



Design and Implementation of Grid Connection of Multilevel Inverter for Improved Power Quality

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Abstract— Multilevel inverters (MLI) have a variety of applications in battery storage system, renewable energy integration, electric vehicle (EV), drives for industry and in various flexible AC transmission system (FACTS). Applications of MLI in battery storage system have greatly increased over the past few decades. Conventional MLIs used for grid integration of battery energy storage is having large number of components and it requires transformer for grid integration. The large number of components and transformer increases the cost, size, weight and losses of the MLI, thus reduces the efficiency of the system. Keeping this in view, the goal of the proposed work is to design a novel reduced switch seventeen-level MLI which is having a lower number of components and do not require transformer for grid integration. This modular nature of proposed MLI is used to increase power handling capacity without introducing additional converters. For this, first proposed reduced switch seventeen-level MLI has been compared with other existing seventeen level topologies which in order to show the effectiveness of proposed topology. After analysis its effectiveness, the proposed MLI has been designed and then closed loop d-q current controller for grid connected mode is analyzed. The different curves are plotted to justify the stability of proposed inverter. The control of output voltage is also included using modified sine pulse width modulation (SPWM) method. The proposed MLI has been implemented in MATLAB/Simulink and validated using real time hardware-in-loop (HIL) emulator.

Keywords— *Multilevel Inverters (MLI), Electric Vehicle (EV), Flexible AC Transmission System (FACTS), Sine Pulse Width Modulation (SPWM) and MATLAB/Simulink.*

I. INTRODUCTION

The concept of multilevel inverters was developed back in 1975 [1,2]. These types of inverters generate an output voltage that resembles a sinusoidal wave by using multiple DC voltage sources. Due to their low harmonic distortion in the output, power electronics inverters are widely used in various industrial applications [3], such as static VAR generation, Flexible AC transmission systems (FACTS), and battery charging applications [4]. Multilevel inverters are also used in traction drives, where they act as rectifiers in vehicles for regenerative braking. However, the complexity of the circuitry, which involves a significant number of switches and the use of multiple DC sources, has prompted research into ways of reducing these complexities. In transformer-less grid-connected photovoltaic (PV) applications, multi-level inverters (MLIs) have solidified their position as the system's fundamental building block [5], [6], [7]. It is feasible to create a small, lightweight system integrated into the grid at a significantly cheaper cost by removing the PV system's massive line frequency transformer. The system's efficiency is also enhanced by the absence of core as well as ohmic losses [8]. The leakage current from the distributed grid side to the solar PV system, however, it may breach safety

regulations due to ground parasitic capacitances as well as ground resistance [9].

Comparing with some traditional H-bridge transformer-less inverters have leakage current issues [10,11], which lowers their common-mode voltages (CMV) at the switching frequency. The issue of charging capacitors that are either twice as large or equivalent to the DC-link voltage affects most of the five-level common-grounded topologies [12,13], that have been previously documented [14]. Additionally, these 5-level boost inverters' capacitors frequently drain a sizable amount of inrush current during which charging, increasing the peak VA ratings of the inverter's components [15]. Due to the significant overall cost and power losses of the inverter, therefore these inverter-based systems are considered useless at higher output levels [16]. Recently, a few high gains switched-capacitor MLIs (SC-MLIs) with fewer switching counts and smaller filters have been produced [17,18]. It is best suited for grid-connected PV applications without transformers, since the design switched capacitor does not include more H-bridges for polarity change. The use of four input sources increases the topology's overall cost [19]. The voltage ripple loss and conduction loss both rise with increasing power levels, decreasing efficiency. When there are more conducting switches and capacitors, there is a rise

in conduction loss, switching loss, and voltage ripple loss, which lowers the efficiency of inverter [20,21]. However, these multisource MLIs have a power mismatch problem as a result of the asymmetry of the DC sources. The power handling capacity can be increased using the modular MLI architecture without the need for additional converters. PV system subjected to fluctuating lighting. Thus, the majority of the existing transformer-free grid-integrated PV inverters are demonstrated for low voltage levels, as can be demonstrated from previous research. The components of these inverters have significantly higher VA ratings because of their large inrush current. The filters and switching frequency on the switches are also substantial. However, because capacitors spend more time discharging than charging, causing more voltage ripple loss, the high-gain SC-MLIs or the high-level are less efficient. For grid-connected PV applications without transformers, many SC-MLIs are also unable to maintain the leakage current below the allowed threshold.

