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# A Multifunctional Isolated High-Gain Converter with NSMRL-Assisted Control for Solar PV and Grid Integrated Electric Vehicle Charging Systems

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**ABSTRACT-** With the growing penetration of electric vehicles (EVs) in the market, multifunctional charging systems are required that are able to integrate renewable energy sources and operate under various charging and driving conditions without any disturbances. This paper proposes a multifunctional isolated High Gain converter (HGC) with a novel sliding mode reaching law (NSMRL) assisted control strategy for solar PV (SPV) and grid integrated EV charging applications. Proposed Architecture for Grid/ PV/ regenerative brake/ hybrid PV-grid charging and propulsion with a single power conversion stage. NSMRL-assisted control contributes to better DC-link voltage regulation, transient response, and strong operation under renewable intermittency and load variations. In MATLAB/Simulink, performance is verified for all operating modes. The simulation results show that bidirectional power flow, smooth mode switching, and energy management are achieved. The results indicate that the proposed approach can significantly improve the power quality and the performance of the converter as the THD of the grid voltage is reduced from 2.54% to 0.73% under steady state operation and 0.79% under plug-in charging.

**KEYWORDS-** Electric Vehicle Charging Station, Isolated High-Gain Buck–Boost Converter, Novel Sliding Mode Reaching Law (NSMRL), Solar Photovoltaic System, Multifunctional Converter, Regenerative Braking, Propulsion Mode, Dc-Link Voltage Regulation, Renewable Energy Integration.

## I. INTRODUCTION

The escalating demand for sustainable transportation has dramatically sped up the adoption of electric vehicles (EVs) driven by the concern of environmental degradation and fossil fuel resources depletion [1][2][3]. The surge in EV adoption has also created a demand for a charging infrastructure that can provide consistent and efficient charging across varying conditions and without interruptions [4] [5]. The integration of renewable energy resources, especially solar photovoltaic (PV) generation is an attractive solution of reducing grid dependency and carbon emission related to battery charging [6] [7]. But due to the intermittent nature of solar energy, it needs to be coordinated with the utility power supply so that power can be available at all the times despite the variation in solar irradiance [8]. A hybrid PV-grid charging system can solve this problem by integrating PV power generation with traditional power grid systems, providing a more efficient use of energy and greater reliability of the energy system [9]. This type of charging design can facilitate sustainable mobility and help to enhance power quality, lower operating cost, and utilize distributed renewable energy in future smart-grid architectures [10].

The conventional EV charging stations are mainly used for battery charging via the utility grid, which has a lack of flexibility when the energy availability and the operating conditions of EVs vary [11]. As the distributed renewable generations have increased, there has been a growing need for multifunction charging architectures that can coordinate multiple energy sources in a single power conversion platform [12]. These charging systems, in general, can perform grid-assisted charging, direct PV charging, hybrid charging (grid and PV), energy recovery (regenerative braking), and drive during vehicle operation. A seamless switch between these operating modes requires coordinated power management, bidirectional energy transfer, accurate DC-link voltage control, and stable battery current control [14]. Thus, converter topology plays a key role as it directly affects voltage conversion capability, energy conversion efficiency, dynamic response and overall system reliability [15]. The choice of a suitable control strategy is also of great importance because charging infrastructure often sees fluctuation in renewable energy sources, variation in loads, voltage variations in the battery and fast mode changes during real operation [16].

To enhance the efficiency, flexibility and energy management in EV charging applications, various converter configurations have been investigated recently [17]. Isolated and non-isolated DC – DC converter has been used to enable PV, grid and battery energy storage as part of a unified charging system [18]. To provide the charging, propulsion, and energy recovery functions, SEPIC, boost, buck–boost, Cuk, and bidirectional converter topologies have been introduced and used in several studies [19]. In parallel, there have been attempts to improve the performance of the converter by using new control methods such as proportional–integral method, fuzzy logic, model predictive control (MPC), sliding mode control (SMC) and smart optimization algorithm [20]. Under various operating conditions, these methods have shown better performance in voltage regulation, charging of batteries and utilization of renewable energy [12] [18] [20]. However, these advances have yet to yield converter designs that can be practically implemented with multiple operating modes while maintaining high voltage conversion ratio, small size, and good dynamic performance under varying operation conditions.

Today, there are a number of charging architectures that integrate photovoltaic generation, supply from the utility, and battery storage, but there are still some technical issues that have to be solved [11,17]. To achieve individual operating modes, multiple converter topologies are often used, resulting in more components, control coordination and hardware complexity [18] [19]. Furthermore, wide operating ranges or higher DC-link voltage might also cause a reduction in conversion capability of the conventional voltage conversion stages [19]. Moreover, proportional–integral (PI) based control has limited adaptability under nonlinear operating conditions, such as renewable energy fluctuations, sudden load variations and frequent switching from charging to driving and vice versa [15] [20]. These constraints can impact charging performance and affect voltage stability, transient response and bidirectional energy flow [16],[20]. To overcome these challenges, a single power conversion architecture and a powerful nonlinear control strategy are necessary to ensure stable operation in all charging/promotion modes, high power conversion efficiency and operation reliability [17] [20].

Considering the identified limitations, a multifunctional EV charging architecture, which is based on the isolated high-gain converter and Novel Sliding Mode Reaching Law (NSMRL)-assisted control strategy, is introduced. The proposed architecture provides common operation framework for grid charging, PV charging, PV/grid charging, propulsion and regenerative braking without necessitating separate converter structure for each operation. The high gain conversion capability provides effective DC-link voltage regulation with galvanic isolation and bidirectional energy transfer. The integration of an NSMRL-assisted control strategy further improves dynamic response by increasing accuracy in current tracking and voltage regulation in the event of quick changes in operating conditions. Energy management is stable between various operating modes and reliable battery charging by coordinated operation of converter and controller, and efficient power flow is achieved.

**Major Contributions**

- A multifunctional isolated High Gain converter is proposed that can be used for grid charging, PV charging, hybrid PV-grid charging, propulsion and regenerative braking operation with a common structure.
- Based on the proposed DC-link voltage control strategy, an NSMRL-assisted control strategy is developed to improve the DC-link voltage regulation, battery current control, and transient response under different operating conditions.
- All the operating modes are comprehensively validated using MATLAB/Simulink to ensure stable power flow and reliable energy management.
- The dynamic performance of the system and the grid voltage THD (2.54% reduced to 0.73% steady-state and 0.79% PIC mode) are compared to a SEPIC converter operating with PI control.

## II. PROPOSED MULTIFUNCTIONAL EV CHARGING ARCHITECTURE

### *A. System Architecture*

Proposed multifunctional EV charging architecture is a combination of solar PV generation, utility-grid supply, battery energy storage and electric vehicle propulsion on a common DC power conversion platform, as shown in Figure 1. Hybrid energy configuration allows for continuous power availability through coordination of renewable energy generation with utility support under various environmental and vehicle operating conditions. The stable power transfer and reliable DC link voltage regulation from the individual subsystems is controlled by an isolated high-gain converter which regulates the energy exchange between them.

Solar PV array is a main source of renewable energy during daylight operation whereas charging demand is made up with utility grid when PV energy is not enough or unavailable. Bidirectional energy transfer ability means that the battery can be charged while the device is plugged in, and the battery energy is transferred to the power plant when the vehicle is being driven. The regenerative braking operation further enhances energy utilization by returning the kinetic energy into the batteries within the same power conversion system. This simultaneous operation reduces loss of energy and enhances charging flexibility during actual driving conditions.

