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Review

The Role of Multilevel Inverters in Mitigating Harmonics and Improving Power Quality in Renewable-Powered Smart Grids: A Comprehensive Review

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Abstract: The world is increasingly turning to renewable energy sources (RES) to address climate change issues and achieve net-zero carbon emissions. Integrating RES into existing power grids is necessary for sustainability because the unpredictability and irregularity of the RES can affect grid stability and generate power quality issues, leading to equipment damage and increasing operational costs. As a result, the importance of RES is severely compromised. To tackle these challenges, traditional power systems (TPS) will have to become more innovative. Smart grids use advanced technology such as two-way communication between consumers and service providers, automated control, and real-time monitoring to manage power flow effectively. Inverters are effective tools for solving power quality problems in renewable-powered smart grids. However, their effectiveness depends on topology, control method and design. This review paper focuses on the role of multilevel inverters (MLIs) in mitigating power quality issues such as voltage sag, swell and total harmonics distortion (THD). The results shown here are through simulation studies using DC sources but can be extended to RES-integrated smart grids. The comprehensive review also examines the drawbacks of TPS to understand the importance and necessity of developing a smart power system. Finally, the paper discusses future trends in MLI control technology, addressing power quality problems in smart grid environments.

Keywords: multilevel inverters; power quality; voltage sag and swell; total harmonics distortion; smart grids

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1. Introduction

The world is adopting more RES because of concern about climate change issues. RES, such as solar (rooftop-solar), wind, hydropower, biofuel, and ocean energy integration into existing power grids, are necessary for sustainability. As per the International Energy Agency (IEA), wind and solar combined will generate more electricity than hydropower to help achieve sustainability and reach net-zero carbon goals [1]. The use of solar and wind power has been increasing exponentially due to their ability to supply electric power and reduce installation costs [2]. Despite such benefits of the RES, their unpredictability and inconsistency pose significant technical challenges to power grid stability and power quality [3]. Smart grids utilise modern technology to control and manage the flow of electrical power from all generation sources to meet variable electric power demands for the end users [4]. Compared to TPS, smart grids offer improvement in stability, reliability, and efficiency to make the electrical power grid capable of handling distributed generation of RES [5].

MLIs are the key power electronics technology in advancing RES-integrated smart grids. Unlike traditional two-level inverters, MLIs generate an output voltage in multiple steps to create an approximate sine wave, reducing power quality challenges like THD, poor power factor, etc. [6]. There are a few advantages of MLIs in RES-integrated smart grids due to their ability to handle higher output voltage, improved efficiency and reduced switching losses. Thus, their use is essential in smart grids. Different topologies of MLIs, such as diode-clamped, flying capacitor, and cascade H-bridge inverters, are being researched currently [7].

A smart grid is a modern power grid equipped with advanced two-way communication, real-time monitoring and advanced control strategies. These features make a smart grid to manage the stability, reliability and efficiency of the distributed generation of RES [8]. The MLI-integrated smart grid plays a crucial role in ensuring a reliable operation and improves the power quality challenges which occur due to voltage and frequency fluctuations when integrated with RES [9]. Power quality challenges should be addressed with the increased adoption of RES-based systems and electrical vehicles (EVs). If not, equipment overheating, increased distribution losses and damage to sensitive equipment can occur. Thus, it is essential to implement MLIs to solve such problems [10]. Despite considerable progress in MLIs and smart grids, several research issues remain unresolved. Most studies have focused on MLI topologies and their potential to improve power quality. MLIs have proven to be effective in reducing THD. Their performance depends on a high penetration of RES, especially in decentralised power systems such as microgrids and distributed generation networks, which has not been fully explored [11]. Figure 1 shows an MLI-based RES-powered smart grid, traditional power plants, and electric vehicle (EV) charging stations. This figure represents a smart grid design that promotes sustainability by integrating RES and advanced power electronics. The use of MLIs helps to improve power quality with distributed generation. The smart meters and supervisory control and data acquisition (SCADA) systems provide real-time control and monitoring of the system. Integrating the energy storage system with the grid improves reliability by controlling the generation and demand of the system. Additionally, the figure highlights the inclusion of EV charging stations with vehicle-to-grid technology, traditional power plants for base load stability.

This review aims to fill some of the existing research gaps by providing a detailed analysis of the role of MLIs in mitigating THD and improving power quality in RES-integrated smart grids.

- To study existing MLI topologies to reduce THD and enhance voltage stability in RES-integrated smart grids.
- To study the role of MLIs in power quality improvement in RES-powered smart grids.
- To identify present challenges and suggest future research areas for optimising MLI performance in RES-integrated smart grids.

This review studies different MLI technologies and their application in RES-integrated smart grids. It explores different MLI designs and control methods and their effectiveness in reducing THD and improving power quality.

