec)**	**Rotor Speed (rpm)**
0.3	178.26	19.9	4.12	1400
0.6	106.51	33.54	0.9	1476
0.8	75.97	31.27	0.47	1486
1	52.40	30.28	0.281	1491

With the increase in modulation index, voltage THD decreases from 178.26% to 52.40% and current THD increases from 19.9% to 30.28%. The motor performance also varies with modulation index variation. Rotor steady speed obtaining time decreases from 4.12 sec to 0.281 sec and rotor speed increases from 1400 rpm to 1491 rpm with increasing modulation index.

Table 3.9 Induction motor performance at THIPWM technique for variable torque Tm (M= 1, f=1 KHz)

Load Torque Tm (Nm)	**Induction Motor Performance**	
	Rotor steady speed obtaining time (sec)	**Rotor Speed (rpm)**
0	0.281	1491
5	0.545	1386
7	0.882	1327
8	1.95	1291
9	Failed	N/A

Table 3.9 shows that rotor steady speed obtaining time increases and rotor speed decreases with increasing torque Tm. When the load torque applied above 8 Nm, the induction motor failed to reach steady-state rotor speed using the THIPWM technique.

3.2.3.1 Effect of carrier frequency on stator current, rotor current and electromagnetic torque

The effect of high carrier frequency on rotor current, stator current & electromagnetic torque is presented in Fig. 3.16 to Fig. 3.21 using the THIPWM method at load torque, Tm=0Nm and modulation index, M=1.

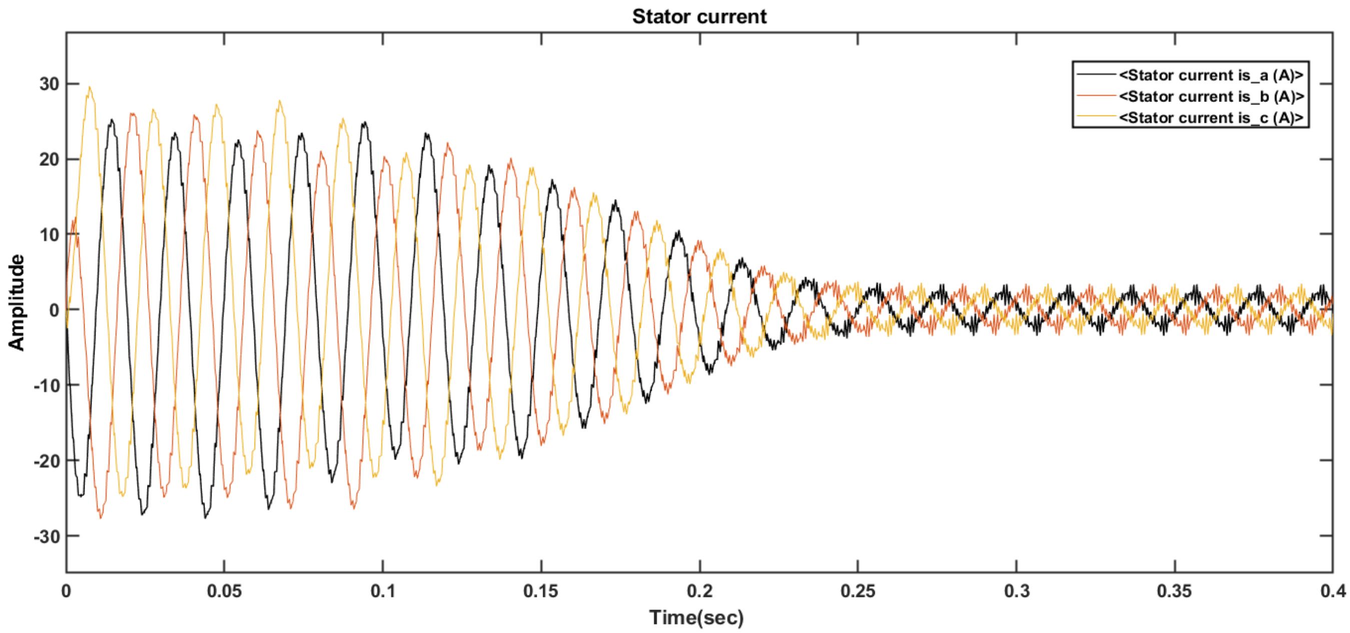


Figure 3.16 Stator currents of induction motor drive at 1 kHz carrier frequency.

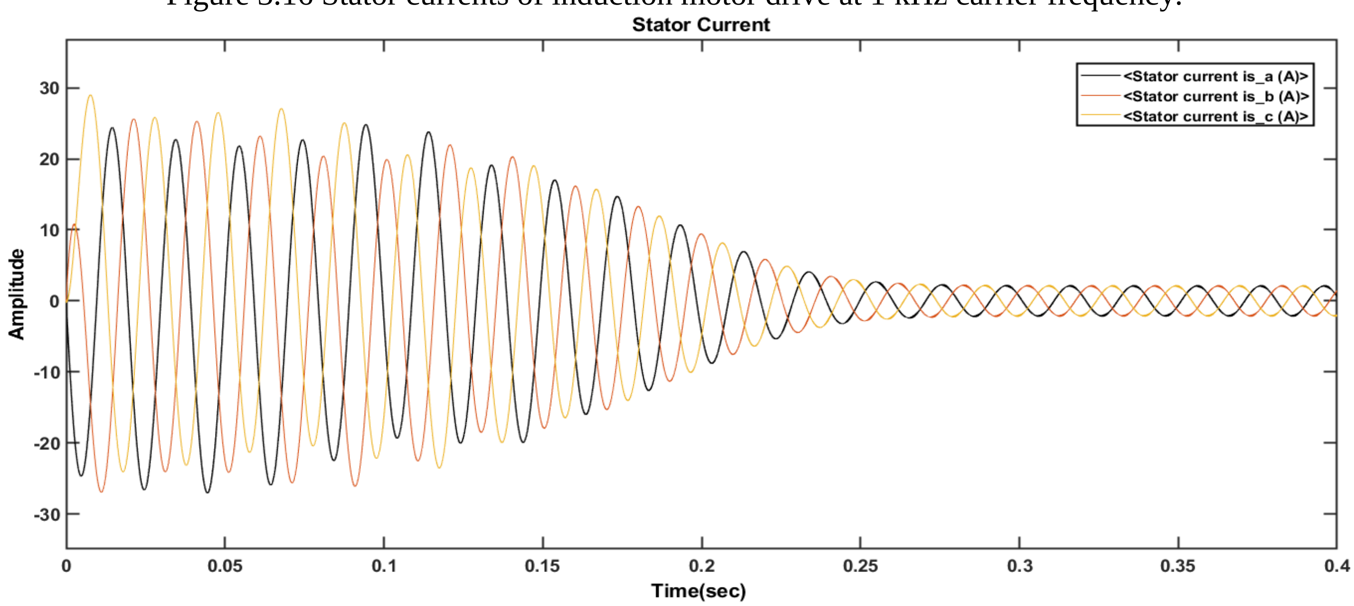


Figure 3.17 Stator currents of induction motor drive at 10 kHz carrier frequency.

From Fig. 3.16 & Fig. 3.17 it can be seen that high modulation carrier frequency reduces stator current distortion. Stator current achieves steady state after some time. A more stable stator current is achieved from applying higher carrier frequency. Similar current output is found in [23] as well.

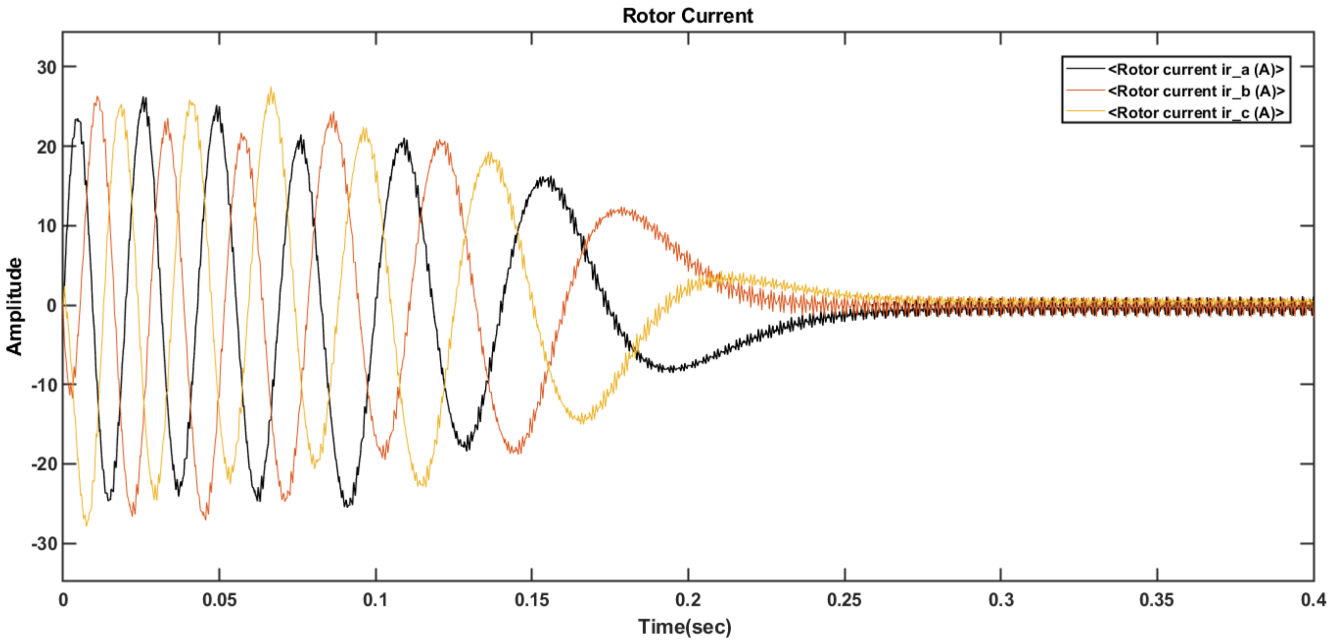


Figure 3.18 Rotor currents of induction motor drive at 1 kHz carrier frequency.

