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PV FED ELECTRIC VEHICLE DRIVE ARCHITECTURE WITH ADVANCED X-BOOST CONVERTER AND CHAOTIC OPTIMIZED CONTROL

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ABSTRACT

The progression in Electric Vehicles (EVs) requires effective, reliable and maintainable power conversion system which is incorporated with Renewable Energy Sources (RESs) for eco-friendly charging. This research presents a hybrid energy system, with PV as primary source for energizing the Brushless DC motor (BLDC) of EV. The intermittent nature results with lower and fluctuated DC output boosted using a novel Extreme gain X-Boost converter. The converter shows higher power conversion with reduced stress and current ripples. The regulation of converter is performed using Proportional Integral (PI) controller with its parameters tuned using Chaotic Parrot Optimization Algorithm (CPOA), providing minimized overshoot, improved steady state error, faster convergences and enhanced settling time. In addition, battery and grid system is incorporated to power the BLDC motor at times of energy scarcity. The developed system is examined through MATLAB simulation under varying operating conditions of PV. The outcomes demonstrates improved converter efficiency of 96.16%, with higher voltage. Moreover, the controller offers reduced settling time of 0.3s with minimized overshoot. In addition, the Total Harmonic Distortion (THD) of the system lies below 5% indicating effective power quality based on IEEE standard limits. This shows that the proposed system offers suitability for EV charging with effective energy management.



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I. INTRODUCTION

The potential toward reduction in greenhouse gas emission, choice from fossil fuels and reduced impact towards environment promoted by development of Electric Vehicles (EVs) in recent years. Owing to increases in EVs growth different aspects of EVs has been developed an explored with its own advantages and limitations. In accordance with the growth, researchers emerged with the idea of eco-friendly charging system, utilization of available Renewable Energy Sources (RESs). Photovoltaic (PV) system has ranked as superior one among all RESs owing to its wide availability and zero emission [1]. Nevertheless, the electrical output of PV is naturally variable and non-linear, owing to its strong dependence on temperature and irradiance. This resulted in unstable voltage and power that makes utilization of PV directly unsuitable for EV application without proper conditioning [2-4]. High gain non-isolated converters is employed to mitigate these limitations between PV and DC link. The converters step up the low DC output into higher level suitable for EV charging system [5]. Moreover, it reduces the ripple current and improved power quality and energy transfer efficiency based on its design. In literature [6] the converter offers higher gain with its switched capacitor and voltage multiplier design, but leads to higher component stress due to more number of components. Single switch Boost converter of [7] shows voltage gain measuring about 3.92 with reduced loss on switching for EV application. Yet, face difficulties under open loop control system. The multiport converter of [8] is designed with Z-quasi resonant type for charging application of EV, operating at 40% duty cycle. The configuration provides reduced stress and ripple but affects system scalability. The converter in [9] is presented with offers soft switching with coupled inductor achieving higher voltage conversion ratio, but increases system complexity and also introduces leakage. Ultra high gain converter [10] integrated with single switch and voltage multiplier unit offers higher gain at lower ratio. However, the increase in component count raises the complexity of circuit.

The high gain converter of [11] for PV application provides improved efficiency at low switching frequency, but ranks with higher ripples due to increase in passive component count. In [12] non-isolated converter offering lower stress with higher gain is produced with its magnetic coupled design offering approximately 96% efficiency. However, introduction of coupled inductor results with complexity in higher power level. Switched capacitor converter in [13] provides wide output range for EV motor drive application with lower duty ratio. The increased capacitor count makes the system more complex is a drawback. In [14] integrated DC-DC converter is proposed with reduced switch count and improved efficiency. Besides the advantage of higher gain the rise passive component count leads to difficulty. Six arm converter in [15] offers low current and ripples with balanced arm current and higher efficiency. But shows poor performance under dynamic conditions. Regulated DC link is crucial for supplying controller power to motor. Owing to the fluctuating nature of PV Maximum Power Point Tracking (MPPT) [16] is employed for extraction of optimal solar power and to regulated converter duty ratio. However, the steady state oscillation of voltage at maximum power points leads to continuous loss of power and affects the system efficiency. In this scenarios, closed loop PI control [17] is integrated for regulation of converter depending on error between measured and reference voltage. But, performance of conventional PI depends highly on optimal selection of gain measures. Moreover, its fixed gain results with higher overshoot, longer settling time and instability.

KEY CONTRIBUTIONS OF THE PROPOSED SYTEM	
Contribution Description	
	A novel integration of PV system with an Extreme Gain X-Boost Converter is proposed to significantly enhance overall power conversion efficiency
	The CPOA-PI controller effectively improves dynamic response, reduces voltage overshoot & minimizes steady state error during converter regulation
	A bidirectional converter governed by an PI controller enables seamless coordination between the BLDC motor drives & grid ensuring uninterrupted operation
	In scenarios of insufficient power from PV and Battery, grid powers the BLDC motor, ensuring continuous energy supply for motor operation
	The proposed work enables intelligent power routing among PV, grid, battery & BLDC motor, maintaining system stability under load variations & PV intermittency conditions

Figure 1: Contributions of Proposed Research.

Source: Authors, (2026).

Henceforth, optimization algorithm [18] has been introduced for automatic tuning of PI gains by minimizing the objective function. Algorithms including Particle Swarm Optimization (PSO) [19], Firefly Optimization Algorithm (FOA) [20], African Vulture Optimization (AVO) [21], Coot Bird Optimization (CBO) [22], Snake Optimization Algorithm (SOA) [23], Water Cycle Optimization (WCO) [24] and many more has been introduced with its own benefits. But struggles with higher overshoot, slower and premature convergence, increased settling time and poor response under varying condition. To overcome these limitation the research incorporates chaos theory for better performance together with the optimization algorithm. Although, PV is widely utilized its harvesting ability last only for few hours, necessitating the need for and additional source for continuous charging operation. To improve the performance of PV system in alignment with supply and demand battery has become a potential solution [25]. The incorporation of Lithium ion battery significantly improved the operational flexibility of EV charging system by balancing power. In order to enhance the performance furthermore, grid connectivity is incorporated to the RES based EV charging system, acting as an auxiliary source [26]. This incorporation supports bidirectional power exchange reducing PV energy curtailment and contributes in grid stabilization via controlled injection and absorption of power. The major contribution of this research is illustrated through Figure 1, followed by organization of research in Figure 2.

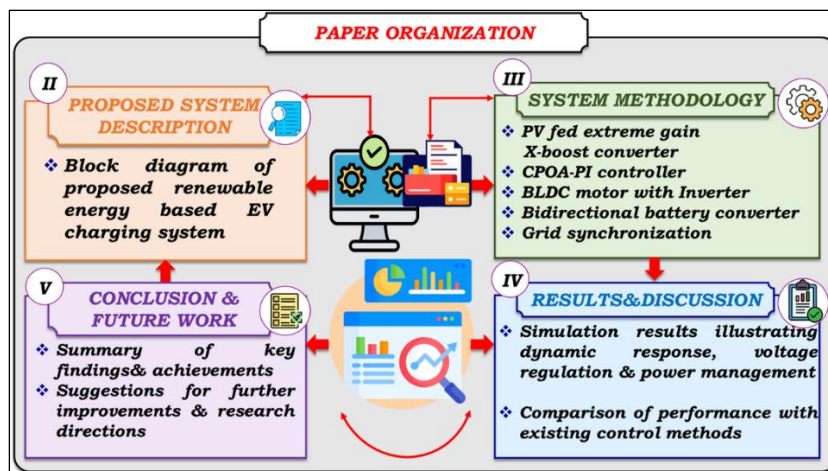


Figure 2: Structure of Paper.

Source: Authors, (2026).

