Single phase seven level Z-source cascaded H-bridge inverter for photovoltaic systems

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ABSTRACT
The Multilevel inverter (MLI) is identified as a viable power electronic unit for distributed energy conversion applications. In this paper discusses the performance of single phase seven level Z (impedance) source cascaded H-bridge inverter topology suited for solar photovoltaic systems. A modified sinusoidal pulse width modulation technique is used to control the switches of the H-bridge inverter. The simulation results are obtained in terms of inverter output voltage and harmonic analysis confirm improvement in voltage boost and reduction in harmonic distortion of the suggested inverter topology. The experimental results match with the simulation values, as verified through a scaled down prototype.

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1. INTRODUCTION
Distributed energy systems employing fuel cell and PV array can easily configure with different topologies of power conversion units for example multilevel inverters are implemented for electrification over the years. Recent advancements of multilevel inverters either in their operating principle and modulation strategy focused for industrial applications and utility systems are found to be interesting and growing for the applications of reactive power compensation, renewable energy system power conversion, resonance circuit, UPS power conversion unit and electric-drive vehicles [1-6].

Multi-level inverters are designed with photovoltaic voltage source, semiconductor switching device and capacitor, and their performance and output are evaluated by their step. The semiconductor switching device must be able to withstand the voltage surge that occurs when switching switches. The main function of multilevel inverters is to convert the dc power to the desired amount of ac power [7, 8]. The topic under study is cascaded multilevel inverter, which is modular in nature and it can be configured with multiple modules [9-13]. Non-transformer power converters are used for the purpose of making such a system low cost, which is the unique function of multilevel inverters are as described in [14-20]. Merits and demerits of cascaded multi-level inverters are discussed through many applications in [21-24]. Infusion of Z-source network into the existing multilevel and other inverter topologies improves the voltage boosting capability which can be preferably used for photovoltaic systems [25, 26]. In this paper, Z-source Cascaded H-bridge multi-level inverter with symmetric configuration its steady-state operation is discussed in section 2, the
employed modulation technique is explained in section 3, Simulation and its experimental discussions are dealt in subsequent sections.

2. **TOPOLOGY DESCRIPTION: Z-SOURCE CASCADED MLI FOR PV SYSTEMS**

   Figure 1 shows the three H-bridges are connected in cascade mode to convert the photovoltaic array dc output to the desired ac power. The output of these three bridges is added together and calculated as the total added value of the inverter. The seven level stepped expression of this system is built in Figure 2.

   Each photovoltaic panel is connected in series and parallel connection mode and their output is connected to each individual H-bridges. The voltage output of H-bridges depends on the value of the photovoltaic system input to them. Also the number of H-bridges depends on the number of photovoltaics array in that system. Better voltage and current can be obtained in sinusoidal design by increasing the levels of the inverter. Also multi-level is considered to be very effective when compared to two level converter. This allows the use of smaller low-pass filters for harmonic reduction [27, 28].

   ![Power circuit of a single phase seven level Z-source cascaded H-bridge inverter](image1)

   **Figure 1.** Power circuit of a single phase seven level Z-source cascaded H-bridge inverter

   ![Output voltage waveform of single phase seven level Z-source cascaded H-bridge inverter](image2)

   **Figure 2.** Output voltage waveform of single phase seven level Z-source cascaded H-bridge inverter

   The proposed single phase seven level cascaded H-bridge Z-source inverter topology is formed by having photovoltaic array connected series interlinked single phase two level inverter and its output voltage is depends on the number of single phase inverter connected in circuit. The number of output voltage levels \(m\) in the phase voltage of symmetrical cascaded MLI is given by

   \[
   q = 2N + 1
   \]
Where, N-number of single phase inverter. In other words, a typical cascade MLI requires a photovoltaic arrays for \(2N + 1\) level.

