American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN: 2320-0936
Volume-14, Issue-8, pp-01-10
www.ajer.org
Research Paper Open Access

MPPT and Boost Converter Effects on Harmonic Reduction in CHB-MLI PV Systems: Modeling and Evaluation

Zaman, Chongkon[1], A. L. Amoo[2] IEEE, Y. S. Haruna[3] IEEE

[1.] *PhD Candidate, Department of Electrical and Computer Engineering, Morgan State University, Baltimore, Maryland, USA.*

[2.] *Department of Electrical and Electronics Engineering, Faculty of Engineering and Engineering Technology, Abubakar Tafawa Balewa University, Bauchi.*

[3.] *Department of Electrical and Electronics Engineering, Faculty of Engineering and Engineering Technology, Abubakar Tafawa Balewa University, Bauchi.*

Abstract

This paper investigates how Maximum Power Point Tracking (MPPT) and DC-DC boost conversion affect harmonic distortion in photovoltaic (PV)-fed Cascaded H-Bridge Multilevel Inverter (CHB-MLI) systems. Three simulation scenarios are examined using MATLAB/Simulink: (i) CHB-MLI with both MPPT and a boost converter, (ii) CHB-MLI with only a boost converter, and (iii) CHB-MLI with only MPPT. The Perturb and Observe (P&O) algorithm is employed for MPPT, and a boost converter is used to raise the PV output voltage to meet the inverter requirements. Results show that the setup with both MPPT and a boost converter yields the lowest Total Harmonic Distortion (THD), producing a more sinusoidal output waveform suitable for grid connection. FFT analysis confirms that harmonic content is significantly reduced when both control strategies are combined. This study emphasizes the combined impact of MPPT and boost converters in improving power quality and performance in multilevel inverter systems for solar applications.

Keywords: *Photovoltaic system, multilevel inverter, CHB-MLI, MPPT, boost converter, THD, harmonic distortion, FFT, Simulink modeling.*

Date of Submission: 27-07-2025 Date of acceptance: 05-08-2025

I. Introduction

The escalating energy demand, coupled with growing environmental concerns, has propelled photovoltaic energy to the forefront as a promising alternative to conventional energy sources, capitalizing on its abundance, pollution-free nature, widespread availability, and recyclability [1]. However, the relatively high initial installation costs and comparatively low energy conversion efficiency of photovoltaic systems remain significant challenges. To maximize the energy extraction from solar panels, maximum power point tracking techniques are essential components of photovoltaic systems, ensuring the system operates at its optimal power output, especially crucial given the non-linear voltage characteristics of photovoltaic generators, which exhibit a unique maximum power point dependent on both temperature and solar irradiance [2] [3]. Electronic transducer control plays a vital role in ensuring the efficient utilization of solar systems, and a modified Perturb and Observe MPPT algorithm, integrated with a fuzzy controller, can be employed to manage a DC-DC boost converter in a photoelectric system, effectively adapting to shading and varying weather conditions [4]. Furthermore, employing MPPT ensures the solar panel operates at its maximum power point, enhancing the overall energy output, which is particularly advantageous when the solar panel interfaces with a battery or grid, optimizing the use of available solar energy and bolstering system performance [5]. Various MPPT techniques and DC-DC converter topologies have been proposed in the pursuit of optimizing photovoltaic systems.

Harnessing the full potential of solar energy necessitates the use of Maximum Power Point Tracking algorithms to ensure that photovoltaic systems operate at peak efficiency, irrespective of environmental conditions [6]. The integration of high-gain DC-DC converters, like the modified positive Luo converter, alongside Type-2 fuzzy neural network controllers, showcases advancements in achieving superior voltage gain and conversion efficiency, making them suitable for two-stage grid-integrated solar photovoltaic systems [7]. Many classical methods have been developed and implemented to track the maximum power point [8]. Fuzzy logic controllers have emerged as a compelling solution for MPPT, offering advantages such as simplicity in design, robustness, and the ability to handle non-linear characteristics of photovoltaic systems, positioning them as a key component in advanced solar energy applications [9]. Fuzzy logic control-based MPPT is designed to track the maximum power point of the PV array under variable solar irradiance and temperature conditions, achieved by controlling the duty cycle of the converter [10]. The incorporation of intelligent maximum power point trackers has been instrumental in augmenting the performance of solar photovoltaic systems across various applications, maximizing the electrical energy harvested from solar photovoltaic sources, which consequently enhances the power delivered by the photovoltaic system [11]. Distributed maximum power point tracking represents a groundbreaking approach to mitigating the challenges posed by mismatching phenomena in photovoltaic applications, facilitating the adoption of a dedicated DC/DC converter for each photovoltaic module [12]. An innovative approach involves the utilization of neural network maximum power point tracking, where a fuzzy logic controller MPPT generates the training databases, optimizing power generation from photovoltaic generators under changing environmental conditions [13].

The pursuit of efficient and reliable maximum power point tracking in photovoltaic systems has led to the development of sophisticated techniques that combine artificial intelligence with conventional methods. Adaptive Neuro-Fuzzy Inference Systems integrate artificial neural networks and fuzzy logic controllers, demonstrating notable performance improvements compared to traditional perturb and observe and gradient descent techniques, showcasing faster convergence, improved stability, and higher efficiency in tracking the maximum power from photovoltaic systems across diverse operating conditions [14]. Artificial intelligence techniques are used for maximum power point tracking in the solar power system, because conventional MPPT techniques are incapable of tracking the global maximum power point under partial shading conditions [15]. A two-layer adaptive control architecture can effectively handle the uncertainties and perturbations in photovoltaic systems and the environment. MPPT algorithms are essential for extracting maximum power from PV systems and can be implemented using various optimization techniques, including particle swarm optimization, artificial neural networks, and fuzzy logic control, offering different trade-offs in terms of complexity, accuracy, and speed.

