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Space vector pulse width modulation realization for three-phase voltage source inverter

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ABSTRACT

This paper presents the implementation of space vector pulse width modulation (SVPWM) for a three-phase voltage source inverter (VSI). SVPWM is a technique used to control the output voltage of VSIs with improved efficiency and precision. The abstract outlines the key steps involved in implementing SVPWM, including reference signal clarification, sector identification, determination of voltage vectors, and switching state calculation. This proposed system provides improved output voltage of the inverter, minimized voltage stress across the switches and reduced total harmonic distortion and electromagnetic interference. The proposed implementation aims to enhance the performance of three-phase VSIs in various applications, such as motor drives, renewable energy systems, and power converters. The simulation results of proposed system are verified using MATLAB Simulink.

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1. INTRODUCTION

Power electronic converters play a pivotal role in modern electrical systems by facilitating the efficient conversion and control of electrical power across various applications [1]–[3]. These converters are essential components in renewable energy systems, industrial motor drives, power supplies, electric vehicles, and more. At the heart of power electronic converters are semiconductor devices known as switches, which enable the manipulation of electrical signals with high efficiency and precision [4].

Switches in power electronic converters serve the crucial function of controlling the flow of electrical energy by either allowing or blocking current flow through the circuit. These switches operate in different modes, such as on/off or pulse-width modulation (PWM), to achieve the desired output voltage and current waveforms [5]. The choice of switch type and control strategy depends on factors such as application requirements, voltage, and current ratings, switching frequency, and efficiency considerations [6]. The most used semiconductor switches in power electronic converters includes metal-oxide-semiconductor field-effect transistors, insulated gate bipolar transistors, silicon-controlled rectifiers and gate turn-off thyristors. These switches are suited for high-power and high-voltage applications but have slower switching speeds compared to metal-oxide-semiconductor field-effect transistor (MOSFETs) and insulated-gate bipolar transistor (IGBTs) [7], [8]. They are commonly used in applications like motor drives, high-voltage direct current (HVDC) systems, and power transmission. The control of switches in power electronic converters is typically achieved through various modulation techniques, such as PWM, space vector pulse width modulation (SVPWM), and hysteresis control, among others. These techniques ensure precise regulation of output voltage and current, while also minimizing switching losses and harmonics [9]–[11].

Voltage source inverters (VSIs) are essential components in numerous power electronic applications, providing a means to convert direct current (DC) into alternating current (AC) voltage with controlled magnitude, frequency, and waveform. VSIs play a crucial role in various domains, including renewable energy systems, industrial motor drives, uninterruptible power supplies (UPS), electric vehicle propulsion systems, and grid-tied inverters for distributed generation [12]–[14]. The fundamental principle behind a VSI involves generating an AC output voltage from a DC input voltage source, typically achieved through semiconductor switches such as MOSFETs or IGBTs [15]. These switches are arranged in a specific configuration to control the flow of current through load in an alternating manner, thereby producing desired AC waveform [16]–[18].

The operation of a VSI involves modulating the switching states of the semiconductor switches to generate the desired AC output voltage waveform [19]. This modulation can be achieved using various techniques, such as PWM, sinusoidal PWM (SPWM), SVPWM, and selective harmonic elimination (SHE), among others. These modulation techniques enable precise control of output voltage characteristics while minimizing harmonic content and switching losses [20], [21].

In this paper, SVPWM is implemented for a three-phase VSI. SVPWM is a technique used to control the output voltage of VSIs with improved efficiency and precision. The abstract outlines the key steps involved in implementing SVPWM, including reference signal clarification, sector identification, determination of voltage vectors, and switching state calculation. This proposed system provides improved output voltage of the inverter, minimized voltage stress across the switches and reduced total harmonic distortion and electromagnetic interference.

2. 3-PHASE VOLTAGE SOURCE INVERTER

A three-phase VSI is a type of power electronic converter used to convert DC power into three-phase AC power [22], [23]. It is widely employed in various applications such as motor drives, renewable energy systems, grid-connected inverters, and industrial power supplies [24]. The operation of a three-phase VSI involves the controlled switching of semiconductor devices to produce a three-phase output voltage waveform, the circuit of three phase VSI is shown in Figure 1.

