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Optimizing Energy Management of Hybrid Battery-Supercapacitor Energy Storage System by Using PSO-Based Fractional Order Controller for Photovoltaic Off-Grid Installation

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ABSTRACT

The integration of hybrid energy sources, such as batteries and supercapacitors, in off-grid photovoltaic installations is of crucial importance. This method promotes energy autonomy, offers operational flexibility, compensates for fluctuations in solar production, and can result in long-term economical savings. It also allows for optimized energy management through efficient storage and redistribution. This work details the design and simulation of a self-sufficient solar system that uses supercapacitors and batteries as part of a hybrid energy storage system. Recognizing the increasing significance of efficient energy systems, this study addresses the importance of such installations in delivering sustainable energy solutions. The FOPI-PSO controller optimized using the Particle Swarm Optimization (PSO) technique; demonstrates greater flexibility with a greater number of parameters, surpassing the adaptability of the conventional PI controller. By using multiple simulation scenarios that take into consideration both variations in load and irradiance, the study compares the effectiveness of both controllers in terms of synchronizing batteries and supercapacitors. The results demonstrate the PSO-based FOPI control strategy's outstanding performance, showing its optimal efficiency and robustness.

1. INTRODUCTION

The quick development of alternative energy technologies has led to an increase in the suitability of off-grid solar systems, which provide a sustainable energy source in isolated or historically unelectrified areas [1]. But because weather patterns and energy consumption are inherently unpredictable, the effectiveness of these systems' energy management is crucial to their viability [2, 3].

One of the efficient solutions to this problem is the use of a hybrid energy storage system made up of [3] in an off-grid photovoltaic system [4]. Because batteries can store a large quantity of energy, they are an essential part of independent energy systems. Nevertheless, limited dynamic response, comparatively long charging times, and degradation over time are some of its major disadvantages [5]. On the other hand, supercapacitors offer significant advantages in terms of high charge and discharge rates, long lifespan, and stable performance over numerous cycles. However, they are limited by their comparatively lower energy storage capacity compared to batteries [6].

The main goal of battery and supercapacitor hybridization is to optimize the inherent advantages of each technology while minimizing the disadvantages of each. Combining the quick charge and discharge times of supercapacitors with the high energy density of batteries will result in a well-balanced energy storage system. It should be possible for this system to adapt quickly and efficiently to changes in solar energy production and energy consumption [7]. It is crucial to point out how important it is to integrate energy management into hybrid energy storage systems. The main goal is to reduce battery stress and extend battery longevity.

As highlighted in the study [8], here is how this strategy operates: the DC output voltage, in this case, is compared to the reference voltage using a particular algorithm. The resulting error is then fed into a proportional-integral (PI) controller. The PI controller generates the total required current (Iref) for the hybrid energy storage system, which is subsequently separated into low-frequency and high-frequency components. This energy management approach is essential for maintaining battery durability and maximizing system performance. Furthermore, integrating a more effective controller offers a substantial chance to improve energy management and further reduce battery stress, which will significantly improve system performance.

Previous work has had a significant influence on research in the field of control techniques for battery-supercapacitor combinations and HESS (hybrid energy storage systems). Koohi-Fayegh and Rosen [9] as well as Luo et al. [10] listed the many electric energy storage technologies that have been developed to date, highlighting the advantages and disadvantages of each storage device, including the two primary parts of the system that are the subject of our work: Lead-acid batteries and supercapacitors. In the field of rural electrification, the integration of standalone photovoltaic power systems has emerged as an important solution.

Addressing the challenge of efficient energy storage, Jing et al. [11] have conducted a comprehensive study on a battery-supercapacitor hybrid energy storage system for standalone PV power systems. The conclusion provided by Jing et al. suggests that the integration of an active secondary energy storage system with a passive primary battery represents an optimal configuration for standalone photovoltaic power system applications. Another aspect to consider is the possibility of a fully active hybrid energy storage system (HESS). While results indicate the potential best combination of a passive primary battery and an active secondary energy storage system, it would be interesting to evaluate the advantages and disadvantages of an active fully HESS despite its high cost. This could give a greater understanding of the choices accessible in the context of standalone photovoltaic power systems.

Alam et al. [12] propose a novel approach employing an optimized fractional-order proportional integral (FOPI) controller integrated with superconducting magnetic energy storage (SMES). Tuned using Particle Swarm Optimization (PSO), the FOPI controller enhances system virtual inertia. Simulations demonstrate improved performance in terms of overshoot, undershoot, and settling time, affirming the effectiveness of this approach.

