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Pulse Width Modulation Inverter Control Methods-A Comprehensive Study

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Abstract

Harmonics in electrical supply refers to the distortion of the normal electrical waveform due to the presence of frequencies that are multiples of the fundamental frequency. The presence of harmonics in electrical supply can lead to a number of problems, including: Overheating of equipment, Power quality issues, Extra energy consumption etc. This research aims to provide a cost-effective solution to reduce harmonics in three phase inverters and improve power factor without using any hardware components such as filters and multi-level inverters and by simply changing control pulses of the inverter switches. This research provides a comparison of three most popular inverter control techniques SPWM control, THPWM control and SVPWM control techniques of three phase inverters. All these techniques were compared with the help of MATLAB-SIMULINK and the best control technique with lower order harmonics and less power factor was determined.

Keywords: Harmonics, SPWM, THPWM, SVPWM, THD

1. Introduction

Inverters are utilized to transform input DC voltage into output AC voltage. In high-power applications, three-phase inverters are frequently preferred. They are utilized in tasks like AC engine speed control and Uninterruptible Power Supplies (UPS). For speed control of asynchronous motors, voltage-type inverters like controllers can be used to provide variable

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frequency and voltage. Both phase inverters and Pulse-Width Modulated (PWM) inverters can be implemented with the Voltage Source Inverter (VSI). To achieve varying output voltage, the DC input voltage can be altered using a step wave inverter. To obtain a DC input voltage between the DC power supply and the inverter, a chopper can be linked. Alternatively, if the input voltage is AC, a rectifier must be connected between the AC power source and the inverter to regulate the variable DC input voltage. The PWM inverter allows for the control of both output voltage and frequency without the need for external control. In cases where the input voltage is DC, the PWM inverter can be directly connected. However, when the input voltage is AC, a diode bridge rectifier is used to obtain DC, which is then connected to the PWM inverter. The use of PWM-based inverters is preferred over stepped wave inverters due to their ability to reduce harmonics, as discussed in this paper.

Various PWM control schemes have emerged during the last two decades, allowing for the regulation of output voltage and frequency. The most common three-phase inverter schemes are SPWM, THPWM, SVPWM and 60° PWM. Schonung and Stemmler first proposed SPWM, the most straightforward approach, in 1964. The appropriate inverter gate signals are generated using this method by comparing a reference sine wave to a triangular carrier signal. THPWM, invented by Buja in 1975, works in the same way as SPWM, but using a reference AC waveform that includes both fundamental and third harmonic components, rather than merely a sinusoidal waveform [1].

On the contrary, SVPWM is a PWM control technique utilized at the final stage of field orientation control to identify the pulse-width modulated signals needed by the inverter switches to generate the appropriate three-phase voltages. PWM approaches are frequently used because of their ease of implementation, control and ability to reduce lower-order harmonics. In this study, the harmonics of SPWM, THPWM and SVPWM techniques will be investigated and compared.

Total Harmonic Distortion, commonly abbreviated as THD, refers to the measurement of distortion present in an electrical signal. THD quantifies the level of harmonics present in a signal that deviates from the fundamental frequency. THD is an important parameter in audio and power systems, as high THD levels can lead to degraded sound quality and decreased efficiency. It is crucial to maintain low THD levels in electrical systems to ensure optimal performance. The presence of nonlinear devices in power systems is a source of harmonic distortion. A device is deemed nonlinear if it does not have a proportional current response to the applied voltage. The IEEE Standard 519- 2014 provides guidelines to manage harmonic distortion in electrical power systems [4]. THD is a significant indicator that measures the quality of the output voltage of an inverter. It is an important factor to take into account since it determines the effective value of harmonic components present in a distorted waveform.

$$THDV = \frac{\sqrt{\sum_{h>1}^{h\,max} V_h^2}}{V_1} \qquad (1)$$

To calculate the harmonic voltage, use the above equation (1)

$$THDI = \frac{\sqrt{\sum_{h>1}^{h\,max} I_h^2}}{I_1} \qquad (2)$$

In order to determine the harmonic current, use the above equation (2).

FFT analysis of the entire techniques is carried out with the help of FFT tool in MATLAB software which make the computing much easier and faster.

1.1 VSI Model

The below Figure 1 shows the three-phase voltage source inverter designed using MATLAB-SIMULINK. It is a 3-leg inverter designed with the help of MOSFET.

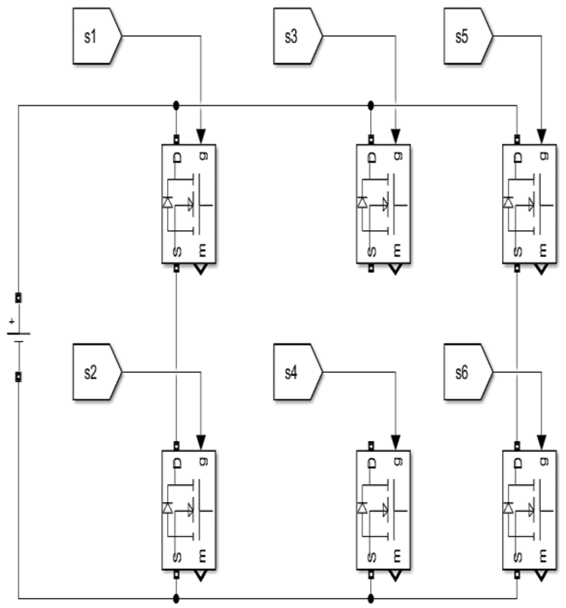

Figure 1. Power Circuit of Three-phase VSI

2. SPWM, THPWM and SVPWM Techniques

2.1 SPWM Control

The PWM is a commonly used technique in both analog and digital circuits, particularly in industrial settings. In order to create the gating signals that activate the inverter switches, it compares a triangular carrier signal with a three-phase sinusoidal reference signal.

The carrier signal has a much higher frequency than the reference signal, and the M.I is calculated as the ratio of the Vref to the Vcarrier

$$M = Vref / Vcarrier \tag{3}$$

Here, Vref represents reference signal and Vcarrier represents the carrier signal.