The operation of the converter is controlled by an NSMRL-assisted control strategy which continuously controls the switching of the converter as per operating conditions and reference signals. Control architecture stabilises the DC-link voltage, controls the battery charging current and enables smooth switching between various operating modes without affecting power flow. The integration of renewable generation, grid support, energy storage, and propulsion in a combined system minimizes the number of hardware components and increases the reliability of the system and its overall performance.

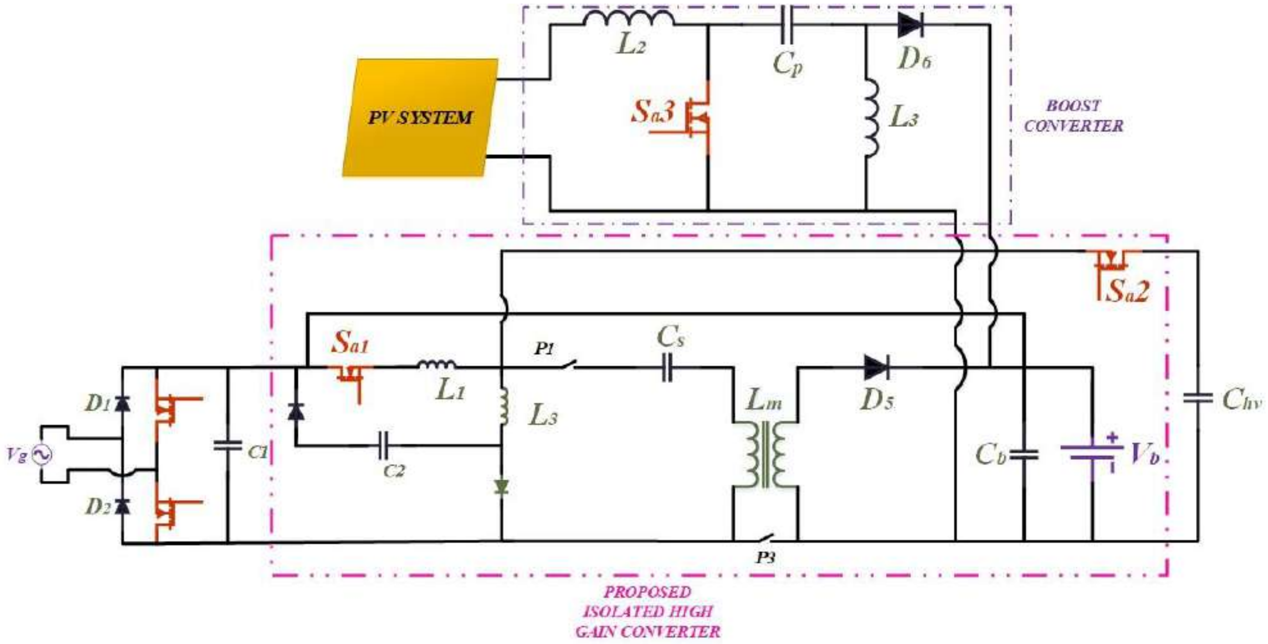



Figure 1: Proposed multifunctional EV charging architecture employing an isolated high-gain converter with NSMRL-assisted control

### B. Operating Principle

The proposed multifunctional EV charging infrastructure integrates power exchange between PVs, the utility grid, electric vehicle drive and battery storage in a single isolated high-gain converter. Energy flow is constantly adjusted based on available energy sources, battery charging needs and vehicle operating modes. Charging architecture automatically switches to an optimum operating condition based on the level of demand and availability of renewable energy, without interruption of energy transfer and without voltage fluctuations in the DC-link.

The charging operation will be conducted with electrical energy from PV generation, utility supply or from both sources. PV generation works in a way of taking the maximum power from the sun, while the utility supply is used to provide additional power when PV generation is not enough. By operating both sources together, continuous charging is possible for the batteries without any interruption due to different irradiance conditions.

In the vehicle propulsion application, the battery energy is fed to the proposed isolated high-gain converter to keep the required DC link voltage for the operation of the motor drive. Converter dynamically adjusts the flow of power as per the load requirement of vehicles while maintaining the stability of voltage and current. If regenerative braking is used, the power is generated and converted in the same manner and energy is fed back into the battery again, enhancing energy utilization and increasing range of use.

The NSMRL assisted control strategy ensures the converter operation under all operating conditions. All reference voltage and reference current signals are monitored continuously in order to control and optimize the switching operation of the converter as well as to ensure the proper battery charging and the stability of the DC-link voltage while switching between charging and driving modes seamlessly. The coordinated control ensures better stability of operation and power transfer in both directions under dynamic operating conditions.

### C. Operating Modes

#### 1) Mode I: Grid Charging Operation

In the first mode, a grid charging operation is performed. The first mode is a grid charging operation.

When the PV generation is not available or not enough to meet the battery charging demand, the PV is operated in grid charging mode. In this situation, the utility power flow is converted through the proposed isolated High Gain converter to install the battery with the reference DC-link voltage. The NSMRL-assisted controller dynamically adjusts the switching of the converter and charging current of the battery to maintain stable voltage conversion and charging performance, even when the source is disturbed or the battery voltage fluctuates.

In this mode, power only flows from the electricity grid to the battery via the converter. The PV source is inoperative, meaning that propulsion and regenerative braking are also inactive. Current regulation and stable operation of the DC-link ensure reliable charging even with limited renewable energy.

#### 2) Mode II: Solar Photovoltaic Charging Operation

Solar photovoltaic charging mode is engaged when the amount of solar energy available is enough to charge the battery. The PV array serves as the main energy source and P&O based MPPT algorithm is used to maximise the amount of power which can be taken from the PV array. The isolated High Gain converter is used to regulate the DC-link voltage and to control the charging current of the battery, even though the solar irradiance changes. The NSMRL-assisted controller continuously monitors the voltage and current reference signals to enhance current regulation and to minimize voltage deviations. The converter operates in a stable manner in view of efficient utilization of renewable energy while the whole charging demand is supplied by the PV array, as the support from the utility remains disconnected.

#### *3) Mode III: Hybrid Grid–Photovoltaic Charging Operation*

Hybrid charging mode is engaged whenever the PV production is not sufficient to meet the charging demand of the batteries, or when PV production fluctuates over time. In this case, both the PV array and the utility grid provide power to the load via the proposed isolated High Gain converter. Renewable energy is used as the primary source and the remaining charging will be provided by the power from the utility, which will allow uninterrupted charging of batteries.

The converter will sum the power of both sources, keeping the DC-link voltage regulated and the battery charging current controlled. NSMRL supports the controller in dynamically adjusting the converter switching to share the power with the PV array and balance the grid power sharing, which maximizes the utilization of renewable energy, decreases dependency on the grid, and ensures stable charging performance in the face of changing environmental conditions.

#### *4) Mode IV: Propulsion Operation*

Once charging is complete and the electric vehicle is placed in a propulsion mode, this mode starts. In this mode, battery energy is injected into the isolated High Gain converter to keep the DC-link voltage at the specified value for the traction inverter. In continuous operation, the converter adapts continuously to changes in the vehicle speed and torque requirement for stable power delivery during propulsion.

In order to avoid voltage fluctuations under dynamic driving condition, the current of battery and switching of the converter controlled by NSMRL will be settled as per the load requirement. True current control and stable DC-link voltage, which leads to better propulsion performance, increased use of energy and safe motor operation.