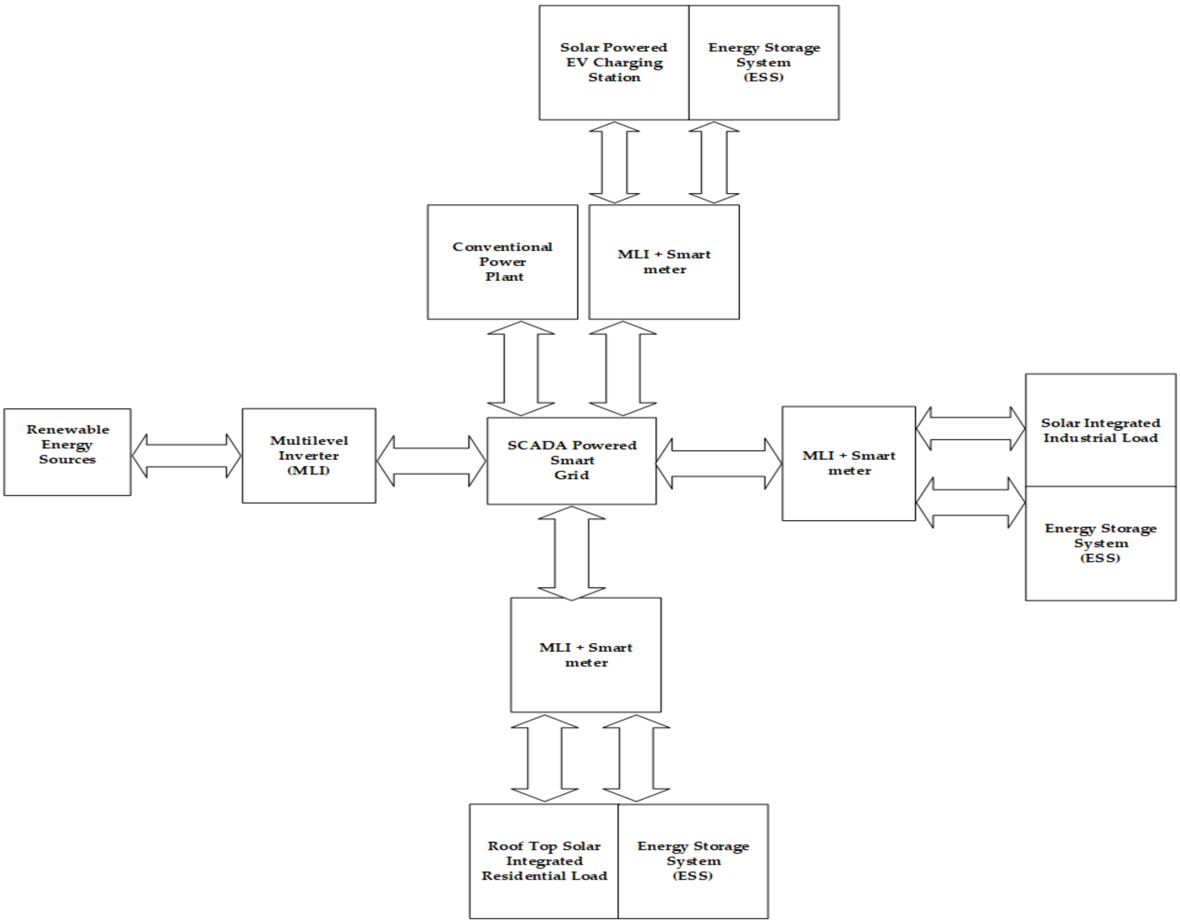

Figure 1. MLI-based RES power smart grid.

2. Power Quality Challenges of RES-Integrated Smart Grids

Adopting RES, such as solar and wind energies, into power grids is essential for achieving global sustainability goals. Integrating RES introduces power quality challenges. These challenges arise because of the discontinuous generation of RES, power electronic converters and distributed generation. Some key aspects of power quality, such as power factor, harmonic distortion, frequency stability, and voltage stability, are essential to grid stabilisation, equipment life spans, and system efficiency [12]. Solar and wind energies have unique behaviours and issues affecting grid performance. Understanding these challenges and identifying current trends is essential to better integrating renewable energy into the smart grid [13]. Improving power quality issues in RES-powered smart grids is essential for maintaining grid reliability. Table 1 gives some of the key power quality issues of solar and wind energies. The table highlights the differences in how these issues occur and can help identify the unique challenges associated with the above energy sources.

Table 1. Power quality issues with solar- and wind-integrated grid.

Power Quality Issue	Solar Energy	Wind Energy	Impact on System	Reference
Voltage fluctuations	Caused by variations in sunlight intensity. Follow a daily cycle, but rapid changes during weather changes can cause variation.	Caused by unpredictable wind speeds, which are more erratic than solar.	Can affect sensitive equipment and lead to power quality issues.	[14]
Harmonics	Caused by inverters; depends on inverter quality and power electronic devices used.	Mitigation is more complex because of inverters and mechanical components in wind turbines.	Can cause equipment overheating and increase transmission losses.	[15]

Table 1. *Cont.*

Power Quality Issue	Solar Energy	Wind Energy	Impact on System	Reference
Super-harmonics	Power electronics converters cause high-frequency harmonics (2–150 kHz). These converters include AC-DC and DC-AC conversion and operate at high switching frequencies to efficiently convert and regulate power. The switching actions in these converters are generated in the power system in PV systems.	Caused by power electronics converters and the variability of wind speed and turbine operation.	These harmonic distortions can introduce electromagnetic interference (EMI), which can disrupt the communication systems within smart grids by interfering with the control signals used to manage the grid. High-frequency EMI can also increase losses in transformers and distribution networks. This can speed up the ageing of insulation and cables and improve maintenance and operational costs.	[16]
Frequency variations	Less important: follow a pattern that is easy to predict, but sudden clouds can bring about rapid changes.	More importantly, significant frequency variations can occur due to unpredictable wind speed.	Can affect the stability of power grid operations, requiring quick response and monitoring.	[17]
Voltage imbalance	Because of the unequal distribution of solar modules across the phases, can be controlled by proper design.	This is more critical due to uneven wind speed across turbines, which may be even more important in large wind farms.	It reduces equipment life and efficiency.	[18]
Poor power factor	Caused by inverter-related operation; can be mitigated with power factor correction devices.	More impact due to large wind farms; reactive power compensation is required.	Leads to poor efficiency transmission and makes the grid unstable.	[19]
Flicker	Less common but can occur where sunlight changes rapidly.	Occurs due to unpredictable wind speed. Mitigated by the static var compensator.	Causes visible light to flicker and interfere with grid equipment.	[20]
Overvoltage	Occurs when solar generation is extremely high, and demand is at its lowest; commonly seen in regions with high rooftop solar penetration.	Occurs when the wind speed is high, and the demand is at its lowest; commonly seen in remote areas where large wind farms exist.	Can damage grid equipment and reduce the equipment lifespan.	[21]
Voltage dips	Caused by a sudden drop in sunlight intensity, such as shading or cloud cover.	Occurs due to sudden changes in wind speed.	May impact sensitive equipment.	[22]

Table 1 shows that addressing power quality issues and the impact of power systems is necessary. There are several methods to solve the power quality issues. Reactive power compensation using power electronics-based control devices like thyristor-controlled reactors (TCR) and thyristor-switched capacitors (TSC) has been used to reduce THD [23]. Unified power quality conditioners (UPQC) effectively improve voltage sags, swells, harmonics, and power quality. Series and shunt active power filters are used to reduce voltage harmonics and improve the performance of RES-powered grids [24]. Advanced control topologies of MLIs help in reducing harmonics, managing reactive power, and stabilising voltage and frequency levels [25]. Energy storage systems (ESS) are used to improve discontinuous generation of RES by storing excess energy generated during periods of high generation for supply in periods of low generation [26]. It can also manage frequency and voltage variation and improve overall grid stability. Flexible AC transmission system (FACTS) devices (static synchronous compensators (STATCOM), static var compensator (SVC) and dynamic voltage restorers (DVR)) are used to stabilise voltage, improve power factor and reduce THD in power grids [27]. Smart grids are digital communication technologies and bidirectional power grids. These systems can do real-time reactive power compensation, which is important for grid stability in RES-integrated grids [28]. Integrating

RES into smart grids is an innovative step in power flow management to improve efficiency and sustainability and meet increasing power demands [29]. They create a more efficient, reliable and flexible power grid. They can accommodate the increasing complexity of renewable energy integration [30]. They facilitate real-time monitoring and control of power supply and demand. They provide improved demand-side management through smart meters and dynamic pricing strategies [31]. Smart grids increase efficiency and reduce peak loads by making real-time monitoring of power flow consumption and cost available to consumers [32]. Integrating EV and vehicle-to-grid (V2G) technologies allows bidirectional power flow between vehicles and the power grid [33]. V2G can be used as mobile energy storage with discharging of power back to the grid during peak hours to improve overall system reliability and efficiency [34]. This adoption integrated the distributed generation systems such as solar and wind with TPS. The integration of RES introduces challenges with power quality and harmonic distortion [35]. Smart grid operations, such as distributed energy resources EV charging operations (V2G and G2V), generate super-harmonics due to high-frequency switching in power electronic devices, such as chargers, inverters, and renewable energy interfaces. It can affect grid stability and the performance of the distribution network. It can be mitigated using passive and active filters, optimising converter designs and implementing grid-side solutions like impedance stabilizers [36]. To overcome such issues, smart grids are integrated with advanced technologies such as MLIs and FACTS. Table 2 compares MLIs with alternative tools like conventional inverters and FACTS devices on different RES-integrated smart grid challenges and factors. The comparison overviews recent challenges and trends in RES-powered smart grids.

