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Research Article

Power-Management Strategies using Super Capacitor for Grid-Connected PV-FC Hybrid System

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Abstract

In this study, we provide state-of-the-art power-management algorithms for improving the performance of grid-connected hybrid systems that include a photovoltaic fuel cell (PV-FC) array, a proton exchange membrane fuel cell (PEMFC), and a super capacitor. Unit-Power Control (UPC) and Feeder-Flow Control (FFC) are the two separate modes of operation of the hybrid system. Under UPC mode, the main grid compensates for fluctuations in load demand by regulating the output of the hybrid source to a reference power. To make the most of fluctuating temperatures and irradiance, the PV array uses a Maximum electricity Point Tracking (MPPT) method to optimally capture electricity. The incorporation of alternate sources, such PEMFC, is necessary to boost system controllability due to the inherent intermittency of PV energy. PV energy is reliant on weather conditions and is unavailable during nighttime. By keeping the feeder flow constant in FFC mode, the hybrid source can handle increased load demand. Accurately determining the feeder reference power is necessary for this. System stability is guaranteed by the suggested technique, which permits a flexible transition between operating modes according to load requirement. Hysteresis is used to reduce the variance in the reference power of the hybrid source and avoid unwanted mode transitions. Improved system performance, stability, and reduced operating mode transition frequency are all results of this strategy's continual optimization of PV array output and PEMFC efficiency. Adding a Super Capacitor to a grid-connected PV-FC hybrid system improves energy management, which in turn increases the system's efficiency and reliability.

Keywords— grid-connected hybrid system, Photovoltaic array, Proton Exchange Membrane Fuel Cell, Super Capacitor, Maximum Power Point Tracking, Feeder-Flow Control

I. INTRODUCTION

The evolution of power-management strategies for grid-connected PV-FC hybrid systems represents a significant chapter in the ongoing saga of sustainable energy solutions. As humanity grapples with the challenges of climate change and an ever-growing demand for electricity, the integration of renewable sources such as solar power and fuel cells has emerged as a beacon of hope for a cleaner and more efficient energy landscape [1]. The roots of this hybrid system can be traced back to the late 20th century when concerns about environmental degradation and the finite nature of fossil fuels began to take center stage [2]. Researchers and engineers [3] embarked on a quest to harness the untapped potential of solar energy, leading to the development of photovoltaic technology. Simultaneously, the concept of fuel cells gained traction as a promising avenue for generating electricity through electrochemical reactions. Unlike traditional combustion processes, fuel cells produce electricity with higher efficiency and fewer emissions [4]. Hydrogen fuel cells, in particular, emerged as a frontrunner due to their potential to utilize hydrogen as a clean and abundant fuel, with water as the only byproduct.

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The synergy between these two technologies became evident as researchers explored ways to create a hybrid system that could leverage the strengths of both PV and FC [5]. The idea was to combine the intermittent yet abundant energy from the sun with the steady and reliable power generation from fuel cells, creating a harmonious and resilient energy ecosystem [6]. The late 20th and early 21st centuries witnessed the gradual maturation of PV-FC hybrid systems [7], with an emphasis on optimizing their performance and integrating them seamlessly into existing power grids [8]. One of the primary challenges was developing robust power-management strategies to ensure the efficient utilization of both solar and fuel cell-generated electricity. One pioneering approach that emerged was the development of smart inverters capable of managing the intermittent nature of solar power. These inverters could dynamically adjust the voltage and frequency of the electricity generated by the PV system, aligning it with the grid requirements. This breakthrough significantly enhanced the stability and reliability of grid-connected PV systems, paving the way for their widespread adoption [9]. As the hybrid system landscape evolved, attention turned to the integration of fuel cells into the equation. The challenge here was twofold: managing the variability of solar power and optimizing the operation of fuel cells to provide a constant and reliable power output. Advanced control algorithms became instrumental in achieving this delicate balance.

