Comparison of three-phase inverter modulation techniques: a comprehensive analysis of SPWM and SVPWM

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Abstract. With the increasing utilization of renewable energy sources like solar and wind, three-phase inverters have become indispensable equipment for grid-connected energy systems, sparking significant research interest in the field of power electronics. This paper presents a comprehensive comparison of two primary modulation techniques employed in three-phase inverters: Sinusoidal Pulse Width Modulation (SPWM) control and Space Vector Pulse Width Modulation (SVPWM) control. The aim is to elucidate their respective advantages and disadvantages, particularly focusing on their performance under various control models. Through a systematic analysis of parameters such as total harmonic distortion under different control schemes including the unity power factor control model, the V/F control model, and the modulation ratio, this paper delves into the operational principles, strengths, and weaknesses of SPWM and SVPWM. Additionally, it elucidates the distinctions between these two modulation techniques and their interconnections. Lastly, the paper provides insights into the future development prospects and identifies potential technical challenges in the realm of pulse width modulation techniques.

Keywords: Sinusoidal pulse width modulation, three-phase inverter, space vector pulse width modulation, total harmonic distortion.

1. Introduction

The development and application of renewable energy sources are receiving increased attention from governments and academic institutions as the world energy crisis deepens and public concern for environmental preservation rises. Among these sources, grid-connected power generation technology using clean energy such as solar and wind energy has emerged as a focal point of current research. Within this context, studying three-phase inverters as core components of grid-connected systems and their modulation systems for suppressing low harmonics holds significant practical significance.

Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Pulse Width Modulation (SVPWM) are the main modulation techniques for inverters and have been widely applied and studied. SPWM modulates the pulse width of the output signal by comparing the reference and carrier signals, while SVPWM modulates the output of a power electronic converter by controlling the magnitude and direction of the voltage space vector. The primary technical differences between SPWM and SVPWM lie in their modulation strategies and voltage utilization. SPWM features a relatively simple modulation strategy but has low voltage utilization, whereas SVPWM, despite its complex modulation strategy, can utilize the DC supply voltage more efficiently, boasting about 15% higher voltage utilization than SPWM. These two techniques play essential roles in the control strategy of power electronic converters, directly impacting converter performance and efficiency. By comparing these two technologies, a better understanding of their advantages and disadvantages can be gained, providing essential references for designing and optimizing power electronic converters to advance grid-connected technology. Consequently, selecting and optimizing the modulation strategy according to specific application requirements remains a crucial topic of ongoing research. Numerous studies have been conducted globally regarding these two modulation techniques. This paper aims to summarize the working principles and characteristics of SPWM and SVPWM control, as well as comparing their total harmonic distortion (THD) under different control models (e.g., unit-factor control, V/F control, and modulation ratio control). Through this comparative analysis, the paper offers a valuable resource for power electronic converter design and optimization. Additionally, it provides insights into the development trends and potential applications of these two technologies.

2. Operating principles and characteristics of SPWM and SVPWM

2.1. Principle and Model of SPWM

Power electronic converters utilize SPWM, a modulation technique that generates a pulse width modulated signal by comparing the carrier signal with the reference signal, as shown in Figure 1. Consequently, SPWM can be viewed as a combination of pulse width modulation (PWM) and sinusoidal signal modulation [1]. In SPWM modulation, the reference signal typically consists of a sine wave with adjustable frequency and amplitude, while the carrier signal is usually a high-frequency triangular or sawtooth wave. The state of the output signal, whether high or low, depends on whether the frequency of the reference signal exceeds that of the carrier signal. Therefore, precise control of the power electronic converter is achieved by modulating the pulse width of the output signal.

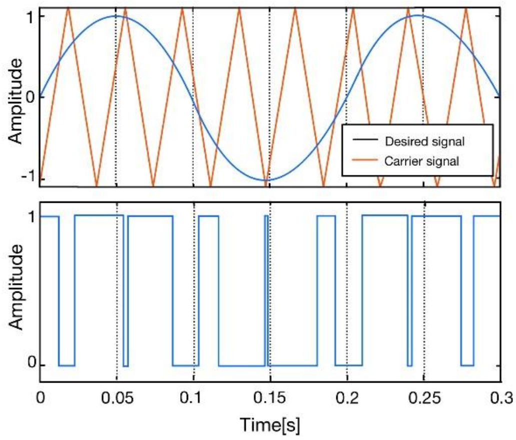


Figure 1. The representative waveform of SPWM.

2.2. Principle and Model of SVPWM

The modulation technique known as SVPWM operates on the fundamental principle of manipulating voltage space vectors. Within the framework of SVPWM, the three-phase voltage is transformed into a two-dimensional space vector at a specific point in time. Subsequently, the desired voltage space vector is achieved by selecting the appropriate switching state and switching time. The distinction lies in the transformation of coordinates, which are then fed into the PWM modulation module, resulting in a PWM wave output for the inverter [2].

