Three-phase five level diode clamped inverter for AC load interfacing in DC Microgrid

Soe Win¹* and Zarchi Linn²

¹, ² Department of Electrical Power Engineering, Yangon Technological University, East Gyogone, Insein Township, Yongon, Myanmar.

*E-mail: soewin.ep@ytu.edu.mm

Abstract. In this paper, diode clamped type three-phase five-level inverter is used for AC load interfacing in DC microgrid. Multilevel inverters generate staircase voltage waveform with a series of power semiconductor switches from several layer voltage DC sources. Therefore, the output voltage waveforms in multilevel inverters can be generated at low switching frequency with high efficiency and low distortion. In two-level inverter, various pulse width modulation (PWM) strategies with high switching frequency is required to obtain a output voltage or a current waveform with a small amount of harmonic content. In existing DC microgrid, three-phase conventional two-level Sine-PWM inverter is used and so, total harmonic distortion (THD) is high. To reduce the THD and the size of AC filter and to get the quality output, diode clamped type three-phase five-level inverter is applied in this research. Level shift multi carrier Sine-PWM method is used for the diode clamped circuit topology. The output waveforms of conventional two-level inverter and diode clamped five-level inverter are measured and compared the each output waveform qualities such as voltage THD, current THD and AC filter size. The performance of five level diode clamped inverter is illustrated by PSIM software and experimental results are carried out with prototype.

Keywords: DC microgrid, AC load interfacing, Five-level inverter, THD, Sine-PWM

1. Introduction

Integrating distributed generations (DG) to the utility grid is gaining popularity day by day for concerning about environmental issue, improving of power quality and reliability issue. DGs based renewable energy sources such as solar and wind energy is increasing because of accessing from natural potential resources. Increasing of interest on harvesting energy from renewable resources formed the system called microgrid which is organized with renewable energy (PVs, wind etc.) as power supply source, power electronics converters as power conditioning system and energy storage devices such as batteries for back up energy system to maintain continuous power supply to the loads. The microgrids can operate either in standalone or grid-connected modes. The hybrid AC/DC microgrids which have advantages of both AC and DC power systems, and are considerable to be the most possible future distribution and transmission systems, are being interested rapidly because of the consisting of DC power sources in microgrids such as Photovoltaics, fuel cell, energy storages and modern DC loads, and considering the existing century-long AC power systems [1].

Power quality and grid synchronizing is one of the main issues in microgrid system between DC, AC bus and AC load interfacing. Two-level inverters require to used high switching frequency PWM methods to obtain a quality output. Moreover, switching loss and semiconductor switching devices
ratings are the main constraints of these two level inverters in high power, high voltage and high frequency applications.

The output voltage waveforms in multilevel inverters can be generated at low switching frequency with high efficiency and low distortion. In recent years, beside multilevel inverters various pulse width modulation techniques have been also developed. The main topologies of multilevel inverters are diode clamped or neutral point clamped multilevel inverter (DCMLI), flying capacitor multilevel inverter (FCMLI) and cascaded H-bridge multilevel inverter (CHBMLI). The diode clamped inverter uses more number of diodes, the flying capacitor inverter uses more number of capacitors while the cascaded H-bridge inverter requires less number by comparing the devices and components used. As the number of levels increases, the multilevel inverter configuration consists of larger number of switching devices and the voltage stress across the each device will reduce, which makes this topology suitable for high voltage application where low voltage rating devices can be used. This result in smaller harmonics, but on the other hand it has more components and is more complex to control.

In this paper, diode clamped type three-phase five-level inverter is considered for improving the existing microgrid system in Electrical Power Engineering Department in Yangon Technological University. Level shift multi carrier Sine-PWM method is used for the diode clamped circuit topology. The output waveforms of conventional two-level inverter and diode clamped five-level inverter are measured and compared the each output waveform qualities such as voltage THD, current THD and AC filter size. The performance of five level diode clamped inverter is illustrated by PSIM software and experimental work will be done as the extended plan of this paper.

![Diagram of proposed hybrid AC/DC Microgrid system with Multilevel Inverters.](image)

**Figure 1.** Configuration of proposed hybrid AC/DC Microgrid system with Multilevel Inverters.
2. Proposed System Configuration

In the existing microgrid system in EP department, YTU, 6kW PV plant and battery bank (20 x 12V, 200Ah batteries in series) are cooperating to supply the electricity for the seminar room and the head office. The inverter in the existing system is only two-level and it allows power flow from DC bus to AC bus. Therefore, in this research, the configuration of interfacing converter is developed which is used to link the DC and AC buses to provide low distortion, high power quality output waveform. In the propose system, three-phase five-level diode clamped multilevel inverter is used for AC bus and AC load interfacing as shown in Figure 1 where PV and energy storage (ES) are connected DC bus with DC to DC converters and DC loads are directly connected to DC bus as shown in Figure 1.