II. LITERATURE REVIEW

Double synchronous reference frame-based power synchronized PLL-less grid-following inverters for unbalanced grid faults N. Mohammed, W. Zhou, and B. Bahrani (2023). This study introduces a novel control framework for grid-following inverters that eliminates the need for conventional Phase-Locked Loop (PLL) mechanisms, which are typically used to synchronize inverter output with the utility grid. Instead, the authors propose a double synchronous reference frame (DSRF) approach integrated with power-synchronization techniques. The primary motivation behind this method is to enhance inverter performance during unbalanced grid fault conditions, where conventional PLLs often suffer from instability and inaccurate synchronization. For grid-connected photovoltaic (PV) systems such as a 1 MW rooftop solar plant, this research is highly relevant. Large-scale PV inverters often face synchronization challenges, especially in weak or fault-prone grids. By adopting PLL-less synchronization, the system can ensure reliable power injection, lower harmonic distortion, and compliance with modern grid codes. This makes the contribution valuable for designing next-generation PV grid integration strategies.[1] An investigation of PLL synchronization techniques for distributed generation sources in the grid-connected mode of operation. S. V. Kulkarni, A. K. Sharma, R. S. Bhat, and S. V. Kulkarni (2023). This paper provides a comprehensive analysis of various Phase-Locked Loop (PLL) synchronization techniques used in distributed generation (DG) systems. The authors compare conventional synchronous reference frame PLL, second-order generalized integrator PLL, and enhanced PLL variants, focusing on their dynamic response, accuracy, and robustness under grid disturbances. The results indicate that while traditional SRF-PLL offers simple implementation, it struggles during frequency deviations and unbalanced faults, leading to instability in DG systems such as solar PV inverters. Advanced PLL methods with adaptive filtering show improved tracking capability and reduced sensitivity to harmonics. For large rooftop PV

plants, synchronization with the utility grid is critical to ensure seamless power injection and compliance with IEEE 1547 standards. The study highlights that PLL performance directly influences inverter stability, harmonic mitigation, and power quality. Importantly, the paper emphasizes the trade-off between complexity and performance: advanced PLLs improve robustness but require higher computational resources. The findings are crucial for 1 MW rooftop PV systems, where multiple inverters operate simultaneously and reliable grid synchronization prevents circulating currents and instability. This review establishes the need for adaptive synchronization strategies for PV-based distributed generation in smart grids.[2] The assessment framework includes detailed stability analysis, damping strategies, and harmonic attenuation capacity, supported by simulations and hardware tests. Results indicate that hybrid design methods combining analytical modeling with optimization provide the best trade-off between cost and performance. For a 1 MW rooftop PV system, where numerous converters operate in parallel, such a systematic evaluation is crucial. Poorly designed filters may lead to instability, higher THD, and reduced system lifetime. This research contributes to the standardization of LCL filter assessment, enabling PV engineers to select appropriate filter parameters that ensure compliance with grid codes while maintaining efficiency. The paper's broad and practical approach strengthens its relevance for both academic research and real-world solar rooftop projects.[7] Harmonic elimination of a fifteen-level inverter with reduced devices. Joshi, V. S. Kale, and M. R. Ramteke (2023). This work explores harmonic elimination in multilevel inverters using a fifteen-level topology with reduced device count. The authors propose an optimized switching strategy that minimizes total harmonic distortion (THD) while reducing the number of semiconductor switches compared to conventional designs. This results in lower costs, reduced switching losses, and improved efficiency. Simulation results demonstrate that the proposed inverter achieves near-sinusoidal output with THD values well within IEEE 519 limits, even under varying load conditions. By reducing device count, the design also improves reliability and ease of implementation, making it attractive for renewable energy applications.

III. PROPOSED MODIFIED

The effective integration of power electronic systems such as multilevel inverters with utility grids requires a structured and methodical approach that encompasses proper modeling, control, synchronization, and testing. This chapter outlines the complete methodology adopted for the modeling, simulation, and implementation of a grid-connected Cascaded H-Bridge (CHB) multilevel inverter, designed to enhance power quality while complying with international harmonic standards. The aim is to demonstrate, through simulation, the ability of the inverter to generate clean AC power from DC sources and inject it seamlessly into the grid. The proposed system uses a 5-level CHB inverter topology, which is favored for its modularity, lower voltage stress

on switches, and high-quality output. Each H-bridge unit is powered by an isolated DC source—commonly available from photovoltaic panels or battery storage systems. The inverter is controlled using a Sinusoidal Pulse Width Modulation (SPWM) technique, which determines the switching behavior to achieve the desired stepped AC output waveform. The inverter's output is then passed through an LC filter to smooth out voltage ripples and reduce high-frequency harmonics before it reaches the grid.

