Optimized Voltage Feed-Forward Control for Photovoltaic-Battery Dc Microgrid Using Enhanced Grey Wolf Algorithm

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ABSTRACT
The integration of Photovoltaic (PV) systems with battery storage in microgrids presents significant challenges in maintaining voltage stability and system efficiency due to the fluctuating nature of solar energy generation and variable load demands. Traditional control strategies, such as feedback control, often fail to respond quickly enough to these fluctuations, leading to voltage instability and reduced system performance. Therefore, this paper presents an optimized voltage feed-forward control for photovoltaic-battery DC microgrid using Enhanced Grey Wolf Algorithm (EGWO) to optimize the system's performance, stability, and energy efficiency. This work uses an Arduino microcontroller, DC-DC converter, battery, IoT device, and optocoupler. The power from a solar panel is effectively converted to the level needed for battery charging using a DC-DC converter. A DC microgrid powered by a PV system and supported by battery energy storage requires precise control to balance energy generation, storage, and consumption. EGWO is integrated with voltage feed-forward control to enhance the performance of a photovoltaic-battery DC microgrid. This work is implemented by using MATLAB, and the BLYNK web app is used to display the results. This work contributes to the advancement of smart grid technologies by providing an optimized control solution that ensures reliable operation, energy efficiency, and reduced dependency on non-renewable energy sources in DC microgrid systems.

Keywords: Solar Panel, DC-DC Converter, Arduino Microcontroller, EGWO, Battery, IoT.

1. Introduction

As the world transitions toward more sustainable and efficient energy systems, PV-Battery DC Microgrids are emerging as a promising solution for decentralized power generation and distribution. These microgrids, which integrate solar energy generation with battery storage, provide an autonomous and reliable source of power, especially in remote or off-grid areas [1-2]. The solar system functions continuously and efficiently due to the carefully chosen component size and technology. Nevertheless, its free availability and other attractive aspects, the PV industry confronts problems such reliability, output power decrease, initial cost, fault sensitivity, and its significant reliance on environmental variables [3-4]. Traditional control strategies often rely on feedback loops, which may be too slow to effectively handle the fast fluctuations that occur in PV systems due to changes in sunlight or demand. However, ensuring stable operation in such systems, particularly in terms of voltage regulation, presents significant challenges due to the variability of solar energy and the dynamic nature of battery charging/discharging cycles [5]. High-power-density DC-DC converters are crucial parts of contemporary electronics because they offer effective ways to increase voltage in a variety of applications. These converters are essential in a variety of applications, including power supply, renewable energy sources, and portable electronics, where the voltage require changed to satisfy the needs of various system components [6-7]. Portable electronics, renewable energy systems, and several other electronic systems that need voltage conversion make extensive use of these. DC Boost converters are widely used when a compact, reasonably priced voltage step-up solution is needed. An inductor, switch, diode, and capacitor make up the simple design of a Zeta and Buck-Boost Converter, which generates [8-9]. Nevertheless, it requires more complex filtering to reduce ripple and maintain stable operation.

For PV applications where the converter must ensure continuous current and high voltage gain, DC-DC converter is employed [10-11]. More optimization techniques are used recently, such as conventional Particle Swarm Optimization (PSO), Genetic Algorithm Optimization (GAO), Artificial Neural Networks (ANN), Proportional Integral (PI), etc. These methods occur when the swarm collectively converges too quickly on a local minimum, missing the global optimal solution. Additionally, the ability to balance exploration and exploitation is dependent on these parameters, and poor selection leads to inefficient search behavior [12-13]. In this work, EGWO is used to achieve the maximum power efficiency without fluctuations. The EGWO is inspired by the social structure and hunting behavior of grey wolves in the wild. In the context of optimization, the algorithm uses a pack of wolves to search for optimal solutions to complex problems. It improves upon the standard GWO by introducing modifications that enhance convergence speed, accuracy, and the ability to escape local minima, making it more suitable for complex control optimization problems in microgrids. Additionally, SOC monitoring process is essential for ensuring efficient, safe, and optimized charging of EV batteries [14]. As the global adoption of EVs grows, SOC monitoring becomes increasingly important in managing charging processes, optimizing battery health, and contributing to the effective operation of the charging infrastructure. The challenge in such systems is to optimize their performance under varying environmental and load conditions [15]. Therefore, this paper proposes an optimized voltage feed-forward control in a PV-battery DC microgrid using EGWO for enhancing the performance of photovoltaic-battery DC microgrids.