If the inverter phase voltage steps is calculated as a value of \(q\), then the line voltage of the inverter is calculated as

\[
k = 2q + 1
\]

and also the steps level for three phase different types of load connection can be calculated as

\[
p = 2k - 1
\]

The ac output voltage of the each single phase H-bridge inverter and the total sum of output voltage \((V_a)\) value of the multilevel inverter as determined by using (4).

\[
V_a = V_{dc1} + V_{dc2} + V_{dc3}
\]

The cascaded H-bridge multi-level inverter desired sinusoidal output voltage can calculate by using (5).

\[
V_p = V_m \sin(\omega t)
\]

To design cascaded multilevel inverter required number of switches for each phase or each H-bridge can estimate as per (6).

\[
N_{sw} = 4N
\]

The operating principle of ZSI Module can be explained as follows. The Z-source inverter is operating at two state of operation such as shoot-through and non-shoot-through states. When the inverter is operating at shoot-through state, the photovoltaic dc output power is converting into ac power and non-shoot-through states condition the power conversion is zero because of dc-link voltage is zero.

The power balance equation of the each Z-source inverter as

\[
\nu_{PN} \times i_{PN} \times (1 - D) + 0 \times D = v_s \times i_s
\]

Where, \(\nu_{PN}\) and \(i_{PN}\) are each H-bridge inverter input voltage and current values, \(v_s\) and \(i_s\) are the each H-bridge inverter output voltage and current values and \(D\) is a duty ratio of the Z-source inverter.

The Z-source inverter output voltage is determined as

\[
V_s = m \times V_{PN}
\]

Where \(m\) defined as \(M \sin \omega t\), \(M\) - modulation index.

From (7) and (8), \(i_{PN}\) is deduced as

\[
i_{PN} = \frac{M_t a}{2(1-D)} (\cos \phi - \cos(2\omega t - \phi)) = I_{PN} + i_{PN}
\]

Both \(I_{PN}\) and \(i_{PN}\) affect the module variables, \(i_{L1}, i_{L2}, v_{C1}\) and \(v_{C2}\).

\[
i_{L1} = l_{L1} + i_{L1}i_{L2} = l_{L2} + i_{L2}\n\]

\[
v_{C1} = V_{C1} + \tilde{v}_{C1}v_{C2} = V_{C2} + \tilde{v}_{C2}
\]

The impedance design of ZSI network [29] is given by

\[
L = \frac{2V_m DT(1 - D)}{3K_{M_s} \cos \phi} \quad \text{&} \quad C = \frac{3DTM_s \cos \phi}{8K_{V_m}(1 - D)}
\]
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Table 1. Simulation parameters

| Components                                      | Parameters |
|------------------------------------------------|------------|
| DC voltage sources (V_{dc1}, V_{dc2}, V_{dc3}) | 12 V each  |
| Z network                                      | 40 mH      |
| L_1 – L_6                                      | 6000 µF    |
| C_1 – C_6                                      | 40 mH      |
| Inductor filter (L_f)                          | 40 mH      |
| Resistive Load (R)                             | 50 Ω       |

Figure 3. Switching pulses generation for the bridges 1, 2 and 3

Figure 4. Boosted DC link voltages, appeared across the bridges 1, 2 and 3 (top to bottom)
Figure 5. Simulated output AC voltages (voltage waveform across bridges 1, 2, 3 and the load) (top to bottom)

Figure 6. Simulated output ac voltage observed through Fourier window

Figure 7. Filtered (Using inductor filter, Lf) phase voltage waveform
5. **EXPERIMENTAL RESULTS**

The proposed seven-level cascaded Z-source inverter circuit has been tested with three DC sources of 12 V with an R load of 50 Ω and the other test parameters used for simulation. The control scheme is programmed with a fixed-point TI-TMS3202812 digital signal processor (DSP) and a programmable logic device. The control signals are sent to insulated gate bipolar transistors (IGBTs) through optical fiber cables. The phase-shifted pulse width modulation technique has been implemented for controlling a seven-level cascaded Z source inverter feeding a resistive load. The sectionalized view of various components present in the overall experimental setup is shown in Figure 8. It consists of a power supply section, provided to give dc supply to the driver circuit and inverter section for energizing the various passive elements present in it. The regulated dc supply of +5 V and ± 15 V is given to the driver circuit IR 2110 and inverter section respectively through IC’s LM 7805, LM 7815 and LM 7915 after buffering actions with low noise immunity with respect to output impedance variations. The switching signals to these IGBT switches are given through IR 2110 drivers with autonomous high and low side referenced output channels which operate up to 500 volts with a feature of high pulse current buffer stage designed for minimum driver cross conduction of standard CMOS output, down to 3.3 V logic suitable for inverter applications.

