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Voltage Balancing for Electric Vehicle Charging Stations Employing a Clamped Neutral Point Converter with a Divided DC Bus

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Abstract: This paper introduces a novel method of voltage balancing in electric vehicle (EV) charging stations for a Clamped Neutral Point (CNP) converter and a split DC bus system. The heart of the system is the hybrid power supply, which integrates the utilisation of a photovoltaic (PV) energy source with a battery energy storage system (BESS). These sources are linked together in a buck-boost converter stage, which controls power transfer according to demand and generation, allowing for effective and secure energy management. The buck-boost converter plays a crucial role in dynamically controlling the voltage level to ensure compatibility in the face of load and input fluctuations. Its most significant characteristic is the use of the CNP converter to provide effective voltage balancing of the upper and lower capacitors on the split DC bus. Through mid-point voltage stabilisation, it alleviates a natural weakness of multi-level power conversion systems, thereby improving system robustness and the power quality supplied to the load. This is especially important in maintaining stable performance in EV charging applications whose voltage variations may impact battery life and charging efficiency. MATLAB/Simulink simulations confirm the system's ability to dynamically share power between the battery and the PV source, offering voltage symmetry across the DC link.

Keywords: Neutral Point Clamp Converter; Energy Storage Management; Three-Level DC-DC Converter; Voltage Balance Management; Split DC-Bus; Battery Energy Storage System.

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1. Introduction

Accelerating the pace of adoption of electric vehicles (EVs) is a significant shift in the global transportation paradigm, driven by environmental concerns, technological advancements, and supportive policies. EVs are fast emerging as the greenest alternative to traditional fossil fuel-powered vehicles with internal combustion engines (ICEs). Evidence of demand is reflected

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in the rising global volume sales, and this trend is expected to continue strongly in the near future. Yet to position EVs as a genuinely sustainable and mass-market choice, some of the limitations on their deployment must be addressed. Some of these include long battery charging times, limited ranges, and a lack of public fast-charging infrastructures. Such properties undermine the experience of using them and limit the usability of EVs for high-mileage or emergency use, particularly for customers based in areas with less comprehensive charging infrastructures [1].

From the grid perspective, the mass penetration of EVs imposes a new set of challenges. The power demand is expected to experience a significant surge as more vehicles transition from petroleum to electric power. Although the current transportation industry is petroleum-driven, the phased transition to electric-powered transportation will inevitably put enormous pressure on the existing power infrastructure. Unless addressed by strong solutions, the imposed stress on the utility infrastructure could be artificial, favouring grid instability, increased operational costs, or a gradual adoption of EVs. This necessitates the development of a futuristic, efficient, and scalable charging infrastructure that can handle high charging rates without destabilising the grid. In such a scenario, a traditional DC bus architecture appears to be a natural fit for utility-level EV charging infrastructure. The design is appealing in that it's simple, efficient, and contains fewer conversion levels, and therefore less costly and less massive. It also facilitates the seamless integration of distributed generation (DG) sources, such as photovoltaic (PV) panels and wind turbines, as well as energy storage devices (ESS), including batteries or supercapacitors. These characteristics render the architecture both future-proof and extremely versatile for use with renewable energy-based microgrids or distributed power systems [2].

The AC-DC converter stage in such systems is crucial and must meet several significant performance requirements. It should guarantee low harmonic distortion to avoid disrupting the operation of other electrical devices, be capable of high-power throughput to support the rapid charging of large numbers of vehicles simultaneously and possess an entirely adjustable power factor to ensure optimal use of grid capacity [11]. Additionally, design enhancements to the I/D converter can simplify its size and complexity, reduce the number of active and passive components, and minimise the system's cost and space requirements. To address these technical requirements, the Neutral Point Clamped (NPC) converter is a great candidate. The NPC converter, with its multilevel topology, offers several benefits, including improved voltage waveform quality, reduced electromagnetic interference (EMI), and enhanced power handling capability. All these benefits are crucial when scaling to fast-charging stations (FCS), where multiple high-power charging units operate simultaneously [12].

The NPC converter also features built-in voltage balance capabilities, which are essential for maintaining symmetrical split DC buses under unbalanced loading conditions. Voltage balance is a central issue for multi-level converter topologies, particularly under conditions of variable loads. In electric vehicle charging stations, due to the power requirements of different vehicles, asymmetrical stress is put on the DC buses [3]. The NPC topology, due to its clamped diode structure and balanced switching strategies, effectively damps voltage unbalances. This enables the stable operation of the inverter stage and provides a high-quality AC power supply to vehicle on-board chargers. In addition, determining unbalanced mode boundaries and developing robust modulation schemes for these unbalanced modes are core research topics addressed in this work. The research will seek to confirm the theoretical framework through comprehensive simulation and experimental studies. Simulation will be performed using MATLAB/Simulink to analyse the system performance under various load and generation scenarios. From these simulations, the research will demonstrate how the NPC converter achieves voltage symmetry, facilitates efficient power conversion, and enables fast and reliable EV charging. A low-voltage prototype of NPC-based FCS will be implemented for experimental validation. The prototype will facilitate real-time experimentation with control algorithms, switching patterns, and energy management strategies, providing valuable insights into field implementation issues and solutions.

