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Article Title: **Artificial Intelligence with Metaheuristic Algorithm Based Optimization for a Hybrid Energy Storage System**

Artificial Intelligence with Metaheuristic Algorithm Based Optimization for a Hybrid Energy Storage System

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ABSTRACT

This paper presents an optimization framework for a hybrid energy storage system (HESS) integrating photovoltaic (PV) and wind energy conversion systems (WECS). The PV system voltage is stepped up using a Cuk converter, controlled by a Particle Swarm Optimization (PSO) tuned Artificial Neural Network (ANN) controller to enhance dynamic performance and ensure maximum power point tracking (MPPT). The Doubly-Fed Induction Generator (DFIG)-based WECS is interfaced through a Pulse Width Modulation (PWM) rectifier regulated by a Proportional-Integral (PI) controller, maintaining stable and efficient power conversion. Both converter outputs converge at a common DC link, whose voltage is subsequently applied to a single-phase Voltage Source Inverter (VSI). This VSI is connected to the grid through an LC filter, ensuring smooth power delivery with minimal harmonics. The proposed system combines AI and metaheuristic algorithms for optimized control, enhancing overall efficiency, reliability and stability of the renewable energy integration into the grid. Simulation results demonstrate the effectiveness of the PSO-ANN and PI control strategies in managing the dynamic interactions and power quality of the hybrid system. The proposed hybrid controller shows 92.47% tracking efficiency and the proposed converter shows 89.6% efficiency.

Keywords: PV, WECS, HESS, Cuk Converter, PSO Optimized ANN based MPPT Controller.

1 Introduction

Electricity has become indispensable in modern life, its demand skyrocketing in tandem with technological advancements. Yet, the primary source of electricity generation fossil fuels casts a long shadow over environmental sustainability. The emission of greenhouse gases from fossil fuel combustion not only contributes to air pollution but also exacerbates global warming. In this context, the utilization of RES like sunlight, wind, and water emerges as a promising solution to

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mitigate these environmental concerns. Wind turbines and hydropower stations further diversify the renewable energy tapping into the kinetic energy of wind and water currents. The integration of these renewable sources into smart grids holds the key to building sustainable and reliable energy systems for the future [1-3].

Given that the PV system generates a low DC voltage that fluctuates with solar irradiance and weather conditions, a converter becomes indispensable for transforming this voltage to a higher level [4]. Various DC-DC converters, including boost [5], buck-boost [6], and others, are employed in PV systems to execute efficient voltage conversion processes. The efficiency of these converters is significantly enhanced by implementing effective control strategies, which not only mitigate steady-state errors, peak overshoot problems, settling times, and overall harmonic distortion but also optimize performance. Control methods can be broadly categorized into conventional and intelligent approaches [7]. Conventional methods like the PI controller offer a straightforward architecture and effectively regulate DC levels. However, they may exhibit shortcomings such as poor performance during sudden load fluctuations and challenges in integrating distributed energy sources into microgrids.

However, the optimization of hybrid RES presents a significant challenge. While the potential of renewable energy is immense, its efficiency and reliability depend on effective management and utilization. To address this challenge, a comprehensive approach is needed, one that combines AI algorithm techniques with metaheuristic optimization algorithms tailored for smart grid environments [8-10].

Photovoltaic systems, despite their promise, face efficiency issues that hinder their widespread adoption. MPPTs play a crucial role in optimizing the performance of PV systems by ensuring they operate at their maximum power output regardless of environmental conditions. Traditional MPPT methods, such as Perturbation and Observation (P&O), while cost-effective, suffer from drawbacks such as slow tracking speed and fluctuation [11, 12]. To overcome these limitations, AI-based techniques, particularly Fuzzy Logic Controllers (FLCs), have been proposed. FLCs offer faster tracking speed and reduced oscillation compared to classical MPPT methods. However, they are susceptible to the drift phenomenon, where abrupt shifts in irradiance levels and operating temperatures can affect their performance [13, 14].

