



RESEARCH ARTICLE

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PV-GRID HYBRID EV CHARGING STATION USING X-GAIN BOOST CLAMP CONVERTER AND OPTIMIZED RNN-MPPT

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ARTICLE INFO

Article History

Received: February 5, 2026

Reviewed: July 31, 2026

Accepted: August 31, 2026

Published: September 30, 2026

Keywords:

Electric vehicle,
Photovoltaic,
Alpine Skiing Optimized,
Recurrent Neural Networks,
Voltage Source Inverter.

ABSTRACT

Electric vehicle (EV) charging infrastructure that incorporates Photovoltaic (PV) electricity provides a feasible technique to lessen dependency on traditional grid power while maintaining clean energy use. In order to provide dependable power distribution under changing operating conditions, this work proposes a hybrid EV charging station architecture to ensure power distribution under varying operating conditions. The system employs X-Gain Boost Clamp Converter, to enhance voltage from PV subsystem which leads to high step-up ratio while reducing switching stress and conduction losses. An MPPT method based on Alpine Skiing Optimized (ASO) Recurrent Neural Networks (RNNs), which provide quick convergence, fewer oscillations, and more flexibility in response to temperature and irradiance changes, is used to optimize PV energy. The system is integrated with grid where, the energy generated by PV in excess amount is distributed to both the sources. The bidirectional converter results in effective charging and discharging of EV battery. Stable grid interaction and sinusoidal power injection are guaranteed by a three-phase Voltage Source Inverter (VSI) through an LC filter on the grid side. Coordinated PI controllers ensure system stability and efficiency by controlling battery current, DC link voltage, and active/reactive power exchange. According to MATLAB simulation, the proposed EV charging station is a good fit for next-generation smart EV charging infrastructures since it achieves high efficiency, enhanced voltage stability, and flexible bidirectional operation.



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I. INTRODUCTION

The rapid progress of EV have improved the request for sustainable and reliable charging infrastructure. Conventional techniques of power production for EV faces lack of energy and causes pollution in the atmosphere by emission of greenhouse gas. To avoid such limitation EVs has the potential to revolutionize transportation sector which is powered by renewable energy sources (RESs) that minimize green gas emission [1]. The incorporation of RES into power system, which expressively developed in latest ages due to growth in environment, and challenges in power system stability [2], [3]. PV has become widely used RES for major power production, PV based system incorporated into EV charging stations offer renewable and eco-friendly for energy resource. The effectiveness of parameter estimation in PV modelling preferred for its simplicity, computational efficiency, although it has no recombination losses in solar cell [4]. PV-grid-EV transactions, to accommodate large scale integration of EV battery charging, which is cost-efficient and proves the effectiveness of optimal EV price in regulating EV charging flow. However it faces limitations including insufficient power gain, increased voltage stress, leakage inductance, and greater number of components [5], [6]. To address various issues such as voltage regulation, power factor correction, and to enhance low PV voltage, DC-DC converters are essential. In [7], [8] DC-DC LLC resonant converter for EV fast charging with limited battery voltage.

The converter operates with minimum losses, simple design, and compatibility, however it causes additional conduction losses, and has low power density, high components. Non-isolated high gain converter enhances voltage gain which precisely respond to dynamic variation in voltage and current, low voltage stress, and reduced conduction losses. However suffers with higher voltage spikes across switches, current ripples and also design complexities [9], [10]. Multi-load and source converter for high efficiency EV applications. It enhances the overall efficiency and reliability, cost-effective and helps to minimize losses. However fluctuations leads to cross-regulation, less robustness and power loss. Buck-boost DC-DC converters for active disturbance in distribution grid enhances the robustness, less cost, and high peak current limitations. Although it has high current limitation but has poor control performance [11], [12]. An interleaved boost converter used for high current applications, the topology has designed for high voltage gain. Although it has not attained high efficiency or voltage gain but offers resolution for increase in output voltage and significantly affect power density. Quadratic boost converter applicable for solving voltage stress challenge, having high voltage gain. Nevertheless, the enhancement is still reflected and suffer from discontinuous current, increasing control complexity [13], [14]. Normally a PV cell is non-linear, and so the power obtained from PV is varied due to ecological circumstances. Moreover an appropriate MPPT algorithm is required to increase the scheme's efficiency and ensuring PV to obtain maximum power and also decreases the need on grid. Incorporating MPPT algorithm into PV system ensures energy flow for optimal and stable energy, it usually fixed within a module that extracts maximum energy from PV array. It enables fast and accurate MPP with reduced steady-state power oscillation with improved Convergence speed. To boost the presentation of PV under compound partial shading MPPT algorithm is provided for faster dynamics with reduced power oscillations. However the major issue of MPPT technique has poor convergence speed and complex computational performance [15], [16]. Particularly conventional Genetic algorithm (GA) based MPPT controller used for attaining maximum power by tuning the controller parameters. It has the most excellent performance and fast convergence with better tracking efficiency, although it has load fluctuations and still weak under varying conditions [17]. Further to enhance the controller performance optimization is essential therefore P&O MPPT Optimization to discourse the hesitations of PV attaining quicker and steady output. It improves switching frequency with high robustness, and grid compatibility. However it requires advanced execution and greater computational difficulty [18]. Henceforth to enhance the system's performance this proposed research introduces ASO MPPT-based RNN controller with X-gain boost clamp converter for EV charging. Recent related works explains few conventional techniques for EV charging system.

II. RELATED WORKS

By [19] have proposed Dual active bridge DC-DC converter for EV charging system. It offers single stage power conversion with wide voltage variation, with better transient performance and has high switching frequency. Eventhough it has wide voltage variation but leads to increase in circulating current and losses which reduce the converter efficiency under light loaded-conditions. In turn [20] have implemented three phase interleaved buck converter for fast charging of an EV battery which has fast dynamic response and robustness with improved flexibility. However the charging process takes several time to charge the battery and requires numerous component count, high cost and less efficiency. According to [21] have offered optimized CNN-MPPT controller for ensuring PV system by three phase grid. It ensures efficient power extraction from the system with reduced steady-state oscillation, faster convergence, and greater tracking accuracy. Nevertheless it exhibits increased computational cost, high THD, and instabilities. By [22] have introduced ANN-MPPT controller for optimal performance under partial shading condition which slightly achieves high power. It offers higher energy fields, enhanced efficiency, and greater adaptability. Though its performances expressively deteriorates under partial shading, and tendency to get trapped in local minima. In turn [23] have presented Particle swarm optimized MPPT controller for real time approach of PV irradiance which is often cost-intensive. It ensures the performance and has the capability of fast decision making. However it lacks adaptability, accuracy under varying irradiance and has low convergence speed. According to [24] have developed Chimp optimization based controller to enhanced micro-grid performance. It optimize the operational efficiency, size of components, achieves energy cost, however the limitations included in this study are system untrustworthiness, slow convergence, and unstable power density. By [25] have described single phase inverters with three phase four-wire system, for grid application. It improves the system stability, robustness, reduced losses, and increased system flexibility. However it leads to load imbalance, overheating, installation requires more complex.