An inverter's output frequency is determined by the frequency of the reference signal, and its amplitude controls the modulation index.The M.I, in turn, affects the rms output voltage. However, when compared to other switching techniques, the SPWM has higher harmonic distortion, especially at high modulation index values. Additionally, SPWM results in high switching losses. Although SPWM is straightforward to comprehend, it cannot make full use of the DC bus voltage [1].

2.2 THPWM Control

The THPWM technique was devised to improve the inverter's performance, and it is an upgraded version of the sinusoidal PWM technique. This technique involves incorporating a third-order harmonic content to the fundamental frequency sinusoidal reference signal. To achieve this, one-sixth of the third harmonic signal is added to the sine wave, enabling the regulation of the fundamental amplitude to reach a peak of 0.866 or unity [1]. The below figure 2 shows reference signal of THPWM strategy.

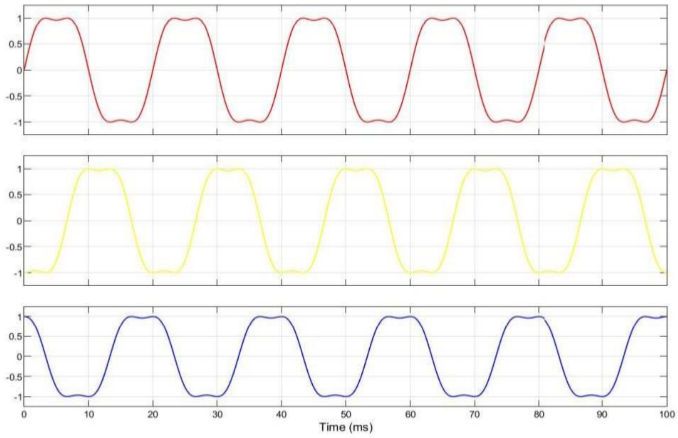

Figure 2. THPWM Reference Signa

The addition of one-sixth of the third harmonic signal to the sine wave at the peak of unity leads to an amplitude of the fundamental signal. To enhance the efficiency of inverters, the THPWM technique was introduced. It involves adding a third- order harmonic to the sine wave's fundamental frequency. This addition of the third harmonic increases the utilization rate of the DC voltage by 15.5%. The output of the comparator is then utilized to regulate the inverter switches in a similar manner to an SPWM inverter.

2.3 SVPWM Control

SVM is a technique utilized to control PWM in electrical systems. It is commonly employed in generating AC waveforms to drive three-phase AC powered motors at different speeds using DC through multiple class-D amplifiers. There exist several versions of SVM that provide varying levels of quality and computational demands [5].

Ongoing research in this area focuses on reducing the overall harmonic distortion (THD) that arises from the rapid switching associated with these algorithms.

2.4 SVPWM Implementation

A carrier-based space vector algorithm or a sector selection technique can both be used to implement SVM. There are several SVPWM implementations, such as carrier-based, reduced switching carrier-based, sector selection-based, and space vector modulation with reduced switching based on carrier switching. Each of these variations has varying computational demands and performance characteristics. Reducing the THD is an area of ongoing research as it can result from the fast switching that is inherent to these algorithms.

This paper presents the implementation of a carrier-based space vector modulation technique with the aid of vector switching with MATLAB-SIMULINK [5].

Table 1. Vector Table

Vector	A^+	B^+	C^+	A^-	B^-	C^-	V_{AB}	V_{BC}	V_{CA}	
V_0 = {000}	OFF	OFF	OFF	ON	ON	ON	0	0	0	zero vector
V_1 = {100}	ON	OFF	OFF	OFF	ON	ON	$+V_{dc}$	0	$-V_{dc}$	active vector
V_2 = {110}	ON	ON	OFF	OFF	OFF	ON	0	$+V_{dc}$	$-V_{dc}$	active vector
V_3 = {010}	OFF	ON	OFF	ON	OFF	ON	$-V_{dc}$	$+V_{dc}$	0	active vector
V_4 = {011}	OFF	ON	ON	ON	OFF	OFF	$-V_{dc}$	0	$+V_{dc}$	active vector
V_5 = {001}	OFF	OFF	ON	ON	ON	OFF	0	$-V_{dc}$	$+V_{dc}$	active vector
V_6 = {101}	ON	OFF	ON	OFF	ON	OFF	$+V_{dc}$	$-V_{dc}$	0	active vector
V_7 = {111}	ON	ON	ON	OFF	OFF	OFF	0	0	0	zero vector

Table 1 shows the eight switching states of SVPWM. The switching states from V0 = {000} and ends with V7 = {111}. During both starting and ending the vector phase voltages and the line voltages will be equal to zero.

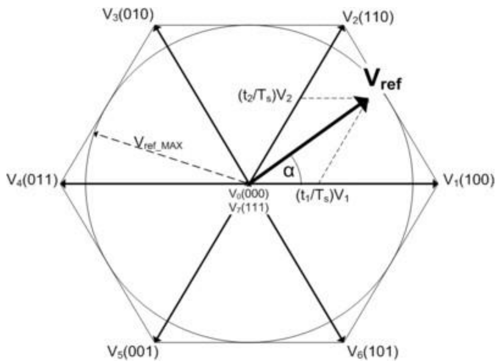

Figure 3. Vector Diagram

Figure 3 illustrates the eight possible switching vectors for a three-leg inverter utilizing space vector modulation. The first sector showcases a sample of the Vref and Vref_MAX denotes the maximum amplitude of Vref that can be attained before non-linear overmodulation takes place.