The main characteristics of SVPWM include higher utilization of DC supply voltage. Furthermore, SVPWM generates smoother motor current waveforms and reduces the harmonic distortion rate of the motor [3]. Additionally, the switching frequency of SVPWM remains fixed, which is advantageous for the design and control of power electronic devices. However, the algorithmic complexity of SVPWM is high, requiring robust computational abilities. Figure 2 shows the representative waveform of SVPWM.

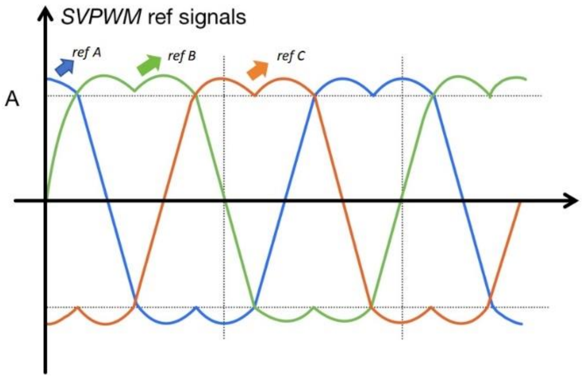


Figure 2. The representative waveform of SVPWM.

3. Comparison of total harmonic distortion (THD) between SPWM

To assess the level of harmonics present in a voltage or current waveform, Total Harmonic Distortion (THD) serves as a crucial performance metric [4]. Each modulation strategy aims to enhance the fundamental component while simultaneously minimizing the presence of harmonic distortions in the output signal. The output voltage of the three-phase inverter is intended to be amplified, and its harmonic content is intended to be reduced through the application of PWM modulation [5]. In this paper, three methods are employed to compare the Total Harmonic Distortion of SVPWM and SPWM.

3.1. Unit-factor control model (UFCM)

To mitigate the current losses introduced into the electrical grid, the term 'unit factor control' in this study is employed to denote the regulation of the power factor during its injection into the grid. A phase-locked loop (PLL) can synchronize the voltage and current connected to the grid.

Figure 3 illustrates the process wherein the instantaneous phase of the output voltage is primarily determined by the phase-locked loop. Subsequently, it is multiplied by sine to obtain a unit sine wave with a value of 1, which is then multiplied by the preset peak value of the grid-connected current to obtain a given current loop signal, I_{ref}. I_{ref} is compared with the grid-side current signal collected by the current transformer to obtain the error value, which is then input into the PI regulator to generate a PWM modulating waveform signal, realizing the conversion of DC to AC [6].

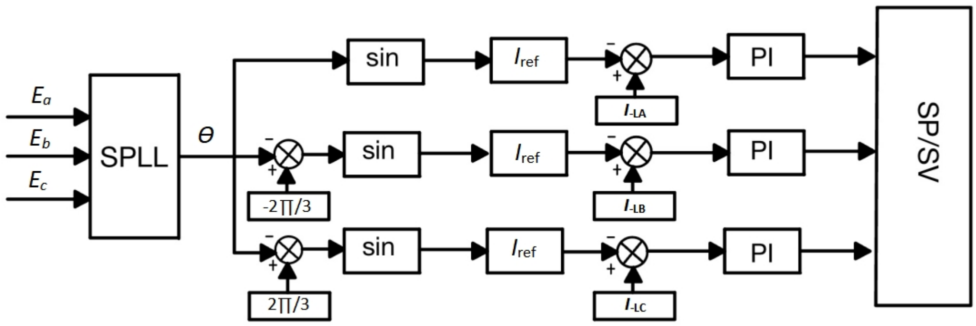


Figure 3. Three-phase grid-connected inverter control block diagram.

The AC-measured three-phase current and voltage waveforms are depicted in Figure 4. It is evident from Figure 4 that, due to the implementation of phase-locked loops, the current and voltage remain in phase, resulting in a power factor of 1 at the grid side. Next, the grid-connected current cycle modulated by SPWM and SVPWM algorithms is analyzed by performing a Fourier analysis of the current cycle modulated by SPWM and SVPWM algorithms.

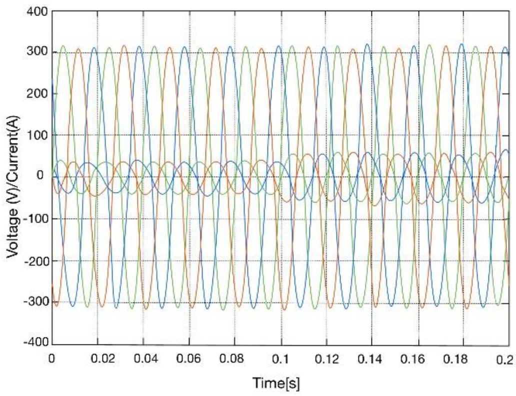


Figure 4. Waveforms of three-phase voltage and current on the AC side.