Harmonic Mitigation in CHB-MLI PV Systems

Cascaded H-bridge multilevel inverters have gained prominence in high-power applications due to their modular structure and ability to synthesize high-quality voltage waveforms, which reduce harmonic distortion and improve system efficiency. By synthesizing a staircase waveform, CHB-MLIs reduce the harmonic content in the output voltage, leading to improved power quality and reduced stress on connected equipment, which is particularly advantageous in grid-connected photovoltaic systems where adherence to stringent harmonic standards is essential. The control of cascaded H-bridge multilevel inverters involves sophisticated techniques like selective harmonic elimination and space vector modulation, which can be optimized to minimize total harmonic distortion and enhance the overall performance of the grid-connected photovoltaic system. The implementation of advanced modulation techniques and control strategies is crucial for mitigating harmonics and optimizing the performance of CHB-MLI-based photovoltaic systems, ensuring compliance with grid codes and maximizing the utilization of solar energy.

The modularity of cascaded H-bridge multilevel inverters allows for easy scalability and redundancy, making them suitable for high-power photovoltaic applications where reliability and maintainability are paramount. This modularity simplifies maintenance and allows for the system to continue operating even if some modules fail, enhancing the overall robustness and availability of the photovoltaic system. Cascaded H-bridge multilevel inverters are suitable for various applications, including renewable energy conversion, grid-tied inverters, and flexible AC transmission systems, among others [16]. The performance of CHB-MLIs can be further enhanced by employing advanced control techniques, such as model predictive control and artificial intelligence-based control, which offer improved dynamic response and harmonic mitigation capabilities [17].

Multilevel inverters are generally employed to synthesize a desired voltage waveform [18]. Multilevel inverters offer a stepped output voltage waveform that approaches a sinusoid, which results in reduced harmonic distortion [19]. The increasing number of voltage levels reduces the total harmonic distortion [20]. Multilevel inverter technology has emerged as a viable solution for high-power applications, offering advantages such as reduced harmonic distortion, lower switching losses, and improved electromagnetic compatibility. These inverters are suitable for high-power applications and can be used to interface renewable energy sources to the grid [21]. Multilevel inverters generate a staircase output voltage waveform, which approximates a sinusoidal waveform with lower harmonic distortion compared to traditional two-level inverters [22].

The demand for reduced harmonics, coupled with the increasing need for renewable energy sources, has led to considerable interest in multilevel inverters [23]. Multilevel inverters are used in static var generation, RES interfacing, and battery-powered applications [24]. Multilevel inverters have drawn in-depth attention in recent years for industrial applications [21]. Multilevel inverters can synthesize the desired output voltage from multiple DC voltages, resulting in reduced harmonic distortion and improved power quality [25]. Many studies have focused on the creation of multilevel inverters, considering both topologies and control techniques, with special attention given to reducing the number of components to minimize power dissipation and costs [26]. A cascaded multilevel inverter can be achieved by connecting several basic units, and an H-bridge can be added to generate both positive and negative voltages [27]. There are various advantages of the cascaded multilevel inverter, such as low voltage stress for each switching device and higher power quality [28]. Harmonic mitigation in cascaded H-bridge multilevel inverter-based photovoltaic systems is achieved through a combination of advanced modulation techniques, optimized control strategies, and appropriate filter designs. The integration of maximum power point tracking algorithms with boost converters and cascaded H-bridge multilevel inverters is essential for optimizing the performance of photovoltaic systems. Switching frequency modulation techniques produce switch commutations at the output fundamental frequency, which reduces certain low-frequency harmonics [29]. Reduced switch count inverters can decrease switching and conduction losses.

II. Literature Review and Research Gap

Existing research extensively covers various modulation techniques for multilevel converters, focusing on harmonic reduction without compromising converter output power [30]. However, research that comprehensively analyzes the interplay between MPPT algorithms, boost converter design, and CHB-MLI control strategies, specifically in the context of harmonic mitigation, is limited [21] [31]. Prior studies have explored the use of simplified neutral point clamped multilevel converters in wind turbine applications, highlighting the importance of advanced control schemes [32]. Most prior studies have not been able to offer a detailed comparison between different MPPT techniques and boost converter designs, especially in the context of CHB-MLI-based photovoltaic systems [33].

The existing literature showcases various approaches to improve power quality in grid-connected systems, including advanced control techniques for multilevel inverters [34]. The efficiency of a five-level inverter can be improved using a model predictive controller [35]. Model predictive control can be implemented without bulky capacitors to reduce overall cost [35]. The single-stage H-bridge grid-connected inverters offer a simple, compact, and economic topology, but they require efficient maximum power point tracking to extract maximum power from the photovoltaic arrays [36]. Previous research has not thoroughly investigated the impacts of various MPPT algorithms and boost converter designs on harmonic reduction in CHB-MLI-based photovoltaic systems [37]. Many works aim to overcome the shortcomings of the P&O algorithm, either by optimizing the methods or by combining them [38]. While there are studies on mismatch mitigation using hardware solutions, they primarily focus on bypass techniques and power electronics methods, often overlooking micro-inverters and DC optimizers [39]. The effectiveness of the ripple correlation control method for maximum power point tracking in a three-phase three-level flying capacitor inverter has been presented, but not CHB-MLIs [40]. The current literature on grid-tied inverters primarily addresses reactive power compensation and harmonic mitigation strategies, utilizing custom power devices and advanced control techniques.

III. Methodology

This research paper conducts a comprehensive evaluation of MPPT algorithms, boost converter designs, and modulation techniques on harmonic reduction in CHB-MLI-based photovoltaic systems.