#### *5) Mode V: Regenerative Braking Operation*

Regenerative braking mode will be engaged whenever the vehicle is slowing down. The traction motor is a generator that transforms mechanical energy into electrical energy as opposed to heat. The recovered energy is returned to the battery in the proposed isolated High Gain converter, which increases the battery's driving range and energy utilization.

The converter is used for energy recovery and controls power flow in both directions, while keeping the DC-link voltage constant and the charging current of the batteries controlled. The controller adjusted by the NSMRL optimizes the switching of the converter according to the braking power and the operation conditions of the battery during the braking process, so as to smoothly recover the energy of the battery, the stress of the battery charging process is reduced, and the battery energy recovery process is performed normally and reliably.

## III. DESIGN AND CONTROL OF PROPOSED ISOLATED HIGH-GAIN CONVERTER

### *A. Converter Configuration*

The proposed isolated high-gain converter is configured as shown in figure 2 in the proposed architecture of the multifunctional EV charging. By eliminating the need for separate converter topologies for each operating mode, Converter offers a common power conversion platform for grid charging, PV charging, hybrid charging, propulsion and regenerative braking. The configuration makes it easier to make the power conversion stage while ensuring that energy is transmitted in both directions and that the DC-link voltage remains constant during the operation of the system.

In the selected operation mode, electrical energy from the PV source, the electric supply or the battery is supplied to the primary side of the converter. The energy is further transformed by a high frequency isolation stage before it is applied to secondary side, ensuring a galvanic isolation and a safe electrical operation. Using these techniques, high voltage conversion ratios can be achieved, while the voltage stress across converter components is kept low by careful selection of passive components, transformer turns ratio and switching devices.

Switching operation is controlled using an NSMRL-assisted control strategy that provides control signals based on reference voltage and current values. The coordinated control of the converter switching ensures stable power transfer, enhanced dynamic performance, and smooth handover between various operating modes. Topology integration and use of a powerful control architecture ensure reliable performance in the presence of fluctuating source availability and load conditions, maintaining load stability and optimal propulsion performance.

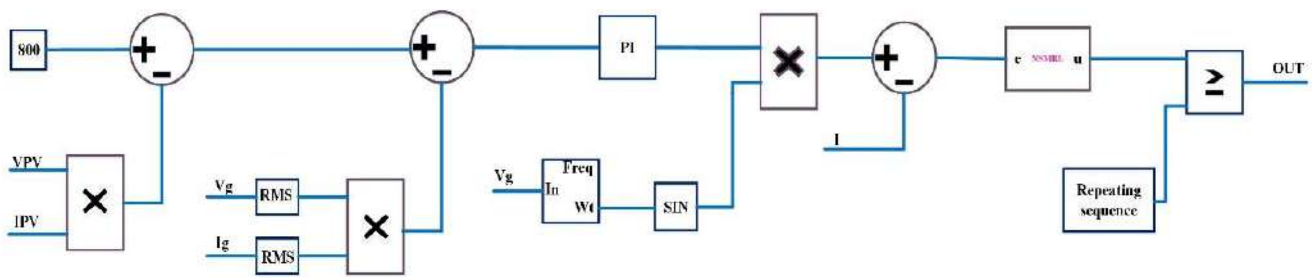



Figure 2: Proposed isolated high-gain converter configuration with NSMRL-assisted control.

### *B. Operating Principle*

The PCC with proposed isolated High Gain converter facilitates the bidirectional power flow of PV source, the power grid, the battery storage, and the traction system by the coordinated switching operation. The converter enables grid charging, PV charging, hybrid charging, propulsion, and regenerative braking to be realized with a common power conversion stage depending on the availability of the sources and the charging demand and condition of the vehicles. The isolation stage is used to regulate the charging current of the batteries and ensure a stable DC-link voltage during the charging stage when electrical energy from the PV array or the utility grid, or both, will be treated through the isolation stage. In propulsion mode, stored battery energy is used to provide the required DC link voltage for constant motor velocity, while regenerative braking sends recouped energy through the same converter for charging the battery. Continuous supervision of converter switching is done by the NSMRL-assisted control strategy that compares the voltage/current reference signal with the voltage/current measured signal to produce the gating pulses, thus ensuring accurate current regulation, stable DC-link voltage, seamless mode switching and reliable operation under different source and load conditions.

### *C. Mathematical Formulation*

With the use of the basic inductor voltage and capacitor current relations, a mathematical model of the proposed converter is constructed. Converter dynamic behavior is controlled by energy storage elements during charging and discharging periods and is galvanically isolated and voltage converted by a transformer. The dynamics of the converter can then be modelled by state equations which include the current of the inductors, the voltage of the capacitors and the DC link characteristics.

The general voltage and current relationships are given by:

$$V_L = L\left(\frac{di_L}{dt}\right) \quad (1)$$

$$I_C = C\left(\frac{dV_C}{dt}\right) \quad (2)$$

In the above example, VLV_LVL and ICI_CIC are inductor voltage and capacitor current, respectively, while LLL and CCC are the value of inductor and capacitor.

The dynamics of the voltage across the DC-link are controlled by:

$$C_{dc}\left(\frac{dV_{dc}}{dt}\right) = I_{conv} - I_{load} \quad (3)$$

$C_{\{dc\}}$ is the DC-link capacitance, $I_{\{conv\}}$ is the current output of the converter, and $I_{\{load\}}$ is the current output of the inverter. Converter equations are derived for individual switching intervals in detail depending on the switching states and the operation of the transformer. They are used as a mathematical basis for designing converter controller and evaluating system stability for various operating conditions.

*Adopted by the NSMRL-Assisted Control Strategy*

A converter output voltage and battery charging current regulation method based on Novel Sliding Mode Reaching Law (NSMRL) is applied to realize accurate output voltage and charging current regulation. The aim of the design of Controller is to enhance the dynamic performance during the change of operating conditions at high rates and yet to keep the converter operating in a stable manner under the disturbances at the source and changes in load. The voltage regulation is realized by an outer control loop while the current regulation is realized by using an NSMRL based reaching law to generate switching signals for converter.

The first step of control algorithm is to check the voltage error

$$e = V_{ref} - V_{dc} \quad (4)$$

V_{ref} is the reference DC-link voltage and V_{dc}Vdc is the measured output voltage of the converter.

To obtain steady state regulation, accumulated error is calculated as

$$e_i = e_i + e\,T_s \quad (5)$$

with $T_s$, the sampling period. Sliding surface is expressed by the formula:

$$s = \lambda e + e_i \quad (6)$$

The positive coefficient, λ, is a sliding coefficient that controls the convergence rate.

In the converter switching, an NSMRL reaching law is used in contrast to conventional proportional – integral regulation to generate switching.

$$u = -k_1\sqrt{|s|sign(s)} - k_2 s \quad (7)$$

where

- $k1 : Nonlinear\ convergence\ gain$
- $k2 : Linear\ damping\ gain$
- $\lambda : Sliding\ surface\ coefficient$
- $T_s : Sampling\ period$
- $u : Converter\ control\ signal$

When operating point is far from sliding surface, the reaching term is proportional to the square root of the difference, which speeds up the convergence rate; when the state trajectory is close to the equilibrium, the reaching term is proportional to the difference, which suppresses the oscillatory behaviour. A combination of both terms would give a fast transient response and smooth operation of the converter.

Therefore, the switching duty ratio of the converter has to be within a practical range, so control signal is limited as:

$$0 \le u \le 1 \quad (8)$$

This way, the converter switching boundaries are not violated and PWM is reliably generated.