The FFT plots of SPWM for the alternating current segment with a three-phase current of 40A and the FFT plots of the alternating current segment with a three-phase current of 60A are displayed in Figures 5 and 6, respectively. This yields a distortion rate of 4.30% at a current of 40A and 0.65% at a current of 60A.

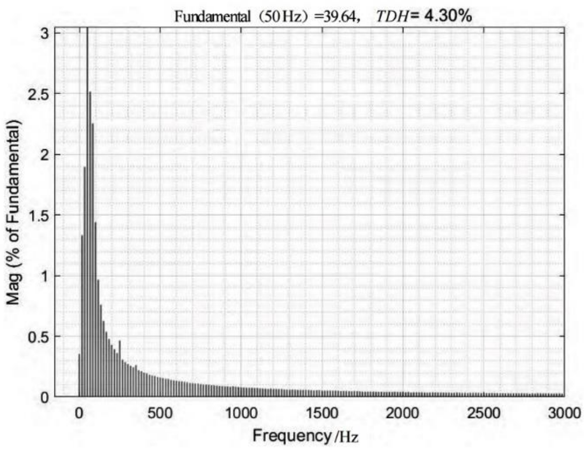


Figure 5. The SPWM FFT analysis of on AC side at 40A[6].

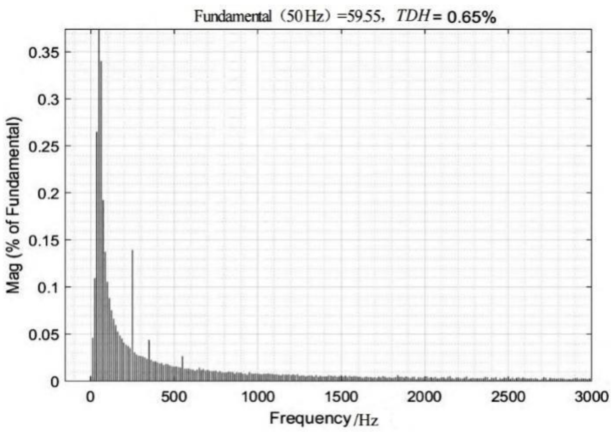


Figure 6. The SPWM FFT analysis at 60A on AC side [6].

The FFT plots of the SVPWM at 40A for the alternating current side and the FFT plots of the SVPWM at 60A for the alternating current side are displayed in Figures 7 and 8, respectively. This yields a distortion rate of 0.48% at a current of 40A and 0.32% at a current of 60A.

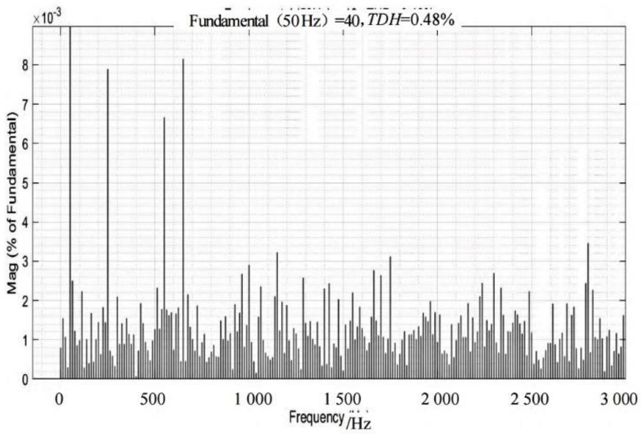


Figure 7. FFT analysis of SVPWM on AC side with three phase currents of 40A [6].

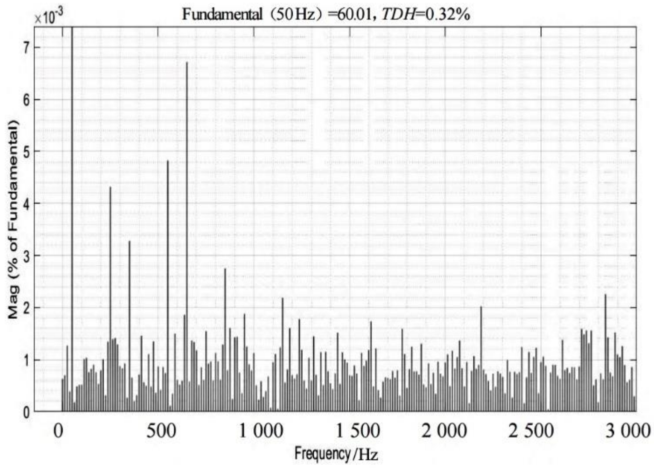


Figure 8. FFT analysis of SVPWM on AC side with three phase currents of 60A [6].