The proposed research methodology will involve a combination of modeling, simulation, and experimental validation to comprehensively assess the impact of MPPT techniques and boost converter designs on harmonic reduction in CHB-MLI PV systems. Detailed system models of a grid-connected CHB-MLI PV system will be developed, incorporating different MPPT algorithms (e.g., Perturb and Observe, Incremental Conductance), boost converter topologies, and modulation techniques. These models will be implemented in simulation software such as MATLAB/Simulink to evaluate the performance of the system under various operating conditions, including variations in solar irradiance, temperature, and load demand. A variety of MPPT algorithms, including Perturb and Observe [41] [42], Incremental Conductance, and advanced techniques like Genetic Algorithm [43], will be modeled and evaluated for their ability to track the maximum power point of the PV array accurately and efficiently [44]. Boost converter designs, including conventional and interleaved topologies, will be analyzed for their impact on voltage gain, efficiency, and harmonic distortion. The performance of the CHB-MLI PV system will be evaluated based on key metrics such as total harmonic distortion, power quality, energy efficiency, and dynamic response. Experimental validation will be conducted using a laboratory prototype of the CHB-MLI PV system to verify the simulation results and assess the practical feasibility of the proposed solutions.

MPPT Techniques and Harmonic Reduction

Classical MPPT techniques, such as perturb and observation, are easily implemented due to their simplicity and perform best under constant irradiance [45]. Advanced algorithms, like those based on GA, can be implemented to improve MPPT robustness [43]. These advanced techniques have proven to be effective and feasible for implementation for MPPT. The integration of advanced control algorithms is critical to improve the performance of battery charging systems using MPPT algorithms [46].

Sliding mode control can also be implemented for MPPT. The implementation of these algorithms is essential for maximizing energy extraction from solar arrays and ensuring stable operation of the grid-connected inverter [47]. By implementing different MPPT algorithms, we can determine which ones are best suited for harmonic reduction.

The perturb and observe MPPT algorithm can be used to optimize solar cell output. When the system operates in the voltage source region of the panel characteristic curve, the panel terminal voltage collapses [48]. Convergence speed is one of the most important features among all different MPPT algorithms [49]. The perturb and observe algorithm is known for its ease of implementation and low computational complexity, but it can be easily affected by changes in irradiance, leading to oscillations around the maximum power point [50].

The incremental conductance algorithm can be used to determine the sign of the change in power-to-voltage, thereby enabling accurate tracking of the MPP, even under rapidly changing atmospheric conditions [51]. A more sophisticated approach to MPPT is sliding mode control, which offers robustness to parameter variations and disturbances [52]. You can set the sliding surface to the MPP condition to ensure the operating point converges to the optimum operating point [52].

Researchers have proposed genetic algorithms to enhance the GMPPT algorithm and estimate the initial optimal operating point [53]. GA, which analyzes the characteristics of the solar panel to extract parameters that are then used for optimization [54], [55]. By embedding a simple MPPT algorithm inside the structure of the GA, the population size and the number of iterations are decreased, thus finding the MPP in a shorter time [55]. The RCC algorithm computes the corresponding duty cycle, which serves as the input to the MRAC layer [56].

Boost Converter Topologies and Harmonic Reduction

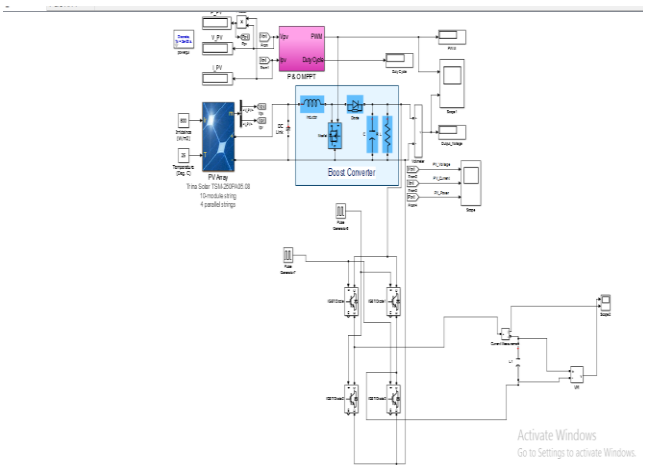


Figure 1: MATLAB Simulink of a 3-Level CHB-ML with MPPT and Boost

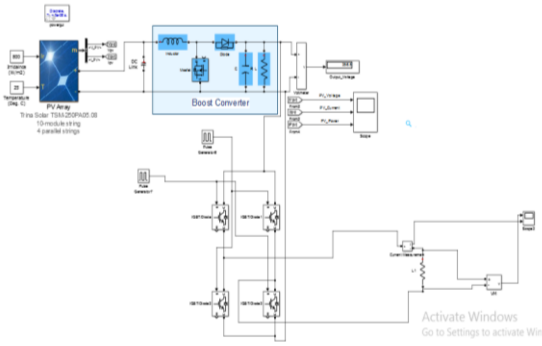


Figure 2: MATLAB Simulink of a 3-Level CHB-ML without MPPT

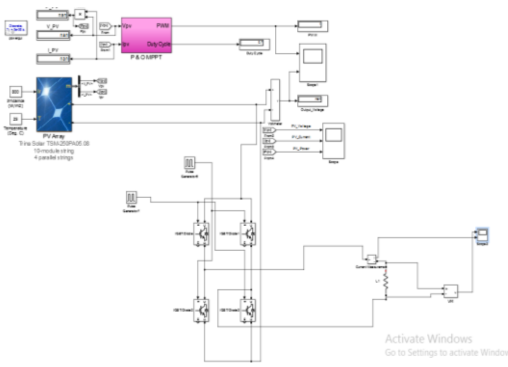


Figure 3: MATLAB Simulink of a 3-Level CHB-ML without a boost converter

Boost converters, which are important for increasing the voltage from the PV array to the DC-link voltage needed by the CHB-MLI, significantly influence the system's harmonic profile. The design and control of the boost converter significantly influence the overall efficiency and harmonic distortion of the PV system. Different types of boost converters, like traditional, interleaved, and soft-switching converters, perform differently when it comes to efficiency, how much they increase voltage, and the amount of unwanted noise they create.