In this paper, a PSO Optimized ANN based MPPT controller is presented for MPPT in PV systems. The hybrid approach combines the strengths of both PSO and ANN to overcome the limitations of traditional MPPT methods. This comprehensive approach not only addresses the challenges of optimizing RES but also paves the way for a sustainable energy future.

The primary contributions of this paper are as follows:

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- A hybrid solar PV and WECS system is presented, where the initial stage utilizes a Cuk converter to optimize power extraction and serve as a voltage enhancer.
- Implementing a PSO Optimized ANN based MPPT controller to fine-tune the converter's parameters.
- Incorporating a three phase inverter in the second stage to channel the generated electricity into the grid.

2 Proposed System

The proposed system aims to enhance MPPT in PV arrays by integrating PSO with ANNs, thereby improving energy extraction efficiency. Figure 1 illustrates the design of a 3 Ø grid-connected hybrid renewable energy system. MPPT systems find application in regulating both wind and photovoltaic energy sources. The Cuk converter is integrated into the PV panel configuration, and the PSO-ANN, known as MPPT, controls the converter unit to maximize solar power output. This converter connects the battery bank to the DC bus, facilitating appropriate charging and discharging procedures under its control. Energy sources are linked to the DC bus via a DC-DC Cuk converter, and their outputs converge at a common DC link. This voltage is subsequently applied to a single-phase VSI, connected to the grid through an LC filter to ensure smooth power delivery with minimal harmonics. Two programmable switches are employed to track the MPP of both renewable energy sources. The DFIG-based WECS interfaces through a PWM rectifier regulated by a PI controller, ensuring stable and efficient power conversion.

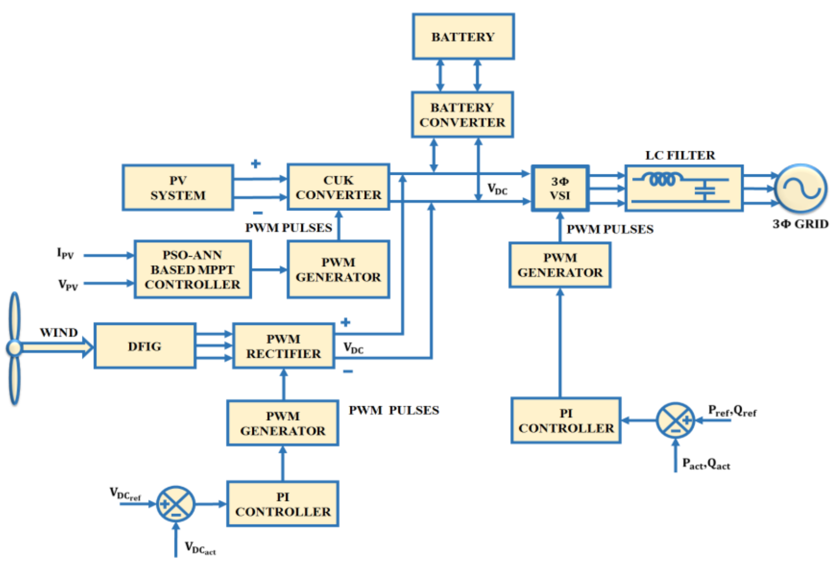

Figure 1: *Proposed Block diagram*

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2.1 PV System Modelling

Solar PV panels utilize the photon-voltage phenomenon to convert sunlight into electrical energy. In an ideal scenario, solar cells would lack series and shunt resistances. However, in practical applications, these resistances are inherent to the PV diode, as depicted in Figure 2. These resistances stem from the inherent resistance of the PV semiconductor and the suboptimal performance of the PN junction diode, necessitating their integration into the system.

