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Original Article

Integrated Energy Management in DC Microgrid Systems with Hybrid PV-PEMFC-Battery Configurations

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Abstract *- This paper presents an in-depth study on the integrated energy management of a DC microgrid system that synergistically combines Photovoltaic (PV) arrays, Proton Exchange Membrane Fuel Cells (PEMFCs) and lithium-ion batteries. The objective is to harness multiple renewable energy sources to meet dynamic DC load demands while maintaining high reliability under fluctuating environmental conditions and varying battery States of Charge (SoC). A standout feature of the system is a 300V, 48AH lithium-ion standby battery, integrated with a sophisticated bidirectional converter, significantly enhancing operational flexibility and energy storage efficiency. A robust 2KW PEMFC system, connected via a DC-DC converter equipped with Proportional-Integral (PI) control, bolsters the system's reliability and responsiveness. This configuration ensures continuous power supply during periods of low solar irradiance and when the battery's SoC drops below 30% by enabling the fuel cell to not only power the DC load but also recharge the battery simultaneously. The simulation results reveal the impressive capability of the proposed energy management system to optimize the utilization of available energy resources. The system demonstrates superior performance in balancing energy supply and demand, enhancing overall efficiency and reliability. This research contributes valuable insights into the practical deployment of hybrid energy systems, paving the way for more resilient and sustainable DC microgrids.*

Keywords **-** *Power quality, Photovoltaics, Micro-grid, THD, Energy management, Power factor, Power filters, Power converters.*

1. Introduction

The increasing burden of global carbon emissions and energy security has prompted the exploration of clean, eco-friendly renewable energy sources for power generation through the microgrid framework. DC microgrids offer a single voltage conversion level between distributed sources and the DC bus, unlike AC microgrids. This reduces the overall construction costs and simplifies control implementation [1, 2]. Historically, AC microgrids dominated due to existing infrastructure, but the rise of renewable energy and DC-powered devices has spurred interest in DC systems [3]. These systems minimize conversion losses, integrate seamlessly with DC loads and accommodate renewable sources like PV arrays and fuel cells without additional conversion equipment. Components of DC microgrids include diverse generation sources, low-voltage DC distribution networks, advanced control algorithms, energy storage and support for both DC and converted AC loads. Over the past decade, DC microgrids have garnered considerable attention from academia and industry due to their demonstrated advantages over AC microgrids, including enhanced reliability, efficiency, control simplicity, integration of renewable energy sources, and the ability to connect DC loads [4].

The conventional electrical grid's dispersed layout necessitates the employment of AC buses to convey electricity over extensive distances from power generation sites to end users. Nevertheless, various devices run on DC power, compelling the integration of AC/DC converters. Recently, there has been a growing interest in DC microgrids due to their advantages over AC microgrids [5]. The foundational form of DC microgrids often involves PV/FC/battery systems, which have extensive applications in various sectors, including telecommunications, smart buildings, and electric vehicles. The advancement of power converters has streamlined the process of integrating Renewable Energy Sources (RESs) to construct microgrids. Effective energy management in microgrids requires sophisticated control and monitoring systems and integration with advanced technologies to adapt to dynamic conditions and optimize performance.

Efficiently harnessing solar energy from PV generators involves maximizing power extraction, typically achieved through Maximum Power Point Tracking (MPPT) techniques. Numerous MPPT algorithms have emerged in the literature, each aiming to track the Maximum Power Point (MPP) for PV modules. These MPPT algorithms aim to optimise power output with varying efficiency and design complexity. The

Authors [6] prove that the benefit of this work lies in its demonstrated ability to enhance the efficiency of PV systems and prolong the lifespan of batteries by implementing a microcontroller-based battery charge controller with MPPT methods. This advancement contributes significantly to the advancement of renewable energy solutions. This work introduces a hybrid MPPT approach to improve energy harvesting at maximum point. The hybrid MPPT uses an FLC algorithm with fine-tuned PI controllers.

The battery represents a significant investment in a PV/Battery system, and optimising the charge/discharge cycle to maximize its lifespan is crucial. This involves implementing measures to prevent overcharging and deep discharging, enhancing the battery's longevity and ensuring efficient utilization within the system [7]. The authors [8] have introduced a power management approach tailored for PV/Battery hybrid systems within islanded Microgrids.

Employing an adaptive droop control strategy, the PV/Battery system functions as a voltage source to meet load requirements while effectively overseeing the battery's charging/discharging operations. The authors [9] demonstrate that integrating a novel EMS-based control strategy in DC microgrids with Dual Energy Storage Systems (DESSs) improves voltage stability and power balance and extends the lifetime of BESSs compared to systems with only a single BESS, as confirmed through simulation results in MATLAB/SIMULINK.

In [8], Droop control methods have found application in microgrids incorporating PV/Battery systems due to their ability to function without access to comprehensive system measurements, which is particularly advantageous in large and intricate setups. Despite widespread use, droop control has several limitations, including suboptimal transient performance and imprecise power allocation among components [10].

The authors [11] provide a detailed methodology and comparative analysis of different optimization algorithms for effective energy management. The work [11] uses more numbers of optimization algorithms such as Sliding Mode Control (SMCS), classical Equivalent Consumption Minimization Strategy (ECMS), White Shark Optimizer (WSO), Manta Ray Foraging Optimization (MRFO), Harris Hawks Optimizer (HHO), Soon Eagle Search (BES) and Artificial Hummingbird Algorithm (AHA) increases the complexity of understanding.