Optoisolator IC TLP 250 is used for gate driving purposes and IC 4506, IC 4081 for buffering actions. Control signals obtained from the FPGA controller are given to the inverter section through these IC’s. The inverter circuit module uses IGBT pack namely FSBB20CH60F IC with protection and gate driving functions. XILINX Spartan 3E FPGA XC3S100E, Field programmable gate array (FPGA) has been chosen to implement the pulse width modulation due to its fast prototyping, simple hardware, and software design. DC voltage of 12V is given to the three H-bridges individually and the output voltage waveform is observed through a power analyzer generating output magnitude of 38 V with grid frequency nearly 50 Hz which is shown in Figure 9. FFT spectrum of the output voltage waveform is measured showing a THD value of 9.4% as shown in Figure 10.

![Figure 8. Experimental setup of the system](image)

![Figure 9. Experimental voltage waveform measured across the resistive load](image)
6. CONCLUSION

Z-source cascaded multilevel inverters play an important role in various power conversion places. They are off-grid and grid integrated solar photovoltaic system, fuel cell, UPS power conversion systems. This multilevel inverter has low electromagnetic interference, high operating efficiency, low switching loss, high quality voltage and higher operating voltage. The simulation and hardware results reach a decision to a excessive level. The proposed inverter exhibits well performance and is most suitable for solar photovoltaic applications.

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REFERENCES

[1] Samir Kouro, Mariusz Malinowski, K. Gopakumar, Josep Pou, Leopoldo G. Franquelo, Bin Wu, Jose Rodriguez, Marcelo A. Perez, and Jose I. Leon, “Recent Advances and Industrial Applications of Multilevel Converters” IEEE Transactions on Industrial Electronics, vol. 57, no. 8, pp. 2553-2580, 2010.
[2] F. Z. Peng and J. S. Lai, Multilevel cascade voltage source inverter with separate DC sources, United States Patent US RE 37126 (5 642 275), Apr 2001.
[3] Han keun Jang, Mutilevel inverter using cascade configuration and control method thereof, United States Patent 8018331, Sep 2011.
[4] Kevin P. Kepley, Cascaded multilevel inverter and method for operating photovoltaic cells at a maximum power point, United States Patent Application 20130285457, Oct 2013.
[5] Jingbo Liu, Thomas Nondahl, Zhongyuan Cheng and Navid Zargari, Cascaded H bridge (CHB) inverter level shift PWM with rotation, United States Patent Application Publication 0036557 A1, Feb 2014.
[6] Gnana Prakash M, Balamarugan M, Umashankar S, “A New Multilevel Inverter with Reduced Number of Switches,” International Journal of Power Electronics and Drive System, vol. 5, no. 4, pp. 63-70, 2014.
[7] José Rodriguez, Jih-Sheng La and Fang Zheng Peng, “Multilevel Inverters: A Survey of Topologies, Controls, and Applications,” IEEE Transactions on Industrial Electronics, vol. 49, no. 4, pp. 724-738, 2002.
[8] Jih-Sheng Lai and Fang Zheng Peng, "Multilevel Converters - A New Breed of Power Converters,” IEEE Transactions on Industry Applications, vol. 32, no. 3, pp. 509-517, 1996.
[9] Keith Corzine and Yakov Familiant, “A New Cascaded Multilevel H Bridge Drive,” IEEE Transactions on Power Electronics, vol. 17, no. 1, pp. 125-131, 2002.
[10] Keith A. Corzine, Mike W. Wielebski, Fang Z. Peng, and Jin Wang, “Control of Cascaded Multilevel Inverters,” IEEE Transactions on Power Electronics, vol. 19, no. 3, pp. 732 -738, 2004.
[11] Mariusz Malinowski, K. Gopakumar, Jose Rodriguez and Marcelo A. Perez, “A Survey on Cascaded Multilevel Inverters,” IEEE Transactions on Industrial Electronics, vol. 57, no. 7, pp. 2197-2206, 2010.
[12] Babaei E, Iran Ali, S and Laali, S, “A New General Topology for Cascaded Multilevel Inverters With Reduced Number of Components Based on Developed H Bridge,” IEEE Transactions on Industrial Electronics, vol. 61, no. 8, pp. 3932-3939, 2014.
[13] Suresh Naturajan, R. Samuel Rajesh Babu, “Comparison of Cascaded H-bridge Inverters for Harmonic Mitigation Considering Various Loads,” International Journal of Power Electronics and Drive System, vol. 8, no. 1, pp. 10-19, 2017.
[14] Sérgio Daher, Jürgen Schmid and Fernando L. M. Antunes, “Multilevel Inverter Topologies for Stand Alone PV Systems,” IEEE Transactions on Industrial Electronics, vol. 55, no. 7, pp. 2703- 2712, 2008.
[15] Remus Teodorescu, Frede Blaabjerg, John. K. Pedersen, Ekrem Cengelci, and Prasad. N. Enjeti, “Multilevel Inverter by Cascading Industrial VSI,” IEEE Transactions on Industrial Electronics, vol. 49, no. 4, pp. 832-838, 2002.

