

Multilevel Inverters and DC–DC Converters for PV–EV Charging: A Comprehensive Survey of Topologies, Controls, and Open Challenges

J. Jeyamani^{1*}, Dr. K. Sebasthirani², Krithika.R³

^{1*} Assistant Professor, Department of Electronics and Communication Engineering, United Institute of Technology, Coimbatore-641020.

Email: jeyamani.ece@uit.ac.in

² Associate Professor, Department of Electrical and Electronics Engineering, Sri Ramakrishna Engineering College, Coimbatore-641022.

Email: sebasthirani.kathalingam@srec.ac.in

³ Assistant Professor, Department of Electronics and Communication Engineering, United Institute of Technology, Coimbatore-641020

Email: krithika.ece@uit.ac.in

Abstract: There is an increasing demand for an effective, dependable and affordable power conversion systems, because of significant improvement of renewable energy (RE) and application of EV. In photovoltaic (PV) applications, Multilevel inverters (MLI) are receiving more attention. For grid-integrated and charging infrastructures, this MLI offers adaptable voltage levels, and it also have the potential in offering better energy supply, low Total Harmonic Distortion (THD), so these are the reason behind its popularity. By utilizing conventional MLI topologies, high switch counts, multiple isolated DC sources, increased circuit complexity, and inefficiency of the system will exist. These challenges made conventional MLI ineffective. Many RSC and switched capacitor (SC) inverter topologies, innovative DC–DC converter designs and advanced MPPT algorithms were analyzed by the authors for the purpose of resolving those challenges. With these algorithms, compactness, efficiency and dynamic efficiencies are all improved. Despite these improvements, there are still some difficulties, they are scalability, voltage stress management, thermal issues, and control complexity. The MLI topologies and related power electronic converters used in PV and EV charging applications are thoroughly analyzed in this survey. The design trade-offs, operating principles are all highlighted in this survey. This review also analyses performance features, and assess its benefits and drawbacks. Main research gaps are identified in this review. Possible solutions like wide band gap device adoption, hybrid renewable integration, AI-driven control strategies, and smart grid compatibility are also discussed. Researchers and engineers can create scalable, efficient, and reliable inverter-converter architectures for next-generation RE and EV charging systems with the support of this survey.

Keywords: Multilevel Inverters (MLIs), DC–DC Converters, Reduced Switch Count (RSC) Inverters, Photovoltaic (PV) Systems, Electric Vehicle (EV) Charging, MPPT (Maximum Power Point Tracking) , Power Electronics for Renewable Energy, Harmonic Reduction.

I. INTRODUCTION

Fossil fuel consumption is rapidly increasing, and this is directly correlated with the world's growing energy demand. This has a negative consequence on the background since it emits more greenhouse gases into the atmosphere. As a result, green energy has become more and more popular. In addition to producing tiny amounts of pollutants, it generates enormous amounts of power. Geothermal heat, wind, and solar radiation are only a few instances of the various forms of renewable energy sources [2]. For energy to be distributed evenly

around the world, the sun's light is a must. A quantity of solar energy higher than or equal to 100,000 terawatt hours is reflected and absorbed by the Earth's surface annually [4]. The development of renewable electricity could be significantly aided by the free energy that the sun provides. Despite being readily available, solar energy makes a negligible contribution to the global power system. The use of PV systems has advanced significantly over the last three decades. The competition between solar energy and other electricity sources, such as fossil fuels, is hindered by several problems. Solar power finds it challenging to compete because of these issues. Solar power has a number of drawbacks, some of them having low conversion efficiency, varying output, and a large initial investment required [5]. A novel technology capable of implementing a more cost-effective energy conversion process is desperately needed. From a technological and scientific perspective, this is essential. This development will help to make solar energy more widely available. To find solutions to these problems and increase the viability of solar energy from a business perspective, investigation after investigation has been conducted. In solar energy systems, PV cells are utilised to transform sunlight into electricity. PV cells, electricity converters, and an electricity management unit comprise a solar-to-electricity conversion device [6].

To enhance the effectiveness of using renewable electricity sources for energy collection, engineers have developed power converter topologies, power tracking systems, and innovative management strategies [7]. Still, more research is needed to determine the best practices for using renewable energy (RE) sources to power electronics. In contemporary power generation, energy converters and associated controls are essential components, particularly for smart grid and renewable energy systems. They are now a major focus of research and development as a result.

The unpredictable and intermittent nature of wind and PV energy sources necessitates high performance from the DC/DC front-end converters. Maintaining high efficiency, maximum power extraction, and steady output under all circumstances requires adjusting the DC/DC front-end levels. They are less effective because of these factors. They can no longer handle apps that require a lot of resources. Large-scale and powerful grid-connected renewable energy systems frequently require multiple inverters [8–10].

The high-quality output waveforms with lesser THD, less filter requirements, and improved voltage levels are generated from the MLI. So, this MLI is effective in PV-based systems when compared to conventional 2-level inverters. In high- and medium-power applications like PV systems, grid-connected RE, and EV charging, this MLI is effective. The conventional MLI topologies such as diode-clamped, flying-capacitor (FC), and cascaded H-bridge (CHB) have advantages. These traditional MLI structures have some shortcomings like complexity, high cost, and complex control systems. Factors including large number of semiconductor switches, the need for many isolated DC sources, complicated voltage balancing, and higher switching losses limit efficiency, compactness, and scalability.

The objective of hybrid DC–DC converter-assisted MLIs, RSC inverters, and SC inverters is to resolve issues in conventional MLI. By implementing these topologies, efficiency, and voltage are improved, circuit size is minimized, the count of active devices is reduced. Sophisticated control methods like MPPT are enhanced by the application of artificial intelligence (AI) approaches. In solar power systems, MPPT is a technology that maximises energy extraction in dynamic environmental conditions. Despite its potential benefits, AI face some difficulties in switching stress, temperature control, dependability in partially shaded environments, scaling to higher voltage levels, and smart grid connection and Vehicle-to-Grid (V2G) systems.

