Implementation of Fuzzy Logic-Based Integrated Hybrid Energy Storage System with Grid-Connected Photovoltaic Power Management Scheme

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Abstract

This paper provides a power management technique based on fuzzy logic for integrating hybrid energy storage systems with grid-connected photovoltaic (PV) systems. The plan aims to optimize the utilization of renewable energy and enhance the stability and reliability of the grid. By effectively coordinating the PV system, hybrid energy storage system, and grid, the proposed scheme enables efficient power flow control and maximizes the self-consumption of PV energy. The fuzzy logic controller analyzes various input variables, such as PV output, energy storage state-of-charge, and grid demand, to make intelligent decisions and optimize the power management process. Simulation results demonstrate the effectiveness of the scheme in improving renewable energy integration, reducing dependency on the grid, and ensuring reliable power supply.

Keywords: Fuzzy Logic, Power management, Grid-connected PV, Hybrid Energy Storage System, Renewable energy.

I. INTRODUCTION

The increasing integration of renewable energy sources (RESs) into distribution systems poses challenges to the reliable and safe operation of existing power systems. The intermittent nature of sustainable energy sources, coupled with random load variations, significantly impacts power quality and system stability. To address these challenges, storage systems with both high energy and high power handling capacities are essential in micro grid environments.

In this paper, an efficient energy management structure is proposed for a hybrid storage system that combines batteries and supercapacitors with a grid-connected photovoltaic system. The battery storage system and supercapacitor work together to efficiently manage both steady-state and sporadic power variations. Providing rapid control over the DC-link voltage to stabilize the system and achieve smooth PV power output.

The energy management scheme allocates average power distribution between the power grid and the battery by monitoring the state of charge (SOC) of the battery. This ensures effective utilization of energy resources while maintaining system stability. Additionally, the inclusion of supercapacitors helps during unanticipated discrepancies between generated power and load requirements, there is current stress on the battery system.

Simulation studies are conducted to validate the performance and efficacy of the proposed energy management scheme, demonstrating its ability to enhance system stability, improve power quality, and optimize energy utilization in grid-connected PV systems with hybrid energy storage. Fuzzy logic control provides a real alternative to conventional control methods, offering greater flexibility and robustness in addressing the challenges posed by complex systems and uncertain operating conditions.

LITERARURE SURVY

"Dynamic power management of PV-based islanded micro grid using hybrid energy storage" suggests a system designed to control the flow of power within a micro grid powered by photovoltaic (PV) sources and hybrid energy storage systems (HESS), which operates independently from the main utility grid. The synchronization or alignment of phases, signals, or operations within the power management system. It could involve coordinating the timing of various components or adjusting the phase angles of current or voltage waveforms to optimize system performance, efficiency, or stability [1]. Power management strategies within micro grids could refer to various optimization or adjustment processes aimed to improving system performance, efficiency, reliability. The specific interpretation would depend on the context of the micro grid's operation, the objectives of the power management strategies, and the technologies and control methods employed [2].Unified control and power management scheme for PV-battery-based hybrid micro grids aims to provide a coordinated approach to system operation, ensuring smooth transitions between grid-connected and islanded modes while optimizing performance and maximizing the utilization of renewable energy resources and energy storage [3].

An effective control and management scheme for an isolated and grid-connected DC micro grid involves sophisticated strategies for mode transitioning, grid interaction control, islanded operation, power management optimization, and potentially, the "rephrasing" of control parameters to ensure seamless operation and maximum performance across different operating modes [4].

Dynamic power distribution and voltage control in a DC micro grid utilizing a hybrid energy storage device likely refers to the adjustment or optimization of control actions, system configurations, or control parameters to ensure effective coordination, stability, and performance under varying operating conditions[5].SOC balancing method for hybrid energy storage system in micro grid rephrase, likely refers to the adjustment or optimization of techniques for managing the energy storage components' state of charge in a hybrid system deployed in a micro grid context, aiming to enhance overall system performance, efficiency, and reliability[6].

Phase-locked loops are control systems commonly used in power electronics for tasks such as grid synchronization, frequency control, and voltage regulation. The paper likely discusses the use of moving average filters within PLLs and their performance characteristics [7].The performance, efficiency, and effectiveness of a bi-directional DC-DC converter controlled by a fuzzy logic controller Focuses on how the bi-directional DC-DC converter regulates energy flow to and from the battery storage system. This includes strategies for charging, discharging, and optimizing the use of battery energy within the micro grid [8].

A control strategy based on IRPT (Instantaneous Reactive Power Theory) for a grid-connected solar photovoltaic power generating system with a 50 kW capacity. The focus may be on improving power quality, which could involve mitigating issues such as harmonics, voltage fluctuations, or reactive power imbalance [9].Focuses on the design, analysis, and implementation of the power management scheme, which may include strategies for optimizing energy generation, storage, and consumption within the grid-connected PV system [10].

The objective of this project is to implement a fuzzy logic-based grid-connected photovoltaic (PV) systems combined with hybrid energy storage systems (HESS) using a power management method. This initiative aims to optimize renewable energy utilization, ensuring efficient and reliable grid operation. By intelligently coordinating PV output with energy storage capabilities, the scheme addresses the variability of solar energy, maintains grid stability, and reduces reliance on non-renewable energy sources. The approach leverages fuzzy logic for adaptive and dynamic control, promoting sustainable energy solutions and supporting the transition towards a more resilient and renewable energy-powered grid.

This paper outlines several limitations associated with the existing Power management strategies are used in grid-connected photovoltaic (PV) systems and hybrid energy storage systems (HESS), which the proposed fuzzy logic-based scheme aims to address:

Low Efficiency: Previous approaches may not optimize the energy conversion and storage processes effectively, resulting in losses and reduced overall system efficiency [10].

Low Consistency: The variability of renewable energy sources like solar power can lead to inconsistencies in power supply. Existing systems might not adequately manage these fluctuations, affecting the stability and reliability of the power grid [10].

The proposed fuzzy logic-based scheme seeks to overcome these limitations by offering a more adaptive, efficient, and reliable power management strategy. This includes better utilization of renewable energy, enhanced grid stability, and an improved balance between power supply and demand through intelligent decision-making processes.

