Decentralized energy management of DC microgrids with PV, wind, BES, and fuel cell

Gestão descentralizada de energia em microrredes de corrente contínua com energia fotovoltaica, eólica, BES e células de combustível

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ABSTRACT
Amidst the evolving energy landscape, there are an increasing demand for sustainability. With the global embrace of renewable sources such as wind and solar power, the urgency for innovative energy management solutions intensifies. This paper presents an energy management system tailored for a decentralized DC Micro-grid catering to a 10 kW DC load. The microgrid combining diverse renewable energy sources incorporating solar panels, wind turbines, battery
energy storage systems (BESS), and a fuel cell serving as an emergency backup solution. The control strategy deployed for efficient operation is a PI cascade control approach. However, to optimize the performance of the controller, the parameter gains of the PI controller are enhanced using a metaheuristic algorithm, specifically the Genetic Algorithm (GA). The proposed system aims to guarantee a reliable and stable power supply to the DC load while maximizing the utilization of renewable energy sources, minimizing hydrogen consumption and decreasing reliance on classical grid source. The effectiveness of the proposed energy management system is validated across simulation studies using MATLAB Simulink under various operating scenarios. These scenarios comprise several environmental conditions, load profiles, and renewable energy availability. The simulation results demonstrate the capability of the system to efficiently manage power flow and enhance overall system performance in decentralized DC microgrid environments.

**Keywords:** microgrid, energy management system (EMS), genetic algorithm (GA), hybrid energy renewable sources (HERS), batteries energy system (BES).

**RESUMO**

No meio da evolução do panorama energético, há uma procura crescente de sustentabilidade. Com a adoção global de fontes renováveis, como a energia eólica e solar, a urgência de soluções inovadoras de gestão de energia intensifica-se. Este artigo apresenta um sistema de gestão de energia adaptado a uma microrrede descentralizada de corrente contínua para uma carga de 10 kW de corrente contínua. A microrrede combina diversas fontes de energia renovável, incorporando painéis solares, turbinas eólicas, sistemas de armazenamento de energia em baterias (BESS) e uma célula de combustível que serve como solução de reserva de emergência. A estratégia de controlo utilizada para um funcionamento eficiente é uma abordagem de controlo PI em cascata. No entanto, para otimizar o desempenho do controlador, os ganhos dos parâmetros do controlador PI são melhorados utilizando um algoritmo metaheurístico, especificamente o Algoritmo Genético (AG). O sistema proposto visa garantir um fornecimento de energia fiável e estável à carga CC, maximizando a utilização de fontes de energia renováveis e diminuindo a dependência da rede elétrica clássica. A eficácia do sistema de gestão de energia proposto é validada através de estudos de simulação utilizando o MATLAB Simulink em vários cenários de funcionamento. Estes cenários incluem várias condições ambientais, perfis de carga e disponibilidade de energia renovável. Os resultados da simulação demonstram a capacidade do sistema para gerir eficazmente o fluxo de energia e melhorar o desempenho global do sistema em ambientes de microrredes DC descentralizadas.

**Palavras-chave:** microgrid, sistema de gestão de energia (SGE), algoritmo genético (AG), fontes renováveis de energia híbridas (HERS), sistema de energia de baterias (BES).
1 INTRODUCTION

Global energy is rapidly shifting toward sustainable and renewable sources to combat environmental damage caused by the traditional use of fossil fuels to produce electricity (Qazi et al., 2019). This transition is mainly due to the evolution of sustainable sources technology like as wind and solar PV and even storage systems (Khan et al., 2021).

In parallel with this development, micro-grid technology is the subject of great attention, as it contributes to improving energy resilience, to the integration of this energy into the electricity networks, to promoting energy independence (Naderipour et al., 2022).

Micro-grids are local energy distribution, expending and even storage systems that can working independently or in coordination with the main grid depending on load demand. They can be divided into two main types direct current (AC) micro-grids and direct current (DC) micro-grids. Although both types share similar operating principles, they differ in terms of voltage level and the form of electrical current used (Azeem et al., 2021).

