International Journal of Trend in Research and Development, Volume 12(5), ISSN: 2394-9333
www.ijtrd.com

A Comprehensive Review on Modern Multilevel Inverter Topologies and Control Strategies for Enhanced Power Quality and Efficiency

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Abstract – Multilevel inverters (MLIs) have emerged as a key solution for high-power and medium-voltage applications, offering improved output waveforms, reduced total harmonic distortion (THD), and greater efficiency in renewable energy integration. This review critically analyzes recent advancements in MLI topologies—including cascaded H-bridge (CHB), modular multilevel converters (MMC), switched-capacitor (SC) designs, and reduced switch-count configurations—highlighting their benefits, challenges, and simulation results. Furthermore, the paper explores novel control techniques such as model predictive control, space vector modulation, and multicarrier PWM, which significantly enhance inverter performance in grid-tied and standalone systems. Comparative assessments from MATLAB/Simulink simulations and hardware-in-loop implementations demonstrate how these designs effectively address harmonic distortions and switching losses. Finally, the paper identifies research trends focused on device count reduction, output quality improvement, and cost-effective configurations, laying a strong foundation for future innovations in power electronics.

Keywords: *Multilevel inverter (MLI), Cascaded H-Bridge (CHB), Total Harmonic Distortion (THD), PWM Techniques, Renewable Energy, MATLAB/Simulink, Control Strategies, Modular Multilevel Converter (MMC), Switched Capacitor (SC), Predictive Control, Grid Integration*

I. INTRODUCTION

In recent years, the need for efficient and reliable power conversion systems has grown rapidly, especially with the increasing demand for renewable energy integration and advanced motor drives. Among various power electronic converters, multilevel inverters (MLIs) have gained prominence due to their ability to deliver high-quality AC output with minimal harmonic distortion, using multiple low-voltage DC sources.

Traditional two-level inverters are often insufficient for medium to high-voltage applications, as they result in high THD, increased electromagnetic interference (EMI), and high switching losses. MLIs address these challenges by generating stepped voltage outputs, which improve the waveform quality and reduce filtering requirements. The most commonly used MLI topologies include:

- Cascaded H-Bridge (CHB) Inverters
- Neutral Point Clamped (NPC) Inverters
- Flying Capacitor (FC) Inverters
- Modular Multilevel Converters (MMC)
- Switched Capacitor (SC) Based Inverters

This review paper evaluates the recent developments in MLI topologies and their control techniques, emphasizing performance metrics such as Total Harmonic Distortion (THD), component count, control complexity, and suitability for renewable energy systems. Notably, techniques such as space vector PWM (SVPWM), multicarrier PWM, model predictive control (MPC), and particle swarm optimization (PSO) have been explored for enhanced control efficiency.

The selected literature spans simulation-based and hardware-in-loop studies that propose novel inverter architectures or enhance existing ones through reduced device counts, optimized switching strategies, or integration with filtering techniques. This review aims to provide insights into the operational improvements and future trends in MLI research, serving as a valuable resource for researchers, academicians, and industry professionals.

II. LITERATURE REVIEW

Raji Krishna; Rani. S; D. Jayanthi (2024) This article presents the case study of various cascaded multilevel inverter topologies. It includes a five-level cascaded H-bridge multilevel inverter and seven and thirty-one levels of cascaded H-bridge inverter topologies with two one-way power switches. Compared to traditional multilevel converters, the number of DC-voltage sources (DCVS), switches, blocking voltages, installation space, and converter costs needed to get the same results decreases drastically in the 7 and 31-level topologies. In this topology, the magnitudes of the necessary DCVS are calculated using special criteria. The construction of the suggested topology employs a minimal quantity of switches and DCVS while also generating a significant number of output voltage steps. The simulation results validate the suggested multilevel converter's functionality and efficacy, employing the closest voltage control technique. Furthermore, a comparative analysis is conducted with other commonly used topologies to assess their performance.

Muhammad Anas Baig; Hassan Abbas Khan; Nauman Ahmad Zaffar (2024) This paper presents a modified direct model predictive control of a symmetric N-level multilevel grid-tied inverter. The proposed framework converts the multi-objective optimization problem of reference tracking and switching error control to a single objective in such a way that an analytical formula to calculate the unconstrained solution is obtained. The unconstrained solution can be used to find the optimal switching state using the proposed Generalized Search Algorithm without exhaustive search and objective function evaluation in every sampling interval. Moreover, a wide frequency range weighting factor tuning method is provided based on particle swarm optimization so that the inverter can operate at a desirable average switching frequency. The proposed idea is validated by applying it on two cascaded units of a 17-level switch ladder multilevel inverter, thus giving 289 levels in a grid-tied configuration. The hardware in-loop validation is also provided for the proposed control scheme.