Inputs:

- **PV Output Energy**: The amount of electrical energy generated by the photovoltaic system, which varies based on solar irradiance, temperature, and other environmental factors.
- **Energy Storage State-of-Charge (SOC)**: The current energy level or charge status of the hybrid energy storage system, which includes batteries and supercapacitors.
- **Grid Demand**: The current demand or load on the electrical grid, indicating the amount of power required by consumers connected to the grid.

Outputs:

- **Optimized Power Flow Control**: Decisions on how to dynamically allocate and direct power among the PV system, the energy storage system, and the grid to ensure efficient use of generated power and stability of the grid.
- **Maximized Self-Consumption of PV Energy**: Adjustments to optimize the direct use of solar energy at the place of generation, reducing dependence on the grid and enhancing the economic benefits of the PV system.
- **Reliable Power Supply**: Management strategies to ensure a consistent and reliable supply of power to the grid, even in the face of variable solar generation and fluctuating demand.

The scheme utilizes a fuzzy logic controller to analyze the inputs and make intelligent decisions, optimizing the power management process to improve renewable energy integration, reduce grid dependency, and ensure a reliable power supply.

II.MATHEMATICAL MODELING

The control system described seems to involve generating the reference current, managing power sharing based on battery SOC, and utilizing PWM for modulation in the bi-directional converter's operation. The specific details and functions of these components would depend on the design and requirements of the system they are implemented in reference current of battery $\boldsymbol{i^*_{B\,r}}$defined as Eq(1)

$$\boldsymbol{i^*_{Br}(t) = f_{B,PMA}\lambda\frac{1}{T_B}\int_{t_{0-t_B}}^{t_0} i_t(t)dt}\text{.........}\mathbf{(1)}$$

$$\boldsymbol{\delta_B = K_{pB}i_{Be}(t) + \frac{K_{iB}}{T_B}\int_{t-T_B}^{t} i_{Be}(t)dt}\text{........}\mathbf{(2)}$$

where $\boldsymbol{t_0, f_{B,PMA}}$ and $\boldsymbol{T_B}$ are the random time instant, the battery average block window length, and the PMA-specified battery control objectives, accordingly; and $\boldsymbol{i_{Be}}$,$\boldsymbol{K_{pB}}$ and $\boldsymbol{K_{iB}}$ are the battery's error current as well as the proportional and integral battery PI controller coefficients. Modulating signal$\boldsymbol{\delta_B}$ defined as Eq(2)

Control Structure for Supercapacitor:

This involves generating reference current, power management algorithms, and controlling the Bidirectional DC-DC Converter (BDDC). The supercapacitor's role seems to involve handling transient, high-frequency components of the overall operating current at the DC connection. This likely involves filtering using a Low Pass Filter (LPF) to smooth out variations in current. reference current of supercapacitor $\boldsymbol{i_{scr}}$defined as Eq(3).

$$\boldsymbol{i_{scr}(s) = i_t(s) - \frac{\omega_c}{s+\omega_c}i_t(s) + G'i_{Bc}(s)}\text{..........}\mathbf{(3)}$$

Finally, the supercapacitor converter, the current reference and regulating signals are computed., presumably based on the reference current and other control parameters. These signals determine how the converter operates to maintain the desired current flow to or from the supercapacitor. Overall, this description outlines the process of generating and utilizing reference currents and control signals within the control system to manage the operation of the supercapacitor in coordination with other components such as the PMA and battery.

$$\boldsymbol{i^*_{scr}(t) = f_{sc.PMA.}i_{scr}(t)}\text{..........}\mathbf{(4)}$$

$$\boldsymbol{\delta_{sc} = K_{psc}i_{sce}(t) + \frac{K_{isc}}{T_{sc}}\int_{t-T_{sc}}^{t} i_{sce}(t)dt}\text{.........}\mathbf{(5)}$$

where $\boldsymbol{f_{sc.PMA.}}$, $\boldsymbol{i_{sce}, T_{sc}, K_{psc}}$and $\boldsymbol{K_{isc}}$ are the PMA-defined goals for the supercapacitorthe supercapacitor's average block window length, the proportional and integral constants of the PI controller, the inaccuracy in the supercapacitor current, and so on. Controlling signal for supercapacitor $\boldsymbol{\delta_{sc}}$defined as Eq (5)

Above are the parameters and constants which are essential components of the control system for the supercapacitor, helping to regulate its behavior, manage current flow, and ensure it operates effectively within the larger power system.

$$\boldsymbol{G' = \frac{V_B}{V_{sc}}}\text{............}\mathbf{(6)}$$

The battery error current compensation factor is denoted by G'.

By utilizing supercapacitors in conjunction with batteries, the system gains the advantage of rapid energy storage and discharge capabilities. When there's a sudden demand for power or a drop in voltage on the DC-link, the supercapacitors can quickly provide the necessary energy to stabilize the voltage, thus restoring the DC-link voltage faster compared to relying solely on the battery.

Control Structure for PV converter:

In the context of controlling a Photo Voltaic (PV) converter, it's essential to design a control system that can handle various operating conditions effectively. This includes ensuring that the reference current for the PV converter is appropriately chosen to enable operation in all anticipated scenarios. Typically, the reference current for the PV converter, denoted as $\boldsymbol{i_{pvr}}$determined based on the system requirements and operating conditions. PV converter controlling signal defined as $\boldsymbol{\delta_{pv}}$ Eq (7)

$$\boldsymbol{\delta_{pv} = K_{ppv} i_{pve}(t) + \frac{K_{ipv}}{T_{pv}} \int_{t-T_{pv}}^{t} i_{pve}(t)dt} \ldots.(7)$$

Where,

$\boldsymbol{i_{pve}}$ $(t)$is the error current as a function of time

$\boldsymbol{K_{ppv}}$ is the proportional coefficient.

$\boldsymbol{K_{ipv}}$is the integral coefficient.

$\boldsymbol{T_{pv}}$ is the PV average block window length.

In this control scheme, the proportional term provides an immediate response to changes in the error current, while the integral term ensures that any long-term deviations from the reference current are corrected over time. This combination of proportional and integral control helps to achieve stable and accurate control of the PV converter's current output.