Conventional boost converters are straightforward and cost-effective; however, they may experience high voltage stress on the switching devices and increased harmonic distortion. Interleaved boost converters can lower input current ripple and enhance efficiency, but they necessitate more complex control schemes. Soft-switching converters, such as zero-voltage switching and zero-current switching converters, can decrease switching losses and boost efficiency, though they may also raise circuit complexity and costs. Selecting the right boost converter topology and control strategy is crucial for minimizing harmonic distortion and maximizing the overall performance of the CHB-MLI PV system. Furthermore, advanced control techniques, including active current shaping and harmonic injections, can be employed to further reduce harmonic distortion and enhance power quality. The design of the boost converter must consider trade-offs in cost, circuit complexity, and the level of harmonics.

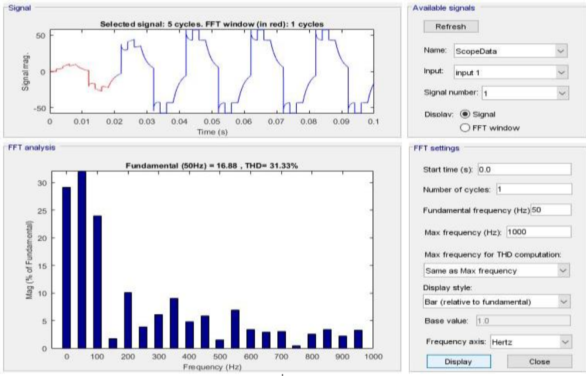
VI. Results and Discussion

This section presents a comparative analysis of the performance of CHB-MLI photovoltaic systems under various control and converter configurations, focusing on harmonic distortion, waveform quality, and adaptability to load conditions. The evaluation is based on MATLAB/Simulink simulations, with planned experimental validation to confirm the simulation outcomes.

Figure 4: FFT Analysis of Output Signal of a 5-Level CHB-MLI with Capacitive Load

Table 1: Comparison between Three-level & Five-level Inverters

Parameters	**3-Level Chb Inverter**	**5-Level Chb Inverter**
Number Of Switches	4	8
Number Of DC Sources	1	2
THD Of Load Voltage With R-Load	95.95%	56.92%



THD Of Load Voltage with LC Load	52.96%	42.99%
THD of Load Voltage with RC Load	45.54%	30.24%

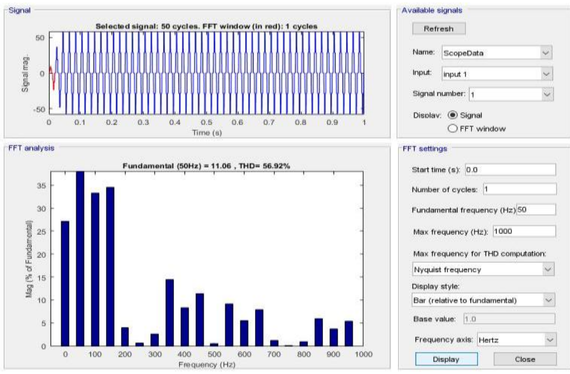


Figure 5: FFT Analysis of Output Signal of a 5-Level CHB-ML

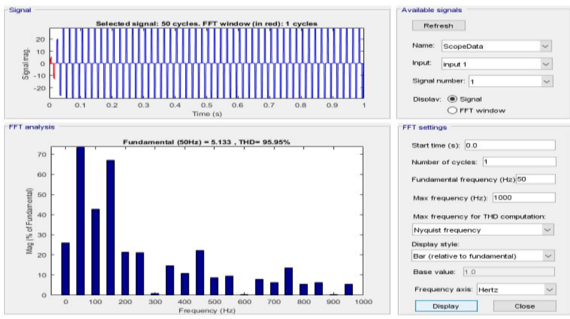


Figure 6: FFT Analysis of Output Signal of a 3-Level CHB-MLI

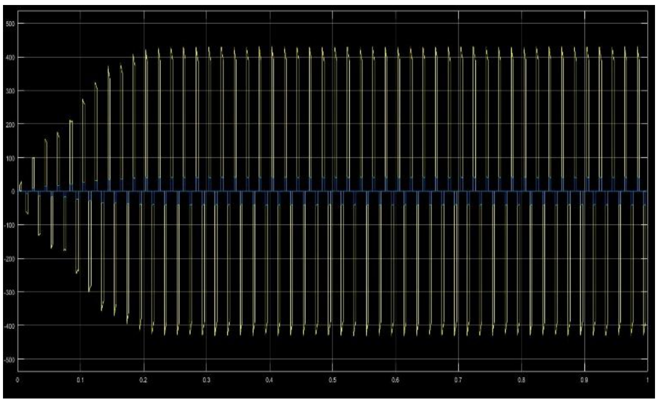


Figure 7: FFT Analysis of Output Signal of a 5-Level CHB-MLI with Capacitive Load

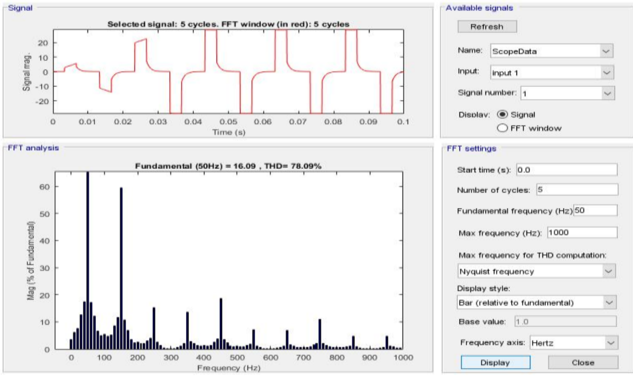


Figure 8: FFT Analysis of Output Signal of a 3-Level CHB-MLI with Capacitive Load

A. Impact of MPPT and Boost Converter on Harmonic Distortion

The incorporation of both Maximum Power Point Tracking (MPPT) and a DC-DC boost converter demonstrated a substantial reduction in Total Harmonic Distortion (THD) across all tested load conditions. The synergistic operation of the Perturb and Observe (P&O) MPPT algorithm and voltage-elevating boost conversion contributes to optimal energy extraction and waveform shaping, resulting in cleaner inverter output.