Motivation from conventional works

Solar power production depends integrally on weather condition, conventional system lacks as panels are exposed to elements which leads to damages including delamination and glass breach. Conventional techniques got stuck in local MPP in searching global MPP that causes high energy losses and also faces slow tracking effect. Furthermore for EV charging the methods faces limitations including lack of charging, voltage fluctuations, and cost complexities. MPPT including P&O, faces significant issues as less adaptable for changing conditions, reduced accuracy. DC-DC converters like buck, and full bridge converters in traditional methods faces difficulties such as, limited efficiency, enlarged component size and weight and occurrence of power losses [26]. In order to succeed all the weaknesses which are faced in conventional schemes, the proposed work introduces an X-Gain Boost Clamp DC-DC converter with Alpine skiing optimized MPPT-RNN controller under PV-grid for EV battery charging applications and also for three phase grid supply. The proposed work contributes are as follows:

Contribution of proposed work

- ◆ The framework integrates an X-gain Boost clamp converter for boosting low voltage from PV system, and supply it to DC bus effectively.
- ◆ ASO-RNN MPPT controller is used to track maximum power from PV under varying conditions and also regulates the converter output.
- ◆ A bidirectional DC-DC converter enables the EV battery to charge and discharge to DC-bus or grid while it is necessary.
- ◆ The system is integrated with three phase VSI or grid using an LC filter that removes unwanted harmonics.
- ◆ Various PI controllers are used for its particular functions as voltage regulation, battery control, and power flow control.

The paper prearranged as: Section-I. Introduction, Section II defines the recent works of related, Section III elaborates the explanation of proposed system and Section IV demonstrates the modelling of proposed method and Section V displays the Result and discussion and Section VI designates the conclusion this work.

III. PROPOSED SYSTEM DESCRIPTION

The proposed system uses PV as an input source and the block diagram illustrated in Figure 1 shows the sophisticated hybrid energy management system for EV. PV utilizes low output due to changing environmental conditions, it is succeeded by an X-gain boost clamp circuit which enhances the PV voltage and ensures or regulates the voltage.

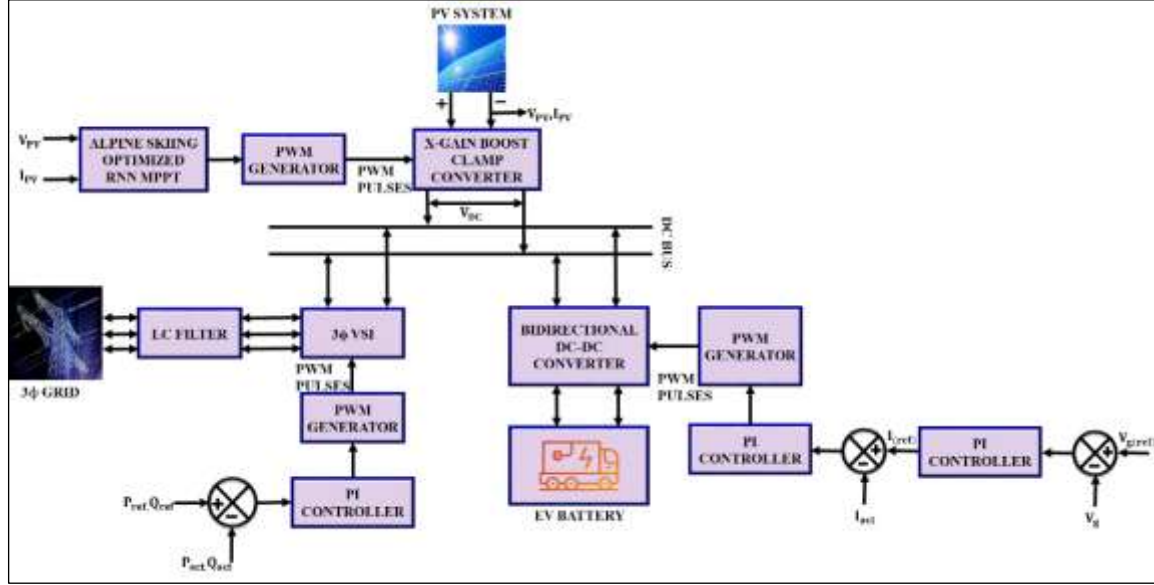


Figure 1: Proposed block diagram.

Source: Authors, (2026).

Figure 1. Shows the proposed block diagram. An ASO-RNN- MPPT algorithm is used to maximize the power from PV and fed into DC-bus. The DC-bus integration act as a main distributor for all DC power in the entire system. Moreover a three phase VSI converts DC power into AC power for three phase grid through an LC filter which is used to remove harmonics, ensures power into the grid. The entire system depends on several PI controllers producing PWM signals through PWM generators using reference voltage and current values. Consequently a bidirectional DC-DC converter is used for both G2V and V2G applications as charging and discharging the battery. A PI controller regulates the power flow to optimize the performance allowing EV to charge from PV or grid.

IV. PROPOSED SYSTEM MODELLING

IV.1 PV CELL MODELLING

PV structure is an electrical power system which generates electricity from sunlight. It consist of numerous components including solar panels, which absorbs sunlight and converts into electricity. The circuit of PV is exposed in figure 2.

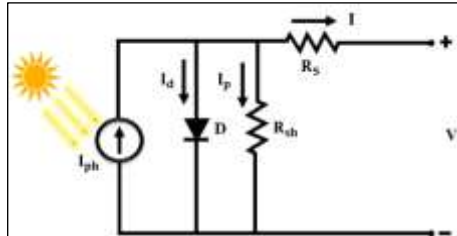


Figure 2: PV circuit.

Source: Authors, (2026).

