Firefly Optimized Energy Management with Improved Boost Converter for Hybrid Charging of Electric Vehicles

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Abstract. Electric vehicles (EVs) are at the forefront of modern mobility solutions. However, integrating EVs with charging infrastructure poses significant challenges. Effective management of grid power and regulation of bus voltage is achieved through the utilization of Renewable Energy Sources (RESs). This research presents an advanced hybrid charging system for EVs utilizing Firefly Algorithm Optimized Proportional Integral (FA-PI) controller in conjunction with Improved Boost converter (IBC). The proposed system integrates Photovoltaic (PV) system with power grid, effectively managing and optimizing the energy flow to ensure efficient charging of EV. The PV system voltage is effectively increased using improved boost converter making it suitable for better handling of PV output to support EV charging and grid integration. The FA-PI controller is incorporated for control of converter, to achieve better response time and stability. The bidirectional converter regulated the charging and discharging cycles of battery. Simulation results using MATLAB confirms that proposed converter results with improved voltage gain and efficiency of92.30%. The use of Improved Boost converter and optimized PI control approach highlights the potential for robust energy management systems for EVs compared to state-of-the-art techniques.

Keywords: Photovoltaic System, Electric Vehicle, FA-PI, Improved Boost Converter, Energy Management

1 Introduction

The global reliance on fossil fuels, for both power production industry and transportation sector is significant concern, as these sectors heavily rely on non-renewable energy sources [1, 2]. With the rising adoption of EVs, the role of PV solar electricity [3] becomes even more crucial. EVs require regular charging, which significantly increase the demand of electricity. Integrating PV system into the EV charging infrastructure [4] provide a sustainable solution by harnessing renewable energy from sun.

A crucial component of PV system is the power electronic converters, where DC-DC converters come in to action, which boost the voltage to a usable level [6]. In Literature [7] Boost converter is presented showing excels in stepping up voltage, making it suitable for PV applications. Despite its effectiveness, the boost converter suffer from significant voltage and current ripples, especially under varying insolation levels, leading to inefficient charging. Cuk converter in [8] offers both step up and down capabilities and are chosen owing to its low ripple current and better operation efficiency. Despite it involves, design complexity and higher losses because of its additional energy transferring stage. SEPIC Converter of literature [9] offers higher voltage gain with reduced component stress and flexibility across operating condition. However, the design potentially reduces the efficiency contrast to other simple converters. The modified Luo converter mentioned in reference [10] provide higher voltage gain with minimized stress across components, but necessitates precise control to maintain stable operation. However, its drawbacks, such as significant voltage and current ripples and inefficiencies under varying load conditions, necessitate improvements. Therefore an IBC is proposed in this research, by addressing the limitations to optimize energy management.

PI controller [11] is the commonly utilized by power electronic converters owing to their simplicity and easier implementation. Despite the widespread adoption, it suffer with dynamic performance specifically under rapid changing condition, with slower response time [12]. Henceforth, optimization algorithms have been developed for tuning the parameters of PI controller. Particle Swarm Optimization (PSO) algorithm [13] enhances the control performance by finding potential K_p and K_i values, offering stable and efficient operation. Nevertheless, it is computationally intensive and necessitates significant power for processing. In reference [14] Gray Wolf Optimization (GWO) algorithm assisted PI controller is proposed for handling nonlinearities to ensure robust control. But it takes long time to converge to an optimal solution. Whale Optimization Algorithm (WOA) [15] Coot Bird Optimization (CBO) algorithm of [16] effectively explores the global search space, minimizing the chance of getting trapped at local minima, despite it needs careful tuning and computational requirement is high.

The unique aspect of the proposed approach lies in the integration of an advanced hybrid charging system that combines a FA-PI controller with an IBC for EV charging. This system addresses key challenges in grid power management and voltage regulation by efficiently utilizing RESs, particularly PV systems. The IBC enhances the PV system's output voltage, making it suitable for charging EVs and grid integration. Unlike conventional Boost converters, the IBC design mitigates voltage and current ripples while achieving a higher improved efficiency, overcoming inefficiencies and operational challenges under varying insolation and load conditions. The novel optimization of the PI controller using the Firefly Algorithm ensures faster response times and improved system stability, surpassing traditional methods. The FA-PI controller offers faster response times and enhanced dynamic performance compared to conventional PI controllers, ensuring robust operation under rapidly changing conditions. Unlike computationally intensive methods like PSO or convergence-slow algorithms like GWO, the Firefly Algorithm provides a balance of computational efficiency and accuracy, allowing for precise tuning of PI parameters with minimal processing requirements. Additionally, the bidirectional converter effectively manages both the charging and discharging cycles of the battery, promoting a more reliable and dynamic energy management system. This integrated approach leads to a significant improvement in efficiency, highlighting the system's potential to revolutionize EV charging infrastructure with better performance and grid compatibility.

