International Journal of Advanced Trends in Engineering and Management
(ISSN 2583-7052)

Vol. IV, No. 06, pp. 33-43, June

Implementation of Interleaved Boost Converter for Improving Performance of PV-Grid System

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ABSTRACT: Photovoltaic (PV) systems with grid networks have developed in reaction to the growing demand for Renewable Energy Sources (RES). RES include wind, solar, hydropower, geothermal and biomass. These resources offer sustainable substitutes to fossil fuels. Among these RES, solar energy is considered as the utmost capable energy source. Nevertheless, due to the fluctuating and inconsistent power formed by the PV system due to dynamical environmental conditions, the power needs to be stepped up for meeting the requirements of the Grid. PV system output power is boosted by Interleaved Boost Converter (IBC) that facilitates enhanced reliability and improved efficiency. Particle Swarm Optimization (PSO) based Maximum Power Point Tracking (MPPT) technique is employed to finely tune the Fuzzy controller parameters. The enhanced DC power is delivered to 3Φ Voltage Source Inverter (VSI), which translates a fixed DC voltage into AC voltage. Proposed system is implemented in MATLAB and comprehensive simulation analysis validate the improved tracking efficiency of 95% and converter efficiency of 92.81% in PV grid system.

Keywords: PV, RES, Maximum Power Point Tracker, Interleaved Boost Converter, PI, Particle Swarm Optimization, PWM.

1. Introduction

Due to population growth and technological advancement, the demand of global energy was increased. Among the energy, solar energy is deliberated as maximum feasible solutions to energy catastrophe [1]. Fossil fuels make over half of global energy production and are the main sources of carbon-dioxide emissions in the power sector. Balancing energy growth with environmental protection is crucial for addressing climatic changes [2].RES reduce global warming and transform the electricity network and considered as sustainable energy supply. In RES, solar energy is considered as the utmost capable energy source [3].

PV is considered as the most popular source of energy and become influential in refining energy access in deprived areas, subsidising to socio-economic growth and dropping dependence on fossil fuels. [4]. Various DC-DC converter topologies has been designed for solar energy harvesting, including Boost, Buck, Cuk and Buck-Boost converter. In particular, development of DC-DC Boost Converter (BC) is crucial for regulating low and unstable DC output voltage from PV arrays. Although, the BC has notable drawbacks, including poor proficiency due to significant output diode reverse recovery loss. Moreover, as duty ratio rises, current and voltage ripples become more prominent, resulting in higher conduction losses [5-6]. The output voltage is lesser than the input voltage when buck type DC-DC converters are utilized. Meanwhile, buck converters are integrally nonlinear and time varying systems due to their switching operation, the design of high performance control strategy is usually a challenging issue [7-8].

Buck-boost converter is suitable for the initial two stage PV grid-connected inverter due to its broad input voltage range. It lowers inductance loss and boost conversion efficiency. However, it face challenges with high gain due to efficiency drops and potential issues with mode transferring when input and output voltages are close[9-10]. Cuk converter is a special type of converter which operates on the principle of indirect energy transfer, storing energy in inductors and releasing it to the output. Although being an inverting converter, the switch is under a proportion of current stress [11-12].

MPPT, a method practised in solar systems to abstract maximum power from PV panels. Typically, MPPT devices are merged into structures that convert voltage or current via electric power converters. MPPT is incorporated with PV system for mining extreme power and it is broadly classified into various types including Perturbation and Observation (P&O), Incremental Conductance (INC), Hill Climbing (HC) and Fuzzy Logic Controller (FLC).[13-14].P&O technique is extensively used and easy to appliance. It amends the voltage to move closer to the desired point by relating the operating points and the allotted values power. Nonetheless, Due to quantization effect and numerical approximations, the presentation of the P&O algorithm employed in a digital device are exaggerated. Additionally, P&O struggle to trace the MPP accurately during promptly varying atmospheric circumstances [15].

INC aims to maximize the output power of a solar panel by enthusiastically altering the functioning point to match the MPP of the panel's power-voltage curve. It overcomes the disadvantages of P&O method in tracking the peak power under fast varying atmospheric conditions. Nonetheless, INC method have various shortcomings such as sudden increase in irradiance cause misinterpret in the direction of maximum power point, slow convergence and oscillations [16]. FLC has appeared as a proficient MPPT method for nonlinear PV, excluding the essential detailed system material. It achieves the MPPT target by utilizing participation functions designed to handle uncertainties caused by shifting environmental conditions. FLC adapt to change in environment conditions and it improves the overall efficiency of the PV, reduced oscillations [17]. Moreover, to fine tune the parameters of FLC the research introduces PSO algorithm. Thereby, optimal power is attained from the PV resulting in enhanced system performance.