Vanchinathan et al. [13] present a novel Whale Optimization Algorithm (WOA) approach for optimal tuning of the Fractional-Order Proportional Integral (FOPI) controller in sensorless speed control of Permanent Magnet Brushless DC (PMBLDC) motors powered by solar PV systems. The study highlights the robustness of PMBLDC speed control under various operating conditions, comparing the effectiveness of WOA with other optimization techniques such as Bat Algorithm (BA) and Grey Wolf Optimization (GWO). It's worth noting that the use of Particle Swarm Optimization (PSO) was not studied in this article.

Saadi and Mohammed [14] aim to optimize power extraction from a Photovoltaic (PV) panel and deliver it to a load system under standard weather conditions. They employ standard Boost DC-DC converters and bidirectional Buck-Boost DC-DC converters for voltage control. Two MPPT control algorithms, Particle Swarm Optimization (PSO) and Incremental Conductance (INC), are compared. Results show that the INC-MPPT algorithm provides a stable PV transient response, while the PSO-MPPT algorithm achieves a good steady-state PV response.

Cabraneet al. [15] proposed an innovative approach for voltage regulation of DC bus in photovoltaic energy storage, utilizing a combination of batteries and supercapacitors. The fuzzy logic-based energy management strategy presented in the study is demonstrated to be effective in maintaining the state-of-charge of supercapacitors and batteries at acceptable levels. However, a thoughtful perspective suggests that a detailed comparison with other control methodologies, such as those based on mathematical models or optimization techniques, would contribute to a more comprehensive evaluation of the benefits of employing fuzzy logic in this specific application.

Guentri et al. [16] conducted an innovative research investigation that employed heuristic methods to explore energy management systems. In addition to demonstrating the efficacy of a strategy based on heuristic techniques like PSO (Particle Swarm Optimization) and GA (Genetic Algorithm) for managing a hybrid energy storage system combining batteries and supercapacitors, their contributions laid the conceptual foundation for energy management in photovoltaic systems. They came to the conclusion that the PSO approach produced the best results. The research could be expanded by exploring the performance of the PSO approach in larger-scale scenarios, to understand its limitations and scalability for more complex applications.

The recent advances in the optimization of Fractional Order Proportional Integral controllers have been greatly influenced by Bouderres et al. [17]. In the context of a grid-connected photovoltaic system, their study focuses on the implementation of the Particle Swarm Optimization (PSO) method to fine-tune the PI and FOPI controller's settings. This method produced more accurate regulation and showed a notable improvement in system performance. However, It is worth considering a relevant perspective that the possibility of integrating even small-scale storage systems has not been adequately considered. Forgetting this could cause the study to ignore the potential advantages of adding even a small storage device to improve system stability or control variations in photovoltaic production.

Due to Zdiri et al. [18] work on the sliding-mode artificial neural network (ANN) control technique, control strategies for hybrid PV-battery-supercapacitor systems have improved significantly. However, it is important to be aware of a potential objection regarding the use of ANN. One aspect deserving closer examination is the inherent complexity and black-box nature of ANN models, which may pose challenges in comprehensibility and interpretability. The transparency of the decision-making process in ANN-controlled systems could be a concern. Future studies may examine approaches to augment the ANN models' transparency, guaranteeing harmony between their potent optimization potential and the comprehensibility necessary for useful application.

Following the review of all these works, the implementation of an energy storage management system is essential, aiming for an optimal and dynamic response to fluctuations in solar production and energy demand. To achieve these objectives, it is crucial to replace conventional controllers with more efficient ones characterized by an extended capacity for adjustment and regulation [19]. Additionally, optimizing the parameters of these controllers is necessary to ensure maximum system efficiency.

The aim of this paper is to propose an innovative technique for controlling the battery and supercapacitor combination in off-grid systems using a hybridization approach, which utilizes a Fractional Order Proportional Integral (FOPI) controller based on Particle Swarm Optimization (PSO). This method seeks to optimize system efficiency, reduce energy losses, and prolong the usable life of storage components by utilizing the enhanced precision of the fractional-order controller and the adaptive parameter modification capability of the PSO algorithm. The implementation of this strategy is justified by the importance of these factors in guaranteeing the reliability as well as sustainability of off-grid photovoltaic systems. To the best of our knowledge, no similar study has been conducted to date.

With this approach, the system was extensively simulated under various load demand and illumination scenarios. The primary goal was to validate the efficiency of the hybrid system in representative scenarios. The system's ability to adjust to changes in operational settings and sustain steady performance in the face of unanticipated changes was then measured by comparing the outcomes in terms of response time and robustness.

We identify and address several key research questions that guide our analysis and methodology, including:

- How to design an effective controller to manage the energy distribution between the battery and supercapacitor to optimize system performance?
- What is the impact of using a fractional-order controller based on PSO compared to traditional approaches on system efficiency, stability, and robustness?
- How to minimize energy losses in the system while maximizing its overall efficiency?