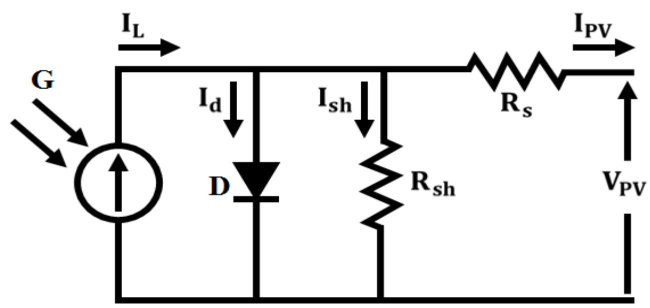

Figure 2: *PV equivalent circuit*

The output current of the solar PV cell can be described using Kirchhoff's law

$$I_{PV} = I_L - I_d - I_{sh} \tag{1}$$

In this context, I_L signifies the load current of the PV diode circuit and I_d refers to the adjusted current in the PV diode circuit and I_{sh} refers to shunt current. Given that the PV system generates a low DC voltage that fluctuates with solar irradiance and weather conditions, a converter becomes indispensable for transforming this voltage to a higher level.

2.2 DC–DC Cuk Converter

Choosing a highly efficient DC-DC converter is crucial to the overall design of a PV model since it improves operating efficiency even more than choosing the best MPPT approach. Hence, careful consideration must be given to selecting the appropriate DC-DC converter for PV systems. Various converter topologies have been explored in previous studies. Regardless of the load value, the buck-boost and cuk converters have proven to be the most effective among them. Lower efficiency is a result of the buck-boost converter's shortcomings, which include poor transient responsiveness, discontinuous input current, and greater peak current. Conversely, the Cuk converter offers continuous input and output current characteristics, and due to its dual inductor configuration, it minimizes output current ripples, leading to reduced power loss. Consequently, the Cuk converter

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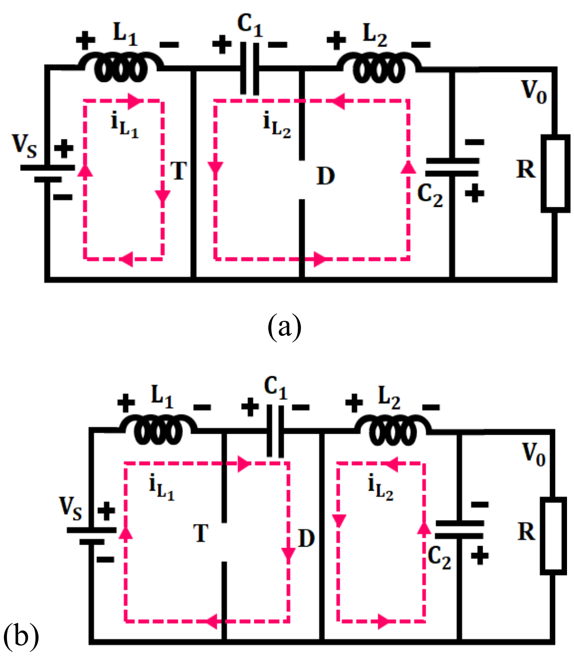
emerges as an optimal choice for powering MPPT designs. Comprising two inductors, two capacitors, a switch, and a diode, the Cuk converter embodies an efficient power supply configuration for PV systems.



(b)