The mathematical expression for PV is expressed as,

$$I = I_{ph} - I_s \left(\exp \left(\frac{V + IR_s}{a N_s V_t} \right) - 1 \right) - \frac{V + IR_s}{R_p} \quad (1)$$

$$V_t = \frac{k T_c}{q} \quad (2)$$

$$I_{ph} = \frac{G}{G_n} (I_{scn} + K_1 (T_c - T_{cn})) \quad (3)$$

$$I_s = I_{sn} \left(\frac{T_c}{T_{cn}} \right)^3 \exp \left(\frac{q E_g}{a k} \left(\frac{1}{T_{cn}} - \frac{1}{T_c} \right) \right) \quad (4)$$

$$I_{sn} = I_{scn} / \left(\exp \left(\frac{V_{ocn}}{a N_s V_{tn}} \right) - 1 \right) \quad (5)$$

From power equation,

$$P = VI \quad (6)$$

$$\frac{dP}{dV} = 1 + \frac{VdI}{dV} \quad (7)$$

$$\frac{I}{V} = -dI/dV \quad (8)$$

Nomenclature: I_{ph} is the photocurrent, where I_s denotes saturation current, parallel resistance is indicated by R_p , R_s signifies series resistance I_{scn} displays short circuit current and open circuit voltage is denoted by V_{ocn} . Therefore the variation occurs in attaining maximum power continuously due to changes in environmental conditions and hence converter is necessary to step up voltage from PV.

IV.2 X-GAIN BOOST CLAMP DC-D-C CONVERTER

The DC-DC converter considered to attain extremely greater voltage, with the combination of boost ad clamp which is nothing but the addition of coupling inductor or switched capacitor in parallel. Figure 3 illustrates the circuit of proposed converter.

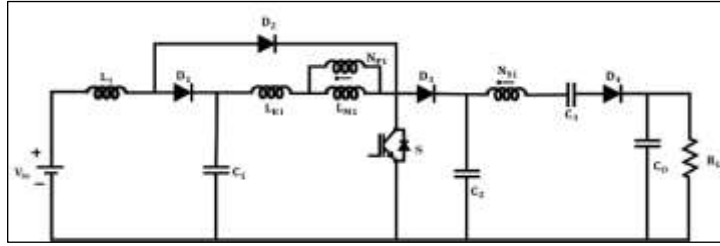


Figure 3: Circuit of proposed converter.
Source: Authors, (2026).

It consist of an inductor as L_1 , capacitors as C_1 , C_2 and C_3 output capacitor as C_o with leakage and magnetizing inductance as L_{k1} and L_{M1} . This topology ensures low ripple with continuous input current and it has a primary and secondary winding as N_{p1} and N_{s1} . It operates under three modes as: Figure 4 shows the circuit for mode1.

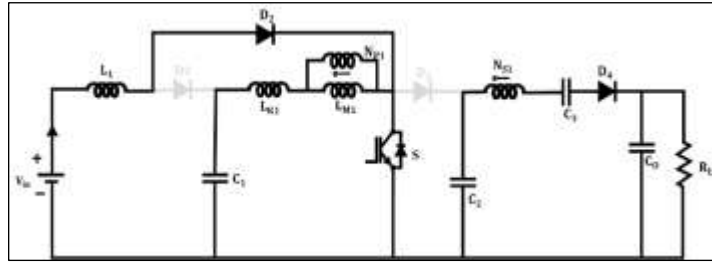


Figure 4: Mode 1.
Source: Authors, (2026).

Mode 1: When switch s is turned ON, inductor L_1 gets supply from input source V_{in} . The current flows around the closed loop through diode D_2 , primary winding N_{p1} . The diodes D_1, D_3 , becomes inactive, capacitor C_1 is charged by magnetizing inductance L_{M1} and C_o supplies output to the load R_L and return back to the source thus storing energy using L_1 . The power components are assumed as ideal and the number of turns is calculated by,

$$n = \frac{N_{s1}}{N_{p1}} \quad (9)$$

The capacitor C_1 voltage is given as,

$$V_{in} = V_{L1} + V_{C1} \quad (10)$$

$$V_{C1} = V_{L_{M1}} + V_{C2} \quad (11)$$

Mode 2: When switch S is OFF, diodes D_2 and D_4 becomes inactive while diodes D_1 and D_3 are in conducting state. The current choose an alternative path to reach the capacitor C_o for supplying power to the load and energy stored in the inductor L_1 in mode1 is discharged. The circuit for mode 2 is shown figure 5.

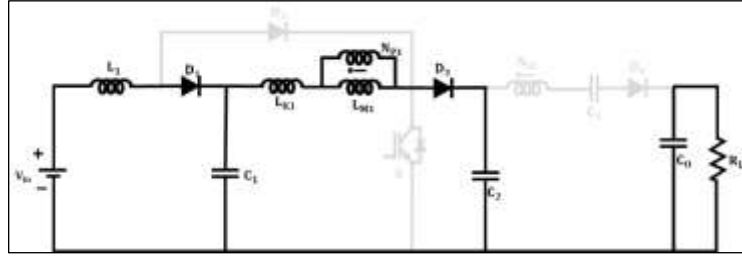


Figure 5: Mode 2.

Source: Authors, (2026).

Mode 3: During this mode the switch is in OFF condition, where the conduction takes place through V_{in} and the current flows through diode D_1, D_3, D_4 while D_2 becomes inactive. The load R_L gets supply by the output capacitor C_o . The circuit is shown in figure 6.

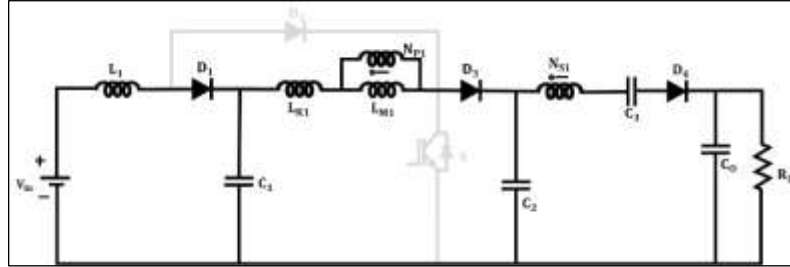


Figure 6: Mode 3.

Source: Authors, (2026).