Ref. [6] sets the power factor to 1. This demonstrates that the harmonic composition associated with SPWM modulation in the network current exceeds that of SVPWM modulation, further indicating the superiority of SVPWM modulation over SPWM modulation. It regulates the amount of power added to the grid, correcting system imbalances and supplying harmonic current compensation. A novel Grid-Connected Inverter Current Control (GCI) technique for enhancing the PV system's current and grid quality is presented in [7]. The methodology comprises a power regulation unit and a harmonic rectification unit. The schematic representation for the GCI management approach is depicted in Figure 9. This schematic allows for the rectification of reactive power and the conveyance of all power harnessed by the photovoltaic system to the network when it operates in the grid-connected power regulation mode.

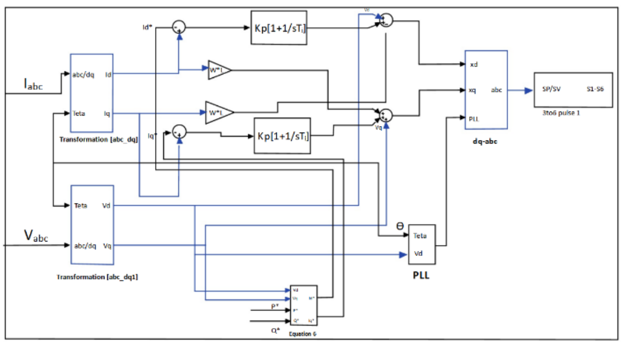


Figure 9. Block schematic of the suggested GCI control approach.

Figures 10(a) and 10(b) display the SPWM pass current-voltage spectrum before compensation and the SPWM current-voltage spectrum after compensation, respectively. As observed, SPWM's

THDi is 4.40% and THDv is 4.47% before compensation. After compensation, THDv is 0.05% and THDi is 0.68%.

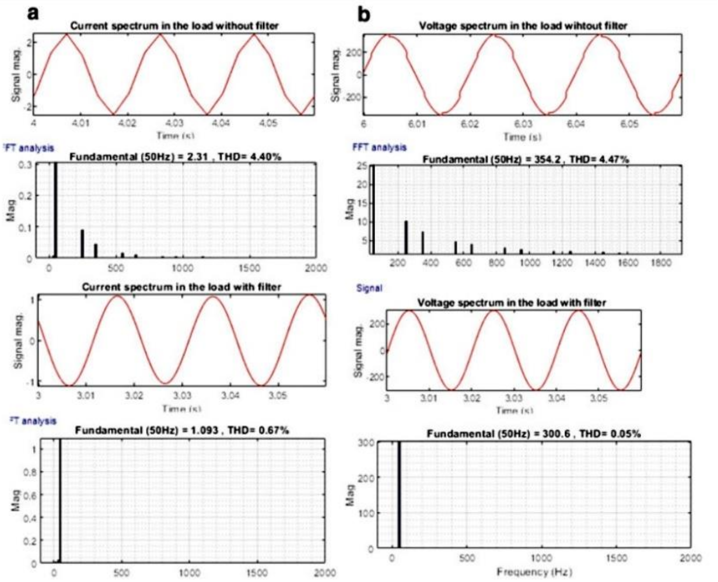


Figure 10. Emission voltage and current spectrums of SPWM (a) devoid of harmonic filtration (b) inclusive of harmonic filtration [7].

Figures 11(a) and 11(b) depict the SVPWM passing the current-voltage spectrum before compensation and after compensation, respectively. As observed, SVPWM's THDi is 4.39% and THDv is 4.47% prior to compensation. After compensation, THDv is 0.04% and THDi is 0.22%.

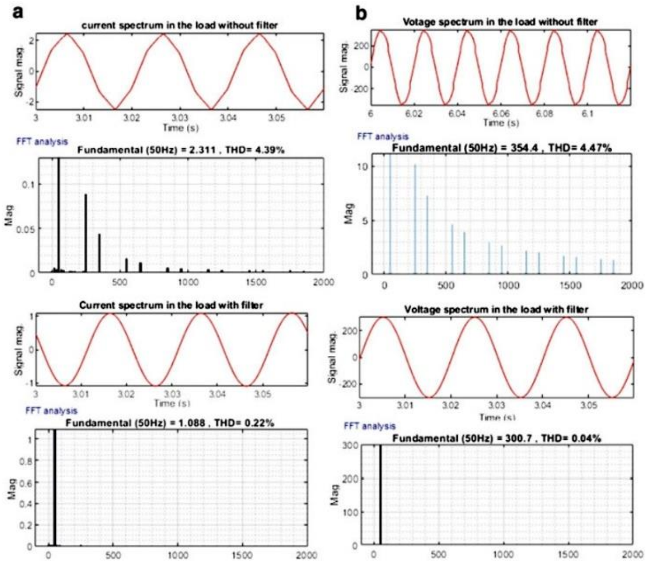


Figure 11. Emission voltage and current spectrums of SVPWM (a) devoid of harmonic filtration (b) inclusive of harmonic filtration [7].