This way, the converter switching boundaries are not violated and PWM is reliably generated.

The controller design with NSMRL (Parameter Shown in Table 1) is found to give better current tracking property, better disturbance rejection capability, less steady state error, and faster voltage recovery in charging, propulsion and regenerative braking modes, than conventional PI controller.

Table 1: NSMRL Controller Parameters

| Parameter | Symbol | Value |
|---|---|---|
| Sampling Time | $(T_s)$ | 50 μs |
| Sliding Surface Gain | $(\lambda)$ | 60 |
| Nonlinear Reaching Gain | $(k_1)$ | 20 |
| Linear Damping Gain | $(k_2)$ | 8 |
| Reaching Law Exponent | $(alpha)$ | 0.5 |
| Controller | — | NSMRL |

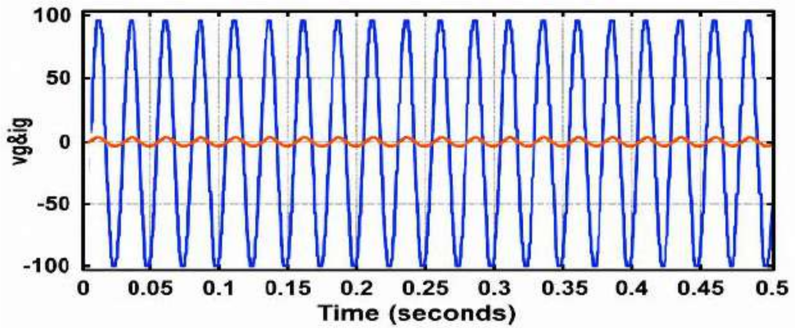
## IV. SIMULATION RESULTS AND DISCUSSION

The performance of the proposed multifunctional EV charging system is checked by simulation using the MATLAB/Simulink environment to ensure the efficiency of the isolated High Gain converter with the proposed NSMRL control under various operating situations and parameter shows in table 2. The simulation study examines the performance of the converter when dealing with battery charging, integration of photovoltaic power, propulsion mode operation and regenerative braking. The analysis of different electrical quantities like grid voltage, grid current, battery voltage, battery current, state of charge (SOC), capacitor voltage, DC-link voltage and harmonic performance tests examines the converter stability and energy management capability. A comparison study with the conventional SEPIC converter is also conducted using a PI controller to show the benefits of the proposed control method in terms of voltage regulation, current ripple, transient response, and charging efficiency of the proposed converter.

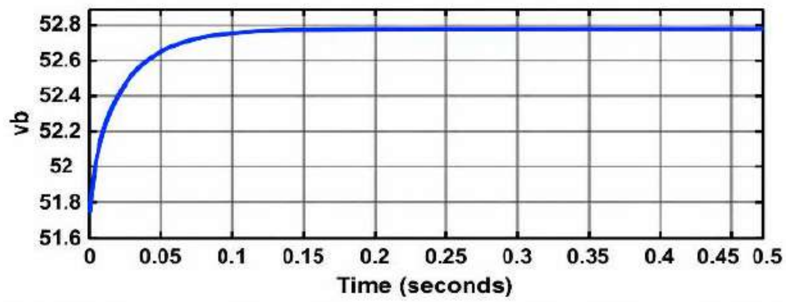
Table 2: Electrical Specifications of the Proposed EV Charging System

| Electrical Specification | Notation | Configured Value |
|---|---|---|
| Utility Supply Voltage | $(V_g)$ | 110 V |
| Utility Supply Frequency | $(f_g)$ | 50 Hz |
| Nominal Battery Voltage | $(V_b)$ | 48 V |
| Battery Energy Capacity | $(Q_b)$ | 26 Ah |
| Regulated DC-Link Voltage | $(V_{\{dc\}})$ | 150 V |
| Converter Inductors | $(L_1, L_m, L_2, L_3)$ | 2 mH (each) |
| Converter Capacitors | $(C_{\{hv\}}, C_s, C_{\{dc\}})$ | 330 μF, 1 μF, 1200 μF |
| Maximum Power Point Tracking | MPPT | (P&O) |

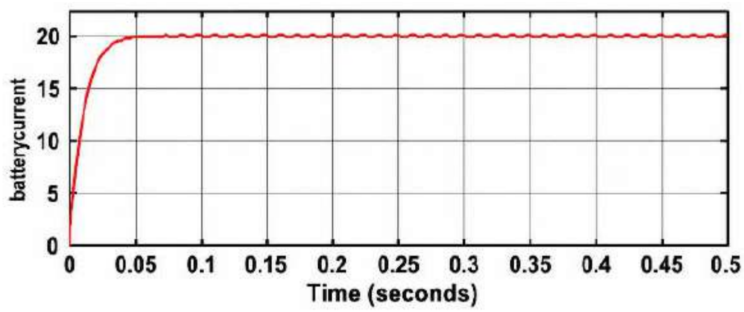
### A. *Steady-State Performance Evaluation of the Proposed Converter*



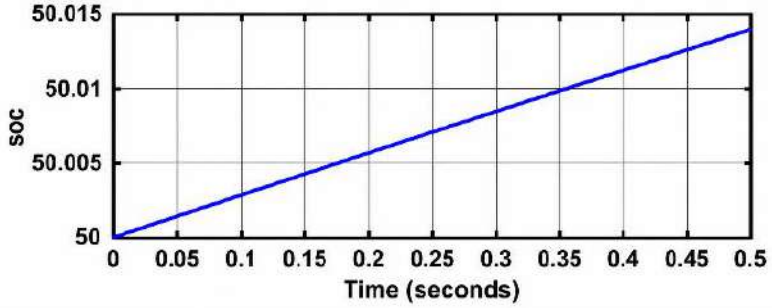

(a)



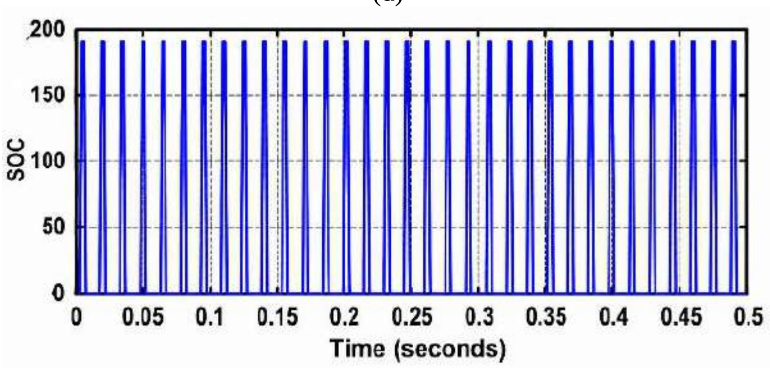

(b)




(c)




(d)




(e)

Figure 3: Steady-state performance of the proposed isolated High Gain converter: (a) Grid voltage and grid current, (b) Battery voltage ,(c) Battery current, (d) Battery state of charge (SOC), (e) Capacitor voltage

To make sure the proposed isolated High Gain converter is operating in a stable manner, the steady-state performance is analysed and validated. The steady state performance is analyzed and validated to ensure that the proposed converter is operating in a steady manner before exploring different operating modes. The measured electrical variables validate that the NSMRL-supported controller quickly settles into stable operation following the converter start-up and provides continuous regulation for all simulation time. The balanced operation of the converter and controller ensures the smooth power flow between the energy grid and battery storage system, which helps to support the upcoming charging and driving phases.