DC micro-grids offer several benefits over AC counterparts, consisting higher efficiency, reduced power conversion losses, and simpler combining of renewable energy sources and energy storage systems. Additionally, DC microgrids are well-suited for applications with predominantly DC loads, such as data centers, telecommunications facilities, and electric vehicle charging stations. These advantages make DC microgrids particularly attractive for decentralized and off-grid applications, where energy efficiency and reliability are paramount (Revathi; Prabhakar, 2022) and it can be considered as a reliable source of storage through the integration of lithium-ion batteries, into micro-grid systems further enhances their performance (Hartani et al., 2021). BESS play a crucial role in removing and smoothing the fluctuations in renewable energy generation, saving excess energy amid periods of low demand, and offering backup power during grid outages. By optimizing energy storage and utilization, BESS contribute to improved grid stability and enhanced renewable energy integration in micro-grid environments (Zhao et al., 2023).

In addition to BESS, fuel cells have emerged as a promising technology for providing reliable and clean power in micro-grid applications. Fuel cells initiate the
conversion of chemical energy directly into electrical energy through an electrochemical process, offering high efficiency and low emissions (Abdelkareem et al., 2021). In DC micro-grids, fuel cells can serve as an emergency backup solution, ensuring continuous power supply during extended periods of renewable energy shortfall or grid disturbances (İnci et al., 2021). To ensure that the micro-grid takes maximum power or performs optimally, the implementation of the Maximum Power Point Tracking (MPPT) is important. MPPT is vital in optimizing the efficiency of power sources within micro-grids. Techniques like the Fuzzy Logic (Maissa et al., 2023), Artificial Neural Networks (ANN), along with Incremental Conductance, are employed to adaptively tune the system in response to varying environmental conditions (Bollipo et al., 2020). The Fuzzy Logic MPPT uses a set of rules to adjust the voltage and current for maximum output, while ANN-based MPPT predicts and adjusts to the optimal power point using historical data and machine learning algorithms (Sarvi; Azadian, 2022). Incremental Conductance directly measures changes in current and voltage to stay aligned with the maximum power point, offering precise control even under rapidly changing conditions. DC converters in micro-grids are integral components that facilitate the efficient conversion and flow of energy between different sources and loads. They can operate in various modes such as boost, buck, or bidirectional, depending on the requirement. These converters ensure that the voltage levels are appropriate for different applications within the grid, thereby stabilizing the energy distribution and enhancing overall performance. By handling variations in power supply and demand efficiently, DC converters play a pivotal role in maintaining the robustness and reliability of micro-grid operations.

This paper focuses on the development and optimization of an energy management system for a decentralized DC micro-grid integrating renewable energy sources, BESS, and fuel cells to supply a 10 kW DC load. The control strategy employs a PI cascade approach enhanced by Genetic Algorithm optimization to ensure efficient operation and maximize renewable energy utilization and Reduction of hydrogen usage in fuel cells. Through simulation studies using MATLAB Simulink, the robustness of the proposed energy management system is evaluated under various operating scenarios,
demonstrating its capability to enhance whole system performance and reliability in decentralized DC micro-grid environments.

2 DESCRIPTION OF HYBRID DC MICRO-GRID

The hybrid decentralized system, as shown in Figure 1, involves components for a DC microgrid. They comprise an 8 kW PV system with a DC converter and a 6 kW wind turbine with a DC converter. A 2.5 kW BESS with a bidirectional DC to DC converter which employed for the charging and discharging, and a 6 kW fuel for emergency power supply, have also been developed. With a total DC load of 10 kW, these integrated renewable energy sources are combined with storage and urgency generation, which will be reliable and resilient to supply energy to the load.