The research gap includes optimising energy management algorithms, which could benefit from advanced adaptive solutions to enhance real-time system responsiveness to dynamic conditions. Additionally, the impact of fluctuating environmental factors on system performance has not been fully explored, and the long-term degradation of PEMFCs, including strategies to optimize fuel cell lifetime and efficiency, requires further study. Battery Management Systems (BMS) also need optimization for better health monitoring and charging cycles. Furthermore, integrating sophisticated control strategies for managing multiple energy sources like hierarchical control, fuzzy logic, or model predictive control would enhance system performance. The economic feasibility of hybrid systems has not been thoroughly examined, with more research needed on installation, maintenance, and comparison to other solutions.

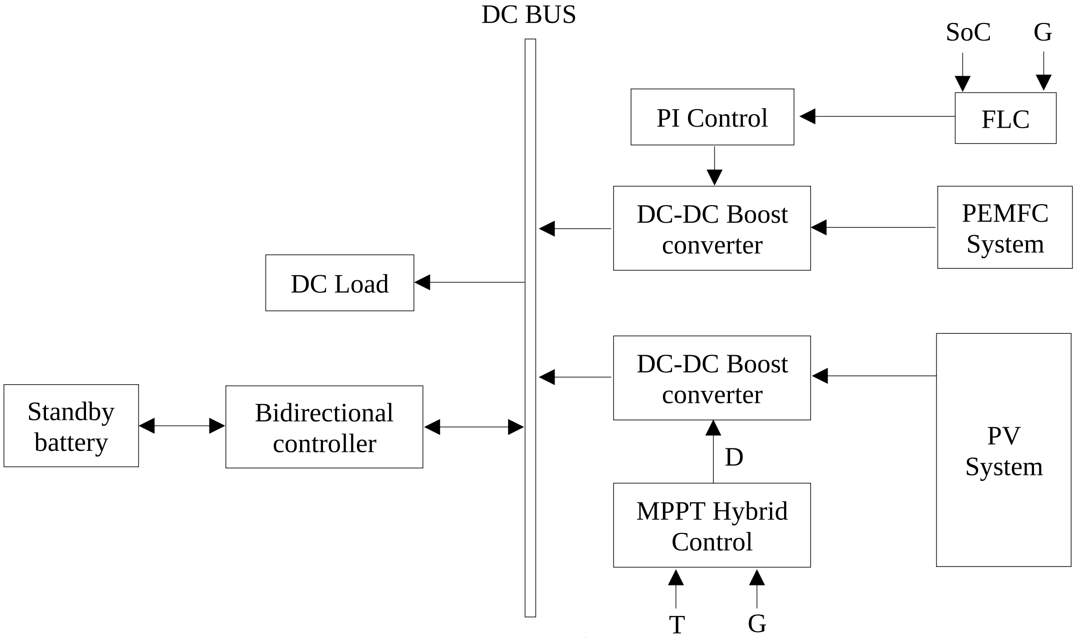


Fig. 1 Block diagram of proposed work

Scalability for large-scale deployments and adaptability to different sectors (residential, industrial, etc.) are other gaps, as is the lack of real-world pilot studies to validate simulation results. Finally, integrating hybrid systems with the grid for energy security, both in islanded and grid-connected modes, requires further exploration. This work proposes a comprehensive DC microgrid system architecture using PV, PEMFC and battery systems with optimized control strategies for integrated energy management to feed DC load. The proposed system ensures the following constraints: (i) Implementing the PV module as a primary source to feed Loads, (ii) ensuring the safe operation of standby considering deep discharge issues, and (iii) When the battery's charge falls below a 30% of SoC & the power generated by the PV arrays is insufficient, the PEMFC is utilized to supply the load.

The major contribution of this paper includes (i) Implementing the designed control strategy to satisfy the above listed constraints, (ii) Simulations were performed to evaluate the effectiveness of the proposed control strategy in DC microgrid systems and the results are presented to demonstrate its performance. The block diagram of the proposed work has been depicted in Figure 1.

The work has been organized as follows: Section two implements the system architecture, including (1) PV system specifications and PEMFC system specifications, (2) Hybrid MPPT control, (3) DC-DC converter design and (4) standby battery with bidirectional converter design. Section three explores the energy management assessment. Section four declares the conclusion of the work.

2. Literature Review

Effective energy management is crucial for enhancing the performance and optimizing the operation of DC microgrids, facilitating smooth coordination among generation, storage, and consumption components. This review offers an in-depth analysis of the latest energy management strategies used in DC microgrid systems. It highlights the main challenges, emerging trends, and potential future developments in energy management for DC microgrids by drawing on a range of existing research, literature, and industry practices.

This approach integrates renewable energy sources, energy storage systems and load management to balance supply and demand. It often employs advanced control strategies and real-time data to enhance energy efficiency and improve system resilience. However, the major drawback is that the DC load fluctuates in different environmental conditions when it comes to multiple renewable energy sources. Battery State of Charge (SoC) also varies. From this review, it is clear that an advanced energy management system for a DC microgrid that integrates PV arrays, PEMFCs, and lithium-ion batteries ensures efficient load management and reliability under varying conditions.

3. System Architecture

3.1. PV System Specifications

The equivalent circuit model of a single solar cell is shown in Figure 2. In this circuit, I_d and I_{sh} diode current and shunt leakage current where I indicate the cell current. R_s is the series resistance of the pn junction cell, and R_{sh} is shunt resistance, which is inversely proportional to leakage current to the ground. The cell current (I) can be calculated by applying KCL at node 'a' to the equivalent circuit [10].