3. Simulation and Results

3.1 Simulation OF SPWM, THPWM & SVPWM

MATLAB Simulink is used for simulating a three-phase voltage source inverter with several PWM control algorithms, including SPWM, THPWM, and SVPWM. The simulation is performed using the following parameters:

Table 2. Simulation Parameters

DESCRIPTION	VALUE
Input DC voltage (V)	415 V
System frequency (Hz)	50 Hz
Load resistance (R)	10 ohms
Load inductance (L)	50e-3 Henry
Switching Frequency	5kHz, 10kHz and 15kHz
Modulating index (M.I)	1 (unity)

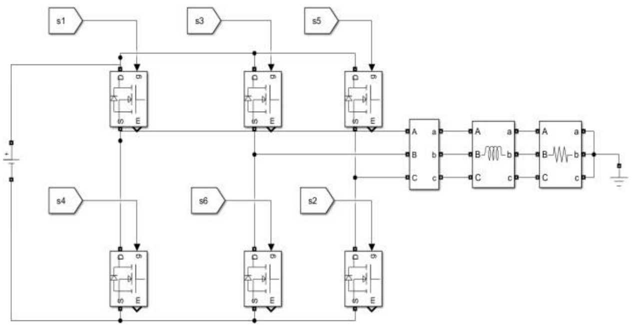

Figure 4. Power circuit of Three-phase VSI with RL Load

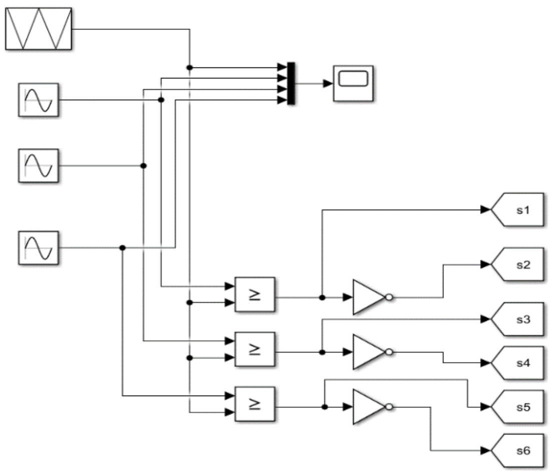

Figure 5. Gating Circuit of SPWM

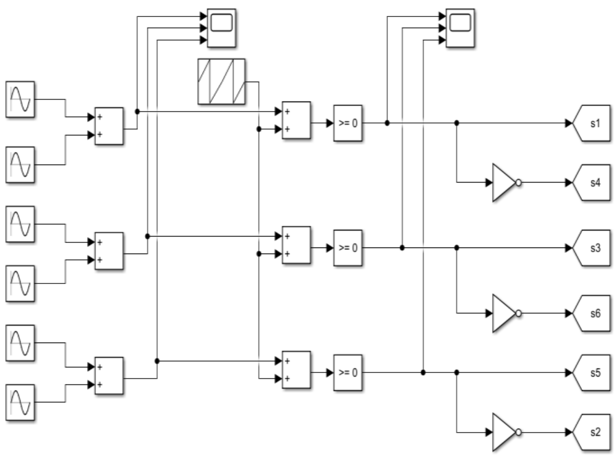

Figure 6. Gating Circuit of THPWM

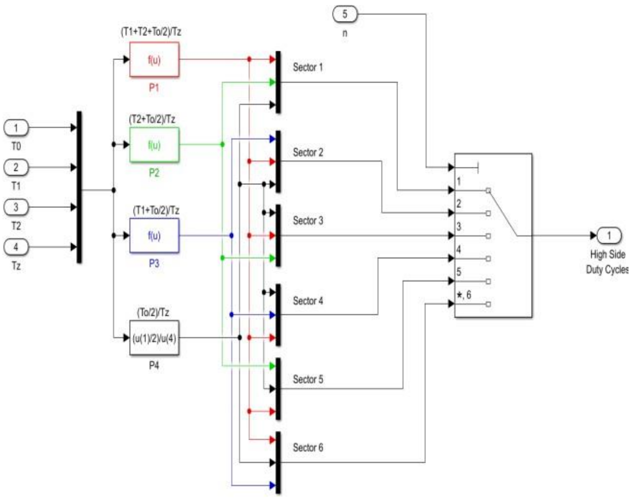

Figure 7. Simulink Model for Switching between Eight Vectors

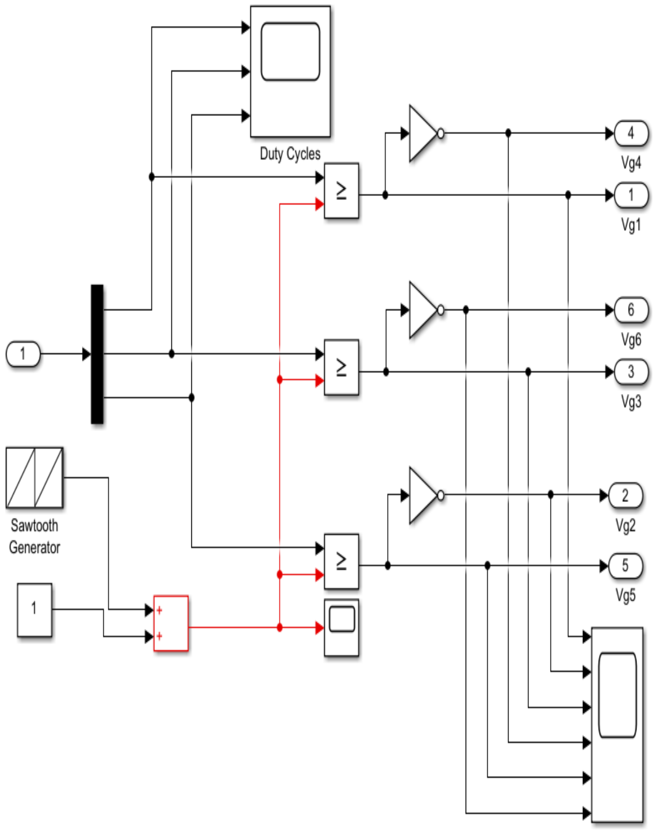

Figure 8. Gating Circuit of SVPWM

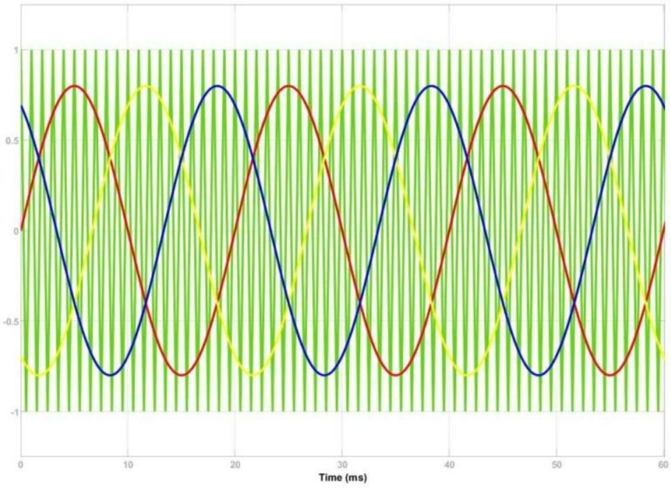

Figure 9. Comparison of Vcarrier and Vref Signal for SPWM

In Figure 9, a comparison is made between the carrier signal and reference signal for SPWM. The carrier signal is a high- frequency triangular wave, while the reference signal is a low- frequency sine wave. The resulting output waveform is a series of pulses with different widths, as demonstrated in the figure.

