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Performance Enhancement of Multi-level Inverters with Different Computation Techniques

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Abstract

Multi-Level Inverters (MLIs) have garnered significant attention in recent years due to their ability to address the limitations of traditional two-level inverters, such as high voltage stress on power devices and increased Total Harmonic Distortion (THD) in output voltage waveforms. This review study explores various computation techniques employed for enhancing the performance of MLIs. MLIs and their significance in modern power electronic systems is it discusses the limitations of conventional control techniques and motivates the need for advanced computation methods to optimize the operation of MLIs. It outlines the objectives and scope of the review study, including the identification of different computation techniques and their impact on MLI performance metrics such as efficiency, Total Harmonic Distortion (THD), and switching losses. A comprehensive analysis of different computation techniques used to enhance MLI performance. It categorizes these techniques into distinct groups such as artificial intelligence-based methods, machine learning algorithms, and fuzzy logic control. Each category is explored in detail, discussing the underlying principles, advantages, and limitations of the respective techniques. Moreover, the review highlights recent advancements and research trends in the field, providing insights into the potential applications and future directions for improving MLI performance through advanced computation techniques.

Major Findings: *Various computation techniques employed for enhancing the performance of MLIs. Conventional control techniques and motivates the need for advanced computation methods to optimize the operation of MLIs. MLI performance metrics such as efficiency, Total Harmonic Distortion (THD), and switching losses.*

Keywords: *Fuzzy Logic Control and Flying Capacitor Inverters, Multi-Level Inverters, Pulse Width Modulation, Selective Harmonic Elimination, Total Harmonic Distortion*

1.0 Necessity for the Enhancement of Multi-level Inverters

The enhancement of multi-level inverters is a critical endeavour driven by their pervasive utilization across various industries and power systems. As compared to conventional two-level inverters, multi-level inverters offer a plethora of advantages that are pivotal for modern electrical systems. These advantages encompass

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significantly improved voltage waveform quality, resulting in smoother output voltage and reduced harmonic distortion, which in turn minimizes the risk of equipment damage and ensures higher system reliability. Moreover, the inherent design of multi-level inverters facilitates lower electromagnetic interference, thus mitigating potential disruptions to nearby electronic devices and communication systems. Another notable benefit is their higher power efficiency, translating into reduced energy losses and operational costs over the long term. In addition to these technical advantages, multi-level inverters find extensive applicability in diverse high-power scenarios, ranging from renewable energy systems to electric vehicles and adjustable-speed motor drives. In renewable energy systems, such as solar and wind power, multi-level inverters enable efficient conversion of DC power generated by photovoltaic panels or wind turbines into AC power suitable for grid integration. Similarly, in electric vehicles, these inverters play a pivotal role in converting DC power from the battery into AC power to drive the electric motor, ensuring optimal performance and energy efficiency. Furthermore, in adjustable-speed motor drives, multi-level inverters offer precise control over motor speed and torque, leading to improved energy efficiency and operational flexibility.

1.1 Stimulus Need for Advancement of Multi-level Inverters

The Multi-Level Inverter (MLI) configuration is uniquely crafted to tackle Total Harmonic Distortion (THD) and mitigate voltage stress on switches under both symmetric and asymmetric operating conditions. The given framework utilizing 18 switches is capable of producing 17 and 49 voltage levels, achieving THD values of 4.14% and 1.45% respectively. The proposed design offers numerous advantages, such as lower switch count, reduced driver needs, and cost savings. These benefits, coupled with empirical data, solidify the adaptability and effectiveness of the topology in various scenarios. The performance of a Modified Packed U-Cells (MPUC) inverter as a simplified solution for traditional multilevel inverter designs. The analysis of the inverter focuses on both its THD and output voltage under different Pulse Width Modulation (PWM) techniques. The noticeable decrease in total harmonic distortion after filtering underscores the success of different multi-carrier level-shifted PWM techniques in enhancing waveform integrity. Real-time hardware implementation of the MPUC topology further validates the findings, emphasizing the importance of PWM techniques in enhancing inverter performance and exploring the benefits of a tiered voltage source inverter, particularly in the realm of solar energy applications. By adjusting the AC output voltages, slight amounts of harmonic distortion can be introduced to waveforms, ultimately enhancing efficiency and minimizing electromagnetic interference. A trial run of a 40W generator model incorporating a 27-level PWM-enabled cascaded multilevel inverter demonstrated successful operation. The potential benefits of multilayer inverters are in improving performance and reliability in solar energy conversion systems.

1.1.1 Limitations of Conventional Two-level Inverters

Utilizing Space Vector Modulation (SVM) in the T-type Neutral-Point-Clamped (T-NPC) inverter for Electric Vehicles (EVs) enhances performance over a range of speeds. Through simulation and experimentation, it is more efficient compared to both the two-level six-switch inverter and the T-NPC inverter with traditional three-level SVM. This cutting-edge method enhances productivity by eliminating the requirement for additional circuit elements or intricate control measures, confirming its cost-efficiency and excellence. Innovative modulation strategies have revolutionized transformer-less three-level NPC multi-level inverters for photovoltaic systems by incorporating space vector PWM to effectively manage common mode voltage problems. Current research focuses on enhancing inverter performance by reducing CMV. Several approaches, including reduced CMV-SVPWM techniques, have been suggested to alleviate CMV complications. However, further investigation is necessary to overcome challenges and discover new advancements in this field. A groundbreaking method has been created to boost wind turbine efficiency by combining advanced neural networks, fractional-order control using pulse width modulation, and a Double-Fed Induction Generator (DFIG). This innovative Fractional-Order Neural Control (FONC) technique surpasses conventional Direct

Power Control (DPC) methods, effectively minimizing power fluctuations, overshoot, and steady-state errors across various operational scenarios and parameter adjustments.