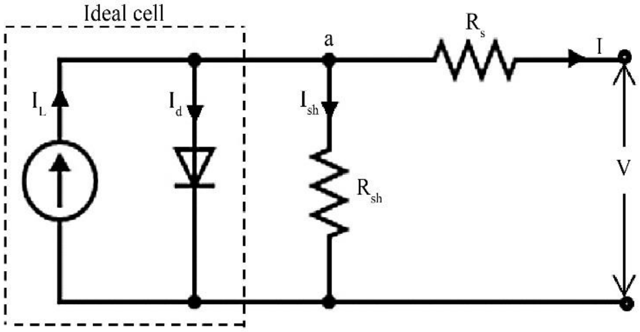


Fig. 2 Generalized equivalent circuit of solar cell

$$\textbf{PV cell current}(\mathbf{I}) = \mathbf{I_L} - \mathbf{I_d} - \mathbf{I_{Rsh}} \quad (1)$$

$$\textbf{Photon current }(\mathbf{I_L}) = [\mathbf{I_{sc}} + \mathbf{K_i}(\mathbf{T} - \mathbf{T_n})] \times \frac{\mathbf{G}}{\mathbf{G_n}} \quad (2)$$

Where, I_{sc} is short circuit current (A), K_i is the short circuit current co-efficient which is provided by the manufacturer datasheet, T is operating temperature (K), T_n is $(25°C)$ nominal temperature at STC, G is Irradiance illuminated on the cell surface (W/cm^2) and G_n is $1000W/cm^2$ at STC [13]. A basic solar cell's electrical characteristics are almost closer to a diode, which is analyzed using the Shockley diode equation, which can be given as [14].

$$\textbf{Diode current}(\mathbf{I_d}) = \mathbf{I_o}\left(\mathbf{e}\,\frac{\mathbf{q(V+I\times R_s)}}{\mathbf{nkT}} - \mathbf{1}\right) \quad (3)$$

Where k is the Boltzmann constant, q is the electron's charge, and n is the ideality factor. The reverse/dark saturation current is caused by the diffusion of minority carriers from the neutral regions to the depletion region in a semiconductor material, and it is highly dependable for temperature variations, and the equation is,

$$\mathbf{I_o} = \mathbf{Ae}^{(-(\frac{\mathbf{qEG}}{\mathbf{kT}}))} \quad (4)$$

Where, A is a constant equal to $1.5e^8 mA/cm^2$ [15].

In Practical conditions, the value of shunt resistance is very large (for ideal solar cell R_{sh} approaches Infinity), and minimum current is consumed by the shunt path. The minimum shunt resistance (R_{sh}) will lead to increased current density due to the series connected (N_S) cells in the PV module. This situation leads to a vast increase in PV panel temperature levels. The series resistance (R_S) is connected in series with the load as the photon current travels through it [16]. The shunt resistance current is given as,

$$\text{Shunt Resistance Current}(I_{sh}) = \frac{V+(I\times R_S)}{R_{sh}} \tag{5}$$

Emitter doping highly influences the open circuit voltage and has relatively less impact on short circuit current, area (100cm*100cm) and thickness (µm) of the semiconductor material. By substituting the LHS values of Equations (2), (3), and (4) in Equation (1), we get

$$I = I_{sc} = I_{ph} - I_o\left(e^{\frac{q(V+I\times R_S)}{nkT}} - 1\right) - \frac{V+(I\times R_S)}{R_{sh}} \text{ for } V_{oc} = 0 \tag{6}$$

The open circuit voltage solar cell is a strong function of temperature and depends on the nature of the semiconductor material. The open circuit voltage of a solar cell at zero cell current is given as,

$$V = V_{oc} = \frac{nkT}{q}\ln\left(\frac{I_L}{I_o} + 1\right) \text{ for } I_{sc} = 0 \tag{7}$$

Each module should generate 36.3V at nominal conditions. The number of modules connected in series and parallel combinations to form a solar array for pre-designed voltage and current requirements is shown in Table 1. The simulation model of the PV system implemented in this work is depicted in Figure 3.

Table 1. Parameters specifications

Sl. No	PV System Parameters	Values
1	Open Circuit Voltage/Module	37.3V
2	Short Circuit Current/Module	8.66A
3	Voltage at MPP/Module	30.7V
4	Current at MPP/Module/Array	8.15A
5	Number of Parallel Strings	1
6	PV Array Open Circuit Voltage (V_{oc})	298V
7	Number of Series Strings	8
8	PV Array Voltage at MPP (V_{mp})	245.6V
9	PV Array Power at MPP (P_{mp})	2000W