3. Five-level Diode Clamped Inverter

Figure 2 shows a five-level diode clamped inverter that uses IGBT devices. In general, an N-level inverter requires 2(N–1) switching devices and 2(N–2) clamping diodes for each phase leg, and (N−1) DC-side capacitors, where each switching device shares $V_{DC}/(N − 1)$ voltage. It produces N-level phase voltage and 2N−1 level line voltage waves. The higher number of levels provides the advantages of a higher power rating and lower output harmonics [2].

![Diagram of five-level diode clamped inverter](image)

Figure 2. The circuit schematic for three phase five level diode clamped inverter [4]

The DC-side capacitor voltage balancing remains a serious problem with a larger number of levels if the inverter handles real power, but the output waveform quality is better and less harmonics content. The switching table for five-level diode clamped inverter is shown in table 1.

| No | Device Switching Status (Phase U) | $V_{out}$ |
|----|----------------------------------|----------|
| 1  | ON ON ON ON OFF OFF OFF ON      | $+V_{UN}$ |
| 2  | OFF OFF OFF OFF OFF OFF OFF     | $+V_{DC}/2$ |
| 3  | OFF OFF OFF ON ON OFF OFF ON   | $0$      |
| 4  | OFF OFF OFF OFF ON ON OFF ON   | $-V_{DC}/2$ |
| 5  | OFF OFF OFF OFF ON ON ON ON    | $-V_{DC}/4$ |
4. Multi-carrier Based PWM Techniques for Multilevel Inverter

There are two types of carrier-based modulation schemes for multilevel inverters. They are phase-shifted and level-shifted modulations. Both modulation schemes can be applied to diode clamped and the switched capacitor multilevel inverter. But, THD content of phase-shifted modulation is higher than level-shifted modulation. Therefore, the level-shifted modulation scheme is selected for diode clamped multilevel inverter. In general, an N-level multilevel inverter requires (N-1) triangular carriers by using level-shifted multicarrier modulation scheme. These (N-1) triangular carriers are vertically disposed with the same frequency and amplitude. There are three different types of level shifted modulation available. They are namely phase disposition PWM, phase opposition disposition PWM and alternate phase opposition disposition PWM. [6].

In multilevel inverters, amplitude modulation index (\( M_a \)) and frequency modulation index (\( M_f \)) are the important parameters.

\[
M_a = \frac{A_m}{(N-1)A_c} \quad (1)
\]

\[
M_f = \frac{F_c}{F_m} \quad (2)
\]

where:

- \( A_m \) = amplitude of reference sine waveform
- \( A_c \) = amplitude of triangular carrier waveform
- \( N \) = number of level of inverter output
- \( F_m \) = frequency of reference sine waveform
- \( F_c \) = frequency of triangular carrier waveform

4.1 Phase Disposition PWM (PDPWM)

In phase disposition PWM method, all the triangular carrier signals are in phase with each other. And they have the same frequency and amplitude.[5] PWM signals are generated by comparing a sinusoidal reference waveform with vertically shifted carrier waveform as shown in Figure 3.

\[ \text{Figure 3. Phase Disposition PWM (PDPWM).} \]

Figure 4. Phase Opposition Disposition PWM (PODPWM).
4.2 **Phase Opposition Disposition PWM (PODPWM)**

For phase opposition disposition (POD) PWM method, all carrier waveforms above the sinusoidal zero axis are zero degree phase shift with same frequency, same amplitude and in phase with each other. All the carrier waveforms below the sinusoidal zero axis have same frequency, same amplitude and in phase but all carrier waves are 180 degree out of phase compare to the carrier waveform that above the sinusoidal zero axis as shown in Figure 4 [5].

![Figure 4](image)

**Figure 4.** Phase Opposition Disposition PWM (APODPWM).

4.3 **Alternate Phase Opposition Disposition PWM (APODPWM)**

In Alternate Phase Opposition Disposition (AOD) PWM, every carrier waveform is phase shifted by 180 degree from its adjacent carrier waveform with same frequency and same amplitude as shown in Figure 5. Odd carrier waveforms are in phase but compare to even carrier waves they are out of phase with 180 degree [5].