The study is organized as follows: Section 2 will give the description and the mathematical modeling of the individual components of the Photovoltaic system. In Section 3, we explore the control strategy employed in the PV system. This includes a detailed examination of the algorithms. Section 4 focuses on the simulation aspect of the study. The final section, Section 5, gives conclusions based on the findings from the modeling and simulation and suggests avenues for future research and improvements.

2. DESCRIPTION OF THE SYSTEM

The off-grid photovoltaic system under investigation is depicted in Figure 1. It comprises a solar PV system connected to the DC bus through a DC-DC boost converter. The hybrid energy storage system (HESS) consists of a combination of batteries and supercapacitors. Each ESS is linked to the DC bus through a DC-DC buck-boost converter.

A DC load is able to be supplied by any of the three sources: the photovoltaic generator is employed as the primary source of power, the batteries are utilized in situations where there is an excess in PV production or a shortage to supply and the SCs are used to minimize variations in either the PV production or the load. A PI controller is utilized to regulate each DC/DC buck-boost converter, the MPPT is used through the DC/DC in order to extract the maximum power from the PV source, and an efficient energy management strategy (EMS) is employed to control the entire system.

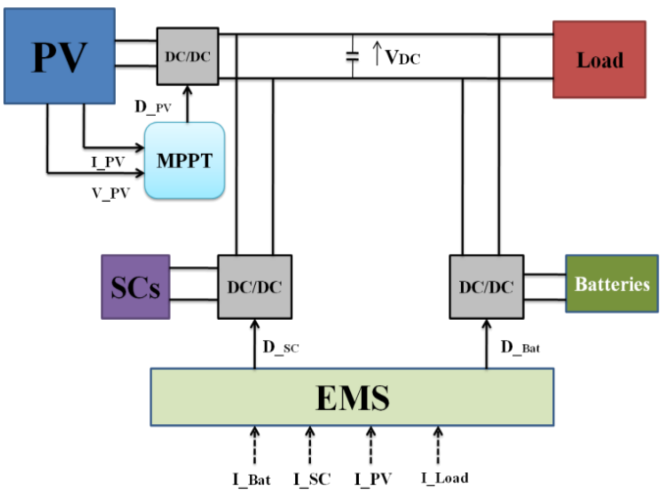

Figure 1. Schematic diagram of off-grid PV systems with HESS

2.1 Modeling of the photovoltaic system

The conventional solar PV model is shown in Figure 2 and consists of a photocurrent, a diode, a parallel resistance (Rp) that represents leakage current, and a series resistance (Rs) that represents internal resistance to current flow. The voltage-current characteristic of a solar cell is given by Eq. (1).

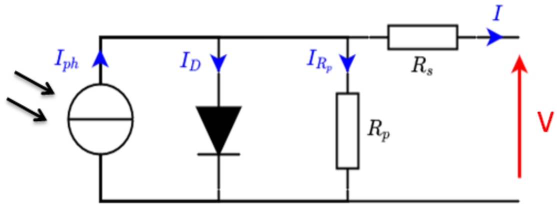

Figure 2. Photovoltaic equivalent circuit model

Eq. (1) gives the voltage-current characteristic of a solar cell [20].

$$I = Iph - Is\left(exp\left(\frac{qV + IRs}{kTcA}\right)1\right) - \left(\frac{V + IRs}{Rp}\right) \tag{1}$$

- I: Current through the solar cell.
- Iph: Photocurrent, representing the light-generated current.
- Is: Reverse saturation current, a characteristic of the solar cell materials.
- q: Charge of an electron.
- V: Voltage across the solar cell.
- Rs: Series resistance, accounting for internal resistance.
- k: Boltzmann constant.
- Tc: Temperature in Kelvin.
- A: Diode ideality factor.
- Rp: Parallel resistance

2.2 Modeling of DC-DC converter

Figure 3 describes the power stage of a buck-boost converter. It consists of the actual load R, the smoothing inductance L, the output smoothing capacitance C, and the two switching transistors Q1 and Q2.

When employing the buck converter mode, Q1 is always OFF and current flows from the DC bus to the EES source (batteries or SCs). Reducing Vdc voltage to charge the EES is possible for the converter by controlling Q2.

The switch Q2 is turned off and the diode in Q2 permits current to flow only in one direction, from the storage source to the DC bus, when the converter is operating in the boost mode. Power for the DC bus can be supplied by the converter by raising the voltage VEES of the ESS by regulating the duty cycle of Q1 [21, 22].

The EES voltage when operating in buck converter mode is:

$$V_{EES} = \frac{Vdc}{D} \tag{2}$$

V_{EES} Can be adjusted by controlling the duty cycle D of the converter.

DC voltage when operating in a boost converter is:

$$Vdc = \frac{V_{EES}}{1 - D} \tag{3}$$

By adjusting the duty cycle D, the gain of the boost converter can be changed.