Among the most basic concepts of this research is the creation of a successful energy management system (EMS). The EMS regulates the best flow of energy between the grid, renewable sources, and storage units as a function of load request, battery state of charge (SOC), and generation capacity. This is a crucial strategy for minimising grid usage, enhancing energy efficiency, and maximising the utilisation of clean energy sources. With the integration of ESS in the charging devices, not only is peak demand minimised, but surplus renewable energy can also be stored and made available for later use, thereby enhancing the overall sustainability of the system. Secondarily, inclusion of a three-phase DC-DC converter as an interface between the energy storage phase enhances system flexibility [4]. The DC-DC converter can draw power from both the upper and lower DC buses to enhance power flow control and improve system response in transient states. Such flexibility reduces hardware requirements on the central converter while maximising what is already owned to do more with less, a very significant factor in cost-effective infrastructure development. The system's modularity also makes it scalable, allowing for the expansion of the network by adding more units without requiring drastic adjustments to the existing infrastructure.

The solution can also be achieved through the combination of smart grid technology and vehicle-to-grid (V2G) applications, in which EVs can be utilised as mobile storage units that feed power back to the grid when needed. The NPC-based split DC bus topology, integrated with renewable energy and energy storage systems, presents a future-focused solution for EV charging infrastructure. Prioritising the underlying issues of voltage balancing, system efficiency, and scalability, this topology addresses the increasing demands for EVs while maintaining compatibility with grid stability and environmental sustainability [5]. The simulation and experimental verification envisioned in this work aim to demonstrate that the architected solution is technically feasible and practical enough to be deployed on a large scale, thereby paving the way for its future widespread deployment.

2. Literature Survey

Electric vehicles represent a relatively recent innovation that is gradually gaining a foothold in the market. They offer several advantages, such as reduced greenhouse gas emissions, fuel savings, and ease of use. In recent years, the installation of renewable energy facilities has been increasing rapidly due to efforts to curb the release of greenhouse gases responsible for global warming and to conserve fossil fuels, which are becoming increasingly scarce. Additionally, the cost of photovoltaic systems is steadily decreasing. Consequently, it is anticipated that the price of photovoltaic energy will continue to decline in the future. However, in Japan, the significant amount of excess electricity from photovoltaic systems negatively impacts the power grid. This paper proposes an EV charging station powered by renewable energy. The proposed station harnesses energy from photovoltaic systems and wind turbines at a low cost to charge a fixed battery. This energy is then used to charge electric vehicles, offering several opportunities for electric power supply from renewable sources at EV charging stations. This paper also presents an energy management and control strategy for the power supply of an electric vehicle charging station. Solar photovoltaic arrays and wind turbines are integrated to replace energy from fossil fuels and reduce carbon emissions. An additional primary source is included to ensure a consistent power supply to the system, and we use Proteus software to simulate the circuit [6].

With the growing interest in electric vehicle (EV) technologies and the decreasing costs of photovoltaic systems, the industrial development of solar-powered battery charging stations for EVs has commenced. While charging EVs at night is convenient due to lower electricity usage, some consumers will always prefer or need to charge their vehicles during the day, even at peak times. This paper proposes and examines an EV charging station that incorporates solar energy as a renewable resource. Equipped with a local battery pack, the station supports semi-fast and fast charging and can be installed in homes and apartment buildings, where the grid's maximum power delivery is capped at 3.6kW. The station utilises converters that are readily available in the market. A simulation model of this charging station is developed, showcasing various operational modes to confirm the system's proper functioning. The rise of electric vehicles is becoming essential in the near future, as it contributes to reducing carbon emissions and footprints, thereby slowing the current rate of climate change. Despite the increase in electric vehicle adoption, customers in the Asian and African regions are concerned about the lack of charging infrastructure and the gap between charging infrastructure and companies [7].

