Harmonic analysis of various SPWM techniques for three phase diode clamped multi-level inverter in MATLAB/Simulink environment

Vivek Saini[1,*], Nikhil Kumar Nigam[2], Joginder Singh[1]

[1]Department of Electriacal Engineering, Ganga Institute of Technology and Management, Jhajjar, Haryana. India
[21]Department of Electriacal Engineering, Delhi Technical Campus, Greater Noida, UP. India

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 paper 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).

1. 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.

2. Diode Clamped Multi Level Inverter

The main concept of this inverter is to use diodes and provides the multiple voltage levels through the different phases to the capacitor banks which are in series. A diode transfers a limited amount of voltage, thereby reducing the stress on other electrical devices. The maximum output voltage is half of the input DC voltage. It is the main drawback of the diode clamped multilevel inverter. This problem can be solved by increasing the switches, diodes, capacitors. Due to the capacitor balancing issues, these are limited to the three levels. This type of inverters provides the high efficiency because the fundamental frequency used for all the switching devices and it is a simple method of the back to back power transfer systems.

3. Pulse Width Modulation

3. 1. Sinusoidal Pulse Width Modulation

In the sinusoidal pulse width modulation, the reference wave is the sine wave. That is compared with the carrier triangular wave, the pulses are produced. That is given to the inverter. The sine wave is greater than the carrier wave the top switches are ON. Otherwise the bottom switches are ON.

*Corresponding Author,
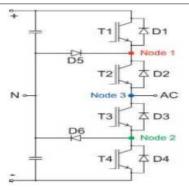**E-mail:** er.nikhil2007@gmail.com

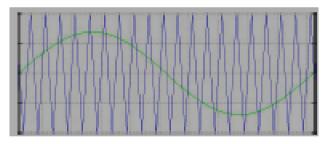**Fig. 1**: Three level Diode clamped inverter

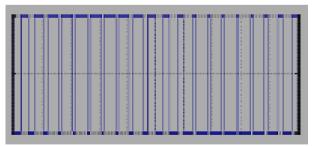
Fig. 2: Comparisons of sine wave with ref wave

Fig. 3: Generating pulse

In carrier based PWM schemes for m level, (m-1) carrier waves are used. The carrier base PWM schemes are classified into two, they are, (i) Phase shifted multi carrier modulation, (ii) Level shifted multi carrier modulation The level shifted multi carrier modulation schemes are classified into three, they are, (i) In phase disposition method (ii) Alternative phase opposite disposition method and (iii) Phase opposite disposition method.

3.2   Third-Harmonic-Injection   PWM   (THIPWM)

The sinusoidal PWM is the simplest modulation scheme to understand but it is unable to fully utilize the available DC bus supply voltage. Due to this problem, the third-harmonic injection

pulse-width modulation (THIPWM) technique was developed to improve the inverter performance.

Following Reference [17], consider a waveform consisting of a fundamental component with the addition of a triple-frequency term:

$$y = \sin\theta + A.\sin3\theta$$

where $\theta = \omega t$ and A is a parameter to be optimized while keeping the maximum amplitude of y(t) under unity.
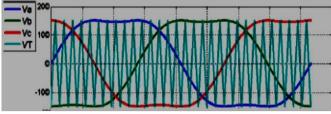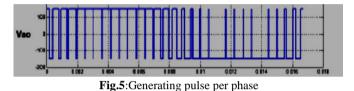

Fig.4: Comparisons of third harmonic wave with ref wave

Fig.5:Generating pulse per phase

The THIPWM is implemented in the same manner as the SPWM, that is, the reference waveforms are compared with a triangular waveform. As a result, the amplitude of the reference waveforms do not exceed the DC supply voltage Vdc=2, but the fundamental component is higher than the supply voltage Vdc. As mentioned above, this is approximately15.5% higher in amplitude than the normal sinusoidal PWM.