1.1.2 Advantages of Multi-level Inverters in the Current Scenario

Determining the perfect frequency for switching in Multilevel Inverters (MLIs) with wind power integration to minimize grid harmonics is crucial. Various optimization methods like MNSGA-II, SALP swarm, genetic algorithms, and particle swarm optimization is employed. A study was conducted to analyze the impact of MLIs at varying levels (7, 11, and 15) on distortion reduction, reliability assessment, and convergence rates. This research provides valuable insights into the efficiency of different multilevel inverter setups in sustainable energy production. Utilizing multi-level inverters is crucial for producing renewable energy with superior sound management qualities. A specialized control system is implemented in these inverters, frequently seen in HVDC and FACTS applications, to decrease harmonic distortions. By implementing PWM techniques, a sophisticated variable carrier frequency APOD control method has been devised to significantly reduce the overall harmonic distortion levels. The utilization of APOD PWM has proven to decrease THD in the output current waveform to an impressive 15.67%, highlighting the effectiveness of this innovative control strategy. The teamwork between a cascaded H-bridge multilevel inverter and a fuzzy logic controller in a solar PV system showcases improved system effectiveness and power cleanliness by making use of multiple inverter stages. The integration of these advanced technologies effectively minimizes harmonics distortion, stabilizes the system, and significantly enhances power quality compared to conventional inverters. Utilizing advanced control strategies in renewable energy systems to enhance overall performance.

1.2 Research Landscape in the Current Innovations

In the current landscape of innovations, there is a notable emphasis on leveraging emerging technologies to address pressing global challenges across various domains. In the field of healthcare, advancements in telemedicine, wearable health monitoring devices, and artificial intelligence-driven diagnostics are revolutionizing patient care delivery and disease management. Moreover, the integration of block chain technology is enhancing data security and interoperability in healthcare systems, facilitating seamless sharing of medical records while ensuring patient privacy. Similarly, in the automotive industry, there is a rapid shift towards electric and autonomous vehicles, driven by advancements in battery technology, sensor systems, and AI-powered autonomous driving algorithms. These innovations not only promise to reduce carbon emissions and enhance road safety but also pave the way for transformative changes in urban mobility and transportation infrastructure. Furthermore, the intersection of artificial intelligence, the Internet of Things (IoT), and big data analytics is driving innovation across sectors, enabling predictive maintenance in industrial machinery, optimizing supply chain management, and enhancing energy efficiency in smart buildings. In the realm of renewable energy, breakthroughs in solar photovoltaics, wind turbine technology, and energy storage systems are accelerating the transition towards sustainable energy sources, contributing to the global fight against climate change. Moreover, advancements in biotechnology, including gene editing tools like CRISPR-Cas9, hold promise for revolutionizing healthcare, agriculture, and environmental conservation efforts. Overall, the current research landscape is characterized by a convergence of cutting-edge technologies aimed at addressing complex societal challenges and fostering sustainable development across various sectors.

1.2.1 Pulse Width Modulation (PWM) Techniques for the Present Implementation

Pulse Width Modulation (PWM) techniques play a crucial role in modern electronic systems, offering precise control over power delivery by varying the width of pulses in a periodic signal. These techniques find widespread application in motor control, power converters, LED dimming, and audio amplification, among other areas, enabling efficient and flexible manipulation of electrical power approached achieving a high-performance and cost-effective PWM control signal with a 120° phase shift for a two-level three-phase inverter[1]. A circuit that

simplifies the generation of the PWM signal without sacrificing efficiency utilizes D flip-flops and a 555-timer to generate the necessary control signals, resulting in improved simplicity and reduced power losses compared to traditional methods. The circuit proposed was put to the test in both PSIM and PROTEUS simulations, displaying its efficacy. Its performance was further validated through hardware implementation in a practical environment proposed that PWM-driven power converters are crucial in connecting renewable energy sources to conventional grids, but they can introduce harmonics that degrade system stability[2]. The space vector-based switching pattern for PWM converters to mitigate harmonic distortion is a significant reduction in THD improved Weighted THD, and reduced thyristor count, leading to lower switching losses. The experiment revealed a significant decrease of 13.49% in THD with the innovative method, proving its effectiveness in improving the systems performance compared to standard SVPWM methods. The active rectifier created by features a unique PWM mode with on- and off-delay compensation, specifically designed for wireless power transfer scenarios, the efficiency and voltage conversion ratio under various operating conditions[3]. With the use of current mode delay compensation and adaptive PWM feedback loops, the proposed rectifier achieves a peak power conversion efficiency of 91.7% and a peak voltage conversion ratio of 93.7%. The innovative approach showcased a significant boost in effectiveness compared to current methods, showcasing at least a 9% uptick in efficiency and voltage conversion capability.