[16] Leon M. Tolbert, Fang Zheng Peng, Tim Cunnyngham and John N. Chiasson, “Charge Balance Control Schemes for Cascade Multilevel Converter in Hybrid Electric Vehicles,” IEEE Transactions on Industrial Electronics, vol. 49, no. 5, pp. 1058-1064, 2002.

[17] Poh Chiang Loh, Donald Grahame Holmes, and Thomas A. Lipo, “Implementation and Control of Distributed PWM Cascaded Multilevel Inverters with Minimal Harmonic Distortion and Common Mode Voltage,” IEEE Transactions on Power Electronics, vol. 20, no. 1, pp. 90-99, 2005.

[18] José Rodríguez, Steffen Bernet, Bin-Wu, Jorge O. Pontt and Samir Kouro, “Multilevel Voltage Source Converter Topologies for Industrial Medium Voltage Drives,” IEEE Transactions on Industrial Electronics, vol. 54, no. 6, pp. 2930-2945, 2007.

[19] E. Villameuva, P. Correa, J. Rodriguez, and M. Pacas, “Control of a single phase cascaded H bridge multilevel inverter for grid connected photovoltaic systems,” IEEE Transactions on Industrial Electronics, vol. 56, no. 11, pp. 4399-4406, 2009.

[20] Haitham Abu Rub, Joachim Holtz, Jose Rodriguez, and Ge Baoming, “Medium-Voltage Multilevel Converters— State of the Art, Challenges, and Requirements in Industrial Applications,” IEEE Transactions on Industrial Electronics, vol. 57, no. 8, pp. 2581-2596, 2010.

[21] Y. M. Park, J.Y. Yoo, and S.B. Lee, “Practical implementation of PWM synchronization and phase-shift method for cascaded H-bridge multilevel inverters based on a standard serial communication protocol,” IEEE Transactions on Industry Applications, vol. 44, no. 2, pp. 634-643, 2008.

[22] S. Vazquez, J. I. Leon, L. G. Franquelo, J. J. Padilla and J. M. Carrasco, “DC voltage ratio control strategy for multilevel cascaded converters fed with a single dc source,” IEEE Transactions on Industrial Electronics, vol. 56, no. 7, pp. 2513-2521, 2009.

[23] Farid Khoucha, Soumia Mouna Lagoun, Khoudir Marouani, Abdelaziz Kheloui and Mohamed El Hachemi Benbouzid, “Hybrid Cascaded H Bridge Multilevel Inverter Induction Motor Drive Direct Torque Control for Automotive Applications,” IEEE Transactions on Industrial Electronics, vol. 57, no. 3, pp. 892-899, 2010.