3. 3. Bus clamped Pulse width modulation (BCPWM)

In BCPWM technique one of the phase is clamped to one of the dc buses for some time. BCPWM methods are of 4 types

- 60-degree clamp
- 30-degree clamp
- Continual clamp PWM
- Split clamp PWM

In 60-degree clamp, every phase clamps during the middle 60-degree duration in every half cycle of itsfundamental voltage. Each phase is clamped to positive dc bus for 60° and negative dc busfor 60°.
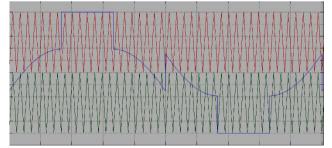

Fig.6: Comparisons of 60 degree bus clamped wave with ref wave

The carrier line cycle is smaller than the fundamental line cycle. If the carrier line cycle is muchsmaller than fundamental line cycle, then the sinusoidal signal almost appears like a straightline. When all the top or bottom devices are ON, then the load is shorted. This is called thezero states of the inverter. Thus, an inverter has two switching states both resulted in shorting of load. This is called the redundancy of inverter. When a small common mode is added the 3 switching, instants shifted to right. The effective interval for active state applied is not changing. But the instant for zero state is changing. One of the zero state decreases at the expense of other.

There is an extreme case in which common mode is added such that red signal is equal to the peak, this results in clamping of the phase.Advantages of BCPWM are
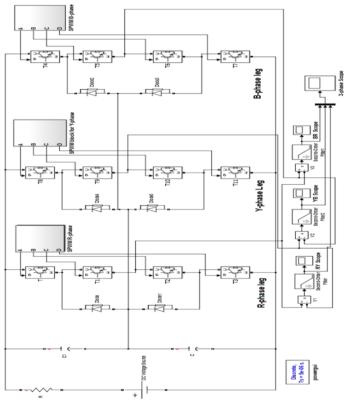
- Switching losses are reduced.
- Higher fundamental voltage.
- Conduction losses are reduced.
- Less harmonic distortion.

4. Simulation Results

This part discusses the MATLAB/Simulink software implementation of SPWM, THIPWM, and BCPWM in the under-modulation region and the over-modulation region.

In addition to the simulation results, this part 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 4.1- 4.6) 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 4.19 - 4.23).
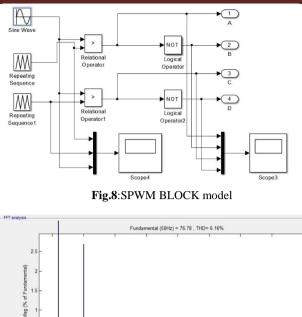

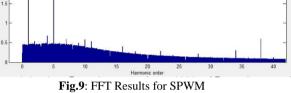**Fig.7**: Simulink Model of the 3 level inverter

The Parameters used in the block are defined below: V_{dc} = 100 V, $R_{Limiting}$ = 10 ohm, Bus Capacitors C = 1 μF, four IGBTs with body diode and inbuilt snubber circuit, Two clamping power diodes of same voltage ratings as that of IGBT.

4.1 SPWM Simulink model & Results

DC Components = 0.1771,
Fundamental peak = 76.76,
Fundamental rms = 54.29,
THD = 6.16 %

Fig.8:SPWM BLOCK model

Fig.9: FFT Results for SPWM
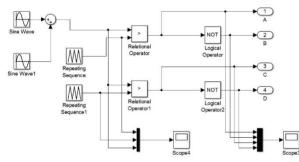
4.2 THIPWM Simulink model & Results

Fig.10: Simulink Model for the generation of THIPWM signal
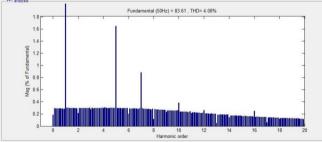

Fig.11: FFT Results for THIPWM

DC Components = 0.1547,
Fundamental peak = 83.61,
Fundamental rms = 59.12,
THD = 4.08 %

4.3BCPWM Simulink model & Results

DC Components = 0.0305,
Fundamental peak = 68.16,
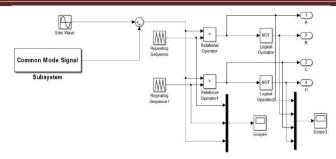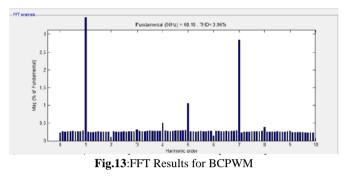Fundamental rms = 53.38,
THD = 3.96 %

Fig.12: BCPWM BLOCK model

Fig.13:FFT Results for BCPWM

4. Conclusions

This paper has evaluated three different PWM techniques, namely SPWM, THIPWM, andBCPWM (in the linear modulation region and over-modulation mode). 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.