- V_{ESS}: Voltage of the energy storage system.

- V_{dc}: DC output voltage of the DC-DC converter.
- D: Duty cycle of the DC-DC converter, representing the fraction of time the switch is turned on.

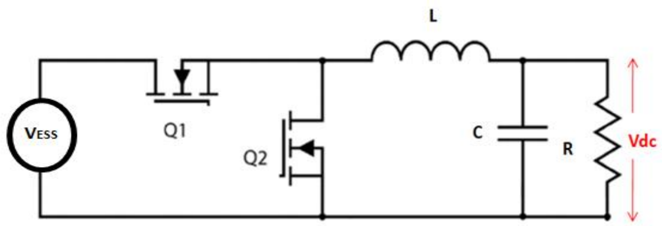

Figure 3. Buck-BOOST DC/DC converter circuit model

3. CONTROL STRATEGY OF PV SYSTEM

The control strategy supervises the HESS's power flow in accordance with the current state of the system. It typically requires constant operation and is complex in order to achieve the various goals. In order to maximize sustainability and energy efficiency, optimal control of the HESS is essential. The following is a list of the control strategies' shared objectives [23, 24]:

- To keep the battery from going into deep discharge.
- To minimize the battery's dynamic stress level, charge/discharge cycle, and peak power demand.
- To hold the DC voltage constant.
- To increase the system's overall effectiveness.

Usually there are two types of control strategies: intelligent control strategies and classical control strategies. Because they don't require complex processing, traditional control strategies like Rule-based controllers and Filtration-based controllers are easy and straightforward to implement [25]. They are typically rigid and sensitive to parameter variation, though [26]. When compared to classical control strategies, intelligent control strategies like the fuzzy logic controller (FLC) are more reliable and effective because they improve the dynamic of the system without needing an exact model of the system [27].

4. PROPOSED CONTROL STRATEGY

This section shows the structure of the suggested control strategy, which aims to minimize the battery's peak current demand and dynamic stress. The LPF and FOPID controller are the two components that make up the control strategy. The Fractional Order Proportional Integral Controller (FOPID) parameters are optimized through the implementation of the PSO algorithm to attain optimal performance. The following sections provide an explanation of the proposed control strategy's structure.

4.1 Low pass filter (LPF)

Photovoltaic power generation and load demand actually fluctuate a lot during operation [28]. The batteries are stressed in the conventional system in order to meet the highly fluctuating. A large amount of heat would be produced inside the battery by the highly fluctuating battery current, which would increase internal resistance and reduce efficiency. To avoid this, we could split the power drift between the generation and consumption sides into two parts: the transient high-frequency component (HFC) and the steady low-frequency component (LFC). The battery is going to manage the LFC, and the SC will deal with the HFC [29].

By doing this, the battery's dynamic stress is decreased, and the high-frequency components are prevented from being supplied by the battery. Figure 4 depicts the diagram of the low-pass filter.

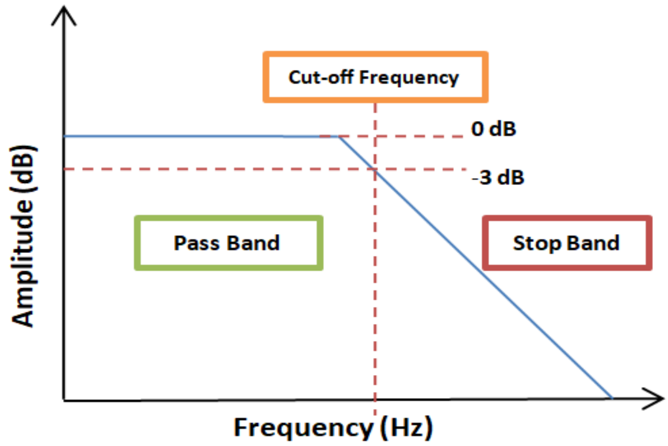

Figure 4. Low pass filter diagram

4.2 Fractional order PID controller (FOPID)

Researchers have been curious about a new PID controller design in recent years because of its advantages over classical PID controllers, which include improving the performance of dynamic, non-linear systems and being less sensitive to changes in system parameters. This new design can be applied in many domains, particularly control theories.

Podlunby has been proposing this control device, known as fractional order PID (or FOPID) [30]. A classical PID controller additionally includes the fractional components of the integral and derivative parts, indicated by λ and μ, in addition to the control parameters Kp, Ki, and Kd.