1.2.2 Topological Advancements of Multi-level Inverters

Recent advancements in the field of multi-level inverters have led to significant improvements in their topology, resulting in enhanced performance, efficiency, and reliability for various power conversion applications introduced the idea that MLIs are gaining popularity in high and medium-power applications[4]. Despite the many benefits they offer compared to traditional two-level inverters, obstacles such as size, cost, gadget count, and switch intricacy have hindered their widespread adoption. To tackle these obstacles, RSC MLIs have been developed, offering a more practical and cost-effective option. The innovations in multilevel inverter designs aim to reduce switch count while still delivering excellent performance and efficiency. Our objective is to highlight the potential of these next-generation MLIs in addressing the drawbacks of traditional topologies explored the benefits of employing a high DC link voltage in light-duty passenger BEVs[5]. They also sought to investigate the feasibility of incorporating MLIs into these vehicles. By examining various traditional multilevel inverter designs commonly found in BEVs and contrasting them with standard 2-level inverters, the researchers provided insights into the current landscape of the field[6]. By examining data from luxury electric vehicles and exploring various mobile lithium-ion options, this study uncovers emerging patterns and potential areas for future investigation in utilizing MLIs in upscale electric cars with high-voltage connections compared the performance of 3 different multilevel inverter schemes - 3-level, 5-level, and

Table 1. Performance comparison (Sengamalai *et al.*,)

Model Name	Acc (%)	Pre (%)	Rec (%)	F1 (%)
ResHybnet (GCN+CNN)	92.62	91.52	92.87	92.19
SVM	90.56	87.68	92.91	90.22
CNN	90.44	87.13	93.40	90.15
GNB	89.69	86.67	92.16	89.33
RF	89.69	87.46	91.04	89.21
LR	89.34	87.36	90.30	88.81
GCN	70.77	62.14	96.34	75.53

7-level - based on a diode clamped MLI configuration. By evaluating how well they minimize total harmonic distortion, we can pinpoint the ideal number of levels needed for improved power quality. This study explores the impact of varying levels on the performance of MLIs, contributing towards the enhancement of power electronics efficiency[7].

Table 1 presents the performance metrics (accuracy, precision, recall, and F1 score) for different models in a classification task. The ResHybnet model, combining GCN and CNN, achieved the highest performance, with an accuracy of 92.62%, precision of 91.52%, recall of 92.87%, and F1 score of 92.19%. SVM and CNN followed closely with solid results, while the GCN model showed relatively lower performance, particularly in accuracy (70.77%) and precision (62.14%). Other models like GNB, RF, and LR also demonstrated competitive performance, but none surpassed ResHybnet. These results highlight the superiority of the hybrid GCN-CNN model in this specific task[8].

2.0 Multi-level Inverter and their Various Topologies

Multi-Level Inverters (MLIs) are essential components in modern power electronic systems, offering numerous advantages such as improved voltage and current waveforms, reduced harmonic distortion, and enhanced efficiency compared to traditional inverters. MLIs achieve these benefits by synthesizing output voltage levels from multiple DC sources, enabling finer control over output waveforms. Various topologies of MLIs exist, each with its unique configuration of switches and capacitors, catering to specific application requirements. Common topologies include the diode-clamped inverter (neutral-point clamped), flying capacitor inverter, and cascaded H-bridge inverter[9]. Each topology offers trade-offs in terms of complexity, cost, and performance, making them suitable for different applications ranging from renewable energy systems to motor drives and grid-tied inverters, continued research and development in MLIs focus on enhancing efficiency, reducing component count, and increasing reliability to meet the evolving demands of modern power conversion systems.

2.1 Classification of Multi-level Inverters

Multi-level inverters are classified based on the number of voltage levels they can generate and the topology of their circuit configuration. The most common classification includes three categories: Diode-clamped or flying capacitor cascaded H-bridge, and neutral-point-clamped or NPC inverters. Diode-clamped inverters, also known as the 3-level or flying capacitor inverters, utilize multiple capacitors to generate additional voltage levels between the DC bus and AC output. Cascaded H-bridge inverters consist of multiple H-bridge cells connected in series, enabling the generation of multiple voltage levels by independently controlling the switches in each cell. Neutral-point-clamped inverters, also referred to as the three-level or NPC inverters, feature a grounded neutral point in the DC bus, which allows for the creation of additional voltage levels by connecting multiple switches to the midpoint of the DC bus. Each classification offers unique advantages and is suitable for specific applications based on factors such as voltage requirements, power ratings, and harmonic performance.

2.1.1 Cascaded H-bridge Inverters for Fault Tolerance

CHB inverters consist of multiple single-phase H-bridge inverter units connected in series. Each H-bridge can generate three voltage levels such as +Vdc, 0, and -Vdc (Vdc being the DC input voltage). By connecting the outputs of these units, the overall output voltage level increases with the number of H-bridges focused on a multi-loop regulator design for Cascaded H-Bridge Multilevel Inverters (CHBMIs) in Photovoltaic (PV) systems. The proposed approach combines a sliding mode control strategy for robust MPPT and a Lyapunov approach for stable PFC. The research contributes to the field by offering a promising control strategy for CHBMIs in PV systems, enhancing system robustness and power quality for efficient solar energy integration with the grid.