The main contribution of the research includes:

- The low DC voltage from PV is enhanced utilizing IBC converter that uses multiple boost converter stages connected in parallel.
- PSO is employed to finely tune the FLC MPPT controller parameters and applied to abstract maximum power from PV panels, under varying environmental circumstances.
- LC filter integrated between VSI and grid minimizes the harmonics and supplies harmonic free AC supply to grid.

2. Literature Survey

Shaoxiong Nie *et al* (2025) [18] have developed an ultra-low input voltage of a high gain DC-DC converter. It is crucial for voltage conversion and effectively supplies energy to sensors, batteries, and other devices. The converter utilizes the Inductor-Switch-Capacitor (LSC) to boost network, which offers various benefits such as high voltage gain, increased output power, and straightforward control mechanisms. Though, this ultra-low-voltage boost converters often have limited output power, hindrance occur in utilizing the full available energy from low-voltage sources like energy harvesting systems.

Hossein Gholizadeh *et al* (2024) [19] have established a non-isolated DC-DC converter by voltage-lift technique. It steps up DC voltage without using a transformer (non-isolated), and utilizes a quadratic boost topology combined with a voltage-lift technique to attain a high gain in voltage and creating it appropriate for high-voltage presentations. Nonetheless, the leakage inductance of the windings causes residual flux and current, which forces a dramatic high voltage stress to the switch.

Immanuel N. Jiya *et al* (2023) [20] have proposed a Renewable Energy Source (RES) incorporation of a multiport DC-DC converter. It permits the flawless combination with numerous RES, containing Photovoltaics (PV), wind power, and fuel cell systems. With high voltage gain both unidirectional buck and boost operations are performed and from the input, power is transmitted to DC and AC buses individually and concurrently. Nevertheless, it has various drawbacks such as, it comprises high number of components, leading to increased system costs thus, reducing system applicability in RES integrations.

Shruti Prajapati *et al* (2024) [21] have implemented a heightened enactment of grid cohesive solar PV system using adaptive MPPT technique. To excerpt the extreme PV power beneath stochastic atmospheric conditions, MPPT technique is required. Usually, MPPT devices are assimilated into an electric power converter system and it is incorporated with a PV system for mining maximum power. Though, it have instability and oscillations near the MPP under rapidly changing environmental conditions, especially during sudden irradiance fluctuations.

Yassine El Alami *et al* (2024) [22] have executed a Discretized PV system with enhanced MPPT control to maximize PV energy utilization. Once discretized PV topology is employed, energy is formed through numerous variation process. Energy is formed independently or at a definite step of the PV arrangement. However, it necessitates a virtuous accepting of how the matching stages operates when other stages are present.

3. Block Diagram Description

The suggested block diagram is displayed in figure 1. The PV module generates voltage and current by utilizing incident solar radiation. Due to fluctuation and various climatic changes, the voltage attained from PV system is very low, to enhance the power IBC is deployed to efficiently boost low voltage.