Table 2. Comparison of MLIs and alternative tools in RES-powered smart grids.

RES-Integrated Smart Grid Challenges and Factors	MLI	Convectional Inverters	FACTS Devices
THD	Offers THD with less use of external filters. Can be a cost-effective solution for a RES-powered smart grid [37].	Requires external filters for harmonics mitigation [37].	STATCOM and SVC are used for reducing harmonics but depend on the external filters [38].
Super-harmonics	MLIs play a pivotal role in addressing the challenges of superharmonics. Advanced switching techniques, such as selective harmonic elimination and space vector modulation, help optimise switching operations to minimise high-frequency emissions [39].	Limited ability to mitigate supra-harmonics requires high-frequency filters, such as LC or LCL filters [40].	SVC, UPFC (unified power flow controller), and STATCOM offer reactive power compensation and voltage regulation to mitigate super-harmonics by dynamically balancing the grid voltage [40].
Voltage control and stability	More effective in controlling voltage fluctuations in RES-integrated grids by real-time monitoring [41].	Voltage regulators are used to control fluctuations but are less flexible in RES-integrated grids [41].	Provides fast voltage and power flow control response times but is less flexible [41].
Efficiency	Provides high efficiency due to reduced voltage stress on semiconductor devices [42].	Low efficiency, especially for high-power applications [42].	Improves overall efficiency by optimising power flow [42].
Integration with energy storage systems	Is easily integrated with external battery sources and hybrid storage to maintain supply and demand [43].	An external system requires control and synchronisation with batteries, which increases the system complexity [43].	Can be integrated with an external storage system, but an additional control system is required [43].
Cybersecurity	AI and blockchain improve security levels and minimize cybersecurity threats [44].	Highly dependent on centralized control; thus, prone to cyber threats [44].	These devices require robust cybersecurity measures [44].
Power quality improvement	Improves power quality by reducing harmonics, voltage flicker and transient [45].	Additional power electronics devices are required to improve power quality [45].	Improves power quality by providing reactive power compensation [46].

Table 2. *Cont.*

RES-Integrated Smart Grid Challenges and Factors	MLI	Convectional Inverters	FACTS Devices
Suitability for sensitive loads	Suitable for sensitive loads and highly unpredictable and distributed renewable power generation [47].	Suitable for low-powered applications [47].	Suitable for modern power grids and EVs but requires additional control systems [47].
Fault tolerance capacity	High, due to modular and hybrid design [48].	Lows [48].	High, due to fast response capability for voltage and frequency variations [48].
Cost	Due to its complex design and the presence of more components, such as capacitors, diodes, and semiconductor switches, has high capital and maintenance costs [49].	Has lower capital and operational cost, but external filter design affects the price and design [49].	Has high maintenance and installation costs [49].

3. A Brief Introduction to Multilevel Inverters

In recent years, power electronics technologies like MLIs have shown advances in reducing complexity with RES integration with the grid. They not only improve THD but also improve the RES-distributed generation to maintain grid stability [50]. MLIs are power electronic devices designed to convert DC voltage into AC voltage with improved output voltage compared to traditional two-level inverters [51]. The innovative MLI design controls the output voltage and current [52]. The basic configuration contains several power semiconductor devices (insulated gate bipolar transistors (IGBTs) and diodes) arranged in a specific topology to create multiple output voltage levels [53]. The basic configurations are diode-clamped MLI, capacitor-clamped MLI, and cascaded H-bridge MLI. Each configuration has characteristics that make its application unique in various uses [54]. Figure 2 shows the classification of MLIs.

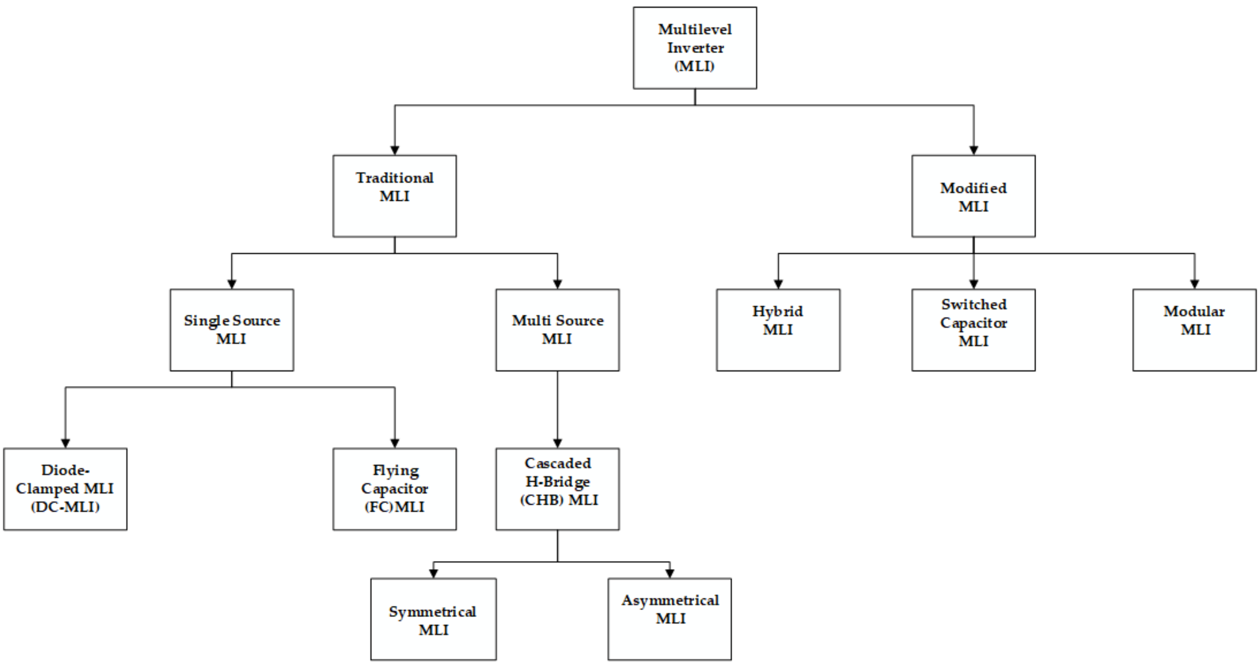

Figure 2. Classification of MLIs [55].