II. LITERATURE SURVEY

A hybrid grid-connected system including a Wind-Photovoltaic-Battery Energy Storage System (BESS), a Fuel Cell (FC), and an Electrolyzer is the subject of the research offered by Gulzar et al. [10]. The study covers topics such as modeling, control, energy management, and operation. Reducing the number of control loops and converters is the goal of the proposed hybrid PV-Wind-FC system, which includes an electrolyzer and BESS. An efficient and economical way to incorporate PV into a hybrid system, this setup does away with the need for a PV converter. A grid-connected hybrid system comprising a renewable distributed generator (wind or PV), a battery energy storage system (BESS) for secondary power, and a FC with an electrolyzer for tertiary power is part of the design. Incorporating a phase shift φs at a cross gain frequency (ωcut) into the system aims to provide a suitable phase margin, eliminate steady-state error, and improve stability. In order to get the most of the power that photovoltaic cells produce, the Grid Side Controller (GSC) helps the utility grid with frequency assistance. Fuzzy logic control is the basis of the energy management approach put out by Ayat et al. [11] for a system of renewable energy sources that is specifically designed to supply a three-phase AC variable load. Supercapacitor (SC), Lithium-Ion Battery, FC, and PV are the components of the system. Reduced hydrogen use and increased battery longevity are two examples of the kinds of goals that fuzzy control may accomplish.

Hybrid Electric Vehicles (HEVs) fuel economy is the primary emphasis of [13], which in turn introduces an Artificial Neural Network (ANN) as the HPMS. We use MATLAB Simulink to analyze a hybrid power supply that includes photovoltaic (PV) panels, PEMFCs, batteries, and ultracapacitors/supercapacitors. When compared to alternative control systems, ANN lowers hydrogen consumption and keeps the battery state of charge (SOC) between 62% and 68%. For a DC microgrid that incorporates fuel cells, solar PV cells, and a BESS, a centralized EMS is suggested in [14]. Minimizing hydrogen utilization while increasing BESS longevity and dependability is the goal of the EMS. It uses a reverse sigmoidal function to modify the fuel cell power supply depending on battery SOC and a PV system de-rating technique. The suggested EMS has been validated for efficacy under different operating situations using simulation and hardware prototype testing. A DC microgrid with PV and FC as major sources and a storage unit for SCs is proposed by the authors of [15]. To maintain system stability, the SC makes up for delayed FC dynamics. A constant DC bus voltage, balanced power sharing between sources, and load management are the goals of differential flatness-based control, which incorporates PI control for SC changes.

With the use of battery SOC, an adaptive power management approach for a standalone microgrid is laid forth in [16]. Using the adaptive droop control, switching between adaptive droop and maximum power point tracking is a breeze. A dynamic test microgrid with different renewable sources and loads is created by enhancing batteries and SC with a proportional-integral controller based on fuzzy logic. This controller manages transient behavior. The challenge of grid voltage and frequency regulation in a PV-rich microgrid due to solar PV intermittencies is addressed in [17]. The authors propose a ramp-rate-based compensation strategy using a hybrid multilevel storage system, including a battery system, hydrogen storage with an electrolyzer and fuel cell, and supercapacitors. Simulations demonstrate effective management of solar PV variations and load demands. The authors show how effective control approaches are in a situation with distinct users in [18]. A Fuzzy Logic Energy Management System (FL-EMS) based on the Mamdani 50 rules is used for SoC recovery and load frequency decoupling. When compared to single-ESS systems, FL-EMS systems with low-control level functions improve resilience and dependability.

A hybrid approach combining photovoltaic (PV), wind turbine (WT), and battery is suggested in [19] for managing power flow in a smart grid that uses HRES. When it comes to real-time scheduling and load forecasting, the Random Forest Manta Ray Foraging Algorithm (RFMRFA) is recommended for best functioning. The simulation results show that RFMRFA is faster than competing approaches in terms of computing time. As a last point, [20] presents a hybrid power producing system that uses photovoltaic fuel cells and is modeled and simulated. A power regulation unit, electrolytic cells, fuel cells/supercapacitors, a solar power generating device, and hydrogen storage are all part of the system. The stability of the system is guaranteed by combining solar devices with fuel cells and supercapacitors, as shown in MATLAB/Simulink simulations.