The steady state analysis of this converter is written as, From equation (11)

$$V_{C_1} = V_{L_{M1}}$$

$$V_{L_{M1}} = V_{C_1} - V_{C_2} - V_{L_{k1}} \quad (12)$$

$$V_{L_{M1}} = \frac{1}{n} (V_{C_2} - V_{C_3} - V_o) \quad (13)$$

The voltage across the magnetizing inductor is

$$V_{L_{M1}} = \frac{1}{n} (V_{C_2} + V_{C_1} - V_{C_3} - V_{C_2})n$$

$$V_{L_{M1}} = V_{C_1} - V_{C_2} \quad (14)$$

Voltage across capacitor V_{C_1}

$$V_{C_1} = \frac{1}{1-D} \quad (15)$$

Similarly for the remaining capacitors follows the same derivative form and the voltage gain is calculated by,

$$V_{gain} = \frac{V_o}{V_i} = \frac{n}{1-D} V_i \quad (16)$$

Therefore the converter attains a better voltage and further the converter output is regulated by controllers.

IV.3 ASO OPTIMIZED RNN-MPPT CONTROLLER

RNN MPPT Controller: The RNN is the deep learning model designed to process data in sequential or series manner. RNN is basically built on NN structure, with additional memory effects. It consist of input, and output layers, with two hidden layers. The RNN structure is illustrated in figure 7.

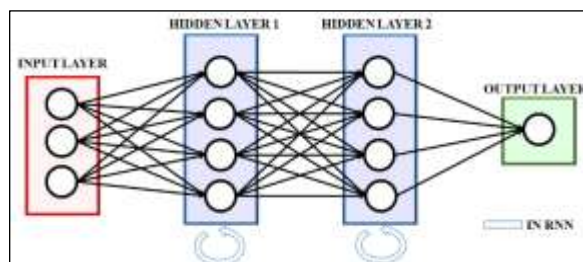


Figure 7: RNN Architecture.

Source: Authors, (2026).

In each layer the information each parameter is well-trained and act an input of the algorithm, and to improve the performance. The parameters of this neural network is not optimized by current values as it is selected based on the hidden layers. It has some sort of short-term memory providing capabilities and also it transfer information within themselves. For achieving better MPP in PV the RNN network used to detect global MPP when there is penetrating climatic conditions and performs optimally. The output of NN model in MPPT is mathematically derived as,

$$I = NET(u) = W_2 \tanh(W_1 u + b_1) + b_2 \quad (17)$$

Moreover it is important to cover all temperature and irradiance values, from the measured data which attain greater accuracy. Thus for tuning the controller parameters ASO optimization is used.

ASO: It is a bio-inspired algorithm, used for resolving complex optimization issues, by optimizing parameters of RNN-MPPT controller. It follows the behaviour of skiers, as stamina and sprint which is randomly called exploration and exploitation for the search of optimal solution. Normally skiing is one of the an interesting and serious sports, skiers participate for attaining championship, thus the skier manners are similar to the exploration and exploitation based on the algorithm. In ASO, the total numbers are allocated to participate at a time, and it consist of three stages: initialization, iteration and last sprint where skier uses levy flight to modify the position. The algorithm describes answer space in this phase, and first population to compute the fitness amounts. Flowchart of ASO is given in figure 8.

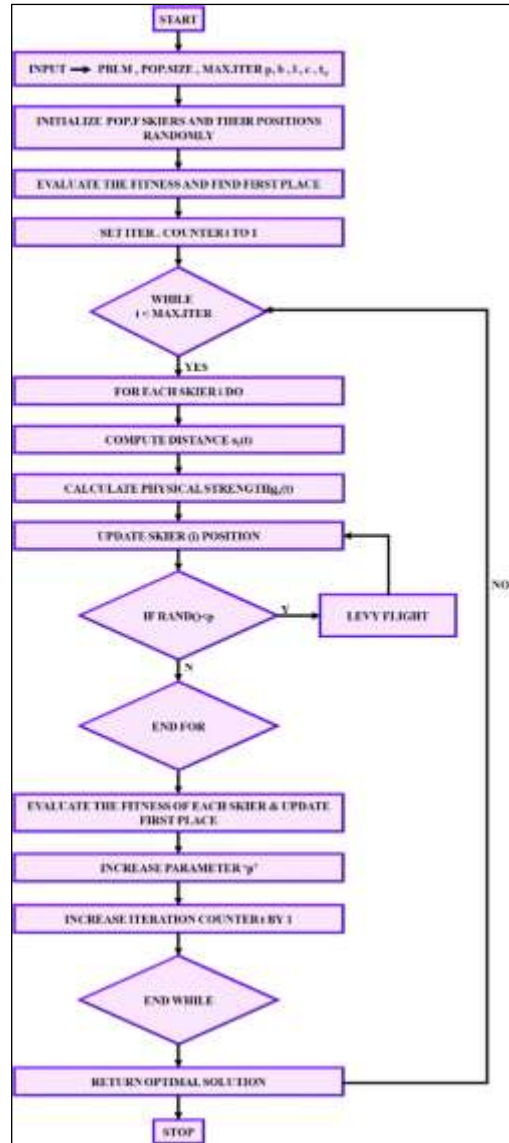


Figure 8: Flowchart of ASO.
Source: Authors, (2026).

The first individual stage is denoted by,

$$s_i(t) = \|z_i(t) - z_b(t)\| \quad (18)$$

The skier's physical strength in next iteration, is given by,

$$g_i(t) = \left(\frac{L}{1 + \exp(-b(z_i(t) - z_o))} \right) \quad (19)$$

Phase vector calculation and skier condition in moving phase,

$$\Delta Z(t) = r \cdot S(t) \cdot G(t) \quad (20)$$

$$Z(t + 1) = Z(t) + \Delta Z(t) \quad (21)$$

The levy flight for skier's is expressed as,

$$Levy(z) = 0.01 \times \left(\frac{r_1 \times \delta}{|r_2|^{1/\gamma}} \right) \quad (22)$$

Where,

$z_i(t)$ represents skier situation, $z_b(t)$ is the iteration situation in first place, z_o indicates sigmoid z value, r denotes stochastic number. Once the skier drops down, the other individual renewed to strive the first iteration. The iteration stops once it reaches the convergence level or maximum number which show the better enhancement. As a consequence, duty cycle has been generated and this results in effective regulation of converter.

IV.4 BIDIRECTIONAL DC-DC CONVERTER

Bidirectional DC-DC converter for battery charging manages power flow in both directions which is charged through source and discharge power to load. The converter conducts the power flow among low-voltage battery and DC bus. The circuit diagram is shown in figure 9.

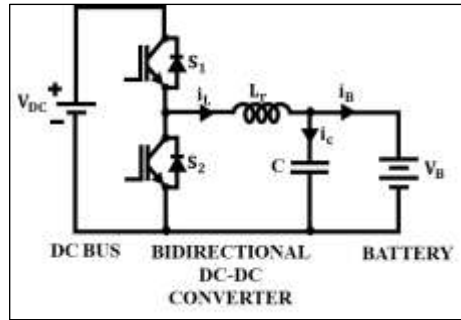


Figure 9: Bidirectional DC-DC converter.
Source: Authors, (2026).