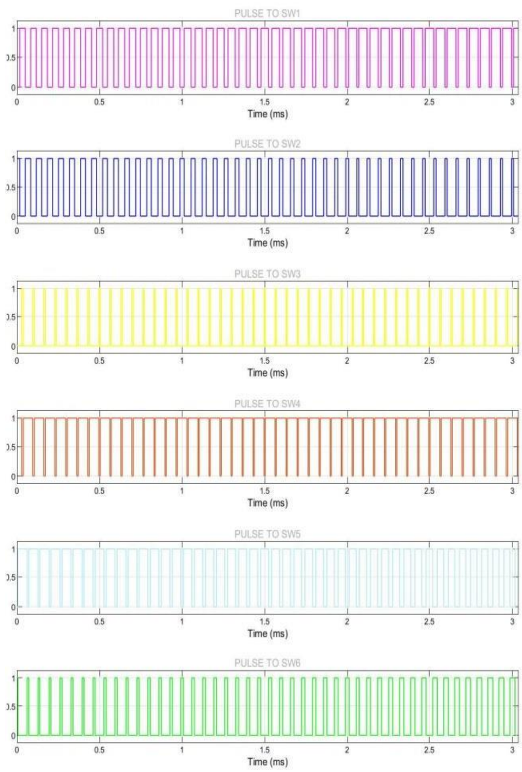

Figure 10. Switching Pulses for Three Phase VSI using SPWM Strategy

In Figure 10, the SPWM strategy is used to generate pulses that trigger the switches of the inverter circuit. The pulses are responsible for controlling the switching of the inverter switches, which ultimately affects the output voltage waveform.

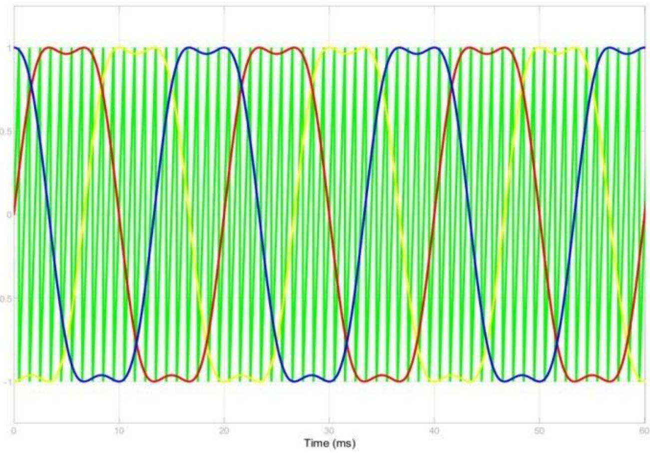

Figure 11. Comparison of Vcarrier and Vref for THPWM.

In Figure 11, a comparison is made between the trapezoidal carrier signal and reference signal for THPWM. The reference signal is a low-frequency sine wave, while the carrier signal is a high-frequency trapezoidal wave.

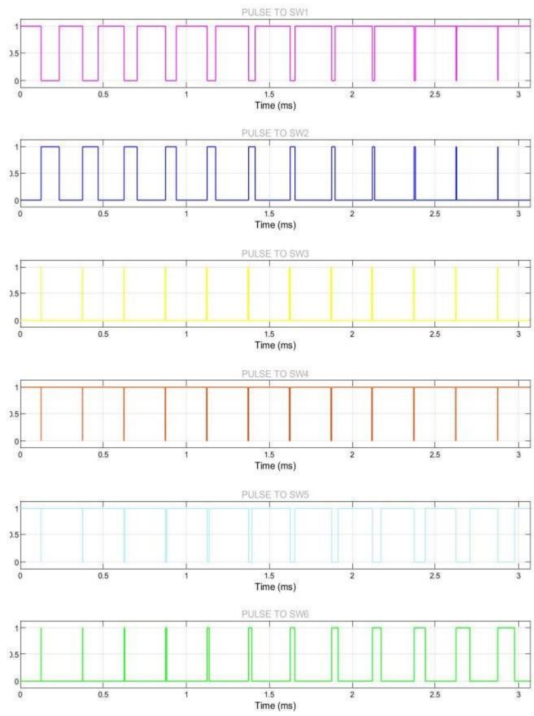

Figure 12. Switching Pulses for Three Phase VSI using THPWM Strategy

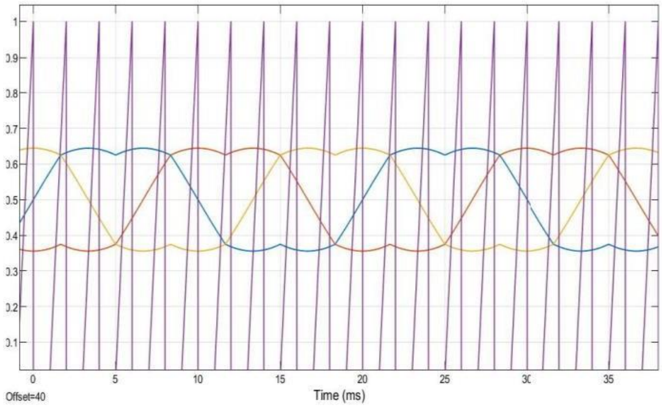

Figure 13. Comparison of Vcarrier and Vref for SVPWM

The illustration in Figure 13 depicts the comparison between the reference signal and carrier signal for SVPWM. The carrier signal is a triangular wave of high frequency, while the reference signal is a low-frequency sine wave.