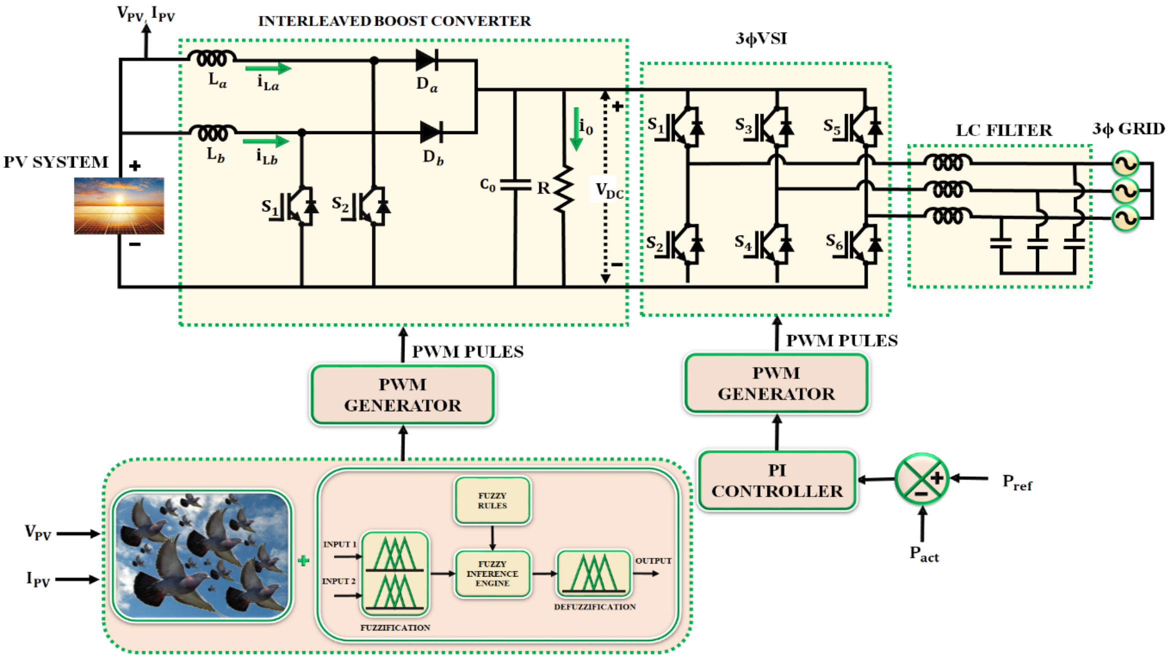

Figure 1: *Proposed model block diagram.*

FLC based MPPT algorithm is utilized to track maximum power under dynamic and steady state condition of PV system. Moreover, to enhance the tracking performance PSO optimization, is employed which to fine tunes the Fuzzy MPPT controller parameters. The attained duty cycle is fed to PWM generator for generation of pulses. Based on the switching pulse the converter operation is carried out. The enhanced DC voltage is delivered to 3Φ VSI, which alters a fixed DC voltage into AC voltage. The LC filter integrated between VSI and grid minimizes the harmonics and supplies free harmonic AC stream to grid. Thereby, actual grid synchronization is achieved.

4. Proposed System Modelling

4.1 PV System Modelling

Solar panels transform solar radiation into electrical energy. PV system is composed of series and parallel connections of PV panels. Current generated from the solar panel is given in equation (1) which highly relies on the irradiance and temperature values. The PV equivalent circuit is illustrated in figure 2

$$I_{pv} = (I_{pv,n} + K_I\,\Delta_T)\frac{G}{G_n} \tag{1}$$

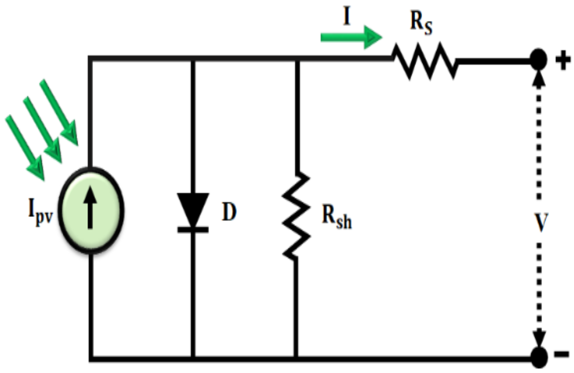

Figure 2: *PV equivalent circuit.*

The PV panel current(I_{pv}) is determined by factors such as irradiance (G) on the panel's surface and the open-circuit current coefficient K_I. At nominal conditions$(25°C\ and\ 1000\ W/m^2\ irradiance)$, the panel generates $I_{pv,n}$, T signifies the actual temperature, T_n is the nominal temperature, and $\varDelta T$ ($\varDelta T = T - T_n$) denotes the temperature difference. The nominal saturation current follows the relationships outlined in Equations (2) and (3).

$$V_t = \frac{N_s, K_t}{q} \tag{2}$$

$$I_0 = \frac{I_{sc,n} + K_I \Delta_T}{\exp\left(\frac{V_{oc,n} + K_V \Delta_T}{aV_t}\right) - 1} \tag{3}$$

Number of series-connected cells (N_s) determines system configuration, while k (Boltzmann constant, $1.38 \times \frac{10^{-23} J}{K}$) and q (electron charge, $1.602 \times 10^{-19} C$). Open-circuit voltage coefficient (K_V) influences voltage behavior, while $I_{sc,n}$ and $V_{oc,n}$ represent nominal open-circuit voltage and short-circuit current, respectively. The series cell voltage $(V_t)$and reverse saturation or leakage current (I_0) contribute to overall electrical performance. The PV panel's output current is derived using Equation (4).