Through the management of the quantity of real and reactive power conveyed via the power network, literature [7] demonstrates that SVPWM modulation generates an output voltage superior to SPWM modulation with minimal THD and switching losses. Through the management of the quantity of real and reactive power conveyed via the power network, it is demonstrated that SVPWM modulation generates an output voltage superior to SPWM modulation with minimal THD and switching losses [7].

3.2. V/F control model

V/F control is a variable speed control method for induction motors. It maintains the motor's flux constant by adjusting the output voltage proportionally to the frequency. To implement V/F control, the ratio of voltage (V) to frequency (F) can be kept constant by adjusting the frequency and amplitude of the three-phase induction motor [8].

Building upon V/F control, we have developed a model of a three-phase PWM inverter. Figures 12 and 13 depict the block diagrams for the SVPWM modulation model using V/F control and the SPWM modulation model, respectively.

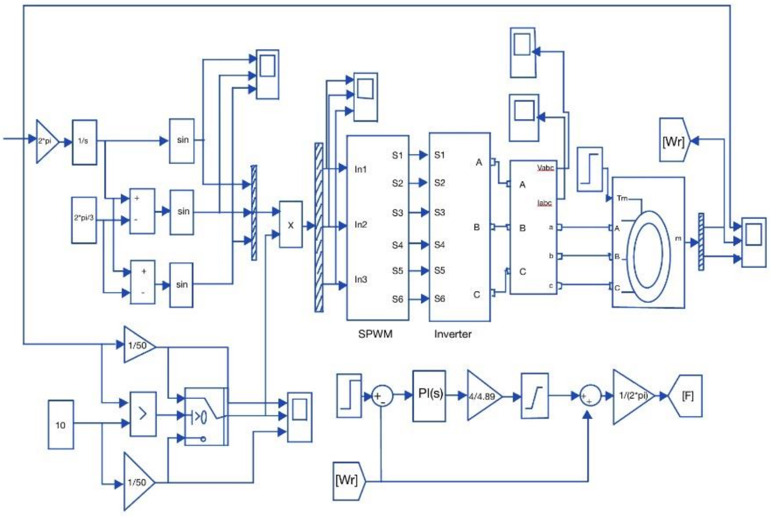


Figure 12. SPWM modeling with V/F.

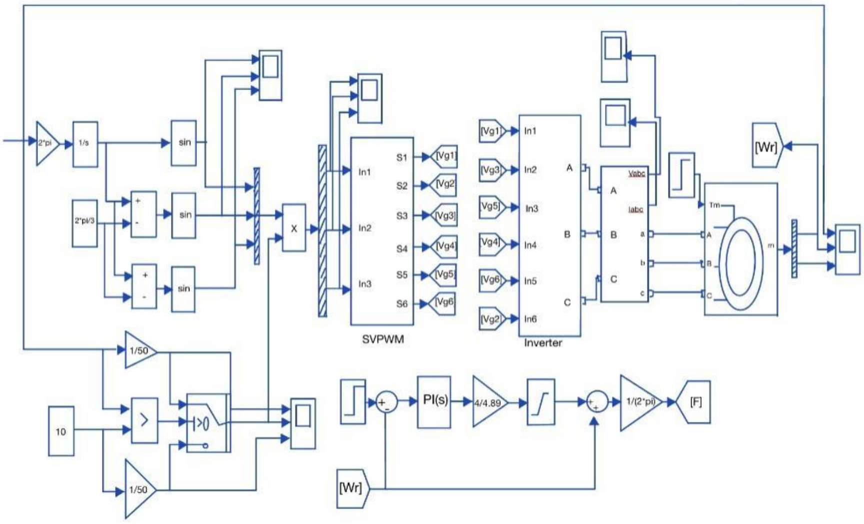


Figure 13. SVPWM modeling with V/F.

As shown in Figure 14, by comparing the speeds of SPWM and SVPWM under closed-loop control, it can be observed that the speed of SVPWM is more stable and takes less time to reach the desired magnitude than SPWM [9].