BCPWM technique can only be applied to a three-phase inverter and it increases the overall system efficiency. The BCPWM is used for controlling the switching of the machine side converter. Advantages of this method include a higher modulation index, lower switching losses, and less harmonic distortion compared to SPWM. BCPWM is the most popular methods for three-phaseinverters because it has a higher fundamental voltage output than SPWM for the same DC bus voltage. The BCPWM is significantly better than SPWM by approximately 15.5%. However, the BCPWM technique is complex in implementation, especially in the over-modulation region.

The BCPWM technique has been deeply studied in the over-modulation region due to its performance benefits when compared to other modulation techniques. Numerous over-modulation algorithms have been proposed in the literature for the control of voltage source inverters [14,12,24]. The simulated results confirm that the over-modulation region leads to a modulation index up to 0.952. This is an extension of around 5%, which is a significant improvement.

References

[1] PS Bhimbra, Power Electronics. Khanna Publishers, Delhi, 2012
[2] M Rashid, Power Electronics Handbook, Academic Press Series in Engineering, 3rd edition 2011
[3] A Aktaibi, A Rahman, A Razali. A Critical Review of Modulation Techniques.http://necec.engr.mun.ca/ocs2010/viewpaper.php?id=13 &print = 1.

IJARI

[4] KV Kumar, PA Michael, JP John, SS Kumar. Simulation and Comparison of SPWM and SVPWM control for Three Phase Inverter, Asian Research Publishing Network, 5(7), 2010, 61-74

[5] JY Lee, YY Sun. A New SPWM Inverter with Minimum Filter Requirement, International Journal of Electronics, 64(5), 1988, 815-826

[6] H Quan, ZGang, C Jie, Z Wu, Z Liu. Study of A Novel Over-modulation Technique Based on Space-Vector PWM, IEEE Computer Distributed Control and Intelligent Environmental Monitoring (CDCIEM), 2011, 295-298

[7] K. Zhou, D Wang. Relationship Between Space-Vector Modulation and Three-Phase Carrier-Based PWM: A Comprehensive Analysis, IEEE Transactions on Industrial Electronics, 49(1), 2002, 186-196

[8] WF Zhang, YH Yu. Comparison of Three SVPWM Strategies, Journal of Electronic Science and Technology of China, 5(3), 2007, 283-287

[9] BK Bose. Modern Power Electrics and AC Drives. Prentice-Hall, Inc., 2002.

[10] J Holtz, W Lotzkat, AM Khambadkone. On Continuous Control of PWM Inverters in the Over-modulation Range Including the Six-Step Mode, IEEE Transactions on Power Electronics, 8(4), 1993, 546-553

[11] J Holtz. On Continuous Control of PWM Inverters in Over-modulation Range Including the Six-Step, IEEE Transactions on Power Electronics, 8(4), 1993, 546-553

[12] DC Lee. A Novel Over-Modulation Technique for Space Vector PWM inverters, IEEE Transactions on Power Electronics, 13(6), 1998, 1144-1151

[13] DG Holmes, TA Lipo. Pulse Width Modulation for Power Converters. John Wiley & Sons, Inc. 2003

[14] JA Houldsworth, DA Grant. The Use of Harmonic Distortion to Increase the Output Voltage of a Three-Phase PWM Inverter, IEEE Transactions on Industry Applications, IA-20(5), 1984, 1124-1228

[15] D Anand, S Jeevananthan. Modeling and Analysis of Conducted EMI Emissions of Single-Phase PWM Inverters, Asian Power Electronics Journal, 4(3), 2010

[16] FI Crowley, HF Leung. PWM Techniques: A Pure Sine Wave Inverter, Worcester Polytechnic Institute Major Qualifying Project, 2010.

[17] Lin W Song, Huang I Bau. Harmonic Reduction in Inverters by Use of Sinusoidal Pulse Width Modulation, IEEE Transactions on Industrial Electronics - IEEE Trans Ind Electron, IECI-27, (3), 1980, 201-207

[18] AM Gole. Harmonic Elimination in SPWM Inverter, 1994, Halifax, Canada.

[19] N Mohan, T Undeland, W Robbins. Power Electronics Converters applications and design, 2nd edition, John Willey & sons, Singapore.

[20] NPTEL- Electrical Engineering - Pulse width Modulation for Power Electronic Converters: http://nptel.ac.in/courses/108108035/