Control Structure for VSC

In the described system, the Virtual Synchronous Converter (VSC) is a crucial component that can function both as an inverter and a converter based on the available power generation and load requirements. The generation of reference current and voltage templates, along with current control, are key aspects of the VSC's operation.

$$\boldsymbol{i_{gr}} = \begin{cases} \boldsymbol{1 - \lambda \bar{\imath}_t \sin \omega t,\ P_R} > 0(insufficient) \\ \boldsymbol{\bar{\imath}_t \sin \omega t\,, P_R} < 0(sufficient) \end{cases}$$

Where, ω is the grid angular frequency.

Overall, the VSC plays a critical role in enabling flexible power conversion and control in the system. By generating reference currents and voltage templates using PLL and implementing effective current control strategies, the VSC can adapt to varying power generation and load conditions, effectively managing bi-directional power flow and ensuring grid stability and reliability.

III. METHODOLOGY

The proposed system's methodology involves integrating a grid-connected photovoltaic (PV) system and a hybrid energy storage system (HESS) integrated into a fuzzy logic-based power management scheme. This integration aims to optimize renewable energy utilization, enhance grid stability, and improve overall energy supply efficiency and reliability. Here's an overview of the methodology and components:

[a]Integration of PV System with HESS:

The system integrates a grid-connected PV system with a HESS, which combines batteries and supercapacitors to leverage their complementary strengths. Batteries offer high energy density, making them suitable for storing energy over longer durations, such as during periods of low solar generation. Supercapacitors, known for their high power density, excel in managing rapid fluctuations in energy demand or generation, such as sudden drops in PV output due to cloud cover. This integration allows for a more efficient and reliable utilization of solar energy by utilizing batteries and supercapacitors according to their respective strengths. By integrating these technologies with the grid, the system maximizes the use of renewable energy and contributes to grid stability, providing a sustainable solution to integrating solar power into existing energy infrastructures. Overall, the methodology combines fuzzy logic-based power management with advanced energy storage technologies to optimize renewable energy utilization and enhance grid stability, thereby improving the efficiency of energy supply.

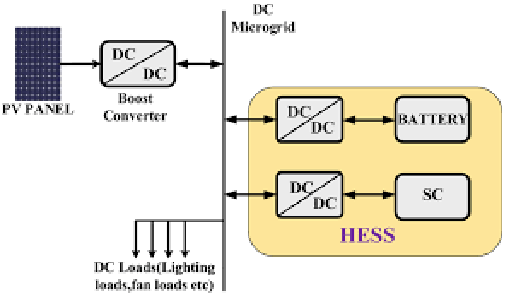


Figure 1: The integration of a Photovoltaic (PV) system with a Hybrid Energy Storage System (HESS).

[b]State of charges for Power Management

The system's operating mode is chosen by the Power Management Algorithm (PMA) based on the available generated power and load power. Equation defines the power modes (P_R) as follows:

$$P_R = P_l - P_{pv}$$

Where,P_R *is the recevied power*,P_l is the load power. P_{pv} is the generated power from the Photo Voltaic (PV) system. Based on Equation power modes of operation are identified:

(a) Insufficient Power Mode (IPM): This mode occurs when the generated power from the PV system is less than the load power, resulting in a positive value for P_R>0. In this case, the system imports additional power from an external source to meet the load demand.

TABLE 1: FUNCTIONAL DESIGNS IN IPM

SOC limit	**Reference current generation**
SOC_b> L and SOC_{sc}> L	i^*_{Br}= λ $\overline{i_t}$, i^*_{scr}= $i^{'}_t$, i^*_{gr}= (1 - λ) $\overline{i_t}$
SOC_b < L and SOC_{sc}> L	$i^*_{Br} \cong 0$, i^*_{scr}=$i^{'}_t$, i^*_{gr}= $\overline{i_t}$
SOC_b > L and SOC_{sc}< L	i^*_{Br}= λ$\overline{i_t}$, $i^*_{scr} \cong 0$, i^*_{gr}= (1 - λ)$\overline{i_t}$ + i$'$
SOC_b< L and SOC_{sc}< L	$i^*_{Br} \cong 0, i^*_{scr} \cong 0, i^*_{gr} = i_t$

TABLE 2: POWER MANAGEMENT IN IPM

SOC limit	**Reference power**
SOC_b> L and SOC_{sc}> L	$P^*_B(t) = \lambda\overline{P_R}, P^*_{sc}(t) = P^{'}_R, P_g(t) = (1-\lambda)\overline{P_R} + P_{loss}$
-SOC_b< L and SOC_{sc}> L	$P^*_B(t) \cong 0, P^*_{sc}(t) = P^{'}_R, P_g(t) = \overline{P}_R + P_{loss}$
SOC_b> L and SOC_{sc}< L	$P^*_B(t) = \lambda\overline{P}_R, P^*_{sc}(t) \cong 0, P_g(t) = (1-\lambda)\overline{P}_R + P'_R + P_{loss}$
SOC_b< L and SOC_{sc}< L	$P^*_B(t) \cong 0, P^*_{sc}(t) \cong 0, P_g(t) = P_R + P_{loss}$

(b)Sufficient Power Mode (SPM): This mode occurs when the generated power from the PV system exceeds the load power, resulting in a negative value for $P_R< 0$. In this scenario, the system generates surplus power beyond the load demand.

TABLE 3: FUNCTIONAL DESIGNS IN SPM

SOC limit	**Reference current generation**
SOC_b ,U and SOC_{sc}< U	i^*_{Br}= $i_{B.ch}$, i^*_{scr}= $i_{sc.ch}$,i^*_{gr}= i_t
SOC_b< U and SOC_{sc}> U	i^*_{Br}= $i_{B.ch}$,i^*_{scr}=$i^{'}_t$,$i^*_{gr} = i_t - i_{scr}$
SOC_b> U and SOC_{sc}< U	$i^*_{Br} \cong 0$, i^*_{scr}=$i^{'}_{sc.ch}$, i^*_{gr}=i_t
SOC_b>U and SOC_{sc}> U	$i^*_{Br} \cong 0, i^*_{scr} = i^{'}_t, i^*_{gr} = i_t - i_{scr}$

TABLE 4: POWER MANAGEMENT IN SPM

SOC limit	**Reference power**
SOC_b< U and SOC_{sc}<U	$P^*_B = -P_{Br}, P^*_{sc}(t) = -P_{scr}, P_g(t) = P_{loss}$
SOC_b< U and SOC_{sc}> U	$P^*_B = -P_{Br}, P^*_{sc}(t) \cong 0, P_g(t) = P_{loss}$
SOC_b> U and SOC_{sc}< U	$P^*_B \cong 0, P^*_{sc}(t) = -P_{scr}, P_g(t) = P_{loss}$
SOC_b> U and SOC_{sc}>U	$P^*_B \cong 0, P^*_{sc}(t) \cong 0, P_g(t) = P_{loss} - P_R$

(c) Floating Power Mode (FPM): This mode occurs when the generated power from the PV system matches the load power exactly, resulting in $P_R = 0$. In this case, the system operates without importing or exporting power, maintaining a balance between generation and demand.