Figure 1. Structure diagram of the proposed DC microgrid

2.1 THE PHOTOVOLTAIC (PV)

The PV system is a component that transform sunlight into electricity (Al-Ezzi & Ansari, 2022), the Figure 2 illustrates the single diode model used to represent this process (Abbassi et al., 2022). This model is a crucial part of the power production system of a photovoltaic setup, which utilizes power converters to regulate its generation. The system is comprised of multiple solar PV panels, each containing solar cells that transform solar energy into DC electricity.

The conduct of these cells is accurately demonstrated by the one-diode model, known for its accuracy and simplicity in terms of components. This model features a photo-current source that changes linearly with the cell's temperature. Attached to this source is a diode, which emulates the photovoltaic (PV) cell's non-
linear characteristics. Additionally, two resistors, the first in parallel and the other in series, are incorporated to depict losses. The model can be described by the following equations:

\[ i_c = i_{ph} - i_r - i_d \]  \hspace{1cm} (1)

Where \( i_d \) represents the diode current.

The photocurrent is expressed as:

\[ i_{ph} = i_{csc} \left( \frac{g}{g^*} \right) \left( 1 + K_i(\theta - \theta^*) \right) \] \hspace{1cm} (2)

Where:

\( g^* \) is Standardized Testing Conditions (STC) irradiance, 
\( K_i \) is the current temperature factor, and 
\( \theta^* \) represents the standard temperature.

The diode saturation current is defined as:

\[ i_{sat} = \frac{i_{csc} \left( \frac{g}{g^*} \right)^3 \exp \left( -\frac{qE_G}{nk} \frac{1}{\theta} \right)}{\left( \exp \left( \frac{qE_G}{nk\theta^*} \right) - 1 \right)^3} \] \hspace{1cm} (3)

Where:

\( E_G \) represents a Bandgap energy, 
\( n \) indicates the idealization index and 
\( q \) refer the electron charge.

The cell current can represented as:

\[ i_c = i_{ph} - i_{sat} \left( \exp \left( \frac{v_c + i_dr_s}{nV_T} \right) - 1 \right) - \frac{v_c + i_dr_s}{r_P} \] \hspace{1cm} (4)

Where \( VT \) is defined as the thermal voltage.
The configuration of the PV array includes $N_s$ panels in series and $N_p$ parallel strings.

The yield current is expressed by:

$$i_{PV} = i_{ph} - i_{sat} \left( \exp \left( \frac{v_{PV} + i_{PV} N_{r_s}}{n N_V} \right) - 1 \right) - \frac{v_{PV} + i_{PV} N_{r_s}}{N_{r_p}}$$

Where:

$v_{PV}$ signifies the voltage from the PV source, and $N = N_s \times N_p$ denotes the total number of panels.

![Figure 2. PV cell model.](source)

Table 1 shows the characteristics of the PV panels utilized in this study.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power (W)</td>
<td>335</td>
</tr>
<tr>
<td>Temperature Coefficient of $V_{oc}$ (%°C)</td>
<td>-0.36</td>
</tr>
<tr>
<td>Temperature Coefficient of $I_{sc}$ (%°C)</td>
<td>0.09</td>
</tr>
<tr>
<td>Current under Maximum Power $I_{mp}$ (A)</td>
<td>8.07</td>
</tr>
<tr>
<td>Short – Circuit Current $I_{sc}$ (A)</td>
<td>9</td>
</tr>
<tr>
<td>Maximum Power Voltage $V_{mp}$ (V)</td>
<td>41.5</td>
</tr>
<tr>
<td>Open – Circuit Voltage $V_{oc}$ (V)</td>
<td>49.9</td>
</tr>
</tbody>
</table>

Source: Author

In the scientific literature, several techniques have been proposed to maximise the performance of a photovoltaic system, such as fuzzy MPPT, incremental control based on neural networks and Perturb & Observe. (P&O) (Bhattacharyya et al., 2020). This method works by varying the voltage of the PV array continuously while observing the resulting changes in the output power as follows: If $\Delta V$ and $P < P_{max}$ Then $\Delta V + e$ else $P = P_{max}$ If the power decreases, the
direction of the disturbance reverses. This approach allows the system to track the maximum power point (MPP) as environmental conditions change, such as variations in sunlight intensity and temperature.