They also worry about the Vehicle-to-Grid concept during fault conditions, which could harm battery health over time. This paper presents an isolation mechanism combined with a grid-connected photovoltaic system that operates in parallel with the main grid, sharing the necessary power with the supply grid. A case study involving five electric vehicles charging at different times illustrates a real-world scenario. Although the penetration of EVs in the transportation sector is rising, traditional internal combustion engine (ICE) vehicles still dominate. To boost EV adoption and achieve sustainable transportation, obstacles such as the high cost of EVs, range anxiety, insufficient charging infrastructure, and grid pollution from EV chargers must be overcome. The high cost of EVs is attributed to expensive energy storage systems (ESS) with high energy density. This paper offers a comprehensive review of EV technology, focusing on electric vehicle supply equipment (EVSE), ESS, and EV chargers. It provides an in-depth discussion on the latest EV chargers, including on- and off-board chargers, and explores different topologies with low- and high-frequency transformers. Various power levels available for charging are also discussed. To alleviate range anxiety, EV chargers based on inductive power transfer (IPT) are examined. The final section of the paper addresses the negative impacts of EV chargers and suggests possible solutions. The international standards established by various institutions and adopted universally are discussed in the latter part of this paper. This paper concludes with a discussion of near-future advancements in EV technology [8].

As electric vehicles (EVs) become increasingly popular, there is a pressing need to address the strain they place on power grids due to their unpredictable and frequent charging demands. Traditional direct current (DC) fast charging stations (FCS) that utilise photovoltaic (PV) systems can help mitigate grid stress and reduce carbon emissions. However, the high costs associated with energy storage systems (ESS) and the inefficient use of grid-connected interlinking converters (GIC) remain significant challenges. This paper introduces a novel DC FCS architecture that relies on a PV system without the need for an ESS, aiming to cut costs. Additionally, the proposed smart charging algorithm (SCA) is designed to optimise the coordination between the grid's source/load characteristics and EVs, maximising the PV system's power output and enhancing GIC utilisation without ESS support for FCS. The SCA includes a self-regulated algorithm (SRA) for EVs and a grid-regulated algorithm (GRA) for GICs [9]. The SRA adjusts the charging power of each EV based on the state of charge (SOC) feedback, ensuring power balance within the FCS, as long as DC bus voltage fluctuations remain within a specified threshold. If the DC bus voltage exceeds this threshold, the GRA intervenes. By employing adaptive droop control, the GRA can boost GIC utilisation while maintaining the charging power for all EVs. Finally, simulation and experimental results are presented to validate the effectiveness of the proposed SCA [10].

3. Methodology

The block diagram shown in Figure 1 is a hybrid power system configuration proposed for electric vehicle (EV) charging or smart grid operation, combining conventional and renewable energy sources, and controlled by microcontroller-based power electronics and control. The system comprises an AC source, a solar panel, DC-DC converters, a three-level neutral-point-clamped (3L-NPC) converter, a driver circuit, a microcontroller, and a load. The combination of these building blocks provides voltage balancing, bidirectional power transfer, and effective energy management. It begins from the AC source, which is a standard grid supply providing alternating current (AC) to the system. The AC source is interfaced with the 3L-NPC converter, which is a three-level neutral-point-clamped multilevel converter. The 3L-NPC converter is a primary building block that facilitates bidirectional power transfer, enabling AC power to be converted into DC (rectification) or vice versa (inversion) based on the load demand or charging/discharge mode. The multilevel configuration offers the benefits of reduced harmonic distortion, improved power quality, and enhanced voltage balancing.