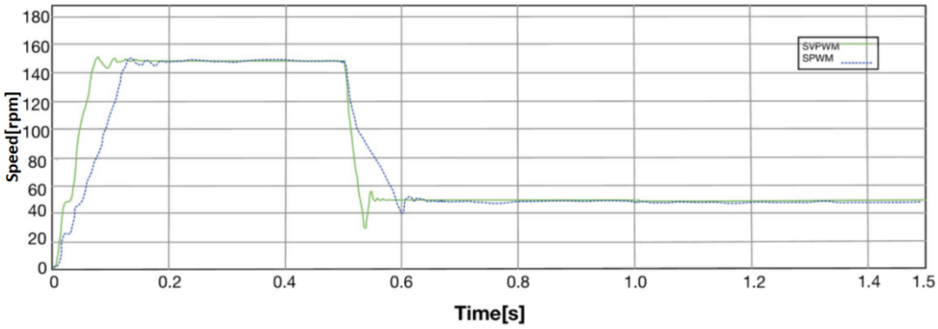


Figure 14. Speed Comparison of SPWM & SVPWM.

When the input voltage/frequency is set to an input speed of 1500 rpm, the FFT analyses of SPWM and SVPWM are shown in Figures 15 and 16, respectively. The THD of SPWM is 32.6%, and the THD of SVPWM is 25.39%.

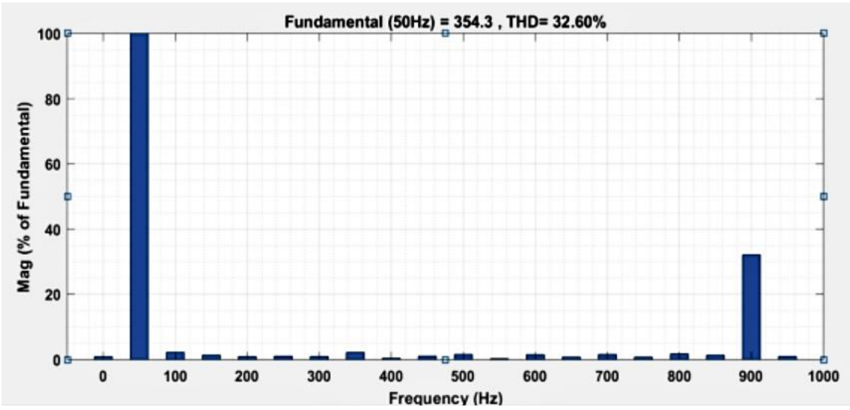


Figure 15. SPWM frequency spectrum at a speed of 1500 rpm [10].

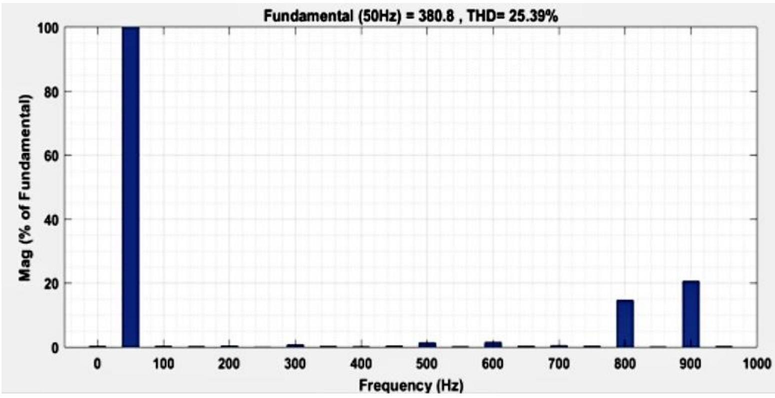


Figure 16. SVPWM frequency spectrum at a speed of 1500 rpm [10].

When the rotational speed is 750 rpm, the FFTs of SPWM and SVPWM are shown in Figures 17 and 18, respectively. The total harmonic distortion value is lower than that at a speed of 1500 rpm. The THD of SPWM is 21.06%, and that of SVPWM is 14.91%.

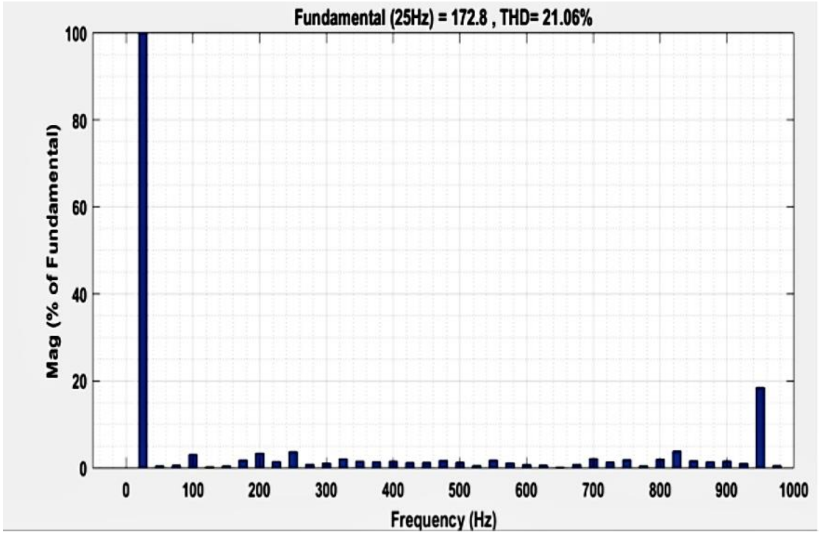


Figure 17. SPWM frequency spectrum at a speed of 750 rpm [10].