II. PROPOSED SYSTEM DESCRIPTION

A PV integrated EV power system drive with effective energy management is presented in Figure 3. PV system is considered as major source for powering the EV motor (BLDC). For effective power conversions this work makes use of Extreme Gain X-Boost Converter is incorporated offering higher gain at reduced duty cycle and stress on components. For regulation of converter CPOA-PI controller is used which fine tunes the gain values with minimized ripple on voltage, reduced overshoot and enhanced system stability. The fine regulated voltage at DC bus using inverter gets converted into AC for powering BLDC motor of EV.

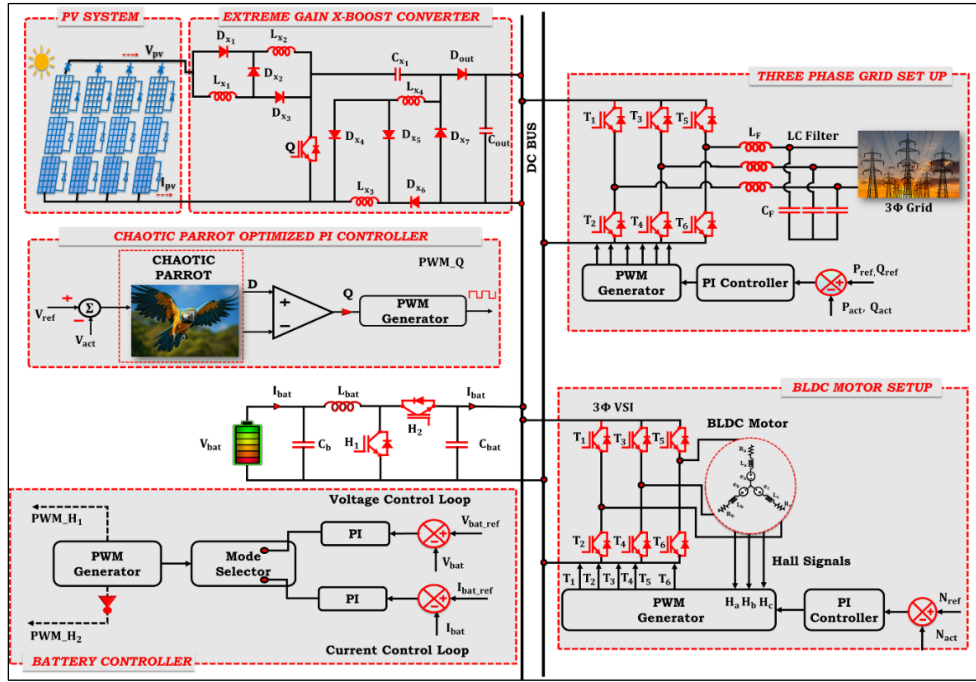


Figure 3: Proposed System Architecture.

Source: Authors, (2026).

The speed of BLDC motor is controlled with PI controller, thereby which smooth and torque free operation is achieved. Moreover, effective energy management is accomplished with the assistance of battery and grid. Table 1 discuss about system performance under source interruption scenarios. Bidirectional converter attached to battery supports in effective charging and discharging of battery. The dual PI controller assist in optimal and safer battery operation and also increases the battery lifespan by avoiding overcharging. In scenarios of deficient energy from PV and battery grid powers the BLDC motor via LC filter and inverter through DC bus. As, consequences effective energy management is achieved and continuous power is supplied to BLDC motor without interruptions.

Table 1: Source Interruption Cases and System Performance.

Condition	System Operation
Absence of PV	Battery powers the BLDC motor via bidirectional converter.
Absence of Battery	PV powers the motor and surplus energy is fed to grid via inverter.
Absence of Grid	PV and battery jointly powers the BLDC motor.
Absence of PV and Battery	Grid servers as a source for powering the load (EV motor)

Source: Authors, (2026).

III. SYSTEM METHODOLOGY

III.1 PV POWERED EXTREME GAIN X-BOOST CONVERTER MODELLING

The work makes use of PV as primary energy generation source with single diode configuration. The model comprises of photocurrent source I_{ph} in parallel with diode and resistance R_s and R_{sh} in shunt and series connection. The current-voltage relation of single diode module of PV is governed by non-linear equation including thermal voltage V_t and output PV current I_{PV} .

$$I_{PV} = I_{ph} - I_0 \left(\exp \left(\frac{V_{PV} + R_s I_{PV}}{n V_t} \right) - 1 \right) - \frac{V_{PV} + R_s I_{PV}}{R_{sh}} \quad (1)$$

Where PV voltage is indicated as V_{PV} , temperature, charge of electron and diode saturation current is signified as T_c , q and I_0 . Diode ideality factor as n , with $V_t = (K_B T_c / q)$, here K_B indicates Boltzmann's constant. Despite the advantage of model, owing to varying temperature and irradiance the voltage generated from PV is lower. In this work it is boosted via Extreme Gain X-Boost converter as shown in Figure 4. The converter is designed with single switch with the combination of switched inductor and voltage lift capacitor network to boost the input voltage. The switching operation of proposed converter is illustrated in Figure 5, with its operating modes in Figure 6.

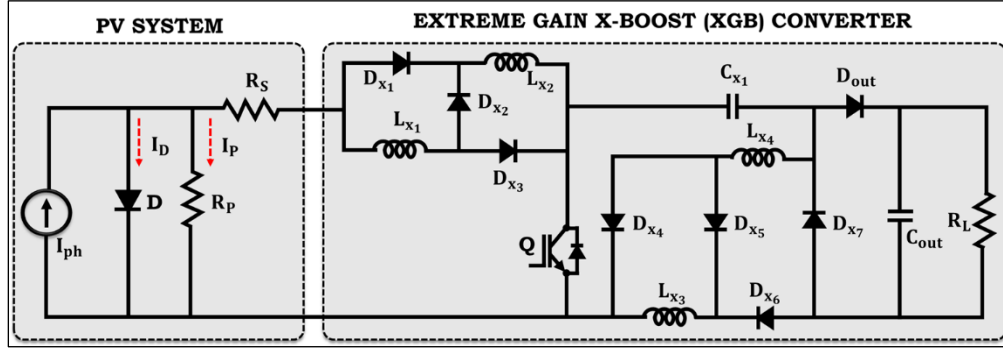


Figure 4: PV fed Extreme Gain X-Boost Converter Configuration.

Source: Authors, (2026).

At mode switch Q is in ON state, with diodes D_{x1} , D_{x3} , D_{x4} , D_{x6} and D_{x7} functions in forward biased condition, with reversed bias of diodes D_{x2} , D_{x5} and D_{out} . At this interval, PV energizes the inductor L_{x1} and L_{x2} , connected parallel and stores energy simultaneously. The capacitor C_{x1} conducts through switch, charging L_{x4} via diode D_{x7} . In the meantime, L_{x3} maintains current continues through D_{x4} and D_{x6} , resulting in near zero across it. As the diode D_{out} is in OFF state, the load gets powered by C_{out} .

$$V_{L_{x1}} = V_{L_{x2}} = V_{PV} \quad (2)$$

$$V_{L_{x4}} = V_{C_{x1}} \quad (3)$$

$$V_{L_{x3}} = 0 \quad (4)$$

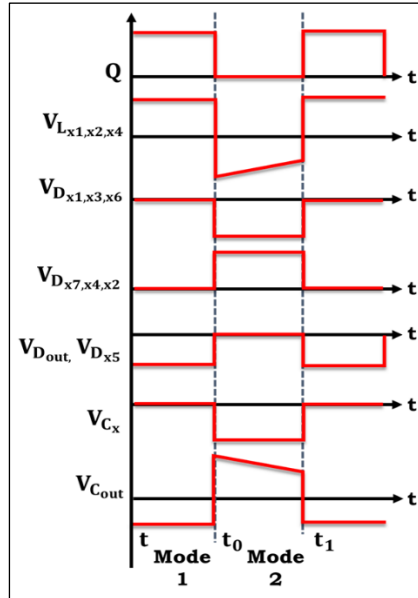


Figure 5: Switching Waveform of Proposed Converter.

Source: Authors, (2026).