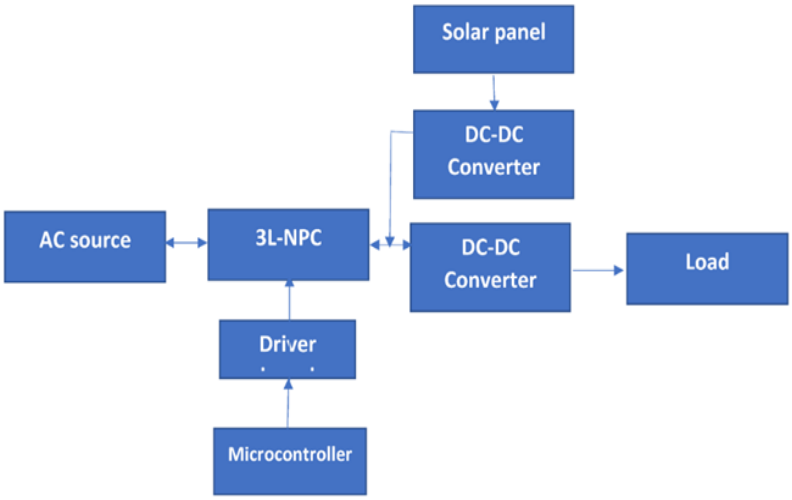

Figure 1: Block diagram of the proposed system

The 3L-NPC converter is passed through a DC-DC converter, which provides the voltage level appropriate for the load or energy storage system. The DC-DC converter is responsible for stepping down or stepping up the voltage, depending on the requirement during operation. Another DC-DC converter is also placed in the solar panel line, serving as the renewable energy source for the system. The power from the solar panel is fed to this converter, which regulates it to the required voltage level for incorporation into the common DC link or bus. The two DC-DC converters provide power balance, along with a steady DC voltage output, to supply to the load, which can be an electric vehicle battery bank, a household unit, or an industrial DC load. The addition of the solar panel introduces a green energy feature to the system, enabling the use of renewable energy for environmentally friendly operations. The microcontroller is the master control unit of the system. It constantly monitors parameters such as voltage, current, and the direction of power flow, and accordingly generates gate pulses or control signals. These control signals are transferred to the driver circuit, serving as an interface between the microcontroller and power electronic switches of the 3L-NPC converter. The driver conditions and amplifies the control signals to efficiently and safely drive the high-power semiconductor devices. The closed-loop control operation implemented using the microcontroller provides optimised switching, voltage regulation, and dynamic system stability. This architecture supports both grid-connected and off-grid operation, providing energy supply from the grid and solar sources individually or in combination to charge the battery or directly supply the load. DC Bus Voltage Splitting, let the total DC-link voltage be Vdc, and it is split between two capacitors:

$$V_{dc} = V_{c1} + V_{c2} \tag{1}$$

For ideal voltage balancing,

$$V_{c1} = \frac{V_{dc}}{2} \tag{2}$$

Phase Output Voltage of NPC Converter: for a three-level NPC converter, each leg can output:

$$V_{aN}, V_{bN}, V_{cN} \in \{+\frac{V_{dc}}{2}, 0, -\frac{V_{dc}}{2}\} \quad (3)$$

Where

$$V_{aN} = +\frac{V_{dc}}{2} : S_1 \& S_2 \, ON$$

$$V_{aN} = 0 : S_2 \& S_3 \, ON$$

$$V_{aN} = -\frac{V_{dc}}{2} : S_3 \& S_4 \, ON$$

Neutral Point Current (I_n), to maintain capacitor balance:

$$I_N = \frac{dQ_1}{dt} = C\frac{dVC_1}{dt} = -C\frac{dVC_2}{dt} \quad (4)$$

Where, C = Capacitance of each DC-link capacitor, V_{C1}, VC_2 = Voltage across each capacitor

Voltage Balancing Control Using Zero-Sequence Voltage

To balance capacitor voltages, introduce a zero-sequence component:

$$V_0 = \frac{1}{3}(V_a + V_b + V_c) \quad (5)$$

4. Simulation and Discussion

The simulation model depicted in Figures 2 and 3 illustrates a sophisticated power management system for an electric vehicle charging station, utilising a Clamped Neutral Point converter topology. This system incorporates a photovoltaic (PV) source, a battery storage unit, and a split DC bus equipped with a voltage balancing feature through a clamped converter, ensuring stable and efficient DC voltage levels for supplying a three-phase load. During the input stage, the PV array supplies DC power that is stepped up by a boost converter to increase the voltage level. Maximum power point tracking and efficiency are controlled by the pulse-width modulation (PWM) technique in the boost converter (Figure 2).