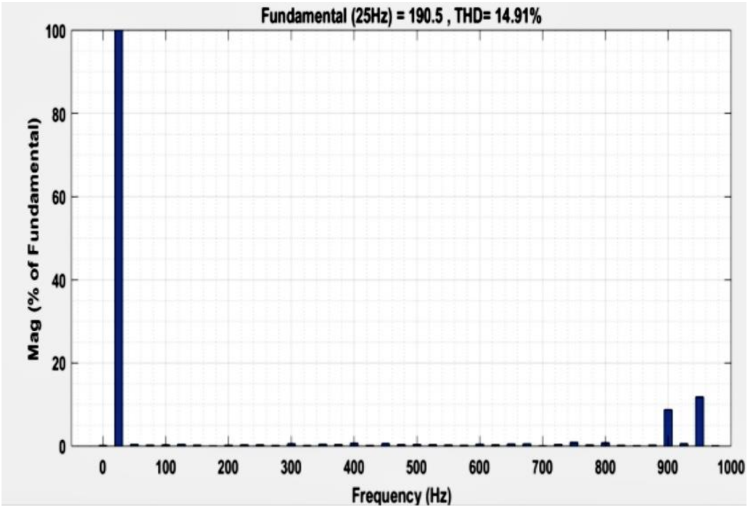


Figure 18. SVPWM frequency spectrum at a speed of 750 rpm [10].

V/F control regulates the three-phase inverter to maintain constant motor torque while adjusting the speed. The results indicate that the SVPWM modulation technique utilizes the DC supply more efficiently than SPWM and exhibits minor total harmonic distortion [10].

3.3. Modulation index

The modulation index (MI), also known as the amplitude ratio, is defined as the ratio between the magnitudes of the reference signal and the carrier signal. The THD value may fluctuate depending on changes in the modulation index [11].

Figures 19 and 20 depict the voltage and current THD of SVPWM and SPWM. The illustration clarifies that an increase in the modulation index leads to a reduction in the THD of both voltage and current. Optimal results are attained for both modulation strategies, SPWM and SVPWM, when the modulation index is 1. With the same modulation index, the fundamental wave value of SVPWM exceeds that of SPWM.

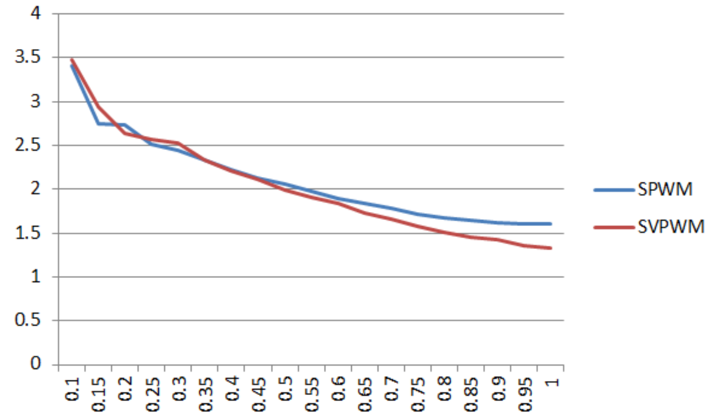


Figure 19. The THD of current MI.