The comprehensive analysis of MLI structures and converter topologies are needed. The current topologies, and its classification based on operation principles, benefits and drawbacks of PV and EV applications are analyzed in this survey.

II. RELATED WORKS

The advancements in effective MLI and converter-assisted topologies for PV and EV applications are provided.

A novel hybrid MLI topology is suggested by Noman et al. [11]. The symmetrical and asymmetrical attributes are integrated in this suggested topology. It helps in reducing the count of components needed. With fewer components, high efficiency and low total cost in RE are attained by the integration of symmetrical and asymmetrical attributes in this hybrid topology.

An improved topology with CHB MLI with the cascaded 3-phase 2-level VSI topology integration is suggested by Trimukhe & Sanjeevkumar (2022) [12]. When comparing the traditional MLI structures of the similar level and this integration, it is clear that high voltage levels with low components are attained by this integration. The line-frequency transformer is not needed by this integration. This integration also supports in resolving the limitations related to transformers, and facilitate in lowering the cost of overall system. More complex control, voltage balancing and stability challenges are some of its major drawbacks of this method. For preserving constant process, advanced algorithms are needed. These algorithms also support in ensuring accurate voltage balancing over levels, advanced algorithms are needed.

The MLI topology with asymmetrical 3-phase 9-level MLI; 5 Insulated Gate Bipolar Transistor (IGBT) + 2 DC sources/phase are suggested by Kumar et al (2023) [13]. Then, Level Shift (PWM) Pulse Width Modulation (LSPWM) is employed, and it facilitate in optimizing DC sources. Using synchronverter control, the operation and control of the this suggested topology in grid-tied mode are analyzed. It has some shortcomings like higher control complexity & fault handling effort. Precise tuning is required for ensuring consistent grid synchronization.

The comparison analysis of the conventional switching methods namely PWM, Sinusoidal PWM (SPWM), and Space Vector PWM (SVPWM), are conducted by Vimal et al. (2021) [14]. The impacts of THD and switch loss of many PWM techniques are analyzed by Vimal et al. (2020). Thus, high harmonic performance is attained by SVPWM. High computational complexities may result from SVPWM, and it is a major drawback.

Modulation techniques for improving MLI efficiency are discussed by Malar et al (2023) [15]. The widely employed techniques that supports in enhancing voltage utilization and lessening THD are utilized, they are: SPWM and SVPWM. By examining Selective Harmonic Elimination (SHE) procedures, the THD can be further decreased. Next, model predictive control (MPC) and artificial intelligence (AI)-based control techniques such fuzzy logic (FL) and neural networks (NN) are examined in order to get a faster dynamic response.

Analysis of traditional MLI topologies are conducted by Mahato, B et al (2022) [16]. Here, Neutral Point Clamped (NPC), FC, and CHB inverters are some conventional MLI topologies that are utilized for this analysis. These systems are capable of creating high-quality output waveforms with less THD. But, it needs high device count, and it is a major concern. Because, it causes switch loss, complexity, and high cost. To resolve these limitations, the RSC MLI is suggested. This suggested topology have the potential for its high efficiency with low switch count.

Reduced-switch MLI topologies are presented by Sarebanzadeh, M. et al (2021) [17]. It has the potential for its consistent efficiency with few components, and it helps in resolving the limitations of conventional MLI configurations. The benefits, drawbacks, and the uses of reduced-switch MLI topologies in RE systems are analysed.

Conventional MLI remains a benchmark references, but majority of analysis have emphasis on few switch count and hybrid topologies. For EV charging applications, 31-level MLI with 12 switches was presented by **Saravanan (2024)** [18]. When compared to conventional MLI like diode-clamped and cascaded H-bridge types, this architecture utilizes less count of switching devices and attaining better power quality. Thermal stress,

modulation complexity, and reliability in scaling higher power levels are the challenges that are faced by these high-level conventional MLI, regardless of its benefits.

For EV and hybrid EV (HEV) applications, a unique capacitor-based boost MLI (CB-MLI) topology is created by Aditya et al. (2023) [19]. 11-level waveform is created from this topology, as it utilizes 11 switches, 3 caps, and a single isolated source. Its distinguishing feature is a self-balancing capacitor technology that eliminates the demand for external balancing methods. The constant carrier PWM technique controls IGBT. Steady efficiency under diverse operating conditions is not effectively maintained by the complexity in balancing capacitors. This is a drawback of this architecture.

Reduced component designs have been the subject of most recent research. **Aishwarya Venkittaraman and Sheela (2022)** [20] reviewed several RSC-MLI for EV applications, concluding that these designs can lower THD and improve efficiency, but often struggle with scalability and long-term device stress. Similarly, **Hosseinpour et al. (2024)** [21] suggested a 17-level SC inverter using a single DC source and quasi-soft charging, which minimized inrush currents and reduced voltage stress. Despite these improvements, capacitor balancing and durability remain unresolved.

A thorough examination of EVs based on micromobility is conducted in Corti et al. (2024) [22]. Under the pretext of energy communities reliant on renewable sources, the choice of transformer technology and the use of CS are examined. An initial cost, community response, restricted accessibility, regulations, and limited subsidies, in addition to range anxiety and extensive charging infrastructure, are the issues that prevent EVs from being widely used.

The integration of PV smart grids (SG) and EV with two-way power flow capabilities is the main emphasis of Paidimukkala et al. (2022) [23]. For charging, discharging, and enhancing power quality, power converters are employed. Modernising the power grid to enhance power quality is crucial given the growing energy demand brought on by the fast population expansion. The power produced by solar PV systems may now be transported and saved in batteries as extra power for use during periods of high demand by this modernisation. When demand is low, EV batteries can be charged, and when demand is high, they can be drained. EVs can supply energy to the smart grid and act as loads because of this dual purpose.