The equation below gives the control law of the fractional order PID controller:

$$u(t) = (Kp + KiD^{-\lambda} + KdD^{\mu})e(t) \tag{4}$$

- $u(t)$ is the controller input
- e(t) is the error

By using the Laplace transform on Eq. (4), Eq. (5) defines the transfer function of this controller under zero initial conditions.

$$G(s) = K_P + K_i s^{-\lambda} + K_d s^{\mu} \tag{5}$$

The fractional orders of the integral and derivative terms are denoted by λ and μ, respectively. The proportional, integral, and derivative gain constants are represented by Kp, Ki, and Kd. The values (λ and μ) for a classical PID controller are equal to 1. Figure 5 illustrates the concept of the FOPID (Fractional Order Proportional Integral Derivative) controller and Figure 6 displays the control domains for FOPID and classical PID.

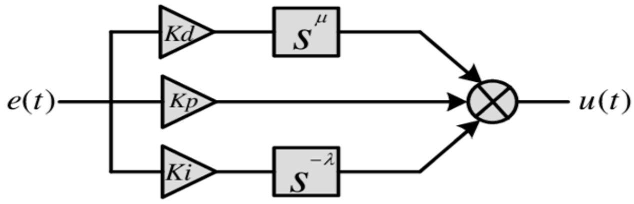

Figure 5. FOPID controller concept

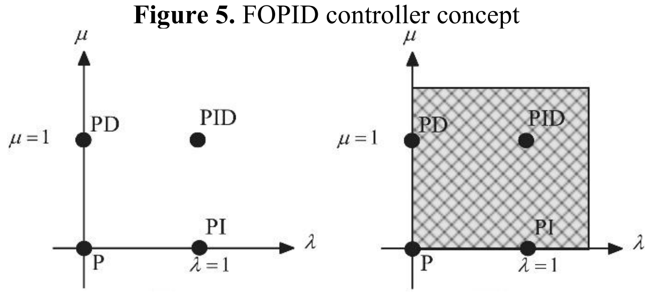

Figure 6. PID controller versus FOPID controller

While the classical PID controller only needs to optimize three parameters, the FOPID controller design requires five parameters. The control system's dynamics can be realized with greater flexibility thanks to this extension [31].

In the context of our work, opting for a FOPI structure with Kd set to zero in the controller is justified by the need to simplify the design, prevent unstable responses, reduce implementation costs, and enhance robustness against variations in system parameters. This choice aligns with our specific objectives.

4.3 Particle swarm optimization algorithm (PSO)

The social behavior of fish and bird flocks searching for food serves as an inspiration for the PSO algorithm, a population-based optimization technique [29, 32, 33], PSO is introduced and discussed. It demonstrates how birds could determine their directions by using the collective knowledge of their group. Therefore, during each flight, birds work as particles that update their positions and velocities based on their own and the group's best experiences.

One of the most popular techniques for resolving optimization issues nowadays is the Particle Swarm Optimization algorithm. Its simplicity, high performance, and cheap computational cost have made it heralded as a promising and effective optimization method. PSO algorithms are widely applied in science and are effective at solving the majority of optimization issues [34, 35].

In order to attain the ideal controller parameters and, consequently, the best system output, the PSO technique is advised in this study to tune the controller gains.

The position and velocity updates for each particle within the population are computed using the following mathematical expressions at each cycle:

$$Vi(k+1) = w.Vi(k) + C1.r1[Pi(k) - xi(k)] + C2.r2[G\,i(k) - xi(k)] \quad (6)$$

$$xi(k+1) = xi(k) + Vi \quad (7)$$

- w: Adaptive inertia factor
- $Vi(k)$: Velocity of particles at iteration k
- $xi(k)$: Position of particles in the search space at iteration k
- $C1$: Cognitive factor controlling the individual behavior of each particle
- $C2$: Social factor controlling the collective behavior of each particle
- $r1$: Random number uniformly distributed in the interval [0, 1]
- $r2$: Random number uniformly distributed in the interval [0, 1]

Figure 7 displays the flowchart outlining the step-by-step process of Particle Swarm Optimization (PSO). This visual guide illustrates how particles update their positions and velocities iteratively, providing a straightforward representation of the optimization algorithm's dynamics.

The control parameters for the PSO technique used to optimize the FOPI controller are listed in Table 1.