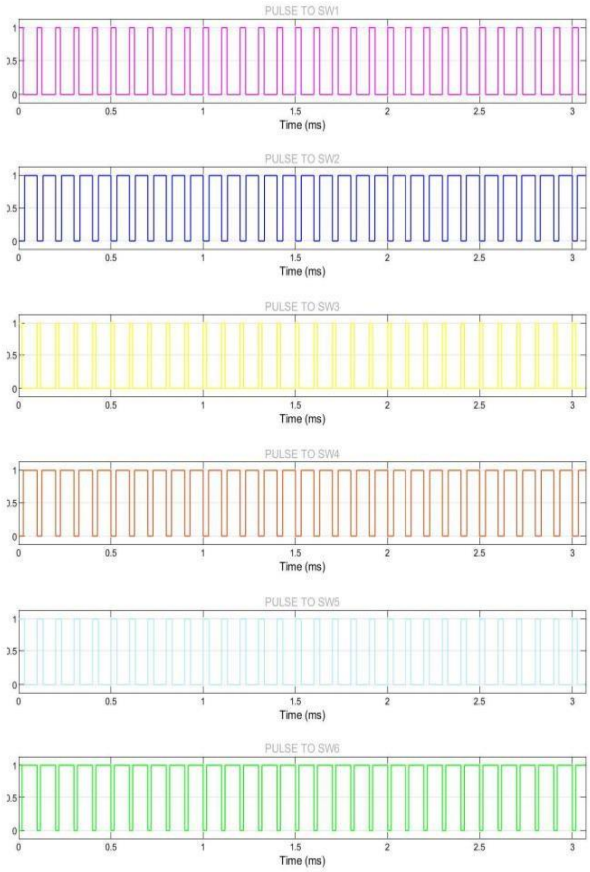

Figure 14. Switching Pulses for Three Phase VSI using SVPWM Strategy

In Figure 14, the SVPWM strategy is used to generate pulses that trigger the switches of the inverter circuit. The pulses are responsible for controlling the switching of the inverter switches, which ultimately affects the output voltage waveform.