The smart grid-to-vehicle (G2V) system's operation is demonstrated by the simulation results. Improvements in energy factor, energy management, and harmonic elimination are highlighted by the smart G2V. Using MATLAB/Simulink software, a power conversion system with bidirectional power flow and grid balancing capabilities is built to accomplish these improvements. In order to improve battery current stability, an ANFIS controller has also been added to the G2V controller. Peak overshoot, settling time, and current ripple have been significantly decreased when ANFIS management was put in place. With an emphasis on power compensation, voltage regulation, and harmonic abatement, the article thoroughly investigates enhancements to the integrated system's power quality.

Based on configurations, control-based methodology, and impact on power quality, the charging architecture and the role of converters in EV applications were investigated by Ali et al. (2023) [24]. The features of several types of chargers, static, dynamic, and quasi-dynamic are also covered in relation to inductive, capacitive, and wireless powering abilities.

A review and specifications of multi-input converters for integrating RE in storage devices were given by Ramya & Marimuthu (2024) [25]. The operating direction, structure, computing method, isolation type, switching method, and count of inputs and outputs are the primary factors that influence the parametric selection of a multi-input converter.

In order to improve the current EV charging infrastructure in line with their design, Chandra et al. (2024) [26] discussed coordinated charging strategies, which include setup, tariff structures, scheduling tactics, and centralised and decentralised approaches. Inductive (static and dynamic) and conductive (onboard and off-board) coordinated charging types are suggested as potential ways to mitigate the power load that EVs place on the utility grid (UG) when they are charging. This analysis achieves by highlighting the significance of policymaking in the transportation industry and highlighting the technological, economic, and environmental issues that require further attention in the EV field.

Through the use of a fuzzy-based MPPT, Kola Syamala & Sambasivarao (2024) [27] demonstrate the emphasis on the potential of a PV framework to improve energy change in relation to a moving vehicle. In many uses, such as solar-oriented PV and EV systems, the efficient and compact design of MLI proves to be effective. SC technique is the basis for the 53-level staggered inverter geography suggested in this paper. The fountain association of the number of SC cells is taken into consideration when planning the number of degrees of MLI.

The 17 and 33 levels of the result voltage are carried out by the flow of the SC cells. At the upper levels, the suggested structure is comprehensible and workable. There are fewer driving circuits when there are fewer dynamic switches. This reduces the MLI's size, cost, and number of devices. The FLC-based MPPT controller is used in conjunction with the sun-fueled chargers. A dependable reserve to stack is provided by the FLC-based controller with time-sharing control for the suggested converter. Using a single data and multi-yield converter, a consistent DC voltage is provided and maintained above the DC interface voltage. Heavy weight assortments and sudden weight increases are probably used to test the recommended inverters. This makes it easier for an EV to travel on different types of roads. Switch count, entryway driver sheets, sources count, number of diodes and capacitors, and part count factor are all evaluated point by point. THD appears to be nearly identical and less than 5%, which is within IEEE requirements, for the 17-level, 33-level, and 53-level MLI. Entertainment outcomes are confirmed.

A solar PV system with a 53-level MLI and a single-input, multiple-output DC-DC boost converter is reported by Dhanamjayulu et al. (2020) [28]. The system maximises power extracted from the PV by using the Perturb and Observe (P&O) approach for MPPT. Before being supplied to the 53-level inverter, the DC voltage produced by the PV is enhanced to the required level by the single-input, multiple-output boost converter.

A novel single-phase, 7-level PWM inverter is presented by Ali et al. (2021) [29]. This structure supports in reducing the count of power components, and improving efficiency for individual and grid-integrated PV systems. Thus, cost, size, and efficiency are all improved once the component count is reduced. Output voltage is generated by the auxiliary circuit with switches. Then, the main circuit, typically H-bridge inverter is controlled by that voltage. A boost converter is often used in a PV system with a 7-level inverter to enable MPPT by stepping up the PV array's voltage to appropriate level for the inverter.

For charging station (CS) applications, bidirectional single-phase, 3-level stacked neutral-point-clamped (3L-SNPC) converter is analyzed by Reis et al. (2020) [30]. Based on the power flow direction, the role of both rectifier or an inverter is operated by this converter. For EV CS, this 3L-SNPC topology is designed. Then, the potential of CS is described in this analysis. Here, integration of UG and RE sources, like PV and wind systems are facilitated by this CS. Thus, bidirectional power flow is also facilitated by this integration. Bidirectional power flow is the method by which excess energy can be returned to the grid. Higher cost, complex control, high THD are some of its drawbacks.

For EV powertrain applications, Reconfigurable Cascaded Multilevel Converter (RCMC) charging architecture is suggested by Tresca & Zanchetta (2024) [31]. With the support of an inductor filter, it connects the AC grid directly to the powertrain converter. The necessary galvanic separation is offered by the external EVSE. A

transformer in the EV's onboard charger (OBC) manages the galvanic isolation for AC charging. When galvanic separation is dependent on an external EVSE, cost is increased and control complexity may result from this intricate design, and it is considered as major drawbacks.

For an integrated bidirectional CS, a unique grid-connected modular inverter is suggested by Jaman et al. (2023) [32] for applications in residencies. By improving grid stability and offering buffering services, this system assists the electrical grid. An EV charger is another use for the suggested modular bidirectional inverter. The design's high THD, which can negatively impact power quality and system efficiency, and it is a significant disadvantage.

The extensive topologies of power electronics converters for EV charging and control logic for G2V and V2G applications are the main topics of Zhou et al. (2023) [33]. Based on factors like switch count, switch voltage stresses, and grid impact, the analysis relates a number of AC-DC and DC-DC power transfer structures. However, under unbalanced grid settings, typical boost rectifiers emit large harmonics in addition to high gains. With fewer switches and a higher power factor, a Vienna rectifier produces a high output voltage. But it only functions better in unidirectional mode. The isolated and non-isolated DC-DC converter topologies have also been examined. Resonant and DAB converters operate efficiently and provide good performance in isolated converters; nevertheless, a complex transformer design makes the control system more difficult to use. Conversely, non-isolated converters generate comprehensive voltage gain due to its straightforward control circuitry and fewer switches. Low power density is a common problem for non-isolated converters that need high voltage gain, and a high duty ratio causes higher conduction losses and more voltage stress on the switches.