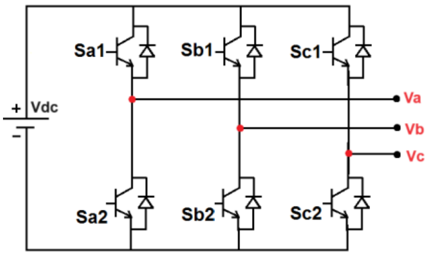


Figure 1. Circuit of three phase VSI

In a three-phase inverter system, maintaining balanced AC output with efficient control and protection mechanisms is crucial. This is accomplished by synchronizing the switching of each arm of the inverter with a 120-degree phase shift between them. As a result, the switches are turned on and off in a coordinated manner to ensure smooth operation and optimal performance. This synchronized switching allows the three-phase inverter to share a single fuse and utilize a common DC power source, simplifying the circuit's control and protection mechanisms. Furthermore, the voltage applied to the load, known as the pole voltage, in a three-phase inverter is akin to that in a half-phase inverter used in single-phase applications. However, in the case of three-phase inverters, this voltage is evenly distributed across three phases to generate a balanced three-phase AC output [25], [26].

In both single-phase and three-phase inverters, two primary conduction modes are utilized: the 120-degree and 180-degree conduction modes. These modes govern the timing and duration of switch conduction. In the 120-degree mode, each switch conducts for 120 degrees of the electrical cycle, whereas in the 180-degree mode, conduction persists for 180 degrees. These modes offer varying degrees of control and impact the quality of the output waveform, allowing for tailored operation to suit specific application requirements.

180° conduction mode: In this operational mode, each device conducts for 180°, activated at intervals of 60°. Output terminals A, B, and C are connected either in a star or 3-phase delta configuration to the load. The diagram below illustrates a balanced load for three phases. During the 0 to 60-degree interval, switches such as S1, S5, and S6 are conducting. Terminals A and C of the load are connected to the positive point of the source, while terminal B is connected to the negative point. Additionally, there is an R/2 resistance between the neutral and positive terminals, and an R resistance between the neutral and negative terminals.

120° conduction mode: In this conduction mode, each electronic device operates for 120°, making it suitable for a delta connection within a load, generating a six-step waveform across one phase. At any given moment, only devices conducting at 120° are active. The ‘A’ terminal of the load can connect to the positive end, while the ‘B’ terminal can connect to the negative end of the source. The ‘C’ terminal of the load operates in a floating state.

3. SVPWM

SVPWM is a sophisticated modulation technique widely used in power electronic converters, particularly in VSIs, to achieve precise control of the output voltage waveform. Unlike traditional modulation techniques such as sinusoidal pulse width modulation (SPWM), SVPWM offers superior performance in terms of output voltage quality, harmonic content reduction, and efficiency optimization. At it is core, SVPWM operates by representing the three-phase output voltage of the inverter in a two-dimensional space vector plane. This plane consists of two axes: the α-axis and the β-axis. The α-axis represents the instantaneous amplitude of the balanced AC voltage, while the β-axis represents the zero-sequence voltage. By manipulating the magnitudes and orientations of the space vectors within this plane, SVPWM determines the switching states of the VSI to generate the desired output voltage waveform. This is achieved by dynamically adjusting the duty cycles of the voltage vectors to approximate the reference voltage vector within the space vector plane, the representation of SVPWM is shown in Figure 2.