2 Description of Proposed System

Hybrid charging framework is proposed for EVs, utilizing advanced technologies integrating PV with electrical grid as shown in Figure 1. The lower voltage from PV system is enhanced using IBC, where the converter is controlled by a PWM generator which operated based on the inputs from FA-PI controller. This ensures optimal voltage regulation by adjusting the PWM pulses to maintain the desired DC voltage levels.

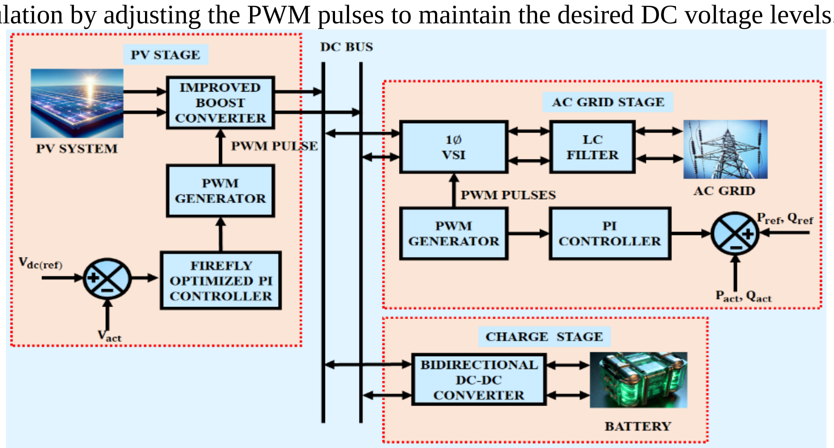

Fig. 1. Framework of the proposed system

The stabilized DC link voltage is fed to 1Φ VSI coupled with LC filter managing the integration of grid power. This is also controlled by a PWM generator and a PI controller ensure synchronized and stabilized power supply is fed to the DC bus. The charging stage features a bidirectional DC-DC converter, regulating the charging and discharging process of EV battery. The supports in maintaining bidirectional flow of power between the battery and DC bus, enhancing reliability and flexibility.

3 System Modelling

3.1 Design of PV System

The primary component of PV system is solar cell, where several solar cells are attached in series to form PV module. This includes photocurrentI_{Ph}, diode linked in parallel with source, a resistance in seriesR_s, shunt resistance R_{sh} arranged in parallel with diode. The equation between output voltage and current for equivalent circuit is given by

$$I_{pv} = I_{ph} - I_{sh}\left(exp\left(\frac{q(V_{pv}+IR_S)}{aN_SKT}\right) - 1\right) - \frac{V_{pv}+IR_S}{R_S} \tag{1}$$

Where photocurrent is represented as I_{ph}, saturation current as I_{sh}, diode ideality factor as a, electron charge as q, Boltzmann's constant as K, cell temperature as T and solar PV cell attached in series. However, to ensure PV system operates efficiently and meets the required voltage levels for charging EVs or grid, DC-DC converters has to be integrated into the system.

3.2 Operation of Improved Boost Converter

The proposed IBC shown in Figure 2, is suitable for applications requiring high voltage conversion ratios such as PV systems, ensuring better performance. The inclusion of additional passive components like inductors L_2, capacitors C_2 ,C_3, C_4 and diodes D_2 ,D_3, D_4,D_5 increases the efficiency significantly without requiring extreme duty cycles. The switching operation of proposed converter is represented in Figure 3.

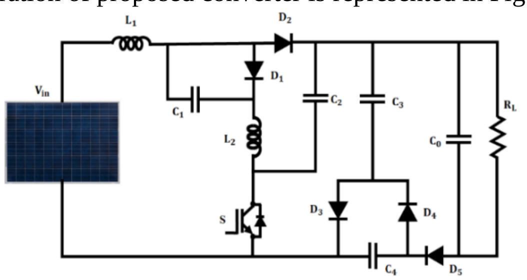

Fig. 2. Configuration of Proposed Improved Boost Converter

When switch S is in ON state, diodeD_3 and D_5 are in reversed bias condition. The input voltage V_{in}charges the inductorL_1. Simultaneously, capacitor C_1 is charged through diode $D_1$and inductor L_2 gets charged as well. At this mode, diodes D_3 and D_5 prevent current flow, owing to reversed bias condition, isolating the output side. Moreover, Capacitors C_2 and C_3 retains energy from previous cycles and the load is powered by the charge inC_0.