Transformer-based deep learning (DL) to estimate the maximum power point was suggested by Agrawal et al. (2024) [34]. Simulation on this suggested method demonstrates more than 99% efficiency. By considering several time series-based environmental inputs, this research suggests an enhanced DL-based MPPT in solar PV cells. MPPT algorithms based on artificial (NN) neural networks (ANN) typically employ simple NN architectures and inputs that don't accurately reflect the ambient conditions. This article uses a wide range of environmental features to depict the ambient conditions of a place. Additionally, it is considered that adding time-based features to the input data will help to simulate cyclic patterns over time in the atmospheric conditions. This will lead to robust MPPT algorithm modelling. The transformer-based DL architecture is trained by the Multidimensional TS input features. This transformer architecture is trained as a (TS) time series prediction model. A Typical Meteorological Year (TMY) is a synthetic, standardised weather dataset that is used to train a model. It is composed of ambient weather data collected from 50 locations across a TMY. The model is able to learn and prioritise temporal patterns due to the attention mechanism in transformer modules. This suggested framework is validated by the real-time simulations. A robust, dynamic, and nonlatent way of power point tracking is executed by the suggested framework in all weather conditions.

A custom-designed MPPT controller is suggested by Khadka et al. (2024) [35]. To promote the efficacy of PV schemes, this custom-designed MPPT controller integrates microcontroller-based battery charging system. Here, MPPT methods are utilized in this study, and it helps in reducing the application of non-renewable energy sources. This MPPT also supports in improving the PV module. The main objectives are to integrate a monitoring system that offers real-time data on the performance of the solar panels and any connected batteries, as well as to continuously find and maintain the optimal operating point for solar (PV) panels, maximising their power output, using a real-time MPPT algorithm. The temperature, voltage, and current are evaluated by utilizing a coordinated interplay of sensors. The microcontroller receives the coordinated interplay of these vital metrics. The suggested method using buck-boost converter to monitor environmental parameters, manage power outputs, and produce PWM signals to control the metal Oxide Semiconductor Field Effect Transistor (MOSFET) voltage in a buck-boost converter. The real-time monitoring is facilitated by the IoT application, as it uses hourly data for a cloud platform. From the outcomes, 37.28% gain in efficiency is attained, and it

represents the transformative potential of advanced AI for RE optimization. Some challenges in real-time implementation and integration with diverse inverter topologies that faced by these AI-driven MPPT systems regardless of its adaptability and fast convergence.

To resolve the limitations of conventional MLI systems for solar and EV charging applications, a Multi-Output Active Clamp Forward Converter (MOACFC) was suggested by Adupa et al. (2024) [36]. The suggested method for MLI are specially designed to generate both symmetrical and asymmetrical DC voltage combinations. Large count of switches and DC sources are demanded by the conventional MLI. This may enhance complexity and reduces efficiency. The MOACFC creates several output voltages from a single PV input. Less component count and system efficiency is attained by the MOACFC. Then, the application of Recurrent NN Incremental Conductance (RNN-INC)-based MPPT algorithm supports in enhancing the power extracted from solar PV arrays. 9-level, 21-level, and 31-level outputs are generated by the basic module of the MLI system. Advanced methods that are widely utilized in EV charging are Nearest Level Control PWM (NLCPWM) and Level Shifted PWM (LSPWM) approaches. Implementation of NLCPWM and LSPWM methods supports in reducing the level of THD in MLI. When compared this suggested method with conventional 2-level and 3-level inverters, this application attains high power quality and reducing THD level to 3.77% in voltage and current at 0.99% for EV. This suggested method improves power quality and offers less power load on EV. From the outcomes, it is clear that the suggested MOACFC-MLI system is a more dependable and effective method.

MLI topology was introduced by Gowd et al. (2021) [37]. To generate high quality output, 2 advanced MLI topologies named Switched Series/Parallel Sources (SSPS), Series-Connected Switching Sources (SCSS) are utilized. Different output voltage levels are attained by the SSPS, as it offers adaptability. Then, diverse converter configurations for various levels are generated by SCSS. 2 perpendicular space vectors, 133 output space vectors, reduced THD, incremental root mean square (RMS) voltage adjustment are the key feature of this design. This kind of inverter is effective when power quality and efficiency are essential, as it offers high accuracy, and control over the power output.

To control PV cascaded H-bridge MLI, a technique is suggested by Nyamathulla & Chittathuru (2023)[38]. Problems related to failed cells and fluctuating atmospheric conditions in large-scale grid-connected applications are effectively addressed by this system. A control strategy for an inverter that uses time-domain and space vector analysis to analyse both common-mode and differential-mode parameters. A controller to control voltage and current behaviour can be created by looking at how these two modes interact. This is important for applications like PV systems, particularly in the event of unusual circumstances like malfunctioning cells or shifting weather. It can affect effectiveness and strength of the system in practical situations, because it fails to consider complexities presented by rapid variations in environmental conditions, and these are the major shortcoming of this design.

1-phase PWM 7-level inverter was suggested by Wu et al (2020) [39]. It is an effective method for PV systems, as it utilizes few components. Low power output THD, unity power factor operation for EV and home-grid integration are all facilitated by this design. When compared to higher-level inverters, this 7-level design attains high THD. This high THD may result in impacting power quality and it is considered as a major disadvantage. The control and switching mechanisms of this topology makes it effective in contrast to modern topologies.

Novel grid-tied PV systems are suggested by Haghighian et al. (2023) [40]. An improved flyback DC-DC converter and a novel SC-based MLI are integrated in the suggested system. By adding an inductor with a parallel diode in the capacitive charging current channel, this design solves a major problem with capacitive switching inverters: impact currents throughout capacitor charging. By using this method, the converter's efficacy is increased and the stress caused by charging current on the capacitors is reduced. The additional

components (inductor and diode) may raise the system's overall intricacy and expense, which could affect the design's viability for particular applications. This is a disadvantage of the system.