At instance when switch is OFF, diodes D_{x2} , D_{x5} , D_{x7} and D_{out} are in forward biased state and diodes D_{x1} , D_{x3} , D_{x4} and D_{x6} in reversed bias state. At this mode L_{x1} and L_{x2} , are reconfigured in series via diode D_{x2} , and the energy stored combines with input source V_{PV} charges C_{x1} to a boosted level. Similarly, L_{x4} discharges its stored energy via D_{out} , transferring power to C_{out} and load. Inductor L_{x3} also gets discharged via D_{x5} , offering continuous current. This state ensures energy transfer from input and intermediate storage elements to output, thereby resulting in higher voltage gain.

$$V_{PV} - V_{L_{x1}} - V_{L_{x2}} - V_{C_{x1}} = 0 \quad (5)$$

$$V_{L_{x1}} = V_{L_{x2}} = \frac{V_{PV} - V_{C_{x1}}}{2} \quad (6)$$

$$V_{L_{x4}} = V_{C_{x1}} - V_{out} \quad (7)$$

$$V_{C_{x1}} = V_{out} \quad (8)$$

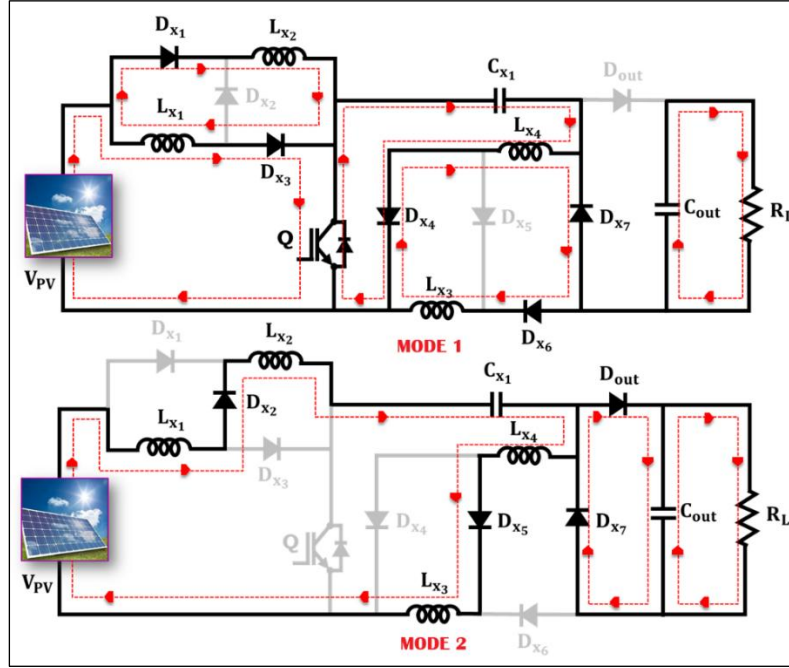


Figure 6: Operating modes of Extreme Gain X-Boost Converter.
Source: Authors, (2026).

With volt-second balance law in continuous conduction mode the expression for inductor $V_{L_{x1}}$ and $V_{L_{x2}}$ are same and is given by.

$$DV_{L_{x1}} + (1 - D)V_{L_{x1}} = 0 \quad (9)$$

$$DV_{PV} + (1 - D)\left(\frac{V_{PV} - V_{C_{x1}}}{2}\right) = 0 \quad (10)$$

$$2DV_{PV} + (1 - D)(V_{PV} - V_{C_{x1}}) = 0 \quad (11)$$

$$2DV_{PV} + (1 - D)V_{PV} - (1 - D)V_{C_{x1}} = 0 \quad (12)$$

$$(1 + D)V_{PV} = (1 - D)V_{C_{x1}} \quad (13)$$

$$V_{C_{x1}} = \left(\frac{1+D}{1-D}\right)V_{PV} \quad (14)$$

Similarly for inductor L_{x4}

$$DV_{L_{x1}} + (1 - D)V_{L_{x1}} = 0 \quad (15)$$

On substitution of expression (3) and (7) in (15).

$$DV_{C_{x1}} + (1 - D)(V_{C_{x1}} - V_{out}) = 0 \quad (16)$$

$$DV_{C_{x1}} + (1 - D)V_{C_{x1}} - (1 - D)V_{out} = 0 \quad (17)$$

$$V_{C_{x1}} = (1 - D)V_{out} \quad (18)$$

$$V_{out} = \frac{V_{C_{x1}}}{1-D} \quad (19)$$

On substitution (14) in (19).

$$V_{out} = \frac{1}{1-D} \left(\frac{1+D}{1-D}\right)V_{PV} \quad (20)$$

Therefore the gain of proposed converter is given by.

$$\frac{V_{out}}{V_{PV}} = \frac{1+D}{(1-D)^2} \quad (21)$$

The converter offer higher gain making it suitable for EV application. But effective regulation is essential to achieve stabilized operation. In this research optimized PI controller is used discussed in following section.

III.2 CHAOTIC PARROT OPTIMIZED PI CONTROLLER

The classical Parrot Optimization Algorithm (POA) inspired by social behavior of parrots is used in solving non-linear problems. Despite its effectiveness, POA algorithm faces limitations when applied for PV-high gain converter frameworks, notably under varying conditions of PV. This resulted in slower dynamic response owing to random initialization and premature convergence. The work flow is presented in Figure 7. To address these challenges, chaos theory is incorporated with POA for enhancement of exploration search space. Here, each parrot indicates PI controller gain values and is represented as.

$$X_i = [K_p^i, K_i^i] \quad (22)$$

Chaos maps are employed for generation of initial population and is given by.

$$X_i^0 = l_b + CC_i(u_b - l_b) \quad (23)$$

Where chaotic sequence generated by chaotic maps is indicated as CC_i , with lower and upper bounds of gain as l_b and u_b .

Step 1: Foraging Behavior (Global Exploration Phase)

Parrots try to identify food by looking their owner and move towards the best position. This means searching for optimal regions in global PI gain space to avoid convergence at premature stage.

$$X_i^{t+1} = (X_i^t - X_{best}) \times Levy(dim) + CC_i(1 - \frac{t}{Max_{iter}})^{\frac{2t}{Max_{iter}}} \times X_{mean}^t \quad (24)$$

Where current location is noted as X_i^t , upcoming update of location X_i^{t+1} , average situation of population as X_{mean}^t , best position after initialization as X_{best} and distribution of levy utilized in simulating the parrots movement like flight as $Levy(dim)$.

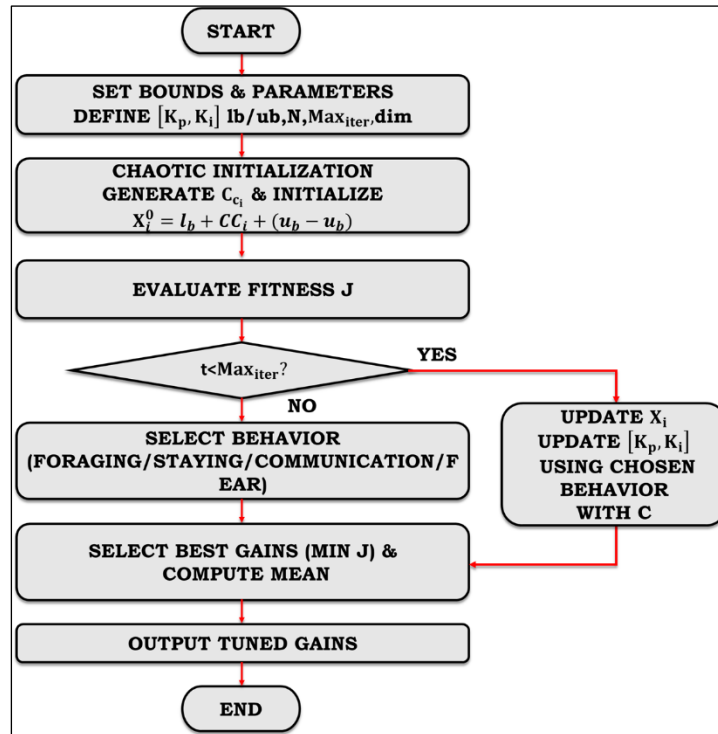


Figure 7: Flow Chart Illustration of CPOA-PI Controller.