The voltage across inductor L_1 and L_2 is expressed as

$$V_{L_1} = V_{in} \tag{2}$$

$$V_{L_2} = V_{in} - V_{C_1} \tag{3}$$

$$V_{C_1} = V_{C_2} = V_{in} \tag{4}$$

$$V_{in} = V_{C_3} - V_{C_4} \tag{5}$$

Similarly, when switch S is turned OFF, diodes D_1, D_2 and D_4 are in reversed biased. The stored energy in inductorL_1 is released through diodeD_2, charging capacitors C_3 and supply to load. Likewise, energy from inductor L_2 is released through diode D_3 charging capacitorC_2. Diodes D_1, D_2 and D_4 block the current flow in the respective paths, assuring efficient transfer of energy. Capacitors C_2 and C_3 aids in booting the output voltage while maintaining stabilized power supply to the load.

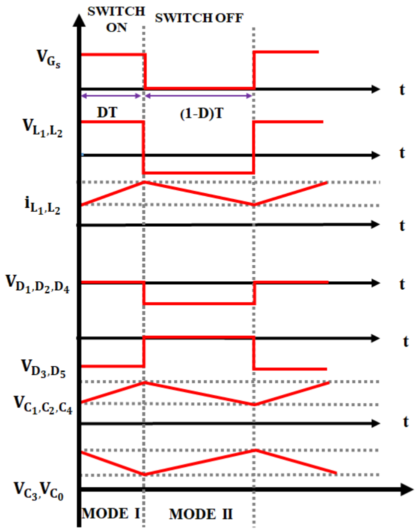

Fig. 3. Switching Operation of Proposed Converter

$$V_{in} = V_{L_1} + V_{L_2} - V_{C_1} - V_{C_2} + V_{C_3} \tag{6}$$

$$V_{L_1} = V_{C_3} \tag{7}$$

$$V_{L_2} = V_{C_2} \tag{8}$$

In accordance with identical inductors indicated by $L_1 = L_2 = L$ and incorporating Equations (4) and (6), the voltage across capacitor $C_3$is expressed as

$$V_{L_{1,2}} = \frac{3V_{in} - V_{C_3}}{2} \tag{9}$$

Where $V_{C_3} = V_{out}$

On applying voltage second balance principle to inductorsL_1 and L_2

$$\int_0^{DT} V_{in} dt + \frac{1}{2}\int_{DT}^{T} \left(\frac{3V_{in} - V_{out}}{2}\right) dt = 0 \tag{10}$$

$$V_{in}DT + \left(\frac{3V_{in} - V_{out}}{2}\right).(1 - D)T = 0 \tag{11}$$

Therefore, the gain of proposed Improved Boost converter is expressed as

$$M = \frac{V_{out}}{V_{in}} = \frac{3-D}{1-D} \quad (12)$$

The Equation (14) demonstrates alignment of output voltage (V_{out}) with input PV voltage (V_{in}) and the duty cycle D. However, controller operation is essential to ensure efficient and reliable operation of converter.

3.3 Firefly Algorithm Optimized PI Controller

The FA is an effective approach for optimizing PI controller, such as K_p and K_i and integrates the natural behavior of fireflies to optimize the PI controller parameters for enhanced system performance. The algorithm begins by initializing a population of fireflies, each representing a set of PI parameters. The attractiveness of each firefly is determined by its brightness, which is linked to the performance of the objective function. Fireflies are attracted to brighter ones, representing better solutions, and they move towards these brighter fireflies according to an attractiveness function that depends on their relative distance. The movement of each firefly is governed by an equation that incorporates both the attractiveness and a randomization factor, ensuring diversity in the search process. Over several iterations, the fireflies converge to the optimal set of PI parameters, minimizing the objective function and improving system response. This approach provides a more efficient and faster optimization process compared to traditional methods, offering better stability and control performance in dynamic systems. The attractiveness of firefly is influenced by its brightness, which is related with objective function. The corresponding flowchart is provided in Figure 4.