2. Proposed Methodology

The block diagram illustrated in Figure 1 presents an optimized voltage feed-forward control in a PV-battery DC microgrid to enhance system reliability. The system consists of the solar panel, DC-DC converter, Arduino, battery, optocoupler, and input/output voltage measurement device.

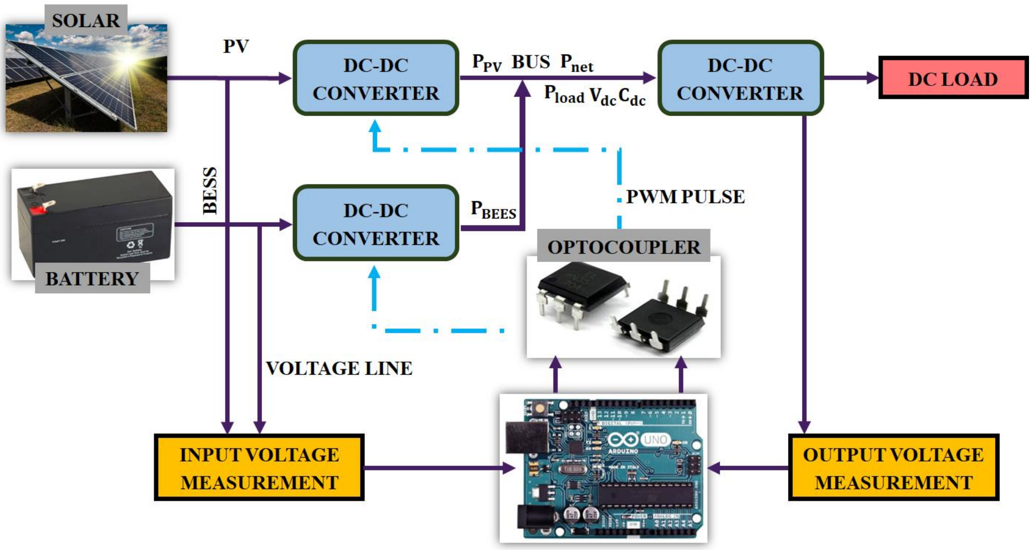

Figure 1 Proposed Block Diagram

The system begins with solar panels generating electricity, where sensors continuously monitor key parameters such as voltage and current. First, the solar panel and battery system supply the input power to the DC-DC converter. This converter is used to improve the low voltage of input into a higher level due to varying weather conditions. The measured input voltage is allowed in the embedded controller of Arduino microcontroller. This controller is connected to an optocoupler and an IoT device. The optocoupler is a connection between Arduino and DC-DC converters. The microcontroller uses the optocoupler to turn the DC-DC converter's switch on or off and control the duty cycle. A DC converter enables both charging and discharging of the battery. Further, the data is uploaded to the BLYNK app cloud database via the IoT module embedded inside the microcontroller. All over the process is monitored and covered by using the IoT system.

2.1 Solar System

A solar panel is a device that converts light energy from the sun into electrical energy using the photovoltaic effect. These panels are commonly used in solar power systems for residential, commercial, and industrial applications. A solar panel is made up of many PV cells that are connected together. These cells are made from semiconductor materials, typically silicon. When sunlight hits these cells, it excites electrons, creating an electric current. Figure 2 shows the solar cell model.