Source: Authors, (2026).

Step 2: Staying Behavior (Local Exploitation Phase)

Parrots remains closer to the owner and makes only small movements. This means fine tuning of PI gain values that are nearby.

$$X_i^{t+1} = X_i^t + X_{best} \times Levy(dim) + CC_i \times ones(1, dim) \quad (25)$$

The dimension vector is noted as $ones(1, dim)$, flight to host is described by $X_{best} \times Levy(dim)$. This phase enables wider exploration of gains with avoidance of repetitive movement.

Step 3: Communication Behavior

In this phase parrots exchange information by flying towards the flock or by distancing itself after communication. This guides weaker solution to get strengthen. It is written by.

$$X_i^{t+1} = \begin{cases} 0.2CC_i \left(1 - \frac{t}{Max_{iter}}\right) (X_i^t - X_{mean}^t), & P \leq 0.5 \\ 0.2CC_i \exp\left(-\frac{t}{rand(0,1)Max_{iter}}\right), & P \geq 0.5 \end{cases} \quad (26)$$

This phase aligns the gain of PI controller towards population mean and accelerates convergence with reduce dispersion of gain values.

Step 4: Fear of Strangers Behavior (Local Minima Escape Stage)

In this phase Parrots flee from strangers and get back quickly towards the owner. Here it escapes local optima and restore diversity in iterations later.

$$X_i^{t+1} = X_i^t + CC_i \times \cos\left(\frac{0.5\pi t}{Max_{iter}}\right) \times (X_{best} - X_i^t) \times \cos(CC_i\pi) \times \left(\frac{t}{Max_{iter}}\right)^{\frac{2t}{Max_{iter}}} \times (X_i^t - X_{mean}^t) \quad (27)$$

This phases forces sudden variations in gain and ensure escaping from poor local solutions. Moreover it shows improved response under non-linear conditions and avoids trapping. This mechanism endures optimal selection of PI controller gain with faster convergence, and offers improved regulation of converter.

III.3 BLDC MOTOR DESIGN

Here in this work BLDC motor is chosen for EV application. The motor comprises of permanent magnet for generating magnetic field. The configuration of BLDC motor is illustrated in Figure 8. Additionally, symmetrical windings are includes that produces trapezoidal back EMF. The higher resistance in permanent magnets makes the rotor current negligible. Driven by the action between windings and magnets the BLDC motor operates. The voltage expression of stator is given by.

$$V_a = r \cdot I_a + L \frac{dI_a}{dt} + \left[\frac{dI_b}{dt} + \frac{dI_c}{dt} \right] + E_a \quad (28)$$

$$V_b = r \cdot I_b + L \frac{dI_b}{dt} + \left[\frac{dI_a}{dt} + \frac{dI_c}{dt} \right] + E_b \quad (29)$$

$$V_c = r \cdot I_c + L \frac{dI_c}{dt} + \left[\frac{dI_b}{dt} + \frac{dI_a}{dt} \right] + E_c \quad (30)$$

For a balanced system it is given by.

$$I_a + I_b + I_c = 0 \quad (31)$$

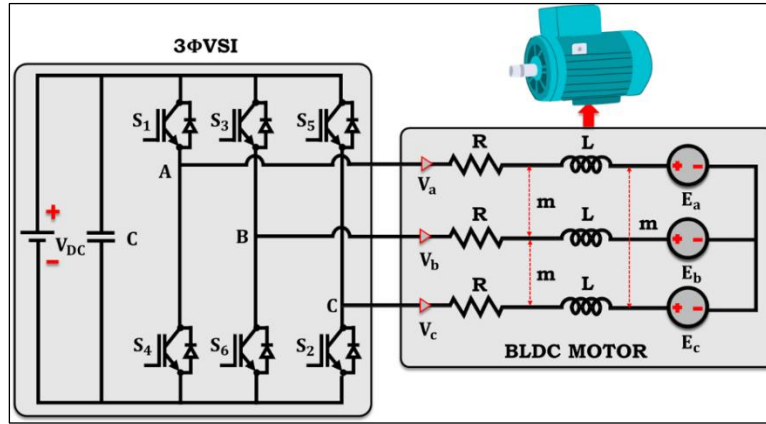


Figure 8: BLDC Motor with Inverter.

Source: Authors, (2026).

The expression of stator voltage is written as.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} r & 0 & 0 \\ 0 & r & 0 \\ 0 & 0 & r \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L - M & 0 & 0 \\ 0 & L - M & 0 \\ 0 & 0 & L - M \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad (32)$$

Phase-to-Phase voltage is given by.

$$V_{ab} = r(I_a - I_b) + (L - M) \frac{d}{dt} (I_a - I_b) + E_{ab} \quad (33)$$

$$V_{bc} = r(I_b - I_c) + (L - M) \frac{d}{dt} (I_b - I_c) + E_{bc} \quad (34)$$

As the system is balanced neglecting mutual inductance,⁸

$$\frac{dI_a}{dt} = \frac{r}{L} I_a + \frac{2}{3L} (V_{ab} - E_{ab}) + \frac{2}{3L} (V_{bc} - E_{bc}) \quad (35)$$

$$\frac{dI_b}{dt} = \frac{r}{L} I_b + \frac{2}{3L} (V_{ab} - E_{ab}) + \frac{2}{3L} (V_{bc} - E_{bc}) \quad (36)$$

The expression for BLDC motor Back EMF phase is written as.

$$E_a = K\omega F(\theta) \quad (37)$$

$$E_b = K\omega F(\theta - \frac{2\pi}{3}) \quad (38)$$

$$E_c = K\omega F(\theta + \frac{2\pi}{3}) \quad (39)$$

Motor constant is indicated by K with position function as $F(\theta)$ and ω representing angular speed. The torque of BLDC motor is noted as .

$$T = \frac{E_a I_a + E_b I_b + E_c I_c}{\omega} \quad (40)$$

For optimal regulation of BLDC motor speed PI controller is incorporated, which effectively minimizes the error produced between actual and reference speed. The output from PI controller is fed to PWM generator for generation of PWM pulses for inverter. This results in regulation of voltage and current from BLDC motor. As a consequence, stabilized and smoother output is achieved for optimal operation of EV.

III.4 BIDIRECTIONAL BATTERY CONVERTER

The system makes use of battery as a supplementary source for powering BLDC motor at times of power demand. The configuration of bidirectional converter used for optimal charging and discharging is illustrated in Figure 9 together with PI controller.

III.4.1 Battery Charging (Buck Operation)

At times of battery charging the converter function in buck mode making use of the DC bus voltage generated in excess amount from PV system. At this instance switch T_1 activates while T_2 acting as a synchronous path. This allows the DC bus voltage to step down to the required level. Energy gets transferred via inductor to power the battery, offering controlled current and avoids overcharging.

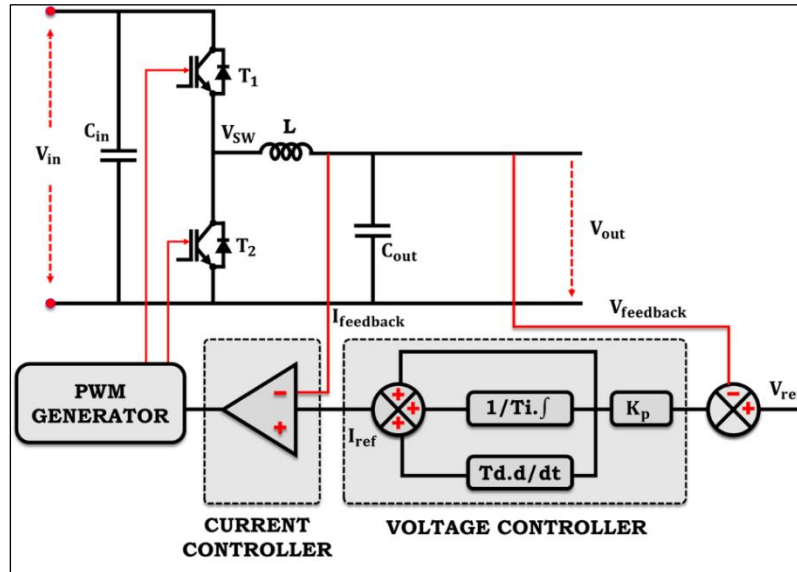


Figure 9: Bidirectional Battery Converter with PI Control.

