International Journal of Engineering, Management, Humanities and Social Sciences Paradigms (IJEMHS)
Volume 31, Issue 03, Quarter 03 (2019)
Publishing Month and Date: July 29, 2019
An Indexed and Referred Journal with Impact Factor: 2.75
ISSN (Online): 2347-601X
www.ijemhs.com

Harmonic Analysis of Various SPWM Techniques for Three Phase Diode Clamped Multi-level Inverter in MATLAB/Simulink Environment

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Abstract

With advances in solid-state power electronic devices and microprocessors, various pulse-width-modulation (PWM) techniques have been developed for industrial applications. For example, PWM-based three-phase voltage source inverters (VSI) convert DC power to AC power with variable voltage magnitude and variable frequency. This thesis discusses the advantages and drawbacks of three different PWM techniques: the sinusoidal PWM (SPWM) technique, the third-harmonic-injection PWM (THIPWM) technique, and the bus-clamped PWM (BCPWM) technique. These three methods are compared by discussing their ease of implementation and by analyzing the output harmonic spectra of various output voltages (poles voltages, line-to-neutral voltages, and line-to-line voltages) and their total harmonic distortion (THD). The simulation results show that both the THIPWM and BCPWM techniques have lower total harmonic distortion than the SPWM technique. The THIPWM and SVPWM techniques in the under-modulation region can both increase the fundamental output voltage by 15.5% over the SPWM technique. Moreover, the SVPWM technique can increase the fundamental output by about 5% in each of the over modulation regions 1 and 2, respectively.

Keywords: *PWM, THD, VSI, SVPWM.*

Introduction

Pulse-width modulation (PWM) is a technique where the duty ratio of a pulsating waveform is controlled by another input waveform. The intersections between the reference voltage waveform and the carrier waveform give the opening and closing times of the switches.

PWM is commonly used in applications like motor speed control, converters, audio amplifiers, etc. For example, it is used to reduce the total power delivered to a load without losses, which normally occurs when a power source is limited by a resistive element.

PWM is used to adjust the voltage applied to the motor. Changing the duty ratio of the switches changes the speed of the motor. The longer the pulse is closed compared to the opened periods, the higher the power supplied to the load is. The change of state between closing (ON) and opening (OFF) is rapid, so that the average power dissipation is very low compared to the power being delivered. PWM amplifiers are more efficient and less bulky than linear power amplifiers. In addition, linear amplifiers that deliver energy continuously rather than through pulses have lower maximum power ratings than PWM amplifiers.

There is no single PWM method that is the best suited for all applications and with advances in solid-state power electronic devices and microprocessors, various pulse-width modulation (PWM) techniques have been developed for industrial applications. For these reasons, the PWM techniques have been the subject of intensive research since 1970s.

Results and Discussion

We describe Simulink models built on the corresponding discussion based on previous chapters. In addition to the simulation results, this chapter includes detailed subsystems of the Simulink models as well as an explanation of the role of every subsystem. Low-pass filters are required at the outputs to filter out the PWM waveforms and visualize the fundamental results. Our simulation analysis does not include the programming of dead time for the switching of complementary switches in an inverter leg.

Simulation results are presented in three groups based on three simulation models. The first group Figures shows simulation results for SPWM and THIPWM. The second group (Figures 4.7- 4.18) presents the under-modulation results for BCPWM. The third group shows the simulation results of region 1 in the over-modulation BCPWM Figures.

THIPWM:

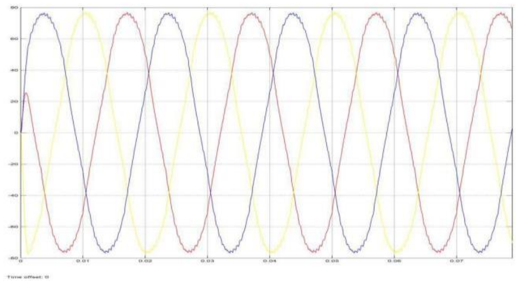

Figure 1: Output Line to Line Voltage for THIPWM

$$V_a = \frac{2}{\sqrt{3}}\left(\sin(\omega t) + \frac{1}{6}\sin(3\omega t)\right)$$

$$V_b = \frac{2}{\sqrt{3}}\left(\sin(\omega t - 2\pi/3) + \frac{1}{6}\sin(3\omega t)\right)$$

$$V_c = \frac{2}{\sqrt{3}}\left(\sin(\omega t + 2\pi/3) + \frac{1}{6}\sin(3\omega t)\right).$$

To visualize the actual results, filtering of the PWM waveforms is required. The line to-neutral voltages Van, Vbn, and Vcn are shown after they have been passed through a second order low-pass filter. Figure shows the line to line voltage of THIPWM. As expected, the magnitude of the phase voltage is about $100/(3^{1/2})$ Volts and 100 Volts for line-to-line voltage, and the results show that THIPWM improves the fundamental voltages compared to SPWM.