In the context of PI controller optimization, each firefly represents a potential solution, defined by specific values of K_p andK_i. Brighter fireflies attract others, guiding the swarm toward optimal parameters. The movement of a firefly toward another is influenced by its relative brightness, a decay factor, and randomization to ensure global exploration and prevent getting stuck in local optima. By iteratively adjusting the positions of fireflies based on this attraction mechanism, FA efficiently converges to optimal K_p andK_i values that minimize error and enhance the dynamic performance of the PI controller. The brightness I is defined as follows,

$$I(r) = I_0 e^{-\lambda r^2} \quad (13)$$

Where light intensity is specified asI_0, distance between fireflies as r and coefficient of light absorption is denoted as λ. The attractiveness $\beta_0$between two fireflies is expressed by

$$A(r) = \beta_0 e^{-\lambda r^2} \quad (14)$$

Where $\beta_0$specifies the attractiveness coefficient at $r = 0$

3.4 Attraction and Movement

Each firefly gets attracted to brighter fireflies that is towards better solution. The movement of firefly$i$ towards a brighter firefly$j$ is governed by the attractiveness and distance between them:

$$x_i^{t+1} = x_i^t + A_0 e^{-\lambda r_{ij}^2}\left(x_j^t - x_i^t\right) + \alpha \epsilon_i^t \quad (15)$$

Where r_{ij} defines the distance between firefly i and j, α randomization parameter ϵ random vectors of range 0 and 1. Now update the position of fireflies depending on Equation (15). This ensures that fireflies move forward the brighter (optimal) solution, thereby iteratively improving the population. After several iterations, the highest brightness (optimal performance) represents the best values of K_p andK_i for PI controller.

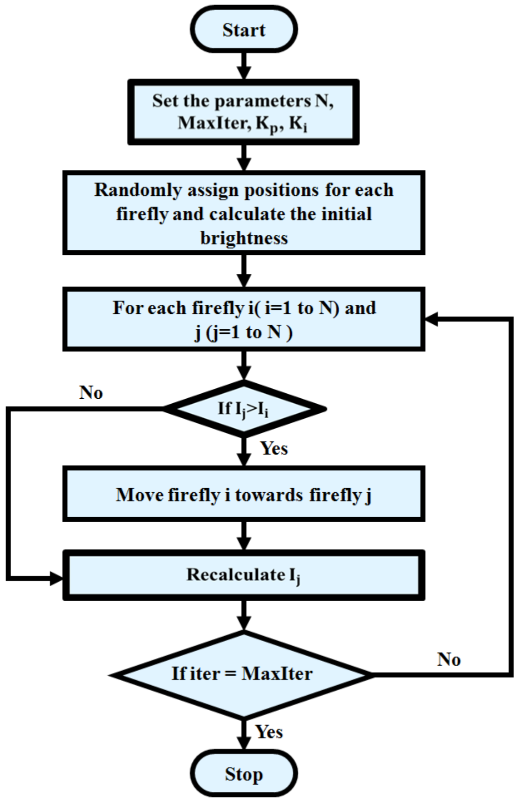

Fig. 4. Flowchart of FA-PI controller optimization

4 Results and Discussion

The system performance is examined in this section utilizing MATLAB Simulink software. The system is assessed with the proposed Improved Boost converter and the FA-PI controller. Table 1 lists the simulation parameters of proposed system designed.

Table 1. Specification of Design Parameters

Parameter	Rating	Parameter	Rating
Solar PV System			
$Total\ power$	$5kW$	$No.of\ Panels$	20
I_{sc}	$8.95\ Amps$	I_m	$8.35\ Amps$
V_{oc}	$37.25\ V$	V_m	$29.95\ V$
Improved Boost Converter			
L_1, L_2	$4.7mH$	C_1, C_2, C_3, C_4	$22\mu F$
C_0	$2200\mu F$	$Switching\ Frequency$	$10kHz$

The waveform for temperature in Figure 5, demonstrates variation of solar panel. Initially, the temperature is maintained at a constant of 35℃, and then drops to 30℃ at approximately 0.2s, revealing lower temperatures. Whereas, the solar intensity is observed to be constant at $800W/m^2$ till 0.4s, after slight increase is experienced resulting in a stabilized value of $1000W/m^2$, further.