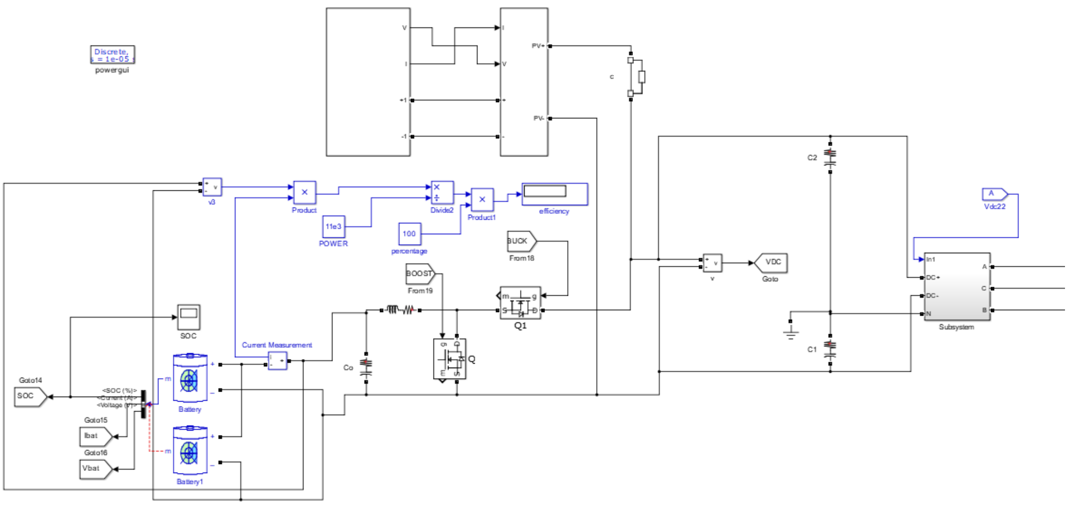

Figure 2: Simulation model of the PV-battery-based DC-DC boost converter system

The increased DC voltage is supplied to a split DC link, which comprises two capacitors (C1 and C2) that form the negative and positive rails of the DC bus, with the midpoint acting as the neutral. This is the foundation of voltage balancing within the split DC system. A buck-boost hybrid converter structure is used for power distribution and voltage regulation. The Q and Q1 switches regulate power flow dynamically to control voltage across the bifurcated DC bus and hold voltage symmetry. The clamped neutral point converter concept is employed in this situation to prevent voltage imbalance between the upper and lower

DC link capacitors, ensuring that neither side of the bus is undercharged or overcharged. This is done by intelligent switching control and by actively clamping the midpoint to the required neutral voltage level (Figure 3).

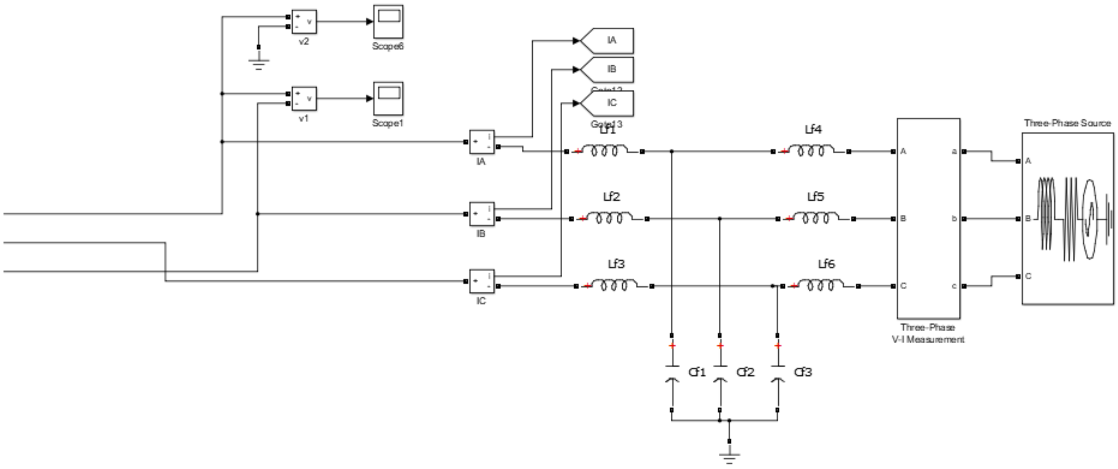

Figure 3: Simulation model of the three-phase grid connection system

The battery storage system is connected in parallel with the PV source through current measurement and SOC blocks. This setup allows the battery to discharge and compensate when solar power generation is low, and to charge when it is high, thereby maintaining a continuous power supply and stable voltage. The SOC monitoring circuit makes the system continually conscious of the battery's health and availability. Power calculation blocks are utilised to determine real-time power output and efficiency. This is achieved by multiplying the current and voltage, followed by scaling the value to kilowatts and determining the efficiency as a percentage. These figures are crucial for system diagnostics and maintaining optimal system performance. The VDC monitoring block and Vdc22 display monitor the voltage on the DC bus to keep it within operating limits. Lastly, the regulated DC voltage is supplied to the three-phase inverter subsystem, where the balanced DC output is converted to three-phase AC power. The produced AC power is supplied to the three-phase EV charging load, offering stable and balanced power suitable for electric vehicle charging. The inverter ensures that all three phases are synchronised, and the clamped neutral point converter maintains a stable midpoint voltage, thereby minimising component stress and enhancing the system's lifespan and reliability. This topology is particularly suited for EV fast charging stations where power quality and voltage balance are of utmost importance for charger and vehicle safety (Figure 4).