It consist of switches s_1 and s_2 and a single inductor and a capacitor. In order to control the battery power, converter operated in buck mode and also voltage regulate during charging state. For V2X operation mode the converter operates under boost mode. The bidirectional converter operating system modelling functions under two modes as buck and boost modes.

(i) Buck mode: when the switch s_1 is ON, the energy flows from DC bus to the battery, during this time, the operating condition the entire system operates in G2V mode and the switch s_1 is controlled by PWM signal (μ_1 and μ_2) still the switch s_2 remains open. The circuit for buck mode is shown in figure 10.

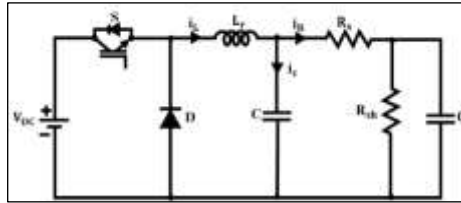


Figure 10: Mode1.
Source: Authors, (2026).

The following equations which is derived from buck mode analysis and it is represented by switching model,

$$L \frac{di_L}{dt} = -r i_L - v_B + \mu_1 V_{DC} \quad (23)$$

$$C \frac{dv_B}{dt} = i_L - \frac{1}{R_B} v_B + \frac{1}{R_S} v_C \quad (24)$$

$$C_B \frac{dv_C}{dt} = \frac{1}{R_S} V_B - \left(\frac{1}{R_S} + \frac{1}{R_{Sh}} \right) v_C \quad (25)$$

Where,

s_1 s_2 - switches, parallel resistance is given by R_{Sh} , R_S is the series resistance and μ_1 and μ_2 are control signals. Where, $\alpha = (X u_1 + (1 - X)(1 - \mu_2))$ X - operating mode and C_B battery capacitance

(ii) Boost mode: During boost mode the switch s_1 is OFF, while the energy flows back from battery to DC bus. The entire system operates under V2G mode and the equivalent circuit is illustrated in figure.11.

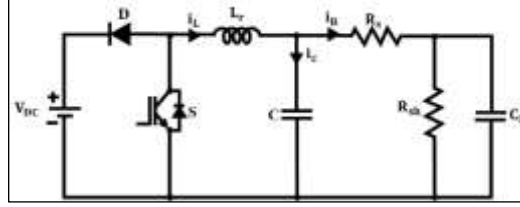


Figure 11: Mode2.
Source: Authors, (2026).

$$L \frac{di_L}{dt} = -r i_L - v_B + \mu_2 V_{DC} \quad (26)$$

$$C \frac{dv_B}{dt} = i_L - \frac{1}{R_B} v_B + \frac{1}{R_S} v_C \quad (27)$$

$$C_B \frac{dv_C}{dt} = \frac{1}{R_S} v_B - \left(\frac{1}{R_S} + \frac{1}{R_{Sh}} \right) v_C \quad (28)$$

From the above equations the switching model for boost mode is derived and similarly the bidirectional mode is operated on the basis of tow modes and mathematically expressed as,

$$L \frac{di_L}{dt} = -r i_L - v_B + \alpha V_{DC} \quad (29)$$

Thus the bidirectional converter model provides a mathematical derivation for switching model and therefore for regulating converter voltage controller is essential.

IV.5 PI CONTROLLER

PI controller regulates the output voltage from the converter by adjusting the duty cycle of switching components and also by regulating power flowing between battery and a DC bus. The block diagram for PI controller is given in figure 12.

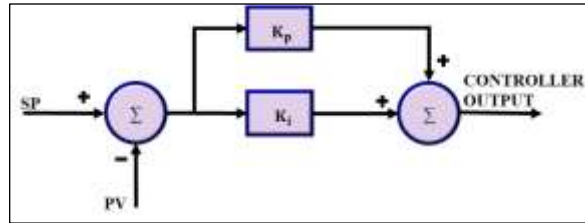


Figure 12: Block diagram of PI controller.
Source: Authors, (2026).

The PI controller functions by comparing measuring the output values and desired set point to produce error signals and minimizing it. The illustrations of error which are corrected by K_p and K_i constants. The required amount added to the controller output rises or fall depending on the error signal. The output of controller is equated by,

$$Ctrl Output = K_p e + K_i \int e(\tau) d\tau \quad (30)$$

By properly tuning with low PI constants the host vehicle track is achieved based on sensor voltage and specifications.

IV.6 THREE PHASE VSI GRID SYNCHRONIZATION

The three phase VSI control approaches are voltage and current control, in voltage control mechanism the power control which is recognized by the output of inverter and grid voltage phase angle difference which is sensitive to grid voltage fluctuations producing substantial harmonics. Similarly in current control method, power components are controlled by PWM methodology, and for power controlling scheme PI controller is used for comparing the output to minimize its instability. The proportional and integral constants are K_p , and K_i where it is multiplied with error for proportional operation and integrated for integral operation. The reference signal is generated and steady state error is minimized during this operation. The dq reference frame is utilized using PI for attaining effective grid synchronization. The output voltage is determined by the mathematical derivation which is given n

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = L \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + R \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega L \begin{bmatrix} -i_q \\ i_d \end{bmatrix} + \begin{bmatrix} e_d \\ e_q \end{bmatrix} \quad (31)$$

Where,

Synchronous reference is represented by d_q , $\alpha\beta$ signifies stationary reference frame, R indicates the Resistance, where L is Inductance, ω presents angular frequency and e_d and e_q is Grid voltage park transformation and the Inverter output voltage park transformation u_q and u_d . Employing two PI controllers which one compares I_d and I_d^* and another one compares I_q and I_q^* minimizing errors to zero. In microgrid system, the generation of stabilized power supply leading to better outcomes with greater dynamic response, efficiency and stability.

V. RESULT AND DISCUSSION

The experimental validation of proposed system using MATLAB is detailed in this section with the parameters listed in Table. The validation is done using the proposed converter and controller strategy under varying condition to determine its effectiveness.

Table 1: Parameter specification.