[24] B. Diong, H. Sepahvand, and K. A. Corzine, “Harmonic distortion optimization of cascaded H-bridge inverters considering device voltage drops and non-integer dc voltage ratios,” IEEE Transactions on Industrial Electronics, vol. 60, no. 8, pp. 3106-3114, 2013.

[25] Mohamad Reza Banaei, Ali Reza Dehghanzadeh, Ali Fazel and Aida Baghbany Oskouei, “Switching algorithm for single Z source boost multilevel inverter with ability of voltage control”, IET Power Electronics, vol. 6, no. 7, pp. 1350-1359, 2013.

[26] V. Saravanan, M. Aravindan, V. Baalaji, M. Arumugam, “Experimental Verification of Single Phase Z Source Inverter for Photovoltaic Applications,” International Journal of Power Electronics and Drive System, vol. 9, no. 2, pp. 698-703, 2018.

[27] Y. Liu, B. Ge, H. Abu Rub and F. Z. Peng, “An effective control method for quasi Z source cascaded multilevel inverter based grid tie single phase photovoltaic power system,” IEEE Transactions on Industrial Informatics, vol. 10, no. 1, pp. 399-407, 2014.

[28] R. Palanisamy, K. Vijayakumar, “Maximum Boost Control for 7-level Z-Source Cascaded H-Bridge Inverter,” International Journal of Power Electronics and Drive System, vol. 8, no. 2, pp. 739-746, 2017.

[29] Dongsun Sun, Baoming Ge, Xingyu Yan, Daqiang Bi, Hao Zhang, Yushan Liu, Haitham Abu Rub, Lazarh Benbrahim and Fang Zheng Peng, “Modeling, Impedance Design, and Efficiency Analysis of Quasi Z Source Module in Cascaded Multilevel Photovoltaic Power System,” IEEE Transactions on Industrial Electronics, vol. 61, no. 11, pp. 6108-6117, 2014.

[30] Javier Chavarria, Domingo Biel, Francesc Guinjoan, Carlos Meza and Juan J. Negroni, “Energy Balance Control of PV Cascaded Multilevel Grid Connected Inverters Under Level Shifted and Phase Shifted PWMs,” IEEE Transactions on Industrial Electronics, vol. 60, no. 1, pp. 98-111, 2013.

[31] Leon M. Tolbert, Fang Zheng Peng, Thomas G. Habetler, “Multilevel PWM Methods at Low Modulation Indices” IEEE Transactions on Power Electronics, vol. 15, no. 4, pp. 719-725, 2000.

[32] Sirirat Sirisuksrapsert, Jih-Sheng Lai, Tian-Hua Liu, “Optimum Harmonic Reduction With a Wide Range of Modulation Indexes for Multilevel Converters,” IEEE Transactions on Industrial Electronics, vol. 49, no. 4, pp. 875-881, 2002.

[33] Zhong Du, Leon M. Tolbert, Burak Ozpineci, and John N. Chiasson, “Fundamental Frequency Switching Strategies of a Seven Level Hybrid Cascaded H Bridge Multilevel Inverter,” IEEE Transactions on Power Electronics, vol. 24, no. 1, pp. 25-33, 2009.

[34] Hossein Sepahvand, Jingsheng Liao, Mehdi Ferdowsi, “Investigation on Capacitor Voltage Regulation in Cascaded H Bridge Multilevel Converters With Fundamental Frequency Switching,” IEEE Transactions on Industrial Electronics, vol. 58, no. 11, pp. 5102-5111, 2011.

[35] Vincent Roberge, Mohammed Tarbouchi, and Francis Okou, “Strategies to Accelerate Harmonic Minimization in Multilevel Inverters Using a Parallel Genetic Algorithm on Graphical Processing Unit,” IEEE Transactions on Power Electronics, vol. 29, no. 10, pp. 5087-5090, 2014.

[36] Rajasekar Selvamuthukumaran, Abhishek Garg, and Rajesh Gupta, “Hybrid Multicarrier Modulation to Reduce Leakage Current in a Transformerless Cascaded Multilevel Inverter for Photovoltaic Systems,” IEEE Transactions on Power Electronics, vol. 30, no. 4, pp. 1779-1783, 2015.
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