Among the three configurations studied—(i) CHB-MLI with MPPT and boost converter, (ii) CHB-MLI with boost converter only, and (iii) CHB-MLI with MPPT only—the first yielded the lowest THD values. This confirms that joint control strategies are essential for harmonic mitigation and power quality enhancement in grid-connected PV systems.

B. Performance of 3-Level vs. 5-Level CHB-MLI

The simulation results highlight the superior performance of the 5-level CHB-MLI compared to the 3-level counterpart. As presented in Table VI, the THD of the load voltage significantly decreased with the increase in voltage levels, particularly under resistive-capacitive (RC) and inductive-capacitive (LC) load conditions. The five-level configuration exhibited:

- **THD with R-load:** 56.92% (vs. 95.95% in 3-level)
- **THD with LC-load:** 42.99% (vs. 52.96%)
- **THD with RC-load:** 30.24% (vs. 45.54%)

This indicates that higher voltage levels in CHB-MLIs allow better waveform approximation to sinusoidal output, thereby reducing harmonic content and improving overall power quality.

C. FFT Analysis of Inverter Output

The Fast Fourier Transform (FFT) analysis provides further insights into the harmonic content of the inverter output across different configurations:

- **Figure 28** illustrates the output spectrum of a 5-level CHB-MLI, showing diminished low-order harmonics and a smoother waveform.
- **Figure 31** depicts the output of a 3-level CHB-MLI, where prominent harmonic peaks are observed.
- **Figures 33 and 34** compare the harmonic performance of both configurations under capacitive loading.

The 5-level inverter maintains its superior performance, while the 3-level system exhibits greater waveform distortion under the same conditions.

These results reinforce the role of inverter topology and control strategies in shaping the harmonic profile of PV-based power systems.

D. Influence of Load Types

The system's harmonic behavior also varied based on load conditions. RC loads were found to produce the lowest THD values, attributed to inherent damping effects that attenuate voltage oscillations. Capacitive loading, particularly in lower-level inverters, aggravated waveform distortion; however, this was mitigated in the five-level configuration, highlighting its robustness under reactive loading scenarios.

E. Converter Topologies and Control Strategy Implications

The choice of boost converter topology was shown to directly influence harmonic performance and system efficiency. While conventional converters offer simplicity, interleaved designs reduce input current ripple and improve THD. Soft-switching converters such as Zero-Voltage Switching (ZVS) and Zero-Current Switching (ZCS) provide further efficiency improvements but introduce additional complexity and cost.

Advanced control techniques, including active current shaping and harmonic injection methods, offer promising directions for further harmonic suppression in CHB-MLI PV systems.

F. Adaptability and Real-Time Performance

The proposed system architecture demonstrated reliable adaptation to dynamic environmental conditions, including solar irradiance variability and load transitions. This adaptability ensures voltage regulation and waveform stability across both grid-connected and standalone operation modes. The complete system is scheduled for experimental validation using a laboratory-scale CHB-MLI PV prototype, which will serve to confirm simulation results and assess real-world feasibility.

VII. Conclusion

This paper has presented a detailed investigation into the effects of Maximum Power Point Tracking (MPPT) and boost converter integration on harmonic reduction in Cascaded H-Bridge Multilevel Inverter (CHB-MLI)-based photovoltaic (PV) systems. Through comprehensive MATLAB/Simulink simulations, three configurations were analyzed—CHB-MLI with both MPPT and boost converter, with MPPT only, and with boost converter only. The Perturb and Observe (P&O) MPPT algorithm was employed in all relevant cases to optimize energy extraction from the PV source under variable conditions.

Simulation results demonstrated that the combination of MPPT and boost converter significantly minimizes Total Harmonic Distortion (THD) in the inverter output, thereby improving waveform quality and ensuring better compliance with grid integration standards. The five-level CHB-MLI showed superior harmonic mitigation capabilities compared to the three-level configuration across all load types (R, LC, and RC), with the lowest THD observed under RC load conditions.

The Fast Fourier Transform (FFT) analysis reinforced these findings, highlighting the reduced harmonic peaks and improved waveform smoothness in systems employing both MPPT and boost conversion. Furthermore, the inclusion of interleaved and soft-switching boost converter topologies has the potential to enhance power quality by minimizing current ripple and switching losses.

Future work will involve experimental validation using a laboratory-scale CHB-MLI PV prototype to confirm simulation results and evaluate the practical implementation feasibility of various MPPT algorithms and converter designs. Overall, this study provides actionable insights into the design of efficient, low-distortion renewable energy systems that are robust under dynamic environmental and load conditions.

References

[1] "Comparison Study of MPPT Algorithms for Solar Photovoltaic Charge Controllers," International Journal of Modern Trends in Engineering & Research, vol. 5, no. 5, p. 15, May 2018, doi: 10.21884/ijmter.. 2018.5135.w74a2.

[2] S. E. Babaa, M. Armstrong, and V. Pickert, "Overview of Maximum Power Point Tracking Control Methods for PV Systems," Journal of Power and Energy Engineering, vol. 2, no. 8, p. 59, Jan. 2014, doi: 10.4236/jpee 2014.28006.

[3] A. O. Baba, G. Liu, and X. Chen, "Classification and Evaluation Review of Maximum Power Point Tracking Methods," Sustainable Futures, vol. 2, p. 100020, Jan. 2020, doi: 10.1016/j.sftr.2020.100020.

[4] S. Al-Chlaihawi and A. N. Hassan, "Analysis and Implementation of Fuzzy Control for the MPPT Based PV Systems," Journal of Physics Conference Series, vol. 1973, no. 1, p. 12012, Aug. 2021, doi: 10.1088/1742- 6596/1973/1/012012.