Figure 3: *Converter mode (a) Switch on (b) Switch off*

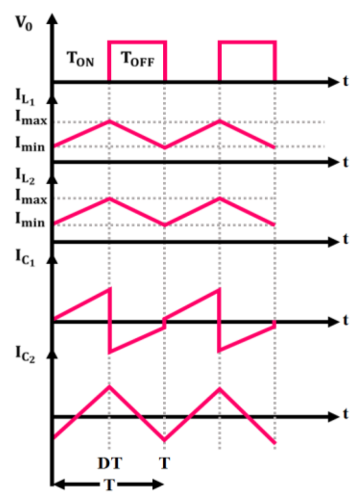


Figure 4: *Time waveform of the proposed converter*

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In the MPPT design, Figure 3 illustrates the two operating modes of the Cuk converter. During the first mode, the switch is on, and the diode is reverse-biased. In this state, with $VC_1 > V_0$, power energy for the load is supplied by capacitor C_1. Conversely, in the second mode, the switch is off, and the diode is forward-biased. Here, capacitor C_1 is charged by V_S through the diode, while the load harnesses energy from inductor L_2. It's a fundamental aspect of the Cuk converter's operating condition in the steady state that the average values of the periodic inductor voltage and capacitor current waveforms are zero. The relationship between the output and input is expressed as follows:

$$\frac{V_O}{V_S} = -\frac{D}{1-D} \tag{2}$$

$$\frac{I}{I_O} = -\frac{D}{1-D} \tag{3}$$

PSO Optimized ANN based MPPT Controller is employed to increase the efficiency of the proposed converter.

2.3 PSO Optimized ANN Based MPPT Controller

PSO, as a stochastic search method, often requires a significant time investment to converge to a global peak. To address this issue, modifications were necessary. In the newly proposed hybrid method, integrating ANN with PSO, the initial particle positions of the PSO algorithm are determined by an ANN. This initial configuration places the particles near the global MPP, thereby constraining the search range of the PSO algorithm. Leveraging this initial setup, the PSO algorithm swiftly identifies the output current of the PV array at the global MPP, facilitating rapid convergence. Additionally, in instances of abrupt changes in solar irradiance, the ANN detects such variations and furnishes updated initial particle positions for the PSO algorithm. This dynamic adaptation enhances the efficiency of the PSO algorithm in navigating the search space. The flowchart illustrating this method is depicted in Figure 5.

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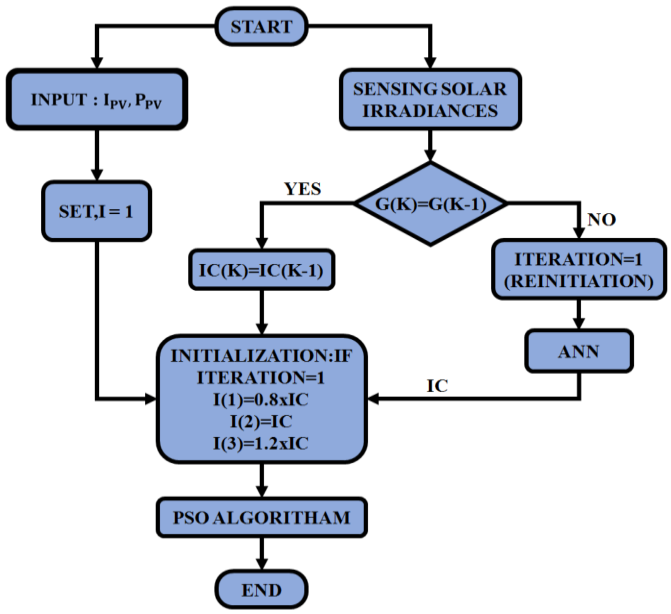

Figure 5: *Flowchart of PSO-ANN Controller*

Within the PSO algorithm, three particles are employed, with one of their positions determined by the ANN. This setup ensures a narrow search space for the PSO algorithm, enhancing its efficiency. The flowchart illustrating PSO-ANN method is presented in Figure 5. The ANN receives the irradiance pattern as input and generates initial particle positions for the PSO algorithm. The PSO algorithm then adjusts the reference current towards the MPP.

3 Results and Discussions

The electrical model of the solar panel, incorporating diverse parameters is simulated using MATLAB. To validate the accuracy of the computed model, actual grid testing is performed. Additionally, MATLAB is utilized to simulate PV cells and Cuk converters. A comparison table depicting the efficiency of different converters is provided to show their performance. Table 1 outlines comprehensive specifications for the PV system settings.