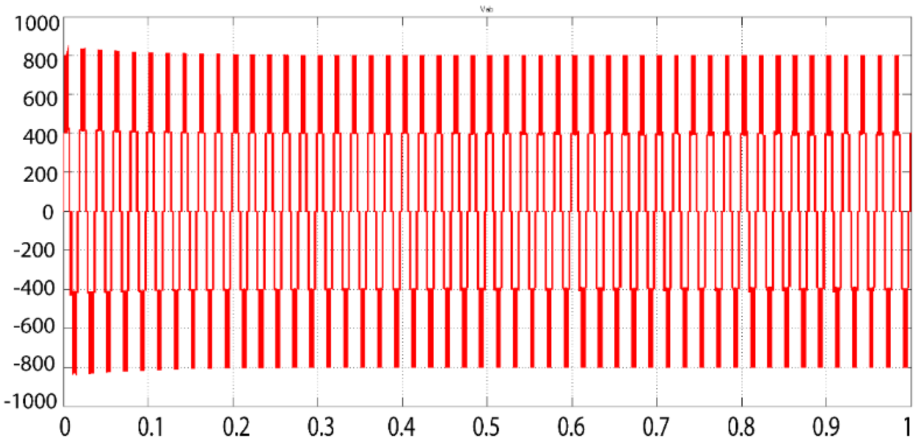

Figure 4: Phase-to-phase input waveform

In the simulation, the NPC converter produces three-phase output waveforms for both phase-to-phase and phase-to-neutral voltages, indicating that the multilevel topology generates stepped voltage waveforms. This leads to improved power quality, reduced switching loss, and better voltage balancing, which are some of the significant advantages of using a three-level NPC converter compared to conventional two-level inverters (Figure 5).

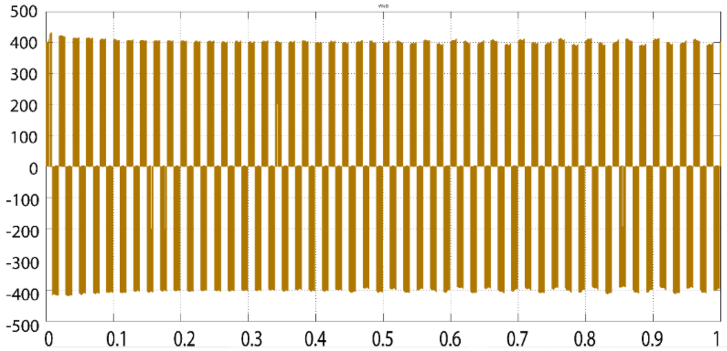

Figure 5: Phase to neutral input waveform

In the simulation, the NPC converter produces three-phase output waveforms for both phase-to-phase and phase-to-neutral voltages, indicating that the multilevel topology generates stepped voltage waveforms. This leads to improved power quality, reduced switching loss, and better voltage balancing, which are some of the significant advantages of using a three-level NPC converter compared to conventional two-level inverters (Figure 6).

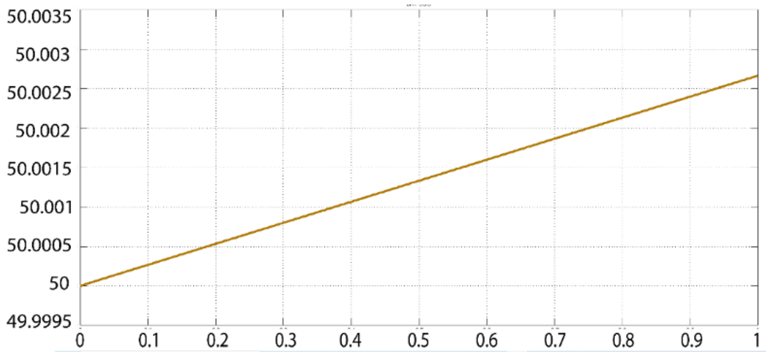

Figure 6: Battery SOC waveform with 96.43 % efficiency

These waveforms ensure that both the NPC converter, in both rectification and inversion modes, operate efficiently, allowing it to manage power exchange between the AC grid and the DC link effectively. The SOC of the battery, as observed under simulation, indicates the dynamic operation of energy storage. If power is delivered to the battery from the solar PV system via the DC-DC and NPC stages, then the SOC increases. The system reported a total charging efficiency of 96.43%, with small losses incurred during the power conversion process (Figure 7).