Source: Authors, (2026).

III.4.2 Battery Discharging (Boost Operation)

At times when PV energy is insufficient to power BLDC motor, the converter functions in boost mode to assist DC bus. In this circumstance T_2 gets actively controlled, that results in delivery energy from battery to inductor, subsequently boosting the DC link voltage. The discharging operation supports in providing uninterrupted supply for powering of BLDC motor.

III.4.3 Control Strategy using PI

The system uses cascaded control scheme, where the outer voltage loop compared the reference and measured DC link voltage for generating reference current, the inner current loop regulates the inductor current for accurate tracking of this reference. The output of controller is given to PWM generator that generates appropriate gating pulses for the switches of converter. This closed loop mechanism supports in maintain stabilized DC link voltage, smoother mode of operation and minimized ripples and enhances the performance.

III.5 GRID SYNCHRONIZATION

The system makes use of Synchronous Reference Frame Phase Lock Loop (SRF-PLL) for effective grid synchronization shown in Figure 10. SRF uses the rotating reference frame to align with grid frequency ensuring accurate tracking of variations in frequency and phase. The three phase input voltage gets transformed into dq frame utilizing Clark's and Park's transformation. Moreover, a feedback loop within the PLL regulate the angular position of dq frame continuously making sure that component of q-axis is zero. This is essential in achieving precise synchronization between grid and the system. Therefore, stable operation is accomplished even under non-linear conditions. The voltage of grid V_{gx}, V_{gy}, V_{gz} at all three phase is indicated as.

$$V_{gx} = V_m \sin \theta \quad (41)$$

$$V_{gy} = V_m \sin \left(\theta - \frac{2\pi}{3} \right) \quad (42)$$

$$V_{gz} = V_m \sin \left(\theta + \frac{2\pi}{3} \right) \quad (43)$$

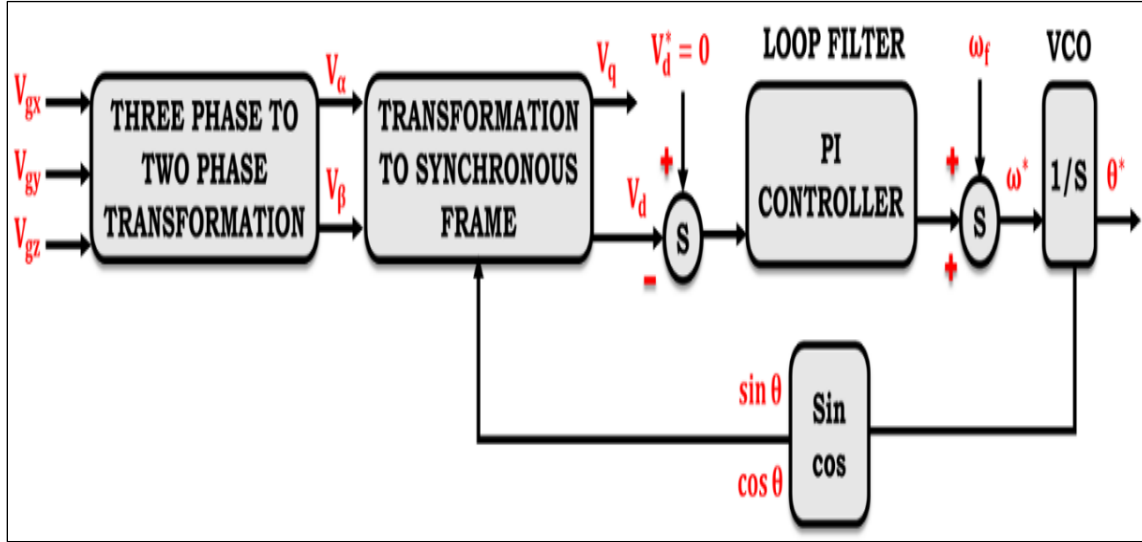


Figure 10: Three Phase SRF-PLL System.

Source: Authors, (2026).

Where θ represents the phase angle. Clark's transformation is performed for conversion of three phase voltage into $\alpha\beta$ frame, accompanied with Park's transform to attain dq frame. The expression of transformation is given by.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_{gx} \\ V_{gy} \\ V_{gz} \end{bmatrix} \quad (44)$$

The dq transformation is accomplished with .

$$T_{qd} = \begin{bmatrix} \sin \theta^* & \cos \theta^* \\ \cos \theta^* & \sin \theta^* \end{bmatrix} \quad (45)$$

The resultant voltages in dq frame is expressed by.

$$V_q = V_m \sin (\theta - \theta^*) \quad (46)$$

$$V_d = -V_m \sin (\theta - \theta^*) \quad (47)$$

Here θ^* represents the phase angle at PLL system. PI controller is incorporated to track phase angle exactly and making the component of q-axis to zero. Once space vector gets synchronized the phase angle θ and θ^* and estimated frequency locks with reference frequency gets aligned.

IV. RESULTS AND DISCUSSION

This section explores the outcomes of proposed XG-Boost Converter together with CPO-PI controller using MATLAB. The validation is carried out using specification detail listed in Table 2.

Table 2: Design Specification of Proposed System.

Parameter	Specification	Parameter	Specification
BLDC Motor			
Pole Pairs	4	Stator Phase Resistance and Inductance	2.3 Ω , 7.68mH
Inertia	0.83×10^{-3}	Back EMF	120°
Viscous Damping	1×10^{-3}	Torque Constant	074
PV System			
Power Rating	30kW	Total No. of Panel	117
No of Panels in Series	13	No of Panels in Parallel	9
Rated Voltage of Single PV Panel	250W	No of Cells Per Module	60
Open circuit Voltage (V_{oc})	36.84V	Voltage at Maximum Power Point	30.72V
Short Circuit Current (I_{sc})	8.32A	Current at Maximum Power Point	7.83A
Temperature Co-efficient at (V_{oc})	-0.359	Temperature Co-efficient at (I_{sc})	0.096995
Saturation Current of Diode	2.8736×10^{-6}	Ideality Factor of Diode	0.99259
Resistance in Series and Parallel	30.6558 Ω & 0.19366 Ω	Light Generated Current	8.3299A
Extreme Gain X-Boost Converter			
$L_{x1}, L_{x2}, L_{x3}, L_{x4}$	0.594mH	C_{x1}	22 μF
Switching Frequency	10kHz	C_0	2200 μF
Lead Acid Battery			
Initial SoC	80%	Rated Capacity	10Ah
Nominal Voltage	420V	Response Time	30s

Source: Authors, (2026).

The developed converter is examined under two different condition together with energy management. The cases are as follows

Case 1: Steady Solar Operation.

Case 2: Dynamic Solar Operation.

Case 3: Battery Energy Mode.

Case 4: Grid Energy Mode.