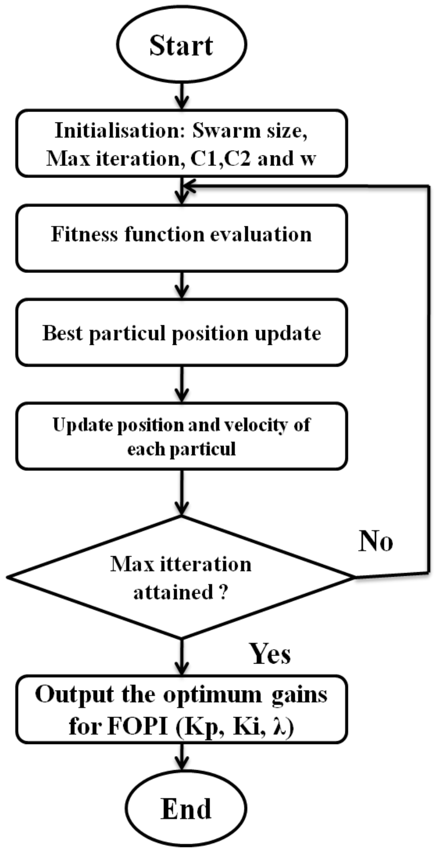

Figure 7. Sequential steps of the Particle Swarm Optimization (PSO) process

Table 1. Parameters of the PSO algorithm

Parameter	Value
Swarm size	50
Max iteration	100
C1	0.2
C2	1.1
w	0.7

The values of the PSO parameters were selected after a thorough analysis of their effects on algorithm performance, combined with empirical adjustments to optimize results within the specific framework of our optimization problem.

The optimization process employs various suitability criteria, such as Integral Absolute Error (IAE), Integral Square Error (ISE), and Integral Time-Weighted Absolute Error

(ITAE), to assess system performance. In the current context, the fitness function utilized to evaluate the performance of the system's output response is the Integral Absolute Error (IAE). The IAE is defined as follows:

$$\text{IAE} = \int_0^t (|Isc\_err|)\,\text{dt} \tag{8}$$

$$Isc_{err} = Isc_{ref} - Isc \tag{9}$$

The use of IAE as the fitness function in the optimization process is justified because it provides an intuitive, robust, and easily interpretable measure of system performance, making it suitable for evaluating and enhancing the efficiency of the proposed control algorithm.

Figure 8 shows the block diagram illustrating the optimization process for the FOPI-PSO controller.

Figure 9 shows the proposed FOPI-PSO HESS control scheme. As was previously mentioned, the main purpose of the SC is to reduce the stress associated with battery charging by absorbing the transient peak energy that arises from sudden changes in load or weather. This will be accomplished by splitting the power drift between the generation and consumption sides into two parts: the transient high-frequency component (HFC) and the steady low-frequency component (LFC).

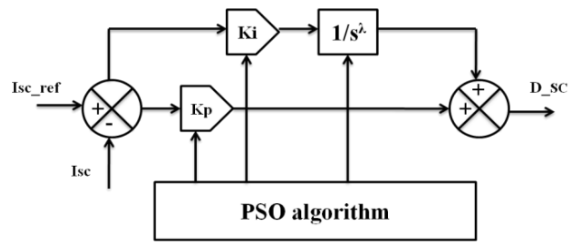

Figure 8. Proposed FOPI-PSO controller bloc diagram

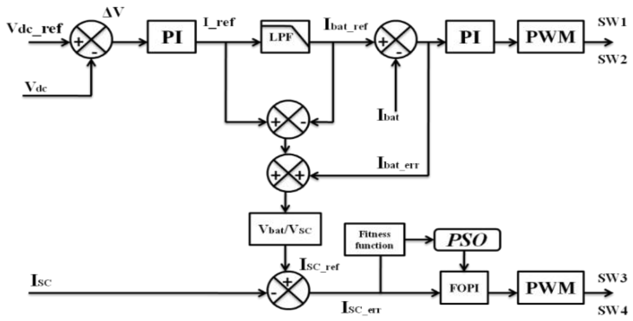

Figure 9. Proposed FOPI-PSO hybrid energy storage system control scheme

The reference voltage and the DC output voltage are compared in this algorithm, and the error is fed to the proportional-integral controller. The hybrid energy storage system's total current required, or I_{ref} is generated by the PI controller.

$$I_{bat\_ref} = \text{lowpassfilter}(I_{ref}) \tag{10}$$

The reference current to the battery represents the low-frequency component of the current. The error *(I_{bat_err})* is sent to the PI controller after I_{bat_ref} and I_{bat}, the actual battery current, are compared. The duty ratios are produced by the PI controller. The PWM generator receives these duty ratios and outputs switching pulses that correspond to battery switches.

The following formula gives the power (P_{bat_uncomp}) that must be supplied by the SC and is not compensated by the battery.

$$P_{Bat_{uncomp}} = V_{Bat}(I_{Bat_{err}} + I_{ref-HF}) \tag{11}$$

$$I_{ref-HF} = I_{ref} - I_{ref-LF} \tag{12}$$

SC is responsible for making up for this uncompensated battery power. As a result, the SC reference current is taken as:

$$I_{SC\_ref} = \frac{P_{Bat_{uncomp}}}{V_{SC}} \tag{13}$$

The battery and SC voltages are denoted by V_{bat} and V_{SC} respectively.

After comparing I_{sc_ref} with the actual SC current (I_{sc}), the FOPI controller receives the error. The necessary duty ratios are produced by the FOPI controller. The PWM generator receives these duty ratios and uses them to produce switching pulses that correspond to SC witches [36].