Figure 1 depicts the cascaded H-bridge inverter topology, which is a popular multilevel inverter configuration. This topology consists of multiple H-bridge cells connected in series, where each H-bridge generates a separate voltage level. The cascading arrangement allows for the synthesis of a higher number of output voltage

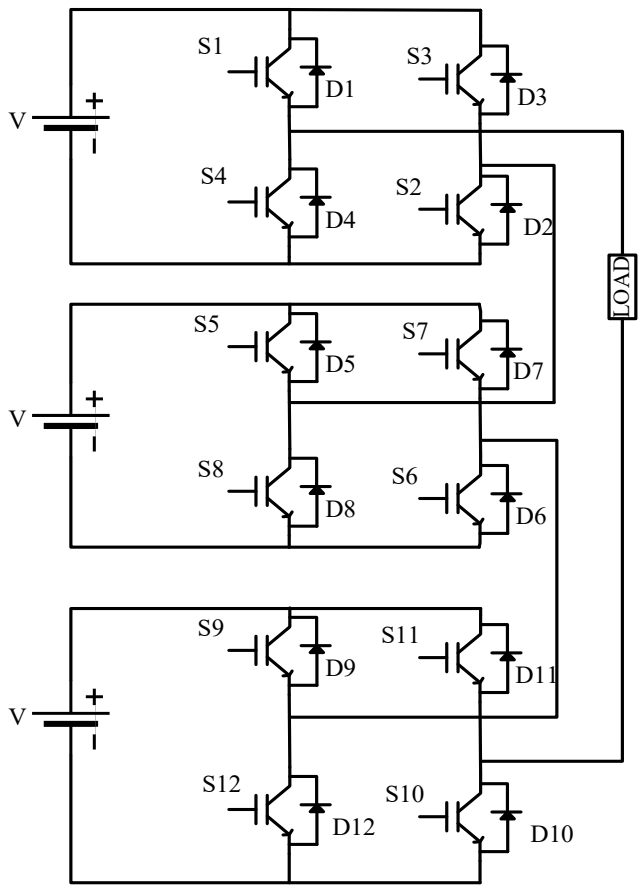


Figure 2. Image of cascaded H-bridge inverter topology (Sivapriya *et al.*).

levels, resulting in a smoother AC waveform with reduced Total Harmonic Distortion (THD). By controlling the switching of each H-bridge, this configuration offers advantages in terms of voltage scalability, power handling, and improved efficiency, making it suitable for high-power applications such as renewable energy systems and motor drives focused on a fault-tolerant Cascaded H-Bridge Multilevel Inverter (CHB MLI) for Solar Photovoltaic (PV) applications. CHB-MLIs are widely used in renewable energy due to their high voltage handling and output waveform quality. A fault-tolerant CHB MLI specifically designed for solar PV systems to ensure continued operation during switch failures. It addresses the challenges of conventional analytical fault diagnosis methods by introducing an AI-based technique for efficient fault detection and classification. The proposed method offers faster diagnosis time and improved accuracy. The fault-tolerant structure maintains functionality during switch failures, demonstrated through simulation and hardware-in-the-loop testing.

Figure 2 illustrates the Selective Harmonic Elimination (SHE) technique used to control multilevel inverters. SHE aims to eliminate specific harmonic frequencies from the inverter's output voltage waveform by adjusting the modulation angles. By selecting appropriate switching angles, this method reduces Total Harmonic Distortion (THD), improving the output

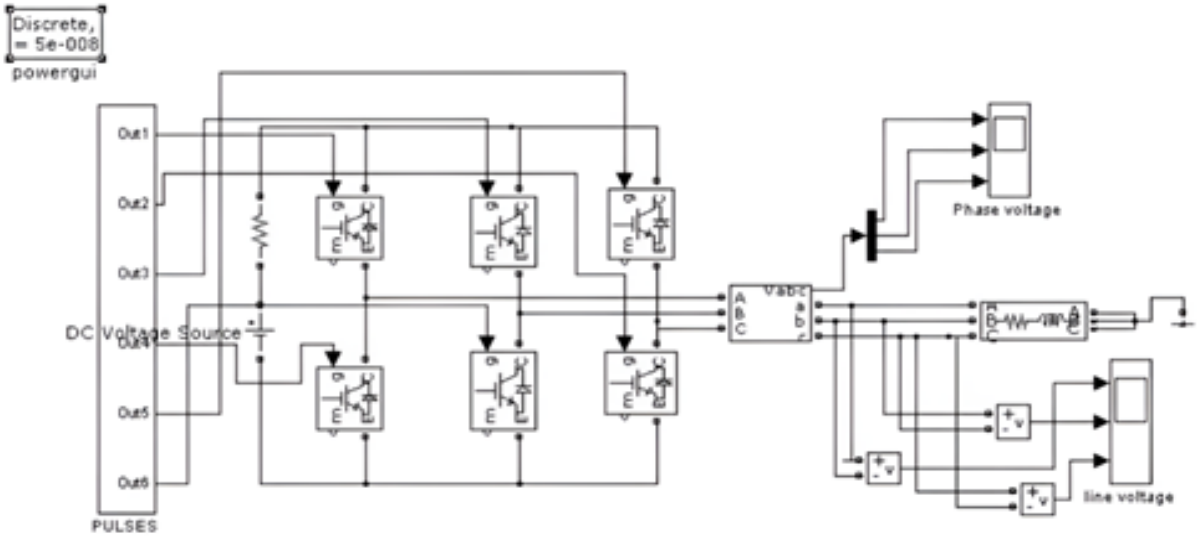


Figure 2. Selective Harmonic Elimination (SHE) for controlling multilevel inverters (Padmanaban *et al*).

waveform's quality. The technique is highly effective in multilevel inverters, where multiple voltage levels are synthesized, allowing for smoother waveforms and reduced harmonic interference. This results in enhanced system performance, efficiency, and reliability, particularly in applications requiring precise and high-quality AC power delivery.