TABLE 5: FUNCTIONAL DESIGNS IN FPM

SOC limit	**Reference current generation**
SOC_b<U and SOC_{sc}< U	$i^*_{Br} = i_{B.ch}, i^*_{scr} = i_{sc.ch}, i^*_{gr} = i^*_{Br} + i^*_{scr}$
SOC_b< U and SOC_{sc}> U	$i^*_{Br} = i_{B.ch}, i^*_{scr} = i'_t, i^*_{gr} = i^*_{Br}$
SOC_b> U and SOC_{sc}< U	$i^*_{Br} \cong 0, i^*_{scr} = i_{sc.ch}, i^*_{gr} = i^*_{scr}$
SOC_b>U and SOC_{sc}> U	$i^*_{Br} \cong 0, i^*_{scr} = i'_t, i^*_{gr} = i_{loss}$

TABLE 6: POWER MANAGEMENT IN FPM

SOC limit	**Reference power**
SOC_b<U and SOC_{sc}< U	$P^*_B(t) = -P_{Br}, P^*_{sc}(t) = -P_{scr}, P_g(t) = P_{loss} + P_{Br} + P_{scr}$
SOC_b< U and SOC_{sc}> U	$P^*_B(t) = -P_{Br}, P^*_{sc}(t) = P'_R, P_g(t) = P_{loss} + P_{Br}$
SOC_b> U and SOC_{sc}< U	$P^*_B(t) \cong 0, P^*_{sc}(t) = -P_{scr}, P_g(t) = P_{loss} + P_{scr}$
SOC_b>U and SOC_{sc}> U	$P^*_B(t) \cong 0, P^*_{sc}(t) = P'_R, P_g(t) = P_{loss}$

Each power mode is further classified based on the State of Charge (SOC) of the battery and supercapacitor. The SOC of each component (SOC_b for the battery and SOC_{sc} for the supercapacitor). The Coulomb counting method can be used to estimate. These SOC values are used to determine the operational strategies within each power mode, facilitating efficient utilization of energy storage components. Operating ideas within each power mode are determined based on the SOC levels and may involve strategies such as charging, discharging, or maintaining SOC within predefined limits to ensure optimal performance and longevity of the energy storage system.

[c]Fuzzy Logic Controller Implementation:

A Fuzzy Logic Controller (FLC) is employed to manage the power flow among the PV system, HESS, and the grid. The FLC analyzes two input variables, such as PV output, grid demand.

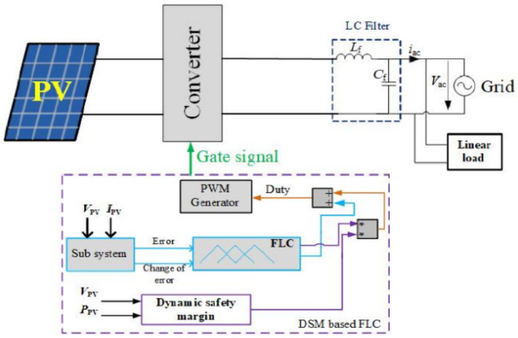


Figure 2: The implementation of a Fuzzy Logic Controller (FLC) within a control system.

A fuzzy decision table is a structured representation used in fuzzy logic to capture decision-making processes in systems where uncertainty or imprecision is present. Unlike traditional decision tables that handle crisp (clear-cut) data, fuzzy decision tables accommodate fuzzy sets and linguistic terms to model vague or uncertain information.

Here's a brief overview of the components and structure of a fuzzy decision table:

1. Attributes: These represent the factors or variables influencing the decision-making process. Each attribute may have a range of possible values or linguistic terms associated with it.

2. Decision(s): The decision or decisions to be made based on the given attributes and their values. These decisions may also be represented using fuzzy sets or linguistic terms.

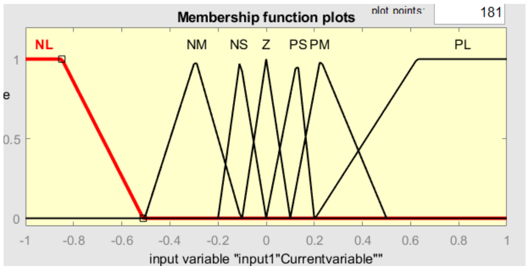
3. Rules: Fuzzy decision tables contain rules that map combinations of attribute values to corresponding decisions. These rules are often expressed in the form of "if-then" statements, where the antecedent (if part) specifies conditions based on attribute values, and the consequent (then part) indicates the decision(s) to be made.

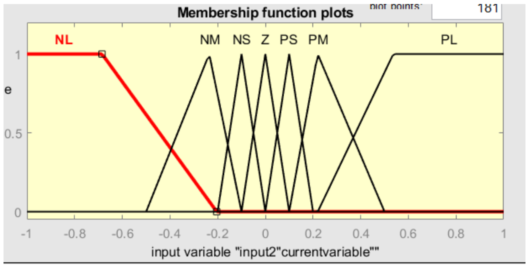
Table 7: Fuzzy rules for PV system

E /ΔE	NL	NM	NS	Z	PS	PM	PL
NL	PL	PL	PL	PL	NM	Z	PL
NM	PL	PL	PM	PL	PS	Z	Z
NS	PL	PM	PS	PS	PS	Z	Z
Z	PL	PM	PS	Z	NS	NM	NL
PS	Z	Z	NM	NS	NS	NM	NL
PM	Z	Z	NS	NM	NL	NL	NL
PL	Z	Z	NM	NL	NL	NL	NL

Negative Large (NL), Positive Large (PL), Negative Medium (NM), Positive Medium (PM), Zero (Z), Negative Small (NS) and Positive Small (PS).The Variable Ranges are NL from -1 to -0.5, NM from -0.5 to -0.1, NS from -0.2 to 0, Z from -0.1 to 0.1, PS from 0 to 0.2, PM from 0.1 to 0.5 and PL from 0.2 to 1.