2.2 WIND ENERGY CONVERSION

2.2.1 Wind Turbine Aerodynamic Model

The wind turbine permits the conversion of the wind dynamic energy into mechanical rotational energy of turbine blades (Chaudhuri et al., 2022). As depicted in Figure 6, the wind generator encompasses a wind turbine, a synchronous permanent magnet generator, and a power converter controlled by an MPPT (Mousa et al., 2021).

The mechanical power $P_t$ generated by the wind turbine can be shown with the following equation:

$$P_t = \frac{1}{2} \rho A C_p(\lambda, \beta) \omega^3$$  \hspace{1cm} (6)

The tip speed ratio $\lambda$ of the wind turbine is defined as:

$$\lambda = \frac{\omega_m R}{\omega}$$  \hspace{1cm} (7)

2.2.2 Model of Permanent Magnet Synchronous Generator

The mathematical model utilised for the analysis of the Permanent Magnet Synchronous Generator (PMSG) is founded upon the subsequent fundamental assumptions: The stator windings in the three-phase system are spread sinusoidally along the air gap of the machine in a symmetrical manner. For the purpose of analysis, any effects of magnetic hysteresis and saturation are disregarded, and the presence and influence of damping windings are not taken into account. The rotor of a permanent magnet synchronous generator (PMSG) is driven directly by a wind turbine, eliminating the need for a gearbox (Pan & Shao, 2020). The variables in the proposed model of the Permanent Magnet Synchronous Generator (PMSG) have been represented in the $dq$ reference frame, which is a synchronous rotating frame. In this frame, the $d - axis$ is adjusted with the direction of the flux vector of the permanent magnet rotor. The
mathematical equations of the PMSG are asserted in the common \(dq\) – \textit{reference} frame, turning in coordination with the electrical angular rotor speed. The final form can be described as:

\[
\vartheta_{sd} = R_s i_{sd} + L_d \frac{d i_{sd}}{dt} - \omega_e \psi_{sq} \tag{8}
\]

\[
\vartheta_{sq} = R_s i_{sq} + L_q \frac{d i_{sq}}{dt} - \omega_e \psi_{sd} \tag{9}
\]

\[
\omega_e = n_p \omega_m \tag{10}
\]

The dq components of the stator flux vector in the dq reference frame are given by:

\[
\psi_{sd} = L_d i_{sd} + \psi_{PM} \tag{11}
\]

\[
\psi_{sq} = L_q i_{sq} \tag{12}
\]

Where:

\(\vartheta_{sd}, \vartheta_{sq}\): dq components of the stator voltage vector;

\(i_{sd}, i_{sq}\): dq components of the stator current vector;

\(\psi_{sd}, \psi_{sq}\): dq components of the stator flux vector;

\(\psi_{PM}\) is the flux established by the permanent magnets

\(\omega_e, \omega_m\) represent the electrical and mechanical angular speed of the PMSG rotor;

\(R_s\) is stator phase resistance;

\(L_d, L_q\) indicate direct and quadrature stator inductances;

\(n_p\) is the number of pole pairs of PMSG.

The electromagnetic torque of PMSG is expressed as follows:

\[
\lambda T_e = \frac{3}{2} n_p (\psi_{sd} i_{sq} - \psi_{sq} i_{sd}) \tag{13}
\]

The equation of mechanical motion of wind turbine system is given by:

\[
T_e + T_i = J \frac{d \omega_m}{dt} + B_f \omega_m \tag{14}
\]
Where:

\( T_t \) represent the mechanical torque of wind turbine.
\( T_e \) is the electromagnetic torque of PMSG;
\( J \) denote the total inertia of the system;
\( B_f \) is the coefficient of viscous friction in WECS mechanical system.