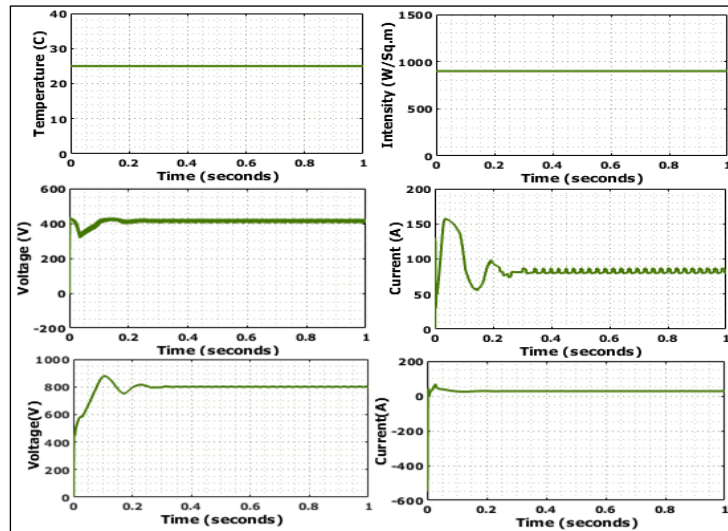


Figure 11: Converter Performance Case 1.

Source: Authors, (2026).

The proposed Extreme Gain X-Boost Converter is validated in case 1 with constant solar operation as shown in Figure 11. Here, the panel temperature and intensity continued at 35°C and 1000 W/m². Depending on this condition the solar output voltage oscillates slightly owing to inherent start-up transients, and continues at 410V. Similarly, output PV current also shows transient at the beginning and continues at 75A, with slight distortions. Based on this output from PV, the converter shows boosted voltage of 800V with initial transients and after 0.3s a stabilized voltage of 800V is continued. Simultaneously, Extreme Gain X-Boost Converter current is continued at 34.5A, further. This shows the converters boosting capability in powering the BLDC motor of EV.

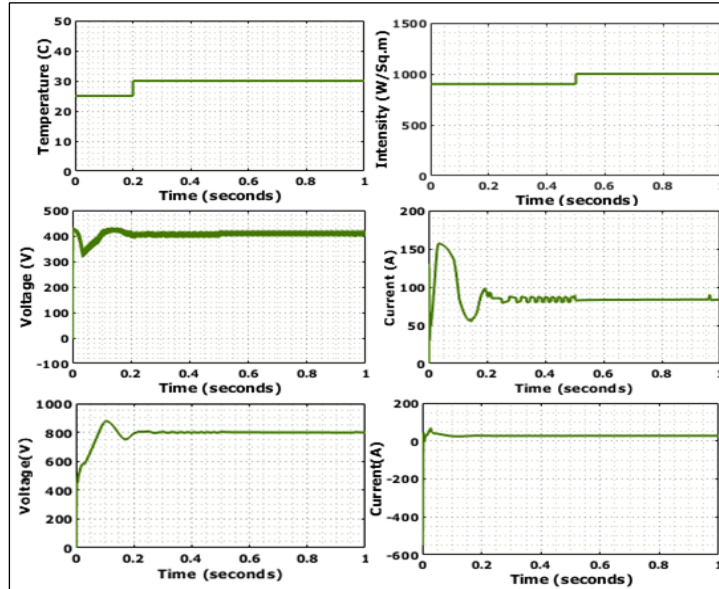


Figure 12: Converter Performance Case 2.

Source: Authors, (2026).

In this case 2 the proposed converter is examined with varying behavior of solar, as shown in Figure 12. The waveform signifies variation in temperature after 0.2s with 30°C, while initially maintained at 25°C. In the same way with intensity level of 900 W/m^2 till 0.5s, a step rise in intensity level is observed where it further continues at 1000 W/m^2 . Based on this instance, voltage output of PV is noticed to be 410 V, with slight oscillation at 0.5 indicating the variation reacted with intensity level. Similarly the proposed Extreme Gain X-Boost Converter voltage rises and continues at 800V with oscillation related to solar behavior. In relation the current is continued at 75A after severe distortions with converter current resulting at 34.5A, respectively.

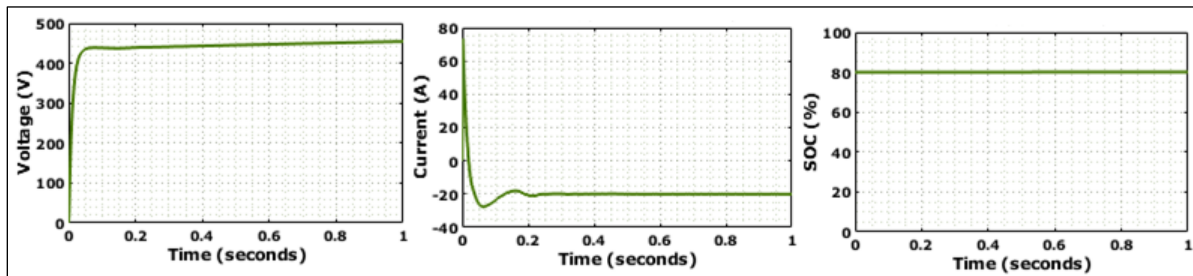


Figure 13: Battery Charging Waveform.

Source: Authors, (2026).

At scenario when, energy is supplied from PV to BLDC motor of EV, the battery makes use of the excess energy and gets energized, the resultant outcomes are shown in Figure 13. It is seen that a stabilized voltage of 450V is accomplished with current indicating negative polarity which means charging of battery. Moreover, the SoC of battery is observed to be at 80%.

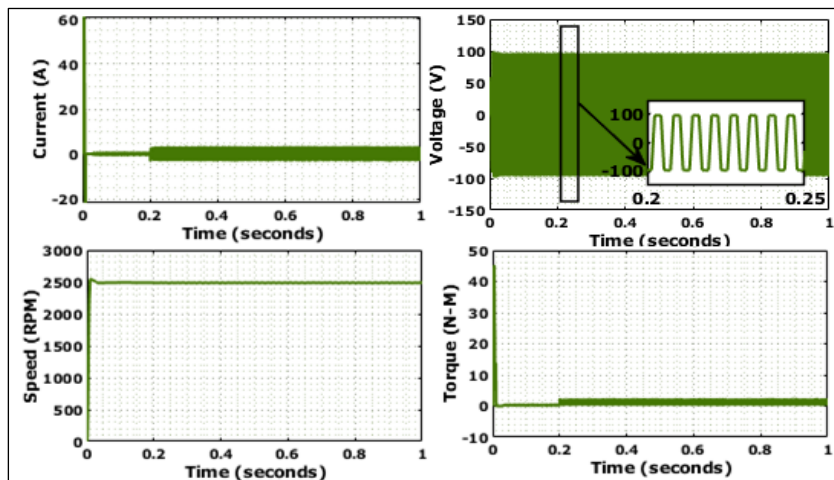


Figure 14: BLDC Motor Operation Powered by PV.

Source: Authors, (2026).

The characteristics waveform of BLDC motor when energized using PV is shown in Figure 14. It is noticed that, 3A current is maintained by the system, with back EMF voltage measuring about 100V is observed. Moreover, the speed of motor is continued at 2500RPM owing the effective speed control using PI controller. Furthermore, the torque of BLDC motor is maintained at 2NM at reduced level.

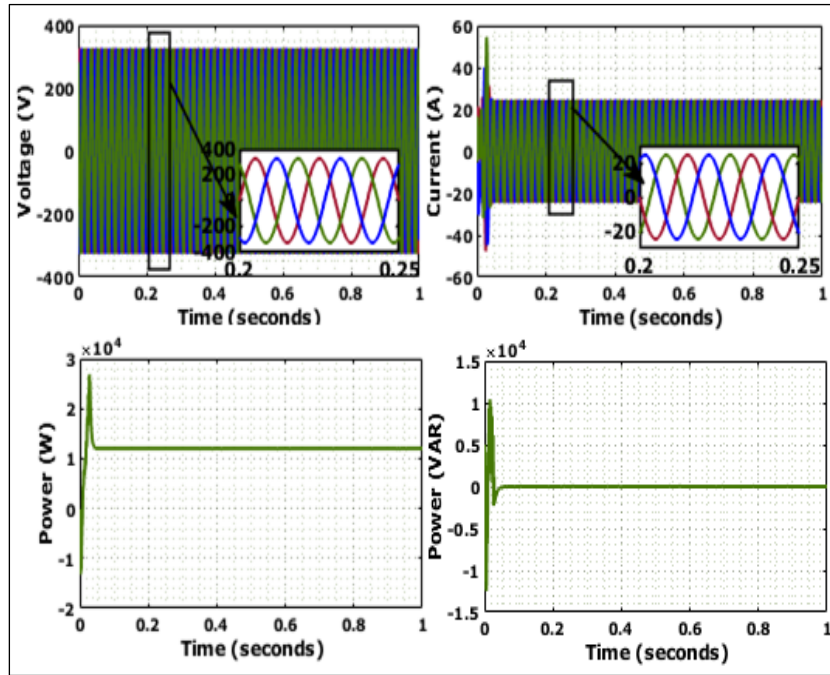


Figure 15: Grid Characteristics Waveform.