[5] S. A. Sarang et al., "Maximizing solar power generation through conventional and digital MPPT techniques: a comparative analysis," Scientific Reports, vol. 14, no. 1, Apr. 2024, doi: 10.1038/s41598-024-59776-z.

[6] A. N. M. Mohammad, M. A. M. Radzi, N. Azis, S. Shafie, and M. A. A. M. Zainuri, "A Novel Hybrid Approach for Maximizing the Extracted Photovoltaic Power under Complex Partial Shading Conditions," Sustainability, vol. 12, no. 14, p. 5786, Jul. 2020, doi: 10.3390/su12145786.

[7] Ö. F. Keçecioğlu, "Robust control of high gain DC-DC converter using Type-2 fuzzy neural network controller for MPPT," Journal of Intelligent & Fuzzy Systems, vol. 37, no. 1, p. 941, Jun. 2019, doi: 10.3233/jifs-181770.

[8] B. S. Ammaiyappan and R. Seyezhai, "Comparative analysis of Maximum Power Point Tracking Algorithms for Photovoltaic Applications," WSEAS TRANSACTIONS ON POWER SYSTEMS, vol. 15, p. 161, Sep. 2020, doi: 10.37394/232016.2020.15.20.

[9] I. A. Elzein and Y. Petranko, "A study of maximum power point tracking algorithm for photovoltaic systems using a fuzzy logic controller," WIT transactions on engineering sciences, vol. 1, p. 409, Dec. 2014, doi: 10.2495/amee140481.

[10] U. Ali, "Z-source DC-DC Converter with Fuzzy Logic MPPT Control for Photovoltaic Applications," Energy Procedia, vol. 90, p. 163, Dec. 2016, doi: 10.1016/j.egypro.2016.11.181.

[11] H. Attia and A. Elkhateb, "Intelligent maximum power point tracker enhanced by sliding mode control," International Journal of Power Electronics and Drive Systems/International Journal of Electrical and Computer Engineering, vol. 13, no. 2, p. 1037, May 2022, doi: 10.11591/ijpeds. v13.i2. pp1037- 1046.

[12] G. Adinolfi, N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, "Design of DC/DC Converters for DMPPT PV Applications Based on the Concept of Energetic Efficiency," Journal of Solar Energy Engineering, vol. 132, no. 2, May 2010, doi: 10.1115/1.4001465.

[13] H. Boumaaraf, A. Talha, and O. Bouhali, "A three-phase NPC grid-connected inverter for photovoltaic applications using neural network MPPT," Renewable and Sustainable Energy Reviews, vol. 49, p. 1171, May 2015, doi: 10.1016/j.rser.2015.04.066.

[14] K. Amara et al., "Adaptive neuro-fuzzy inference system based maximum power point tracking for stand-alone photovoltaic system," International Journal of Modelling Identification and Control, vol. 33, no. 4, p. 311, Jan. 2019, doi: 10.1504/ijmic 2019.107480.

[15] K. Y. Yap, C. R. Sarimuthu, and J. M.-Y. Lim, "Artificial Intelligence Based MPPT Techniques for Solar Power System: A review," Journal of Modern Power Systems and Clean Energy, vol. 8, no. 6. Springer Nature, p. 1043, Jan. 01, 2020. doi: 10.35833/mpce.2020.000159.