Table 1: *Parameter Specifications*

Parameters	Rating
PV system	
Peak power	10 KW
Capacity	5W
Number of panels	20

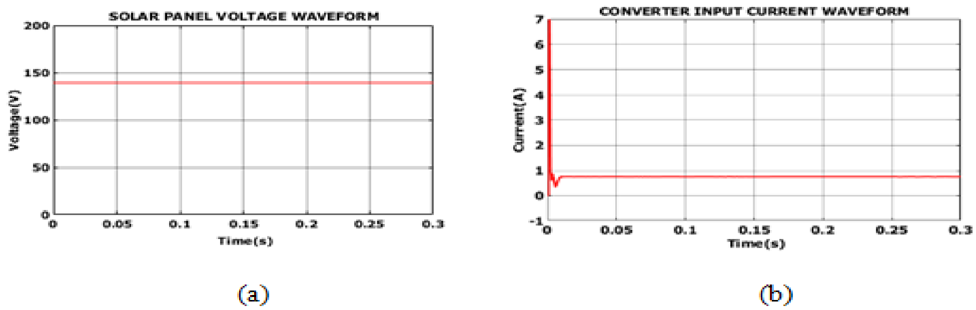

Figure 6: *PV output waveform (a) Voltage (b) Current*

Figure 6 illustrates the output depicting the voltage from the PV panel, which remains steady at 140 V. Nevertheless, fluctuations in operating conditions affect the voltage passing through the panel, functioning as the input to the converter.

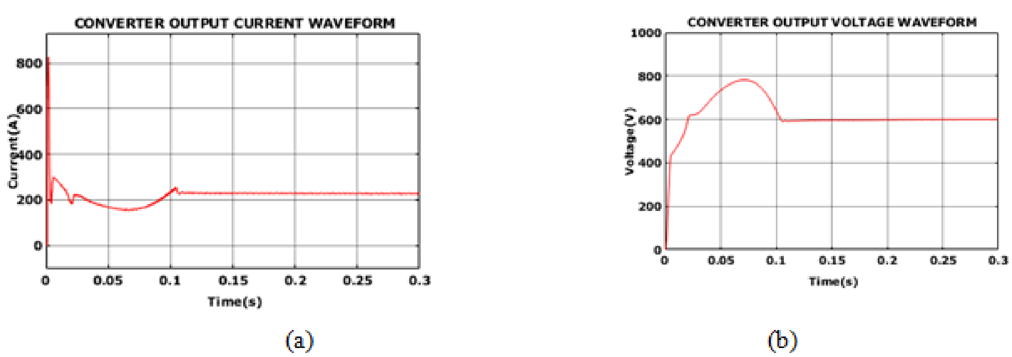

Figure 7: *Converter output (a) Current (b) Voltage*

Figure 7: shows the variability in the output from the PV panel, the DC source is incorporated as the PV voltage source. Employing the proposed converter, multiple DC voltage sources are adjusted to generate a consistent output current of 210 amps and voltage of 600 V. The controller receives the error signal to sustain consistency, effectively minimizing the error.

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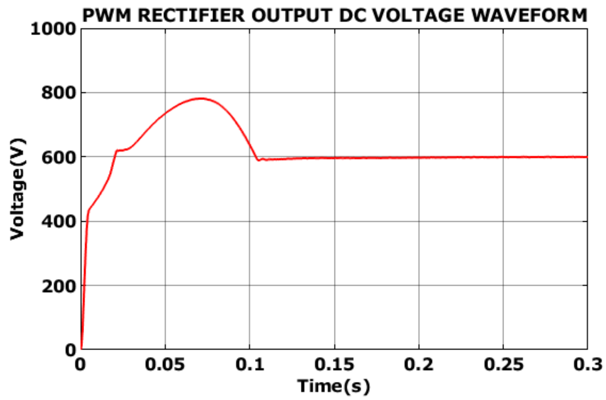