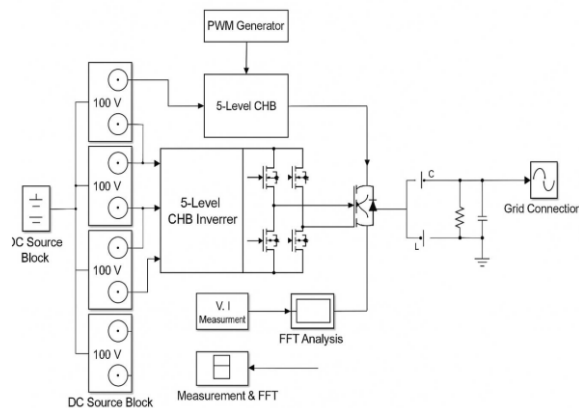


Figure 1 5-level Cascaded H-Bridge (CHB) multilevel inverter system

B. Simulation Environment

A reliable and flexible simulation environment is essential for accurately modeling, analyzing, and optimizing power electronic systems before their physical implementation. In this research, the entire simulation of the 5-level Cascaded H-Bridge (CHB) multilevel inverter system is carried out using MATLAB/Simulink, which provides a comprehensive suite of tools for dynamic modeling, signal processing, power systems, and power electronics applications.

MATLAB/Simulink is widely used in academia and industry due to its ease of use, rich component libraries, and the ability to simulate both linear and nonlinear systems with high precision. For this project, it offered a suitable platform to develop and test a MLI model that integrates various subsystems such as control logic, switching circuits, synchronization modules, and waveform analysis tools. It also supports time-domain and frequency-domain simulations, which are essential for power quality assessment and harmonic analysis.

C. Preventive and Corrective Actions

In any power conversion system—especially one as complex and modular as a Cascaded H-Bridge (CHB) multilevel inverter—ensuring long-term operational efficiency and safety requires a structured strategy for both preventive and corrective maintenance actions. While preventive actions aim to stop faults before they occur, corrective actions are essential for restoring system functionality after a failure. Together, these approaches ensure high system availability, lower maintenance costs, and improved reliability, particularly

in grid-connected applications where downtime can lead to operational and financial losses.

D. Safety Considerations

Safety is a fundamental pillar in the design, operation, and maintenance of power electronic systems, especially in grid-connected multilevel inverters. A Cascaded H-Bridge (CHB) multilevel inverter involves the handling of high voltages, high-frequency switching, and direct grid interfacing, all of which introduce risks to personnel, equipment, and connected infrastructure. Therefore, adopting comprehensive safety measures at every stage of operation—from system startup to routine maintenance—is not just a recommendation but an essential requirement.

IV. SIMULATION RESULT ANALYSIS

A. Waveform Analysis

The performance of a multilevel inverter system, particularly when connected to a utility grid, is primarily evaluated through its ability to generate high-quality voltage and current waveforms. In this section, the simulated waveforms of the proposed 5-level Cascaded H-Bridge (CHB) inverter are analyzed in detail to validate its performance under ideal operating conditions. The analysis includes inverter output voltage, grid current, load current, and filtered output, providing insights into the system's efficiency, switching behavior, and overall power quality.

The simulation was carried out using MATLAB/Simulink with realistic switching parameters and proper grid synchronization. Key variables such as DC input, PWM control timing, filter parameters, and grid voltage were carefully configured to replicate actual field behavior. The waveform analysis is presented in a systematic manner below.

- **Inverter Output Voltage Waveform-** The unfiltered output of the 5-level CHB inverter exhibits a distinct stepped waveform, which is a hallmark of multilevel inverter topologies. Each H-bridge module contributes an incremental voltage level, and their cumulative operation results in an output that approximates a sine wave more closely than conventional two-level inverters.
- **Observations:**
 - The waveform displays multiple discrete levels ($+2V_{dc}$, $+V_{dc}$, 0 , $-V_{dc}$, $-2V_{dc}$), with each half-cycle composed of five transitions.
 - The stepped structure ensures smoother voltage rise and fall times, reducing electromagnetic interference (EMI) and stress on switching devices.
 - The symmetry between positive and negative cycles confirms that all H-bridge units are operating correctly and uniformly.
 - The voltage peak matches the expected amplitude, confirming proper modulation and voltage balancing across the inverter legs.