4. Membership Functions: Each attribute and decision in a fuzzy decision table is associated with membership functions that quantify the degree to which a value belongs to a particular linguistic term or fuzzy set. These membership functions determine the fuzziness or uncertainty of the data. .





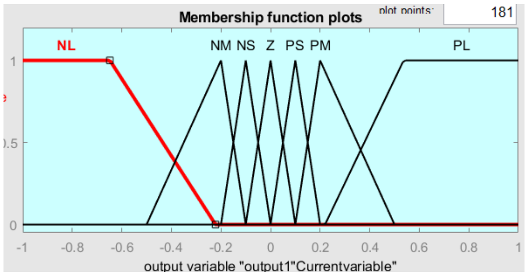


Figure 3: Input& Output current membership functions of duty cycle.

5. Fuzzy Values: Instead of precise values, fuzzy decision tables work with fuzzy values, which represent degrees of membership to linguistic terms or fuzzy sets. These fuzzy values allow for the representation of uncertainty or imprecision in the decision-making process.

Fuzzy decision tables are particularly useful in domains where data may be incomplete, ambiguous, or subjective, such as expert systems, control systems, and decision support systems. They enable the modeling and analysis of complex decision scenarios by incorporating human-like reasoning and handling uncertainty effectively.

Tuning these parameters effectively is essential for designing a fuzzy logic controller that can accurately model and control complex systems, making decisions based on imprecise or uncertain information. Parameter tuning often involves empirical methods, expert knowledge, or optimization techniques to achieve desired system performance.

[d]Dynamic Power Flow Control:

Dynamic Power Flow Control, facilitated by a Fuzzy Logic Controller (FLC), marks a significant step towards efficient renewable energy management. This system adeptly manages the intricate balance between charging and discharging the Hybrid Energy Storage System (HESS) and regulating the supply of Photo Voltaic (PV) power to the grid. By interpreting various inputs, such as the state-of-charge of energy storage and PV output, the FLC ensures that energy distribution is both optimized for self-consumption and conducive to grid stability. This adaptive approach not only maximizes the use of generated solar energy but also plays a crucial role in maintaining a stable and reliable power grid, highlighting the potential of intelligent control systems in the era of renewable energy.

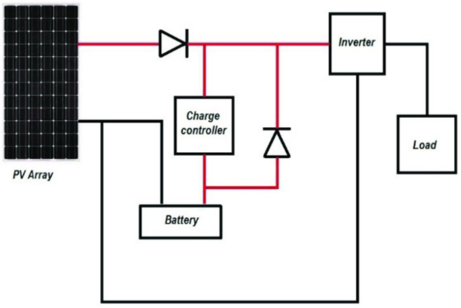


Figure 4: The dynamic power flow control strategy implemented in the integrated PV system with HESS.

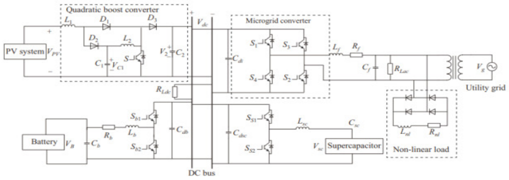


Figure 5: The architecture of a grid-coupled Photovoltaic (PV) system with a Hybrid Energy Storage System (HESS).

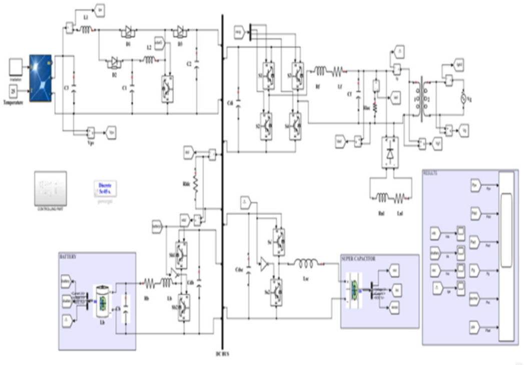


Figure 6: A Simulink model of a grid-coupled Photovoltaic (PV) system with a Hybrid Energy Storage System (HESS).

The architecture described here outlines a grid-coupled photovoltaic (PV) system with Hybrid Energy Storage Systems (HESS). Let's break down the components and their functions:

1. Quadratic Boost Converter Components (L_1, L_2, C_1, C_2, D_1, D_2, D_3, S):These components are part of the quadratic boost converter, responsible for efficiently converting the PV panel's output voltage to a higher DC-link voltage. Inductors (L_1, L_2) and capacitors (C_1, C_2) are used for energy storage and voltage smoothing. Diodes (D_1, D_2, D_3) control the direction of current flow. Switches (S) control the operation of the converter.

2. Grid Connection Components (V_g, V_{dc}): V_g represents the grid voltage, while V_{dc} represents the voltage at the DC bus.

3. Energy Storage Components (C_b, C_{db}, C_{sc}, V_{sc}, V_B, Sb1, S_{b2}, L_b, R_b, Lsc, S_{S1}, S_{S2}): C_b and C_{db} are capacitors associated with in that order, the battery and the bi-directional converter. C_{sc} stands for the capacitance of the supercapacitor. V_{sc} being its terminal voltage. V_B represents the battery voltage. S_{b1} and S_{b2} are IGBT switches of the battery bi-directional converter. The corresponding resistor is called Rb, and the inductor that is connected to the battery bi-directional converter is called L_b. A bi-directional inductor-supercapacitor converter is called an L_{CS}, with S_{S1} as well S_{S2} representing the associated IGBT switches.

4. LC Filter (L_f, R_f, C_f): Used at the output of the Voltage Source Converter (VSC) to balance currents and voltages on the AC side.

5. Micro grid Converter (S_1, S_2, S_3, S_4): These switches (IGBT switches) control the micro grid converter's operation, allowing it to function as an inverter or rectifier based on operational requirements.