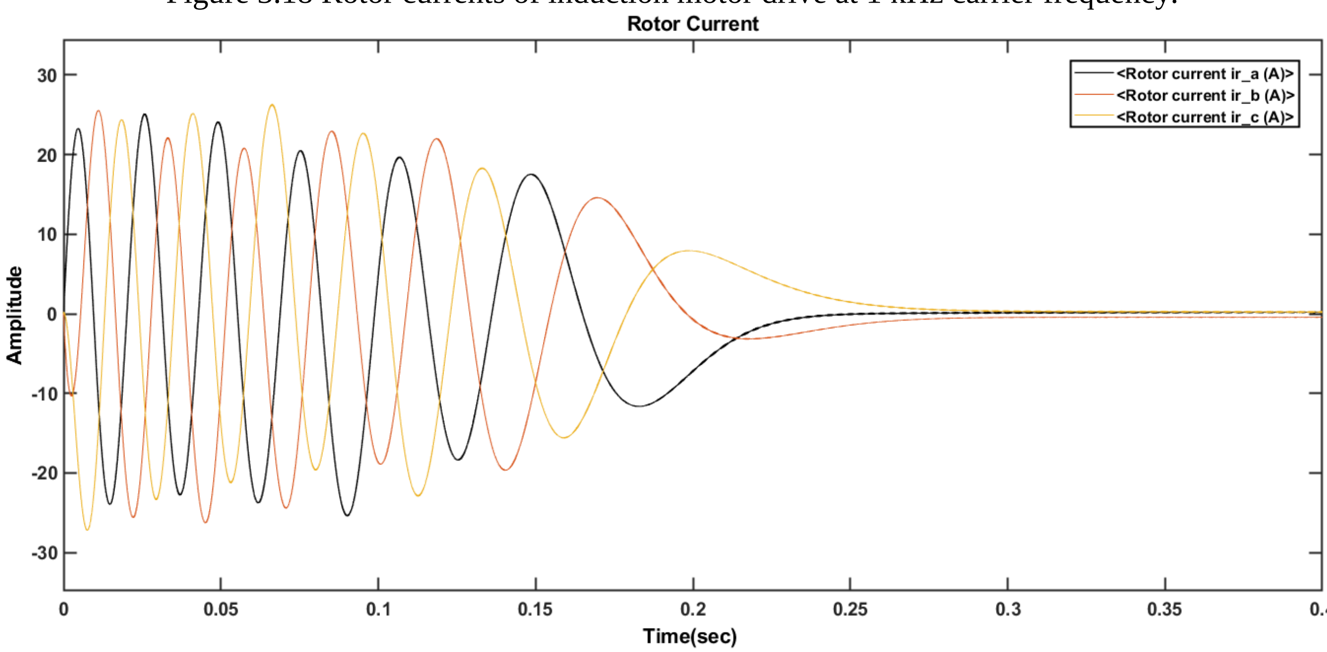


Figure 3.19 Rotor currents of induction motor drive at 10 kHz carrier frequency.

Fig. 3.18 & Fig. 3.19 show that high carrier frequency reduces rotor current distortion and produces stable rotor current output than 1 kHz carrier frequency. Rotor current achieves steady state after 0.3 sec. Similar current output is found in [23] as well.

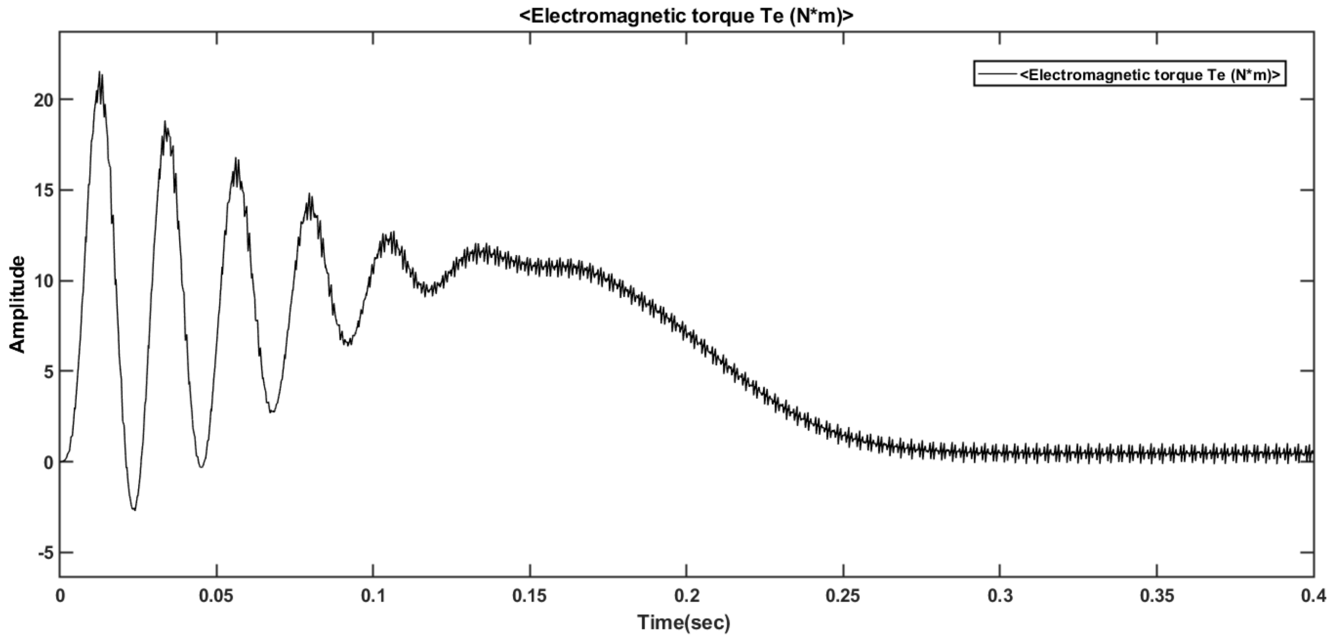


Figure 3.20 Electromagnetic torque of induction motor at 1 kHz carrier frequency.

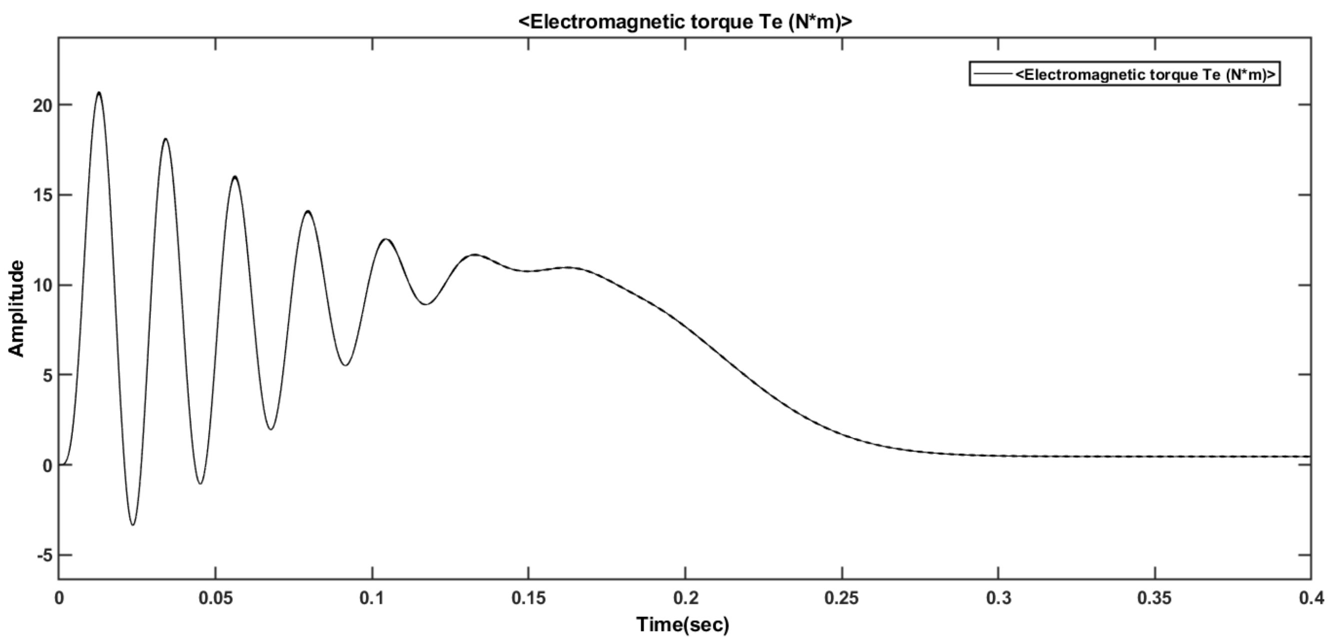


Figure 3.21 Electromagnetic torque of induction motor at 10 kHz carrier frequency.

From Fig. 3.20 & Fig. 3.21 it can be seen that electromagnetic torque distortion reduces with an increase in carrier frequency. More stable electromagnetic torque is achieved from the higher carrier frequency.