$$I = I_{pv} - I_0 \left[exp\left(\frac{V}{V_t a}\right) - 1 \right] \tag{4}$$

The diode ideality constant, typically ranging between 1 and 1.5, helps characterize the diode's behavior in the circuit. The current (I) represents the electrical output drawn through the PV panel.

$$I = I_{pv} - I_0 \left[exp\left(\frac{q(V+IR_S)}{kT}\right) - 1 \right] - \frac{1}{R_{sh}}(V + IR_S) \tag{5}$$

Equation (5) defines the current in the PV equivalent circuit, accounting for the effects of both series and parallel resistances in the system. Although power attained from PV system is clean and sustainable it is highly infuenced by the environmental conditions. Therefore, it is essential to step-up the PV power by DC converter.

4.2 Interleaved Boost Converter

The diagram of IBC is shown in Figure 3. It contains inductor L_a and L_b are parallel to each other, switch S_1 and S_2 are parallel to each other, Diode D_a and D_b are parallel to each other. Thus developing two parallel channels among input and output circuits. The gate signal are delivered by two switches forming 180° out of phase.

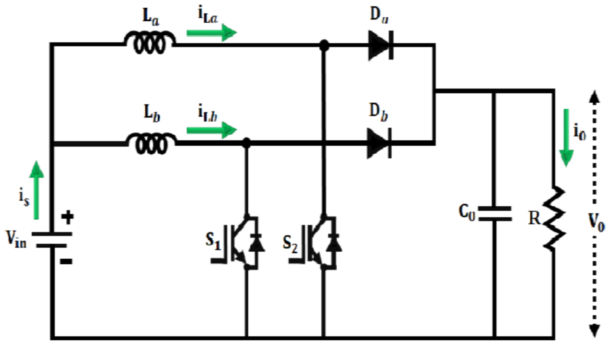

Figure 3: *Schematic diagram of Interleaved Boost Converter*

The expression 6 is used to define the inductor value, through D_{max} being the maximum duty cycle value of 0.75 and V_{min} being the smallest input voltage (100V). The peak inductor ripple current is 20% of the average inductor current.

$$L_{phase} = \frac{V_{in} D}{f_s \Delta i_L} \tag{6}$$

Capacitor rate is attained via expression 7 by taking 2% peak to peak capacitor ripple.

$$\Delta V_{out} = \frac{V_{in} D}{T_s C_{out} R} \tag{7}$$

With this technique, the output voltage ripple is decreased and the ripple frequency is doubled.

4.2.1 Modes of Operation:

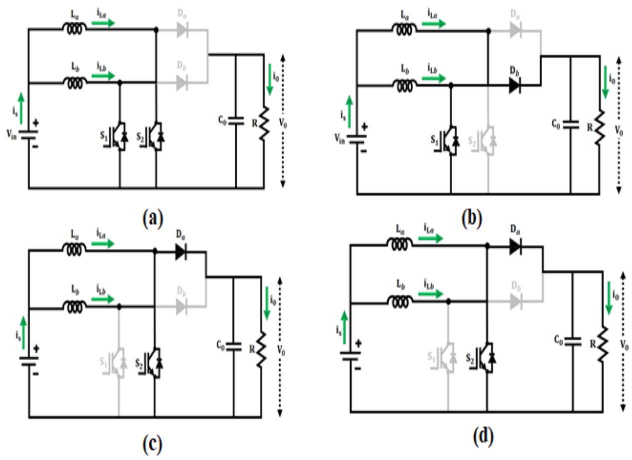

Figure 4: *IBC Converter (a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4.*

Mode 1: In mode 1, the Switches S_1 and S_2 are in on state, Diodes D_a and D_b are in off state, Inductors L_a and L_b are in on state and Capacitor

C_0 is in on condition. Figure 4 a displays the diagram of this mode.

$$\frac{di_{L1}}{dt} = \frac{V_S}{L_1} \tag{8}$$

$$\frac{dv_0}{dt} = \frac{V_0}{RC} \tag{9}$$

$$\frac{di_{L2}}{dt} = \frac{V_S}{L_2} \tag{10}$$

Mode 2: In this mode, the Switch S_1 is in on state and switch S_2 is in off state, Diode D_a is in off state and D_b is in on state, Inductors L_a is in on state and L_b is in off state and Capacitor C_0 is in on state. Figure 4 b express the equivalent circuit for this mode.