There are various classification methods for MLIs; in this paper, MLIs are mainly classified into two broad categories, based on structure, application, and control. These are traditional and modified MLIs. The traditional MLI contains traditional MLIs like diode-clamped MLI, flying capacitor MLI and cascaded H-bridge MLI. The modified

MLI is developed by modifying traditional MLIs for specific applications. They can be either hybrid MLI, modular MLI, or switched-capacitor MLI, amongst many others. The cascaded H-bridge (CHB) multilevel inverters are more suitable for renewable energy sources than the diode-clamped (DC-MLI) and flying capacitor (FCMLI) inverters because of their modularity, flexibility, and compatibility with multiple isolated DC sources such as solar panels and batteries. This allows the integration of distributed renewable energy systems by enabling the independent operation of each module, which is particularly useful for handling the variable and decentralized nature of renewables. Additionally, a CHB MLI produces a lower THD with fewer components, reduces filtering requirements, and improves power quality. FCMLI and DC-MLI face challenges in capacitor balancing and diode management. A CHB MLI avoids these issues and offers better reliability and efficiency. In this study, a seven-level cascaded H-bridge multilevel inverter was designed. Figure 3 shows the block diagram for the seven-level CHBMLI simulation. This demonstrates the detailed setup, including the number of H-bridge modules and modulation technique used. The simulation results of the output voltage are shown in Figure 4. A sinusoidal wave is superimposed over the simulated waveform. The stepped output voltage waveform closely follows a sinusoidal shape, effectively reducing the THD. This reduction in harmonics minimises issues such as voltage fluctuations, electromagnetic interference (EMI), and equipment overheating, thereby enhancing the overall stability and reliability of smart grids. This justifies the use of MLIs in modern smart grids, highlighting their critical role in addressing power quality challenges associated with renewable energy integration.

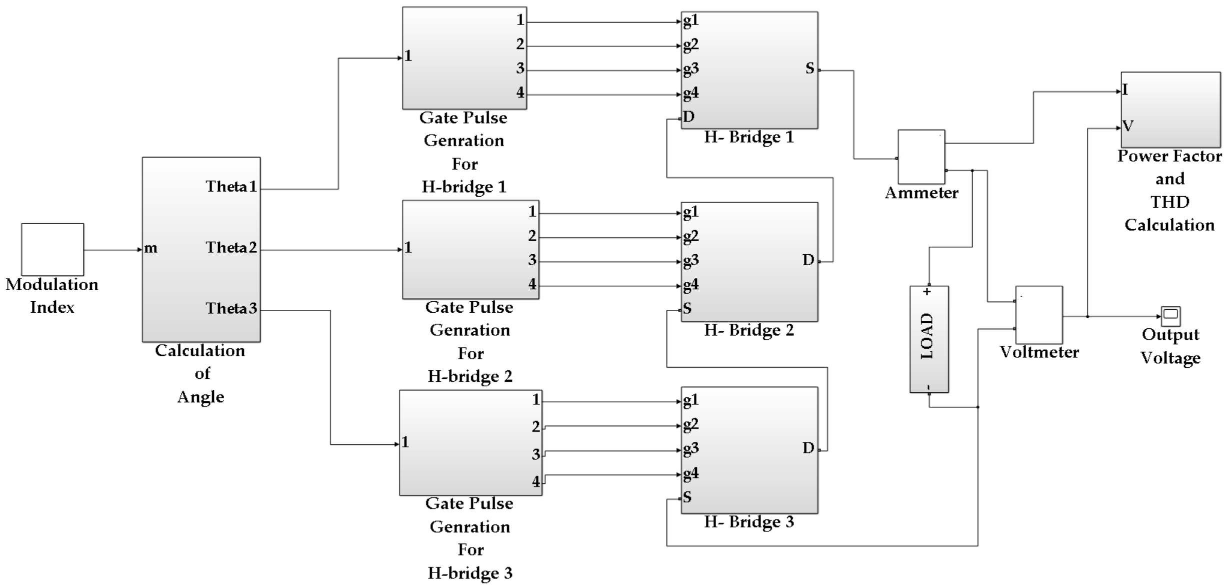

Figure 3. Simulation diagram 7-level cascaded MLI.

MLIs are one of the most promising technologies in power electronics to improve the power quality issues in RES-powered smart grids [56]. Unlike traditional two-level inverters, MLIs generate multiple voltage levels, all nearly sinusoidal, and will reduce THD without using any complex filters. They also minimise electromagnetic interference (EMI) and switch losses [57]. These characteristics make MLIs ideal for applications in smart grids that integrate with various RES like solar and wind. Different MLI topologies have been developed for multiple grid requirements, and each topology offers benefits in solving challenges in terms of complexity, control strategies, harmonic performance, and bidirectional power flow, which is essential for V2G systems, allowing EVs to supply power back to the grid during peak demand periods, thereby enhancing grid stability [58].

Based on their structure, operation, and control, they can be classified into several types, as shown in Table 3. This classification is important for determining their suitability in various RES-powered grid applications