3.2.4 TPWM Technique fed induction motor drive performance:

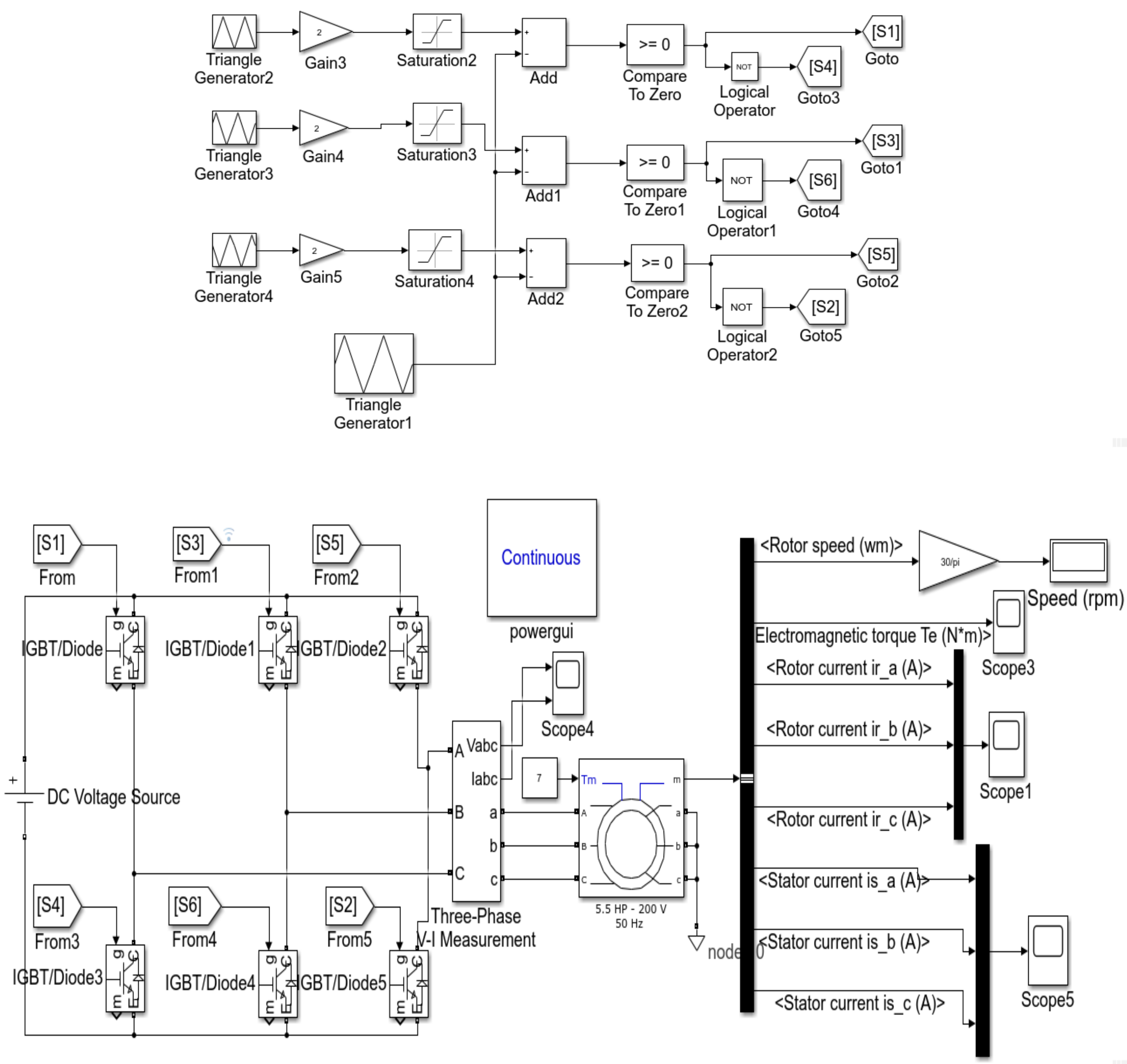


Figure 3.22 Simulation Schematic diagram of TPWM technique fed Induction motor drive.

Fig. 3.22 shows a simulation schematic diagram of TPWM technique fed Induction motor drive from which inverter output THD value and motor parameters like rotor current, stator current, electromagnetic torque and rotor speed is found.

Table 3.10 Inverter output and motor performance at TPWM technique for variable carrier frequency (Tm= 0 Nm, M=1)

Carrier Frequency F (Hz)	Inverter Output		Motor Performance	
	Voltage THD (%)	Current THD (%)	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)
1000	55.17	36.37	0.295	1491
5000	54.49	14.41	0.295	1491
10000	54.5	13.22	0.295	1491
20000	54.5	12.9	0.295	1491
30000	54.43	12.84	0.295	1491

From Table 3.10, it can be seen that the current THD value decreases significantly from 36.37% to 12.84% with the increase in carrier frequency. Insignificant change occurs in output voltage THD value with the carrier frequency. Rotor steady speed obtaining time and rotor speed don't change with the carrier frequency variation.

Table 3.11 Inverter output and motor performance at TPWM technique for variable modulation index (Tm= 0 Nm, f=1 kHz)

Modulation index, M	Inverter Output		Motor Performance	
	Voltage THD (%)	Current THD (%)	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)
0.3	164.11	31.3	3.29	1417
0.6	98.35	36.15	0.76	1478
0.8	74.7	32.09	0.45	1487
1	55.17	36.37	0.295	1491

With the increase in modulation index, voltage THD decreases from 164.11% to 55.17% and current THD increases from 31.3% to 36.37%. The motor performance also varies with modulation index variation. Rotor steady speed obtaining time decreases from 3.29 sec to 0.295 sec and rotor speed increases from 1417 rpm to 1491 rpm with increasing modulation index.

Table 3.12 Induction motor performance at TPWM technique for variable torque Tm (M=1, f=1 kHz)

Load Torque Tm (Nm)	Induction Motor Performance	
	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)
0	0.292	1491
5	0.563	1384
7	0.97	1324
8	Failed	N/A
9	Failed	N/A

Table 3.12 shows that rotor steady speed obtaining time increases and rotor speed decreases with increasing torque Tm. When the load torque applied above 7 Nm, the induction motor failed to reach steady-state rotor speed using the TPWM technique.

3.2.4.1 Effect of carrier frequency on stator current, rotor current and electromagnetic torque

The effect of high carrier frequency on rotor current, stator current & electromagnetic torque is presented in Fig. 3.23 to Fig. 3.28 using the TPWM method at load torque, Tm=0Nm and modulation index, M=1.

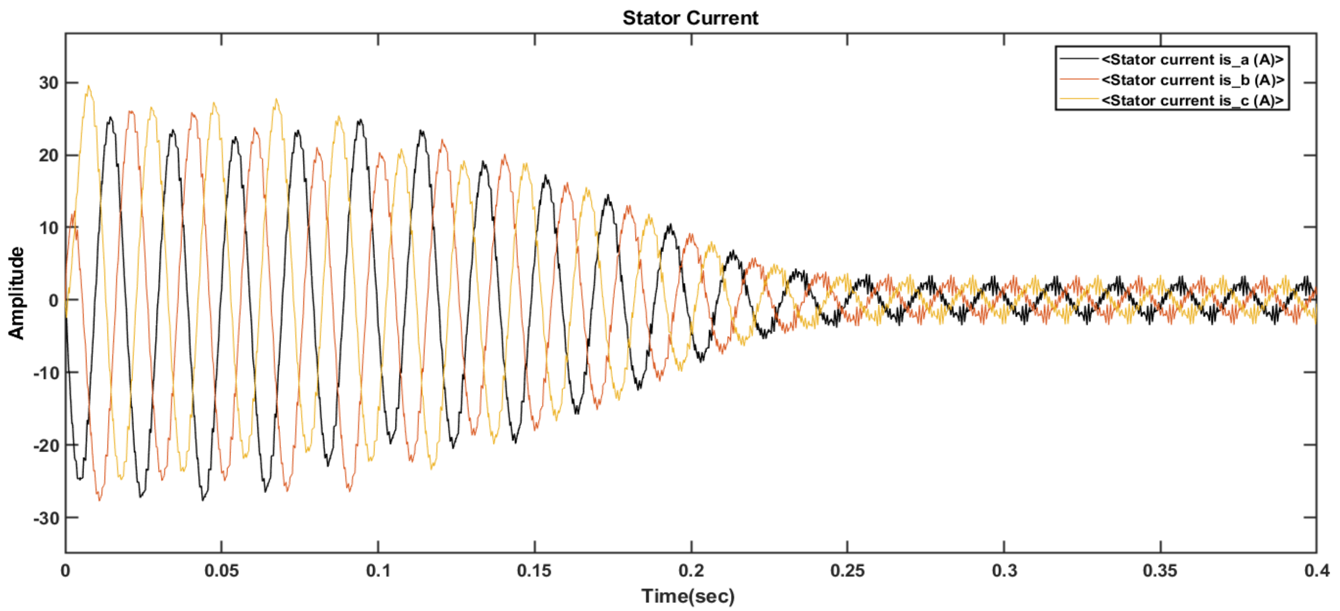


Figure 3.23 Stator currents of induction motor drive at 1 kHz carrier frequency.