III. PROPOSED SYSTEM MODEL

A supercapacitor is prominently shown in Figure 1, which is a schematic depiction of a grid-connected PV-FC hybrid system. Power is distributed to loads at the Point of Common Coupling (PCC) using this system's interconnection with the main grid. In this intricate and interconnected system, the PV panels and PEMFC, which are nonlinear voltage sources, are the most important parts. The PV panels and fuel cells are the main power sources since they convert solar radiation into usable electricity via electrochemical processes. The nonlinear voltage source models capture the complexities of these energy sources' behavior by accounting for their variable features. A dc/ac inverter's dc side is where the system's dc-dc converters are linked, making it easier to incorporate these power sources into the grid. To make it work with the grid and loads, this setup converts the direct current (dc) electricity from the fuel cell and PV panels to alternating current (ac). Particularly important as an MPPT controller is the dc/dc converter that is linked to the PV array. In order to maximize the power output of the PV panels, maximum power point tracking (MPPT) is a must-have. It changes the operating point to the maximum power attainable under different environmental circumstances.

The Perturbation and Observation (P&O) methodology is the selected method in this system out of many MPPT algorithms that have been suggested in the literature. Since it relies so little on observed data and has a straightforward structure, the P&O approach is preferred. The system's feedback mechanism enables it to adapt the PV array's operating parameters on the fly, keeping it functioning at maximum power point regardless of variations in solar irradiation. A distinctive feature of the system illustrated in Figure 1 is the incorporation of a supercapacitor, denoting an advanced energy storage element. Positioned within the hybrid system, the supercapacitor plays a pivotal role in enhancing power management. Supercapacitors are known for their rapid charge and discharge capabilities, making them ideal for mitigating the intermittent nature of renewable energy sources. This dynamic energy storage component acts as a buffer, absorbing excess energy during peak generation periods and releasing it when the demand on the grid is high or during periods of reduced solar input. The inclusion of the supercapacitor contributes to grid stability by smoothing out power fluctuations and enhancing the reliability of the overall system.

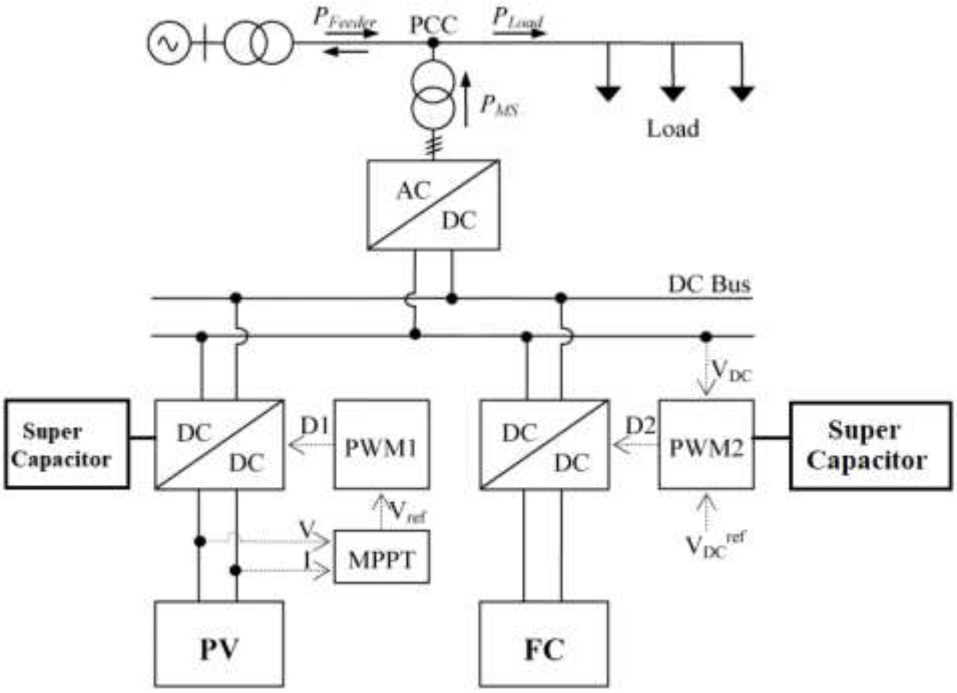

Fig. 1. Grid-connected PV-FC hybrid system with Super Capacitor.