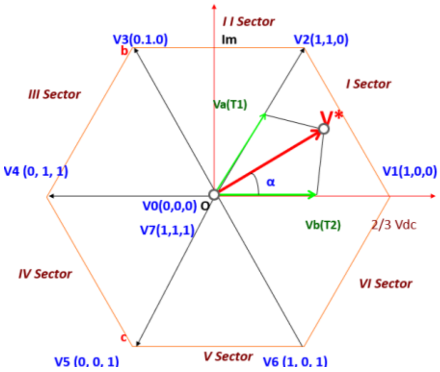


Figure 2. Representation of SVPWM

The key advantages of SVPWM includes improved output voltage quality: SVPWM enables the synthesis of output voltage waveforms that closely resemble pure sinusoidal waveforms, resulting in reduced harmonic distortion and improved power quality. Optimal utilization of DC link voltage: SVPWM maximizes the utilization of the DC link voltage, leading to increased efficiency and reduced switching losses. Flexibility and Precision: SVPWM provides greater flexibility and precision in controlling the output voltage amplitude, frequency, and phase angle, making it suitable for a wide range of applications. Reduced EMI and acoustic noise: by minimizing harmonic distortion, SVPWM helps reduce electromagnetic interference (EMI) and acoustic noise, enhancing the overall performance and reliability of the power electronic system.

The key steps involved in implementing SVPWM for a VSI include:

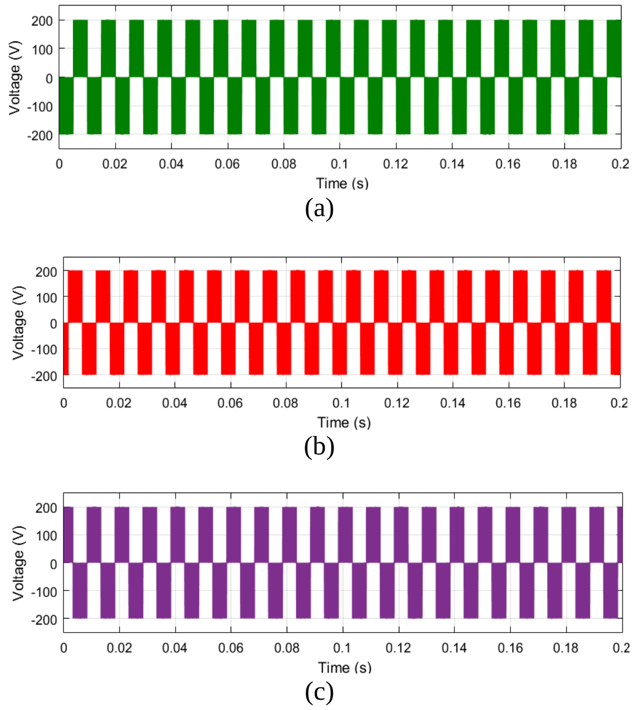
- Reference voltage generation: the desired output voltage is first converted into α-β reference signals, typically derived from a control algorithm or external command.

- Space vector generation: the reference voltage vectors are then mapped onto the space vector plane, where their magnitudes and orientations are determined.
- Sector identification: the space vector plane is divided into six sectors based on the position of the reference voltage vector. This helps determine the appropriate active voltage vectors for each sector.
- Voltage vector selection: the active voltage vectors are selected based on their proximity to the reference voltage vector within the space vector plane.
- Switching state determination: the switching states of the inverter switches are then determined to approximate the selected voltage vectors and generate the desired output voltage waveform.

By dynamically adjusting the duty cycles of the selected voltage vectors, SVPWM achieves precise control of the output voltage waveform while minimizing harmonic distortion and switching losses. This results in improved power quality, increased efficiency, and reduced EMI compared to traditional modulation techniques. The switching times calculation typically involves determining the on-time and off-time of each switch during each modulation period. This calculation is crucial for achieving precise control of the output voltage waveform and minimizing harmonic distortion in SVM-based VSI operation. It is important to note that the specific methodology for calculating switching times may vary depending on the modulation technique used and the control strategy employed in the VSI system. Advanced techniques such as SVPWM may involve additional considerations for optimizing switching times and achieving higher performance.