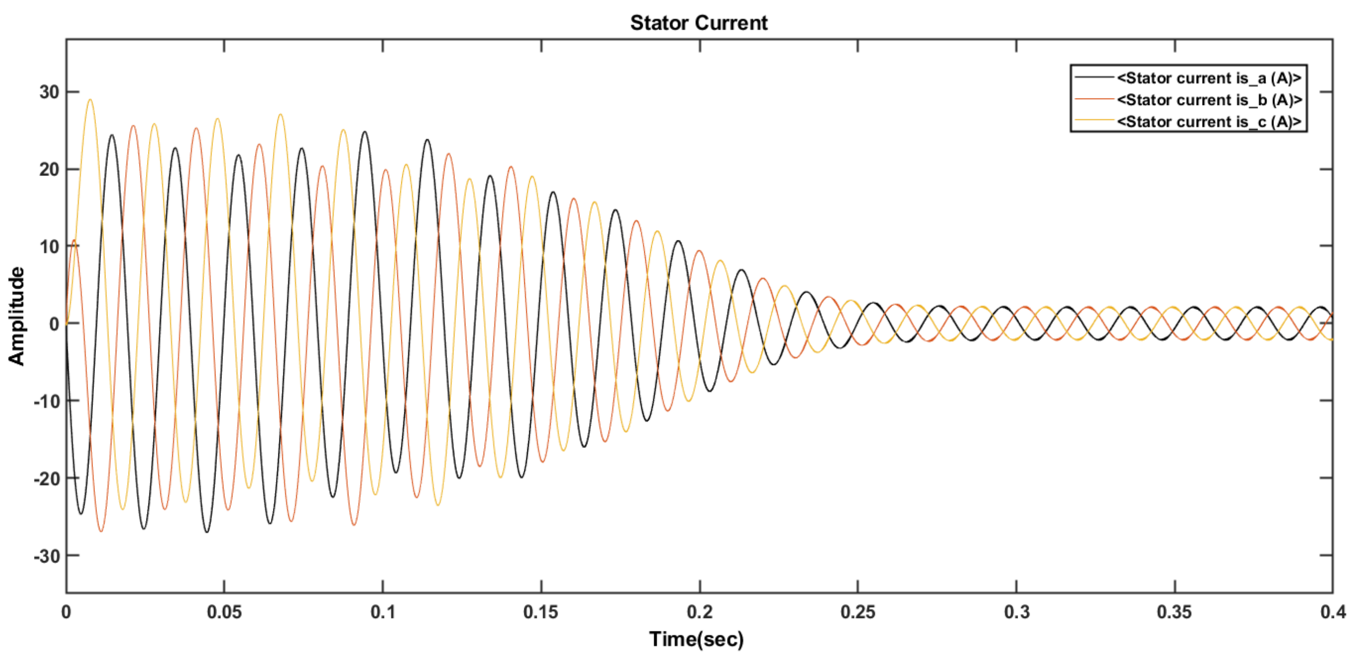


Figure 3.24 Stator currents of induction motor drive at 10 kHz carrier frequency.

From Fig. 3.23 & Fig. 3.24 it can be seen that high modulation carrier frequency reduces stator current distortion. Stator current achieves steady state after some time. A more stable stator current is achieved from applying higher carrier frequency. Similar current output is found in [23] as well.

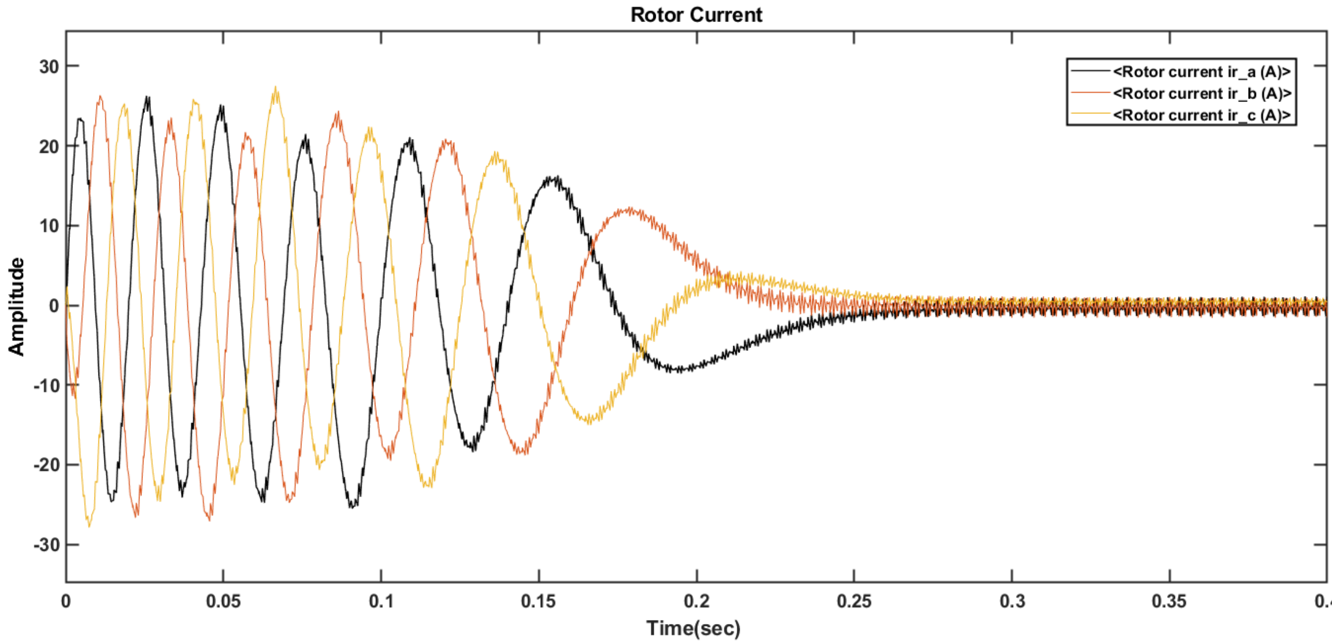


Figure 3.25 Rotor currents of induction motor drive at 1 kHz carrier frequency.

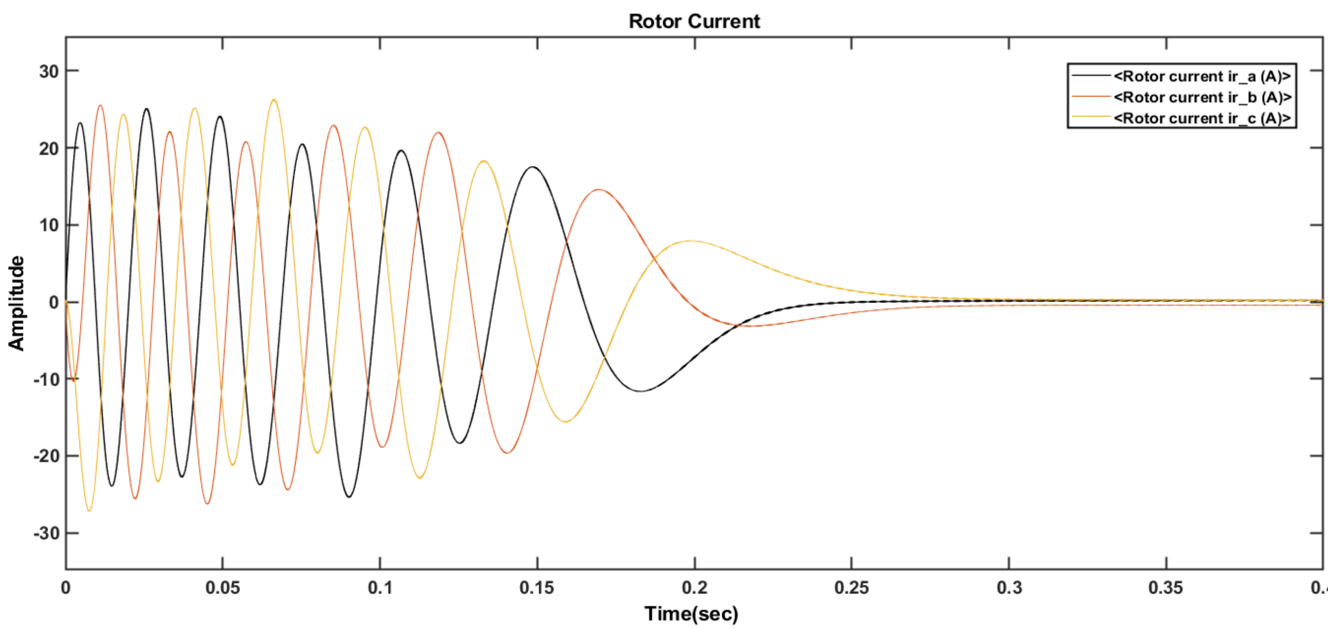


Figure 3.26 Rotor currents of induction motor drive at 10 kHz carrier frequency.

Fig. 3.25 & Fig. 3.26 show that high carrier frequency reduces rotor current distortion and produces stable rotor current output than 1 kHz carrier frequency. Rotor current achieves steady state after some time. Similar current output is found in [23] as well.