2.1.2 Flying Capacitor Inverters for Voltage Balancing

FC inverters employ several capacitors connected between different DC voltage levels. Similar to NPC inverters, various combinations of capacitor voltages are added to the output to generate different voltage levels focused on the design challenges of Integrated Motor Drives (IMDs) in high-performance industrial applications, particularly in managing thermal issues during high overload torque demands[12]. ML-FCis are explored for their potential to improve efficiency and power density. A straightforward design procedure is employed to achieve 99% efficiency at nominal operation for both options. The study justifies the GaN-based 3L FCi as a superior solution due to its higher power density and reduced design complexity. An equipment demonstrator of the 3L GaN FCi IMD is implemented, validating high efficiency (98.94%) at nominal operation and adequate overload capability. Integrated Motor Drives (IMDs) are used in high-performance industrial applications, particularly in managing thermal issues during high overload torque demands. ML-FCis are explored for their potential to improve efficiency and power density. A straightforward design procedure is employed to achieve 99% efficiency at nominal operation for both options. An equipment demonstrator of the 3L GaN FCi IMD is implemented, validating high efficiency (98.94%) at nominal operation and adequate overload capability[13].

2.2 Selection Criteria for the Inverter Topology

The selection criteria for the inverter topology in the context of "performance enhancement of multi-level inverters with different computation techniques" primarily focus on factors such as efficiency, voltage levels, harmonic reduction, and complexity. Multi-level inverters are preferred for high-power applications due to their ability to produce high-quality output voltage with reduced Total Harmonic Distortion (THD). The inverter topology should support scalable voltage levels, ensuring minimal losses while maintaining high efficiency across varying operating conditions. Computation techniques, such as optimization algorithms and control strategies, are employed to improve switching sequences and reduce switching losses, further enhancing performance[14]. Additionally, factors like cost, reliability, and ease of implementation play a significant role in selecting the appropriate topology, ensuring that the system meets both performance and economic requirements for real-world applications[15].

Table 2 shows the 3 power scenarios (P1, P2, and P3) demonstrate the varying conditions of DC sources, load characteristics, modulation index (m), and fundamental frequency (f). In the 1st scenario (P1), four DC sources of 10V each supply a load with a 40-ohm resistor and 0.1H inductor, with a modulation index of 0.98. The 2nd scenario (P2) increases the DC sources to 10V, 10V, 20V,

Table 2. Power scenarios with modulation index and load characteristics

Scenario	DC sources V1, V2, V3, V4	Load (R,L)	Modulation Index (m)	Fundamental Frequency (f)
1st (P1)	10[V], 10[V], 10[V], 10[V]	40[n],0.1[H]	0.98	50[Hz]
2nd (P2)	10[V], 10[V], 20[V], 20[V]	60[N],0.15[H]		
3rd (P3)	10[V], 20[V], 70[V],140[V]	240[n],0.6[H]		

and 20V, providing a load of 60N and 0.15H inductance, with a modulation index of 50Hz. In the 3rd scenario (P3), the DC sources range from 10V to 140V, with a more complex load of 240 ohms and a 0.6H inductor, was featuring higher voltage and load parameters. Each scenario affects system performance in terms of output waveform quality and load handling.

2.2.1 System Specification and Power Quality of the Inverter

The system specification and power quality of an inverter are crucial factors in determining the efficiency and reliability of power conversion in various applications. Inverter systems are designed to convert Direct Current (DC) to Alternating Current (AC), with their specifications focusing on parameters such as input and output voltage, current ratings, power capacity, switching frequency, and efficiency. For instance, in high-power applications, the inverter must handle higher voltage levels and maintain stable output despite varying load conditions[16]. The inverter's efficiency is a key specification, as it dictates how much energy is lost during the conversion process, with higher efficiency leading to better overall system performance and reduced operational costs. Power quality refers to the characteristics of the AC output from the inverter, particularly in terms of its waveform, harmonic distortion, and stability. A high-quality inverter output has minimal harmonic distortion, which is critical in preventing damage to sensitive equipment and ensuring compliance with grid standards[17]. Multi-level inverters, for example, are designed to reduce Total Harmonic Distortion (THD) by generating more voltage levels, leading to smoother waveforms and improved power quality. The switching frequency also plays a significant role, as it impacts both the size of the inverter and the level of harmonic content. Proper control strategies are essential to maintain the desired power quality, especially in systems that operate under dynamic conditions or with variable loads. Overall, the combination of robust system specifications and high power quality ensures

Table 3. Modulation techniques and their impact on THD and angle (Hosseinpour *et al.*)

Modulation	SPWM	PSO	SSA
Index	THD (%)		a1(deg)
0.850	13.21	7.21	6.46
0.875	13.04	6.34	5.92
0.900	12.76	6.17	5.67
0.925	12.48	5.91	4.60
0.950	12.16	5.68	4.54
0.975	11.84	5.13	4.13
1.000	11.41	4.84	3.92
1.025	10.94	4.69	3.84
1.050	10.69	4.18	3.67
1.075	10.38	4.34	3.65
1.100	9.610	4.04	3.05
1.125	9.150	3.76	2.85
1.150	8.640	3.48	2.45
1.175	8.270	3.16	2.39
1.200	7.560	2.81	2.31

optimal performance and long-term reliability in power conversion applications[18].