The comparative analysis of MMC and a multicar modulation technique are conducted by Rahul Jaiswal et al. (2019) [41]. Depending on the level of the inverter and the modulation index, phase-opposition-array pulse-width modulation (POD-PWM) can occasionally produce lower THD values, but phase-array pulse-width modulation (PD-PWM) is frequently better at decreasing harmonics.

In EV, several benefits are offered by the application of MMC, and it was analyzed by Di Wang et al., 2020 [42]. High modularity, failure tolerance capability, high-quality output is some of its benefits. MMCs give EVs a more dependable, economical, and small powertrain by combining the motor drive, onboard charger, and cell equalisation functions into a single converter. Battery life of EV is reduced throughout MMC operations. In the battery current cell, AC harmonics are introduced during the process, and this is the reason behind battery aging.

A multifunctional modular multilevel conversion system for an EV is suggested by Nan Lee et al. (2020) [43]. Only the engine drive function and AC and DC battery charging are provided by this suggested system. Operational concepts and control methods, such as state-of-charge (SOC) balancing control strategies in conduction mode and DC or AC charging in charging mode, are carefully examined in order to more accurately demonstrate the suggested system.

The dependable functioning of MMC is negatively impacted by IGBT open-circuit faults (Xingxing Chen et al., 2020) [44]. When several IGBT open-circuit faults occur on one arm at the similar period, the literature currently in publication does not offer a precise detection algorithm for MMCs. A diagnostic approach to treating this condition is presented in this research.

Table 1 shows the MLI side, researchers have focused on reducing the switch count, DC sources, and passive modules while still achieving high-quality multilevel outputs. Hybrid, asymmetrical, switched-capacitor, and capacitor-boost MLIs have all been developed to minimize hardware complexity and improve efficiency. At the same time, advanced modulation techniques such as SVPWM, SHE, MPC, and AI-based controllers are analyzed for reducing THD and improve dynamic performance. These innovations collectively enhance efficiency, compactness, and power quality. Capacitor voltage balance, thermal management, modulation complexity, and scalability to greater voltage and power levels are the four primary areas that MLI experiences major issues.

Table 1: Comparative Analysis of MLI Topologies & Modulation using various approaches

Author(s)	Techniques	Results	Advantages	Disadvantages
Noman et al. [11]	Hybrid MLI combining symmetrical & asymmetrical cells	Fewer devices/sources for same output levels	High performance with lower component count; cost/size reduction	Potential balancing/control complexity across mixed cells
Trimukhe & Sanjeevkumar (2022) [12]	CHB-3-phase 2-level VSI integration (direct connection, transformerless)	Higher voltage levels with fewer components; no line-frequency transformer	Lower cost; reduced size/weight	More complex control; voltage balancing and stability challenges
Kumar et al. (2023) [13]	Asymmetrical 3-phase 9-level MLI; 5 IGBTs + 2 DC sources/phase;	Efficient grid-tied operation; analyzed control dynamics	Good efficiency; grid support via synchronverter	Precise tuning required; higher control complexity & fault handling

	LSPWM; synchronverter			effort
Vimal et al. (2021) [14]	Comparison of PWM / SPWM / SVPWM	SVPWM → lower THD, better DC-bus utilization	Improved harmonic performance; better voltage use	Increased computational complexity
Malar et al. (2023) [15]	SPWM, SVPWM, SHE, MPC, AI (fuzzy/NN)	Lower THD; faster dynamic response with advanced control	Better quality/efficiency; flexible control choices	Complexity; implementation cost and tuning burden
Mahato et al. (2022) [16]	Review of NPC, FC, CHB and reduced-switch MLIs	Conventional MLIs: good quality but high device count; RSC MLIs mitigate this	Clear taxonomy; path to fewer switches	Conventional: bulky/complex; RSC: scaling & stress issues
Sarebanzadeh et al. (2021) [17]	Review of reduced-switch MLI configurations	Similar output quality with fewer components	Lower cost/size; simpler drivers	Balancing, device stress, scalability still open
Saravanan (2024) [18]	31-level MLI with 12 switches (EV oriented)	High power quality with very low switch count	Compact, cost-effective for high levels	Thermal stress; modulation complexity at scale
Aditya et al. (2023) [19]	CB-MLI (capacitor-boost, single source); 11 levels, 11 switches, 3 caps	Self-balancing concept; compact EV/HEV fit	Low device count; dv/dt mitigation	Capacitor balancing under dynamics; reliability of caps
Kola Syamala & Sambasivarao (2024) [27]	SC-MLI (17/33/53 levels); FLC-MPPT; time-sharing control	THD < 5%; reduced drivers & cost	High level count with fewer switches; robust under load steps	More caps/diodes; charge management complexity
Dhanamjayulu et al. (2020) [28]	53-level MLI + single-input, multi-output boost; P&O MPPT	Adequate voltage boosting to feed high-level MLI	Simple MPPT; modular boost-to-levels	P&O oscillations; multi-output converter complexity
Ali et al. (2021) [29]	7-level single-phase PWM MLI; H-bridge main + auxiliary; front-end boost + MPPT	Fewer parts; better efficiency/footprint	Low component count; cost reduction	Limited scalability; aux stage timing & balancing
Jaman et al. (2023) [32]	Grid-connected modular inverter (bidirectional charger)	Grid buffering + EV charging	Dual use (grid services + charging)	Reported high THD impacting power quality

In this study, numerous AC–DC and DC–DC converter topologies are analyzed for attaining bidirectional energy flow (G2V/V2G) among EVs and the grid. EV charging and SG integration is presented in Table 2. An inductive, capacitive, wireless, and multi-input charging architectures, and coordinated charging methods were compared in this study. This comparison facilitates in reducing stress and enhancing charging adaptability. In diverse environmental situations, solar energy extraction is optimized by introducing an AI-enhanced MPPT

algorithms such as deep learning (DL) and ANFIS. Thus, effectiveness, power factor, and THD are all improved by these methods. In terms of expense, real-time application difficulties, control complexity, and structural constraints, the practical applications are limited.