$$\frac{di_{L1}}{dt} = \frac{V_S}{L_1} \tag{11}$$

$$\frac{di_{L2}}{dt} = \frac{V_S}{L_2} - \frac{V_0}{L_2} \tag{12}$$

$$\frac{dv_0}{dt} = \frac{i_{L2}}{C} - \frac{V_0}{RC} \tag{13}$$

Mode 3: In this mode, the Switch S_1 is in off state and S_2 is in on state, Diode D_a is in on state and D_b is in off state, Inductors L_a and L_b is in off state and CapacitorC_0 is in on state. Figure 4 c illustrates the equivalent circuit for this mode.

$$\frac{di_{L1}}{dt} = \frac{V_S}{L_1} - \frac{V_0}{L_1} \tag{14}$$

$$\frac{di_{L2}}{dt} = \frac{V_S}{L_2} \tag{15}$$

$$\frac{dv_0}{dt} = \frac{i_{L1}}{C} - \frac{V_0}{RC} \tag{16}$$

Mode 4: In this mode, the Switches S_1 and S_2 are in off state, Diode D_a is in off state and diode D_b is in on state, Inductor $L_a$is in off stage and $L_b$is in on stage and Capacitor C_0 is in on stage. Figure 4 d shows the diagram for this mode.

$$\frac{di_{L1}}{dt} = \frac{V_S}{L_1} - \frac{V_0}{L_1} \tag{17}$$

$$\frac{di_{L2}}{dt} = \frac{V_S}{L_2} - \frac{V_0}{L_2} \tag{18}$$

$$\frac{dv_0}{dt} = \frac{i_{L1}}{C} + \frac{i_{L2}}{C} - \frac{V_0}{RC} \tag{19}$$

The transfer utility of the interleaved boost converter are given as follows

$$\frac{V_{0(s)}}{V_{in(s)}} = \frac{1+sRC}{(1-D)\left[1+s\frac{L}{R(1-D)^2}+s^2\frac{LC}{(1-D)^2}\right]} \tag{20}$$

$$\frac{V_{in(s)}}{d_{(s)}} = \frac{1+sRC}{(1-D)^2\left[1+s\frac{L}{R(1-D)^2}+s^2\frac{LC}{(1-D)^2}\right]} \tag{21}$$

The timing figure of a suggested converter is shown in Figure 5

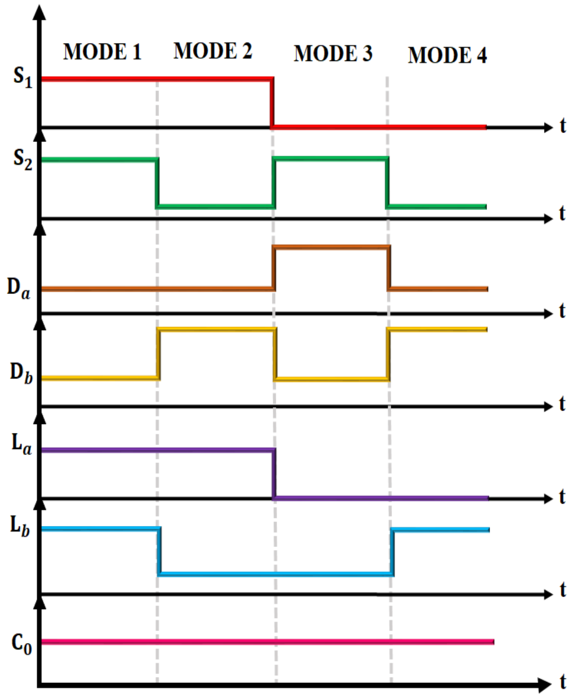

Figure 5: *Proposed converter timing diagram.*

4.3 PSO Optimized FLC Based MPPT Controller

For FLC, there are lavish usages for renewable energy sources. Intricate tracking performance is caused by the non- linear nature of solar PV panels and the climate. As an outcome, FLC-based MPPT methods are utilized to track the MPP in solar PV structures with less intricate format and data necessities. Three foremost stages are used to summarize the FLC design and operation. These stages involves defuzzification, rule evaluation and fuzzification. The microprocessor analyses the duty ratio (D) rate later assessing the PV array's voltage. The fine-tuning signal for the DC-DC converter is formed by the standards of D and specified by the gate driver circuit.