### 2.3 FUEL CELL

The Proton Exchange Membrane Fuel Cell (PEMFC) harnesses hydrogen and oxygen to produce electrical energy and is well-suited for both stationary and mobile uses due to its lower operational temperatures. The hydrogen and oxygen necessary for the PEMFC are generated via water electrolysis in a PEM electrolyzer. The electrolyte is comprised of proton-conductive polymer membranes (Mtolo; Saha, 2021). In the PEMFC, proton transfer is facilitated by a specialized membrane that separates two electrodes, an anode and a cathode. At the anode, hydrogen gas splits into positively charged hydrogen ions (protons) and electrons. The protons pass through the membrane to the cathode, while the electrons flow through an external circuit to produce an electric current. At the cathode, oxygen merges with the electrons and protons to create water. This process also creates heat, that is controlled through a cooling system. Numerous benefits are served by PEMFCs, including high power density, quick start-up, minimal emissions, and silent operation (Tariq et al., 2023). However, they depend on a steady deliver of hydrogen and oxygen, and their efficiency may be affected by low-temperature conditions, membrane wear, and contamination. Figure 4 depicts the configuration of a PEMFC (Tariq et al., 2023).

At the anode, the chemical reaction is shown by:

\[
\text{H}_2 \rightarrow 2\text{H}^+ + 2e^- \tag{15}
\]

Conversely, the reaction at the cathode proceeds as described as:

\[
2\text{H}^+ + 2e^- \rightarrow \text{H}_2 \tag{16}
\]

\[
\text{H}_2 + 2e^- + \frac{1}{2} \text{O}_2 \rightarrow 2\text{H}^+ + 2e^- \tag{17}
\]
The complete reaction can be given as,

\[ \text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O} \] \hspace{1cm} (18)

The polarization curve for the PEMFC reveals three distinct phases including concentration losses, ohmic losses, and activation losses. The activation phase is nonlinear and reflects detailed aspects of the electrochemical reactions in the cell. Ohmic losses primarily occur in the membrane, while concentration losses originate from the variance in reactant concentration within the PEMFC.

The total cell voltage is expressed as:

\[ V_{\text{cell}} = E_{\text{cell}} - V_{\text{act}} - V_{\text{ohmic}} - V_{\text{conc}} \] \hspace{1cm} (19)

Where:

- \( E_{\text{cell}} \) is the open circuit voltage,
- \( V_{\text{act}} \) represents the activation polarization,
- \( V_{\text{ohmic}} \) is the ohmic’s loss, and \( V_{\text{conc}} \) refers to the concentration losses.

The voltage of the PEMFC, dependent on the number of series-connected cells (\( Xn \)), is given by:

\[ V_t = Xn \times V_{\text{cell}} \] \hspace{1cm} (20)

**2.4 BATTERIES ENERGY STORAGE SYSTEM BESS**

Battery Energy Storage (BESS) Systems play a pivotal role in modern energy management, particularly within micro-grids, where they enhance stability, flexibility, and efficiency (Abdelhalim et al., 2023). Lithium-ion batteries, favored for their high energy density and longevity, are often central to these systems. Integration of these batteries into a micro-grid involves an intricate balance of charging and discharging cycles managed through advanced control systems to optimize energy use and maintain power stability. The process can be visualized using an equivalent circuit diagram, typically representing the battery with a voltage source (emf) and internal resistance. The basic equations governing the charging
and discharging mechanisms are crucial for understanding the energy flow. Figure 3 the circuit diagram of lithium battery accompanied by equations for charging and discharging (Zhou et al., 2021).