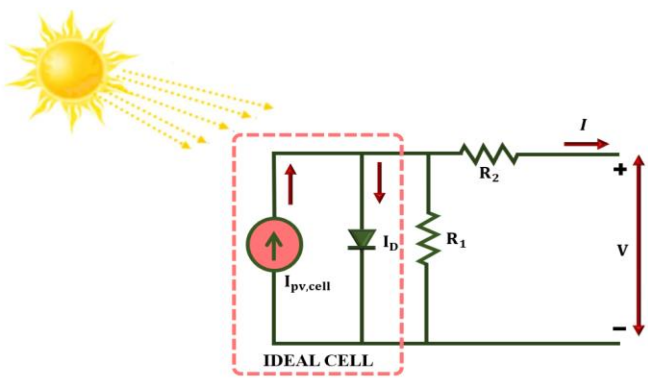

Figure 2 Equivalent circuit of solar cell

The output current of the solar cell is represented as:

$$I = I_{SC} - I_O \left\{exp\left[\frac{q(V+IR_S)}{KT}\right] - 1\right\} - \left(\frac{V+IR_S}{R_P}\right) \quad (1)$$

Where, I_{SC} - Short circuit current, I_O - Diode reverse saturation current, q - Electric charge, K - Boltzmann's constant, T - Junction temp, V- Output voltage, R_S - Series resistance and R_p - Parallel resistance.

2.2 Arduino Micro controller

An Arduino microcontroller refers to a microcontroller board based on an Arduino platform, which is a popular free software electronics platform for IoT applications, such as remote monitoring and control of devices and sending sensor data to the cloud. Arduino is connected to the internet through modules like Wi-Fi or Ethernet shields. The platform includes both hardware and software that allows users to write code and interact with the hardware. Figure 3 displays the Arduino microcontroller.

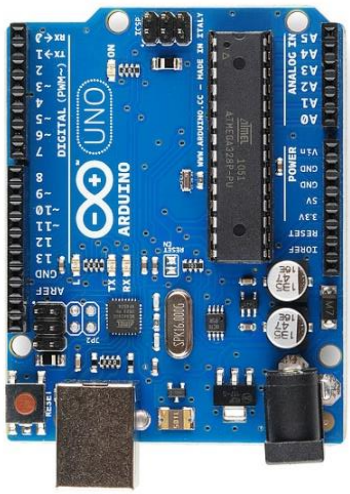

Figure 3 The Arduino Microcontroller

The microcontroller is the central processing unit on the board, which executes the code written in the Arduino programming language. It interacts with external hardware components like sensors, motors, LEDs, and more, based on the instructions from the Arduino code.

2.3 DC – DC Converter

An electrical device that changes the amplitude of voltage of a direct current source is called a DC-DC converter. It regulates voltage to provide stable output voltages, which is essential in powering sensitive electronic devices. There are several different types of DC-DC converters, each serving specific purposes. The two main categories are buck and boost, but there are also more specialized configurations. The operations of the DC-DC converter are presented in Figure 4.

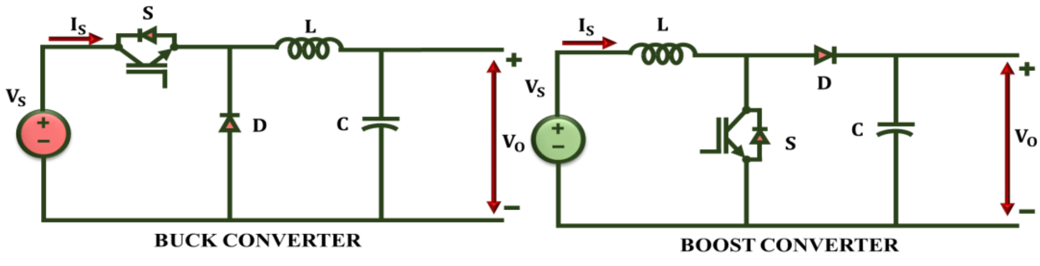

Figure 4 The Operations of the DC- DC Converter

DC-DC converters work based on switching technology and typically use inductors or capacitors to store and release energy.