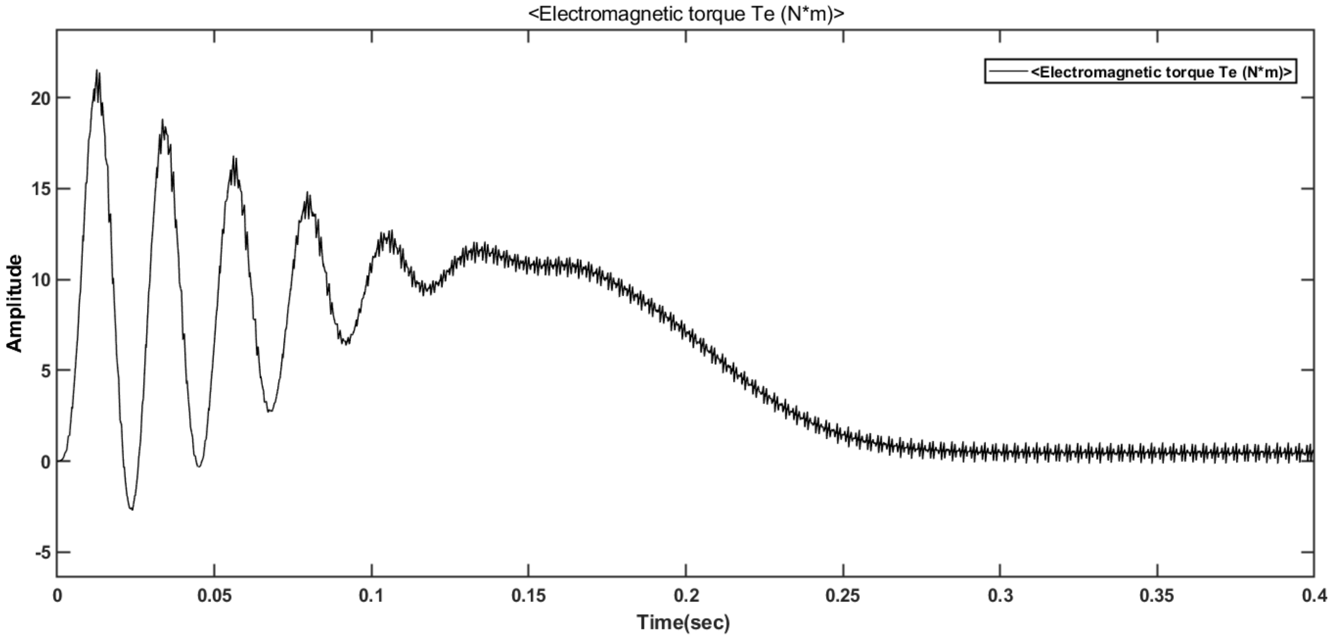


Figure 3.27 Electromagnetic torque of induction motor at 1 kHz carrier frequency.

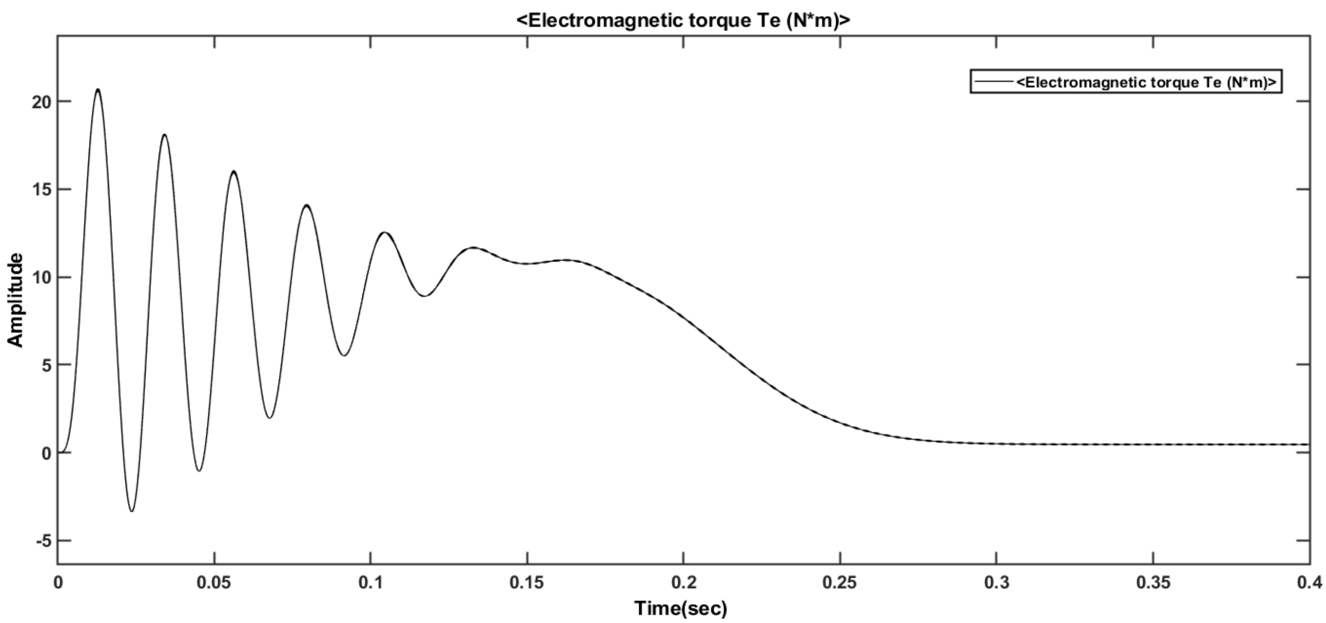


Figure 3.28 Electromagnetic torque of induction motor at 10 kHz carrier frequency.

From Fig. 3.27 & Fig. 3.28 it can be seen that electromagnetic torque distortion reduces with an increase in carrier frequency. More stable electromagnetic torque is achieved from the higher carrier frequency.

3.2.5 SVPWM technique fed induction motor drive performance:

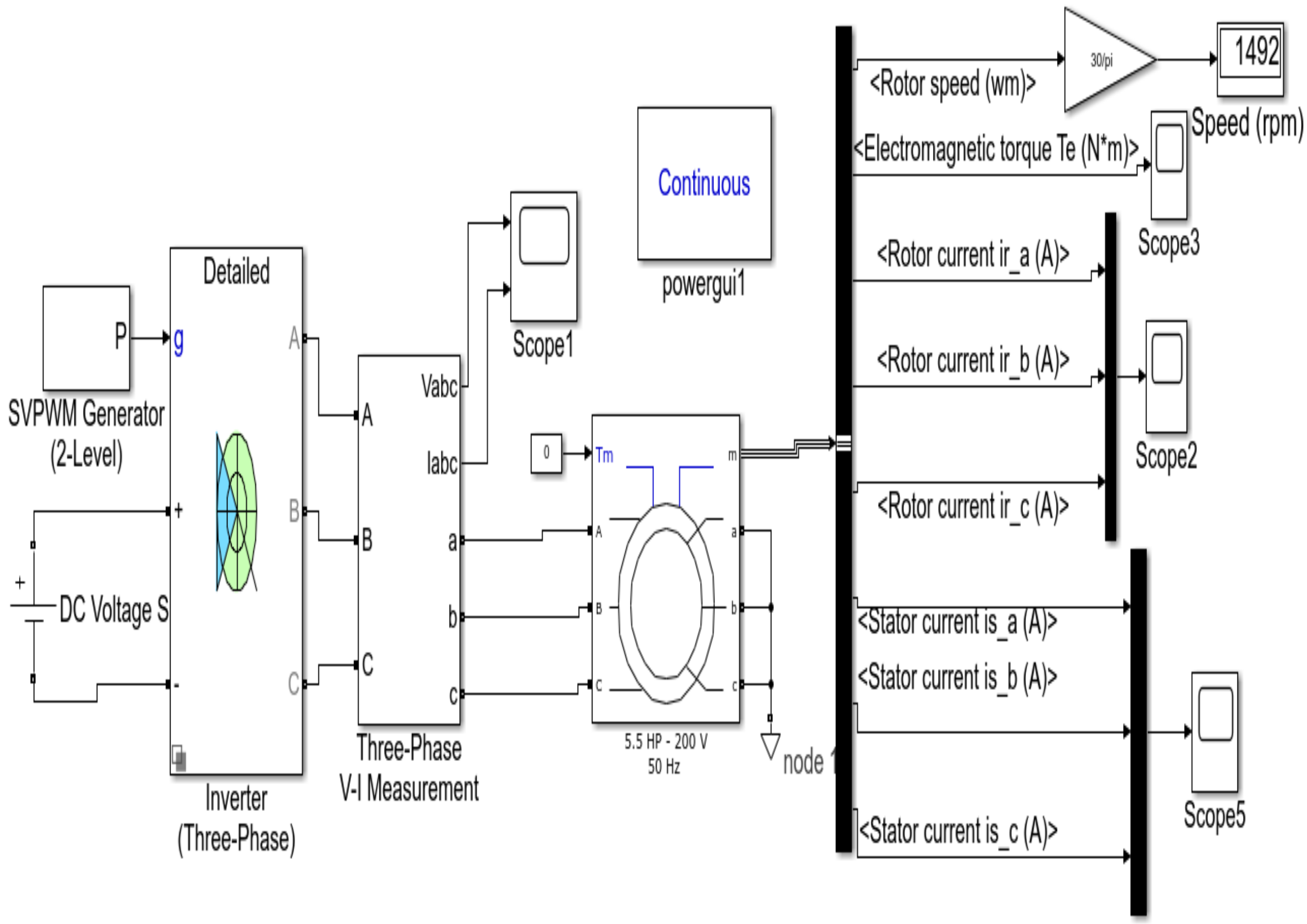


Figure 3.29 Simulation Schematic diagram of SVPWM technique fed Induction motor drive.

Fig. 3.29 shows a simulation schematic diagram of SVPWM technique fed Induction motor drive from which inverter output THD value and motor parameters like rotor current, stator current, electromagnetic torque and rotor speed etc. are found.

Table 3.13 Inverter output and motor performance at SVPWM technique for variable carrier frequency (Tm= 0 Nm, M=1)

Carrier Frequency F (Hz)	Inverter Output		Motor Performance	
	Voltage THD (%)	Current THD (%)	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)
1000	52.53	30.29	0.296	1491
5000	52.21	5.88	0.296	1491
10000	52.27	3.06	0.296	1491
20000	52.29	1.77	0.296	1491
30000	52.3	1.40	0.296	1491

From Table 3.13, it can be seen that the current THD value decreases significantly from 30.29% to 1.40% with the increase in carrier frequency. Insignificant change occurs in output voltage THD value with the carrier frequency. Rotor steady speed obtaining time and rotor speed don't change with the carrier frequency variation.