In Figure 3 the grid voltage and current waveforms show good sinusoidal shapes and stable sync during the operation period. The current response is dominated by the amplitude of the grid voltage, and the current is in phase with the voltage with good switching efficiency and balance transfer of power. This coordinated operation reduces power quality disturbances and aids in providing reliable performance when charging from the grid.

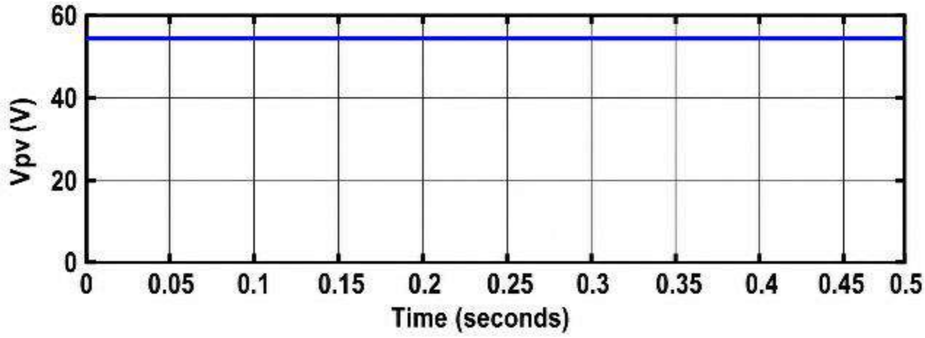
The effectivity of the proposed control strategy is further confirmed by the charging characteristics of the batteries. The voltage of the battery rises to the target voltage without overshooting, and the current charging the battery quickly approaches a more or less steady value, with almost no oscillations. By implementing the nonlinear reaching law, the charging error is compensated, ensuring stable current regulation, increase charging efficiency and reduce electrical stress on the battery.

As the charging interval proceeds, the battery state of charge (SOC) rises steadily, demonstrating the continuous transfer of energy and the efficient management of battery power. Smooth SOC variation is an indicator of the proper regulation of charging power, which can help ensure better battery reliability and long-term energy storage. Also, the intermediate capacitor voltage is maintained well even under the high-frequency converter switching, which indicates that the voltage is properly buffered and stable DC-link operation is maintained during continuous charging.

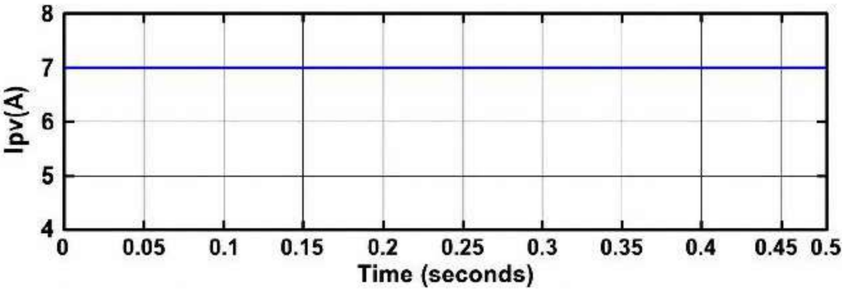
The power quality is measured by Fourier Frequency Transform (FFT) analysis of the grid voltage. A spectrum is obtained that shows that the fundamental takes precedence and higher order harmonics are suppressed. The measured grid voltage THD in the range of 0.73% is significantly below the limit recommended by IEEE (5%). This is a sign of excellent harmonic performance and high-quality power transfer. Minimization of the harmonic distortion also lowers interference, makes the converter more efficient and makes it more compatible with utility grid requirements.

The steady state investigation shows that the proposed isolated HGC operating in conjunction with the NSMRL-assisted controller is capable of maintaining stable voltage operation, smooth charging of the battery, transferring the necessary amount of energy, and maintaining excellent power quality. The results are used to reliably evaluate the converter in different charging and driving modes, showing its suitability for multifunctional EV charging applications.

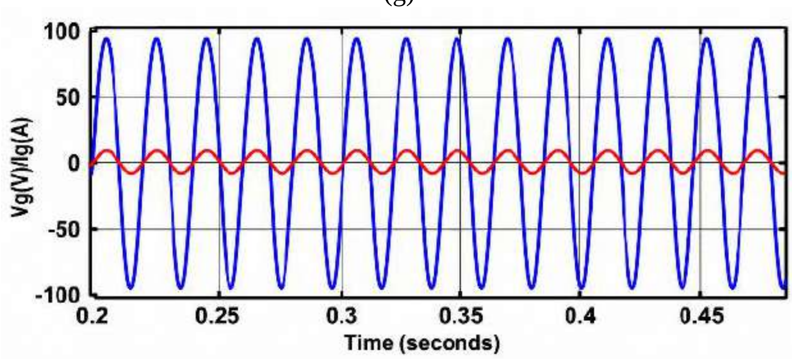
### *A. Performance Analysis Under Different Operating Modes*



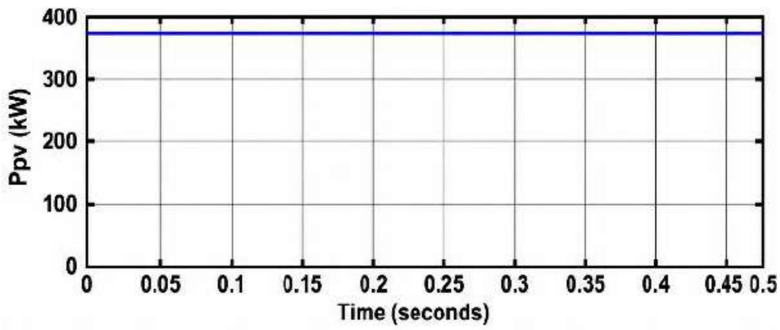

(f)




(g)

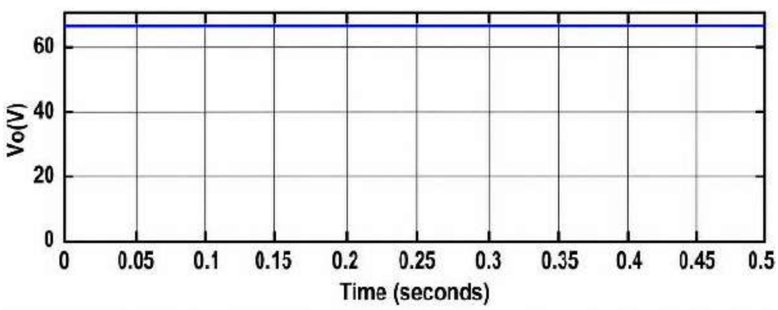



(h)

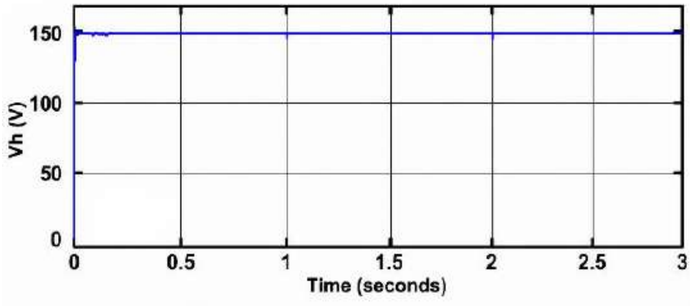



(i)