Step-Down (Buck)

The input DC voltage is rapidly switched on and off by the transistor. The inductor stores energy during the "on" phase and releases it during the "off" phase. The capacitor smooths the voltage, and the result is a lower, regulated DC voltage at the output. The output voltage is given,

$$V_{out} = D \times V_{in} \tag{2}$$

The output voltage V_{out} and input voltage V_{in} in a buck converter are related by the duty cycle D which is the fraction of time the switch is on in each switching cycle.

Step-Up (Boost):

Similar to the buck converter, but instead of stepping down the voltage, the converter uses inductors to "store" energy and boost the voltage during the switching cycles, then smooths the output with a capacitor. In a boost converter, the output voltage is,

$$V_{out} = \frac{V_{in}}{1-D} \tag{3}$$

In DC-DC converters, energy is transferred between inductors, capacitors, and other components.

2.4 Enhanced Grey Wolf Algorithm

The EGWO is a nature-inspired optimization algorithm based on the leadership and hunting behaviors of grey wolves in the wild. The primary goal of the optimization process is to minimize voltage fluctuations at the DC bus and to ensure optimal energy management. The proposed EGWO's flowchart is illustrated in Figure 5.

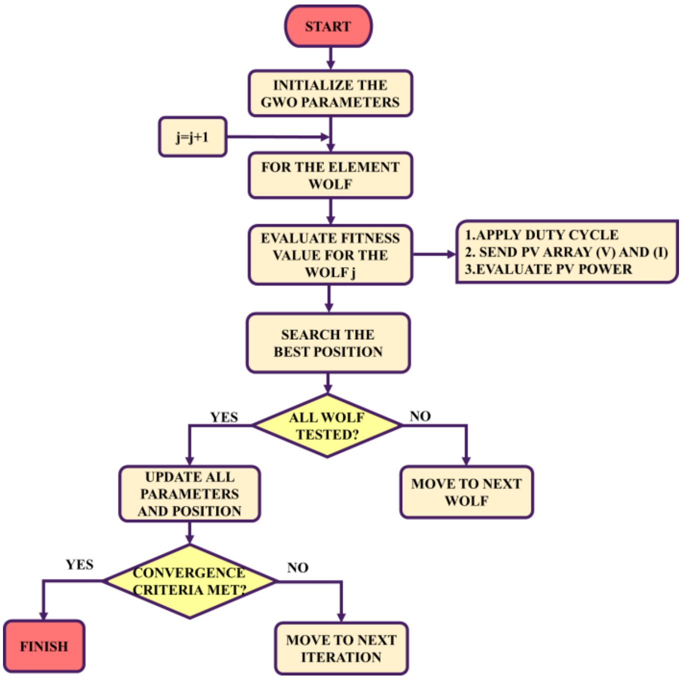

Figure 5 The Flowchart of EGWO Algorithm

Initialization:

Initialize the wolf population with random positions representing different sets of control parameters. Evaluate the fitness of each wolf using the defined objective function.

Fitness Calculation:

For each wolf (control parameter set), simulate the PV-battery microgrid's behavior under different environmental conditions to evaluate the fitness.