Table 3 compares the Total Harmonic Distortion (THD) and the modulation angle (a1) for 3 different modulation techniques: SPWM (Sinusoidal Pulse Width Modulation), PSO (Particle Swarm Optimization), and SSA (Salp Swarm Algorithm). As the modulation index increases from 0.850 to 1.200, the THD generally decreases for all techniques, indicating improved output waveform quality[19]. Among the three, the SSA technique consistently achieves the lowest THD, suggesting it provides superior harmonic performance. Additionally, the modulation angle (a1) values vary, with SSA showing more favourable results, contributing to better efficiency and reduced distortion in inverter output[20].

2.2.2 Thermal Management and Safety for the Inverter

Thermal management is a critical aspect of inverter design, as the components involved in the power conversion process, such as semiconductor switches and capacitors, generate heat during operation. If this heat is not effectively dissipated, it can lead to overheating, reduced efficiency, and even failure of the inverter. Proper thermal management techniques, such as using heat sinks, fans, liquid cooling systems, and thermal interface materials, are employed to ensure that the temperature of the components remains within safe operating limits. Advanced materials with high thermal conductivity are often used to improve heat dissipation, and temperature sensors are integrated into the system to monitor and regulate the thermal conditions. Efficient thermal management helps to prolong the lifespan of the inverter, maintain its performance, and prevent thermal stress that can lead to component degradation or catastrophic failure. Safety is another crucial consideration in inverter design, as the system operates under high voltages and currents. To ensure safe operation, inverters are equipped with multiple protection mechanisms, including overcurrent protection, overvoltage protection, and short-circuit protection. These safety features help prevent damage to the inverter and surrounding equipment in the event of faults or abnormal conditions. In addition, grounding and insulation protocols are implemented to protect users from electrical shock hazards. Regular maintenance, system monitoring, and compliance with international safety standards are essential to ensure the inverter operates safely over its lifetime. Together, thermal management and safety protocols play a pivotal role in ensuring that inverters perform reliably while safeguarding both the equipment and users[21].

3.0 Various Techniques used for Performance Enhancements in Multi-level Inverters

The enhancement of performance in multi-level inverters relies on a variety of techniques aimed at improving voltage waveform quality, reducing harmonic distortion, and increasing overall efficiency[22]. These techniques encompass advanced modulation schemes, capacitor voltage balancing methods, and innovative control strategies tailored to specific inverter topologies and applications developed and regulated the grid-integrated PV system for the mitigation of harmonics with incorporation of SAPF. The reference current signal is estimated by employing a suitable control technique, allowing the PV-integrated SAPF to deliver active or reactive power to the grid and reduce harmonic contents. This harmonic compensation ability is crucial for ensuring the efficiency and stability of the power system[23]. It is observed from the simulation and real-time results that the PQ improvement in the case of the proposed MWH ADALINE-based SAPF is comparatively better in terms of THD concerning that of the cases with ANFIS and WH ADALINE-based SAPF controllers under all operating conditions[24].

3.2.1 Machine Learning for the Performance-based Computation Techniques

Machine learning is transforming performance-based computation techniques by leveraging data-driven models to optimize system parameters, improve efficiency, and enhance performance in various applications, including multilevel inverters. Dou *et al.*, presented the challenges and advancements in AI and profound learning for small data in molecular science, including chemical and biological disciplines. The goal is to explore the potential solutions to the constraints faced by researchers when

dealing with small datasets, such as data diversity, noise, imbalances, and high dimensionality. The findings reveal that recent mechanical forward leaps in ML, DL, and AI have enabled significant progress in addressing small data challenges, with various advanced algorithms and techniques providing solutions for data-driven scientific discovery in the molecular sciences. In conclusion, the study highlights promising trends in overcoming small data challenges for future research in molecular science. Demir *et al*., suggested the rapid growth in the number of Metal-Organic Frameworks (MOFs) and their potential applications has led to the need for more efficient methods for identifying optimal MOFs for specific applications. High-throughput computational screening approaches given atomic recreations have been utilized to examine and recognize promising MOFs. Utilizing information-driven science strategies, for example, AI can speed up the plan and disclosure of MOFs by laying out models that decipher complex design execution connections. In this survey, we feature the logical leap forwards in the computational displaying of MOFs and examine cutting-edge draws near, from sub-atomic recreations to ML calculations, with bits of knowledge on future open doors and difficulties in the field.