Parameter	Rating
PV System	
Rated Power	10kW
Open Circuit Voltage	37.25V
Short Circuit Current	8.95A
No. of panels connected in series	11
No. of panels connected in parallel	2
Switching frequency	10kHz
Proposed converter	
Switching frequency	10kHz
Inductor L_1	4.7mH
Capacitor C_1, C_2, C_3	22 μ F
Capacitor C_O	2200 μ F

Source: Authors, (2026).

Case 1. Constant condition

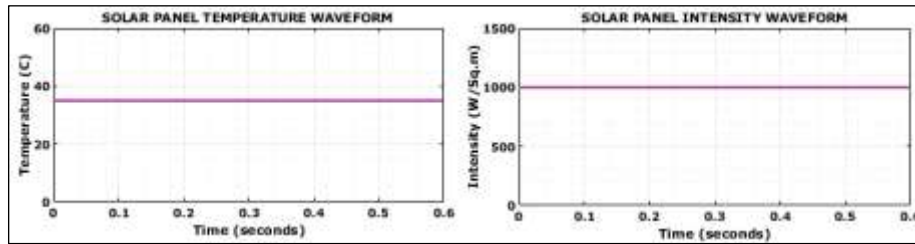


Figure 13: Characteristics of PV temperature and intensity.

Source: Authors, (2026).

Figure 13 presents the waveform of solar intensity and temperature. The waveform represents how PV performs under stable environmental condition. The temperature waveform shows approximately 35°C which remains constant with 0.6s of its time period. Similarly the intensity is 1000 W/sq.m respectively.

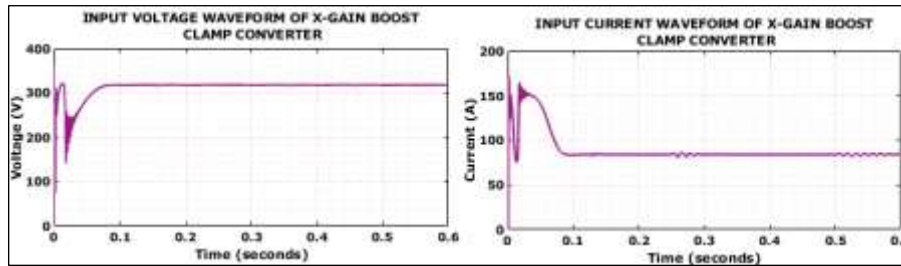


Figure 14: Proposed Converter input waveform (case1).

Source: Authors, (2026).

The proposed X-gain boost clamp DC-DC converter input and voltage waveform is represented in figure 14. The input voltage waveform shows that the voltage stabilizes approximately 320V with a quick settling time of 0.1s. Additionally the input current waveform displays the achieved current of 80A with minute ripples at a rise time of 0.02s and both the waveforms shows a steady operating wave with 0.6s of its time period under constant condition.

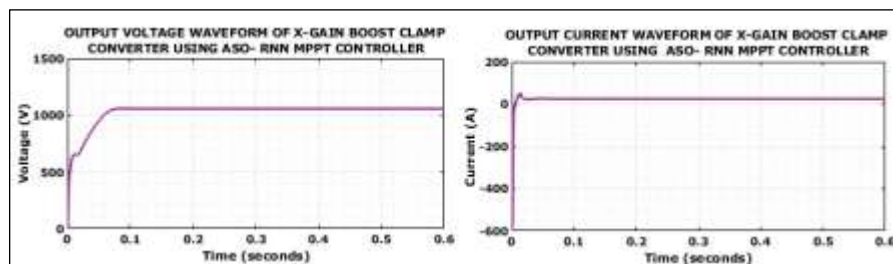


Figure 15: Output waveform of proposed converter (case 1).

Source: Authors, (2026).

Figure 15. displays the output waveform of proposed converter using ASO MPPT-RNN controller. The output voltage waveform shows the obtained high voltage with less fluctuations of 1050V at 0.1s and the converter output current showing 25A with some initial ripples of time period 0.6s correspondingly. Thus the converter provides an extreme high voltage gain with less settling time.

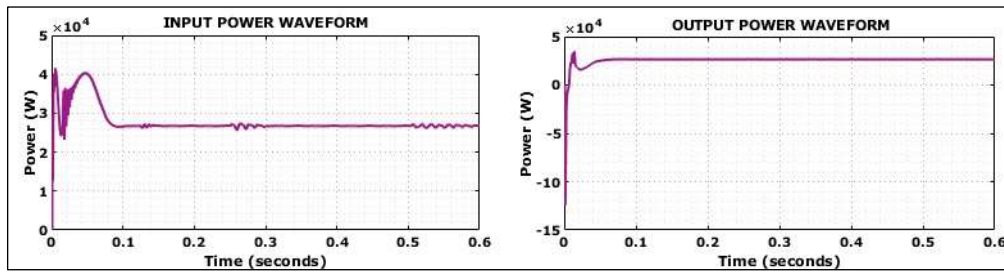


Figure 16: Power waveform (case 1).

Source: Authors, (2026).

Figure 16. Illustrates the power waveform of proposed converter. The input power waveform represents the obtained input power of converter settles to a stable value approximately $2 \times 10^4 W$ with initial transient spikes in power at 0.6s of time period. Moreover the power output waveform shows $3 \times 10^4 W$ of output at a quick settling time of 0.1s which exhibits high frequency oscillations.

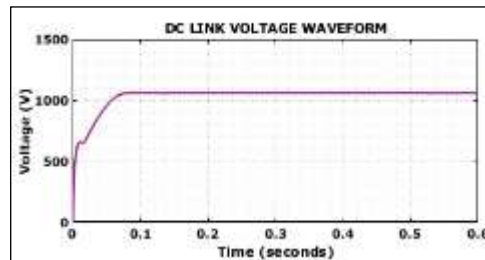


Figure 17: DC-link voltage waveform (case 1).

Source: Authors, (2026).

Figure 17 illustrates DC-link voltage waveform. The voltage in DC-link waveform showing 1050V with a quick settling time of 0.1s over a time period of 0.6s. This voltage is used to store energy temporarily usually in capacitors and it is significant which remains charged for mean time even after power is removed.

Case 2: Varying condition

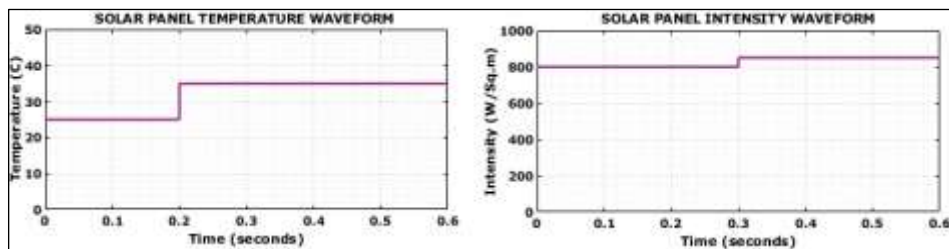


Figure 18: PV waveform (case 2).