Position Update:
Update the position of the wolves based on the positions of the alpha, beta, and delta wolves using the encircling prey concept, where the wolves move toward the best solution (alpha) with adjustments from the beta and delta wolves.
Convergence:
The optimization process continues iteratively, with the wolves updating their positions until the algorithm converges to an optimal solution or a stopping criterion is met.
Control Application:
The optimal control parameters found by GWO are applied to the system, updating the voltage feed-forward control parameters. The following is the equation the at the GWO utilized for this,

$$\vec{X}(t+1) = \overrightarrow{X_p}(t) - \vec{A} \times \vec{D} \qquad (4)$$

$$\vec{D} = \left|\vec{C} \times \overrightarrow{X_p}(t) - \vec{X}(t)\right| \qquad (5)$$

The current iteration is indicated here. The location of the current solution is represented by $\vec{X}(t+1)$, while the position of the intended output is represented by $\overrightarrow{X_p}(t)$. The vector coefficients, denoted by$\vec{A}$, $\vec{C}$, and $\vec{D}$, are computed using the formula below,

$$\vec{A} = 2\vec{a}r_1 - \vec{a} \qquad (6)$$

$$\vec{C} = 2\overrightarrow{r_2} \qquad (7)$$

where r_1 and r_2 are randomly selected vectors in [0, 1]. It offers an advanced solution to optimize energy management, maintain voltage stability, and reduce power losses. GWO's nature-inspired optimization can efficiently tune the system's control parameters in response to dynamic changes in solar irradiance, load, and battery status, ensuring optimal performance and energy efficiency.

2.5 Battery
Batteries are essential to store extra solar energy during times of strong sunshine and supply electricity when solar generating is less sufficient. A battery consists of two electrodes: the anode and the cathode and an electrolyte that allows for the movement of ions between the electrodes. The battery is shown in Figure 6.

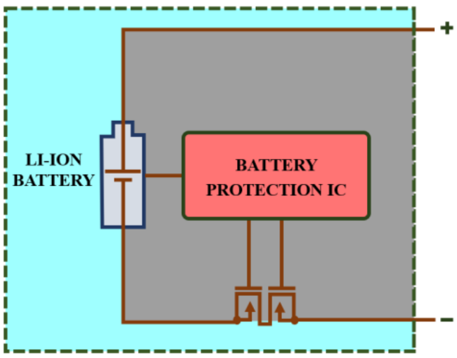

Figure 6 The Battery

The anode and cathode of a battery perform a chemical process during discharge, producing electrons that power electrical devices via an external circuit. The ions move through the electrolyte to balance the charge during this process. When a battery is charged, an external electrical power source supplies power that reverses the chemical reaction, storing energy in the form of chemical potential.

2.6 Optocoupler
An optocoupler is used to transfer electrical signals between two isolated circuits by using light. It provides

electrical isolation while allowing data transmission through optical means. Optocouplers are commonly used in applications where electrical isolation is required, such as in power supplies, communication systems, and protection circuits. It provides galvanic isolation between input and output. This means the input and output circuits are electrically isolated from each other, preventing harmful voltage spikes from one side to affect the other side. Figure 7 illustrates the optocoupler.

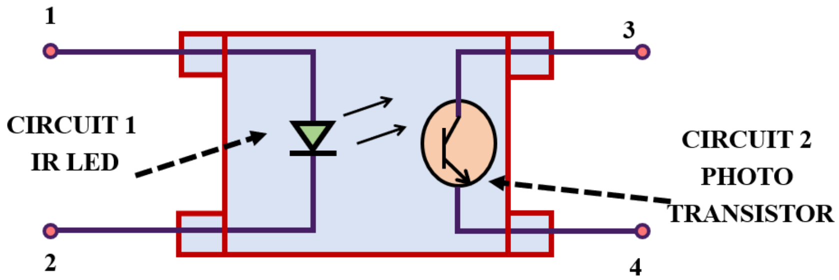

Figure 7 The Optocoupler.

It operates at different speeds and frequencies depending on the type of optocoupler used. It provides galvanic isolation, which protects sensitive circuits from high voltages or current surges. Further, it is designed for high-speed applications such as data transmission or Pulse-Width Modulation (PWM) in circuits.

3. Results and Discussions

In this work, an optimized voltage feed-forward control with EGWO is implemented for a PV-battery DC microgrid. MATLAB software is employed to simulate it, and the web app result is provided using the Blynk app.