3.2.2 Hybrid AI Approaches for Efficient Multilevel Inverters

Hybrid AI approaches combine the strengths of different artificial intelligence strategies to upgrade the efficiency of multilevel inverters, leveraging the synergies between techniques like machine learning, fluffy rationale, and developmental calculations for ideal execution and control. Rasheed *et al*. suggested using an ANN controller to create a 5-level modified flowed H-span staggered inverter (M-CHBMI) that reduces THD and enhances yield voltage and current. The final results uncovered that the upgraded CHB-MLI inverter's higher levels lower the harmonic contents. Lower THD at the voltage and current result waveform has also been obtained by ANN control. Padmanaban *et al*. suggested the technique is effective and provides real firing angles with a few iterations leading to a better capability of confronting local optima values. The 11-level inverter arrangement is developed to verify the simulation results experimentally. A dSPACE RTI1104 controller is required to create pulses to run the IGBTs, which are IKW75N60T, 600V, and 75A IGBT utilised for CHBMLI with 50Hz frequency. Ghasemiyeh *et al.* recommended the study aims to estimate stock exchange values using a mixture of fake brain network models and met heuristic calculations, such as genetic algorithms, particle swarm optimisation, enhanced cuckoo search, and cuckoo search genetic algorithms. The proposed model's outcomes show that molecule swarm improvement is a popular met heuristic method for stock cost expectation, based on the statistical performances of the aforementioned approaches. Li, Y., Zhang *et al.* suggested the TS algorithm (IPSO-TS) for PWM inverter switching angle selection, the PSO and TS algorithms are both enhanced in the suggested IPSO-TS algorithm to increase their convergence when computing numerous switching angles. Based on the simulation results, the combination pace of the improved PSO and improved TS has grown significantly, almost three times; IPSO-TS also offer advantages in terms of computing speed and convergence accuracy.

3.2.3 Total Harmonic Distortion (THD) in the Inverter Output Voltage Waveform

Total Harmonic Distortion (THD) in the inverter output voltage waveform is a critical measure of the quality of the AC signal produced by an inverter. THD quantifies the presence of harmonics, which are unwanted frequencies that distort the ideal sinusoidal waveform of the AC output. These harmonics are generated due to the switching process of the inverter and can cause various issues, such as inefficiency, overheating of electrical components, and interference with sensitive equipment. A high THD indicates significant distortion, leading to poor power quality, while a low THD signifies a cleaner, more sinusoidal output. Multi-level inverters are designed to reduce THD by generating a higher number of voltage levels, resulting in a smoother waveform and less harmonic content. Control techniques, such as optimized switching strategies, can also be employed to further minimize THD, thereby enhancing the performance and reliability of the inverter in both standalone and grid-connected systems. Reducing THD is essential for improving the efficiency and longevity of the overall power system and ensuring compliance with power quality standards.

Table 4. State of the art of survey for multi-level inverters and computation techniques

Author	Technique	Objective	Results	Limitations
Solatialkaran *et al.*[20]	Derivation of the mathematical expressions, for inverter ripple, damping losses, and grid-side inductor sizing.	Optimize inverter-side inductor and damping resistor selection for improved power quality.	Reduced voltage stress, harmonic generation, and enhanced power quality validated through experiments and simulations.	Applicability limited to harmonics within 2-150 kHz range; focus on power electronics equipment harmonization.
Wendel *et al.*[23]	Rapid control prototyping with hardware and software design.	Implement computationally intensive algorithms for power electronics systems.	Minimized latency, high signal integrity, and versatility in controlling various converters.	Limited discussion on specific algorithms or applications, potential scalability challenges with complex systems.
Taheri *et al.*[21]	Proposing a new symmetrical multi-level inverter topology for improved performance.	To reduce power element count and enhance output voltage levels for various loads.	Better semiconductor count, lower losses, and reduced total blocking voltage compared to previous topologies.	Limited to simulations and experimental verification for a 9-level inverter; real-world scalability and applications not explored.
Singh *et al.*[18]	Parallel connection of inverter legs with coupled inductors for multi-level PWM output.	Lower effective series inductance for high-quality PWM voltages.	Low fundamental voltage drops, high-frequency output, improved PWM quality.	Limited to 3-phase systems, specific inverter leg configurations for varying voltage levels.
Ahmad *et al.*[2]	Selective Harmonics Elimination (SHE) PWM using fast convergent Homotopy Perturbation Method (HPM).	Efficient computation of switching angles for multilevel inverters at a faster rate.	Accurate switching angles computed multiple solutions in modulation index range, validated using FPGA controller.	Challenging task due to non-linear transcendental equations, limited solutions for some modulation indexes.

4.0 State of Art of Survey

This state-of-the-art survey delves into multi-level inverters, exploring various computation techniques applied in their design and operation. The review encompasses an analysis of recent advancements, challenges, and potential future directions in the realm of multi-level inverters, offering valuable insights for researchers and practitioners in the field.

Table 4 summarizes various research studies focusing on inverter technologies. Each study highlights different techniques, objectives, results, and limitations. For

example, Solatialkaran *et al.* optimized inverter-side components for better power quality, while Ahmad *et al.* addressed challenges in selective harmonics elimination for multilevel inverters.

4.1 Comparison of Performance Analysis and Comparison of Multilevel Inverters

Performance analysis and comparison of multilevel inverters involve evaluating various parameters such as output waveform quality, harmonic distortion, efficiency, and switching frequency. Through simulations or experimental tests, different staggered inverter geographies and control strategies are scrutinized to assess their suitability for specific applications. Key factors include voltage levels, scalability, complexity, and cost-effectiveness. By comprehensively analyzing these aspects, researchers and engineers aim to identify the most suitable multilevel inverter configuration for diverse power electronic applications, considering trade-offs between performance metrics and implementation challenges.