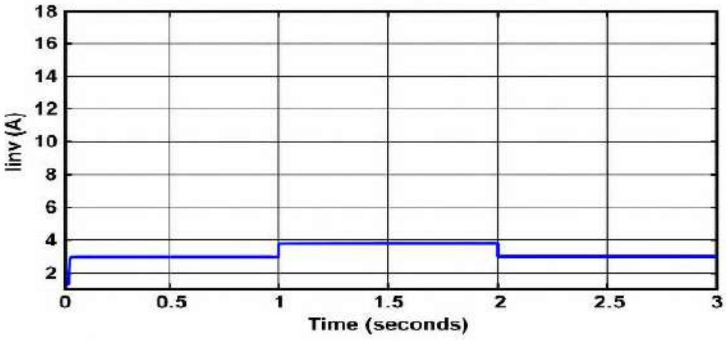
Figure 4: Simulation results of PIC mode. (f) PV voltage, (g) PV current, (h) Grid voltage and current, (i) PV power




(j)

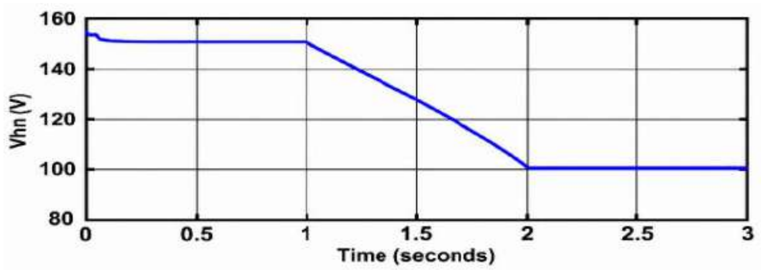



(k)

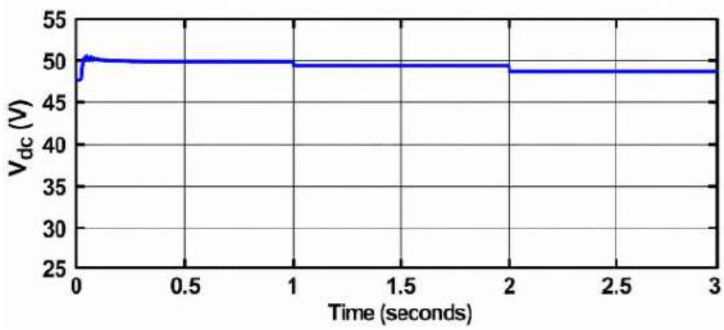



(l)

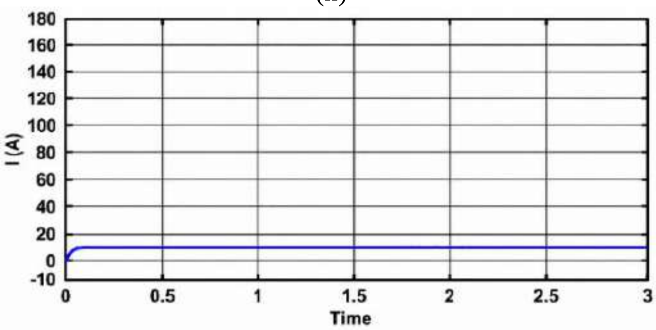
Figure 5: Simulation results of PIC and Solar PV operating modes. (j) Battery voltage (k) High-voltage DC-link voltage (l) High-voltage DC-link current




(m)




(n)




(o)

Figure 6: Simulation results of propulsion (PP) and regenerative braking (RB) modes (m) High-voltage DC-link voltage (n) Battery voltage(o) Battery current

The proposed multifunctional EV charging system is analyzed in various operating conditions to ensure the isolated High Gain converter maintains continuous energy flow regardless of the energy conditions. The operating modes investigated are plug-in charging (PIC), hybrid PV-grid, propulsion, and regenerative braking. The proposed NSMRL-assisted controller controls the operation of the converter to ensure stable voltage, balanced current and coordinated power flow between the available energy source in all the modes. In figure 4 smooth transitions between operating modes with minimal voltage and current oscillations are shown using simulation results.

The utility grid is used as the main charging source during PIC mode and the PV array is not in use. The grid voltage and current are still in phase, which means that the converter and the utility supply are working in harmony. The FFT analysis of the corresponding power quality gives a grid voltage THD of 0,79 %, which is excellent during battery charging. The voltage, current, and power stability of the PV system also reflect its converter initialization and readiness for integration with renewable energy sources.

Upon the availability of photovoltaic generation, the converter automatically switches to the hybrid PV-grid charging mode in which the charging power is distributed between the PV array and the utility grid. The suggested energy management solution will dynamically adjust the power sharing as per the availability of renewable energy and continuously provide uninterrupted charging to the batteries. In Figure 5 the voltage and current of the batteries is kept well-regulated with minimal variation while the high voltage DC-link maintains almost constant voltage. The charging current of the DC-link follows the charging demand smoothly without any noticeable oscillations, which shows a fast dynamic response of the proposed NSMRL controller, and good coordination among the renewable power sources and the grid power source.

In propulsion mode Figure 6, propulsion energy is fed to the traction system via the isolated High Gain converter from the battery. The simulation results show stable DC-link voltage in all situations of vehicle load and variable DC-link current depending on the demand for propulsion. The battery voltage is maintained at a constant level, and the battery current is regulated with low ripple, indicating the current regulation accuracy and less electrical stress. Therefore, under dynamic driving conditions, the power delivery to the traction inverter is guaranteed with continuous regulation of the DC-link voltage.

When braking, the kinetic energy recovered is sent back to the battery by the proposed converter. The DC-link voltage is well regulated between propulsion and regenerative operation, and the battery voltage stays almost constant. The battery current quickly stabilizes to the desired charging value, avoiding large transients, thus showing the efficient recovery of energy and the controlled bidirectional power flow. The proposed NSMRL controller consequently guarantees stable operation of the converter, low charging stress and battery protection during braking.

Generally, the proposed multifunctional EV charging system is found to be stable during all the operational modes investigated. The isolated High Gain converter has been proven to be able to provide continuous energy transfer with various operating conditions, by effectively regulating the PV power, the battery charging power, the DC-link voltage and the interaction with the grid. The results are consistent, confirming that the proposed NSMRL-assisted control strategy offers good energy management, bidirectional power flow, and fast charging performance for practical electric vehicle applications.