The function, f (D) = P_{pv} (22)

MFs are utilized to change the sharp values into fuzzy values throughout the fuzzification stage. In extreme PV systems, the FLC's input is the slope of the P_{pv} versus V_{pv} curve. FLC input variables are termed by the following equations .The diagram of FLC is shown in Figure 6.

$$e(k) = \frac{p(k)-p(k-1)}{v(k)-v(k-1)} \tag{23}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{24}$$

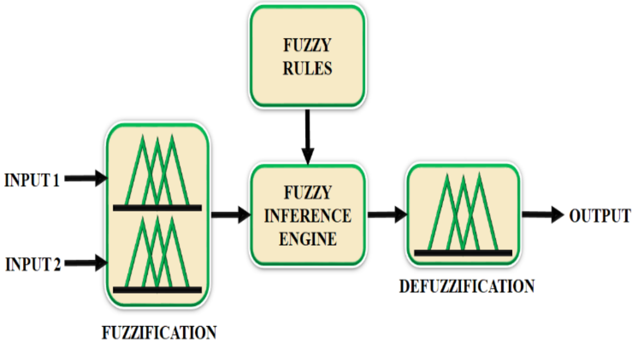

Figure 6: *FLC structure*

The output variable is,

$$\Delta D(k) = D(k) - D(k-1) \tag{25}$$

Rule evaluation practices fuzzy instructions within a fuzzy processor to define control actions based on input values, always generating a fuzzy output. Defuzzification translates a fuzzy output into a crisp, numerical significance that is utilized to regulate a system. The expected output of an FLC is certainly the crisp value derivative from the fuzzy set after defuzzification. Frequently, FLC outputs characterise alterations to reference voltage or duty cycle. These alterations are established on input changes in power and voltage, are then used to regulate system. Though, more MFs lead to higher accuracy in the fuzzy logic system, similarly they increase processing time. Conversely, fewer MFs lead to faster processing but potentially lower accuracy. Figure 7 displays output and input MFs. However, FLC based MPPT system have various drawbacks include increased complexity in implementation, potential for drift under changing irradiance and the need for significant computational resources.

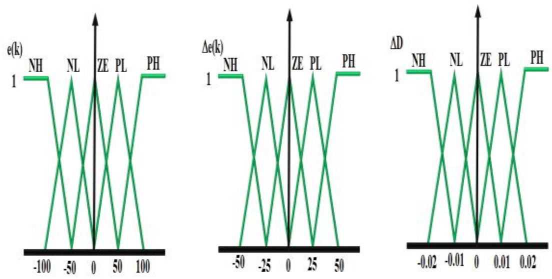

Figure 7: *Input and Output MFs*

To overcome these issues PSO optimized controller is used, which solves the problem of non-linear system optimization. PSO technique is a strong stochastic optimization method created on the movement of intelligence of swarms. In this algorithm, numerous cooperative representatives are utilized to interchange facts gained in its individual search process. Each representative is mentioned to a particle following two simple rules. Through this way, each particle finally approaches an optimal solution. Figure 8 displays the flow chart of PSO based MPP.

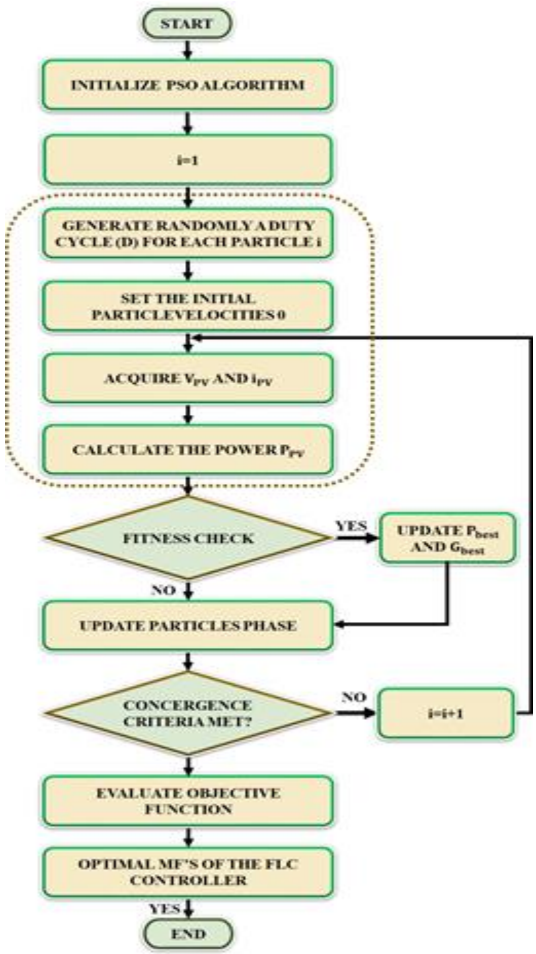

Figure 8: *PSO MPPT flowchart*

The following equations shows the standard PSO method.