Table 3.14 Inverter output and motor performance at SVPWM technique for variable modulation index (Tm= 0 Nm, f=1 kHz)

Modulation index, M	Inverter Output		Motor Performance	
	Voltage THD (%)	Current THD (%)	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)
0.3	177.77	18.14	4.2	1397
0.6	143.13	29.79	0.88	1475
0.8	77.19	31.01	0.49	1486
1	52.53	30.29	0.296	1491

With the increase in modulation index, voltage THD decreases from 177.77% to 52.33% and current THD increases from 18.14% to 30.29%. The motor performance also varies with modulation index variation. Rotor steady speed obtaining time decreases from 4.2 sec to 0.296 sec and rotor speed increases from 1397 rpm to 1491 rpm with increasing modulation index.

Table 3.15 Induction motor performance at SVPWM technique for variable torque Tm (M=1, f=1 kHz)

Load Torque Tm (Nm)	Induction Motor Performance	
	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)
0	0.296	1491
5	0.59	1383
7	1.00	1321
8	Failed	N/A
9	Failed	N/A

Table 3.15 shows that rotor steady speed obtaining time increases and rotor speed decreases with increasing torque Tm. When the load torque applied above 7 Nm, the induction motor failed to reach steady-state rotor speed using the SVPWM technique.

3.2.5.1 Effect of carrier frequency on stator current, rotor current and electromagnetic torque:

The effect of high carrier frequency on rotor current, stator current & electromagnetic torque is presented in Fig. 3.30 to Fig. 3.35 using the SVPWM method at load torque, Tm=0Nm and modulation index, M=1.

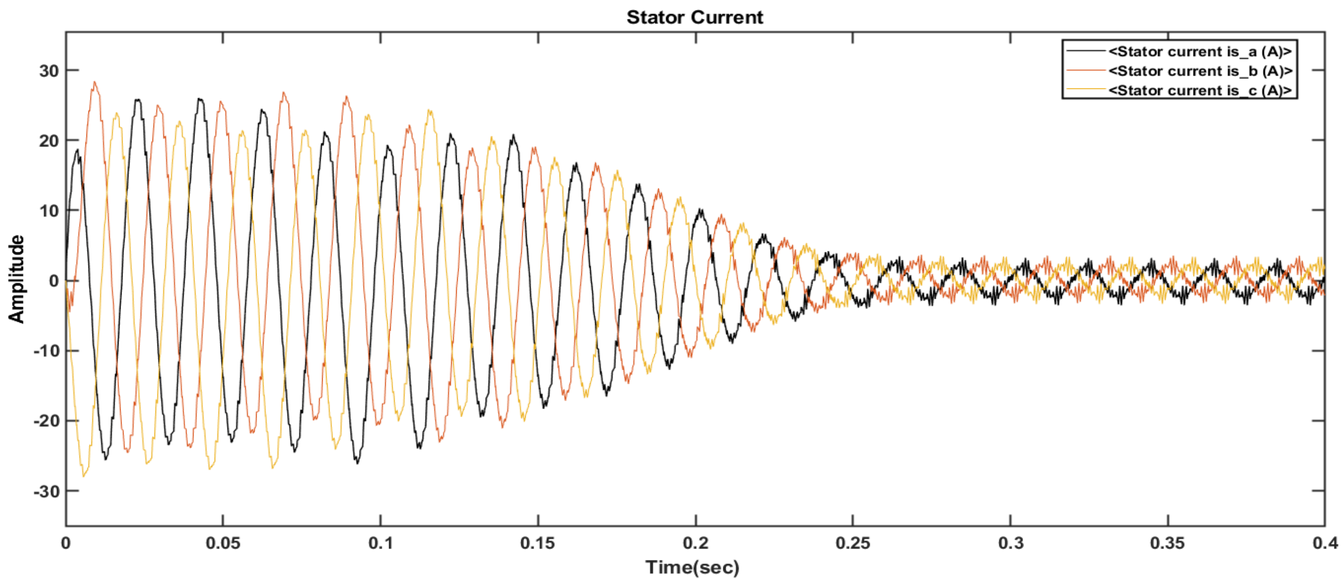


Figure 3.30 Stator currents of induction motor drive at 1 kHz carrier frequency.

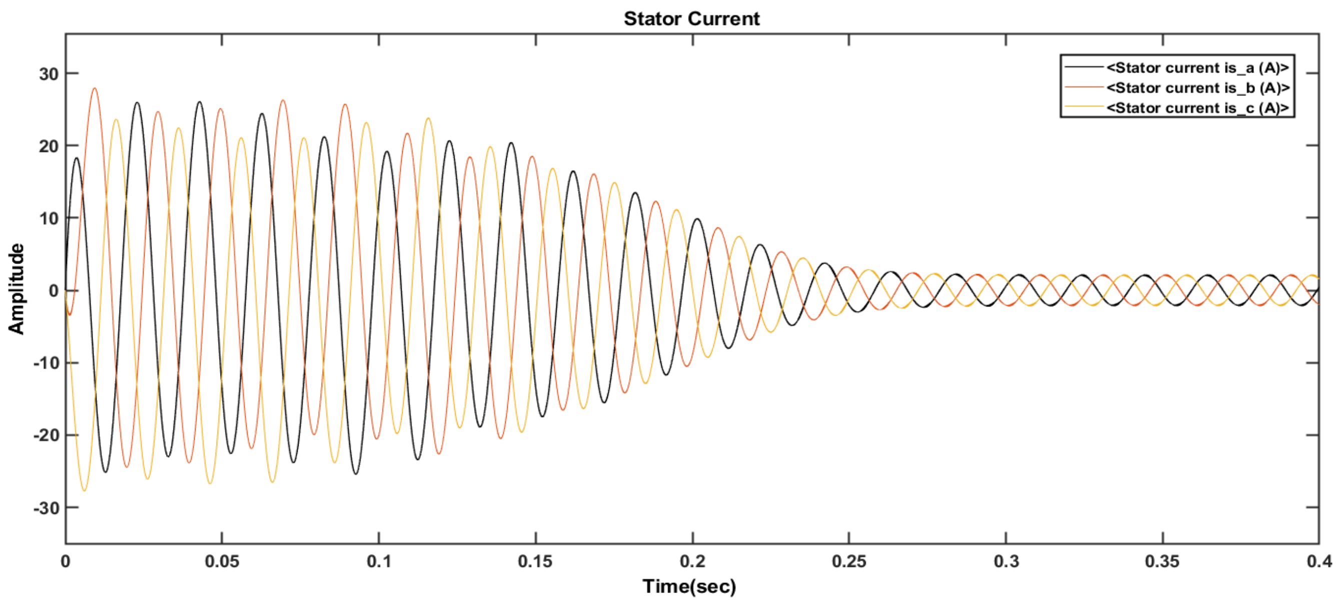


Figure 3.31 Stator currents of induction motor drive at 10 kHz carrier frequency.

From Fig. 3.30 & Fig. 3.31 it can be seen that high modulation carrier frequency reduces stator current distortion. Stator current achieves steady state after some time. A more stable stator current is achieved from applying higher carrier frequency. Similar current output is found in [23] as well.

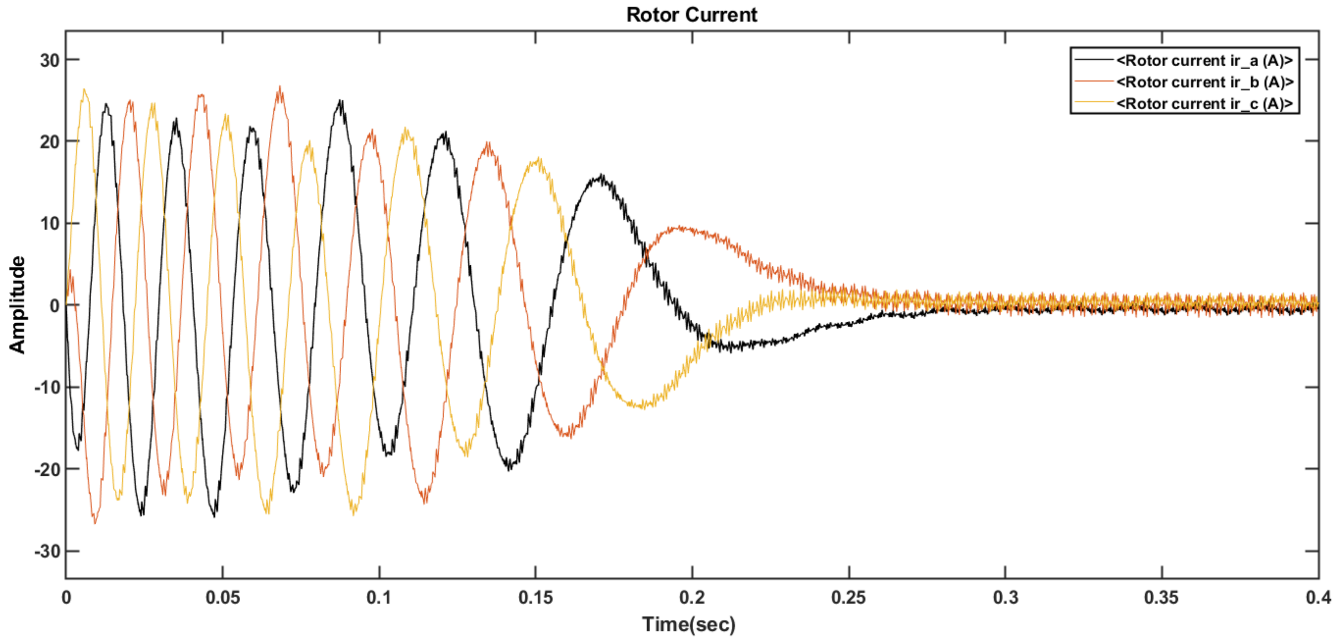


Figure 3.32 Rotor currents of induction motor drive at 1 kHz carrier frequency.