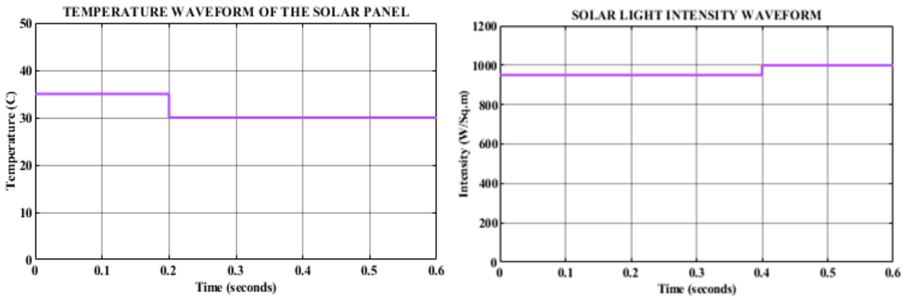

Fig. 5. Temperature and Intensity Waveforms of PV system

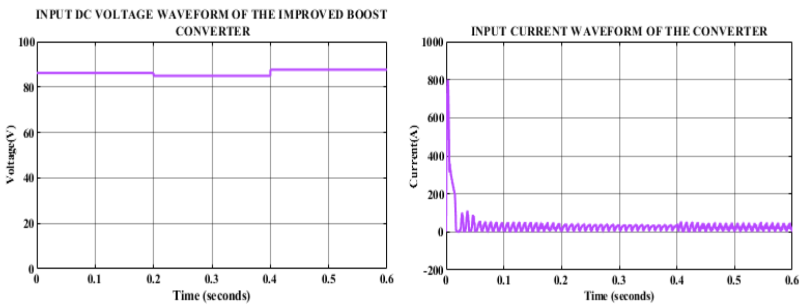

Fig. 6. Input PV V-I Characteristic Waveforms

The DC input voltage and current (V-I) from PV system, which is utilized as input to converter is illustrated in Figure 6. The input DC voltage for converter is relatively stable at 85V initially, after slight drop in voltage is seen owing to changes in temperature. After this the increase, in intensity results with increased voltage level of 85V, for the rest of the period. Concurrently, the current for input initially attains a sharp spike reaching approximately 800A. After, certain period the current decreases and stabilize around 65A, with small oscillations.

The performance of proposed converter using PI and FA-PI controller is illustrated in Figure 7. It is noticed that, by using controller a stabilized DC link voltage of 300V is accomplished. However, by using PI controller stabilization of voltage is achieved after 0.55s, whereas the FA-PI controller shows optimal performance at 0.43s. The current waveform of proposed converter reveals spikes at initial stage, followed by current measuring 17A with slight distortions. The Figure 8 demonstrated three subplots illustrating the voltage, current and State of Charge (SOC) of a battery over period of .0.6s. It is noticed that, the voltage of battery remains constant at 48A with current around 3A, showing minimal variation. Moreover, an SOC of 80%, is attached.