Source: Authors, (2026).

Under the scenario of BLDC powered by PV, the excess energy is fed to grid as shown in Figure 15. It is seen that a stabilized grid voltage measuring about 380 V with current ranging about 20A is achieved by the system. Furthermore, with real power measure of 13,500 W, the system response with reduced reactive power indicating minimal losses and improved power quality.

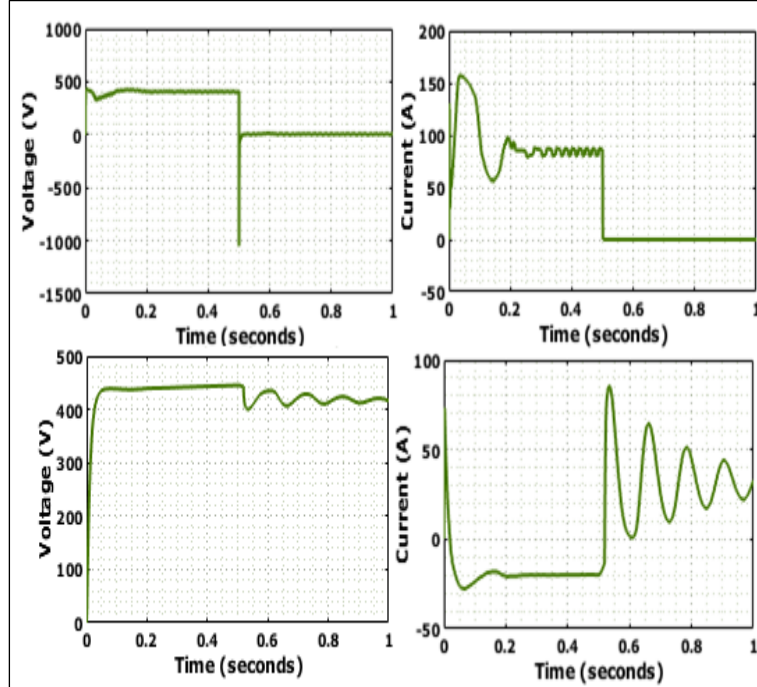


Figure 16: Case 3: PV Cut of and Battery Powering Condition.

Source: Authors, (2026).

The system is examined under condition, when energy from PV is insufficient to power the BLDC motor, and the outcomes are illustrated in Figure 16. The PV voltage and current is continued with 400V and 75A till 0.5s, after gets dropped. At this instance, the battery takes the responsibility for powering. It is seen that till 0.5s voltage is maintained at 450V, without any oscillations, after due to cut-off condition of PV oscillation is noticed indicating discharge, however tends to offers 420V approximately. From the current waveform, the discharging scenario is clearly observed where the current increases from negative to positive level.

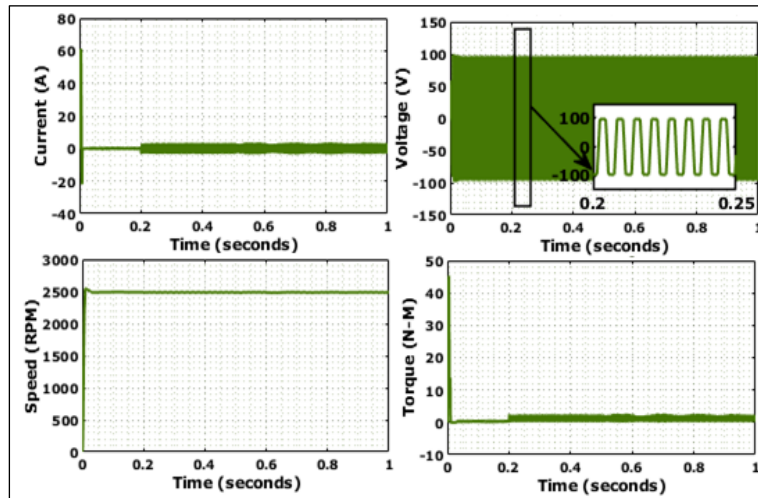


Figure 17: BLDC Motor Operation Powered by Battery.

Source: Authors, (2026).

The BLDC motor performance when powered using Battery is presented in Figure 17. It is seen, the current, back EMF voltage, speed and torque of BLDC motor is continued at 3A, 100V, 2500RPM and 3NM with initial oscillations till 0.2s. However, owing to cut of condition of PV 0.5s, minor distortion is noticed. But stabilized performance is continued further, with the assistance of battery.

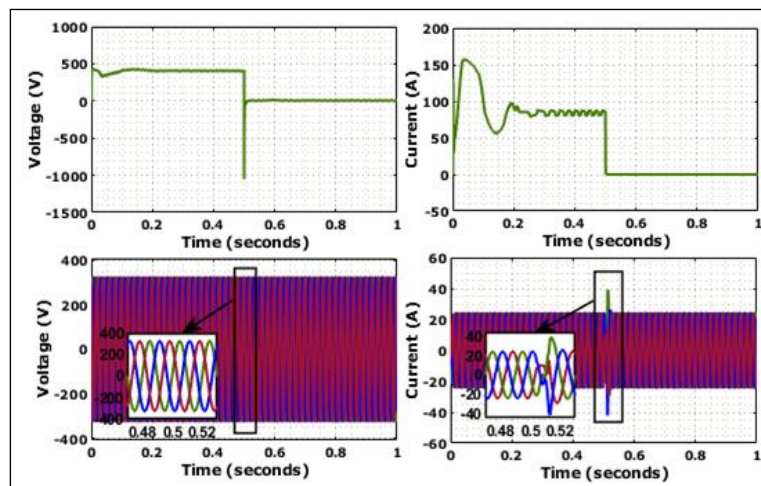


Figure 18: Case 4: Grid Powering Scenario.

Source: Authors, (2026).

In this Case 4, the energy generated from PV and battery is insufficient to power the motor, as seen in Figure 18. Voltage and Current level of 410V and 75A is sustained with initial oscillation till 0.5. After voltage from PV drops down indicating unable to supply energy anymore. At this circumstance, the BLDC motor gets energized using grid, with voltage of 380 and current showing the drop at 0.5s and continued with 20A further.

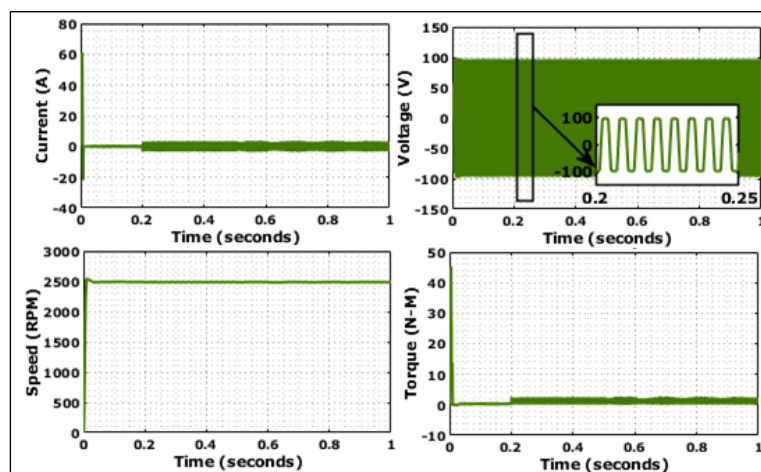


Figure 19: BLDC Motor Operation Powered by Grid.