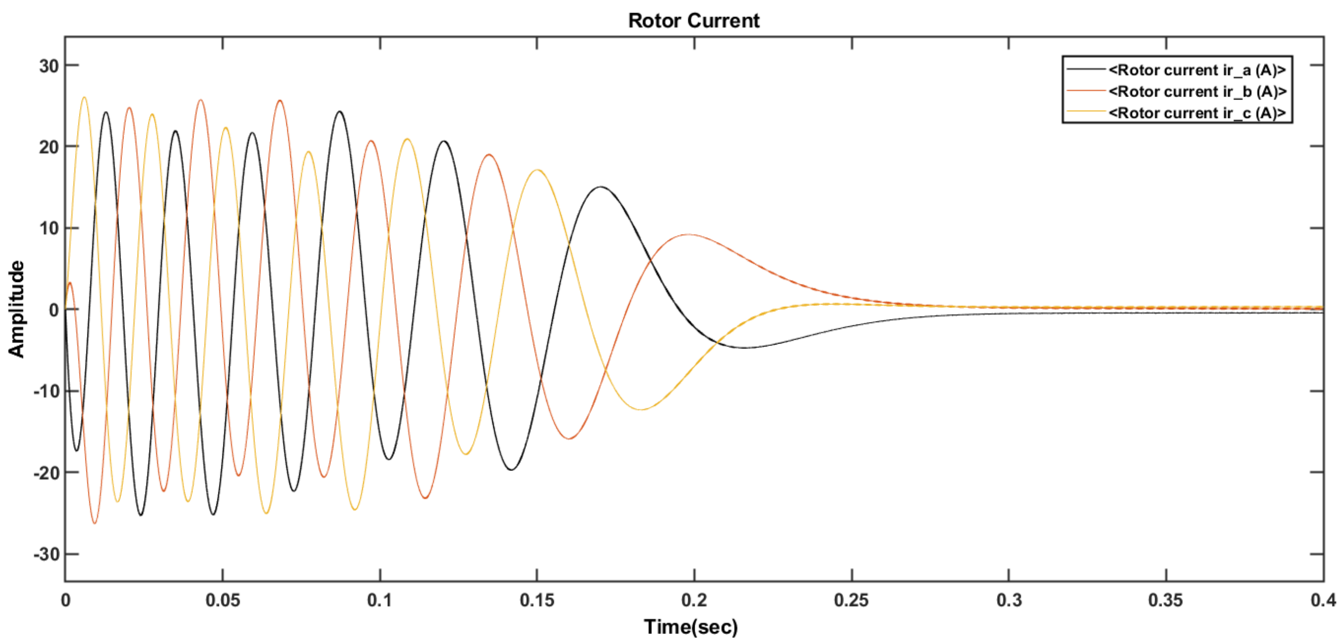


Figure 3.33 Rotor currents of induction motor drive at 10 kHz carrier frequency.

Fig. 3.32 & Fig. 3.33 shows that high carrier frequency reduces rotor current distortion and produces stable rotor current output than 1 kHz carrier frequency. Rotor current achieves steady state after some time. Similar current output is found in [23] as well.

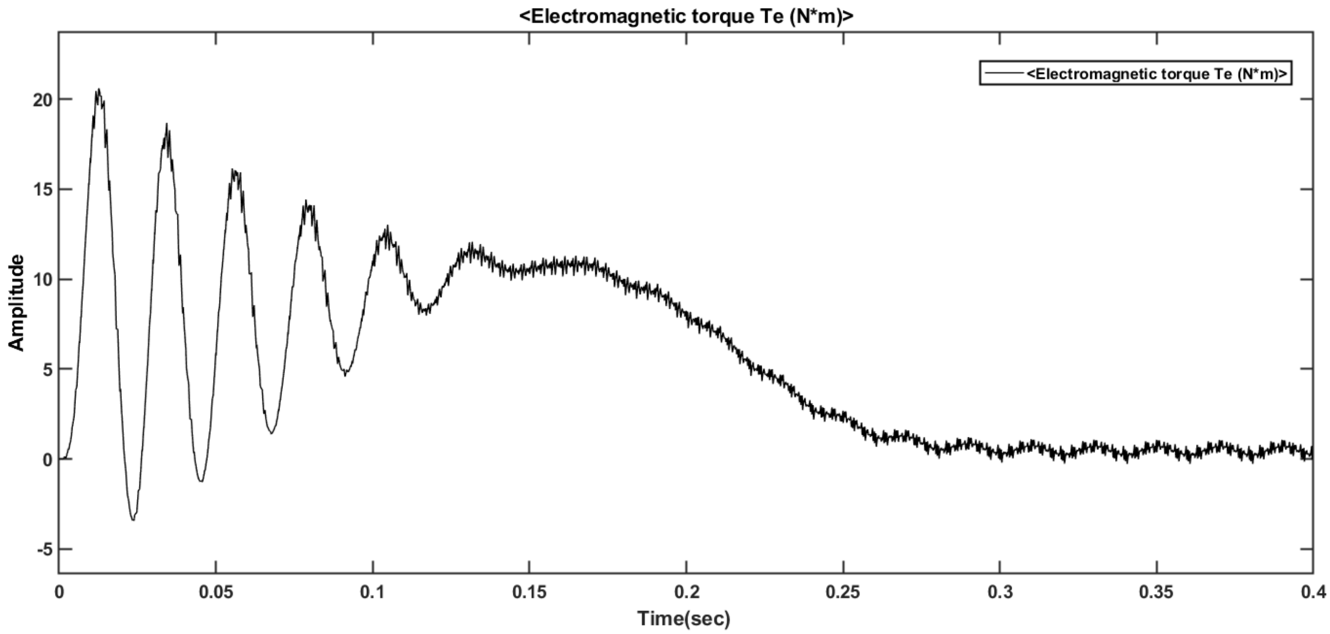


Figure 3.34 Electromagnetic torque of induction motor at 1 kHz carrier frequency.

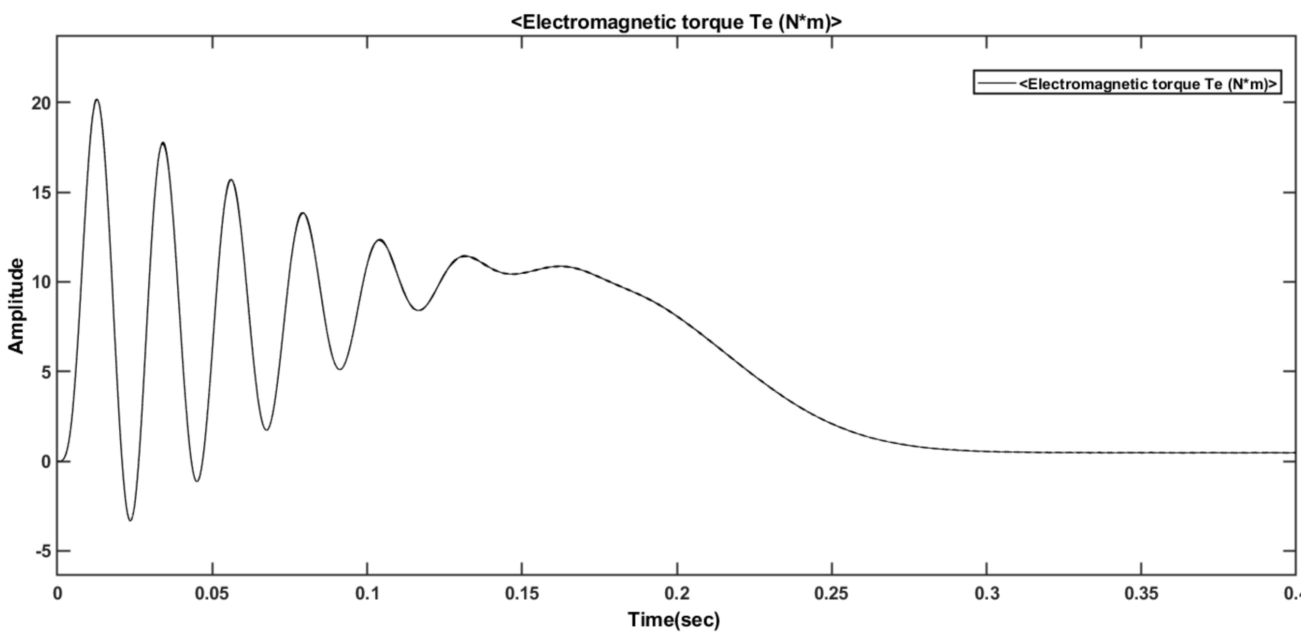


Figure 3.35 Electromagnetic torque of induction motor at 10 kHz carrier frequency.

From Fig. 3.34 & Fig. 3.35 it can be seen that electromagnetic torque distortion reduces with an increase in carrier frequency. More stable electromagnetic torque is achieved from the higher carrier frequency.