$$v_i(k+1) = wv_i(k) + c_1r_1(p_{best,i} - x_i(k)) + c_2r_2(g_{best} - x_i(k)) \quad (26)$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (27)$$

PSO technique is introduced to reduce the difficulty in finding MPP and develop the enactment of MPP under dissimilar atmospheric conditions.

5. Result and Discussion

Proposed system is authorized using MATLAB and their obtained outcomes are discussed in this section along with the comparative analysis, to determine performance efficiency of recommended system. Table: 1 displays specifications of parameters for PV system and IBC.

Table 1: *Parameter Specifications*

Parameter	Specifications
PV System	
Rated Power	$10kW$
Open circuit voltage	$37.25V$
Short circuit current	$8.35A$
No. of panels connected in series	16
No. of panels connected in parallel	3
Interleaved Boost Converter	
Switching frequency	$10kHz$
Inductor L_a, L_b	$4.7mH$
Capacitor C_0	$2200\mu F$

Case1: Constant Condition

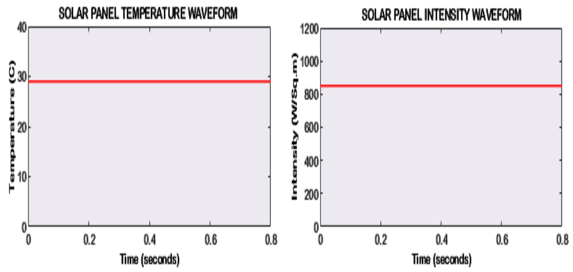

Figure 9: *Solar panel Temperature- Intensity waveform.*

Figure 9 presents the PV panel temperature and intensity waveform under constant condition. The temperature of PV system is constantly maintained at 28^0 C throughout the system and the intensity at 810 W/Sq.m throughout the system

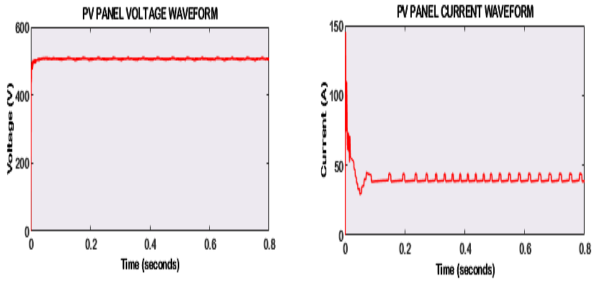

Figure 10: *Solar panel Voltage-Current waveform*

Figure 10 represents the PV panel Voltage and Current waveform under constant condition. In PV panel, the voltage waveform rapidly increases and maintains at 480 V throughout the system. While, the current waveform initially fluctuates and then it flows to 40A throughout the system, minor oscillations.

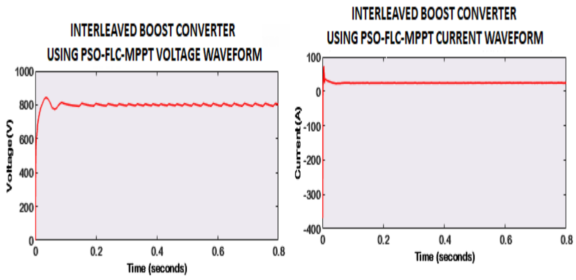

Figure 11: *Interleaved Boost Converter using PSO-FLC-MPPT Voltage-Current waveform*

Figure 11 displays Voltage and Current waveform of IBC using PSO-FLC-MPPT under constant condition. The voltage waveform of converter is maintained at 810V throughout the system. Meanwhile, the current waveform shows rapid increases and then maintained at 22A throughout the system.