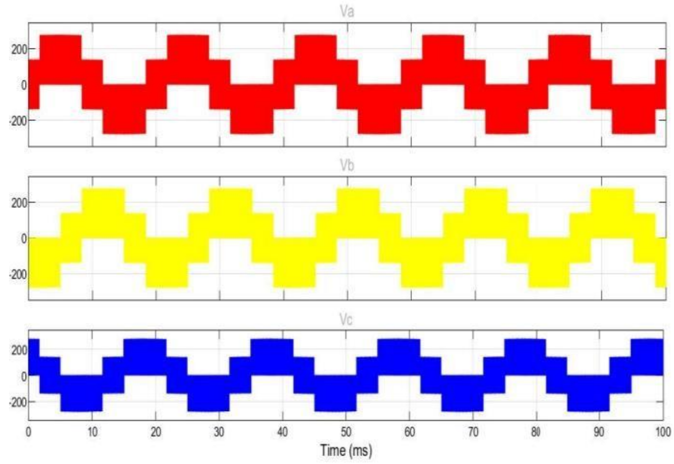

Figure 15. Phase Voltage Waveforms of SPWM Strategy

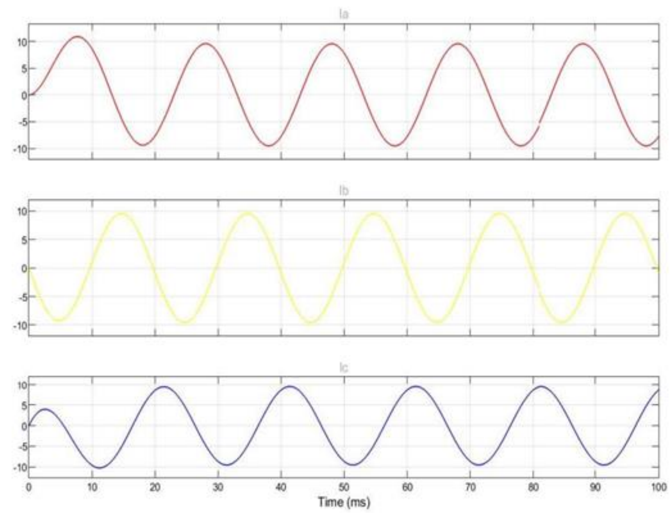

Figure 16. Phase Current Waveforms of SPWM Strategy

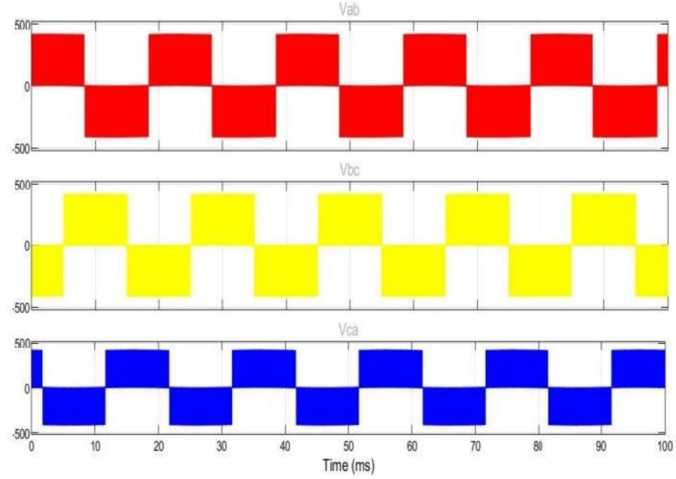

Figure 17. Line-Line Voltage Waveforms of SPWM Strategy

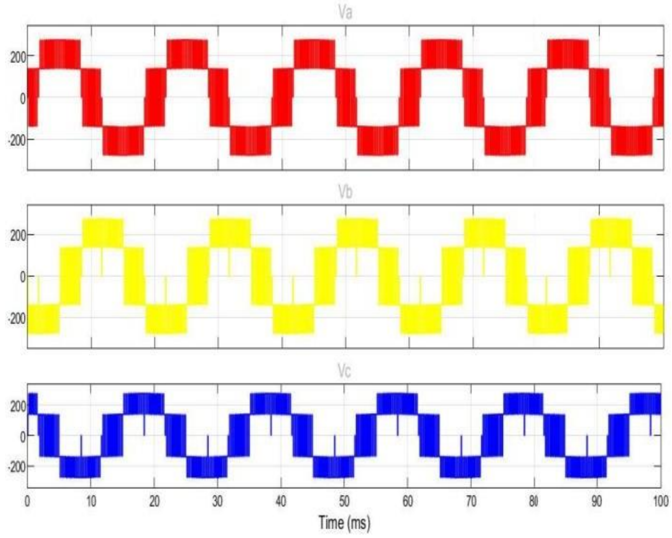

Figure 18. Phase Voltage Waveforms of THPWM Strategy

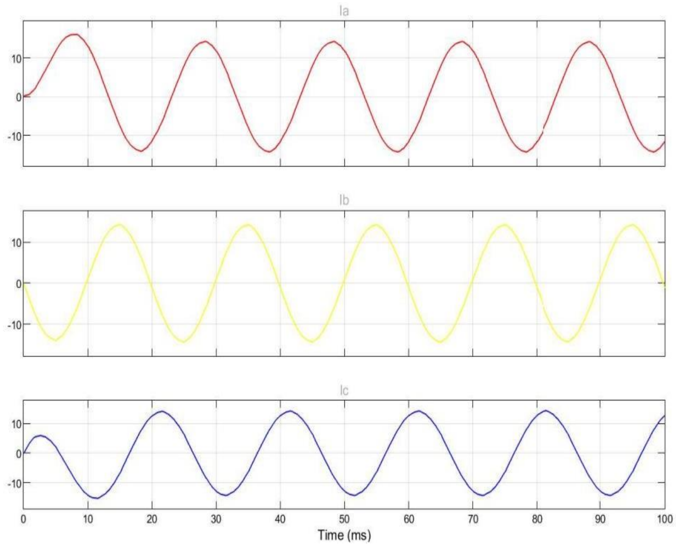

Figure 19. Phase Current Waveforms of THPWM Strategy

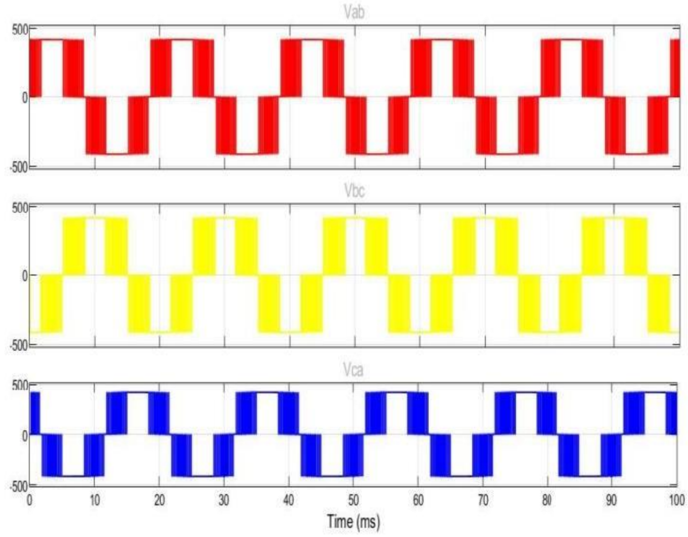

Figure 20. Line-Line Voltage Waveforms of THPWM Strategy

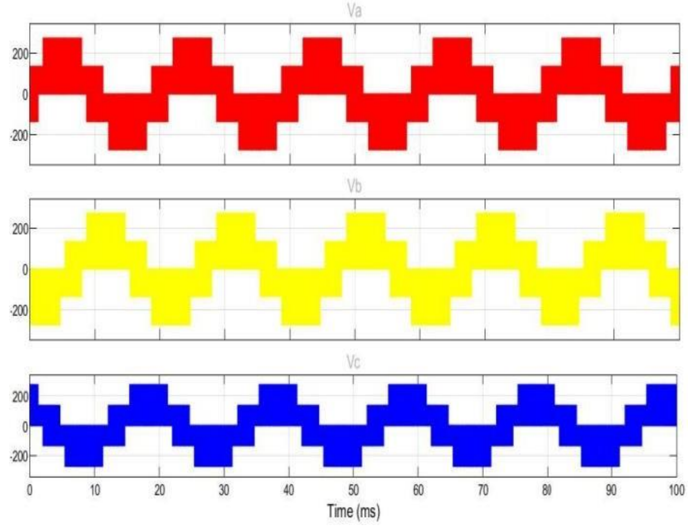

Figure 21. Phase Voltage Waveforms of SVPWM Strategy

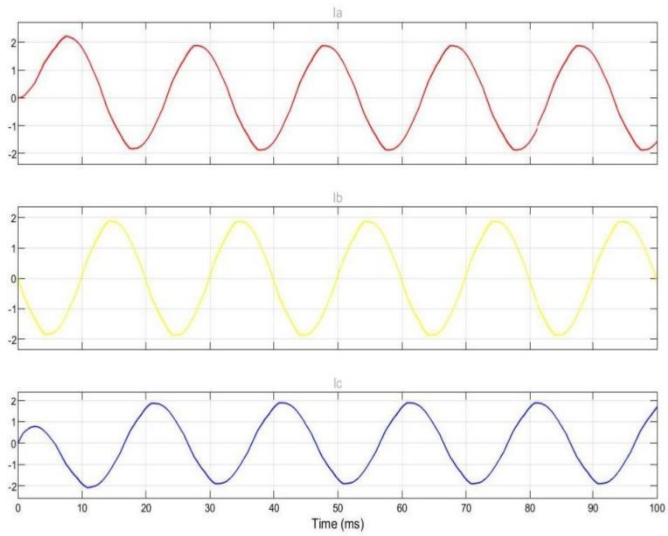

Figure 22. Phase Current Waveform of SVPWM Strategy

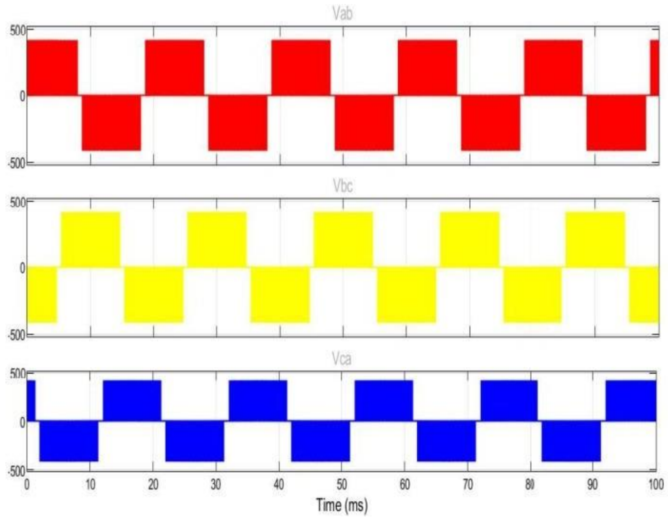

Figure 23. Line-line Voltage Waveform of SVPWM Strategy

THDI Analysis

The following figures depicts the frequency spectrum of AC current for various control strategy used in this research,