3.3 Comparative Analysis of PWM techniques

Table 3.16 Inverter output comparison between PWM techniques for varying carrier frequency (M=1 & T=0 Nm)

Carrier Frequency F (Hz)	SPWM		SDPWM		THIPWM		TPWM		SVPWM	
	Voltage THD (%)	Current THD (%)	Voltage THD (%)	Current THD (%)	Voltage THD (%)	Current THD (%)	Voltage THD (%)	Current THD (%)	Voltage THD (%)	Current THD (%)
1000	68.83	35.86	55.75	31.64	52.40	30.28	55.17	36.37	52.53	30.29
5000	68.84	7.11	55.1	7.26	52.31	6.01	54.49	14.41	52.21	5.88
10000	68.56	3.58	54.83	4.98	52.16	3.02	54.5	13.22	52.27	3.06
20000	68.48	1.85	54.74	4.23	52.14	1.51	54.5	12.9	52.29	1.77
30000	68.59	1.29	54.89	4.07	52.31	1.01	54.43	12.84	52.3	1.40

Table 3.16 shows that the SPWM method fed inverter contains highest THD values compared to all other technique. With increasing carrier frequency, current THD values decreased significantly for all the techniques. THIPWM and SVPWM method fed inverter output contains lowest amount of harmonics compared to other methods.

Table 3.17 Motor performance comparison between PWM techniques for varying carrier frequency (M=1 & T=0 Nm)

Carrier Frequency F (Hz)	SPWM		SDPWM		THIPWM		TPWM		SVPWM	
	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)
1000	0.392	1488	0.306	1491	0.281	1491	0.295	1491	0.296	1491

Carrier Frequency F (Hz)	SPWM		SDPWM		THIPWM		TPWM		SVPWM	
	Rotor steady speed obtaining time (sec)	**Rotor Speed (rpm)**	**Rotor steady speed obtaining time (sec)**	**Rotor Speed (rpm)**	**Rotor steady speed obtaining time (sec)**	**Rotor Speed (rpm)**	**Rotor steady speed obtaining time (sec)**	**Rotor Speed (rpm)**	**Rotor steady speed obtaining time (sec)**	**Rotor Speed (rpm)**
5000	0.392	1488	0.306	1491	0.281	1491	0.295	1491	0.296	1491
10000	0.392	1488	0.306	1491	0.281	1491	0.295	1491	0.296	1491
20000	0.392	1488	0.306	1491	0.281	1491	0.295	1491	0.296	1491
30000	0.392	1488	0.306	1491	0.281	1491	0.295	1491	0.296	1491

Table 3.17 shows that carrier frequency change does not affect rotor speed or rotor steady-state speed obtaining time. Lowest rotor steady speed obtaining time was found for THIPWM method.

Table 3.18 Inverter output comparison between PWM techniques for varying modulation index (f=1 kHz & T=0 Nm)

Modulation index, M	SPWM		SDPWM		THIPWM		TPWM		SVPWM	
	Voltage THD (%)	**Current THD (%)**	**Voltage THD (%)**	**Current THD (%)**	**Voltage THD (%)**	**Current THD (%)**	**Voltage THD (%)**	**Current THD (%)**	**Voltage THD (%)**	**Current THD (%)**
0.3	201.38	16.25	142.82	29.35	178.26	19.9	164.11	31.3	177.77	18.14
0.6	119.46	34.48	86.48	34.29	106.51	33.54	98.35	36.15	143.13	29.79
0.8	91.98	35.88	65.41	32.78	75.97	31.27	74.7	32.09	77.19	31.01
1	69.06	36.03	55.75	31.64	52.40	30.28	55.17	36.37	52.53	30.29

Table 3.18 shows that modulation index affect inverter performance. When modulation index is increased, voltage THD decreased and current THD increased significantly. SPWM technique contained highest

voltage THD values whereas TPWM technique contained highest current THD values when modulation index is varied.

Table 3.19 Motor performance comparison between PWM techniques for varying modulation index (M=1 & T=0 Nm)

Modulation index, M	SPWM		SDPWM		THIPWM		TPWM		SVPWM	
	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)	Rotor steady speed obtaining time (sec)	Rotor Speed (rpm)
0.3	6.05	1362	1.9	1448	4.12	1400	3.29	1417	4.2	1397
0.6	1.2	1468	0.56	1483	0.9	1476	0.76	1478	0.88	1475
0.8	0.65	1482	0.37	1488	0.47	1486	0.45	1487	0.49	1486
1	0.392	1488	0.306	1491	0.281	1491	0.295	1491	0.296	1491

Table 3.19 shows that modulation index affect motor performance a lot. High modulation index reduces Rotor steady speed obtaining time significantly and increases rotor speed. At modulation index 1, THIPWM method Rotor steady speed obtaining time was 0.281 sec at 1491 rpm.

Table 3.20 Induction motor performance comparison between PWM techniques at M=1, f=1 kHz

Torque Tm(Nm)	SPWM		SDPWM		THIPWM		TPWM		SVPWM	
	Rotor steady speed obtaining time(sec)	Rotor speed (rpm)	Rotor steady speed obtaining time(sec)	Rotor speed (rpm)	Rotor steady speed obtaining time(sec)	Rotor speed (rpm)	Rotor steady speed obtaining time(sec)	Rotor speed (rpm)	Rotor steady speed obtaining time(sec)	Rotor speed (rpm)
0	0.392	1488	0.306	1491	0.281	1491	0.292	1491	0.296	1491
5	1.075	1334	0.61	1379	0.545	1386	0.563	1384	0.59	1383
7	Failed	N/A	1.10	1315	0.882	1327	0.97	1324	1.00	1321

Torque Tm(Nm)	SPWM		SDPWM		THIPWM		TPWM		SVPWM	
	Rotor steady speed obtaining time(sec)	Rotor speed (rpm)	Rotor steady speed obtaining time(sec)	Rotor speed (rpm)	Rotor steady speed obtaining time(sec)	Rotor speed (rpm)	Rotor steady speed obtaining time(sec)	Rotor speed (rpm)	Rotor steady speed obtaining time(sec)	Rotor speed (rpm)
8	Failed	N/A	Failed	N/A	1.95	1291	Failed	N/A	Failed	N/A
9	Failed	N/A	Failed	N/A	Failed	N/A	Failed	N/A	Failed	N/A

Table 3.20 shows that rotor speed decreases and rotor steady speed obtaining time increases with increasing load torque for all the PWM techniques. This similarity is found in other research work too [23, 26]. THIPWM method fed induction motor run at highest rotor speed at lowest rotor steady speed obtaining time for variable load torque condition. When load torque was varied from 0 Nm to 8 Nm, rotor speed decreased from 1491 rpm to 1291 rpm and steady speed obtaining time increased from 0.281 sec to 1.9 sec. SPWM method fed induction motor run at the lowest rotor speed of 1488 rpm and highest rotor steady speed obtaining time of 0.392 sec at 0 Nm applied torque. At 5 Nm, rotor steady speed obtaining time was 1.075 sec and rotor speed was 1334 rpm for SPWM method. SPWM method failed to reach steady-state rotor speed when 7 Nm torque was applied and this similar condition is found in [26]. When the load torque applied above 7 Nm, the induction motor failed to reach steady-state rotor speed for SDPWM, TPWM and SVPWM techniques. THIPWM fed induction motor drive can run at a much higher load condition (8 Nm) compared to any other methods.

3.4 Chapter Summary

This chapter covers the results and analysis of this thesis work. A comparative study is discussed for five different PWM techniques fed induction motor drive. The analysis was done by varying modulation index, carrier frequency, and a load torque of induction motor drive to see motor characteristics like rotor current, stator current, rotor speed, rotor steady speed obtaining time, etc. and also see inverter parameters like voltage THD, current THD as well. Observation shows the THIPWM technique gives better performance compared to other PWM techniques. Inverter output THD values were found the lowest for the THIPWM technique. Motor obtained the highest rotor speed at the lowest steady-state obtaining time for the THIPWM technique as well. THIPWM technique fed motor to run at higher load torque than any other technique. The modulation index should be kept 1 to get optimum inverter performance. High carrier frequency is recommended as well which reduces THD values from the inverter and gives stable rotor current, stator current and electromagnetic torque. The higher switching frequency decreases the audible noise that can be heard from the motor. The reduced current distortion translates into lower rotor heating of the motor and a higher motor efficiency. Excess rotor heating can cause the rotor to expand or elongate, which could result in the rotor impacting the bearing surface.

Chapter 4 Conclusion

A comparative study of five PWM techniques fed induction motor drive using MATLAB/Simulink simulation is presented in this paper. The PWM technique which gave the best induction motor drive performance is selected by analyzing and comparing various parameters like rotor speed, rotor steady speed obtaining time, inverter output voltage THD%, and current THD% etc.

The simulation result proves that the Third Harmonic Injected PWM (THIPWM) technique provided the best induction motor drive performance among all the five PWM methods. THIPWM inverter produced the lowest inverter output THD values compared to all other PWM techniques where voltage THD value is 51.36% and the current THD value is 30.28% at carrier frequency 1 kHz & modulation index 1. THIPWM technique fed induction motor has given the highest rotor speed at the lowest rotor steady-state speed time and can operate at higher load conditions than any other PWM technique. Only THIPWM technique fed induction motor run at load torque 8 Nm and produced stable rotor speed 1291 rpm at 1.95 sec. Simulation results show that high carrier frequency reduces THD value from inverter output and also reduces distortion from rotor current, stator current & electromagnetic torque of induction motor drive which in turn reduces motor audible noise and increases efficiency & precision of the motor as well. Hence, it is suggested that designers should adopt to THIPWM technique with high carrier frequency and modulation index for the optimum induction motor drive performance.

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