A. Super Capacitor

The electrostatic energy storage principles are the basis of operation for supercapacitors, ultracapacitors, and electric double-layer capacitors (EDLCs). In contrast to conventional capacitors, which rely on charge separation in a dielectric substance to store energy, supercapacitors use electrostatic energy storage at the interface of a porous electrode and an electrolyte. Supercapacitors are great for uses that call for short bursts of energy because of their fast charging and discharging times. Supercapacitors have a longer cycle life than regular batteries because the energy they store is electrostatic. Supercapacitors are great because they can function in a variety of situations because to their broad temperature range. Because of their rapid energy storage and release capabilities, supercapacitors find widespread usage in electric car regenerative braking and other burst power applications. They mitigate the effects of energy production and consumption changes in renewable energy systems by acting as energy buffers. Memory backup systems use supercapacitors as a backup power source to keep data intact in the event of a power loss. A supercapacitor's comprehensive functioning entails many essential steps:

Step 1: Electrode Structure: Activated carbon or another very porous substance with a large surface area is the material of choice for the two electrodes in a supercapacitor. Maximizing the ability to store electrostatic charges requires a large surface area.

Step 2: Electrolyte: An electrolyte, which might be an organic or water-based solution with ions, is used to separate the electrodes. Electric current may flow because the electrolyte acts as a medium for the transfer of charges between the electrodes.

Step 3: a double layer of charges arises at the interface between the electrolyte and each electrode as a result of applying a voltage across the electrodes. Supercapacitors store charges primarily via this electrostatic double layer.

Fourth Step: Electrochemical Methods: As electrolyte ions are deposited onto the electrode surface, an electrostatic double layer is formed. Because it can be turned back on, this method is great for storing and releasing electrical energy efficiently. Supercapacitors have a high cycle life since no chemical reactions happen during the adsorption/desorption process.

The fifth step is charging, also known as adsorption. When a voltage is provided to the supercapacitor, electrons are pushed between the electrodes. This attracts and adsorbed ions from the electrolyte onto the electrode surfaces. The result is an increase in the charge density within the electrostatic double layer.

Step6: Discharging (Desorption): Ions desorb from the electrodes and return to the electrolyte, releasing the stored charges, when the supercapacitor is linked to a load. This causes electricity to flow across the circuit and power the gadgets that are linked to it.

Supercapacitors have a lower energy density than batteries, but a higher power density that allows for fast charge and discharge cycles (Step 7: Energy Density and Power Density). Power density is related to the rate of energy delivery, while energy density measures the total amount of energy that may be stored.

B. P&O MPPT algorithm

The PV array has a DC/DC converter that acts as a Maximum Power Point Tracking (MPPT) controller. The Maximum Power Point Tracking (MPPT) technique is crucial for maximizing the power output of the Photovoltaic (PV) array. Numerous methods have been suggested in the literature to accomplish this objective. The used system utilizes the Perturbation and Observation (P&O) MPPT algorithm, which is widely adopted because to its simple feedback structure and little dependence on measured parameters. Figure 2 provides a detailed explanation of the P&O method with power feedback control, revealing the process used to dynamically modify the reference voltage. This method is crucial in optimizing the operation of the PV system at its greatest power point, hence improving total energy efficiency. The method begins by obtaining voltage and current data from the PV array, then using this information to compute the power output. The core of the P&O method is in determining the maximum power point, which occurs when the derivative of power with respect to voltage is zero. The critical point represents the most favorable operational state for the PV system.

The P&O method utilizes a feedback mechanism to get the optimal power point by adjusting the reference voltage by a certain increment. This adjustment is derived from the estimated derivative and guarantees that the system effectively follows and sustains operation at the highest power point. The P&O algorithm's simplicity and efficacy, together with the incorporation of power feedback management, make it an appropriate selection for this hybrid PV-FC system.