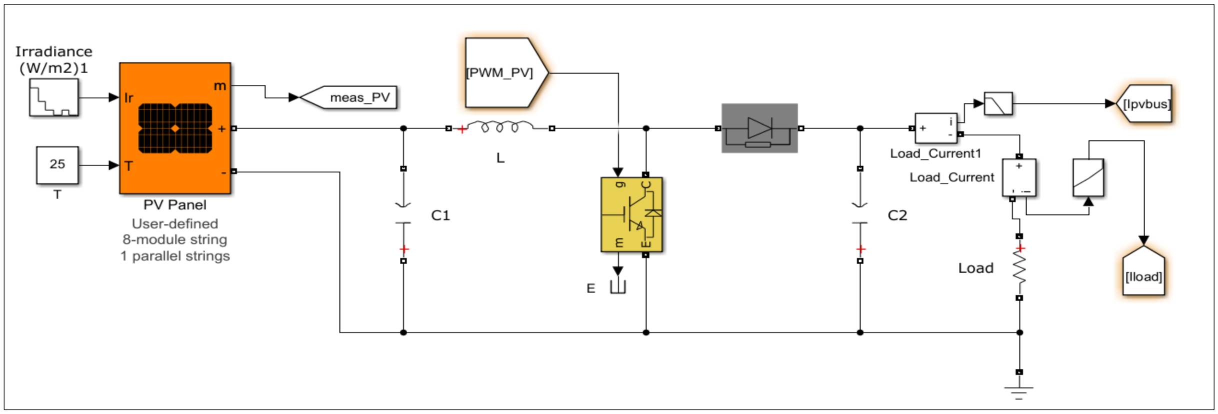


Fig. 3 Simulink model of PV system with DC-DC boost converter

3.2. Design and Optimization of PEM Fuel Cell

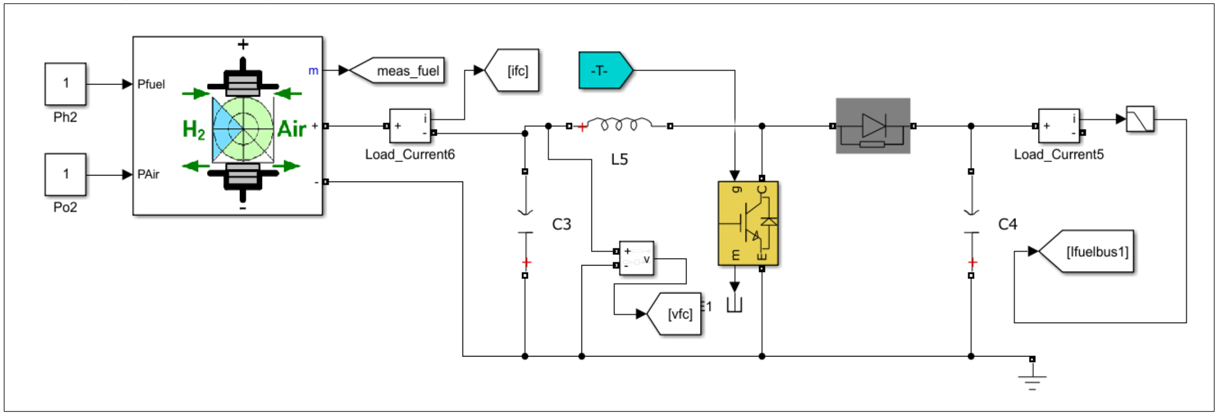


Fig. 4 Simulink model of PEMFC system with DC-DC boost converter

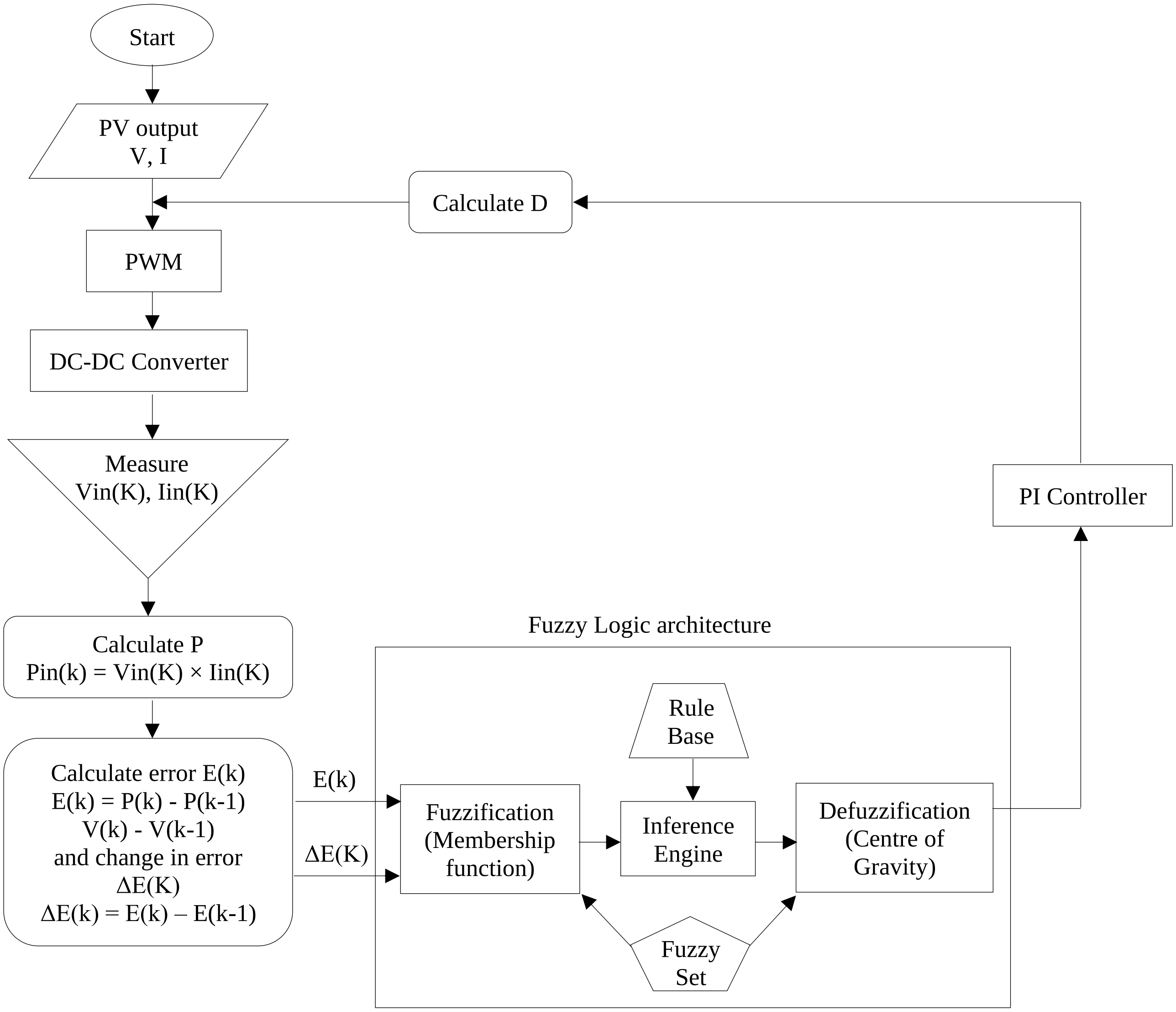


Fig. 5 Flowchart for FLC algorithm

Table 2. PEM fuel cell specifications

Sl. No	Parameter	Value
1	Standard Cell Potential (E^0_{cell})	1.115V
2	Ideal gas constant (R)	8.314J/(mol·K)
3	System temperature (T)	328K
4	Faraday's constant (F)	96,485 C/mol
5	Nominal utilization of H2 (pH_2)	99.92%
6	Nominal utilization of O2 (pO_2)	1.813%
7	I_{stack} nominal	52A
8	I_{stack} maximum	100A
9	V_{stack} nominal	24.23V
10	V_{stack} maximum	20V
11	P_{stack} nominal	1259.96W
12	P_{stack} maximum	2000W
13	$R_{internal}$	0.061871 Ω