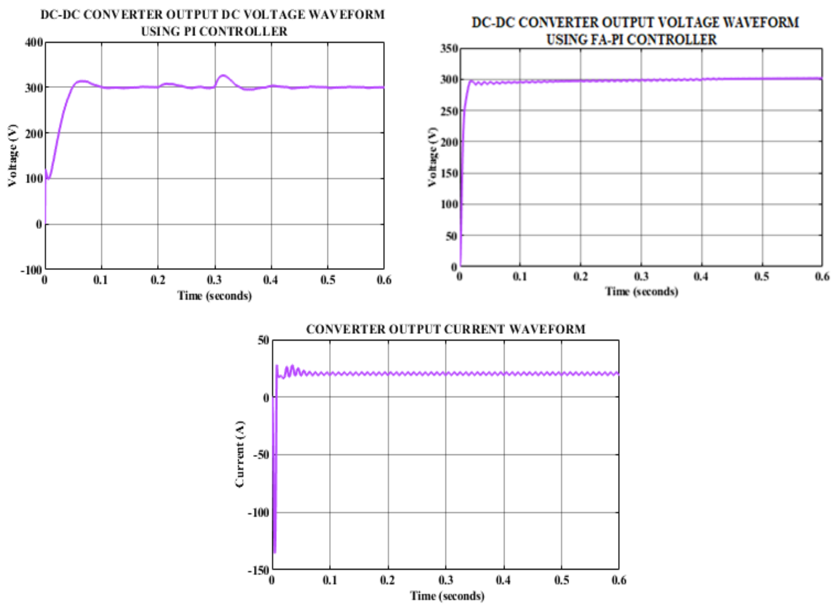

Fig. 7. Improved Boost Converter V-I Characteristics

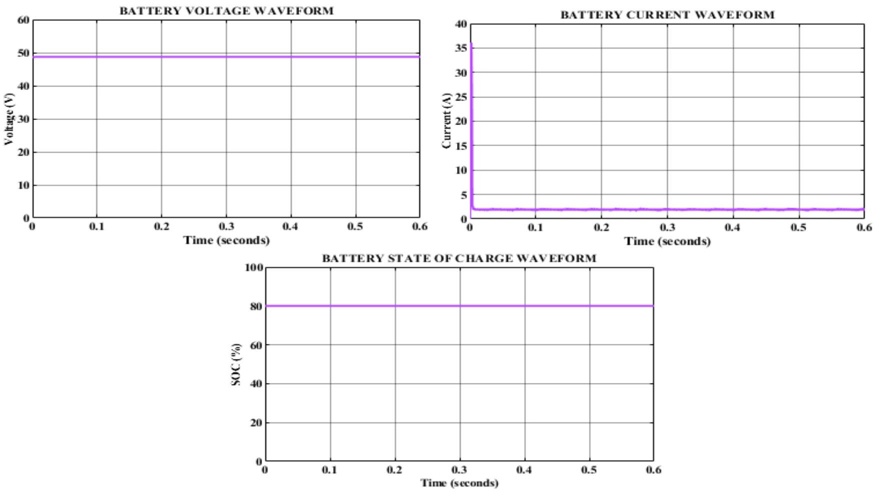

Fig. 8. Battery Characteristics (Voltage, Current, SOC)

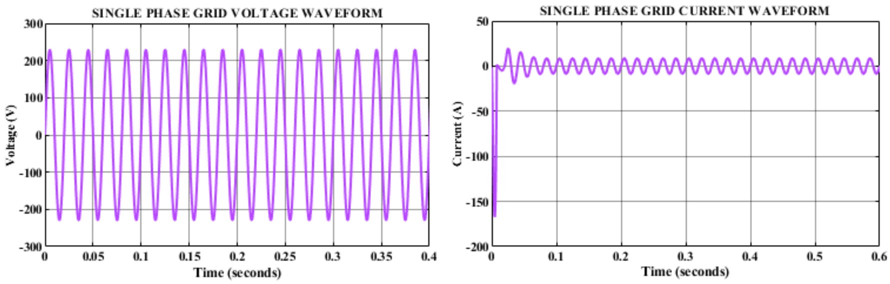

Fig. 9. Single Phase Grid Characteristics Waveform

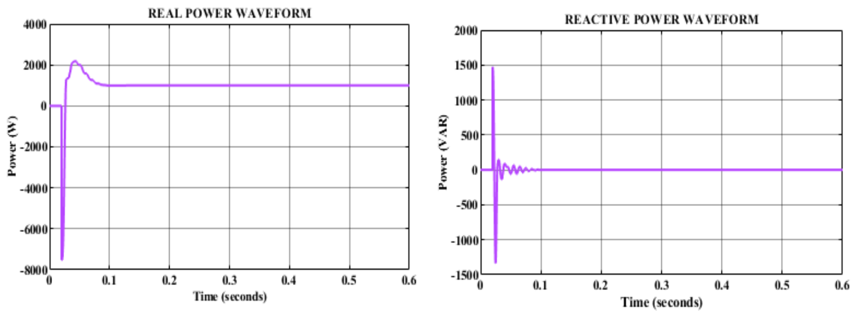

Fig. 10. Real and Reactive Power Waveforms

The waveform showing characteristics of single phase grid is depicted in Figure 9. The grid voltage shows stabilized voltage of 230V, with current of 8A is attained. This relation indicates purely resistive load, where voltage and current waveforms are synchronized. The waveforms in Figure 10, demonstrates that, with initial fluctuations, the real power stabilizes and provides steady real power delivery, whereas the reactive power waveform shows initial spikes and stabilizes. This indicates that efficient and consistent delivery of power is accomplished with minimal reactive losses.

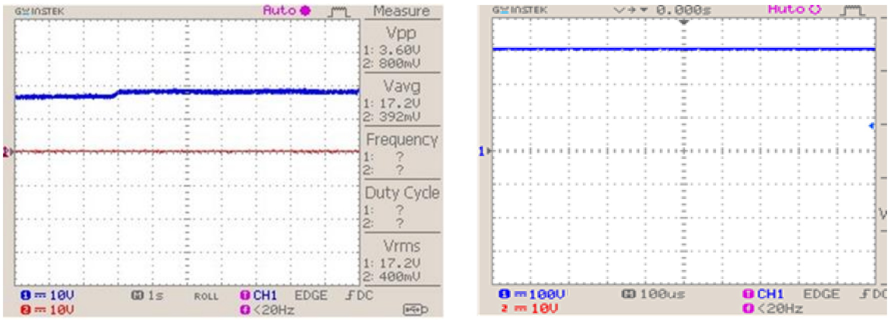

Fig. 11. Experimental validation of PV output under varying conditions and converter output

Figure 11 denotes the experimental outputs of PV system under varying conditions and the outcomes exhibits a surge in voltage level. However, the attained converter output maintains a steady value of 300V irrespective of the variations of irradiation and temperature.