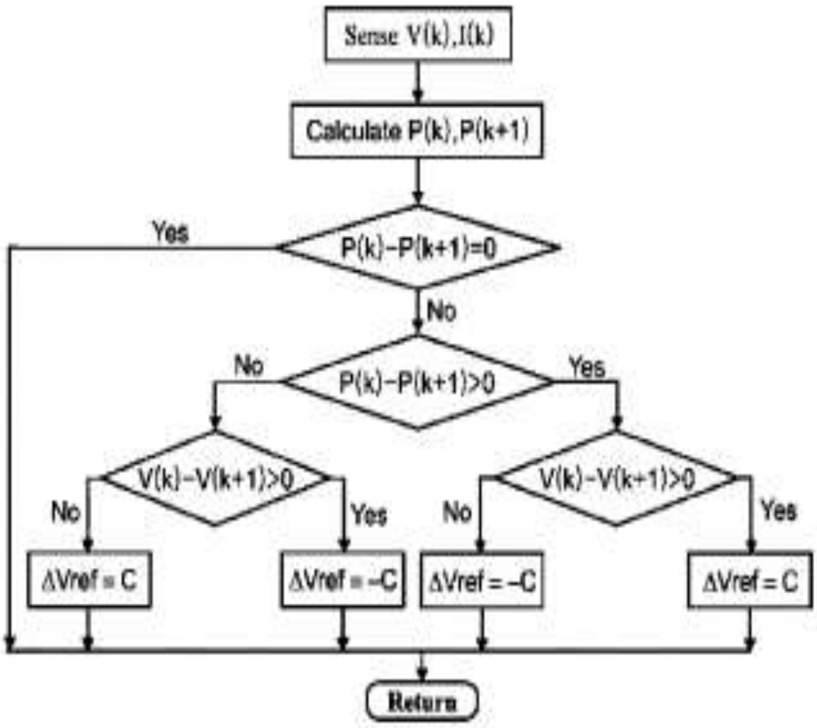

Fig. 2. P&O MPPT algorithm.

C. PEMFC Model

The PEMFC Model offers a thorough comprehension of the stable characteristics inherent in a PEMFC inside the grid-connected PV-FC hybrid system. This model is based on the representation of the nonlinear correlation between voltage and current density, which is explained by analyzing a polarization curve. Equation (6) encapsulates the voltage output of the PEMFC and introduces the idea of Nernst's "thermodynamic potential." The potential mentioned here is a vital parameter that indicates the reversible or open-circuit voltage of the fuel cell. It serves as a fundamental reference point for comprehending the electrochemical characteristics of the fuel cell.

$$V_{\text{out}} = E_{\text{Nernst}} - V_{\text{act}} - V_{\text{ohm}} - V_{\text{conc}} \qquad (6)$$

The activation voltage drops, an essential aspect of the PEMFC's performance, is detailed in Equation (7). This drop is expounded through the Tafel equation, where the constants, denoted by *a* and *b*, represent coefficients in volts per Kelvin. The Tafel equation is fundamental in capturing the activation losses within the fuel cell, shedding light on the intricacies of the electrochemical reactions occurring at the electrodes.

$$V_{\text{act}} = T[a + b\,ln(I)] \qquad (7)$$

Equation (8) further contributes to the model by accounting for the overall ohmic voltage drop. This drop arises from the collective impact of the ohmic resistance within the PEMFC, encompassing the resistance of the polymer membrane and electrodes, along with the resistances of the electrodes themselves. Understanding this ohmic voltage drop is critical for assessing the internal losses within the PEMFC and optimizing its efficiency.

$$V_{\text{ohm}} = IR_{\text{ohm}}. \qquad (8)$$

The concentration voltage drops, outlined in Equation (9), adds another layer of complexity to the model. This drop reflects the influence of concentration gradients within the PEMFC, capturing the impact of reactant concentrations on the overall performance. As reactants move through the fuel cell, variations in concentration can lead to voltage losses, and Equation (9) quantifies this effect, providing a comprehensive insight into concentration-related losses.

$$V_{\text{conc}} = -\frac{RT}{zF} ln\left(1 - \frac{I}{I_{\text{limit}}}\right). \qquad (9)$$

D. MPPT Control

The MPPT Control is an essential component for maximizing the efficiency of renewable energy systems. In the grid-connected PV-FC hybrid system, it is crucial in ensuring that the PV array runs at its highest power output for improved energy efficiency. The paragraph acknowledges the existence of many MPPT algorithms mentioned in the literature, including incremental conductance (INC), constant voltage (CV), and P&O. Of these strategies, the P&O and INC techniques are emphasized as often used for attaining optimal power point tracking. The INC technique is recognized for its strong performance in the face of rapidly fluctuating atmospheric conditions, but it is also known for its hardware demands, particularly the use of four sensors, and the possible consequences of longer conversion times on power consumption. The attention thereafter turns to the predilection for the P&O technique inside the hybrid system being discussed. The benefits of the P&O technique, such as its reliance on only two sensors, less hardware needs, and cost efficiency, are highlighted. The relationship between the speed at which the P&O technique is carried out and the amount of system loss is clearly explained, emphasizing the need of a fast MPPT procedure in reducing power loss during tracking periods. This justification supports the choice to use the P&O technique for regulating the MPPT procedure in the grid-connected PPV-FC hybrid system.