Source: Authors, (2026).

Figure 18 displays the PV temperature and intensity waveform. At varying condition the temperature in the PV panel remains 25°C upto 0.2s of time period. After the particular time period the temperature suddenly rises to 35°C. The solar intensity waveform shows the intensity variations from 800 to 850W/ sq.m at 0.3s of time period respectively.

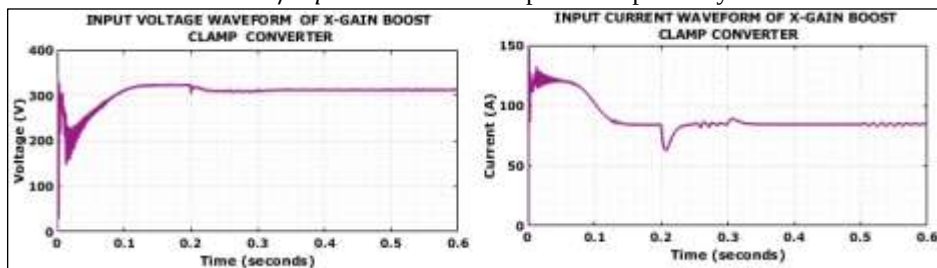


Figure 19: Input waveform of Proposed Converter (case 2).

Source: Authors, (2026).

The input voltage and current waveform of proposed X-gain Boost Clamp converter is presented in figure 19. The input voltage waveform shows voltage of 320V during 0.2s with initial voltage sags with a settling time as 0.3s. Furthermore the converter input current waveform shows ripples at 0.2s and provides steady state current of 80A respectively during 0.3s of time period.

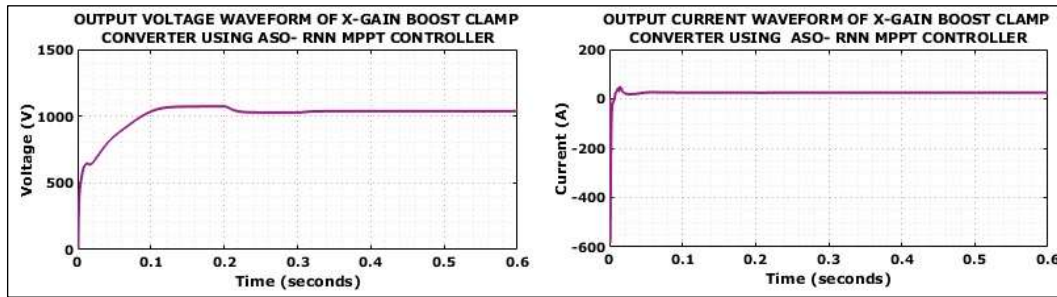


Figure 20: Output characteristics of Proposed Converter (case 2).
Source: Authors, (2026).

Figure 20 displays the output waveform of proposed converter using ASO optimized RNN MPPT controller. The output voltage of converter is 1050V approximately at 0.3s of settling time for initial fluctuations and similarly the converter output current waveform showing 25A of current with less ripples and a quick settling time of 0.1s. Thus the voltage and current of converter is remains similar under varying conditions.

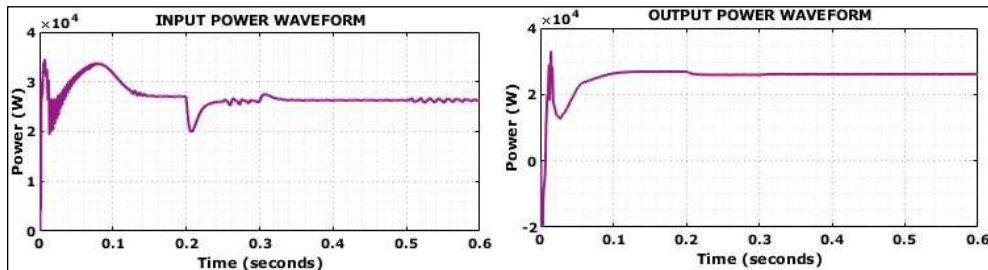


Figure 21: Power waveform (case 2).
Source: Authors, (2026).

The power waveform is illustrated in figure 21. The input power waveform shows initial fluctuations and reach a peak value over 0.3s of time period followed by overshoot and few oscillations. Additionally the output waveform indicates the initial ripples and settles down at 0.2s of time, where it is being used to regulate the power flow and the stable value establishes the effectiveness of control system.

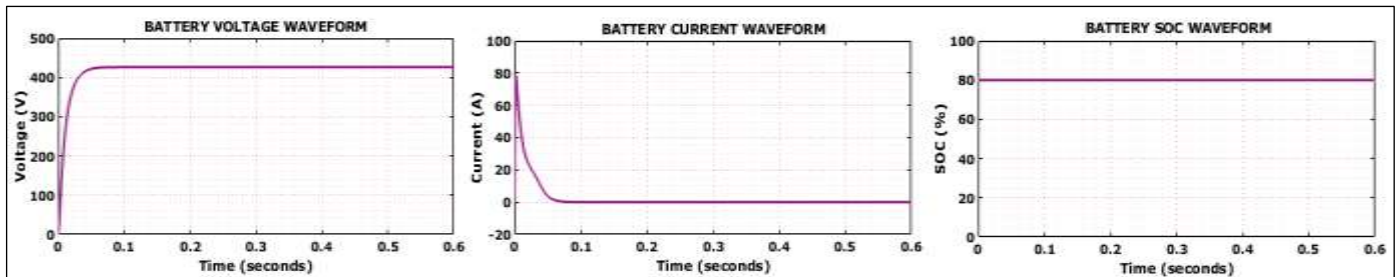


Figure 22: Battery voltage, current and SOC waveform.
Source: Authors, (2026).

Figure 22 represents the battery SOC, voltage and current waveform. The battery voltage waveform 420V with rise time 0.03s and settling time of 0.1s. Similarly the current in battery is a negative gain while it rises up to 80A and suddenly drops to null state and thus indicating the battery is fully charged. Subsequently the SOC of battery is 80% which remains constants for overall time period.