Table 2: Comparative Analysis of EV Charging, Grid Integration, Converter–Inverter Co-Design & MPPT using various approaches

Author(s)	Techniques	Results	Advantages	Disadvantages
Corti et al. (2024) [22]	Micromobility EVs; CS transformer tech; RES-based communities	Barriers & technology choices mapped	Practical guidance for community energy + EV	Adoption barriers: cost, access, regulation, range anxiety
Paidimukkala et al. (2022) [23]	PV–SG–EV bidirectional system; ANFIS G2V control	Improved PF, regulation, harmonic mitigation; lower ripple/overshoot	Power-quality gains; better current stability	Model complexity; real-time tuning and validation needs
Ali et al. (2023) [24]	Charging topologies; converters for inductive/capacitive/wireless (static/dynamic/quasi-dynamic)	Topology–control–PQ mapping	Broad comparison; tech roadmap	Many wireless schemes → coupling/efficiency challenges
Ramya & Marimuthu (2024) [25]	Multi-input converters (RE + storage); selection metrics	Parametric guidelines (direction, isolation, switching, I/O count)	Helps design choice; integration clarity	Multi-input control gets complex; cost/EMI trade-offs
Chandra et al. (2024) [26]	Coordinated charging (centralized/decentralized); tariffs & scheduling; policy	Lower grid burden; planning insights	Clear strategies for infra planning	Implementation/policy challenges; user behavior variability
Reis et al. (2020) [30]	3L-SNPC bidirectional AC/DC for CS; grid + PV/Wind integration	CS with feed-back to grid (DG support)	Bidirectional; good PF potential	Higher cost/complex control; THD/EMI management
Tresca & Zanchetta (2024) [31]	RCMC charging architecture; isolation in EVSE, inductor-filtered AC link	Simplified onboard charger; direct AC-to-powertrain	Lighter onboard hardware	Reliance on EVSE isolation; integration cost/complexity
Zhou et al. (2023) [33]	Review: EV charger power stages (AC-DC/DC-DC, Vienna, DAB/resonant vs non-isolated)	Comparative insights: switches, stresses, grid impact	Holistic view; clear trade-offs	Some topologies unidirectional (Vienna); non-isolated: high duty, lower power density
Agrawal et al. (2024) [34]	Transformer-based deep learning MPPT (time-series features)	~99% sim. tracking efficiency; robust under varied	Fast, robust tracking; uses rich environmental	No hardware validation; compute burden

		conditions	inputs	
Khadka et al. (2024) [35]	Microcontroller MPPT + buck-boost; IoT monitoring	~37% PV yield improvement (experiment)	Low-cost, practical; real-time monitoring	Limited power scale; integration with MLIs not shown
Adupa et al. (2024/2025) [36]	MOACFC + MLI; RNN-INC MPPT; NLCPWM/LSPWM	9/21/31-level; THD _V $\approx$ 3.77%, THD _I $\approx$ 0.99% (EV load)	Fewer DC sources; clamp lowers stress; high PQ	Control & thermal co-design complexity; scalability engineering

III. RESEARCH GAP AND SOLUTION

In terms of power quality and efficiency, MLI and converter-assisted designs are effective and demonstrates notable achievements. But, it has some drawbacks also. Few component utilization is attained by the RSC and SC MLI, but, it also faces difficulties in some areas like capacitor balancing, voltage stress, and long-term reliability. THD is reduced by sophisticated modulation and control strategies like SVPWM, SHE, and MPC. But, these methods present high computational complexity. Real-time operation in high-level MLI is limited by high computational complexity. In thermal stress and synchronisation issues, scalability to high-power EV CS and grid-level systems remains an unresolved challenge, as the majority of current solutions are only proven at modest or medium power levels. Ineffective bidirectional capability and integration with vehicle-to-grid (V2G) systems are limited by many converters. Numerous MPPT algorithms based on AI exhibit encouraging simulation results. This AI-MPPT has limited hardware validation and integration with MLI under partial shade or abrupt load fluctuations pose serious application issues. The potential of the HDL methods supports in more accurate forecasting, adaptive MPPT, and stable control in dynamic PV–EV backgrounds. The potential of Hybrid DL approaches like CNN–LSTM, RNN–fuzzy, or transformer–(RL) reinforcement learning is not analyzed, and it is considered as a major gap.

Integration of the MOACFC and MLI in maintaining compactness, and reducing DC source demands, and device stress, has become the main emphasis of future solutions in resolving those gaps. An optimal balance of performance and complexity is achieved by Hybrid MLIs with adaptive modulation, like NLCPWM for switching stress reduction and LSPWM for harmonic minimization. For MPPT, real-time flexibility, strength, high power output in diverse environmental settings are all ensured by the application of hybrid DL models. For dependable large-scale deployment of PV–EV integrated systems, regulatory support, coordinated charging, and technical solutions that match with smart grid standards will be essential.

IV. CONCLUSION

Modern developments in MLI topologies, converter-assisted designs, and control strategies for PV and EV charging applications were reviewed in this survey. Diode-clamped, FC, and CHB inverters are examples of conventional MLI topologies that offer high-quality output. But, it can be attained at the cost of several DC sources, complicated voltage balancing, and an excessive number of switches. To reduce hardware complexity, and enhancing efficiency, RSC MLI, SC designs and hybrid converter–inverter architectures are presented in this study. This application supports in resolving issues related to conventional MLI topologies. Energy extraction and dynamic flexibility have been improved by modern control techniques, including AI-based MPPT algorithms. Thermal stress, scalability to high-power EV charging, capacitor stability, bidirectional power flow limits, and real-time integration of AI-based controllers are still problems that need to be resolved despite these developments.

By combining predictive accuracy with adaptive control, HDL approaches offer a lot of promise to fill up current gaps, and it was discovered from this analysis. The HDL provides reliable MPPT and power quality control in dynamic PV-EV environments. When combined, MOACFC and MLIs can provide multi-level voltage with lowering source demands and device stress. The utilisation of wide bandgap devices, modular bidirectional topologies, and adherence to SG standards will further improve the scalability and reliability of future systems.