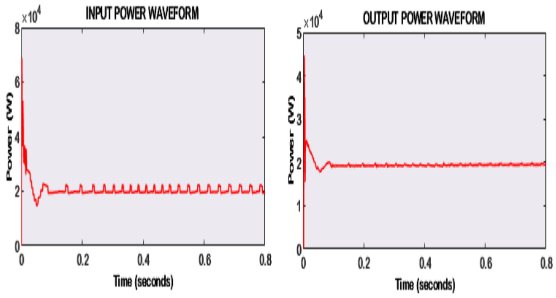

Figure 12: *Power waveform of Input and Output*

Figure 12 demonstrates power waveform of input and output under constant state. The input power promptly increases to 7W and attain a minor fluctuations then falls to 2W and constantly maintained throughout the system. The output power rapidly increases at initial stage and gradually falls to 2.5W and continues further.

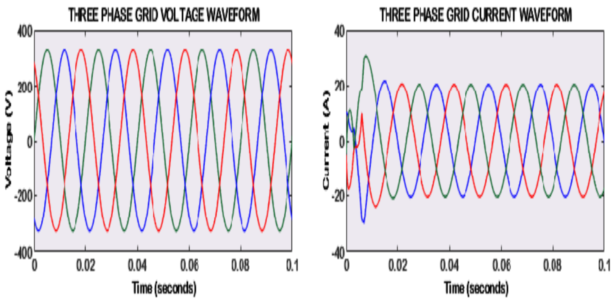

Figure 13: *Voltage- Current waveform of three phase grid*

Figure 13 illustrates Voltage and Current waveform of three phase grid. A pure sinusoidal voltage and current measuring 300V and 18A is attained by the system. The sinusoidal outcomes demonstrates the effective elimination of harmonics.

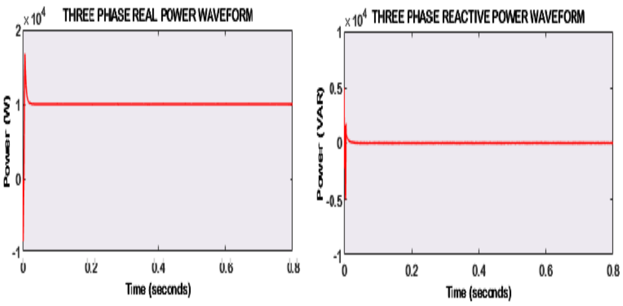

Figure 14: *Three phase Real– Reactive power waveform*

Figure 14 visualizes real and reactive power waveform of three phase system. The real power waveform initially rises before stabilization and maintain a steady state power throughout the system. The reactive power waveform primarily increases and indicating a balanced power throughout the system.

Table 2: *Comparison in efficiency of various approaches.*

MPPT TRACKING APPROACH	TRACKING EFFICIENCY
Perturbation and Observation	84.57%
Incremental Conductance	85%
Hill Climbing	89%
Proposed	95%

Table 2 shows the comparison in efficiency of various approaches. The proposed PSO based FLC MPPT attains improved tracking efficiency of 95% related to existing MPPT approaches.

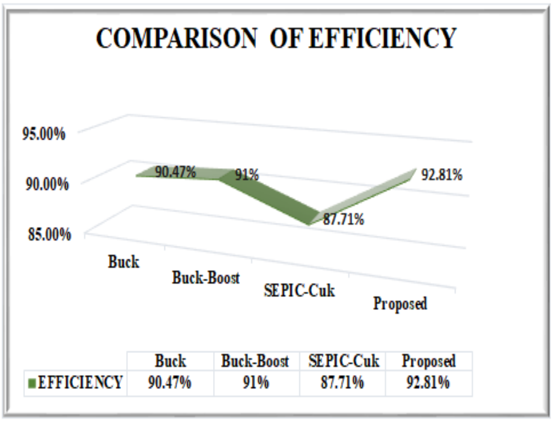

Figure 15: *Comparison of efficiency*

Figure 15 reveals the comparison of proficiency of suggested converter with existing converter topologies. From the graph, it shows that suggested converter achieves the highest efficiency of 92.81% outperforming other converters.

6. Conclusion

This paper presents an interleaved boost converter and particle swarm optimized FLC based MPPT controller for enlightening the performance of PV grid system. PV system output power is boosted by IBC facilitating enhanced reliability and improved efficiency. Fuzzy Logic controller tracked the power from the PV panel and to maximize the power point PSO optimization is implemented. PSO optimization maintains the maximum power under numerous climatic irradiance, guaranteeing stability and smooth grid integration. The expected outcomes are validated through MATLAB simulation. Consequently, the proposed converter delivers a proficiency of 92.81% and tracking efficiency of 95%, making it superior choice for enlightening the performance of PV grid system compared to conventional converter.

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