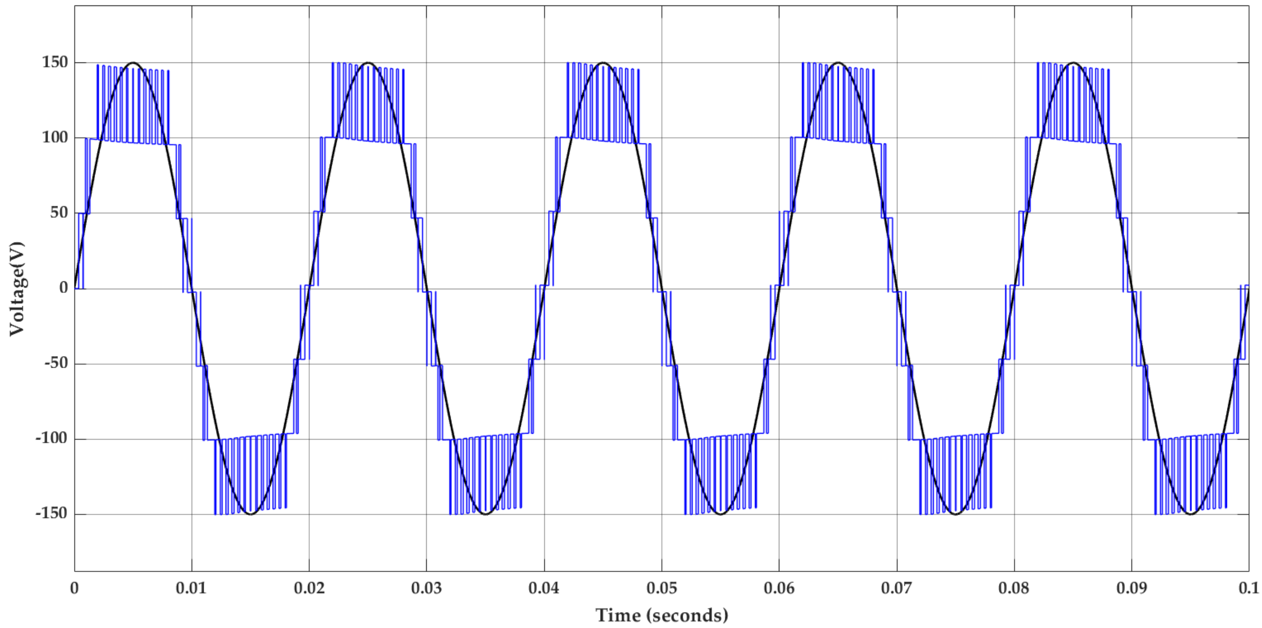

Figure 4. Simulated output voltage waveform compared with a sinusoidal signal.

Table 3. Role of MLIs in RES-powered smart grid.

MLI Topology	Key Features	Challenges	Recent Trends and Innovations
Diode-Clamped MLI or Neutral Point-Clamped Multilevel Inverter(NPC) [59]	Uses diodes to clamp the voltage at specific levels. Reduces voltage stress on switches.	Complexity increases with the number of levels due to more diodes.	Reduction in the number of clamping diodes through advanced topologies like hybrid NPC inverters.
	Ideal for medium- to high-voltage applications.	Deficient performance under unbalanced load conditions.	Applications in offshore wind farms due to high voltage requirements.
Cascaded H-Bridge (CHB) Inverter [60]	Series connection of multiple single-phase H-bridge cells.	Requires separate isolated DC sources for each H-bridge module.	Modular design makes it suitable for solar PV and wind energy systems.
	Can generate higher voltage levels without increasing complexity.	More complex control algorithms are needed for harmonics and balancing.	Can be used for hybrid energy sources (solar, wind, and battery) to reduce the number of isolated DC sources.
Flying Capacitor (FC) Inverter [61]	Uses high-frequency capacitors to achieve multiple voltage levels.	Requires more capacitors, which increases cost and volume.	Advanced voltage control algorithms are needed to reduce complexity.
	Capacitors provide self-balancing without any complex control schemes.	Balancing becomes difficult as the number of levels increases.	Simplified designs for medium-voltage applications.
Modular MLI [62]	Simple, modular design makes it suitable for high-voltage applications.	Requires complex control for balancing and synchronisation across modules.	Widely used in high-voltage direct current (HVDC) transmission.
	Each can module runs at low voltage. It reduces stress on power devices.	Excessive cost and increased footprint due to many submodules.	Used in STATCOM-based systems.

Table 3. *Cont.*

MLI Topology	Key Features	Challenges	Recent Trends and Innovations
Hybrid MLI [63]	Gives combined features from different MLI topologies to create a hybrid design.	Creates complexity in design and control challenges due to combining different topologies.	Hybrid (CHB + NPC) inverters can reduce harmonics in large-scale renewable energy plants.
	Can reduce component count while achieving higher voltage levels.	Hybrid configurations may require advanced control algorithms.	Requires a focus on cost-effective hybrid designs for medium-voltage applications.
Switched-capacitor MLI [64]	Uses DC link capacitors to achieve multiple levels without separate DC sources.	Increases control complexity due to switching capacitors at high frequencies.	Uses self-balancing capacitor control algorithms to improve efficiency.
	Reduces the number of DC sources compared to traditional MLIs.	Limited use into high voltage levels.	Can be used in distributed generation systems.

The MLI's design involves various challenges and complexity. This issue increases system costs and requires advanced control algorithms to improve effectiveness. Multiple switching devices introduce the need for advanced fault detection and protection strategies. This study highlights the importance of THD as a major power quality issue. High THD levels can cause other power quality issues such as a decreased power factor and increased voltage fluctuations. The THD of the inverter is calculated using the following formula [43]:

$$THD = \sqrt{{V_2}^2 + {V_3}^2 + {V_4}^2 + \ldots + {V_n}^2}/V_1 \quad (1)$$

where

V_n = RMS value of the nth harmonic voltage, and

V_1 = RMS value of the fundamental voltage.

The power factor (PF) improves as harmonics reduce as THD improves. This is evident from the relation [65]:

$$PF = cos\varnothing/\sqrt{1 + \left(\frac{THD}{100}\right)^2} \quad (2)$$

The modulation techniques also reduce electromagnetic interference and directly control power quality standards. This makes MLIs suitable for modern electrical grids. Modulation techniques such as fundamental switching frequency or high switching frequency are utilised in MLIs. The fundamental switching frequency has one or two commutations per cycle, whereas the high switching frequency has multiple commutations per cycle [66]. Selective harmonic elimination and space vector control are fundamental switching frequency modulation types. The high-frequency modulation techniques are classified into two major techniques—pulse width modulation (PWM) and space vector modulation (SVM). The PWM modulation is further classified into multicarrier and single-carrier modulations. The various modulation techniques are shown in Figure 5.

Modulation techniques are important for enhancing the power quality by reducing THD. Each technique uses unique methods for minimising harmonics, improving efficiency, and ensuring stable power systems. They play vital roles in renewable energy systems and smart grids by improving the efficiency and reliability of power inverters. They also improve the power quality by reducing the THD and providing control over the power flow. Techniques such as selective harmonic elimination, space vector pulse width modulation, and third-harmonic injection are designed to reduce harmonics, thereby enhancing the efficiency and stability of power systems. These techniques are essential in applications ranging from industrial drives to renewable energy systems, where maintaining a high-power quality is critical. A detailed explanation of the modulation techniques is presented in Table 4.