Swarnim; Sushma Kamlu (2024) Multi - level inverter (MLI) circuits are frequently used in power production, power quality devices, and energy transmission, among other applications. Conventional MLI have certain limitations, such as a larger percentage Total Harmonic distortion (THD) % and a lower voltage magnitude. In this work, various topologies for (five-level) cascaded multilevel inverter are designed and implemented. The first topology is of Conventional Cascaded Multilevel Inverter design and the second topology, on the other hand, Cascaded Multilevel Inverter with a 6-switch count. H-bridges are connected in series to produce the required number level for the voltage output. These topologies are designed with the different PWM techniques i.e., Multicarrier SPWM and SVPWM and are compared for better THD value in the output voltage side with the increased no levels, it becomes more complex to apply the space vector PWM technique. Thus, an easier and simpler methodology (which is proposed in several literatures) have been applied. Total four topologies (also with and without filter) are designed and simulated in MATLAB simulation software and compared as well. Also, to further reduce the harmonics a low pass LC filter is designed and applied to the inverter circuit. The stated article presents a comparison within each topology based on its input DC voltage, percentage THD, Vrms, number of switches, as well as H-bridge prerequisite, among other factors. SIMULINK/MATLAB is used to determine how well the entire system is functioning.

Tarek Fouda (2024) Multilevel inverters convert DC voltage to AC voltage by using lower DC voltage at the input, with the help of an electronically controlled device. One of the primary challenges linked to these devices is the Total Harmonic Distortion (THD) present in the output waveforms. In this research paper, concise overview of Total Harmonic Distortion (THD) is presented for different cascaded H-bridge multilevel inverter topologies, in particular, the five-level and seven-level inverters illustrate this concept well. The five-level inverter employs eight switches, whereas the seven-level inverter uses twelve switches. Each H-bridge inverter circuit operates with separate DC sources. The inverter employs an Insulated Gate Bipolar Transistor (IGBT) serves as the switching component and a gating block to regulate the operation of the IGBT switching. Simulation results and waveform analysis are provided to confirm the research findings. The study also explores the effect of varying the switching frequency of the carrier wave on the total harmonic distortion of the output waveforms. The paper highlights the significance of choosing the right switching frequency according to application requirements to enhance the performance and efficiency of cascaded multilevel inverters.

Surasmi N L; Shiny G (2023) Multilevel inverters are superior to conventional two level inverters in high and medium power industrial applications. A hybrid multilevel inverter control is proposed to mitigate the harmonic distortions in the output phase voltage waveforms of induction motor drives. An open-ended induction motor fed with a neutral point clamped three level main inverter on one side and a two level inverter with a floating capacitor on the other side is proposed. The two level inverter is switched to act as a series active filter with null active power supply to the motor, while the three level inverter is pulsed using space vector modulation technique. Thus, the two level inverter will cancel out the voltage distortions in the motor phase voltages. With this configuration, the motor phase voltage harmonic distortions are within the IEEE 519 standards, thereby improving the drive efficiency and motor life-span. The proposed system is simulated and collated with three level neutral point clamped inverter and dual inverter fed open-ended induction motor drive and found to have better harmonic performance.

Kruthi Jayaram (2023) Power inverters is used to convert DC to AC and helps in providing AC output at any desired level using appropriate switching and control startegy. Multilevel converters help in providing AC output at any desired level by taking lower level DC input voltages of switches. Multilevel inverters are finding their prominence and applications in various fields nowadays to create a smoother stepped output waveform a multilevel inverter is convenient to use. If the voltage level is increased, the waveform becomes smoother. Due to industrial applications, growing day-by-day, for medium and high voltage applications, modular multilevel converter (MMC) is more relevant. In this paper, nine level modular multilevel inverter is implemented in MATLAB/Simulink. The inverter presented in the paper gives nine level output voltage. The complete circuit is simulated in MATLAB/Simulink and the outcomes for the same is presented in the paper.