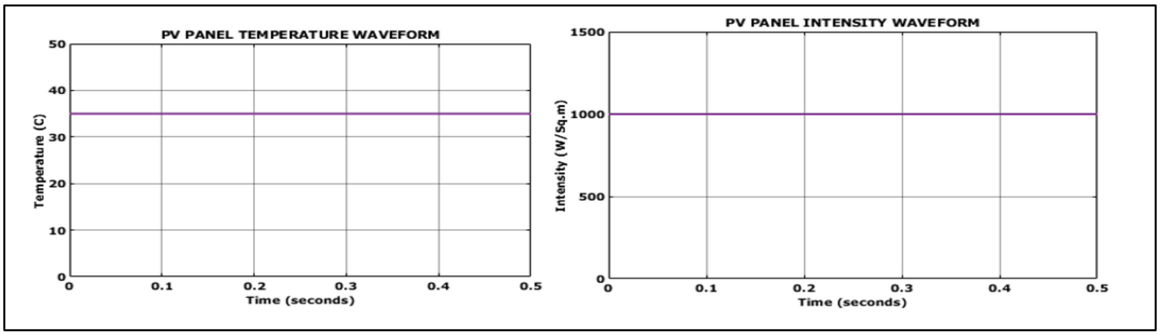

Figure 8 Solar Temperature and Intensity Waveform

Figure 8 shows the solar temperature and intensity waveform. The temperature value is 35°C, and the intensity value is stable at 1000 (W/Sq.m), in constant of environment.

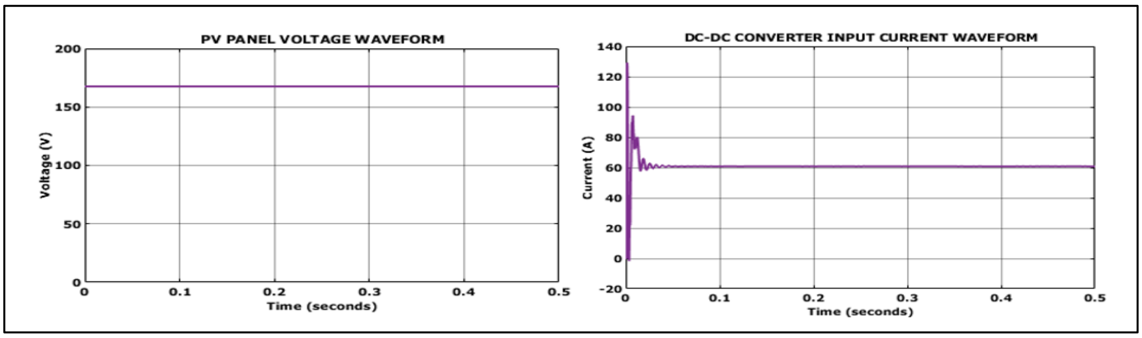

Figure 9 Voltage and Current Waveforms of PV Panel

The PV voltage and current waveforms are displayed in Figure 9. In Figures, the voltage is achieved at 170V and the current is attained at 60A.