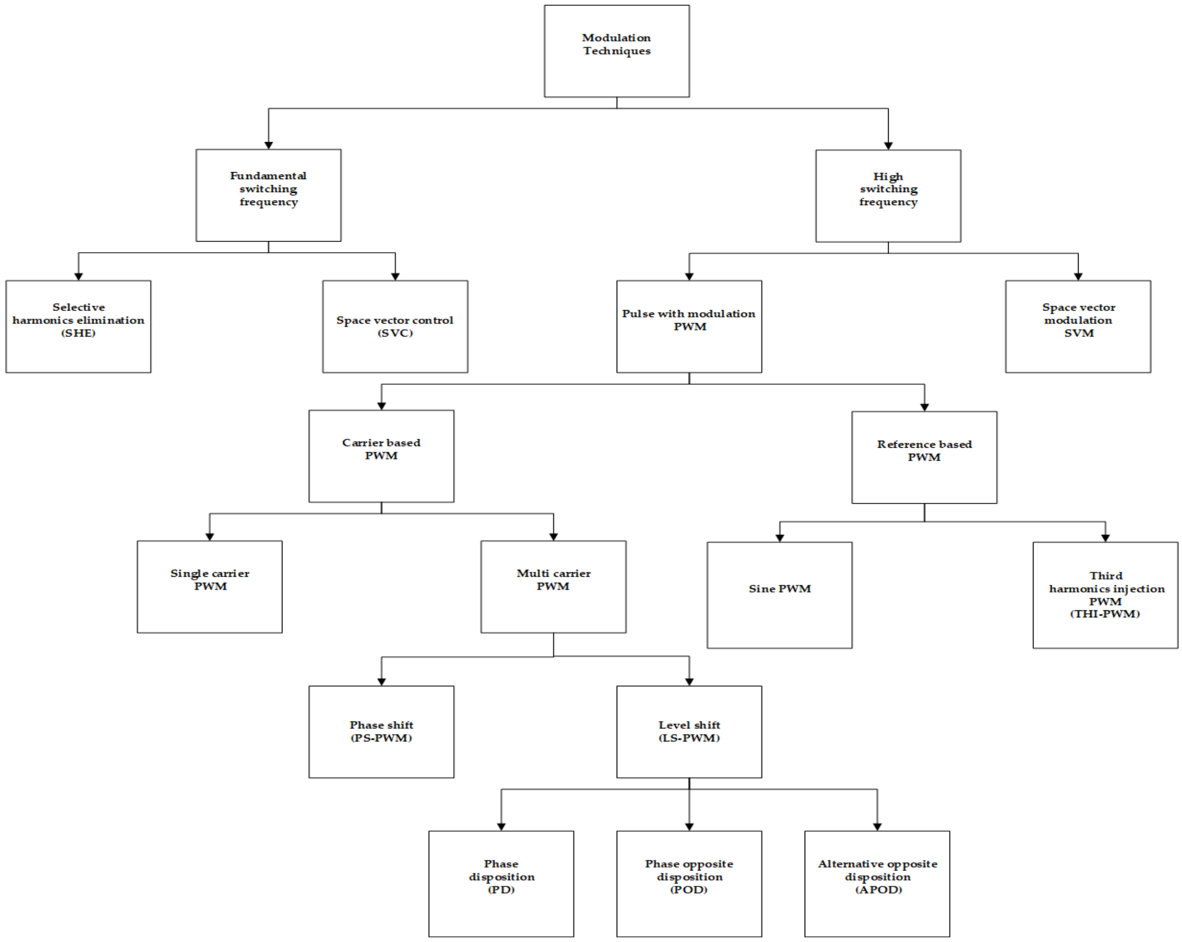

Figure 5. Classification of modulation technique [67].

Table 4. Modulation techniques for improving power quality.

Modulation Technique	Role in Improving Power Quality	Advantages	Disadvantages	Applications	Recent Trends
Selective Harmonic Elimination (SHE) [68]	Reduces lower-order harmonics, improves efficiency and reduces power losses.	Effective harmonic reduction and enhances overall efficiency.	Complex mathematical computations, difficult real-time implementation.	Transformers, motors, power distribution systems.	Use of metaheuristic algorithms for efficient problem-solving in multilevel inverters.
Space Vector Pulse Width Modulation (SVPWM) [69]	Improves voltage utilisation, reduces THD, and enhances system stability.	Lowers harmonic distortion, optimises voltage usage.	Complex calculation requires advanced control algorithms.	High-power applications, renewable energy integration, motor drives.	Development of discontinuous SVPWM techniques to reduce common-mode voltage and inverter losses.
Phase-Shifted PWM (PS-PWM) [70]	Balances harmonic distribution, lowers switching losses, and improves efficiency.	Reduces harmonics and switches stress.	Requires precise control for optimal performance.	High-voltage applications, high-power inverters.	Combining Phase-Shifted PWM with Phase Disposition PWM to enhance DC link voltage utilisation and output harmonics.
Phase Opposition Disposition (POD) PWM [70]	Reduces overall THD, enhances power stability, and minimises voltage distortions.	Superior harmonic distribution, better THD performance.	Slightly more complex than PD PWM.	Solar PV systems, smart grids, high-efficiency power converters.	Enhanced control strategies to further lower harmonic distortion rates.

Table 4. *Cont.*

Modulation Technique	Role in Improving Power Quality	Advantages	Disadvantages	Applications	Recent Trends
Alternate Phase Opposition Disposition (APOD) [70] PWM	Reduces THD, increasing power efficiency and waveform quality.	Enhanced harmonic mitigation compared to POD PWM.	Higher complexity in implementation.	Power converters, advanced inverter applications.	Comparative studies highlight its effectiveness in reducing THD in induction machine applications.
Phase Disposition (PD) PWM [71]	Reduces harmonic content in output voltage, ensuring better waveform quality.	Simple and effective method for harmonic reduction.	Moderate THD performance, less effective for higher-order harmonics.	Multilevel inverters, industrial motor drives.	Reducing the number of independent DC voltage sources while maintaining low harmonic content.
Third Harmonic Injection (THI) [72]	Increases modulation index, reduces THD, and improves output voltage waveform.	Effective in reducing lower-order harmonics, increases output voltage.	Requires additional circuitry control and modulation complexity.	High-power applications, smart grids, industrial power systems.	Zero sequence power balancing compensation to enhance DC bus utilisation without extra harmonics

To evaluate the role of various modulation techniques in reducing THD, MATLAB R2024b simulations were developed for different modulation techniques. The simulation model consists of three DC sources. The inverter was operated at a standard reference frequency of 50 Hz and utilised a carrier frequency of 1 kHz and modulation of 0.8. Table 5 provides a comparative analysis of THD (%) for various modulation techniques.

Table 5. THD comparison of various modulation techniques in MLIs.

Modulation Techniques	THD (%)
Selective Harmonic Elimination (SHE)	23.56
Space Vector Pulse Width Modulation (SVPWM)	20.12
Phase-Shifted PWM (PS-PWM)	24.65
Phase Opposition Disposition (POD) PWM	22.99
Alternate Phase Opposition Disposition (APOD) PWM	24.10
Phase Disposition (PD) PWM	24.55
Third Harmonic Injection (THI)	21.13

Table 5 shows the THD comparison of various modulation techniques in MLIs. Lower-order harmonics, such as the 3rd, 5th, and 7th, impact power quality by causing voltage distortion, increased transformer losses, and overheating in electrical equipment. Higher-order harmonics are easier to filter out using passive LC filters. Among the techniques, SVPWM achieves the lowest total THD and provides better voltage utilisation. However, it is computationally complex and challenging to implement for higher-level inverters. SHE optimises switching angles to eliminate lower-order harmonics, improving grid performance by reducing voltage distortion. THI improves DC bus utilisation, allowing inverters to generate higher fundamental voltage without increasing the DC-link voltage, making it advantageous for low-voltage PV and wind systems. Figures 6 and 7 present the FFT analysis of the inverter output voltage for SVPWM and THI techniques, illustrating their effectiveness in mitigating lower-order harmonics. These two techniques offered the lowest THD compared to all the other modulation techniques investigated. The FFT plots of other techniques are omitted for brevity.