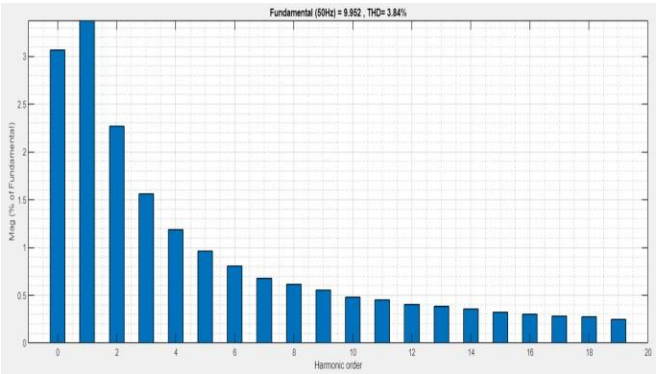

Figure 24. THDI of SPWM at 5 kHz Vcarrier

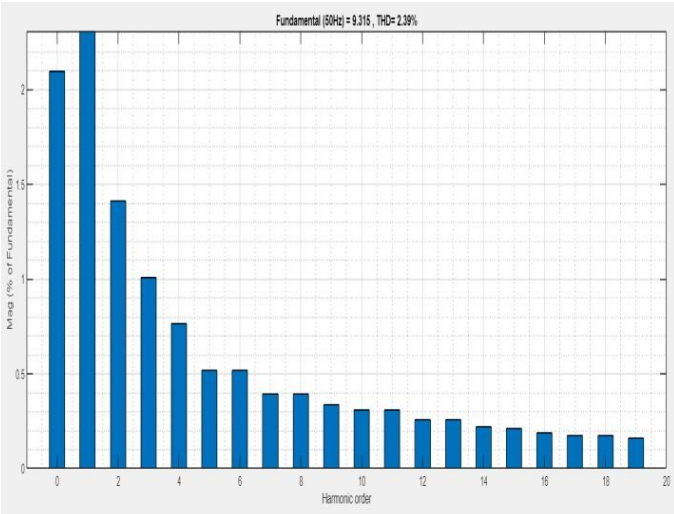

Figure 25. THDI of SPWM at 10 kHz Vcarrier

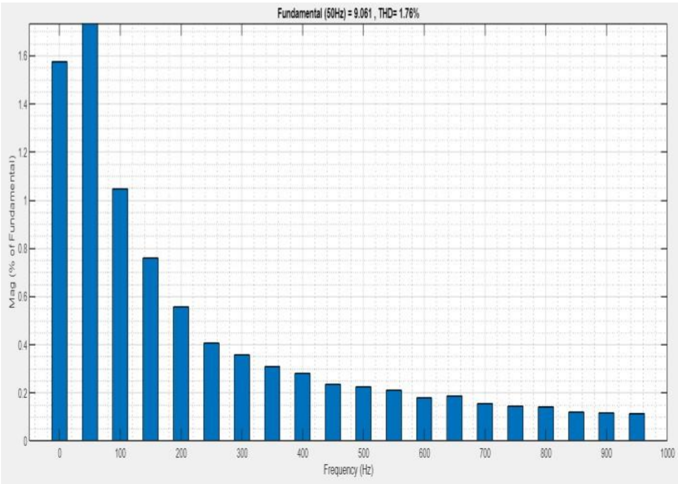

Figure 26. THDI of SPWM at 15 kHz Vcarrier

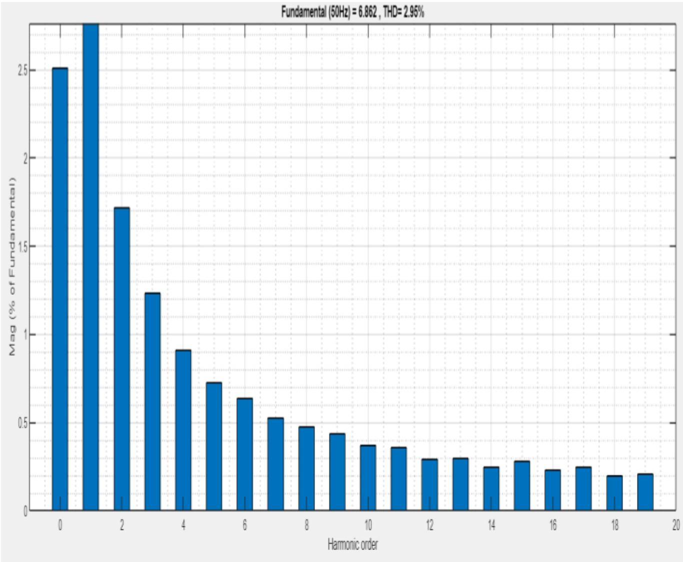

Figure 27. THDI of THPWM at 5 kHz Vcarrier

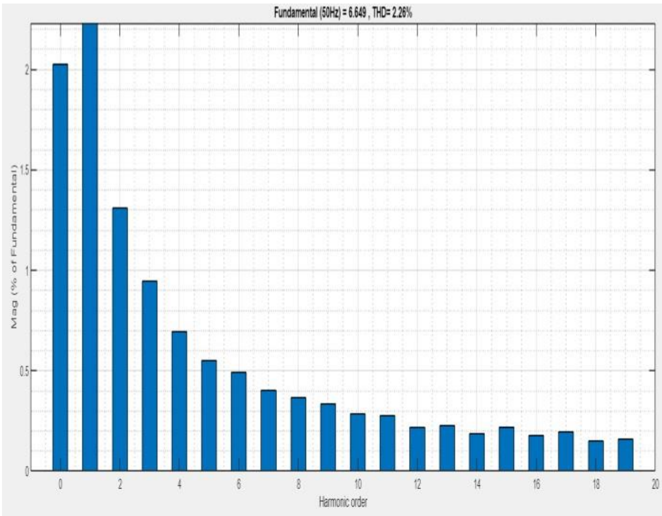

Figure 28. THDI of THPWM at 10 kHz Vcarrier.