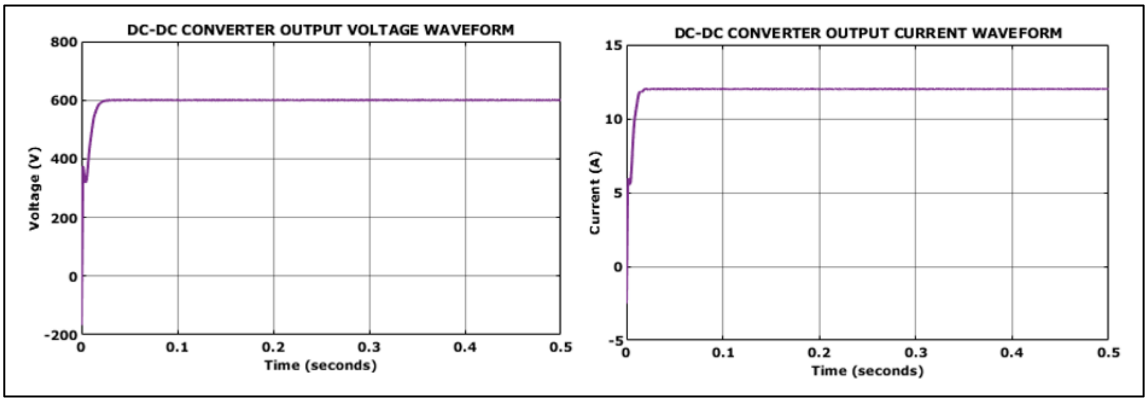

Figure 10 Output Voltage and Current Waveform of the DC-DC Converter

The output voltage and current waveform of the DC-DC converter are given in Figure 10. In this instance, the output voltage is continuously increased from 0V to 600V. Similarly, the output current is attained at 12A.

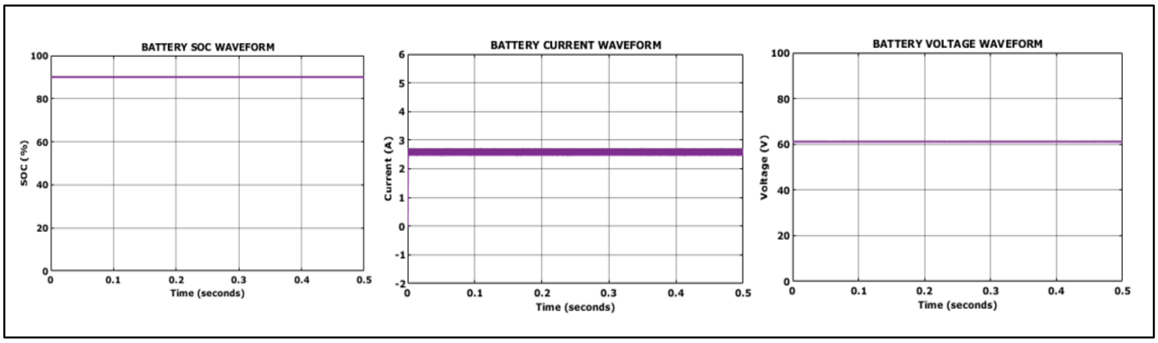

Figure 11 SOC, Current and Voltage Waveforms of Battery

Figure 11 presents the SOC, voltage and current waveforms of the battery. In Figure, is attained the 90% of SOC values according to power. In the battery, the voltage is attained at 62V, and it flows constantly. The current is attained at 2.5A to 2.7A, and it flows constantly.

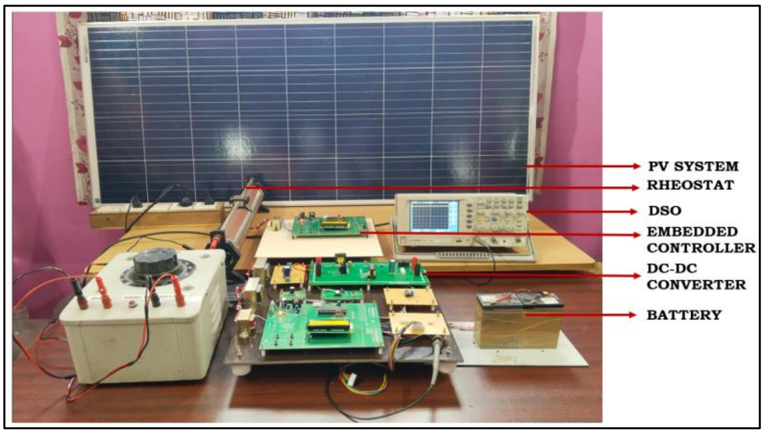

Figure 12 Hardware Setup Image of the Proposed System

Voltage measurements are included inside the setup used to measure the input and output of the voltage. The DC-DC converters are utilized to ensure the PV system operates at its maximum efficiency. Additionally, using the Arduino controller and Node MCU is used to collect the exact values and upload them to the BLYNK App. Overall, this hardware setup monitors the optimized voltage feed-forward control for the PV-battery DC microgrid.