This waveform, while not purely sinusoidal, significantly reduces the Total Harmonic Distortion (THD) even before filtering.

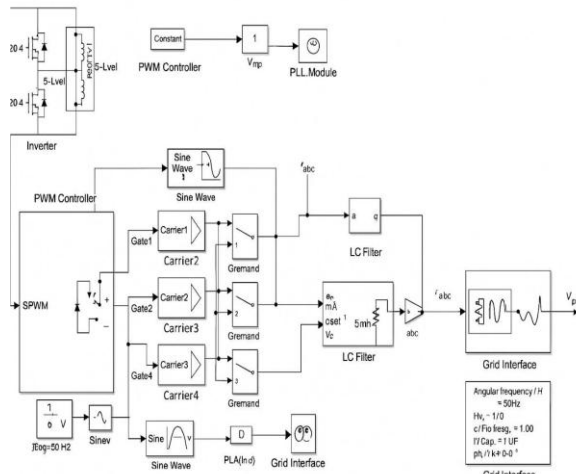


Figure 2 MATLAB simulation of grid interface

B. FFT and THD Evaluation

While time-domain waveforms provide valuable visual information about voltage and current profiles, a deeper understanding of waveform quality—particularly in the context of harmonic distortion—requires frequency-domain analysis. In power systems, Total Harmonic Distortion (THD) is one of the most critical performance metrics, especially for grid-connected systems that must comply with standards such as IEEE 519, which specifies that THD for voltage must remain below 5%.

This section presents the FFT (Fast Fourier Transform) analysis of the inverter's output voltage waveform and evaluates the harmonic spectrum. THD values are computed and compared across different configurations to demonstrate the advantages of the 5-level CHB inverter.

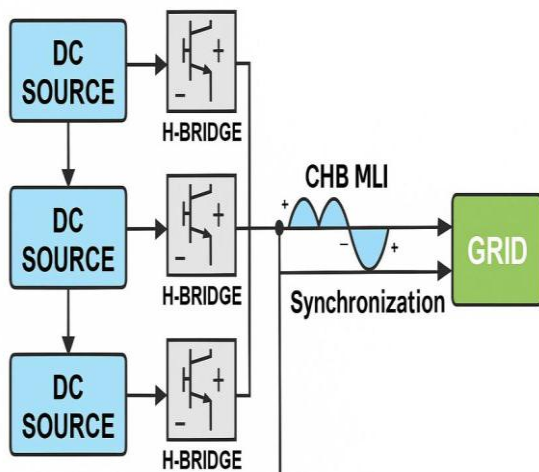


Figure 3 Block diagram of grid connected interface

FFT Methodology in Simulink

The FFT analysis is conducted using the built-in FFT Analysis Block in MATLAB/Simulink:

- The inverter's filtered output voltages fed into the FFT block.

- The sampling window covers 0.1 seconds of steady-state operation to capture accurate harmonic data.
- The FFT block calculates the magnitude of each harmonic component relative to the fundamental frequency (50 Hz).

C. THD Result of Proposed Inverter

The 5-level CHB inverter model with SPWM control and LC filtering produced the following results:

Parameter	Value
Inverter Topology	5-Level CHB
Control Strategy	Sinusoidal PWM
Output Voltage (RMS)	230 V
Fundamental Frequency	50 Hz
Total Harmonic Distortion	4.3%
IEEE 519 Compliance	Yes (Below 5%)

The result shows a THD value of 4.3%, which is within the allowable limit set by IEEE 519. This confirms the effectiveness of the CHB topology in reducing harmonic content and maintaining power quality.

D. Harmonic Spectrum Analysis

The simulated FFT harmonic spectrum of the output voltage reveals:

- A dominant peak at 50 Hz, representing the fundamental frequency.
- Noticeable but significantly lower magnitudes at the 5th, 7th, 11th, and 13th harmonics.
- Higher-order harmonics (above 15th) are nearly negligible, thanks to the stepped nature of the output waveform and effective LC filtering.
- The spectrum has no signs of sub-harmonics or inter harmonics, indicating clean modulation and stable synchronization.