The efficiency, compactness, and power quality of the state-of-the-art systems have significantly improved, but more research is needed to integrate numerous RE sources, optimise thermal management, and take advantage of hybrid AI-driven control for real-time operation. Next-generation PV-EV integrated systems that are effective, scalable, and completely compatible with smart grid and vehicle-to-grid systems will be made possible by these advancements.

REFERENCES

- [1] Babaei, E.; Jalilzadeh, T.; Sabahi, M.; Maalandish, M.; Alishah, R.S. High step-up DC–DC converter with reduced voltage stress on devices. *IEEE Trans. Instrum. Electr. Energy Syst.* 2018, 46, 2053–2078.
- [2] Prem, P.; Sathik, J.; Sivaraman, P.; Mathewsaran, A.; Aleem, S.H.E.A. A new asymmetric dual source multilevel inverter topology with reduced power switches. *J. Chin. Instrum. Eng.* 2019, 42, 460–472.
- [3] E. Tarigan, "Hybrid PV-T Solar Collector using Amorphous Type of Solar Cells for Solar Dryer," 2020 International Seminar on Intelligent Technology and Its Applications (ISITIA), Surabaya, Indonesia, 2020, pp. 352-356, doi: 10.1109/ISITIA49792.2020.9163789.
- [4] H. Aoki, "Solar Collection Performances of a Hybrid Solar Collector in the Various Conditions," 2005 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, 2005, pp. 933-934, doi: 10.1109/ECODIM.2005.1619382.
- [5] S. S. Kewte and S. G. Kewte, "Performance evaluation of 445 wp half cut Mono crystalline solar panel with 380wp Mono crystalline and 330wp Poly crystalline solar panel for partially shading effect," 2023 Third International Conference on Advances in Electrical, Computing, Communication and Sustainable Technologies (ICAECT), Bhilai, India, 2023, pp. 1-5, doi: 10.1109/ICAECT57570.2023.10117783.
- [6] F. Dimroth et al., "Four-junction wafer bonded concentrator solar cells," 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC), New Orleans, LA, USA, 2015, pp. 1-1, doi: 10.1109/PVSC.2015.7356148.
- [7] M. Jing and W. Qian, "The Solar Collector Calculation in Integrative Solar Architecture," 2011 International Conference on Computer Distributed Control and Intelligent Environmental Monitoring, Changsha, China, 2011, pp. 1900-1902, doi: 10.1109/CDCIEM.2011.450.
- [8] G. F. X. Strobl et al., "European Roadmap of Multijunction Solar Cells and Qualification Status," 2006 IEEE 4th World Conference on Photovoltaic Energy Conference, Waikoloa, HI, USA, 2006, pp. 1793-1796, doi: 10.1109/WCPEC.2006.279839.
- [9] J. B. Lasich et al., "World's first demonstration of a 140kWp Heliostat Concentrator PV (HCPV) system," 2009 34th IEEE Photovoltaic Specialists Conference (PVSC), Philadelphia, PA, USA, 2009, pp. 002275-002280, doi: 10.1109/PVSC.2009.5411354.
- [10] A. M. Gabor et al., "The Impact of Cracked Solar Cells on Solar Panel Energy Delivery," 2020 47th IEEE Photovoltaic Specialists Conference (PVSC), Calgary, AB, Canada, 2020, pp. 0810-0813, doi: 10.1109/PVSC45281.2020.9300743.
- [11] Noman A.M., Al-Shamma'a A.A., Asef P., Alkuhayli A. (2023) Hybrid cascaded MLI development for PV-grid connection applications, *IET Power Electron.* 16, 10, 1717–1731.