This text offers more understanding of the control strategies used to attain maximum power, namely voltage-feedback control and power-feedback control. The voltage-feedback control method, which utilizes the solar-array terminal voltage to manage the array at its highest power point, is criticized for disregarding the influence of irradiance and cell temperature. The constraint necessitates the use of power-feedback control, which considers these environmental influences, making it a more resilient method for attaining the highest power output in the photovoltaic array. The text then on to explain the P&O MPPT algorithm with power-feedback control, as seen in Figure 2. The algorithm entails the assessment of PV voltage and current, followed by power computation, and the modification of the reference voltage according to the power derivative. The goal is to achieve the greatest power point by dynamically adjusting the reference voltage, emphasizing the closed-loop aspect of the control mechanism.

The requirements for the characteristics of the buck-boost converter are described, with a focus on the need to maintain stability and efficiency throughout the energy conversion process. The paragraph provides insight into the function of the buck-boost converter, which includes a gate turn-off device (GTO) that is regulated by a gate signal generated by comparing a sawtooth waveform with the control voltage. The alteration in the reference voltage acquired by the MPPT method functions as an input for pulse-width modulation (PWM), producing a gate signal to regulate the buck-boost converter. This control system enables the effective monitoring of the highest amount of power, finally guaranteeing that the collected energy is transferred to the AC side using a DC/AC converter.

E. Control of Hybrid System

The management of the hybrid system in the microgrid involves a sophisticated coordination of many modes with the goal of maximizing performance, improving stability, and achieving smooth integration with the main electrical grid. The control architecture consists of three primary modes: UPC, FFC, and a Mixed Control Mode. In the UPC mode, Distributed Generators (DGs), which serve as the hybrid source in this system, are responsible for controlling both the voltage magnitude at the connection point and the injected power. This mode is based on the principle of continuous power regulation. In case there is an increase in demand inside the microgrid, the excess power is obtained from the main grid.

In the FFC mode, DGs control both the voltage magnitude and the power flow at the connection point. In this context, the DGs assume the task of meeting the extra load requirements, hence providing a steady load from the utility's point of view. The mixed control mode is a combination of two approaches, where a single DG may regulate either its power output or the power flow in the feeder. This mode seamlessly integrates the ideas of UPC and FFC, providing a versatile and adaptable control technique. An extensive analysis is conducted to examine the coordination of UPC and FFC modes, aiming to determine the most effective use of each control mode and to create benchmark values for their functioning. The analysis also considers the limitations imposed by the PV and PEMFC sources in the hybrid system. Both sources have distinct limits, requiring careful consideration when determining reference power levels to assure adherence to these limitations. The suggested operational approach, explained in the next section, is to minimize the frequency of mode changes. The primary objective of this strategic focus is to optimize the overall system performance and stability by minimizing superfluous transitions between control modes. The suggested operational approach, based on minimizing mode transitions, signifies a notable progress in optimizing the control of hybrid systems. The system can effectively manage power production, load demands, and stability by strategically deciding when to apply each control mode and setting reference values for optimum operation. This helps prevent needless interruptions and maintain a harmonic balance. The strategic approach is especially vital in microgrid settings, where dispersed energy sources must dynamically adjust to changing circumstances.

F. Operating Strategy of Hybrid System

The operational strategy of the hybrid system is a complex algorithmic method that aims to discover the best control mode for the hybrid source and establish reference values for each control mode. The primary objective is to guarantee that the PV component functions at its utmost output power while complying with stipulated limitations. The algorithm chooses between the two main control modes, namely the UPC mode and the FFC mode, depending on changes in load and the PV output. In the UPC mode, the hybrid source controls both the voltage magnitude and injected power. The reference output power depends on the PV output and the limitations placed on the FC output. The procedure dictating this decision is outlined in Subsection A and shown in Figure 3. This diagram illustrates the sequential operational approach of the hybrid source in the UPC mode, with a focus on the complexities associated with achieving optimum performance while accounting for the dynamic fluctuations in load and PV output.