The mathematical modeling of PEM Fuel Cells involves considering various electrochemical and thermodynamic processes. One of the fundamental parameters to calculate in a PEMFC is the stack power. The PEM Fuel Cell stack reference parameters have been extracted from SIMULINK with 2KW PEMFC, as given in Table 2. The simulation diagram of the PEMFC system with a DC-DC boost converter is depicted in Figure 4. The stack power (P_{stack}) can be calculated by considering the voltage (V_{cell}) across a single cell and the current (I_{stack}) passing through the stack. Ohm's Law gives the relationship:

$$P_{stack} = I_{stack} \times V_{stack} \tag{8}$$

Now, the voltage across a single PEM Fuel Cell (V_{cell}) is a function of the cell potential (E_{cell}) and the current passing through the cell (I_{cell}). This relationship can be expressed as follows:

$$V_{cell} = E_{cell} - I_{cell} \times R_{internal} \tag{9}$$

Where, $R_{internal}$ is the internal resistance of the fuel cell. The internal resistance of the fuel cell can be calculated and modified from the modification of Equation (8).

Where, n (≈2) is the number of electrons in the electrochemical reaction. The efficiency formula is crucial for evaluating the effectiveness of a power generation system in converting fuel into usable energy, as given in Equation (9),

$$\eta(\%) = \frac{\text{calculated stack power}}{\text{fuel energy input}} \times 100 \tag{10}$$

3.3. Hybrid MPPT Control for PV System

3.3.1. FLC MPPT Controller Model

FLC is designed to handle problems where input information is vague, ambiguous, imprecise, noisy or missing. This is particularly useful when traditional control systems struggle due to uncertainty [20]. FLC provides a systematic and efficient framework for incorporating linguistic fuzzy information from human experts. This is valuable in fields where human expertise is crucial [21]. Fuzzy logic simplifies the design complexity of control systems.

FLC is a versatile and effective methodology for dealing with complex systems where uncertainty and imprecision are prevalent. Its rule-based linguistic approach makes it accessible and practical for various applications.

3.3.2. PI Controller Model

In this paper, an intelligent controller by P-&-O algorithm based on PI controller has been developed, which works well in minimizing the error between PV voltage (V_{pv}) and the output reference voltage generated by P-&-O algorithm or MPPT block (V_{ref}). An Error voltage (V_{error}) is measured by subtracting V_{ref} from V_{pv}, which is fed to a fine-tuned PI controller. The V_{error} signal is fine-tuned in a transfer function-based auto-tuning application in Simulink, which is sent to the PWM generator to provide the duty cycle adopted next to drive the IGBT based Boost converter. This proposed intelligent controller system forces the implemented system to operate using this value of duty cycle, ensuring that the system operates with negligible ripples and at the desired maximum power point [18]. The K_p and K_i values of auto tuned PI controller are 0.00229 and 0.00192462, respectively. The Simulink model of the intelligent controller is shown in Figure 6.

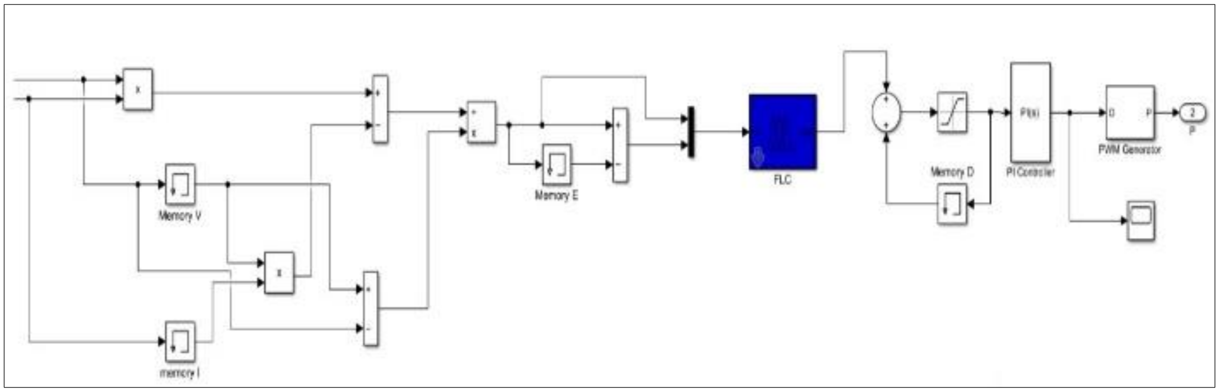


Fig. 6 Hybrid controller using FLC algorithm and fine-tuned PI controller

3.4. DC-DC Boost Converter Model

3.4.1. For PV System

The boost converter is an effective power conversion device in which the input voltage is boosted without a transforming device. In this process, the system power (input and output) is kept constant by adjusting the current [19]. This boost up process is carried out by power electronic elements like an inductor, diode, power switch and a filter capacitor connected in parallel with a PV array. This paper uses IGBT as a power switch and receives gate pulses from the proposed intelligent controller. The parameters are designed as follows,