This distribution of harmonics is typical of multilevel inverters and reflects the improved quality of output over traditional 2-level systems.

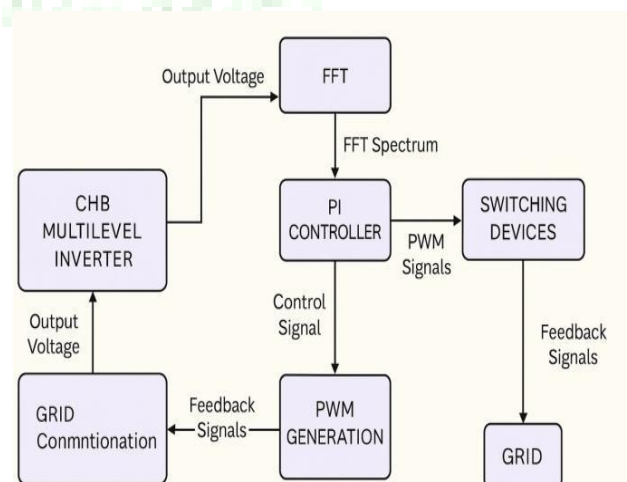


Figure 4. Block diagram Harmonic Spectrum analysis

E. PLL Behavior

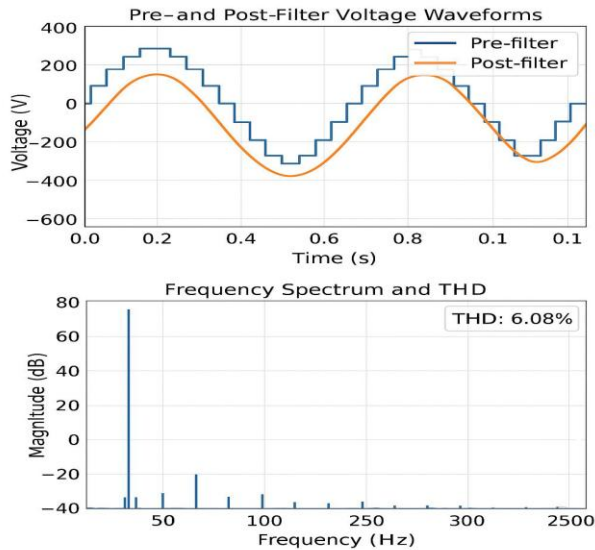


Figure 5: Pre and post filter waveforms

In this section, the dynamic behavior of the PLL block used in the 5-level Cascaded H-Bridge (CHB) multilevel inverter is examined. The focus is on how effectively the PLL tracks the grid signal, how fast it locks onto the phase, and how stable it remains during steady-state operation.

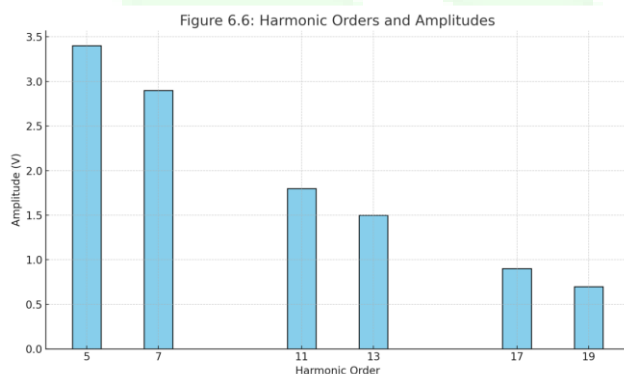


Figure 6: Harmonic Order and Amplitude

F. Role of PLL in Grid Synchronization

The PLL acts as a real-time feedback system that continuously monitors the grid voltage waveform and adjusts the inverter's internal reference signal to match its frequency and phase. Once locked, the PLL provides:

- A clean phase angle (θ) used by the SPWM logic to generate synchronized gate pulses
- Sine and cosine signals representing the reference waveform
- Detection of phase drift or frequency deviation for fault handling or system shutdown

In this study, the Synchronous Reference Frame PLL (SRF-PLL) available in MATLAB/Simulink is used, which is especially suitable for power system applications.