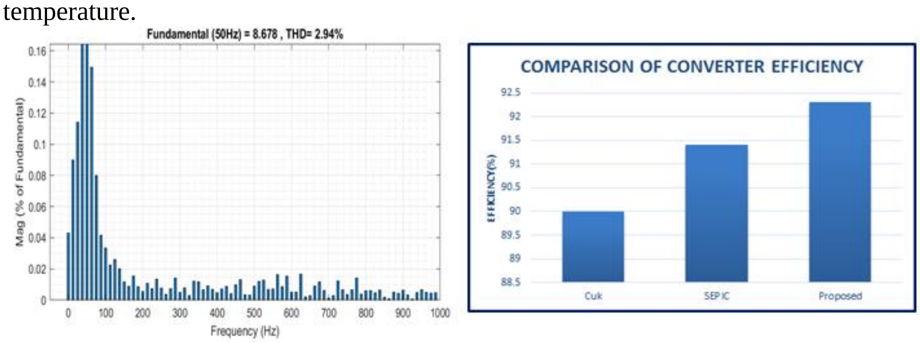

Fig. 12. Grid Current THD Waveform and Efficiency Comparison

The THD waveform for grid current is represented in Figure 12, indicating THD of 2.94%.The efficiency of proposed converter shown in Figure 12 compares Cuk [17] and SEPIC [18]. The proposed improved boost converter grades with improved efficiency of 92.30%, whereas efficiency ranging from 88% to 91.4% is accomplished by converters of [17-18].

Table 2. Comparison of proposed converter with existing ones

Converters	Total number of components			Efficiency (%)
	Switches	Capacitors	Inductors	
Boost [19]	2	4	2	90.21

Interleaved Buck-boost [20]	4	3	3	85.1
High gain Cuk [21]	1	6	4	90.3
High gain SEPIC [22]	3	3	1	91.4
Proposed IBC	1	5	2	92.30

Table 2 represents the comparison of the proposed converter with existing ones in literature in which the proposed IBC provides an improved efficiency of 92.3% while the Boost, Interleaved Buck-boost, high gain Cuk and high gain SEPIC exhibits an efficiency of 90.21%, 85.1%, 90.3% and 91.4% respectively.

Table 3. Comparison of Controller Settling Time

Controller	$\boldsymbol{Rise\ Time\ (t_r)}$	$\boldsymbol{Peak\ Time\ (t_p)}$	$\boldsymbol{Settling\ Time\ (t_s)}$
PI	$\mathbf{0.01}\boldsymbol{s}$	$\mathbf{0.03}\boldsymbol{s}$	$\mathbf{0.55}\boldsymbol{s}$
GWO-PI	0.001s	0.02s	0.485s
FA-PI	$\mathbf{0.001}\boldsymbol{s}$	$\mathbf{0.01}\boldsymbol{s}$	$\mathbf{0.43}\boldsymbol{s}$

The performance of PI controller, GWO-PI controller and FA-PI controller is tabulated in Table 3, based on converter control. From the table it is evident that the proposed FA-PI controller ranks best with faster settling time of 0.43s, compared to PI controller with 0.5s, GWO-PI controller with 0.485s and this makes the FA-PI controller a superior choice towards regulation of converter.

5 Conclusion

This paper presents novel solution for EV charging system with energy management using improved boost converter and FA-PI controller. The effective combination of PV, grid and battery storage system offers continuous and reliable power supply for charging of EV. The proposed IBC enhances the energy conversion process, with FA-PI controller supports is maintaining stabilized operation. The MATLAB results demonstrates that the proposed converters stands out with higher efficiency of 92.30%. Moreover, the system developed has achieved reduced THD of 2.94%, indicating improved quality of power. Significant improvements from the results makes the proposed system highly suitable for charging of modern EVs. Future work, could explore advanced machine learning for predictive maintenance and control, together with incorporation of multiple RESs for enhanced versatility.

References

1. Blaabjerg, F., Yang, Y., Kim, K. A., Rodriguez, J.: Power electronics technology for large-scale renewable energy generation. Proceedings of the IEEE 111, 335-355 (2023).
2. Gulzar, M. M., Iqbal, A., Sibtain, D., Khalid, M.: An innovative converterless solar PV control strategy for a grid connected hybrid PV/wind/fuel-cell system coupled with battery energy storage. IEEE Access 11, 23245-23259 (2023).