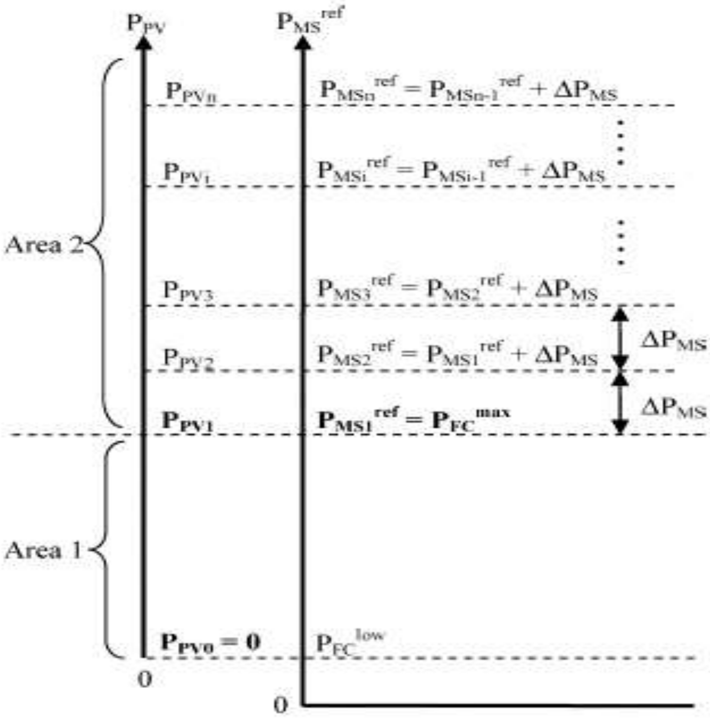

Fig. 3. P&O Operation strategy of hybrid source in the UPC mode.

The operating algorithm is primarily guided by the need to meet the limitations represented by PPV, PFC, and PLoad, which respectively indicate the power output from the PV, FC, and overall load. After identifying these limitations, the algorithm flexibly chooses between UPC and FFC modes, adjusting the control technique to match the current circumstances. The primary objective is to reduce the frequency of mode transitions to improve the stability of the system and raise its overall efficiency. The reference output power in the UPC mode is a crucial parameter that is derived via complex calculations considering the PV output and limitations on FC output. The reference value is essential for optimizing the functioning of the hybrid source and guaranteeing that the PV system functions at its highest possible power output.

IV. RESULTS AND DISCUSSION

Figure 4 illustrates the suggested Simulink model of a Grid-Connected PV-FC system with a supercapacitor. It visually represents the architecture of the system and its linked components. The simulation model incorporates essential components, including the PV array, fuel cell, supercapacitor, and related control systems, inside the Simulink framework.

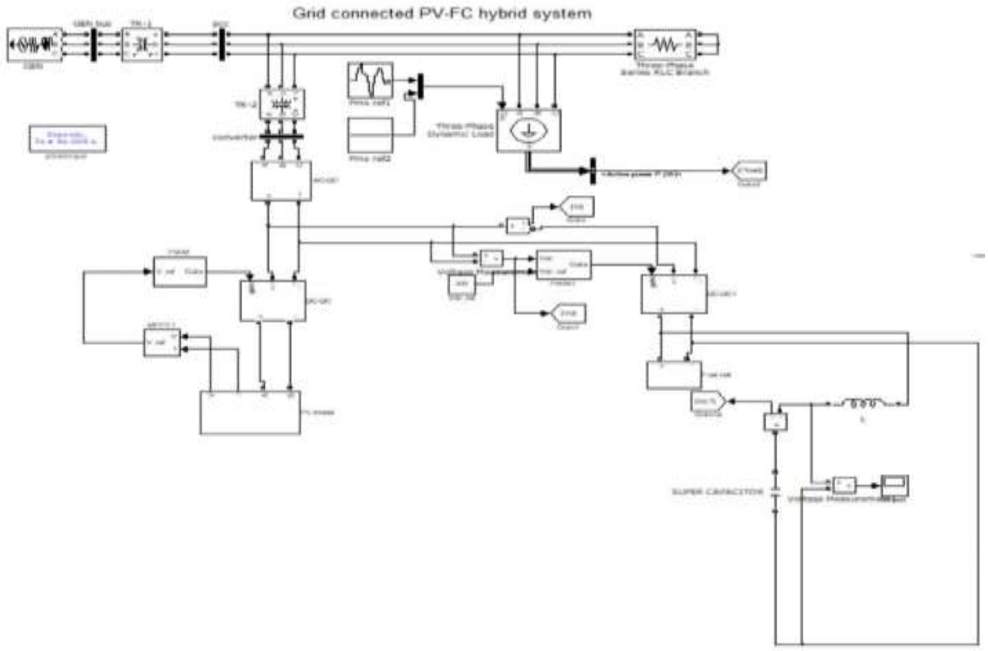

Fig. 4. Proposed Grid Connected PV-FC Simulink model with super capacitor.