Figure 8: *PWM rectifier voltage waveform*

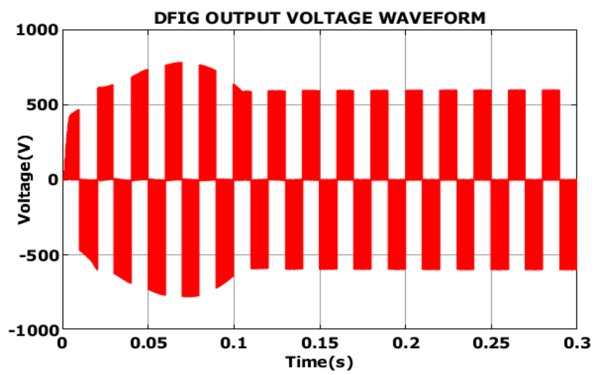
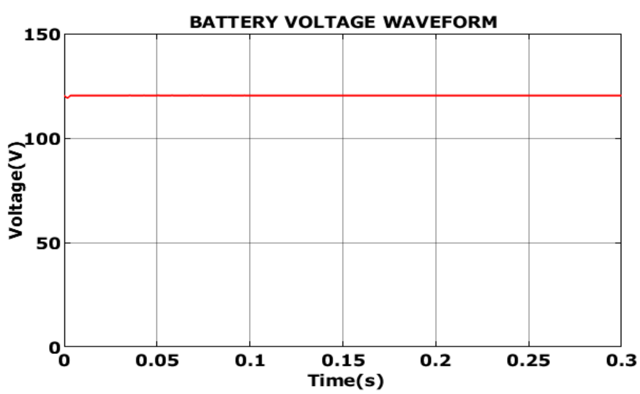


Figure 9: *DFIG voltage waveform*



(a)

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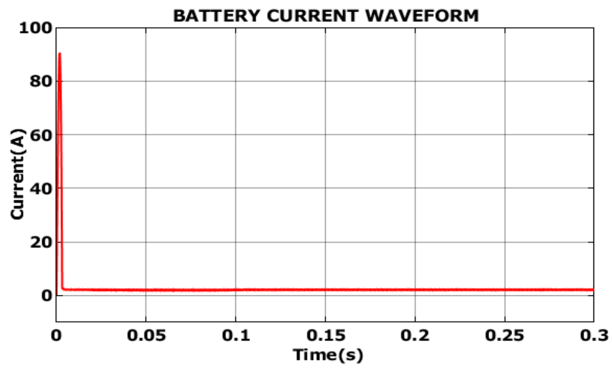

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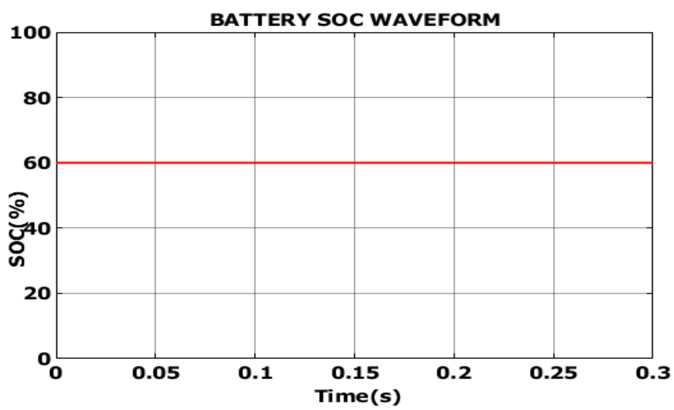

(c)

Figure 10: *Battery waveform (a) Voltage (b) Current (c) SOC*

Initially, fluctuations are observed in both battery voltage and current waveform, which quickly stabilize afterward as shown in figure 10 (a) and 10 (b). Figures 10: (c) present the waveforms representing the battery voltage and current, respectively. As shown in Figure 8: a, the battery's SOC is around 60%. When the SOC falls below 60%, the battery converter operates in buck mode for charging purposes. Conversely, it shifts to boost mode for battery discharge when the SOC exceeds 60%.