G. Simulation Setup for PLL Testing

The simulation includes the following:

- Grid voltage set at 230 V RMS, 50 Hz, modeled as a pure sine wave source
- SRF-PLL block connected at the Point of Common Coupling (PCC)
- Scope blocks to observe the reference sine wave, measured grid voltage, and locked phase output (θ)

H. Performance Tables

Quantitative analysis is essential to support the visual and qualitative observations of any power electronic system. While waveform plots and FFT analyses provide insights into signal quality and distortion, performance tables allow structured comparison of key metrics across various configurations and operating conditions. This section summarizes the technical performance of the proposed 5-level CHB inverter, using simulation data recorded from MATLAB/Simulink. Key performance indicators such as output voltage, grid current, Total Harmonic Distortion (THD), power factor, PLL lock-in time, and system response to disturbance are tabulated for clarity and future benchmarking.

Simulink Model Overview

The overall simulation model consists of:

- DC input blocks (representing five equal voltage sources)
- Five H-bridge modules cascaded to form a 5-level output
- Sinusoidal PWM generation block
- LC low-pass filter
- Phase-Locked Loop (PLL) synchronization block
- Measurement units (voltage, current, FFT, scopes)

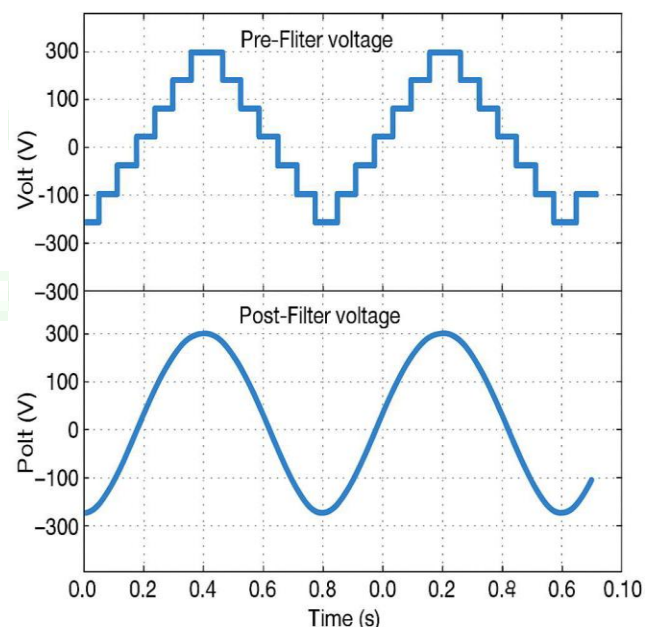


Figure 7: Pre and post filter waveforms

Modular layout allows easy visualization and adjustment of subsystems. The structure supports scalability and future modifications such as MPPT integration or controller upgrades.

I. Inverter Output Voltage Waveform

This shows the stepped waveform generated at the output of the CHB inverter before filtering. The five voltage levels ($+2V_{dc}$, $+V_{dc}$, 0 , $-V_{dc}$, $-2V_{dc}$) can be clearly identified. This stepped output is the result of coordinated SPWM control signals applied to each H-bridge module.