![Figure 5](image)

**Figure 5.** Alternate Phase Opposition Disposition PWM (APODPWM).

![Figure 6](image)

**Figure 6.** Control Structure of Diode Clamped MLI with Synchronous Control.
5. Inverter Control in Grid Integration
The block diagram of the synchronous controller for the grid-connected inverter is represented in Figure 6. It can be seen from the figure that the inverter has two PI controllers to compensate the current vector components that are defined in synchronous reference frame (dq). Because of coordinate transformations, \( i_q \) and \( i_d \) are DC components and therefore, PI compensators reduce the error(s) between the desired current \( I^*_d \) (\( I^*_q \)) and the actual current \( I_d \) (\( I_q \)) to zero. The output energy and power factor can be controlled via changing d-axis current and q-axis current. In such a structure, Voltage feed forward control and cross-coupling terms are usually used for improving the performance of PI controller. [7]

6. Simulation Results
For the comparison of results, conventional two-level three-phase inverter and five-level diode clamped three-phase inverter models are used. In both of the models, switching frequency is chose 5kHz and 2 Ω, 20mH per phase RL load is applied. Firstly, simulation output waveforms of conventional inverter (2-level) inverter and diode clamped inverter (5-level) inverter are observed and measured the THD content with open loop control. From the simulation results, it can be noted that the waveform quality of 5-level diode clamped inverter is superior compare with the 2-level inverter.

Figure 7. Output Waveforms of Conventional Three-phase Inverter.

Figure 8. Output Waveforms of Five-level Diode Clamped Three-phase Inverter.
Line current, phase voltage and line voltage waves of conventional 2-level inverter and 5-level diode clamped three-phase inverter are shown in Figure 7 and Figure 8. Then, THD content of line voltage and line current for 2-level inverter and 5-level inverter with different switching PWM techniques are shown in Table 2. Phase Disposition PWM (PDPWM) output waveform is the best result among the different multi-carrier level shaft PWM methods.

Table 2. Comparison of total harmonic distortion.

| Inverter Type                                               | Total harmonic distortionTHD(%) |
|-------------------------------------------------------------|---------------------------------|
|                                                             | Line Voltage | Line current |
| Three-phase conventional inverter (2 level) with Sine-PWM   | 67.87%        | 34.69%       |
| Three-phase diode clamped inverter (5level) with PDPWM      | 23%           | 0.31%        |
| Three-phase diode clamped inverter (5level) with PODPWM     | 37%           | 0.46%        |
| Three-phase diode clamped inverter (5level) with APODPWM    | 33.4%         | 0.42%        |

For the grid-connected operation, 5-level diode clamped inverter is controlled by synchronous controller is used. Output performance grid connected operation is shown in Figure 9. From the simulation results, line current magnitude and load power transfer is effectively controlled with I*\(_d\) (I*\(_q\)) .

![Figure 9. Output Performance of Five-level Diode Clamped Three-phase Inverter with Grid Connected.](image)

7. Discussion and Conclusion
In this paper, the performance of five-level diode clamped three-phase inverter is studied compared with the 2-level inverter. From the simulation results, waveform distortion of 2-level inverter is high. So, the switching frequency of inverter is increased and large capacity of AC side line filter is required to improve the waveform quality. But, in 5-level DCMLI, relatively good waveform quality is obtained with medium switching speed and small capacity of AC side line filter. In grid connected operation, line current magnitude and load power flow is effectively control with synchronous controller with multi-level PWM generator. For the future plan, prototype 5-level DCMLI is constructed and testing the performance.
References

[1] Farzam Nejabatkhah, and Yun Wei Li, “Overview of Power Management Strategies of Hybrid AC/DC Microgrid”, IEEE Transactions on power electronics, Vol. 30, No. 12, December 2015.

[2] Xiaoming Yuan, and Ivo Barbi, “Fundamentals of a New Diode Clamping Multilevel Inverter”, IEEE Transactions on power electronics, Vol. 15, No. 4, July 2000.

[3] N. S. Choi, J. G. Cho, and G. H. Cho, “A general circuit topology of multilevel inverter,” IEEE PESC’91, 1991, pp. 96–103.

[4] Tolbert, L.M., and Habetler, T.G, “Novel multilevel inverter carrier-based PWM methods”, IEEE Conference on Industry Application,1998.

[5] YorkSergio Alberto González, Santiago Andrés Verne, and María Inés Valla, “Multilevel Converters for Industrial applications”, ISBN-13: 978-1-4398-9562-7 (eBook - PDF), Taylor & Francis Group, LLC, 2014.

[6] D.G. Holmes, and T.A. Lipo, “Pulse Width Modulation for Power Converters: Principles and Practice”, IEEE Press, Piscataway, NJ, 2003.

[7] Yilmaz Sozer, and David A. Torrey, “Modeling and Control of Utility Interactive Inverters”, IEEE Trans On Power Electronics, Vol. 24, No. 11, November 2009.

Acknowledgements
The authors would like to thank the support of JICA EEHE project in Yangon Technological University, Myanmar.