6. Load Components (R_{nl}, L_{nl}, RL_{ac}, RL_{dc}):R_{nl} and L_{nl} represent the resistor and inductor connected to a single-phase bridge rectifier for non-linear loads, respectively. RL_{ac} and RL_{dc} are resistive AC and DC linear loads, respectively.

This architecture integrates various components to facilitate efficient power transfer between the grid, PV system, and energy storage systems, while accommodating loads that are non-linear and linear. Applying quadratic boost converters to and bi-directional converters ensures high efficiency and effective power regulation within the system.

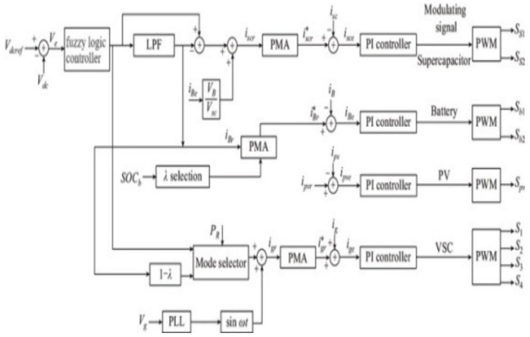


Figure 7: The control strategy for converters associated with the supercapacitor, battery, PV array, and utility grid in a system with a Hybrid Energy Storage System (HESS).

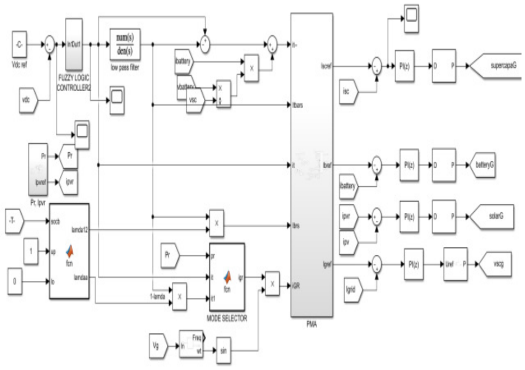


Figure 8: A Simulink model representing the control strategy for converters associated with the supercapacitor, battery, PV array, and utility grid in a system with a Hybrid Energy Storage System (HESS).

The converter control structure described involves several key components and processes:

1. Generation of Reference Current: This stage involves determining the reference current values required for different components of the system. Parameters such as average power required for PV (P_{Ravg}), transient power required for PV (P_{Rtrans}), and reference PV current ($i_{pvr)}$ are considered in this process.

2. Algorithm for Power Management: An algorithm is employed to manage power within the system efficiently. The algorithm takes into account factors such as PV generation, load requirements, and energy storage conditions to optimize power flow and utilization.

3. Control of Various Current Converters: This step involves controlling the current converters within the system to regulate power flow according to the established reference currents. Different converters may include those for PV, utility grid, battery, and supercapacitor.

4. Power Management Arrangement: The suggested power management arrangement. Components such as low pass filters (LPF) and moving average filters (MAF) are utilized to extract and process current components for different purposes.

5. Components and Techniques Used: Low Pass Filter (LPF): Used to extract the average current component for the utility grid and battery. AC load need is estimated using the Moving Average Filter (MAF). works as a Finite Impulse Response (FIR) filter in linear phase and, under some circumstances, can be an ideal LPF.

6. Operation Mode Selection: The suitable mode of operation is chosen by the Power Management Algorithm (PMA) based on PV generation and load

requirements. This mode selection influences the generation of reference currents and subsequent control stages.

7. Current Control Stages: The reference currents determined by the power management algorithm undergo current control stages .These stages ensure that the actual currents align with the desired reference values, facilitating efficient power flow.

8. Switching Pulse Generation: Finally, the switching pulses for all power converters are generated to synchronize and control their operation effectively, based on the determined reference currents.

In summary, the converter control structure described involves a systematic approach to regulate power flow within the grid-connected system, considering various factors such as PV generation, load requirements, and energy storage conditions. This ensures optimal utilization of resources and efficient operation of the system.

[g]System parameters:

Table 8: System parameters

Specification	**Parameter**	**value**
PV array	v_{pv} i_{pv}	40V 20A
Super capacitor	V_{sc} i_p C_{sc} i_{mc}	16.2V 200A 58F 19A
Battery	C_B V_B	14Ah 12V
Battery BDDC	R_b L_b C_b C_{db}	o.5Ω 5mH 220µF 220µF
Super capacitor BDDC	L_{sc} C_{dsc}	5mH 220µF
VSC	L_f C_f C_{di}	10mH 1 µF 2200µF
Quadratic boost PV converter	$L_1 = L_2$ C_1 C_2	5mH 110 µF 220 µF
Linear and non-linear load parameters	R_{Ldc} R_{Lac} R_{nl} L_{nl}	50 Ω 10 Ω 30 Ω 1mH
Utility grid	V_g	230V
	f	50Hz
Dc bus voltage	V_{dc}	100V
LPF	f_{LPF}	1Hz
MAF	f_{MAF}	100Hz

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IV. RESULTS & CONVERSATION

Simulations using the MATLAB (R2018a) software environment are carried out to verify the suggested approach.

The validation of the proposed power management system through simulation and analysis is a critical step in demonstrating its practical viability and effectiveness. Through rigorous simulation exercises, the system's ability to enhance the integration of renewable energy, notably from photovoltaic (PV) sources, into the grid is meticulously evaluated. These simulations provide concrete evidence of the system's potential to significantly reduce dependency on traditional energy sources by optimizing the use of locally generated solar power. Furthermore, the system's robustness in ensuring a consistent and reliable power supply, even under fluctuating environmental conditions and variable demand, is thoroughly tested. This process not only highlights the system's capabilities in managing energy flows between the PV system, the Hybrid Energy Storage System (HESS), and the grid but also showcases its adaptability and efficiency in real-world scenarios.