4. SIMULATION RESULTS AND DISCUSSIONS

In a simulation study of SVPWM implementation for a three-phase VSI, several key aspects are typically analyzed and discussed. Simulation results and discussions for SVPWM implementation in a three-phase VSI should provide valuable insights into the performance, efficiency, and effectiveness of the modulation technique in achieving high-quality output voltage and optimal system operation. The simulation results of proposed system are verified using MATLAB Simulink. The Figure 3 shows the stepped output voltage of VSI system for Figure 3(a) Phase-A, Figure 3(b) Phase-B and Figure 3(c) Phase-C with voltage of 200 V. Space vector signal generation of proposed VSI system shown in Figure 4, in that Figure 4(a) shows reference vector signal and Figure 4(b) shows the comparison with carrier signal.

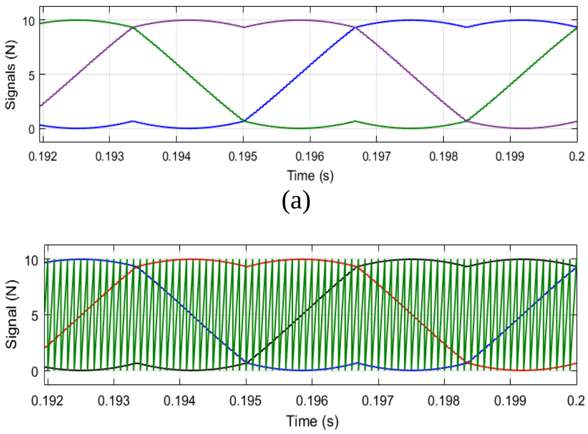

(a)

(b)

(c)

Figure 3. VSI stepped output voltage (a) phase A, (b) phase B, and (c) phase C

The Figure 5 shows the switching pulses generation using SVPWM for the switches S_{A1}-S_{C3}. Signal comparison for reference vector generation is shown in Figure 6, by calculating dq voltages from abc conversion; by calculating real and imaginary part of the system with determination of angle and magnitude. By determining the angle and magnitude of reference vector location, the sector of 2-level SVPWM can be tracked, which is shown in Figure 7. The Figure 8 shows the THD analysis for VSI-output voltage with 2.41% with voltage value of 200 V. Switching pulse generation-comparison of space vector signal with carrier signal is shown Figure 9.



(a)

(b)

Figure 4. Space vector signal generation (a) reference signal and (b) comparison with carrier signal