### B. Comparative Performance Analysis

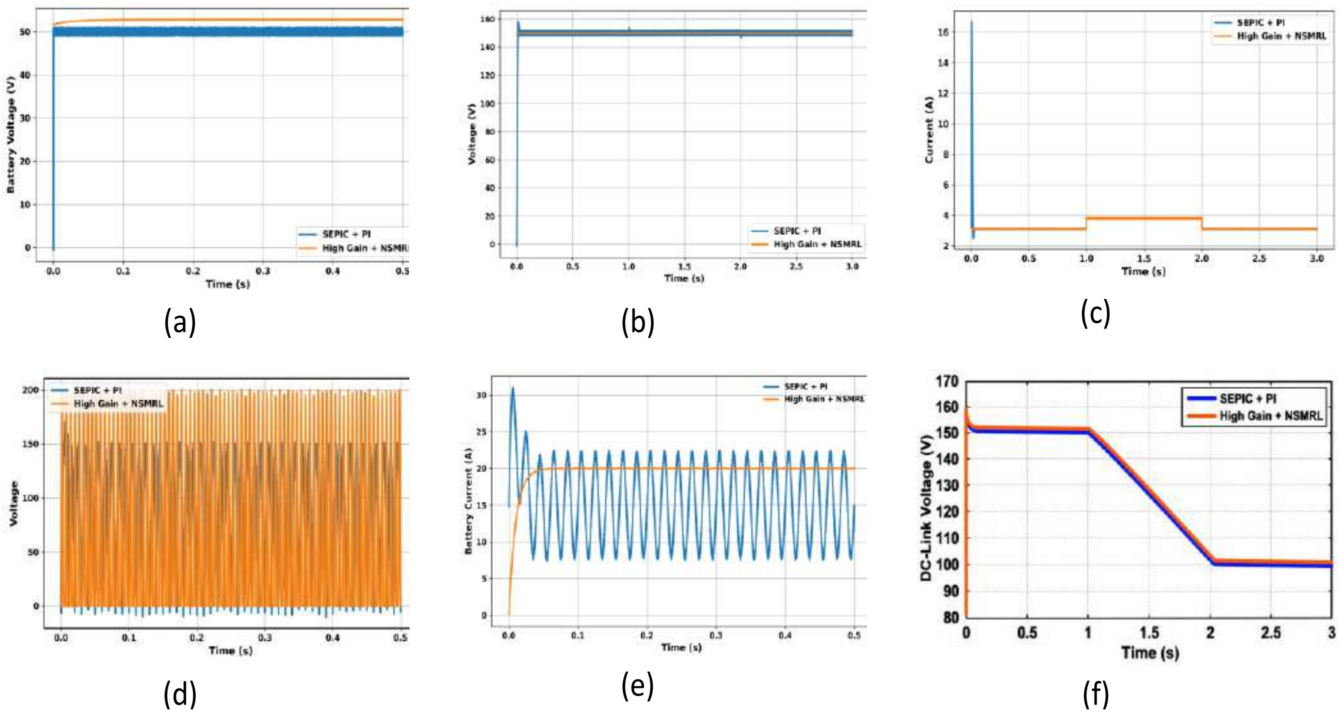



Figure 7: Comparative performance of the conventional SEPIC + PI controller and the proposed isolated High Gain converter with NSMRL controller

The performance of the proposed control method is evaluated by comparing the performance of the conventional SEPIC converter with the proposed isolated High Gain converter integrated with NSMRL controller under the same operating condition shown in Figure 7. The comparison is done in the area of battery charging, converter output, and DC link regulation. In the simulation, the proposed controller has been shown to give a faster dynamic response, voltage regulation, and better charging performance throughout the operating period.

From the battery voltage comparison, it can be seen that the proposed converter has better charging characteristics. The desired voltage reference is achieved by both controllers in a faster rate with very small steady state deviation in the proposed High Gain converter. The typical SEPIC converter, on the other hand, has slower voltage convergence because of the limited disturbance rejection capability of the PI controller. The non-linear reaching law, which keeps continuously compensating voltage error, ensures better charging accuracy and stable battery operation.

The proposed controller is further validated by the output voltage of voltage source converter. The proposed converter delivers a much smoother output waveform than the conventional converter with less switching fluctuations, which results in better grid synchronization, higher power transfer, and lower electrical stress in the converter switches when compared to the conventional converter.

The proposed NSMRL controller also provides better regulation of battery current. Compared with the conventional PI controller, the proposed controller is able to suppress the current ripple during charging quickly and the charging profile is smoother. Under transient operating conditions the effectiveness of the nonlinear reaching law is evident from the reduced current ripple which will reduce the heat in the batteries, improve charging efficiency and reduce switching losses in the converter.

Also, the proposed controller shows excellent DC-link voltage and current regulation. The operation transitions result in much lower transient voltage variations and current oscillations than in the conventional SEPIC converter. Fast voltage compensation via the NSMRL-based control law allows to keep the DC-link voltage constant, and adjust the current smoothly as the load demand changes. The stable DC-link characteristics provide better inverter performance, facilitate equal power splitting between PV array, battery, and grid, and boost the overall reliability of the converter.

In addition, the proposed controller offers a considerable enhancement in the harmonic performance of the grid connected charging system. The grid voltage THD of the conventional SEPIC converter with PI control is 2.54%, while that of the proposed isolated High Gain converter is 0.73% and 0.79% in steady state operation and plug-in charging (PIC) mode, respectively, which is 71.26% and 68.90% reduction in THD. The results show that the proposed NSMRL-assisted control strategy is able to obtain disturbance rejection capability superior to the traditional DTC, with improved power quality.

In conclusion, the comparative study substantiates the performance of the proposed isolated High Gain converter in combination with the NSMRL controller over the traditional SEPIC converter with PI controller. The results show the effectiveness of the proposed control strategy through improved battery voltage regulation, smooth charging current, enhanced stability of DC-link, lowered harmonic distortion, and quick transient response. The enhancements solidify the proposed converter as a resilient and efficient solution for multifunctional applications with integrated renewable energy charging for EVs.

### *C. Quantitative Performance Evaluation*

Table 3: Quantitative Performance Evaluation of the Proposed High Gain + NSMRL Controller

| **Performance Parameter** | **SEPIC + PI** | **High Gain + NSMRL** | **Improvement** |
|---|---|---|---|
| Battery Voltage (Final) (V) | 49.699 | 52.798 | +6.24% |
| Battery Voltage (Peak) (V) | 50.999 | 52.798 | +3.53% |
| Battery Current (Final) (A) | 14.850 | 20.026 | +34.86% |
| Battery Current (Peak) (A) | 31.072 | 20.027 | 35.55% lower peak |
| DC-Link Voltage (Peak) (V) | 157.936 | 150.000 | 5.02% overshoot reduction |
| DC-Link Voltage (Steady State) (V) | 149.470 | 150.000 | +0.35% |
| Inverter Output (Final) | 3.098 | 3.102 | +0.11% |

Table 3 Performance comparison between the conventional SEPIC + PI controller and the proposed isolated High Gain converter with NSMRL controller. The numerical performance indices are further confirming the benefits of the proposed controller. The proposed isolated High Gain converter with NSMRL has the advantages of high battery charging voltage, low peak battery current, good DC-link voltage regulation and low transient overshoot compared with the conventional SEPIC + PI topology. The improvements demonstrate increased dynamic response, increased energy conversion efficiency, and minimized electrical stress of the converter and battery components. The results of the proposed control strategy are presented and compared with the observations of the waveform, respectively with the quantitative performance indices, showing a good agreement and substantiating the robustness of the proposed control strategy and its applicability in practical applications for multifunctional EV charging.

Table 4: Harmonic Performance Comparison of the Proposed and Conventional Controllers

| THD Parameter | SEPIC + PI | High Gain + NSMRL | Improvement |
|---|---|---|---|
| Grid Voltage THD | 2.54% | 0.73% | 71.26% Reduction |
| Grid Voltage THD (PIC Mode) | 2.54% | 0.79% | 68.90% Reduction |

## V. CONCLUSION

The authors in this paper introduced a Novel Sliding Mode Reaching Law (NSMRL) assisted control scheme for solar PV and grid integrated electric vehicle charging systems. To realize a unified power conversion architecture that allows grid charging, PV charging, hybrid PV-grid charging, propulsion and regenerative braking without the need for multiple converter stages. The proposed NSMRL controller was able to successfully control the charging current and the DC-link voltage of the battery, and was well capable of handling the variability of renewable power sources and load variations. Detailed MATLAB/Simulink studies showed stable bi-directional power flow, smooth operating mode changeovers, and energy management as required in all operating modes. The proposed converter showed better performance compared to a conventional SEPIC converter with PI control shown in Table 4, in terms of grid voltage THD reduction, with 71.26% at steady state and 68.90% at plug-in charging mode. Furthermore, the proposed control strategy was verified to be effective by the improved DC-link voltage regulation, the smoothness of the battery charging characteristics, the decrease in current ripple, and the enhancement of the dynamic response. The outcomes of these measurements show that the proposed multifunctional charging architecture is a promising solution for efficient, reliable and renewable energy-integrated EV charging systems. Future research will address the real-time implementation in hardware and experimental validation to further assess the controller's performance in real operating conditions and explore its potential for high-power fast charging infrastructure and vehicle-to-grid (V2G) implementation in a smart-grid environment.