a) Duty Cycle (D): $1 - \frac{V_{in}}{V_{out}}$

b) Ripple Content (ΔI_o): $20\% * I_o$

c) Value of Inductor (L): $\frac{V_{in} * D}{\Delta I_o * f_s}$

d) Value of Capacitance (C): $\frac{D * I_o}{\Delta I_o * f_s}$

e) Load Resistance (R_o): $\frac{V_o}{I_o}$

3.4.2. For PEMFC System

The DC/DC boost converter is specifically designed for this application using the most commonly used method, as shown in the equations below,

$$I_{outmax} = \frac{P}{V_{out}} \tag{11}$$

$$\Delta I_L = 0.01 \times I_{outmax} \times (V_{out}/V_{in}) \tag{12}$$

$$\Delta V_{out} = 0.01 \times V_{out} \quad (13)$$

$$L = \frac{(V_{in} \times (V_{out} - V_{in}))}{(\Delta I_L \times f_s \times V_{out})} \quad (14)$$

$$C = C_{IN} = C_O = \frac{\left(I_{outmax} \times (1 - (V_{in}/V_{out}))\right)}{(f_s \times \Delta V_{out})} \quad (15)$$

$$D = \frac{(V_{out} - V_{in})}{V_{out}} \quad (16)$$

Where, I_{outmax} is converter output current, ΔI_L is change in inductor current, P is maximum power delivered by PEM Fuel Cell (2KW), V_{out} is converter output voltage or DC link voltage (440V), V_{in} is maximum voltage delivered by fuel cell system (20V), f_s is sampling frequency (10KHZ), ΔV_{out} is change in converter output voltage, L is inductor and C is filtering capacitance.

3.5. Standby Battery with DC-DC Bidirectional Converter

The battery we have chosen in this work is based on the load selection of the PV system and fuel cell. From that, a 300V, 48AH lithium-ion (Li-ion) battery system is used in this proposed system. It operates at a switching frequency of 10kHz and integrates a bi-directional converter alongside an auto-tuned Proportional-Integral (PI) controller, creating an advanced energy storage and management setup. The auto-tuned PI controller significantly enhances the bi-directional converter's efficiency and responsiveness, optimizing performance during both the charging and discharging cycles. With a DC link reference voltage of 440V, this system ensures efficient energy routing and maximizes the battery's performance and lifespan.

First, the switching frequency is 10kHz to balance efficiency and responsiveness. Second, the DC link reference voltage is maintained at 440V to ensure stable operation and optimal power flow. Third, the inductor and capacitor values are selected based on the converter's operating parameters to minimize ripple and ensure stable operation. The unique model of the bidirectional DC/DC converter implemented in the standby battery has been calculated using Equations (17), (18), (19), (20), and (21), respectively,

$$I_{outmax} = \frac{P_{PV}}{V_{out}} \quad (17)$$

$$\Delta I_L = 0.01 \times I_{outmax} \times \left({V_{out}}/{V_{in}}\right) \quad (18)$$

$$\Delta V_{out} = 0.01 \times V_{out} \quad (19)$$

$$L = \frac{(V_{in} \times (V_{out} - V_{in}))}{(\Delta I_L \times F_{SW} \times V_{out})} \quad (20)$$

$$C = \frac{(I_{outmax} \times (1 - (V_{in}/V_{out})))}{(F_{SW} \times \Delta V_{out})} \quad (21)$$

The system incorporates an auto-tuned PI controller. This controller dynamically adjusts its proportional and integral gains for optimal performance across varying operating conditions. Finally, the system is designed with efficiency optimization in mind, aiming to maximize energy transfer efficiency during both charging and discharging cycles. This enhances the system's overall performance and extends the battery's lifespan. The simulation diagram of a battery storage device with a DC-DC bidirectional converter is depicted in Figure 7.

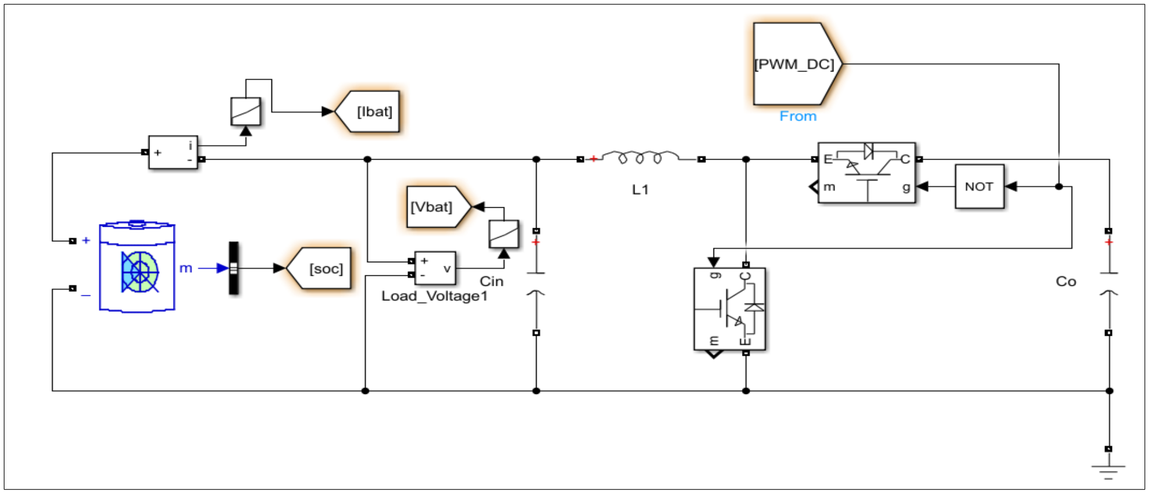


Fig. 7 Battery storage with DC-DC bidirectional converter

4. Energy Management Assesment

Regarding energy management, integrating PV, PEMFC and battery technologies within a micro-grid framework holds promise for enhancing efficiency, resilience and sustainability in power distribution systems. This PV/PEMFC/Battery micro-grid system is designed with specific constraints. The system primarily relies on PV modules to supply power to the loads, utilizing solar energy efficiently. From 0-1 sec, with irradiance at 1000 W/m², the PV modules are active, charging the battery while supplying power to the load. During this time, the PEMFC remains idle as PV generation is sufficient. The PV voltage, current and power are shown in Figure 8.