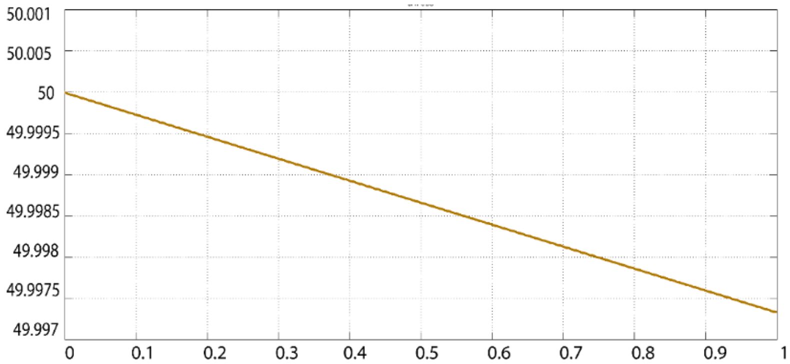

Figure 7: Bidirectional power flow when the battery is charged

The efficiency is high, indicating the proper functioning of the power electronic converters and the implementation of an appropriate control strategy through the microcontroller or control logic. While reducing the battery charge, the system operates in grid-feeding mode, and the excess power is fed back to the utility grid. Both modes of power exchange are facilitated through the NPC converter, which reverses its operating mode from inverter to rectifier. It provides opportunities for the reserved DC power within the battery to be converted into high-quality AC and synchronised with the grid's parameters. This feature enables smart grid integration and energy optimisation, allowing the system to function as a distributed generation unit.

5. Hardware Results

The hardware implementation depicted in Figure 8 is a solar-powered hybrid energy conversion system featuring a Neutral Point Clamped (NPC) converter, which serves as both a voltage regulator and battery charger for various applications, such as charging stations for electric vehicles (EVs) or smart grid applications. The system begins with a PV solar panel, the primary source of renewable energy.

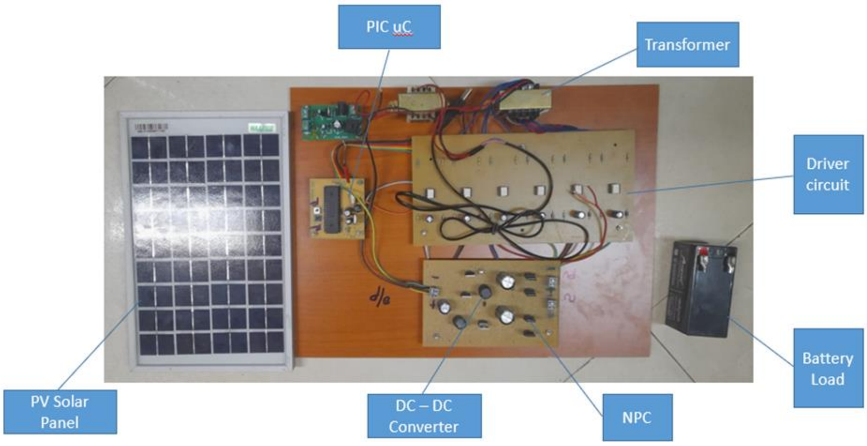

Figure 8: Hardware of the proposed system

The panel is used to transform sunlight into direct current (DC) electricity, which is converted by downstream electronics. The DC output is supplied to a DC-DC converter, whose function is to stabilise the voltage level to meet the input requirements of the NPC converter and the energy storage device. The converter ensures that the variable energy generated by the solar panel due to changes in solar irradiance is maintained constant before it is passed on to the next stage. The Neutral Point Clamped (NPC) converter, also known as a three-level inverter or multilevel converter, is a key component in the circuit, as it inverts or regulates the DC voltage. NPC converters are recognised for their reduced output waveform with low harmonic distortion, higher efficiency, and improved voltage balancing compared to conventional two-level inverters (Figure 9). The NPC converter typically employs a combination of switching components (e.g., IGBTs or MOSFETs) and diodes to achieve voltage clamping and multilevel output. In this configuration, the NPC converter manages the power flow between the DC-DC converter and the battery load, enabling the control of proper charging voltages and current rates. The NPC converter enables bidirectional operation, allowing for the discharging of the battery as needed. The overall power processing process is controlled by a PIC µC, which tracks real-time operating conditions of input solar voltage, output voltage, current, and battery status.

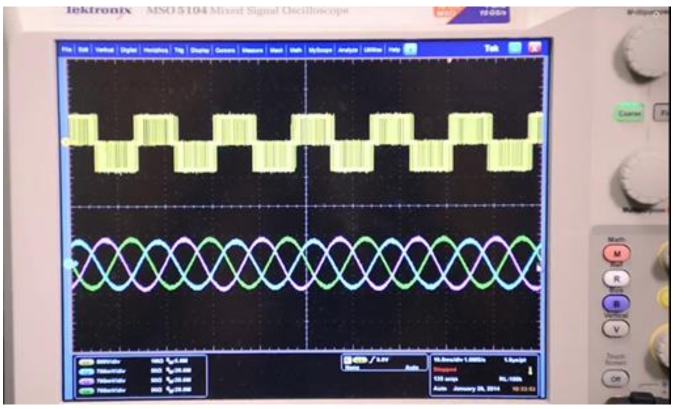

Figure 9: Clamped NPC three-level waveform

As per programmed conditions and feedback loops, the microcontroller sends accurate control signals to regulate the NPC converter and DC-DC converter switches (Figure 10). These signals are initially conditioned by the driver circuit, which serves as both a signal conditioner and a power amplifier. The driver circuit translates low-power microcontroller signals into high-power gate pulses required to drive the semiconductor devices in the NPC stage. This enables power devices to operate efficiently and safely under various load conditions and input voltages. There is also a transformer integrated into the design, likely for voltage stepping or isolation. It serves to isolate the power and control lines or change the voltage level between phases, depending on the design requirements.