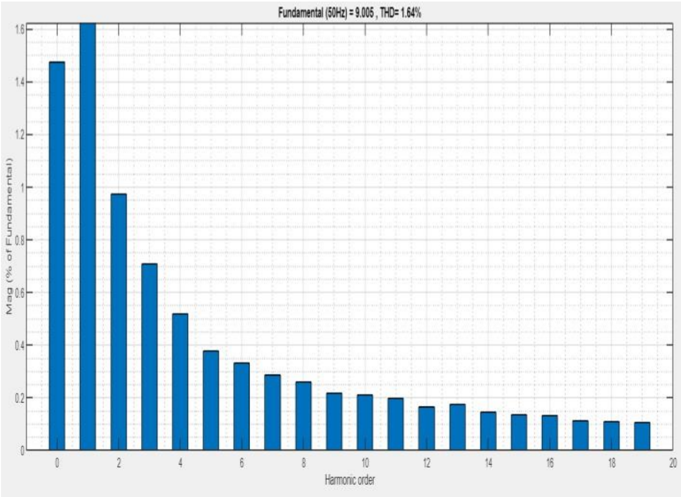

Figure 29. THDI of THPWM at 15 kHz Vcarrier.

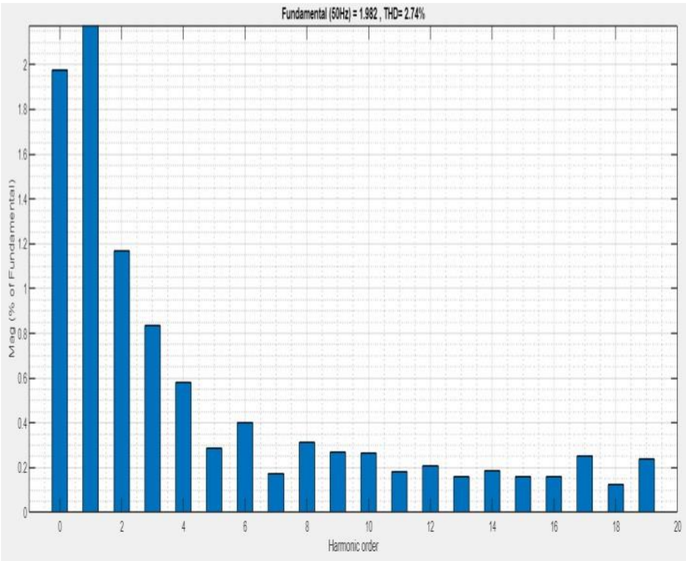

Figure 30. THDI of SVPWM at 5 kHz Vcarrier.

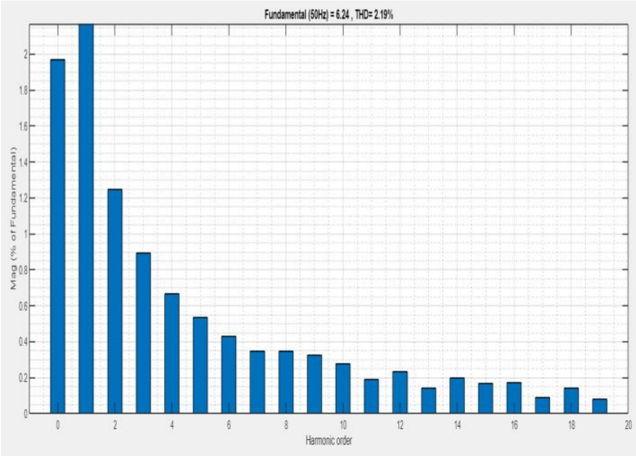

Figure 31. THDI of SVPWM at 10 kHz Vcarrier.

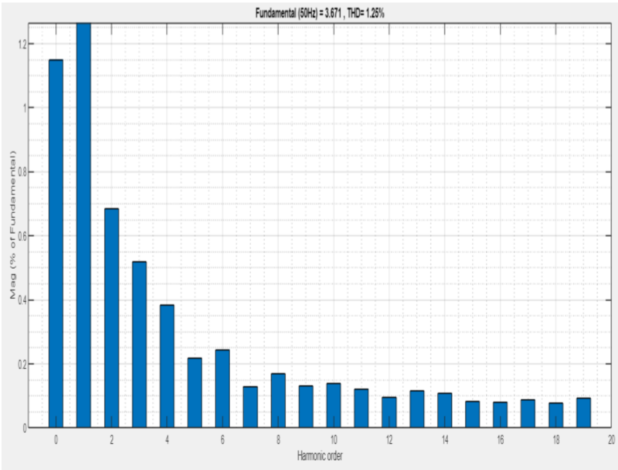

Figure 32. THDI of SVPWM at 15 kHz Vcarrier.

4. Results

This study aimed to evaluate the THDI of voltage source inverters using different modulation techniques such as SPWM, THPWM and SVPWM. The study varied the frequency of the carrier signal between 5 kHz,10 kHz and 15 kHz and compared the THDI values of SPWM, THPWM and SVPWM. The findings of the study are presented in Table-3.

Table 3. THDI Results

CARRIER FREQUENCY (HZ)	SPWM THDI %	THPWM THDI %	SVPWM THDI %
5000	3.8	2.9	2.7
10000	2.4	2.2	2.1
15000	1.7	1.5	1.2

5. Conclusions

This research has investigated the performance of a three- phase VSI controlled by three different strategies: SPWM, THPWM, and SVPWM. The study examined the current THD at various carrier frequencies ranging from 5kHz, 10kHz and 15kHz and the simulation results were compared. The results, presented in Table 3, indicate that SVPWM produces a higher quality of output current compared to SPWM and THPWM. The study found that the current THD of all three control techniques: SPWM, THPWM and SVPWM inverters remained well below the 5% threshold specified by IEEE standards, despite some variations in THDI with changes in carrier frequency. Overall, the study highlights the superior performance of SVPWM and its potential as an effective control strategy for VSIs.

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