Standby operation is carefully managed to prevent deep discharge issues, ensuring the longevity and safety of the battery system. During 1-2 sec, irradiance drops below 600 W/m², and the PV output decreases, prompting the battery to step in and support the load. The battery begins to supply the necessary power to load and maintain system stability, as shown in Figure 9.

When the battery's State of Charge (SoC) falls below 30%, and the power generated by the PV arrays drops below 600 W/m², the PEMFC system is engaged to supply the load by PI controller action, guaranteeing continuous operation even during adverse conditions as depicted in Figure 10. At 3sec, when the battery's SoC declines to below 30%, indicating a potential risk of power interruption, the PEMFC is activated to provide additional power. Meanwhile, the battery resumes charging to refill its energy reserves.

Integrating PV, PEMFC, and battery technologies within a micro-grid enhances power distribution efficiency, resilience and sustainability by dynamically managing energy sources based on solar irradiance and battery state of charge, ensuring continuous and reliable power supply. The response standby battery's SoC for various operating modes is shown in Figure 11. The Stability of DC bus voltage is shown in Figure 12.

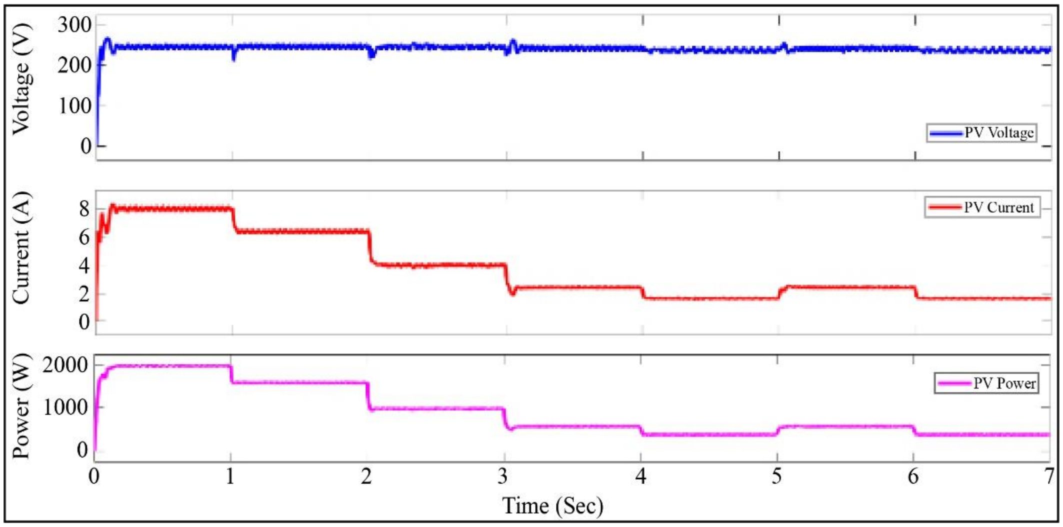
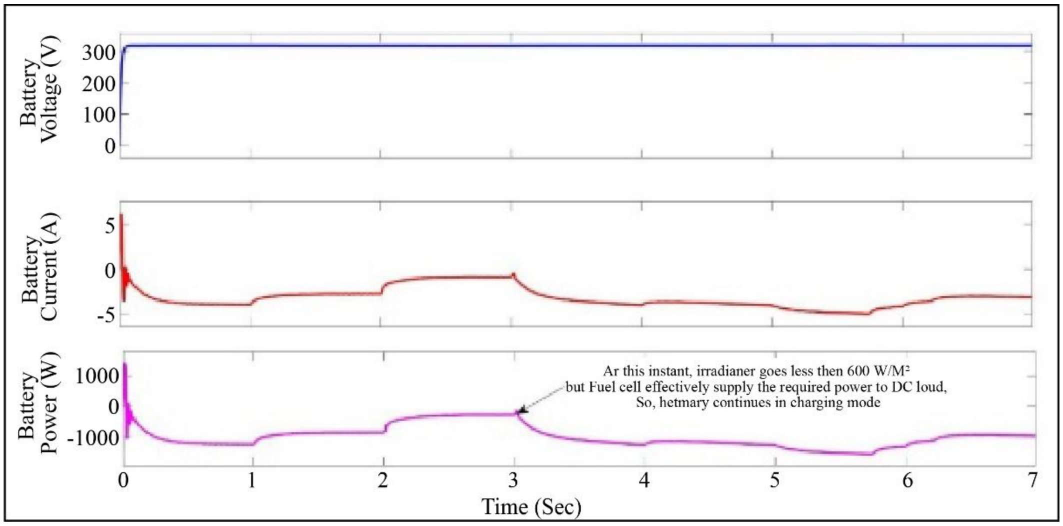


Fig. 8 PV system behavior under variable irradiances



Ar this instant, irradianer goes less then 600 W/M²
but Fuel cell effectively supply the required power to DC loud,
So, hetmary continues in charging mode