Output Response

(A)Performance with Variation in PV Power:

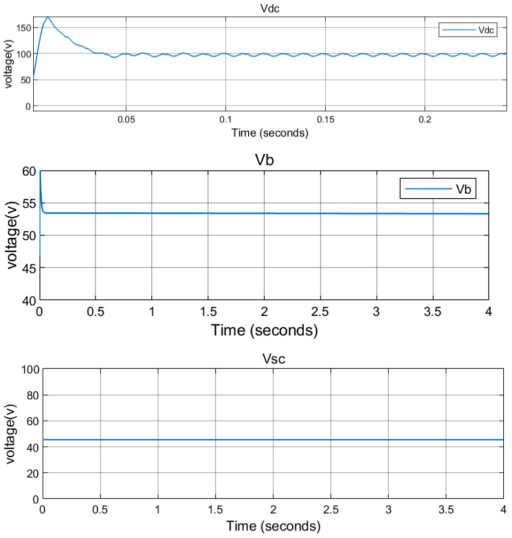
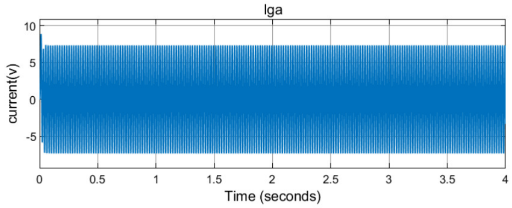


Figure 9: the voltages in a system with variable photovoltaic (PV) power, including the DC connection, battery, and supercapacitor.

The deployed control techniques performed under various PV power generating scenarios are shown in Fig 9. When the system's irradiance changes from 1000 W/m2 to 600 W/m2, the PV power generation varies at t=2s. Even with this shift in PV output, the DC bus voltage quickly reaches its stable level again in 0.03 seconds, with a very small undershoot of 0.89V well within the permissible range. The shorter settling time signifies the quick achievement of the DC-bus voltage's ultimate value, effectively fulfilling the given error standards.



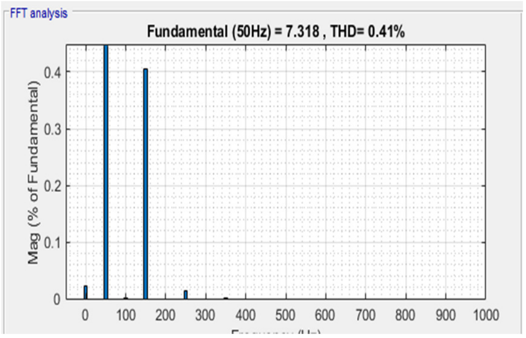


Figure 10: The total harmonic distortion (THD) of the utility grid current in a PV-powered system that varies in power.

The Total Harmonic Distortion (THD) of grid current in response to variations in PV power shown in Fig10. It is evident that the THD of utility grid current measures at 0.41%, falling within the acceptable THD range as defined by IEEE standards. The existence of harmonics within the system may result in several problems, including overheating of equipment, malfunctioning of electronic devices, and elevated voltage stress and heating of capacitors. These difficulties may shorten the lifespan of appliances and increase load losses within the system. Therefore, it is essential for harmonics to remain within specified limits to ensure proper system operation and longevity of equipment.

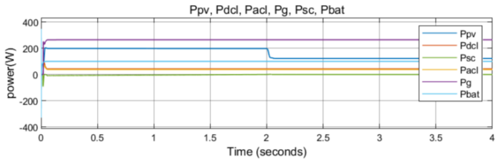


Figure 11: The power variations of various components in a system with photovoltaic (PV) power variation, Power of PV, DC load, AC load, utility grid, supercapacitor, and battery.

(B)Performance with Variation in Load

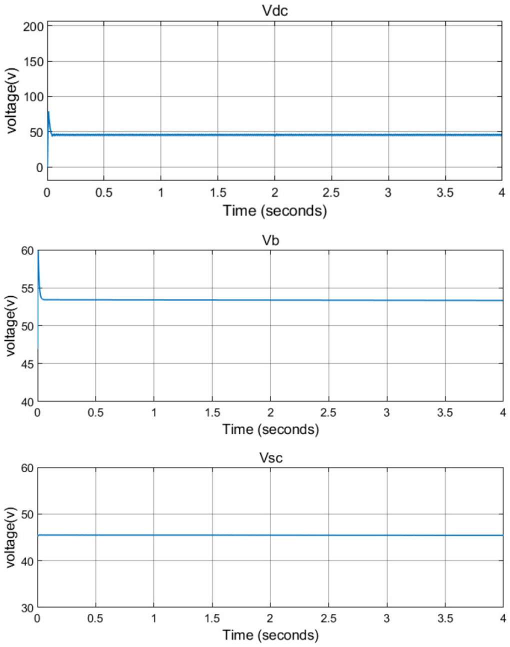


Figure 12: The voltages of the DC link, battery, and supercapacitor in a system experiencing load variation.

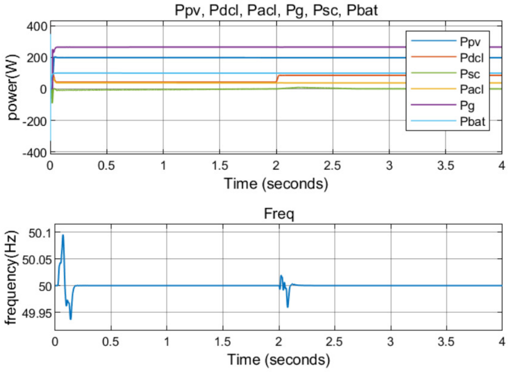


Figure 13: The power variations of various components in a system experiencing load variation. PV power, DC and AC loads, utility grid power, supercapacitor power, battery power, and frequency.

Illustrate the control techniques' performance in the presence of load variation shown in Fig12&13. The supercapacitor manages the power grid manages the average power requirement, while the transient power and batteries are handled to maintain the DC bus voltage. Therefore, it would be careless to stick with the fixed frequency of 50 Hz in the face of a sudden change in the load needs. The power quality supplied to the loads is severely degraded when a micro grid is linked to any renewable energy source due to frequency variation. Therefore, it's critical to keep the frequency within the bounds in order to improve power quality.