Figure 3. Lithium battery's equivalent circuit

In the case of discharging, the formula used to calculate the battery voltage is presented as follows:

\[ V_{Bat} = E0 - K \cdot \frac{Q}{Q-it} \cdot i^* - K \cdot \frac{Q}{Q-it} \cdot it + A \cdot \exp(-B \cdot it) \]  

(21)

In the case of charging, the equation for the battery voltage is formulated as follows:

\[ V_{Bat} = E0 - K \cdot \frac{Q}{it+0.1Q} \cdot i^* - K \cdot \frac{Q}{Q-it} \cdot it + A \cdot \exp(-B \cdot it) \]  

(22)

In the described model, \( A \) represents the amplitude related to the exponential zone, while \( B \) serves as the reciprocal of the time constant within this zone. \( E_{Bat} \) denotes the voltage of the when it is disconnected from any load, and \( E0 \) is defined as the battery's steady voltage. The term \( I_{batt} \) refers to the current involved in the charging or discharging processes. \( K \) is utilised to indicate the voltage that associated due to the polarization. Additionally, \( Q \) describes the battery’s utilized capacity, specifying how much of the total capacity has been used. Finally, \( V_{Bat} \) is the voltage noticed at the electrical contact points of the battery’s.

Where SOC formula is provided as:
\[ SOC = SOC_0 - \frac{1}{Q_N} \int_0^t i_{Bat} dt = SOC_0 - \frac{it}{Q_N} \]  

(23)

\[ it = \int_0^t i_{Bat} dt \]  

(24)

Where:

\( SOC_0 \) denotes the battery's initial charge level, with \( Q_N \) indicating its nominal capacity.

\( i_{Bat} \) represent battery current, and it represents the accumulated charge over time \( t \).

3 CONTROL STRATEGY AND ENERGY MANAGEMENT SYSTEM

3.1 CONTROL STRATEGY

PI (Proportional-Integral) controller designed for a power management system to regulate the distribution of power between a battery storage unit and a DC power source derived from DC sources. The objective of this control system is to maintain a steady DC voltage output \( V_{dc} \) at a reference value of 330 volts, despite variations in load demand or the intermittent nature of the power supply from DC link.

In a cascade control system, the control strategy is arranged in a hierarchy of loops called the inner loop and the outer loop. The outer loop is responsible for setting the primary control target, which, in this case, is the DC voltage \( V_{dc} \). The reference value for \( V_{dc} \) is set at 330 volts. The PI controller in this outer loop measures the actual \( V_{dc} \) and adjusts its output to correct any deviation from the reference. This output from the first control block becomes the setpoint for the inner loop. The inner loop is designed to respond more quickly to changes and typically controls a more immediate aspect of the system, such as current. The PI controller in the inner loop takes the setpoint from the first block and compares it with the actual current measurement. It then regulates the control elements to adjust the power from either the DC sources or the battery, or both, to match the desired current that would maintain the \( V_{dc} \) at 330 volts. The Figure 4 represent the schematic diagram of the PI controller (Leal et al., 2023).
Figure 4. The cascade PI controller

Figure 5 illustrates a control mechanism engineered for the optimization of power output from a fuel cell. The system initiates its process by receiving two primary inputs: the power demand of the load (Pl) and the voltage generated by the fuel cell (Vfc). These inputs are subsequently directed. The role of the PI controller is to adjust the fuel cell's current (Ifc) accurately, ensuring that the power output aligns with the required demand (Oussama et al., 2023).

3.2 GA ALGORITHM

Genetic Algorithms (GAs) offer a powerful alternative for tuning PID controller gains. Unlike traditional methods, GAs don’t require a deep understanding of the system's dynamics. Instead, they mimic natural selection to evolve a population of potential gain combinations. The Figure 6 represent the flowchart process of how GA function (Borase et al., 2021). The best performers are then used to create new generations with improved control characteristics. This iterative process allows GAs to find optimal gains that enhance the performance of PID controllers in systems like bidirectional DC-DC converters.
The target function $J$ for this project is determined by examination the integral absolute error ($J_{AE}$) of the DC bus voltage discrepancy $\Delta V_{DC}$, as indicated in the following equation:

$$J = \int_0^T |\Delta V_{DC}| \, dt = |V_{DC}^* - V_{DC}| \, dt$$  \hspace{1cm} (25)$$

Where:

$V_{DC}^*$ indicate the reference voltage and $V_{DC}$ represent the measured voltage.