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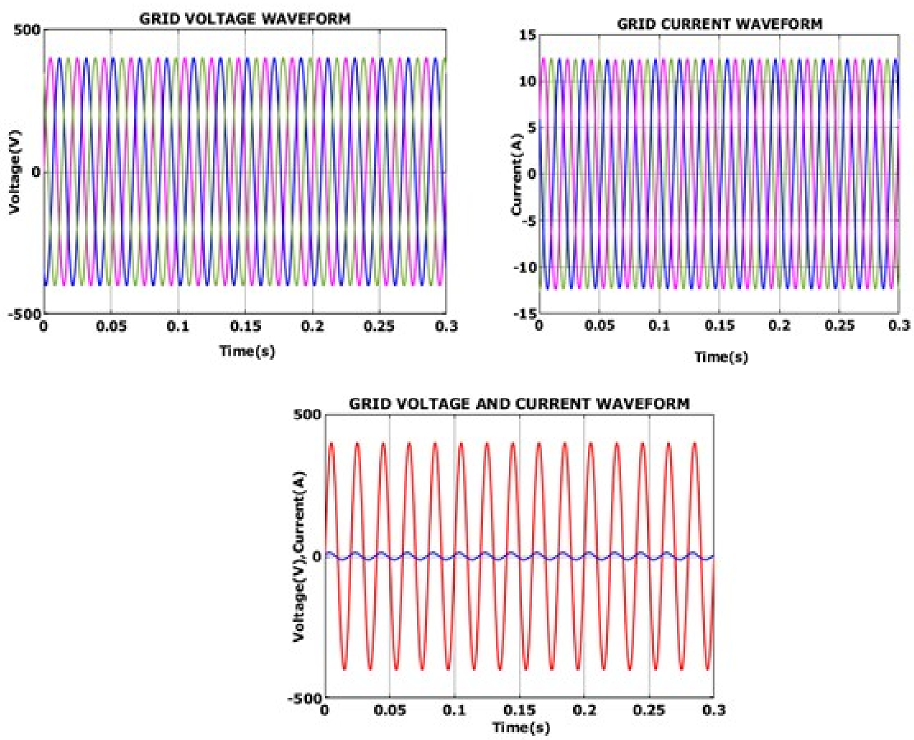
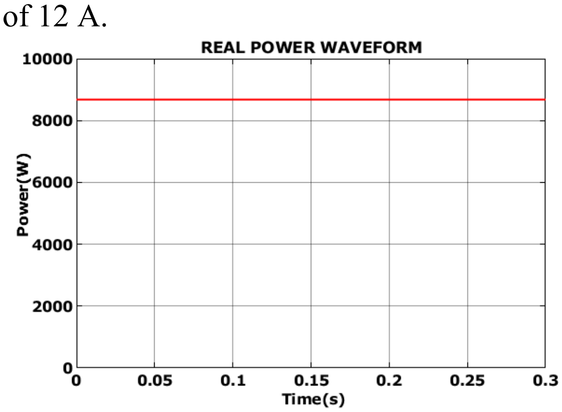


Figure 11: *Output Waveforms of Grid Side*

In Figure 11: the waveforms illustrating the grid voltage and current are presented. The synchronization of grid voltage by the PI controller ensures stability in both voltage and current, devoid of any fluctuations. Throughout, the grid voltage remains steady at 430 V, while the current maintains a constant level of 12 A.