(C)Performance with IPM

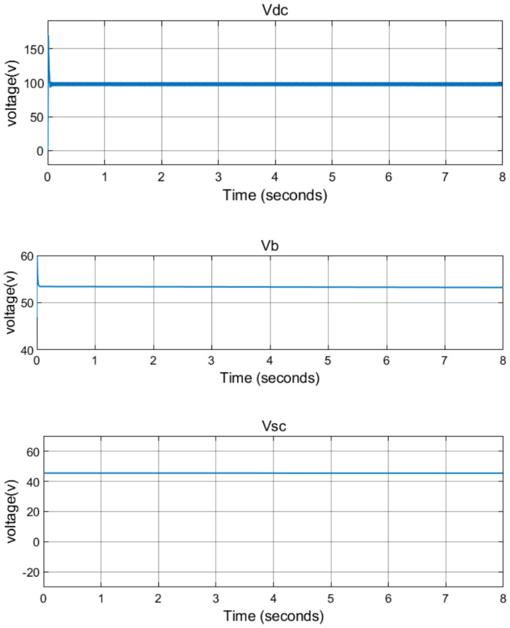


Figure 14: The voltages of the DC link, battery, and supercapacitor in a system utilizing Insufficient Power Modules (IPMs).

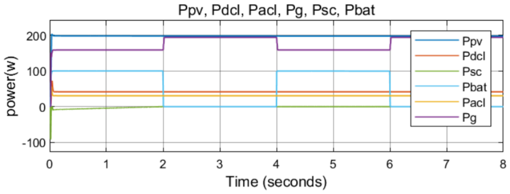
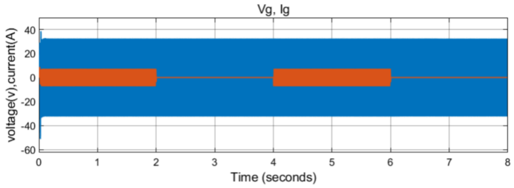


Figure 15: the power variations of various components in a system utilizing Insufficient Power Modules (IPMs). PV system power, battery, supercapacitor, utility grid, and DC and AC loads.

The supercapacitor and batteries both go into idle mode. Only in order to maintain a steady DC link voltage does the power grid supply the entire shortfall of power demand. As seen in Figs. 14&15, the DC bus voltage rapidly returns in any state in IPM. To verify the four substates, deliberate modifications are made to the storage devices' SOCs. Fig. 15 displays the corresponding power changes. The micro grid's seamless operation is mostly dependent on the supercapacitor.



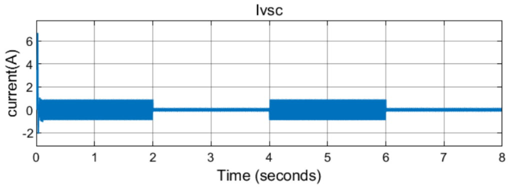


Figure 16: Represents the current waveform of a Voltage Source Converter (VSC) in a power system with an Insufficient Power Module (IPM).

When the supercapacitor system is within the predefined SOC limits, it actively participates in meeting transient power demands. As a result, the VSC current undergoes smoother changes, as the supercapacitor assists in mitigating rapid fluctuations in power demand. This helps in achieving a more stable and reliable operation of the VSC system. Overall, integrating a supercapacitor system with a VSC, especially when equipped with IPM technology, enhances the system's ability to handle transient power variations effectively. By leveraging the rapid energy storage and discharge capabilities of supercapacitors, the system can achieve smoother transitions in current and voltage, ensuring optimal performance and reliability is shown in Fig 16.

(D)Performance of SPM

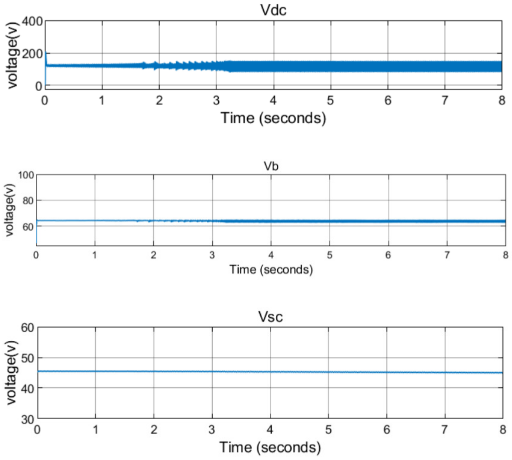


Figure 17: The voltages of the DC link, battery, and supercapacitor in a system utilizing (SPM).

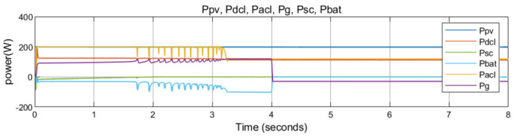


Figure 18: the power variations of various components in a system utilizing (SPM). PV system power, battery, supercapacitor, utility grid, and DC and AC loads.

Based on the rated charging currents of each component—the battery and the supercapacitor—charge. Whatever extra power is left over once the storage devices are charged is fed back into the power system. Fast-changing the power grid controls average power overall, while the supercapacitor provides transient power. The battery stops working and the supercapacitor only provides the short-term power needed when the grid is unable to meet the system's total power needs. The PV's extra power is fed into the electrical grid after the loads have been supplied. Any state in SPM, however, as shown in Fig. 17&18.

Table 9: Comparison for Settling Time t_s, Peak Overshoot M_p, Total Harmonic Distortion THD.

Parameter	**PI controller**	**FLC controller**
t_s	0.15	0.03
%M_p	1.00%	1.00%
%THD	1.11%	0.41%

To demonstrate the robustness and efficacy of the proposed scheme, several performance metrics are analyzed for different methods under varying PV generation conditions. Specifically, the evaluation includes total harmonic distortion (THD), voltage overshoot/undershoot (M_p) of the DC-bus voltage, and settling time (t_s). The graphical comparison of these metrics for different methods is presented in the table, where "Method 1" refers to the approach described in [10] utilizing a PI controller and the "Proposed Method" employs an FLC controller.

V. CONCLUSION

In conclusion, the fuzzy logic-based Power management plan for combining hybrid energy storage with grid-connected solar (PV) installations provides an effective solution to overcome challenges associated with PV integration and energy storage in power grids. This scheme harnesses the combined advantages of PV generation and energy storage to optimize power flow. By leveraging fuzzy logic, capable of handling imprecise and uncertain data, the power management scheme can dynamically control energy storage system charging and discharging based on real-time conditions. This adaptive approach enables efficient utilization of renewable energy and storage capacity, leading to improved THD value0.41% grid stability.

The integration of PV and energy storage systems presents several benefits. Excess energy generated during periods of high PV generation can be stored for later use, reducing reliance on the grid and minimizing wastage. Conversely, during times of low PV generation or high demand, stored energy can be discharged to compensate for shortfalls, ensuring a dependable power supply.

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