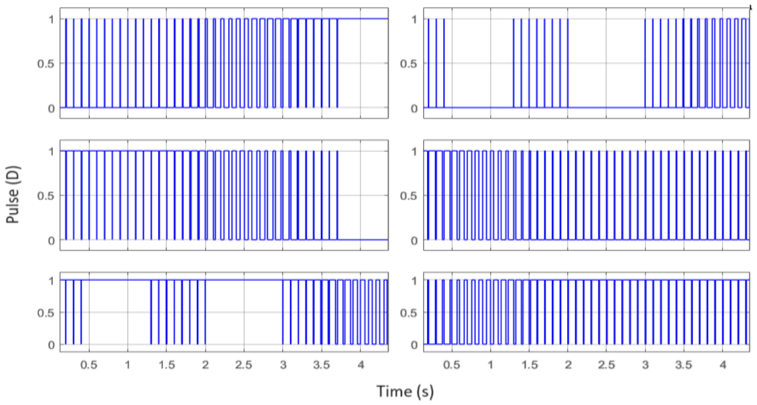


Figure 5. Switching pulses generation using SVPWM

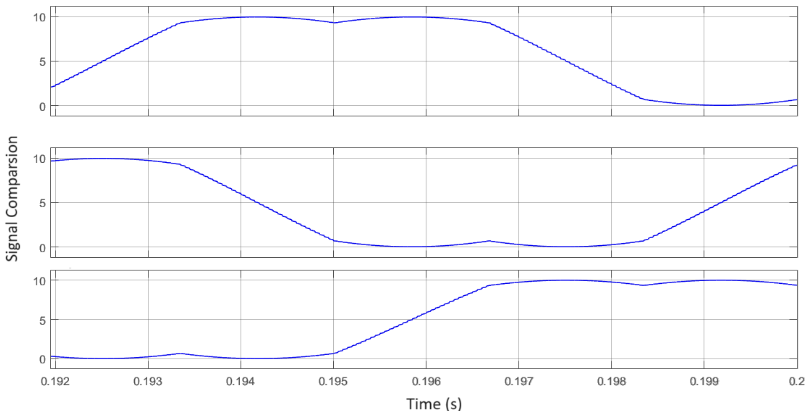


Figure 6. Signal comparison for reference vector generation

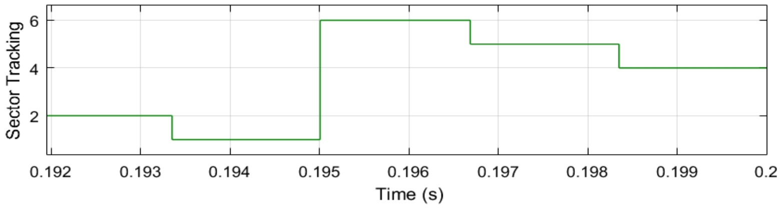


Figure 7. Sector tracking for reference vector generation

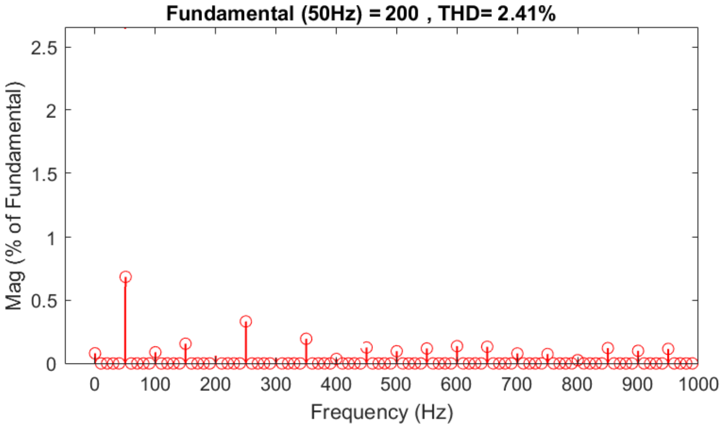


Figure 8. THD analysis for VSI-output voltage

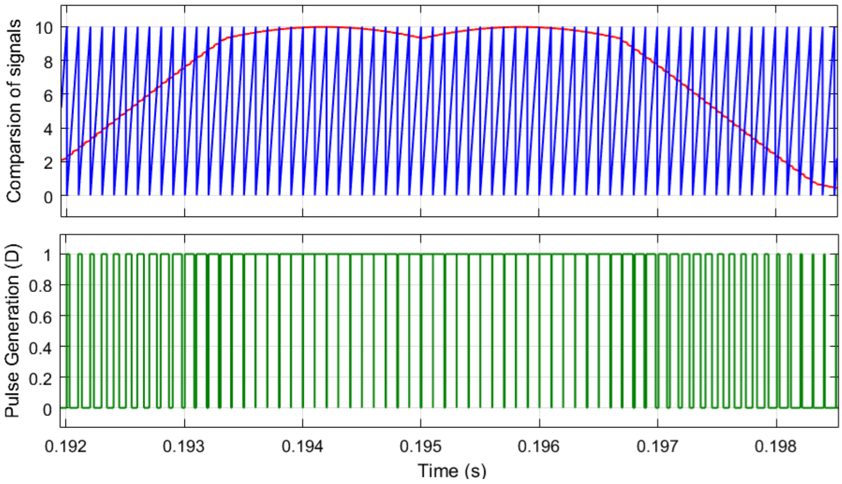


Figure 9. Switching pulse generation-comparison of space vector signal with carrier signal

5. CONCLUSION

The implementation of SVPWM for a three-phase VSI offers several significant advantages in terms of output voltage quality, efficiency, and control precision. Through simulation studies and analysis, the following key points are achieved like improved output voltage, minimized common mode voltage, reduced total harmonic distortion and less voltage stress across the switching devices. The THD for output voltage of VSI is reduced to 2.41% with improved voltage level of 200 V stepped output voltage. The simulation results and analysis validate the advantages of SVPWM and underscore its significance in advancing the field of power electronics and VSI technology.

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