SPWM:

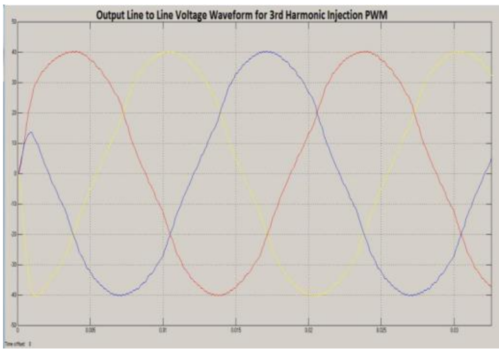

Figure 2: Voltage Waveform for Sin-Triangle Comparison PWM for 3-Phase Neutral point clamped Inverter

To visualize the actual results, filtering of the PWM waveforms is required. The line to-neutral voltages Van, Vbn, and Vcn are shown after they have been passed through a second order low-pass filter. As expected, magnitudes of the phase voltages (Van, Vbn, and Vcn) are about 0.5Vdc. The output voltage waveforms show that the higher the switching frequencies, the smoother the output voltage waveforms, as expected.

BCPWM:

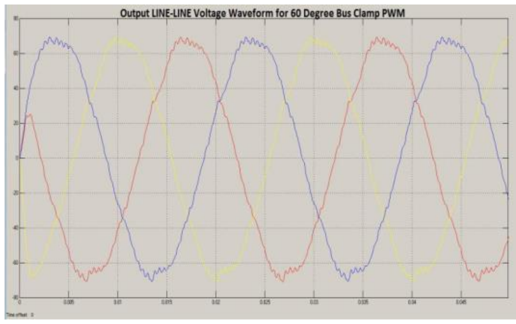

Figure 3: Line to line output voltages for BCPWM with modulation index 1.0

To visualize the actual results, filtering of the PWM waveforms is required. The line to-neutral voltages Van, Vbn, and Vcn are shown after they have been passed through a second order low-pass filter. Figure 4.10 and 4.11 shows the line to line voltage of THIPWM. As expected, the magnitude of the line-to-line voltages is higher for same modulation index in comparison to the other PWM techniques, and the results show that BCPWM improves the fundamental voltages compared to SPWM & THIPWM.

Results Comparison between SPWM, THIPWM and BCPWM with Harmonic Distortion

The harmonic results for the pole voltage Vro in the SPWM technique. As expected, we do not see a third harmonic in SPWM. Comparing the data of in Table 6.1, we conclude that the harmonics has shifted to higher frequency side bands. There magnitude is significant as the frequency approaches the carrier signal frequency.
The harmonic results ofVao in the over-modulation region of BCPWM. Overall, the spectrum of this technique is similar to the THIPWM. However, it has a higher fundamental voltage and a lower value of the 3rd harmonic. We also see additional harmonic values around the carrier frequency (30th harmonic) and a lower THD (%) with a higher modulation index.
The line-to-line voltages are undistorted since the third harmonic components in the phase waveforms cancel out. The line-to-neutral voltages do not contain the third harmonic because this is a three-phase three-wire system. This means that there is no neutral connection to the wye-connected balanced load, and the triple harmonic of the load currents must be zero.

Conclusion

This thesis has evaluated three different PWM techniques, namely SPWM, THIPWM, and BCPWM (in the linear modulation region and over-modulation mode 1). The contributions of the thesis are as follows:

The thesis has provided a thorough review of three techniques with a special focus on the operation of BCPWM in the over-modulation modes.

In this thesis, Simulink models for all three techniques have been developed and tested in the MATLAB/Simulink environment. The BCPWM model can generate both the operation of the under-modulation region of BCPWM as well as the over-modulation region.
The thesis discusses the advantages and drawbacks of each technique. Their simulation results are compared and analyzed by plotting the output harmonic spectra of various output voltages, and computing their total harmonic distortion (THD).
As seen from the simulation results, BCPWM and THIPWM have a superior performance compared to SPWM, especially in the over-modulation region of BCPWM. The SPWM technique is very popular for industrial converters. It is the easiest modulation scheme to understand and implement. This technique can be used in single-phase and three-phase inverters.
The THIPWM technique operates by adding a third harmonic component to the sinusoidal modulating wave. It is possible to increase the fundamental by about 15:5% and, hence, allow a better utilization of the DC power supply. From the shape of the line-to-line voltages, the resulting flat-topped waveforms allow over-modulation with respect to the original SPWM technique.

Future Scope

There is couple of interesting topics suggested for future research:

Further simulation studies should be performed in over-modulation region of BCPWM as a special case of SVPWM with neural networks and The Neural Network toolbox of MATLAB. Neural network implementation is very fast and can increase the switching frequency of power switches in the inverter.

Many papers in the literature have reported that the dead time of Bus Clamped PWM has an influence on drive systems. To circumvent this problem, it is important to research how to compensate for the dead time effect to increase the performance of drive systems.

Compare switching losses of Space Vector and BCPWM.

Further studies of the values of the modulation methods in the laboratory.

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