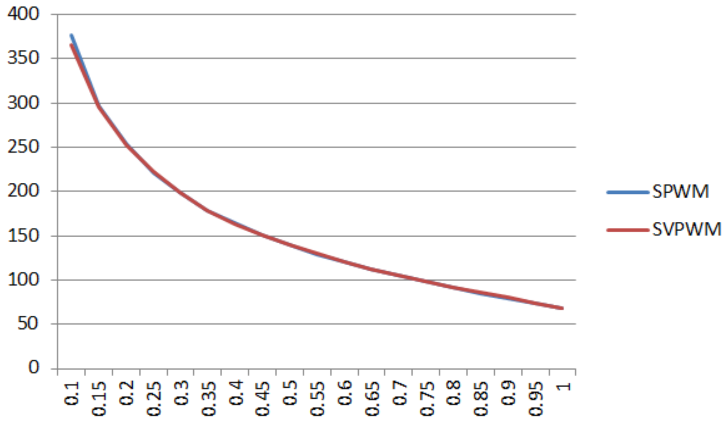
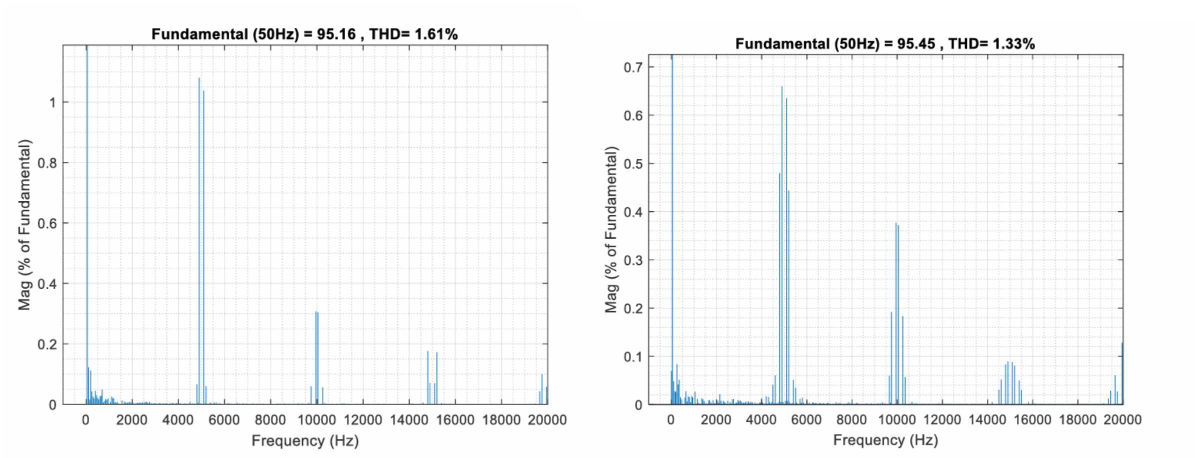


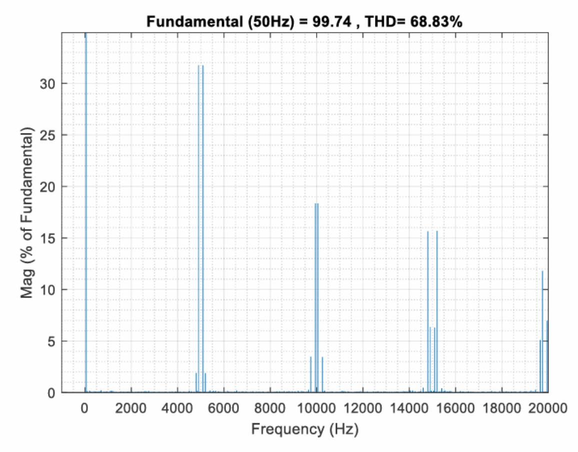
Figure 20. The THD of input voltage MI.

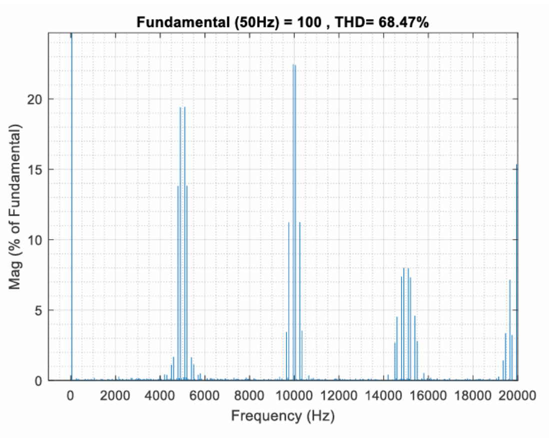
From the FFT analysis of SPWM and SVPWM in Figure 21 and Figure 22, it can be concluded that the THD of current for SPWM and SVPWM is 1.61% and 1.33%, respectively, while the THD of voltage for SPWM and SVPWM is 68.83% and 68.47%, respectively. By calculating the Vmax values of SPWM and SVPWM, it is evident that the output voltage utilization of SVPWM is about 15% higher than that of SPWM [12].



(a) (b)

Figure 21. FFT analysis plot for current (a) SPWM (b) SVPWM [12].





(a) (b)

Figure 22. FFT analysis plot for Voltage (a) SPWM (b) SVPWM [12].

4. Conclusion

In this thesis, a comprehensive comparative analysis of SPWM and SVPWM modulation techniques in three-phase grid-connected inverters is conducted. The performance differences between the two techniques in various application scenarios, such as the unit-factor control model, V/F control model, and modulation ratios, are explored. The findings demonstrate that, in certain situations, the SVPWM modulation technique can more effectively reduce THD and produce higher-quality output waveforms compared to the SPWM modulation technique. This discovery provides essential insights for selecting a more suitable modulation strategy when designing and optimizing three-phase grid-connected inverters. Furthermore, experimental setups of pulse width modulation systems are necessary for future applications to achieve enhanced stability, efficiency, and reduced THD.

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