(a)

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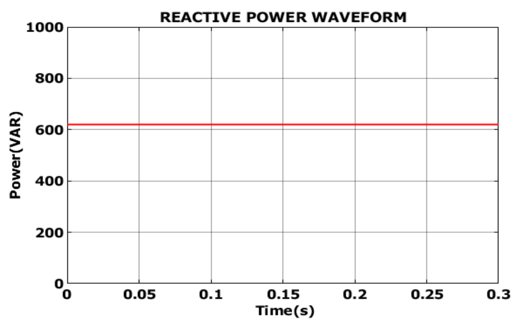
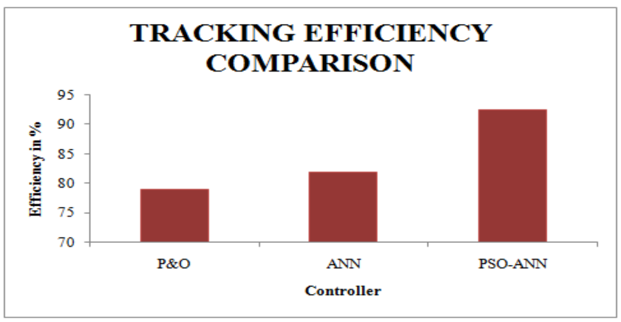


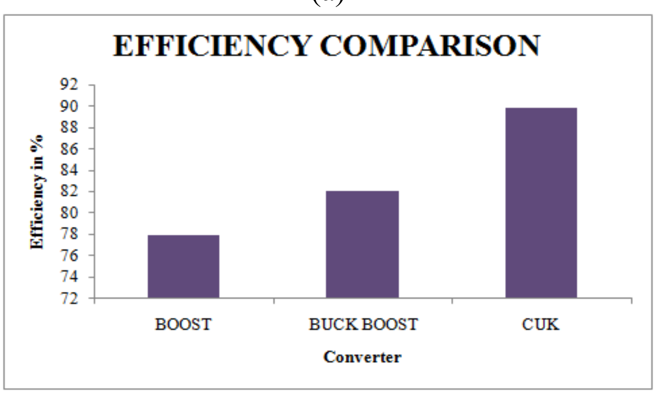
(b)

Figure 12: *Power waveform (a) Real (b) Reactive*

The waveforms depicted in Figure 12: indicate the real and reactive power. The magnitude of reactive power steadily increases until it reaches a constant value of 620 W, while the real power remains constant at 8250 W.



(a)



(b)

Figure 13: *Comparison (a) Controller accuracy (b) Converter efficiency*

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Figure 13: displays the comparison of the converter and controller in which the proposed hybrid controller shows 92.47% tracking efficiency and the proposed converter shows 89.6% efficiency.

4 Conclusion

This study offers a hybrid approach to optimizing renewable energy generation within a smart grid framework and presents an innovative method aimed at enhancing solar energy harvesting efficiency. The PV system voltage is stepped up using a Cuk converter, controlled by a PSO tuned ANN controller to enhance dynamic performance and ensure MPPT. The DFIG-based WECS is interfaced through a PWM rectifier regulated by a PI controller, maintaining stable and efficient power conversion. The approach combines the PSO algorithm and ANNs to enhance MPPT in PV arrays. By integrating PSO's optimization capabilities with ANNs' predictive abilities, the proposed algorithm dynamically adjusts the array's operating point to maximize power output across changing environmental conditions. Compared to conventional MPPT methods, this hybrid approach demonstrates superior accuracy and adaptability, resulting in optimized energy extraction from PV arrays. The findings underscore the algorithm's potential to improve overall PV system performance. Its capacity to adapt to variable conditions, track the maximum power point, and maintain stability in load power positions it as a promising tool for enhancing the efficiency and reliability of solar energy utilization. PSO efficiently explores the solution space and converges on the global maximum power point, while ANN utilizes historical data to predict future optimal power points, offering real-time adaptability. By integrating these robust methodologies, the hybrid PSO-ANN MPPT algorithm enhances the efficiency of PV conversion and strengthens the prospects for renewable energy integration. The proposed hybrid controller shows 92.47% tracking efficiency and the proposed converter shows 89.6% efficiency.

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