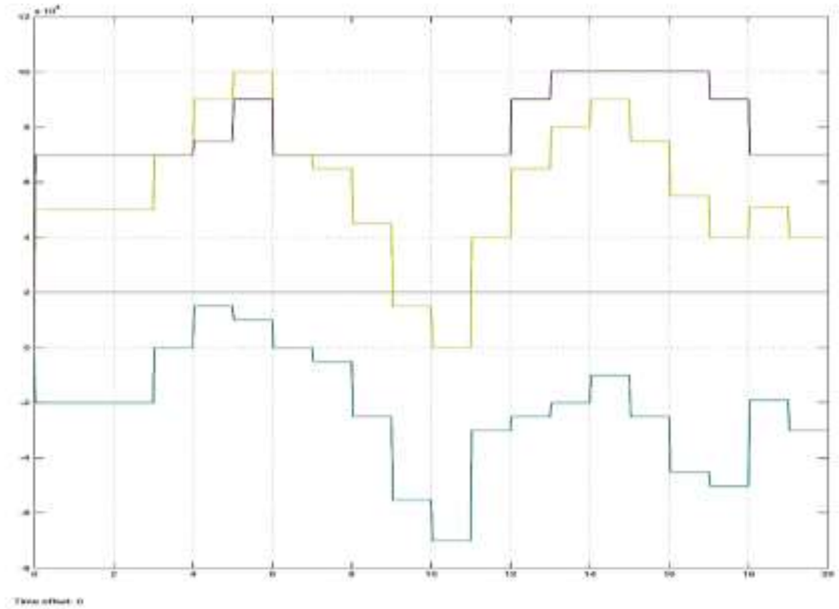

Fig. 5. Simulink output of entire proposed system.

The PV array, depicted by suitable mathematical models, represents the non-linear characteristics of solar energy conversion. Similarly, the fuel cell model accurately represents the electrochemical mechanisms responsible for the conversion of fuel into electrical energy. The supercapacitor, strategically placed within the system, is expected to be shown by a dynamic model, illustrating its charge and discharge properties and its function in storing energy. The Simulink model incorporates essential converters and inverters to establish a connection between the DC and AC components, guaranteeing a smooth integration with the grid.

Figure 5 displays the Simulink output of the whole proposed system, providing a comprehensive understanding of the dynamic behavior and performance metrics of the simulated PV-FC hybrid system with a supercapacitor. The output visualization is expected to consist of time-domain waveforms, plots, and graphs that depict several system characteristics, such as voltage, current, power output, and state of charge for the supercapacitor. The dynamic changes of these parameters provide useful insights into the system's reaction to fluctuating circumstances, such as fluctuations in solar irradiation, fuel cell production, and grid demand. In addition, the Simulink output may include efficiency curves that demonstrate the system's ability to maximize power production and storage.

V. CONCLUSION

The grid-connected photovoltaic-fuel cell hybrid system has several benefits that jointly establish it as an innovative solution in the field of renewable energy. By using PEMFC, the system harnesses clean and sustainable energy sources, hence decreasing dependence on non-renewable fossil fuels. Nonlinear voltage source models are used to enable precise depiction of the characteristics of these sources, hence improving the ability to make accurate predictions. Integrating a MPPT controller enhances the efficiency of PV panel performance, while the P&O algorithm, renowned for its simplicity, facilitates instantaneous modifications. One notable benefit is the strategic use of a supercapacitor, which offers a high power density, fast charging and discharging abilities, and a long cycle life. This energy storage component functions as a buffer, reducing the irregularity of renewable sources and improving the stability of the power system. Enhanced economic feasibility is reinforced by increased effectiveness, less operational interruptions, and flexibility in response to changing environmental circumstances. In summary, this hybrid energy system has great potential as a viable and robust alternative for achieving a sustainable and resilient energy future.

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