The synergy between FOPI regulator and PSO optimization lies in their complementary strengths. While FOPI provides a robust and adaptive control framework capable of handling system uncertainties and nonlinearities, PSO facilitates automatic tuning of regulator parameters to achieve optimal performance. This combination leverages the benefits of both methodologies, resulting in a powerful and versatile control strategy.

In this study, the exclusive use of FOPI-PSO on the supercapacitor control loop (Figure 8) was motivated by the necessity for a specialized optimization approach customized to the complex dynamics and diverse parameters associated with supercapacitor control. This targeted application enables a more precise adjustment and adaptation of FOPI controller parameters to enhance the overall performance of the supercapacitor within the system.

By introducing the derivative term, the controller may become more sensitive to noise and disturbances in the system, requiring more precise parameter tuning. Additionally, adjusting five variables simultaneously for a FOPID controller, instead of three variables for a FOPI controller, will be necessary to avoid undesirable behaviors such as overshoot. Therefore, in certain situations, such as with the FOPI controller mentioned earlier, it may be preferable to opt for controllers without a derivative term [17, 19, 30] when implementation complexity needs to be reduced without impacting the overall system performance.

5. SIMULATION AND RESULTS

A simulation using the MATLAB/Simulink program was conducted to verify the effectiveness of the suggested method and compare it with the classical technique. The control diagram shown in Figure 7 is implemented.

Two scenarios are used to test two control strategies: the conventional PI and the suggested FOPI-PSO.

5.1 Situation 1: Intermittent solar radiation

In this particular case, the experimental setup involves the utilization of fluctuating solar irradiation in conjunction with a constant power load (*Pload*=1000W), as visually represented in Figure 10.

The dynamics of *Ppv*, *Pbat*, and *Pload*, three different power components are shown in Figure 11. Due to an energy deficit, the battery first discharges between 0 and 0.5 seconds. At 0.5 seconds, the increase in solar irradiation results in a slight energy surplus, automatically transitioning the battery into a charging mode until 1 second. When the irradiation level rises after 1 second, the battery automatically absorbs the extra energy and charges fast for 1 to 1.5 seconds. Finally, at 1.5 seconds the battery enters a slow charging condition that lasts between 1.5 and 2 seconds due to a decrease in radiation.

The supercapacitor's response during the simulation is shown in Figure 12, which compares the proposed FOPI controller with the traditional PI controller. In order to reduce the stress on the battery, a rise in irradiation in both scenarios causes the supercapacitor to absorb a small amount of energy (at 0.5 seconds and 1 second). When the radiation drops (at 1.5 seconds), the supercapacitor covers up the difference in energy during the transient phase, consequently reducing battery stress constantly.

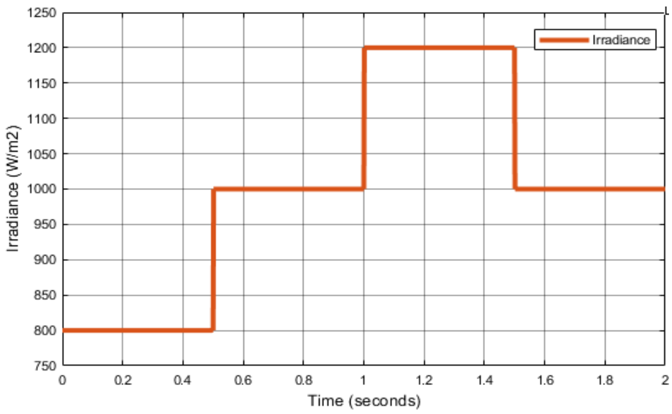

Figure 10. Solar irradiance

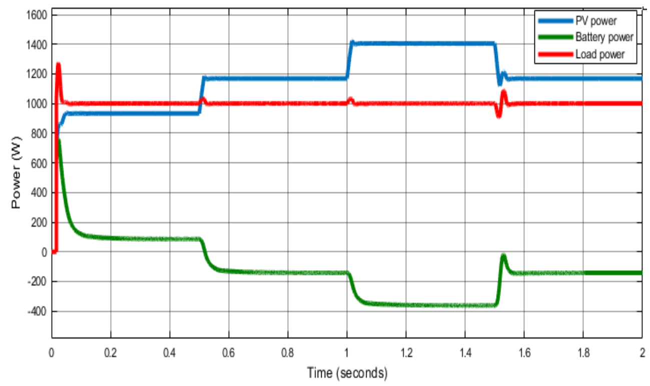

Figure 11. Power responses of PV, batteries and load with variable solar irradiance