Table 5. Harmonic distortion analysis of different inverter topologies (Sharma *et al.*)

Topology	Voltage THD %	Current THD %
5-Level H-bridge inverter	33.98	32.02
7-Level H-bridge inverter	22.04	22.77
5-Level flying capacitor inverter	34.11	32.04

Table 5 presents voltage and current THD percentages for different inverter topologies, including 5-level H-bridge, 7-level H-bridge, and 5-level flying capacitor inverters. As far as voltage THD, the 7-level H-bridge inverter exhibits the lowest distortion at 22.04%, followed closely by the 5-level H-bridge inverter at 33.98%. Similarly, for current THD, the 7-level H-bridge inverter also demonstrates the lowest distortion at 22.77%, with the 5-level H-bridge and 5-level flying capacitor inverters showing slightly higher values at 32.02% and 32.04%, respectively. These findings provide insights into the harmonic performance of different inverter topologies, aiding in the determination of fitting configurations for various power electronics applications.

5.0 Challenges and Future Directions

Addressing the challenges and future directions for enhancing the performance of multi-level inverters with different computation techniques involves overcoming several hurdles. These may include optimizing modulation strategies to minimize harmonic distortions, enhancing control algorithms for better dynamic response and stability, integrating advanced semiconductor devices for higher power density and efficiency, and developing robust thermal management solutions to mitigate overheating issues. Additionally, exploring novel computation techniques such as artificial intelligence and machine learning algorithms could offer opportunities to further improve the efficiency, reliability, and scalability of multi-level inverter systems in diverse applications ranging from renewable energy integration to electric vehicle propulsion.

5.1 Hardware Implementation Considerations in Multi-level Inverters

Hardware implementation considerations in multi-level inverters play a crucial role in ensuring the efficiency, reliability, and performance of these systems. Key aspects include the selection of suitable semiconductor devices such as Insulated Gate Bipolar Transistors (IGBTs) or Silicon Carbide (SiC) MOSFETs to handle high voltages and currents with minimal losses. Optimal gate drive circuitry design is essential to ensure fast switching speeds and accurate control of the switching devices. Moreover, the layout and packaging of the inverter components must be carefully engineered to minimize parasitic inductances and capacitances, thereby reducing switching losses and electromagnetic interference.

5.2 Real-time Computational Efficiency

Real-time computational efficiency is paramount in various applications, particularly those requiring rapid decision-making and response times, like independent vehicles, modern robotization, and continuous control frameworks. Achieving real-time computational efficiency involves optimizing algorithms, hardware architectures, and system configurations to ensure that computations are performed within stringent time constraints. This often requires leveraging parallel processing techniques,

efficient data structures, and algorithmic optimizations to minimize computational overhead and latency. Additionally, hardware acceleration using specialized processors, such as GPUs, FPGAs, or dedicated ASICs, can significantly enhance computational throughput and reduce response times for real-time applications. Furthermore, the use of lightweight models, model compression techniques, and quantization methods can reduce the computational complexity of deep learning algorithms without sacrificing accuracy, enabling real-time inference on resource-constrained devices. Overall, maximizing real-time computational efficiency is essential for enabling high-performance, responsive systems in various domains, driving innovation and advancement in critical applications.

5.3 Emerging AI Techniques for Inverter Control

Emerging AI techniques are revolutionizing inverter control by offering advanced solutions for optimizing performance, enhancing efficiency, and enabling smart grid integration. Machine learning algorithms, such as neural networks and reinforcement learning, are being utilized to develop predictive control strategies that adapt in real-time to changing operating conditions and grid demands. These techniques enable inverters to anticipate and mitigate grid disturbances, optimize power flow, and improve overall system stability. Moreover, AI-based fault detection and diagnosis algorithms enhance the reliability and robustness of inverters by enabling proactive identification and isolation of faults, thereby minimizing downtime and maintenance costs. Based on the examination, the MLP-ANN model has been made to test the practicality of the proposed framework under different OCF conditions. The prepared brain network precisely identifies the broken h-scaffold and switch matches inside 8 ms and 16 ms for all the SS and DS issues with 96% order exactness. Additionally, it fostered the vital issue lenient control approach utilizing the repetitive h-span unit to give the total answer for OCFs.

6.0 Summary

The necessity for the enhancement of multi-level inverters arises from the limitations of conventional two-level inverters and the advantages offered by multi-level inverters in the current scenario. Conventional two-level inverters suffer from issues such as higher harmonic distortion and lower voltage waveform quality, which can lead to reduced efficiency and reliability in power systems. On the other hand, multi-level inverters provide improved voltage waveform quality, reduced harmonic distortion, and higher power efficiency, making them ideal for various high-power applications such as renewable energy systems, electric vehicles, and grid-connected power converters. The research landscape in the current innovations of multi-level inverters includes advancements in Pulse Width Modulation (PWM) techniques and topological advancements to enhance their performance and capabilities. Various techniques are employed for performance enhancements in multi-level inverters, including conventional techniques and Artificial Intelligence (AI) based approaches. Conventional techniques such as Selective Harmonic Elimination (SHE) and Space Vector Modulation (SVM) are used for controlling multi-level inverters to improve their performance.

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