Pradeep Kumar; Poonam Singhal (2023) The demand for electric power in India is rapidly increasing, and there is a need to shift from non-renewable energy sources to renewable energy. Among renewable sources, solar energy is widely available and commonly used. Solar cells generate direct current (DC) power, which needs to be converted to alternating current (AC) for domestic use. Inverters play a crucial role in converting solar DC power to AC power. Due to this, Multilevel inverter technology has gained significant importance in the field of high-power medium-voltage energy control. This paper overviews various multilevel inverter topologies like diode-clamped inverters (neutral-point clamped), capacitor-clamped (flying capacitor), and cascaded multicells with separate DC sources. The study also focuses on these converters' control and modulation methods, such as multilevel sinusoidal pulsewidth modulation. In this project, the simulation of multilevel inverters is done using MATLAB SIMULINK software. Future development opportunities in high-voltage, high-power devices are also highlighted.

Md Showkot Hossain; Md Akib Hasan; Nurul Ain Mohd Said (2023) Modern power converters are an essential component in the real-time deployment of renewable energy which makes the renewable energy harness more efficient. In medium power applications, multilevel inverters (MLI) seem to be a viable alternative to conventional inverters. This article attempts to provide a brief overview of new reduced device count multilevel inverter topologies focusing on renewable energy applications. This review article examines the most recent topologies into two categories which are single-source and multiple-source multilevel inverters. In recent times, researchers have tried to employ a small number of components in multilevel inverters in order to achieve low voltage stress and increased efficiency. Moreover, the overall comparison of these topologies is shown in a tabular representation. This comparison is based on the needed number of switches, number of de supplies, Number of capacitors & diodes, and the number of levels (NL) that are achieved by the multilevel inverter topologies. In addition to this, the equivalent THD of the output and efficiency arc taken into consideration.

Gouri Deshmukh; Pradyumn Chaturvedi; Vedashree Rajderkar (2022) The concept of multilevel power electronic converters is introduced and later widely accepted for medium and high power applications. The numerous multilevel converter topologies are being used as a power converter in various existing applications. Among the widely accepted conventional topologies, the Cascaded H-bridge (CHB) multilevel inverter is investigated in this paper. The CHB inverter with equal as well as unequal DC sources is studied in detailed manner; and the comparative analysis is done for the same. The MATLAB simulation results for CHB multilevel inverter with equal DC sources are presented. The in-phase Sinusoidal Pulse Width Modulation (SPWM) methodology is considered here as a control technique.

MarifDaula Siddique; Sanjib Kumar Panda (2022) Over the last few decades, the research related to multilevel converters has exponentially raised. The use of switched-capacitor (SC) based modules in multilevel inverters is a well-established area of study within the field of power electronic converters. Also, for a few years, single-stage SC-based boost inverters are extensively researched which can be linked to the number of papers published. Without the use of bulky inductors or transformers, the voltage-boosting capability can be achieved with the integration of SC modules with multilevel inverters. In recent years, several SC modules have been developed for the integration with MLIs to increase the number of levels and/or the voltage gain. In this paper, a design methodology for the SC-based multilevel inverter has been discussed. The design methodology has been divided into three different sections of the converter and different combinations have been discussed. Lastly, a comparison table has been provided considering all the developed topologies using a single SC modules.

CONCLUSION

Multilevel inverters have revolutionized power conversion by offering modular, scalable, and efficient solutions for modern energy systems. This review consolidates findings from ten recent studies that explored advancements in inverter topology, switching strategies, and harmonic mitigation methods.

Key takeaways include:

- Topological Improvements: CHB, MMC, and SC-based inverters show great promise in reducing switch count and enhancing output waveform smoothness while maintaining voltage gain.
- Control Strategies: Techniques like SVPWM, multicarrier SPWM, and model predictive control (MPC) optimize inverter performance, particularly in grid-tied and motor drive applications.
- Harmonic Performance: THD remains a critical metric, and modern designs integrated with LC filters or hybrid inverters help keep it within IEEE-519 standards.
- Simulation and Real-Time Validation: Extensive use of MATLAB/Simulink simulations, along with HIL testing, demonstrates the practical feasibility of the reviewed systems.

Despite notable progress, challenges such as cost-effective implementation, thermal management, and real-time controller integration persist. Future research should focus on compact, AI-driven control strategies, wide-bandgap semiconductor usage, and better integration with renewable energy grids to achieve smarter, more resilient inverter systems.

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