[16] C. Buccella, M. G. Cimoroni, and C. Cecati, "Mitigation Technique for Cascaded H-Bridge Multilevel Inverters Based on Pulse Active Width Modulation," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 11, no. 1, p. 999, Aug. 2022, doi: 10.1109/jestpe 2022.3196062.
[17] İ. Çolak, E. Kabalcı, and R. Bayındır, "Review of multilevel voltage source inverter topologies and control schemes," Energy Conversion and Management, vol. 52, no. 2, p. 1114, Oct. 2010, doi: 10.1016/j.enconman.2010.09.006.
[18] V. Singh, S. Gupta, S. Pattnaik, and R. K. Dewangan, "New hybrid cascade multilevel inverter with fewer number of switches," p. 1, Dec. 2014, doi: 10.1109/34084poweri.2014.7117692.
[19] M. Madhushree, "Design and Analysis of 15-Level Multilevel Inverter with Reduced Number of Switches for Renewable Applications," International Journal of Engineering Research and Applications, no. 9, Oct. 2020, doi: 10.17577/ijertv9is090442.
[20] A. Siadatan, E. Afjei, M. Rafiee, and M. Montazeri, "Higher voltage level and lower total harmonic distortion in a new setting of multilevel inverter," vol. 3, p. 435, Jun. 2012, doi: 10.1109/icias 2012.6306233.
[21] K. Maheswari, R. Bharanikumar, V. Arjun, R. Amrish, and M. Bhuvanesh, "A comprehensive review on cascaded H-bridge multilevel inverter for medium voltage high power applications," Materials Today Proceedings, vol. 45. Elsevier BV, p. 2666, Dec. 30, 2020. doi: 10.1016/j.matpr.2020.11.519.
[22] C. Buccella et al., "Recursive Selective Harmonic Elimination for Multilevel Inverters: Mathematical Formulation and Experimental Validation," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 11, no. 2, p. 2178, Nov. 2022, doi: 10.1109/jestpe 2022.3221154.
[23] B. Mahato, S. Majumdar, S. Vatsyayan, and K. C. Jana, "A New and Generalized Structure of MLI Topology with Half-bridge Cell with Minimum Number of Power Electronic Devices," IETE Technical Review, vol. 38, no. 2, p. 267, Feb. 2020, doi: 10.1080/02564602.2020.1726215.
[24] A. Bughneda, M. Salem, A. Richelli, D. Ishak, and S. Alatai, "Review of Multilevel Inverters for PV Energy System Applications," Energies, vol. 14, no. 6, p. 1585, Mar. 2021, doi: 10.3390/en14061585.
[25] P. Archana, "Closed Loop Control of Multi Level Inverter Using Reverse Voltage Topology," SSRN Electronic Journal, Jan. 2019, Accessed: Jan. 2025. [Online]. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3536955
[26] E. Parimalasundar, R. Jayanthi, K. Suresh, and R. Sindhuja, "Investigation of efficient multilevel inverter for photovoltaic energy system and electric vehicle applications," Electrical Engineering & Electromechanics, no. 4, p. 47, Jun. 2023, doi: 10.20998/2074-272x.2023.4.07.
[27] M. S. Sujatha, S. Sreelakshmi, E. Parimalasundar, and K. Suresh, "Mitigation of harmonics for five-level multilevel inverter with fuzzy logic controller," Electrical Engineering & Electromechanics, no. 4, p. 52, Jun. 2023, doi: 10.20998/2074-272x.2023.4.08.
[28] A. S. Mohamad, N. Mariun, N. Sulaiman, and M. A. M. Radzi, "A new cascaded multilevel inverter topology with minimum number of conducting switches," p. 164, May 2014, doi: 10.1109/isgt-asia.2014.6873783.
[29] I B. F. Citarsa, I. N. W. Satiawan, I. K. Wiryajati, and S. SUPRIONO, "Performance analysis of cascaded h-bridge multilevel inverter using mixed switching frequency with various dc-link voltages," in IOP Conference Series Materials Science and Engineering, IOP Publishing, Jan. 2016, p. 12003. doi: 10.1088/1757-899x/105/1/012003.
[30] N. S. Hasan, N. Rosmin, Dygku. A. Awg. Osman, and A. H. Musta'ámal, "Reviews on multilevel converter and modulation techniques," Renewable and Sustainable Energy Reviews, vol. 80, p. 163, May 2017, doi: 10.1016/j.rser.2017.05.163.
[31] M. S. Varna and J. Jose, "Seven-level inverter with nearest level control," p. 1, Mar. 2014, doi: 10.1109/icgccee 2014.6922346.
[32] P. Mlodzikowski, A. Milczarek, and M. Malinowski, "Application of Simplified Neutral Point Clamped Multilevel Converter in a Small Wind Turbine," Electrical Control and Communication Engineering, vol. 5, no. 1, p. 5, May 2014, doi: 10.2478/ecce-2014-0001.
[33] S. R. Khasim and C. Dhanamjayulu, "Design and Implementation of Asymmetrical Multilevel Inverter With Reduced Components and Low Voltage Stress," IEEE Access, vol. 10, p. 3495, Jan. 2022, doi: 10.1109/access 2022.3140354.
[34] S. Jahan et al., "An Advanced Control Technique for Power Quality Improvement of Grid-Tied Multilevel Inverter," Sustainability, vol. 13, no. 2, p. 505, Jan. 2021, doi: 10.3390/su13020505.
[35] M. A. Ayub, S. Aziz, Y. Liu, J. Peng, and J. Yin, "Design and Control of Novel Single-Phase Multilevel Voltage Inverter Using MPC Controller," Sustainability, vol. 15, no. 1, p. 860, Jan. 2023, doi: 10.3390/su15010860.
[36] M. Hammami, G. Grandi, and M. Rudan, "An improved MPPT algorithm based on hybrid RCC scheme for single-phase PV systems," p. 3024, Oct. 2016, doi: 10.1109/iecon 2016.7793032.
[37] A. Mizukoshi and H. Haga, "Voltage Harmonic Analysis of Typical PWM Strategies in a Dual Inverter with Floating Capacitor in the Partial-Load Condition," IEEJ Journal of Industry Applications, vol. 11, no. 1, p. 163, Sep. 2021, doi: 10.1541/ieejjia 21007243.
[38] D. Séra, T. Kerekes, R. Teodorescu, and F. Blaabjerg, "Improved MPPT Algorithms for Rapidly Changing Environmental Conditions," in 2006 12th International Power Electronics and Motion Control Conference, Aug. 2006, p. 1614. doi: 10.1109/epepemc 2006.4778635.
[39] H. Bassi, Z. Salam, M. Z. Ramli, H. F. Sindi, and M. Rawa, "Hardware Approach to Mitigate the Effects of Module Mismatch in a Grid-connected Photovoltaic System: A Review," Energies, vol. 12, no. 22. Multidisciplinary Digital Publishing Institute, p. 4321, Nov. 13, 2019. doi: 10.3390/en12224321.
[40] M. Hammami, M. Ricco, A. Ruderman, and G. Grandi, "Three-Phase Three-Level Flying Capacitor PV Generation System with an Embedded Ripple Correlation Control MPPT Algorithm," Electronics, vol. 8, no. 2, p. 118, Jan. 2019, doi: 10.3390/electronics8020118.
[41] M. D. Kundalik and P. Karpagavalli, "Perturb and Observe Algorithm in Maximum Power Point Tracking (MPPT) for Solar Generation," International Journal of Innovative Technology and Exploring Engineering, vol. 9, no. 4, p. 5447, Feb. 2020, doi: 10.35940/ijitee.b7710.029420.
[42] L. Atik, P. Petit, J.-P. Sawicki, Z. T. Ternifi, G. Bachir, and M. Aillerie, "Comparison of four MPPT techniques for PV systems," AIP conference proceedings, vol. 1758, p. 30047, Jan. 2016, doi: 10.1063/1.4959443.
[43] Y. Shaiek, M. B. Smida, A. Sakly, and M. F. Mimouni, "Comparison between conventional methods and GA approach for maximum power point tracking of shaded solar PV generators," Solar Energy, vol. 90, p. 107, Feb. 2013, doi: 10.1016/j.solener.2013.01.005.
[44] J. Salim, M. S. Alwan, and Б. М. Албакер, "A Conceptual Framework and a Review of AI-Based MPPT Techniques for Photovoltaic Systems," Journal of Physics Conference Series, vol. 1963, no. 1. IOP Publishing, p. 12168, Jul. 01, 2021. Doi: 10.1088/1742 6596/1963/1/012168.
[45] M. L. Katche, A. B. Makokha, S. O. Zachary, and M. S. Adaramola, "A Comprehensive Review of Maximum Power Point Tracking (MPPT) Techniques Used in Solar PV Systems," Energies, vol. 16, no. 5. Multidisciplinary Digital Publishing Institute, p. 2206, Feb. 24, 2023. doi: 10.3390/en16052206.
[46] H. C. Yang, J. A.-F. Yahaya, and A. Ponniran, "The Study of MPPT Algorithm for Solar Battery Charging System," Malaysian Journal of Science and Advanced Technology, p. 109, Aug. 2022, doi: 10.56532/mjsat.v2i3.56.