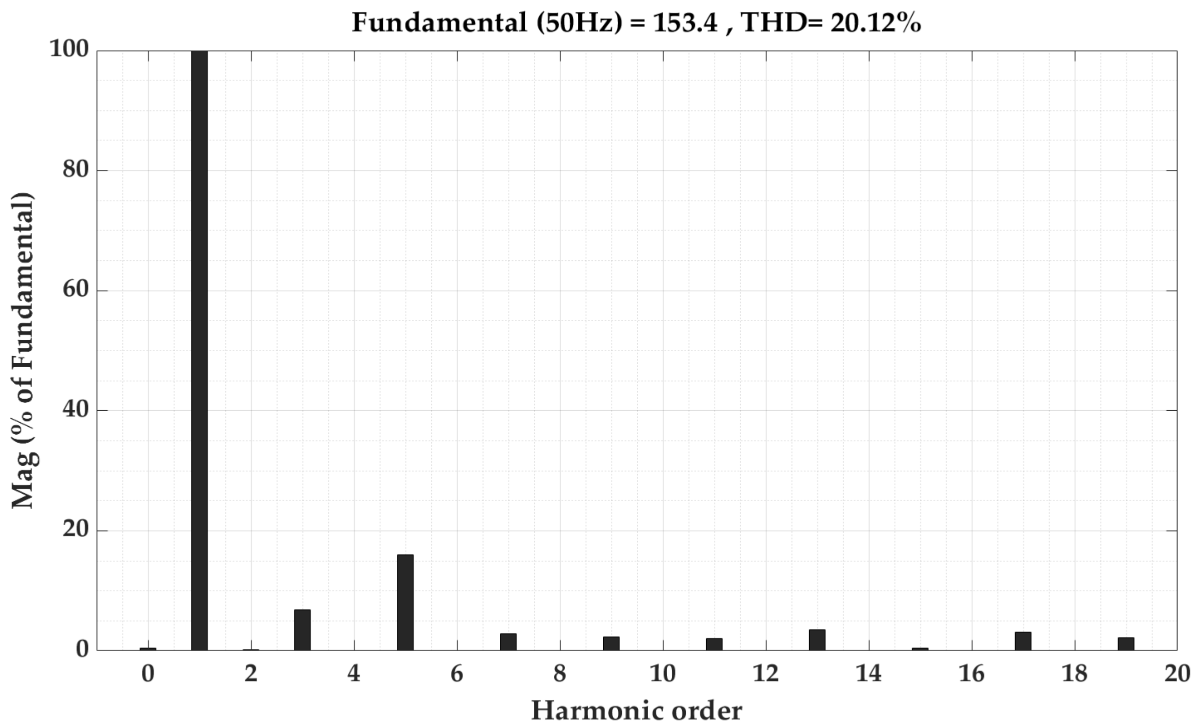

Figure 6. FFT analysis for SVPWM modulation technique.

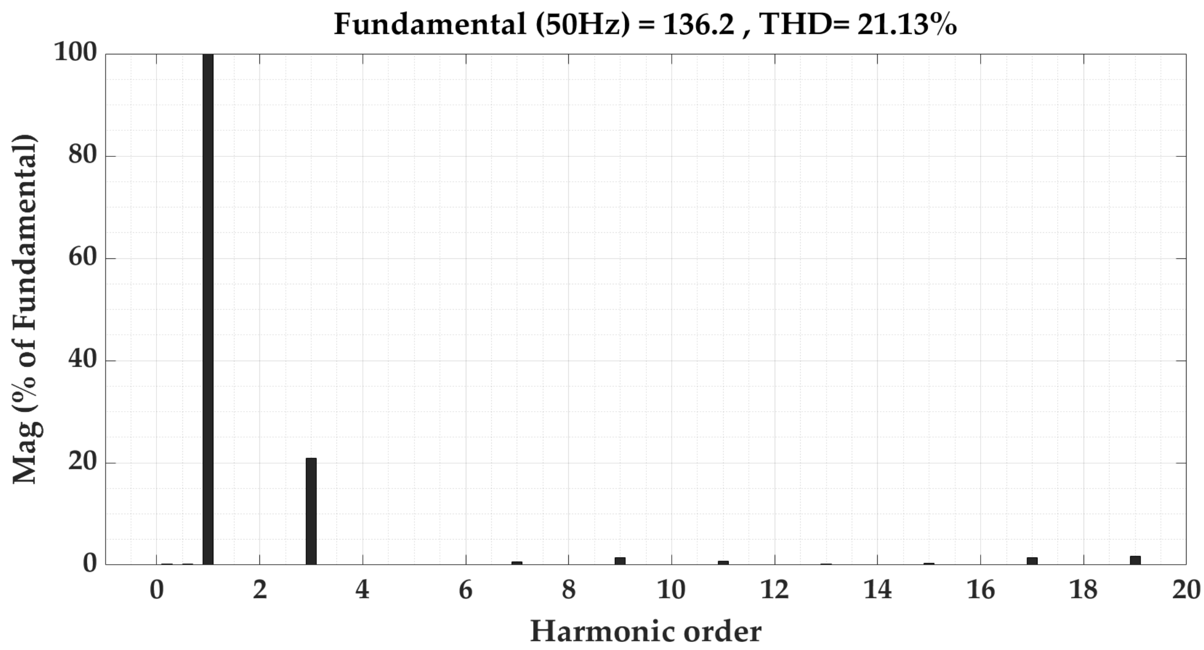

Figure 7. FFT analysis for THI modulation technique.

3.1. Advantages of Multilevel Inverters

1. Harmonic performance
    i. Reduced harmonic distortion: MLIs produce an approximate sinusoidal voltage waveform to reduce THD. This minimises effects such as equipment overheating, system failures, and increased losses [73].
    ii. Improved energy conversion efficiency: Lower THD improved the efficiency of power grids [74].
2. Reliability and operational flexibility

   i. Improved reliability: MLIs are designed in such a way that the system can continue functioning even if one module or switch fails [75].
   ii. Modular expansion: MLIs allow for modular expansion with other inverter modules to be integrated into the system. This adaptability is important for RES integration with the TPS [76].
3. Power factor correction and grid stability
   i. Power factor correction: MLIs offer power factor correction that reduces reactive power penalties imposed by distribution companies. They also improve the transmission and distribution of power [77].
   ii. Grid stability: MLIs can improve voltage and frequency variation and provide stability and reliability [77].
4. Versatility and modulation techniques
   i. Compatibility with modulation techniques: MLIs are compatible with modulation techniques such as PWM and sine wave PWM. This flexibility allows designers to improve inverter performance based on specific requirements [78].
   ii. Minimised switching losses: Different modulation strategies can be used to minimise switching losses and improve overall system efficiency [79].
5. Environmental benefits
   i. Support for renewable energy: MLIs solve power quality and distributed generation challenges with RES [80].