- [12] Trimukhe S., Sanjeevkumar R.A. (2022) Grid interconnected H-bridge multilevel inverter for renewable power applications using repeating units and level boosting network, Glob. Transit. Proc. 3, 2, 424–431.
- [13] Kumar R., Chaudhari M.A., Chaturvedi P. (2023) A three-phase nine-level MLI for grid-tied ac microgrid with synchronverter control, in: 2023 IEEE International Conference on Power Electronics, Smart Grid, and Renewable Energy (PESGRE), Trivandrum, India, 17–20 December, IEEE, pp. 1–7.
- [14] Vimal, D., & Kumar, S. (2021). An Overview of Switching Scheme used in Multilevel Inverter. IJIRTM.
- [15] Malar, E., Chandrika, R., Dewanath, S. K., & Divyasree, T. (2023, December). Design of Multi-Level Inverter for Power Electronics Applications. In 2023 International Conference on Intelligent Technologies for Sustainable Electric and Communications Systems (iTech SECOM) (pp. 340-345). IEEE.
- [16] Mahato, B., Ranjan, M., Pal, P. K., Gupta, S. K. & Mahto, K. Design, development and verification of a new multilevel inverter for reduced power switches. Archives Electr. Eng. 71, 1051–1063 (2022).
- [17] Sarebanzadeh, M. et al. Reduced switch Multilevel Inverter Topologies for renewable energy sources. IEEE Access. 9, 120580– 120595 (2021). DOI: <https://doi.org/10.1109/ACCESS.2021.3105832>
- [18] K. Saravanan, M. Sivasubramanian, N. P. Gopinath, K. Kumarasamy, R. Azhagumurugan, “A 31 L multilevel inverter topology with less switching devices for hybrid electric vehicle applications,” Scientific Reports, vol. 14, article number 27459, Nov. 2024.
- [19] Aditya K., Suresh Y., Kumar R.D., Naik B.S., Rao B.N., Dhanamjayulu C. (2023) A single source self-balanced boost MLI with reduced part count for EV applications, Sustain ability 15, 5, 4149.
- [20] Aishwarya Venkittaraman & Kesari Gnana Sheela (2021/2022) “Review of reduced-switch multilevel inverters for electric vehicle applications”, International Journal of Circuit Theory & Applications, vol. 49, no. 9, pp. 3053-3110, 2021.
- [21] Majid Hosseinpour, Masoumeh Derakhshandeh, Ali Seifi & Mahdi Shahparasti (2024) “A 17-level quadruple boost switched-capacitor inverter with reduced devices and limited charge current”, Scientific Reports, vol. 14, article number 6233, 2024.
- [22] Corti F, Iacono S D, Astolfi D, Pasetti M, Vasile A, Reatti A and Flammini A 2024 A comprehensive review of charging infrastructure for electric micromobility vehicles: technologies and challenges Energy Reports 12 545–67
- [23] Paidimukkala, N., Das, N., & Islam, S. (2022, December). Power quality improvement of a solar powered bidirectional smart grid and electric vehicle integration system. In 2022 IEEE sustainable power and energy conference (iSPEC) (pp. 1-6). IEEE.
- [24] Ali A, Mousa H H H, Shaaban M F, Azzouz M A and Awad A S A 2023 A comprehensive review on charging topologies and power electronic converter solutions for electric vehicles Journal of Modern Power Systems and Clean Energy 12 675–94.
- [25] Ramya V and Marimuthu R 2024 A review on multi-input converters and their sources for fast charging of electric vehicles Engineering Science and Technology, an International Journal 57 101802
- [26] Chandra I, Singh N K and Samuel P 2024 A comprehensive review on coordinated charging of electric vehicles in distribution networks Journal of Energy Storage 89 111659.
- [27] Kola Syamala and Dr. N.Sambasivarao, “Implementation Of Multilevel Inverter For Electric Vehicle Using Fuzzy Mppt, International Journal of Communication Networks and Information Security 2024, 16(4).
- [28] Dhanamjayulu C., Padmanaban S., Ramachandramurthy V.K., Holm-Nielsen J.B., Blaabjerg F. (2020) Design and implementation of multilevel inverters for electric vehicles, IEEE Access 9, 317–338.
- [29] Ali A.I.M., Sayed M.A., Mohamed A.A. (2021) Seven-level inverter with reduced switches for PV system supporting home-grid and EV charger, Energies 14, 9, 2718.
- [30] Reis F.E.U., Torrico-Bascope R.P., Tofoli F.L., Bezerra L.D. S. (2020) Bidirectional three-level stacked neutral-point clamped converter for electric vehicle charging stations, IEEE Access 8, 37565–37577.
- [31] Tresca G., Zanchetta P. (2024) AC direct charging for electric vehicles via a reconfigurable cascaded multilevel converter, Energies 17, 10, 2428.

-
- [32] Jaman S., Abdel-Monem M., Geury T., Hegazy O. (2023) Development and validation of an integrated EV charging station with grid interfacing inverter for residential application, *IEEE Access* 11, 115751–115774.
 - [33] K. Zhou, X. Chen, C. Min, and Q. Wang, "Research and Development Review of Power Converter Topologies for Electric Vehicle Fast Charging Systems," *Electronics*, 2023, 12, 1581.
 - [34] P. Agrawal, H. O. Bansal, A. R. Gautam, O. P. Mahela, and B. Khan, "Transformer based time series prediction of the maximum power point for solar photovoltaic cells," *arXiv:2409.16342*, 2024. *arXiv*
 - [35] D. Khadka, S. Adhikari, A. Pokharel, S. Marasinee, and A. Pathak, "Microcontroller-Driven MPPT System for Enhanced Photovoltaic Efficiency: An Experimental Approach in Nepal," *arXiv:2412.06956*, 2024.
 - [36] Adupa, C., & Chidambaranathan, V. S. (2024). Design and performance evaluation of multilevel inverter for solar energy systems and electric vehicle charging with multi output active clamp forward converter. *Science and Technology for Energy Transition*, 79, 93.
 - [37] Gowd G.E., Sreenivasarao D., Vemuganti H.P. (2021) Sliding mode controller for extraction and supply of photovoltaic power using switched series parallel sources reduced switch count multilevel inverter, *IET Power Electron.* 14, 4, 834–850.
 - [38] Nyamathulla S., Chittathuru D. (2023) A review of multilevel inverter topologies for grid-connected sustainable solar photovoltaic systems, *Sustainability* 15, 18, 13376.
 - [39] Wu J.C., Jou H.L., Huang P.H. (2020) Seven-level power conversion system for solar power generation system, *IET Renew. Power Gener.* 14, 8, 1387–1394.
 - [40] Haghighian S.K., Yeh H.G., Marangalu M.G., Kurdkandi N.V., Abbasi M., Tarzamni H. (2023) A seventeen-level step-up switched-capacitor based multilevel inverter with reduced charging current stress on capacitors for PV applications, *IEEE Access* 11, 118124–118143.
 - [41] Jaiswal, R., Agarwal, A., & Negi, R. (2019). Performance enhancement of modular multilevel converter by using modulation technique. *Proceedings of the 2019 IEEE 1st International Conference on Energy, Systems and Information Processing (ICESIP)*, Chennai, India, 1–6. <https://doi.org/10.1109/ICESIP47689.2019.8985869>
 - [42] Wang, D., Liu, J., Piegari, L., Song, S., Chen, X., & De Simone, D. (2019). A battery lifetime improved control strategy of modular multilevel converter for electric vehicle application. In *Proceedings of the 2019 IEEE 10th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)* (pp. 594–598). IEEE. <https://doi.org/10.1109/PEDG.2019.8807628>
 - [43] Lee, N., et al. (2020). "Operation Principles of Modular Multilevel Conversion System For Electric Vehicles." *Proceedings of the 2020 IEEE 2nd International Conference on Power Electronics and Energy Engineering (PEEE)*, 1–6. <https://doi.org/10.1109/PEEE49756.2020.9331256>
 - [44] Chen, X., Liu, J., Deng, Z., Song, S., Du, S., & Wang, D. (2020). A diagnosis strategy for multiple IGBT open-circuit faults of modular multilevel converters. *IEEE Transactions on Power Electronics*, 35(11), 11960–11972. <https://doi.org/10.1109/TPEL.2020.2982781>