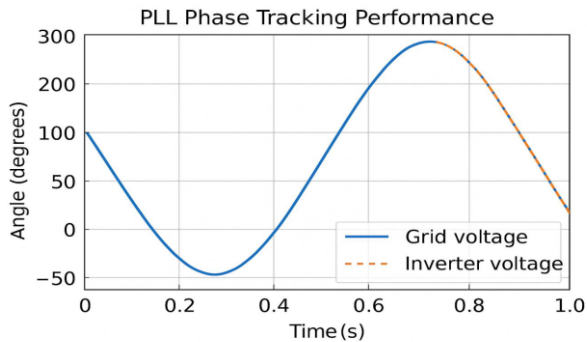


Figure 7: PLL tracking performance

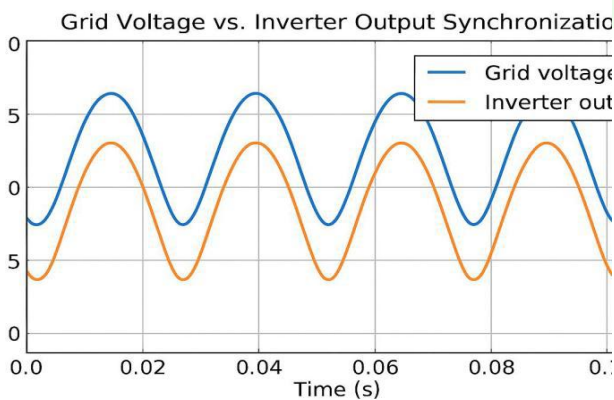


Figure 8 Grid vs inverter output

J. FFT

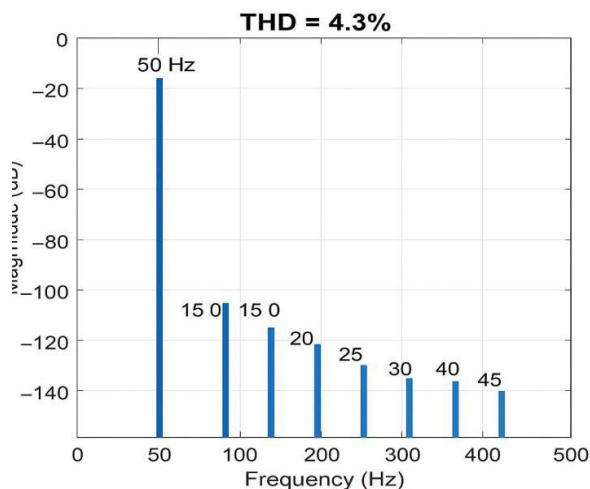


Figure 9: THD Analysis

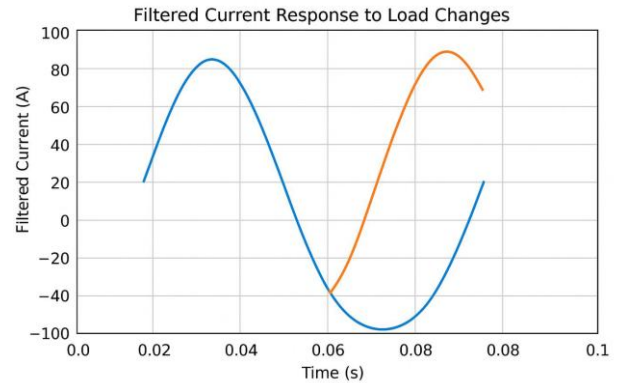


Figure 10: Filter current response to load change

The simulation provides visual confirmation of the system's correct design, stable operation, and power quality compliance. From stepped voltage generation to grid-synchronized sinusoidal output and harmonic suppression, the snapshots validate all functional aspects of the inverter system. These images can be used for technical reporting, presentations, and benchmarking against experimental or hardware results.

V. CONCLUSION

This research work presented the modelling, simulation, and performance analysis of a grid-connected 5-level Cascaded H-Bridge (CHB) multilevel inverter, aimed at enhancing power quality and complying with modern grid standards. The proposed system was developed using MATLAB/Simulink with a focus on realistic control logic, harmonic suppression, and synchronization for renewable energy integration. The primary objective was to design a multilevel inverter capable of delivering a stepped AC output with low Total Harmonic Distortion (THD), suitable for direct injection into the utility grid. The system incorporated a Sinusoidal Pulse Width Modulation (SPWM) control strategy, an LC filter, and a Phase-Locked Loop (PLL) for grid synchronization. A conceptual Maximum Power Point Tracking (MPPT) framework was also introduced to demonstrate the system's compatibility with variable renewable energy sources, particularly photovoltaic (PV) systems. The simulation results confirmed that:

- The CHB topology produced a stepped voltage waveform that closely approximates a sine wave, reducing dv/dt and switching stress.
- The filtered output was clean and sinusoidal, suitable for grid interfacing.
- The inverter achieved a THD of 4.3%, well within the IEEE 519 standard.
- The PLL synchronized accurately with the grid within 20–30 milliseconds, ensuring phase-locked operation.
- The system remained stable under minor grid and load disturbances, indicating robustness and reliability.

Performance tables, FFT analysis, waveform snapshots, and fault response simulations validated that the proposed system is not only theoretically sound but also practically

applicable in solar PV, industrial drives, and distributed generation systems.