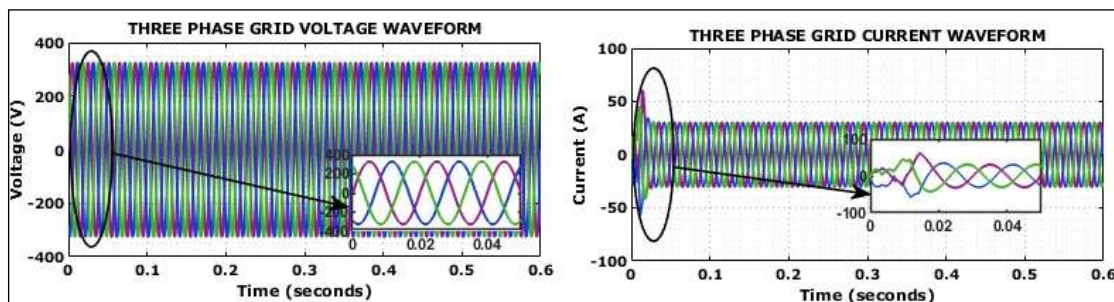


Figure 23: Three phase grid voltage and current waveform.
Source: Authors, (2026).

Figure 23 demonstrates three phase grid voltage and current waveform. The grid voltage waveform describes the voltage oscillates between 300 to -300V as the waves are sinusoidal and balanced. The current waveform, fluctuates around 50 to -50A, both the waveform shows the system's stable operation.

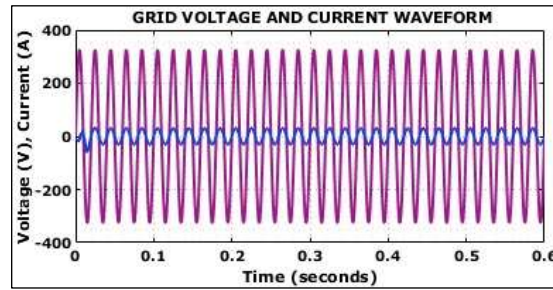


Figure 24: In phase Grid voltage and current waveform.
Source: Authors, (2026).

Figure 24 signifies grid voltage and current waveform. The grid voltage is indicated in purple colour sinusoidal wave and the obtained voltage is 350V approximately and the current waveform shows 25A approximately, which are in-phase indicating effective power transmission.

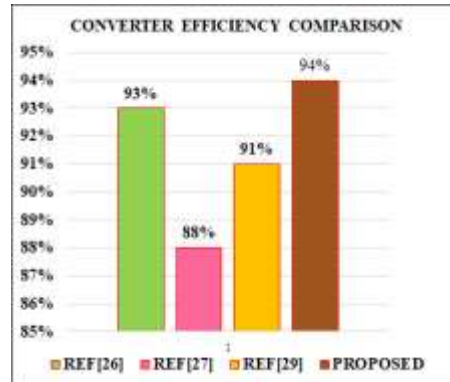


Figure 25: Efficiency comparison of converter.
Source: Authors, (2026).

Figure 25. Shows the of converters efficiency comparison. The proposed converter efficiency is compared with other converters, it achieves the greater efficiency of 94%, while the remaining converters in ref [27] has 93%, where ref [28] attains 88% and in ref [29] the efficiency is 91%.

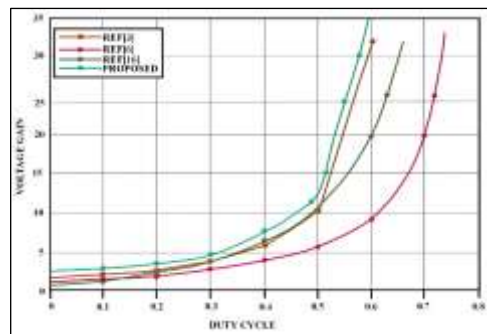


Figure 26: Voltage gain comparison.
Source: Authors, (2026).

Figure 28 explains the voltage gain characteristics. The proposed model voltage gain is more accurate than the other methods which is demonstrated in the graphical representation. The voltage gain shown in blue curve indicates the proposed method which is greater than the other methods.

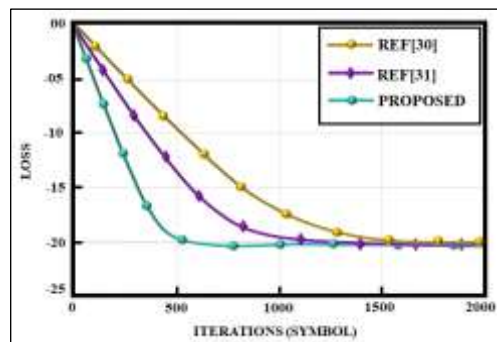


Figure 27: Convergence graph.
Source: Authors, (2026).

Figure 27 illustrates the convergence graph. The proposed model achieves a very fast convergence comparing with other techniques, where the blue line indicates the proposed algorithm that attains a very fast convergence.

Table 2: Illustrates comparison of component.

Components	Ref [9]	Ref [30]	Proposed
Capacitor	5	1	4
Inductor	2	2	1
Switches	2	4	1
Diodes	5	4	4

Source: Authors, (2026).

Table 2 represents the components compared to proposed converter. The proposed converter had less component count compared to others as the proposed converter has a single switch which describes the performance of the system with less number of components.

Table 3: Illustrates the tracking efficiency comparison of MPPT.

MPPT Algorithm	Tracking efficiency
Hybrid PSO based MPPT ref [31]	97.3
P&O MPPT ref [32]	84.7
Proposed	98.4%

Source: Authors, (2026).

The table 3 describes the various controllers regarding MPPT algorithm. The conventional methods denotes the efficiency of tracking speed, while compared to the proposed method as it has 98.4% tracking efficiency and very fast convergence, where the other controllers in ref [31] shows 97.3% and in P&O MPPT in ref [32] which has only 84.7% of tracking efficiency.

VI. CONCLUSION

This research presents an advanced energy management system with the development renewable energy powered grid system. The system incorporates a novel X-gain boost clamp converter offering improved voltage gain, with reduce component stress. In addition, the employed ASO-RNN MPPT supports in optimal tracking of PV power with faster convergence even under varying scenarios of PV. Moreover, the integrated battery and grid system complements the power demand by offering energy at times of lower irradiances from PV. MATLAB Simulink outcomes reveals that, the proposed converter results with boosted efficiency of 94%, with very fast convergence, where each phase lies within the IEEE standard limit. This makes the proposed system appropriate for effective EV charging owing to its advanced energy management system.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: I. Mahendravaraman

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Writing-original draft: I. Mahendravaraman

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