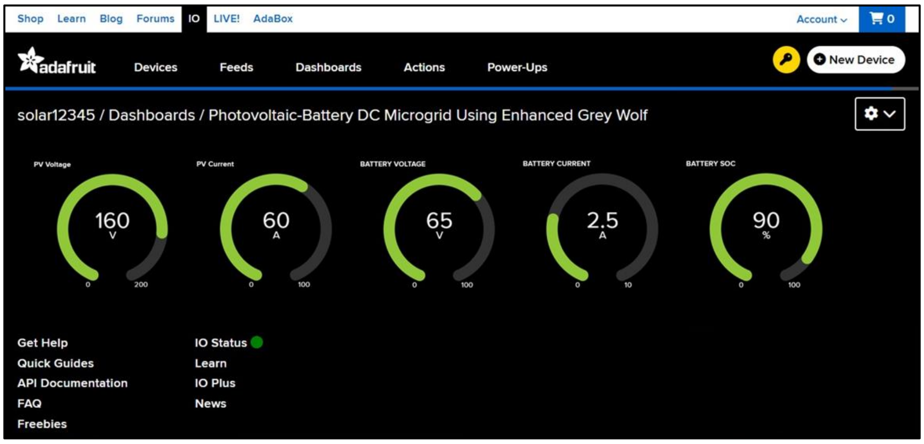

Figure 13 IoT Outcome Page of the Proposed System

Figure 13 shows the IoT outcome page of the proposed system. As depicted in the figure, it gathers the information, like PV voltage of 160V, PV current of 60A, battery voltage of 65V, battery current of 2.5A, and battery SOC of 90%, and displays the values on the IoT web page for voltage feed-forward control strategy.

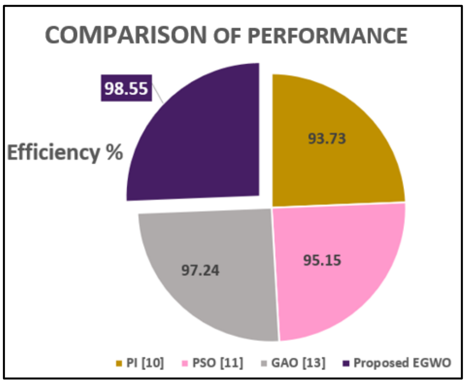

Figure 14 Comparison of Efficiency

The efficiency of various optimization techniques and the proposed optimizer are compared in Figure 14. The PI is 93.73%, the PSO is 95.15%, the GAO efficiency is 97.24%, and the proposed EGWO has a highest efficiency of 98.55%. Further, the proposed EGWO algorithm's capacity to enhance performance is demonstrated by this pie chart.

4. Conclusion

In this work, an optimized voltage feed-forward control strategy for a PV-battery DC microgrid is proposed. Additionally, the EGWO algorithm is used for optimal controller parameter tuning. It improved voltage regulation and better energy management between the PV source and the battery, leading to enhanced overall system performance. The result session found the different solar irradiance levels and battery charge states and its superior ability to reduce voltage fluctuations and maintain steady-state operation. The findings of the experiment show high efficiency of 98.55%, PV voltage of 160V, PV current of 60A, battery voltage of 65V, battery current of 2.5A, and battery SOC of 90%, which has been obtained in simulation. This work successfully demonstrated the ability of the EGWO algorithm to improve the performance of the voltage feed-forward control system in terms of voltage regulation, efficiency, and stability of the microgrid.

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