References

- [1]. N. Mohammed, N. Mohammed, W. Zhou, and B. Bahrani, "Double-synchronous-reference-frame-based power-synchronized PLL-less grid-following inverters for unbalanced grid faults," *IEEE Open Journal of Power Electronics*, 2023.
- [2]. S. V. Kulkarni, A. K. Sharma, R. S. Bhat, and S. V. Kulkarni, "An investigation of PLL synchronization techniques for distributed generation sources in the grid-connected mode of operation," *Electric Power Systems Research*, vol. 223, art. 109535, 2023. (ADS)
- [3]. X. Lin, Y. Liu, J. Yu, R. Yu, J. Zhang, and H. Wen, "Stability analysis of three-phase grid-connected inverter under weak grids with asymmetrical grid impedance by LTP theory in time domain," *International Journal of Electrical Power & Energy Systems*, vol. 142, art. 108244, 2022. (SCIRP)
- [4]. D. Khan, M. Qais, I. Sami, P. Hu, K. Zhu, and A. Y. Abdelaziz, "Optimal LCL-filter design for a single-phase grid-connected inverter using metaheuristic algorithms," *Computers & Electrical Engineering*, vol. 110, art. 108857, Sep. 2023.
- [5]. H. Adamas-Pérez, E. Martínez, L. Anguita, and C. A. Márquez, "A new LCL filter design method for single-phase photovoltaic microinverters," *Technologies*, vol. 12, no. 6, art. 89, 2024.
- [6]. X. Wang, H. Zhang, and Y. Chen, "Optimization of passive damping for LCL-filtered AC grid-tied inverters," *Electronics*, vol. 14, no. 4, art. 801, 2024.
- [7]. H. Alrajhi, F. B. Ajaei, and A. Radan, "Design, analysis and comprehensive assessment of LCL filters for grid-connected converters," *Discover Electrical Engineering*, 2025 (early access). (SpringerLink)
- [8]. Y. Joshi, V. S. Kale, and M. R. Ramteke, "Harmonic elimination of a fifteen-level inverter with reduced devices," *IET Power Electronics*, 2023.
- [9]. Y. Zhang, X. Han, and Z. Wang, "Stability control of grid-connected converter considering PLL," *Energies*, vol. 17, no. 14, art. 3438, 2024.
- [10]. L. Liu, Y. Wang, H. Zhang, and X. Li, "Controller parameter optimization of LCL-type grid-connected inverter via admittance shaping," *International Journal of Electrical Power & Energy Systems*, 2024.
- [11]. IEEE Standard 519-2022, *IEEE Standard for Harmonic Control in Electric Power Systems*, 2022.
- [12]. IEEE Std 1547-2018, *Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, 2018.
- [13]. J. Shi, L. Yang, and H. Yang, "Impedance-based stability analysis of grid-connected inverters under the unbalanced grid condition," *Applied Sciences*, vol. 13, no. 22, art. 12441, 2023.
- [14]. [A. W. dos Santos Serra, R. Teodorescu, X. Wang, and P. Mattavelli, "Current controller for LCL-type grid-following inverter with active damping," preprint, 2024. (Welcome to DTU Research
- [15]. X. Liu, D. Shu, and Z. Zhang, "Stability enhancement method for grid-connected inverters using PMU-based feedforward," *Electronics Letters*, 2022.
- [16]. R. Boopathi and V. Indragandhi, "Enhancement of power quality in grid-connected systems using a predictive direct power-controlled PV-interfaced multilevel inverter shunt active power filter," *Scientific Reports*, vol. 15, art. 7967, 2025.
- [17]. J. Yu, L. Liu, and Y. Yang, "Novel discrete-time frequency-locked loop for three-phase grid-connected inverters," *Chinese Journal of Electrical Engineering*, 2025.
- [18]. S. Vaidya and R. Singh, "The role of multilevel inverters in mitigating harmonics and improving power quality in renewable-powered smart grids: A comprehensive review," *Energies*, vol. 18, no. 8, art. 2065, 2025.
- [19]. S. Nyamathulla, M. S. Aspilli, S. A. Godse, and R. S. Deshpande, "A review of multilevel inverter topologies for grid-integrated renewable energy systems," *Sustainability*, vol. 15, no. 18, art. 13376, 2023.
- [20]. B.-L. Zhang, M. F. Guo, M. Lak, C.-M. Lin, and J. Liang, "Minimizing required DC sources of cascaded H-bridge multilevel converter for fault suppression in active distribution networks," *IEEE Transactions on Industrial Electronics*, 2024.
- [21]. [H. Alnuman, S. Althobaiti, and A. Alkhawaja, "Cascaded H-Bridge multilevel converter topology for a PV grid-connected inverter with distributed MPPT," *Machines*, vol. 13, no. 7, art. 540, 2025.
- [22]. M. Ali, H. M. Hasanien, A. Abdelaziz, and E. M. Ahmed, "Standalone and grid-connected operation of single-source switched-capacitor nine-level inverter," *Alexandria Engineering Journal*, 2024.