[47] R. Gimazov and S. Shidlovskiy, “Simulation Modeling of Intelligent Control Algorithms for Constructing Autonomous Power Supply Systems with Improved Energy Efficiency,” MATEC Web of Conferences, vol. 155, p. 1032, Jan. 2018, doi: 10.1051/matecconf/201815501032.
[48] S. Bandri, Z. Zulkarnaini, A. Syofian, and A. Effendi, “The application of perturb and observe algorithm to optimize solar cell output,” Journal of Physics Conference Series, vol. 1185, p. 12012, Apr. 2019, doi: 10.1088/1742 6596/1185/1/012012.
[49] M. Hlaili and M. Hfaiedh, “Comparison of Different MPPT Algorithms with a Proposed One Using a Power Estimator for Grid Connected PV Systems,” International Journal of Photoenergy, vol. 2016, p. 1, Jan. 2016, doi: 10.1155/2016/1728398.
[50] M. F. N. Tajuddin, M. S. B. Arif, S. M. Ayob, and Z. Salam, “Perturbative methods for maximum power point tracking (MPPT) of photovoltaic (PV) systems: a review,” International Journal of Energy Research, vol. 39, no. 9. Wiley, p. 1153, Feb. 05, 2015. doi: 10.1002/er.3289.
[51] M. A. Elgendy, D. J. Atkinson, and B. Zahawi, “Evaluation of incremental conductance MPPT algorithm at low perturbation rates,” in 8th IET International Conference on Power Electronics, Machines and Drives (PEMD 2016), Jan. 2014. doi: 10.1049/cp 2014.0429.
[52] M. Alsumiri, L. Jiang, and W. Tang, “Maximum Power Point Tracking Controller for Photovoltaic System Using Sliding Mode Control,” Jan. 2014, doi: 10.1049/cp 2014.0884.
[53] T. Tafticht, M. Tchakala, and M. J. Rahman, “GMPPT approach for photovoltaic systems under partial shading conditions using a genetic algorithm,” International Journal of Power Electronics and Drive Systems/International Journal of Electrical and Computer Engineering, vol. 13, no. 2, p. 1238, May 2022, doi: 10.11591/ijpeds. v13.i2. pp1238-1245.
[54] S. Hadji, J. Gaubert, and F. Krim, “Real-Time Genetic Algorithms-Based MPPT: Study and Comparison (Theoretical and Experimental) with Conventional Methods,” Energies, vol. 11, no. 2, p. 459, Feb. 2018, doi: 10.3390/en11020459.
[55] S. Dărăban, D. Petreuș, and C. Morel, “A novel MPPT (maximum power point tracking) algorithm based on a modified genetic algorithm specialized on tracking the global maximum power point in photovoltaic systems affected by partial shading,” Energy, vol. 74, p. 374, Jul. 2014, doi: 10.1016/j.energy.2014.07.001.
[56] Q. Zhang, “maximum power point tracking in photovoltaic systems using model reference adaptive control,” Jan. 2013, Accessed: Dec. 2024. [Online]. Available: http://d-scholarship.pitt.edu/16560/1/zhangqh_etd2012.pdf
[57] Ş. Özdemir, N. Altın, and İ. Sefa, “Fuzzy logic based MPPT controller for high conversion ratio quadratic boost converter,” International Journal of Hydrogen Energy, vol. 42, no. 28, p. 17748, Mar. 2017, doi: 10.1016/j.ijhydene.2017.02.191.
[58] J.-K. Shiau, M.-Y. Lee, Y.-C. Wei and B.-C. Chen, “Circuit Simulation for Solar Power Maximum Power Point Tracking with Different Buck-Boost Converter Topologies,” Energies, vol. 7, no. 8, p. 5027, Aug. 2014, doi: 10.3390/en7085027.
[59] A. K. Pati and N. C. Sahoo, “Adaptive super-twisting sliding mode control for a three-phase single-stage grid-connected differential boost inverter based photovoltaic system,” ISA Transactions, vol. 69, p. 296, May 2017, doi: 10.1016/j.isatra.2017.05.002.
[60] M. Golla, K. Chandrasekaran, and S. P. Simon, “PV integrated universal active power filter for power quality enhancement and effective power management,” Energy Sustainable Development/Energy for sustainable development, vol. 61, p. 104, Feb. 2021, doi: 10.1016/j.esd.2021.01.005.
[61] M. E. Akdogan and S. Ahmed, “Control Hardware-in-the-loop for Voltage Controlled Inverters with Unbalanced and Non-linear Loads in Stand-alone Photovoltaic(PV) Islanded Microgrids,” arXiv (Cornell University), Jan. 2020, doi: 10.48550/arxiv 2007.05306.
[62] T. Sutikno, W. Arsadiando, A. Wangsupphaphol, A. Yudhana, and M. Facta, “A Review of Recent Advances on Hybrid Energy Storage System for Solar Photovoltaics Power Generation,” IEEE Access, vol. 10. Institute of Electrical and Electronics Engineers, p. 42346, Jan. 01, 2022. doi: 10.1109/acce
Ss 2022.3165798.