However, GA-based tuning is powerful, it can be computationally demanding, requiring significant resources and time. To optimize efficiency and effectiveness, careful selection of fitness functions, crossover/mutation managers, population size, and stopping criteria is crucial. In essence, Genetic Algorithms provide a robust and adaptable optimization tool for tuning PID controller parameters in bidirectional DC-DC converters. Their evolutionary search capabilities allow them to discover parameter combinations that maximize system performance and refine control of the converters.

### 3.3 EMS Strategy

The Figure 7 depicts a proposed energy management system for a DC micro-grid. Photovoltaic (PV) solar is the primary source of power, with wind, battery energy storage system (BESS), and fuel cell acting as emergency sources. The system incorporates six operational modes, which are detailed in Table 2.
This table outlines the operational modes of a system that likely manages power from various sources and conditions under which each mode is activated. The table compares production (PRES), load demand (PLOAD), battery state of charge (SOC), energy from photovoltaic sources (PPV), wind power (Pwind), battery energy storage systems (BESS), and fuel cells (PFC).

Mode 1 is activated when production is greater than the load and the SOC is below 90%, indicating that excess energy is available and is directed towards charging the batteries. This suggests an emphasis on energy storage when supply exceeds demand, and the battery is not fully charged.

Mode 2 occurs when production is still higher than the load, but the SOC is above 90%, meaning the batteries are nearly or fully charged. Here, the management system disable the maximum power point tracking (MPPT) of the PPV and Pwind to protect the BESS from overcharging.

Mode 3 is activated when the load is greater than the production and the SOC is above 30%. This indicates a situation where the demand is higher than the renewable supply, but the battery has enough charge to assist in meeting that demand. It involves combining supply from renewable sources and the battery to meet the load requirements.
Mode 4 is selected when the load demand exceeds the sum of production, battery’s output, and fuel cell contribution. This suggests a high-level demand scenario where the system activates a fuel cell as an additional power source to meet the load.

Finally, Mode 5 is used when the load is so high that it surpasses the combined capacity of production, battery’s, and fuel cell. In this extreme case, the system disconnects the load from the system, likely as a protective measure to prevent system overload or failure.

Overall, the table provides a strategic operational framework for managing a hybrid power system that includes renewable energy, battery storage, and fuel cells, ensuring energy supply meets demand and system components are protected.

<table>
<thead>
<tr>
<th>State</th>
<th>Description</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>(PRES &gt; PLOAD &amp; SOC &lt; 90%)</td>
<td>Excess power presented, the additional</td>
</tr>
<tr>
<td></td>
<td></td>
<td>power is directed towards charging the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>batteries</td>
</tr>
<tr>
<td>Mode 2</td>
<td>(PRES &gt; PLOAD &amp; SOC &gt; 90%)</td>
<td>Close the (MPPT) of the (PPV) and Pwind</td>
</tr>
<tr>
<td></td>
<td></td>
<td>for protect the (BESS)</td>
</tr>
<tr>
<td>Mode 3</td>
<td>(PLOAD &gt; PRES + PBES &amp; SOC)</td>
<td>Combined supply from renewables and</td>
</tr>
<tr>
<td></td>
<td>(&gt; 30%)</td>
<td>battery to supply the load</td>
</tr>
<tr>
<td>Mode 4</td>
<td>(PLOAD &lt; PRES + PBES + PFC)</td>
<td>Activation of (FC) as an additional</td>
</tr>
<tr>
<td></td>
<td></td>
<td>power source</td>
</tr>
<tr>
<td>Mode 5</td>
<td>(PLOAD &gt; PRES + PBES + PFC)</td>
<td>Disconnection the (Pload) from the system</td>
</tr>
</tbody>
</table>