3.2. Applications of Multilevel Inverters in Renewable Energy-Integrated Smart Grids and EV Charging Stations

Integrating smart grids with RES and EV has various applications in power grids. MLIs improve the power quality and efficiency of the system. This section will discuss the use of MLIs in RES-integrated smart grids and EV charging stations, along with their benefits and their role in improving the system's stability and efficiency

1. Improving power quality in smart grids
   i. Reduction of harmonic distortion: The advantage of MLIs is their ability to produce an approximate sinusoidal voltage to improve THD. This reduction in harmonics is essential to maintain power quality and solve other issues like equipment overheating and increased losses [81].
   ii. Voltage regulation and stability: MLIs improve voltage regulation and stability in smart grids by providing a stable and continuous power supply. This is important for RES-powered grids [82].
2. Integration with renewable energy sources
   i. Efficient energy conversion: MLIs make efficient conversion of DC power generated by RES into grid AC power possible [83].
   ii. Maintain grid standard: MLIs can maintain necessary grid standards and codes for RES-integrated grids [84].
3. Supporting EV charging infrastructure
   i. Bidirectional charging (V2G): MLIs provide bidirectional charging, allowing EVs to consume power from the grid and supply it back to it. V2G technology helps to maintain supply and demand during peak hours and frequency variation [85].
   ii. Load management: Integrating MLIs in EV charging stations improves load management. It also ensures that the charging process does not overload the grid. This is achieved by real-time monitoring and control. MLIs also help to

optimise the charging schedules based on grid conditions and the availability of renewable energy [86].

4. Improving system reliability and flexibility
   i. Modular design: The system can continue to operate at reduced capacity and maintain reliability in critical situations such as undervoltage due to the flexibility of MLIs [87].
   ii. Adaptability to variable inputs: MLIs can operate with multiple sources. This enables MLIs to deal with varying inputs from different RES. This is essential for managing the unpredictable nature of RES. This also ensures a continuous and reliable power supply [88,89].
5. Economic Benefits
   i. Cost savings: MLIs operate with higher efficiency owing to their ability to produce near-sinusoidal waveforms, which helps in reducing switching and conduction losses. The modular design of MLIs ensures fault tolerance and reduced maintenance costs. By optimising power quality, they enable more efficient energy consumption, especially in renewable energy systems. They also improve the efficiency and reliability of generation, transmission, and distribution networks. This leads to cost savings in the power generation. They are also able to manage peak loads, which reduces the need for conventional peak-load power plants like diesel plants [90].

4. Future Directions

MLIs play a significant role in enhancing power quality in RES-powered smart grids. The increase in use of RES requires improved MLI technologies and control strategies to solve the power quality challenges of RES-powered smart grids. Despite the benefits of using MLIs to enhance the quality of power, more research work must be done to overcome their disadvantages and improve their use in smart grids.

The implementation of MLIs within existing power grids presents some challenges. Some of the significant challenges are as follows:

1. Technical Challenges
   i. Synchronisation with existing systems: Integration of MLIs into existing grids requires maintenance of synchronisation standards. This can be complex due to the diverse range of equipment and technologies already in use [91].
   ii. Harmonics management: MLIs are used to reduce THD. This can be challenging in RES-powered grids. It is difficult to ensure that all components operate without introducing any problems [92].
   iii. Control and coordination: It is important to maintain control and coordination for MLIs with other grid components, such as traditional inverters and transformers, to maintain grid stability and performance [93].
2. Economic Challenges
   i. High initial costs: The development of MLIs requires high capital costs in terms of equipment, installation and integration. This can be a barrier for utilities and grid operators, especially in sectors with limited financial resources. It requires additional components, such as capacitors, switches, and diodes, increasing material and component costs. Implementing advanced control algorithms and switching strategies necessitates higher spending on software development and hardware integration [94].
   ii. Operational and maintenance costs: MLIs demand skilled persons for installation and precise tuning, which adds to the upfront costs. It also requires

ongoing maintenance and operational management, the cost of which can be added to the overall costs but is essential for long-term sustainability. MLIs generate higher switching losses due to the need to combine voltages of different modules (Vdc, 2Vdc, 3Vdc). This inefficiency can increase operating costs [95].

3. Regulatory and standardisation challenges
   i. Compliance with standards: It is essential to ensure that MLIs meet existing grid regulations and standards [96].
4. Integration with renewable energy sources (RES)
   i. Intermittency of RES: The variable nature of RES introduces challenges for the stable operation of MLIs. Effective integration requires advanced control strategies to manage intermittency and ensure a reliable power supply [97].
   ii. Energy storage integration: Integrating energy storage systems with MLIs is essential to mitigate the unpredictability of RES. It also adds another layer of complexity and cost to the implementation process [98].
5. Infrastructure and grid management
   i. Grid modernisation: Upgrading the existing grid with MLI and RES integration is necessary. This includes transmission and distribution networks and implementing smart metering and system control technologies [99].
   ii. Cybersecurity: As MLIs and smart grid technologies are highly dependent on digital communication, it is critical to ensure appropriate cybersecurity measures to protect against potential cyber threats [100].
6. Smart grid integration: Research into how MLIs work on demand response and are integrated with microgrid technologies can lead to a more integrated approach to improving power quality [101].
7. Impact of Distributed Generation (DG): The presence of DG is increasing with the rise of RES. It is, therefore, important to study the impact of DG on grid stability and power quality. Long-term studies of real-time data will provide guidelines to integrate DG technologies using MLIs [102].

5. Conclusions

This review highlights the role of MLIs in improving power quality and reducing harmonic distortion through simulation studies using DC sources and can be extended to RES-powered smart grids. As RES increases, it is important to control power quality and harmonics, which are thus essential for grid stability and performance. The review focuses on the versatility of MLI configurations in various applications. These inverters control voltage regulation and reliability and maintain power quality standards. The review highlights the need for continued innovation and development in the field of MLIs to support the RES generation. Future research should focus on the long-term analysis of MLIs with RES-powered grids, energy storage, and advanced control algorithms. The environmental and economic impacts of MLIs are important for advancing towards a sustainable energy future. In conclusion, MLIs are important in achieving efficient and environmentally friendly power systems.

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