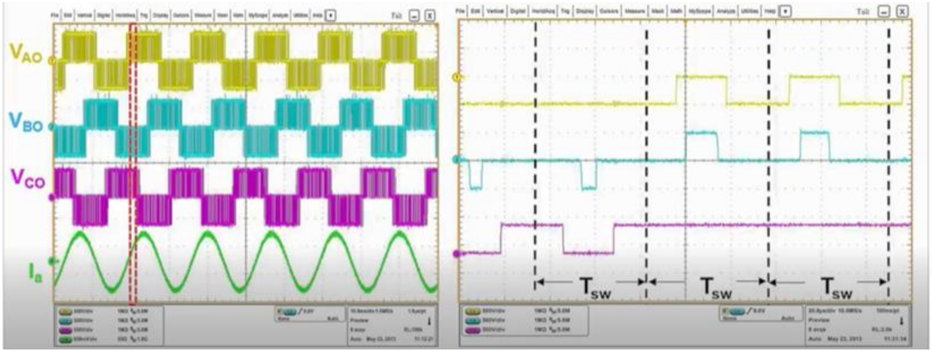

Figure 10: Phase-to-phase voltage, current, and switching waveform of NPC

The battery load mounted on the output is the energy storage device, e.g., lead-acid or lithium-ion battery, that stores the regulated power for utilisation at some later time. It is the last receiver of the energy flow and can be utilised to feed back into the system or an external load, depending on the mode of operation. Table 1 illustrates the hardware used.

Table 1: Components used in hardware

Element	Structures	Task
Power supply	Input 220VAC to output 15VDC	Provides a power supply
DC-DC Converter	Input DC: 18-20V	Variable input and Fixed DC voltage
	Output DC: 15V	
NPC Converter	Input DC:15V	Converts DC-AC and AC-DC in two modes
	Output AC: 30V	
Pulse driver	MCT2E-optocoupler	MCT2E is a phototransistor opto-coupler
	Diode forward voltage 1.25V	
	Collector-emitter voltage 30V	
	On-state collector current 5mA	
Microcontroller	dsPIC 30F2010	Pulse generation to drive the switch
	24-bit wide instructions, 16-bit wide data path	
	Wide operating range (2.5V to 5.5V)	
Battery	12VDC, 7.2Ah	Sealed maintenance-free

6. Conclusion

Simulation results validate the efficiency of the proposed clamped neutral point (CNP) converter with a split DC bus for maintaining voltage balance in electric vehicle (EV) charging. In this setup, driven by a hybrid photovoltaic (PV) and battery system, the power supply remains stable and uninterrupted through dynamic regulation of the energy flow according to real-time conditions. The CNP converter serves an important function in limiting asymmetrical voltage distribution among bipolar DC link capacitors, thereby improving the removal of mid-point voltage drift—a common issue in multi-level converter topologies. Stability greatly improves the performance and reliability of the subsequent three-phase AC load and inverter. Dynamic switching control enables a rapid response to source and load changes, ensuring voltage symmetry and minimising power quality degradation. The battery state of charge (SOC) is constantly monitored to achieve maximum energy efficiency and extend battery life, enabling intelligent energy management techniques. Additionally, DC-AC conversion is extremely stable, with minimal harmonic distortion, making it highly compatible with efficient EV charging units. The simulation validates the topology's ability to produce clean, balanced, and stable power output. In total, this system is a compact, modular, and combined renewable structure poised for future scalable EV charging infrastructure that is both environmentally and technically beneficial for transportation.

6.1. Future Scope

The suggested NPC-based solar-powered converter system can be further advanced by integrating IoT for remote monitoring, incorporating advanced control techniques such as fuzzy logic or model predictive control for optimisation, and managing multiple renewable energy sources. It can be upgraded to higher power levels and integrated into smart grids and electric vehicles. GaN or SiC devices will replace conventional switches for maximum efficiency and minimum size. With the addition of smart battery management and grid synchronisation, it will be more suitable and reliable for smart cities, EV charging systems, and applications, while making energy consumption sustainable and intelligent in next-generation power systems.

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Ethics and Consent Statement: All authors confirm that the study was performed in compliance with ethical research standards, ensuring informed consent, participant privacy, and data confidentiality throughout the process.

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