Fig. 9 Battery performance under different scenarios

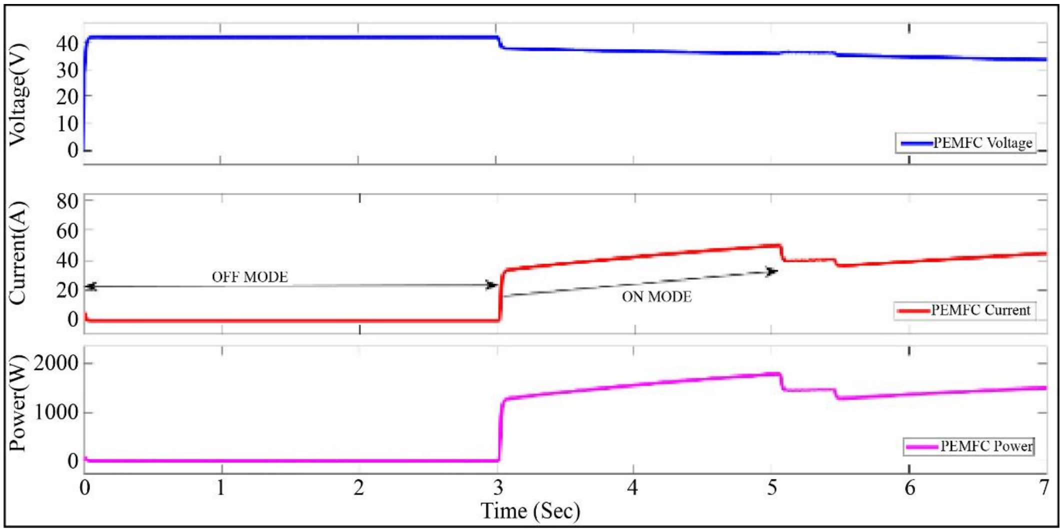


Fig. 10 Performance of PEMFC system within a micro-grid operation

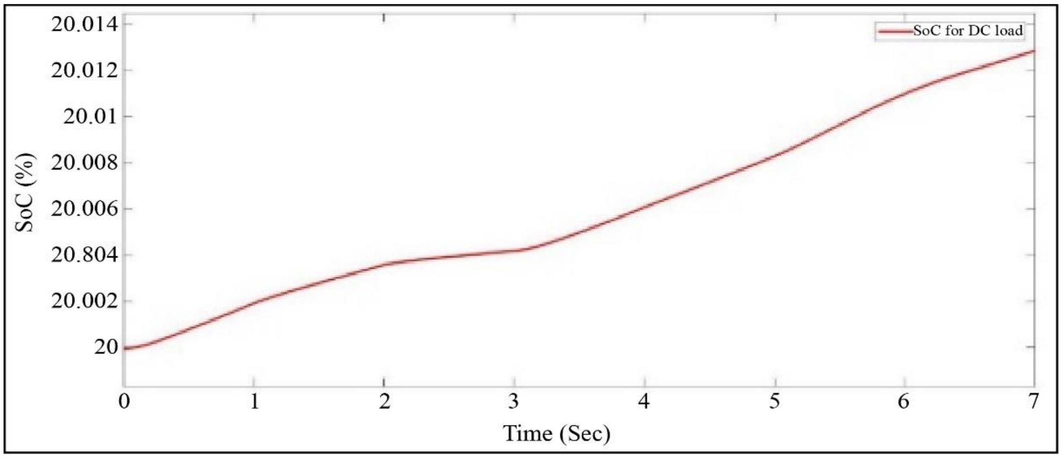


Fig. 11 Battery SoC in various scenarios

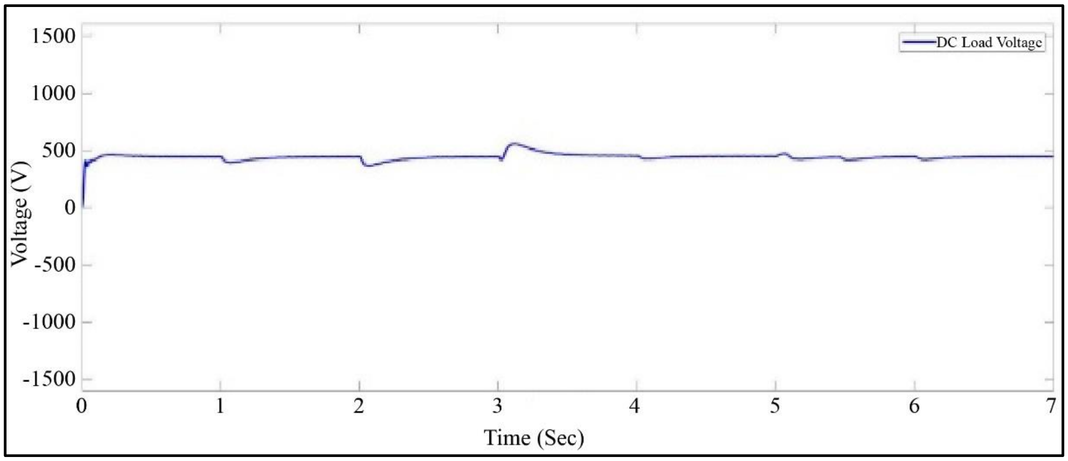


Fig. 12 DC load voltages under different scenarios

5. Conclusion

This paper presents a novel integrated energy management approach for a DC microgrid system employing a hybrid configuration of PV arrays, PEMFC and lithium-ion batteries. The proposed system optimizes the utilization of multiple energy sources to ensure a reliable power supply for

DC load under varying environmental conditions and battery SoC. It includes a 300V, 48AH lithium-ion battery with a bidirectional converter and a 2KW PEMFC system with PI control, which enhances system versatility and reliability. The developed control strategy effectively manages energy distribution, activating the PEMFC when PV output is insufficient, and battery SoC falls below 30%. Simulation results validate the efficiency of the energy management strategy, demonstrating substantial improvements in power quality and system performance. This comprehensive study underscores the potential of hybrid PV-PEMFC battery systems in advancing the reliability and efficiency of DC microgrids, with significant implications for sustainable power distribution.

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