Source: Author

4 RESULTS AND DISCUSSION

As a result, the proposed energy management system was simulated within the MATLAB Simulink environment. Figure 8 illustrates the VDC voltage throughout the entire simulation period. It was observed that the VDC maintained stability and accuracy in response to various conditions. This includes all load alterations and the fluctuations in PV power associated with changes in irradiation and temperature. The robustness of the VDC voltage under these dynamic conditions underscores the system’s reliability in managing energy effectively, despite external variable factors that typically impact performance.
Figure 8. DC-bus voltage of the EMS during the simulation

Source: Author

However, Figure 9 and Figure 10 provide detailed depictions of the voltage and current curves, respectively. These figures further demonstrate the system’s capacity to maintain optimal performance. Specifically, Figure 9 showcases the consistency of voltage levels, while Figure 10 highlights the current profiles under the same varying conditions of load and photovoltaic power changes due to environmental factors. Together, these curves reinforce the system’s adaptability and its effective control mechanisms that ensure continuous operation within the desired parameters.

Figure 9. Battery voltage under different conditions

Source: Author

Figure 3. Battery charging and discharging current under different conditions

Source: Author
Figure 12 represent the power curve of this proposed EMS system. In the beginning section, stretching from 0 to 0.1 sec, a load demand of 10 kW is met by the energy contributed by the battery's in conjunction with the DC power sources.

The ensuing phase, spanning 0.1 to 0.4 sec, is characterized by an examination to determine whether the PV and Wind power output is exceeded by the load and whether a decline in the BESS State of Charge (SoC) to below 30% occurs. Upon these status being satisfied, the provision of power is undertaken by the fuel cell. The interval from 0.4 to 2.4 sec that observed the PV & wind output exceeding the load demand, with the excess energy being allocated toward the battery's recharge. The period between the interval between 2.4 to 3 minutes, the SoC is maintained above 30% as depicted on Figure 11 and energy production from photovoltaic panels and wind turbines fails to meet the micro-grid's load demands.
Consequently, the deficit in power is compensated for by the battery storage system, which discharges its stored energy. This results in the battery’s energy reserves being utilized to maintain an uninterrupted supply and ensure the load requirements are continuously met, despite the shortfall from renewable sources. In the end of simulation, covering 3 to 4 minutes, is characterized by an absence of production from both photovoltaic and wind sources, due to environmental factors such as lack of sunlight or wind. Under these circumstances, the load demands are solely dependent on the battery storage, which discharges its stored energy to maintain continuous power supply within the micro-grid. The flexibility embedded in this strategy is indicative of its capability to sustain an uninterrupted supply of energy, notwithstanding the fluctuations inherent in renewable energy outputs.

5 CONCLUSION

This work discussed the development and validation of an Energy Management System (EMS) for a decentralized DC micro-grid that integrates multiple renewable energy sources, consisting photovoltaic (PV) panels, wind turbines (WT), battery’s energy (bes) storage, and fuel cells. Utilizing a metaheuristic algorithm, the EMS was designed to enhance control gains, thereby maintaining stable DC bus voltage and effectively managing power flow under assorted conditions. The performance of the EMS was validated through MATLAB Simulink simulations, which confirmed its capability to stabilize voltage and manage dynamic power distribution effectively. The results indicate that the EMS can adapt to fluctuations in energy production and consumption, ensuring efficient operation of the micro-grid without sacrificing system stability. The potential for employing such a system in decentralized settings is significant, enhancing the reliability and efficiency of energy distribution in areas where traditional grid infrastructure is absent or inadequate. Further research will aim at optimizing the algorithm and expanding system capabilities to accommodate larger and more complex micro-grid configurations.

The discoveries from this study provide valuable insights into the practical challenges and solutions associated with deploying adaptable and resilient energy management systems in renewable energy-based micro-grids. In our future endeavors, we aim to integrate artificial intelligence for advanced energy management within this system to achieve optimal performance.
REFERENCES