## REFERENCES


[1] J. de la Cruz, Y. Wu, J. E. Candelo-Becerra, J. C. Vásquez, and J. M. Guerrero, "Review of Networked Microgrid Protection: Architectures, Challenges, Solutions, and Future Trends," *CSEE Journal of Power and Energy Systems*, vol. 10, no. 2, pp. 448–467, Mar. 2024. Available from: https://doi.org/10.17775/CSEEJPES.2022.07980

[2] K. Singh, M. Badoni, and Y. N. Tatte, "A Multifunctional Solar PV and Grid Based On-Board Converter for Electric Vehicles," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 4, pp. 3717–3727, Apr. 2020. Available from: https://doi.org/10.1109/TVT.2020.2971971

[3] J. Guo, "A Novel Proportional-Derivative Sliding Mode for Load Frequency Control," *IEEE Access*, vol. 12, pp. 127417–127425, 2024. Available from: https://doi.org/10.1109/ACCESS.2024.3454794

[4] R. M. Sallinen, T. Roinila, and H. Abdollahi, "Stability Analysis and Adaptive Resonance Damping of Multi-Converter System Applying Bidirectional Converter," in *Proc. IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL)*, Nov. 2020. Available from: https://doi.org/10.1109/COMPEL49091.2020.9265778

[5] K. Li, J. Ding, X. Sun, and X. Tian, "Overview of Sliding Mode Control Technology for Permanent Magnet Synchronous Motor System," *IEEE Access*, vol. 12, pp. 71685–71704, 2024. Available from: https://doi.org/10.1109/ACCESS.2024.3402983

[6] M. M. Butt, A. Iqbal Kashif Butt, and I. Ahmad, "Integral Sliding Mode and Integral Supertwisting Sliding Mode Control for Ship Course-Keeping," *IEEE Access*, vol. 13, pp. 9006–9014, 2025. Available from: https://doi.org/10.1109/ACCESS.2025.3528126

[7] L. Guo, X. Chen, J. Chen, P. Luo, and L. Zhao, "CLLCLC Topology Based on Adaptive Excitation Inductance for the Improvement of Bidirectional DC-DC Converter Efficiency," *IEEE Access*, vol. 11, pp. 137594–137605, 2023. Available from: https://doi.org/10.1109/ACCESS.2023.3329965

[8] K. D. N. Cavalcante, M. B. El Kattel, P. P. Praca, S. O. Demercil, F. L. M. Antunes, and L. H. S. C. Barreto, "13 kW High-Efficiency Six-Arm High-Gain Transformerless Floating Interleaved Bidirectional Buck-Boost DC-DC Converter for EV Applications," *IEEE Access*, vol. 12, pp. 183901–183917, 2024. Available from: https://doi.org/10.1109/ACCESS.2024.3511493

[9] P. Ragasudha and S. Hemamalini, "Performance Analysis of a High Gain Bidirectional DC-DC Converter Fed Drive for an Electric Vehicle With Battery Charging Capability During Braking," *IEEE Access*, vol. 12, pp. 14499–14511, 2024. Available from: https://doi.org/10.1109/ACCESS.2024.3357726

[10] Z. Zhang *et al.*, "Multi-Objective Optimization of DC Microgrids Under Stability Constraints," *IEEE Open Journal of Power Electronics*, vol. 6, pp. 2040–2052, 2025. Available from: https://doi.org/10.1109/OJPEL.2025.3634835

[11] L. V. Strezoski, N. G. Simic, and K. A. Loparo, "A Robust Short-Circuit Calculation Method for Islanded, Grid-Connected, and Utility Microgrids," *Journal of Modern Power Systems and Clean Energy*, vol. 13, no. 1, pp. 325–337, 2025. Available from: https://doi.org/10.35833/MPCE.2023.001041

[12] S. Chen, G. Zhang, S. S. Yu, Y. Mei, and Y. Zhang, "A Review of Isolated Bidirectional DC-DC Converters for Data Centers," *Chinese Journal of Electrical Engineering*, vol. 9, no. 4, pp. 1–22, Dec. 2023. Available from: https://doi.org/10.23919/CJEE.2023.000034

[13] C. Liu *et al.*, "Microgrid Building Blocks: Concept and Feasibility," *IEEE Open Access Journal of Power and Energy*, vol. 10, pp. 463–476, 2023. Available from: https://doi.org/10.1109/OAJPE.2023.3282188

[14] P. Henrique Aquino Barra, R. Augusto Souza Fernandes, and D. V. Coury, "Adaptive Hybrid Tripping Microgrid Protection Strategy With Embedded Hardware Validation," *IEEE Access*, vol. 13, pp. 76271–76288, 2025. Available from: https://doi.org/10.1109/ACCESS.2025.3565226

[15] Barati, B. Ahmadi, and O. Keysan, "A Hierarchical Control of Supercapacitor and Microsources in Islanded DC Microgrids," *IEEE Access*, vol. 11, pp. 7056–7066, 2023. Available from: https://doi.org/10.1109/ACCESS.2023.3237684

[16] Saha *et al.*, "Optimal Sizing and Siting of PV and Battery Based Space Microgrids Near the Moon's Shackleton Crater," *IEEE Access*, vol. 11, pp. 8701–8717, 2023. Available from: https://doi.org/10.1109/ACCESS.2023.3239303

[17] H. Gaied, A. Flah, H. Kraiem, and L. Prokop, "A Comparison Between the Quality of Two-Level and Three-Level Bidirectional Buck-Boost Converter Using the Neural Network Controller," *IEEE Access*, vol. 12, pp. 94323–94336, 2024. Available from: https://doi.org/10.1109/ACCESS.2024.3403769

[18] S. Fattaheian-Dehkordi, M. Fotuhi-Firuzabad, M. Shahidehpour, and M. Lehtonen, "A Distributed Framework for Minimizing the Asymmetrical Power Request in Multi-Agent Microgrids With Unbalanced Integration of DERs," *IEEE Access*, vol. 12, pp. 116041–116054, 2024. Available from: https://doi.org/10.1109/ACCESS.2024.3446468

[19] Kefale Wassie, L. Negash Lemma, and A. Tadesse Kassie, "HGAPSO-Based Third Order-SMC, ST-SMC, and SMC Strategy for AAV Control: A Comparative Analysis," *IEEE Access*, vol. 13, pp. 52821–52840, 2025. Available from: https://doi.org/10.1109/ACCESS.2025.3553146

[20] B. Alhassan, M. A. Shehu, V. Gali, and T. D. Do, "Disturbance Observer-Based Super-Twisting SMC for Variable Speed Wind Energy Conversion System Under Parametric Uncertainties," *IEEE Access*, vol. 13, pp. 11003–11020, 2025. Available from: https://doi.org/10.1109/ACCESS.2025.3528772

## CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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