3. Kavin, K. S., Karuvelam, P. S., Devesh Raj, M., Sivasubramanian, M.: A Novel KSK Converter with Machine Learning MPPT for PV Applications. Electric Power Components and Systems (2024).
4. Vandana, J., Singh, B.: A grid connected PV array and battery energy storage interfaced EV charging station. IEEE Transactions on Transportation Electrification, 9, 3723-3730 (2024).
5. Kumar, N., Singh, H. K., Niwareeba, R.: Adaptive control technique for portable solar powered EV charging adapter to operate in remote location. IEEE Open Journal of Circuits and Systems 4, 115-125 (2023).
6. Ilahi, T., Izhar, T., Qaisar, S. M., Shami, U. T., Zahid, M., Waqar, A., Alzahrani, A.: Design and performance analysis of ultra-wide bandgap power devices-based EV fast charger using bi-directional power converters. IEEE Access 11, 25285-25297 (2023).
7. Pathak, P. K., Yadav, A. K., Padmanaban, S., Twala, B., Kamwa, I.: Design of smart battery charging circuit via photovoltaic for hybrid electric vehicle. IET Renewable Power Generation (2023).
8. Pandey, R., Singh, B.: A Cuk converter and resonant LLC converter based E-bike charger for wide output voltage variations. IEEE Transactions on Industry Applications 57, 2682-2691 (2021).
9. Kushwaha, R., Singh, B., Khadkikar, V.: An isolated bridgeless Cuk–SEPIC converter-fed electric vehicle charger. IEEE Transactions on Industry Applications 58, 2512-2526 (2021).
10. Navamani, J. D., Geetha, A., Almakhles, D., Lavanya, A., Mohamed Ali, J. S.: Modified LUO high gain DC-DC converter with minimal capacitor stress for electric vehicle application. IEEE Access 9, 122335-122350 (2021).
11. Li, X., Guo, L., Huang, D., Li, P., Zhu, L., Zhu, J., Wang, Y., Wang, C.:A reduced RLC impedance model for dynamic stability analysis of PI-controller-based DC voltage control of generic source-load two-terminal DC systems. IEEE Journal of Emerging and Selected Topics in Power Electronics 9, 7264-7277 (2020).
12. Haque, M. R., Salam, K. M., Razzak, M. A.: A modified PI-controller based high current density DC–DC converter for EV charging applications. IEEE Access 11, 27246-27266(2023).
13. Reddy, M. M., Varma, P. S., Lenine, D.: Improving gain of real time PI controller using particle swarm optimization in active power filter. Microprocessors and Microsystems 97, 104760 (2023).
14. Younus, S. M., Kutbay, U., Rahebi, J., Hardalaç, F.: Hybrid gray wolf optimization–proportional integral based speed controllers for brush-less dc motor. Energies 16, 1640 (2023).
15. Yang, X., Guan, J.: PI parameters tuning for frequency tracking control of wireless power transfer system based on improved whale optimization algorithm. IEEE Access (2024).
16. Hussien, A. M., Turky, R. A., Alkuhayli, A., Hasanien, H. M., Tostado-Véliz, M., Jurado, F., Bansal, R. C.: Coot bird algorithms-based tuning PI controller for optimal microgrid autonomous operation. IEEE Access 10, 6442-6458 (2022).
17. Haider, Z., Ulasyar, A., Khattak, A., Zad, H. S., Mohammad, A., Alahmadi, A. A., Ullah, N.: Development and Analysis of a Novel High-Gain CUK Converter Using Voltage-Multiplier Units. Electronics 11, 2766 (2022).
18. Maroti, P. K., Padmanaban, S., Holm-Nielsen, J. B., Bhaskar, M. S., Meraj, M., Iqbal, A.: A new structure of high voltage gain SEPIC converter for renewable energy applications. IEEE Access 7, 89857-89868 (2019).
19. Ramanathan, G. G., Urasaki N.: Non-isolated interleaved hybrid boost converter for renewable energy applications. Energies 15(2), 610 (2022).

20. Carbajal-Retana M., Hernandez-Gonzalez L., Ramirez-Hernandez J., Avalos-Ochoa J. G., Guevara-Lopez P., Loboda I., Sotres-Jara L. A.: Interleaved buck converter for inductive wireless power transfer in DC–DC converters. Electronics 9(6), 949 (2020).
21. Haider Z., Ulasyar A., Khattak A., Zad HS., Mohammad A., Alahmadi A. A., Ullah N.: Development and Analysis of a Novel High-Gain CUK Converter Using Voltage-Multiplier Units. Electronics 11(17), 2766 (2022).
22. Maroti P. K., Padmanaban S., Holm-Nielsen J. B., Bhaskar M. S., Meraj M., Iqbal A.: A new structure of high voltage gain SEPIC converter for renewable energy applications. IEEE Access 7, 89857-89868 (2019).