Source: Authors, (2026).

Despite of variation is power source only minor distortions is noticed in BLDC motor characteristics at 0.5s, due to exchange of power sources, as shown in Figure 19. However, stabilized operation is attained with current level of 2A, back EMF voltage of 100V, speed of 2500RPM and torque at 3NM, respectively.

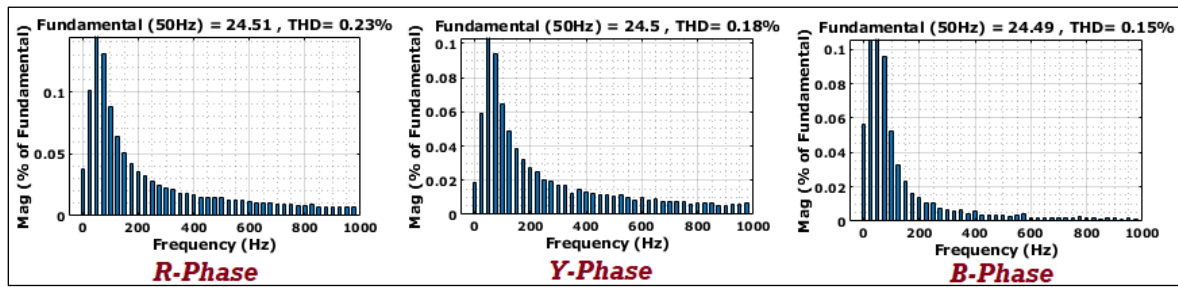


Figure 20: Three Phase Grid Current THD Waveform.

Source: Authors, (2026).

The system accomplished improved power quality with reduced harmonics, as evident from Figure 20. FFT analysis is carried out on the proposed three phase grid system. It is noticed that harmonics measure of 0.23% for R-Phase, 0.18% for Y-Phase and 0.15% for B-Phase is attained by the three phase system, signifying that the THD of all three phases lies within the IEEE harmonics standards.

IV.1 COMPARATIVE ANALYSIS

Table 3: Comparison of Converter Analysis.

Converter Reference	Voltage Gain	Efficiency (%)
Reference [6]	$\frac{1}{(1-D)^2}$	90
Reference [8]	$\frac{1-D}{1-2D}$	91.5
Reference [9]	$\frac{2N-1}{(1-D)(N-1)}$	95
Reference [10]	$\frac{6}{1-D}$	95.4
Reference [11]	$\frac{1+3D}{1-D}$	95
Reference [12]	$\frac{2kN-1}{(kN-1)(1-D)}$	96
Reference [13]	$\frac{(2-D)^2}{(1-D)^2}$	92.08
Proposed	$\frac{1+D}{(1-D)^2}$	96.16

Source: Authors, (2026).

The proposed converter performance is listed in Table 3 with its gain measure and efficiency. The table clearly indicates that the proposed converter with its voltage multiplier unit ranks with boosted voltage efficiency of 96.16% together with higher gain, in contrast to Ref [6], [7-13]. This highlights the effectiveness of proposed converter for EV motor drive application.

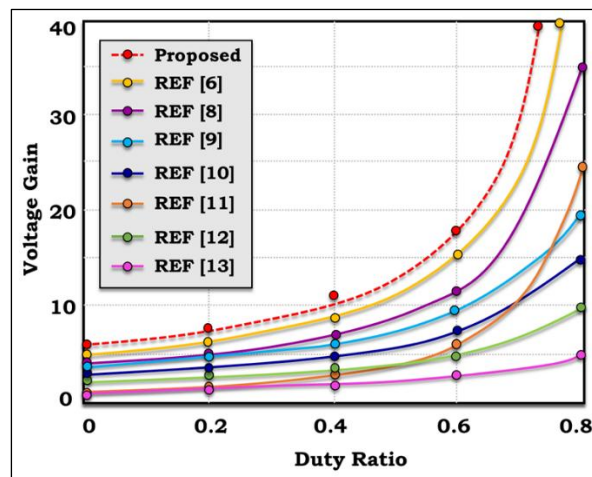


Figure 21: Comparison of Voltage Gain.

Source: Authors, (2026).

The voltage gain comparison of proposed Extreme Gain X-Boost converter is examined with other converter topologies in Ref [6], [7-13] is shown in Figure 21. It is observed that in comparison to other converters the Extreme Gain X-Boost converter results with higher gain which eventually results in higher conversion efficiency. This shows the converters capacity towards high power applications like EVs.

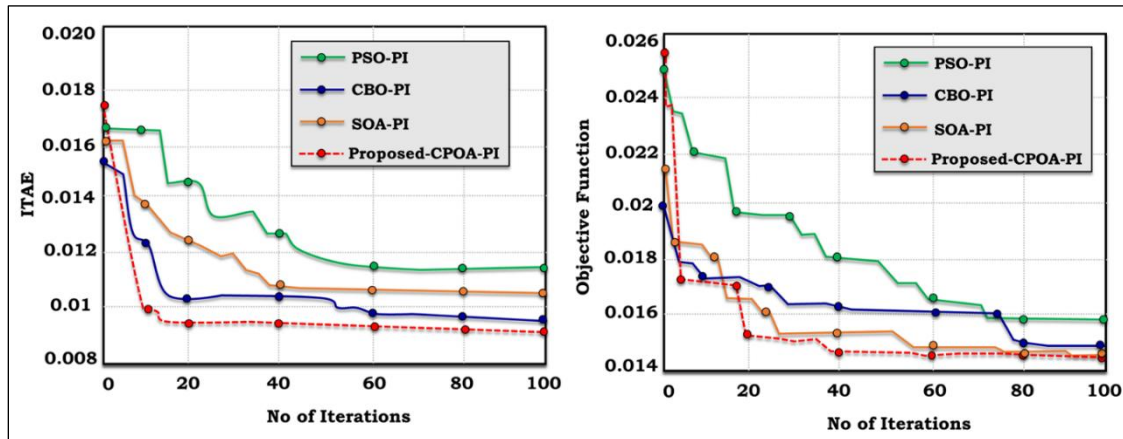


Figure 22: Comparison of ITAE and Convergence.

Source: Authors, (2026).

The comparative analysis of error and convergence for different control algorithm is illustrated in Figure 22. The assessment is done between control approaches including PSO [19], CBO [22], SOA [23] and the proposed CPOA-PI controller. It is seen that compared to other optimization algorithm in tuning PI controller the CPOA with its chaos theory shows minimized error with faster convergence. This makes the proposed optimized controller potential for regulating converters.

V. CONCLUSION

This research presents and RESs integrated EV charging system for powering BLDC motor of EV with PV as primary source of energy generation. The incorporated Extreme Gain X-Boost converter offers enhanced voltage with reduced stress on semiconductor devices and higher efficiency. The CPOA-PI controller significantly improves the regulation of converter by providing stabilized DC link voltage with reduced steady state error, suppresses oscillation, minimized settling time and faster convergence compared to conventional PI controller. The bidirectional converter with battery ensures continuous operation of BLDC motor with any interruptions at time of insufficient power delivery from PV system. Moreover, to tackle scenarios of PV and Battery run of or scarcity grid powers the BLDC motor via inverter for effective drive operation. The obtained result on MATLAB demonstrates that the proposed converter results with higher converter efficiency of 96.16%, voltage gain and controller showing faster settling time at 0.3s, respectively. Furthermore, improved power quality is achieved by the system showing THD within the IEEE standard with below 5%. Thereby, the developed hybrid charging system accomplishes effective energy management offering uninterrupted supply to power EV drive. Future work may focus on extending the developed system with higher converter configuration with hardware implementation using FPGA platform.

VI. ACKNOWLEDGMENTS

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