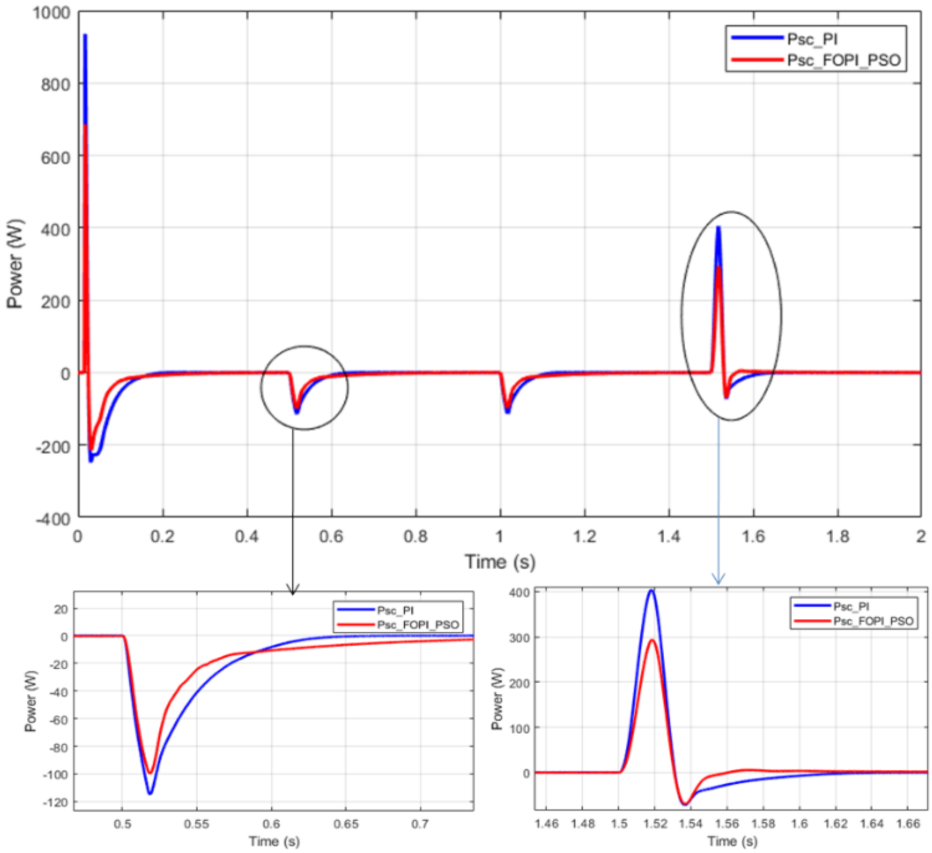

Figure 12. Power responses of SCs for variable solar irradiance with PI and FOPI-PSO controllers

When the Fractional Order Proportional Integral (FOPI) controller is applied, a discernible improvement becomes apparent in the response characteristics of the supercapacitor. This enhancement is particularly notable in terms of efficiency, and SC's energy utilization.

5.2 Situation 2: Fluctuating load

The objective of the second simulation scenario is to assess the proposed control scheme under different load conditions. A constant PV generation of (Ppv=1180W) was maintained.

The performance of the Energy Management System (EMS) under varying loads is depicted in Figure 13.

Figure 14 shows the SCs power responses under dynamic load conditions. The incorporation of both the Proportional-Integral controller and the proposed FOPI-PSO controllers aimed at refining the charging and discharging behavior of the supercapacitor underscores the noteworthy advantages of the Battery-Supercapacitor Hybrid energy storage system (HESS). This enhancement is important in achieving a substantial reduction in battery stress.

Similar to the simulation with varying irradiation, noteworthy enhancement in the supercapacitor response is evident with the utilization of the FOPI controller.

With the implementation of the FOPI controller, it is noteworthy that the supercapacitor exhibits reduced energy consumption. This observation can be attributed to the improved charging and discharging dynamics of the supercapacitor, facilitated by the more effective control provided by the integral term of the FOPI controller. This controller enables a more precise management of the energy stored and released by the supercapacitor, thereby contributing to a more efficient utilization of energy and a potential reduction in overall consumption.

Additionally, it's worth noting that Figure 14 provides a visual representation of the Battery State of Charge (SOC) throughout the simulation. The initial SOC is 60%.

From 0 to 0.5 seconds: Energy surplus leads the battery into fast charging mode. At 0.5 seconds: Despite a current demand supported by the supercapacitor (Figure 13), the energy surplus persists. From 0.5 to 1 second: The battery operates in slow charging mode. At 1 second: A new current demand, supported by the SC, prompts the battery to transition from charging to discharging mode due to a slight energy deficit. From 1 to 1.5 seconds: The battery is in slow discharging mode. At 1.5 seconds: Another current demand supported by the SC causes the battery to enter fast discharging mode. From 1.5 to 2 seconds: The battery remains in fast discharging mode due to a substantial energy deficit.

The Battery SOC, as shown in Figure 15, gives clarity on how the system responds dynamically during these stages of operation.

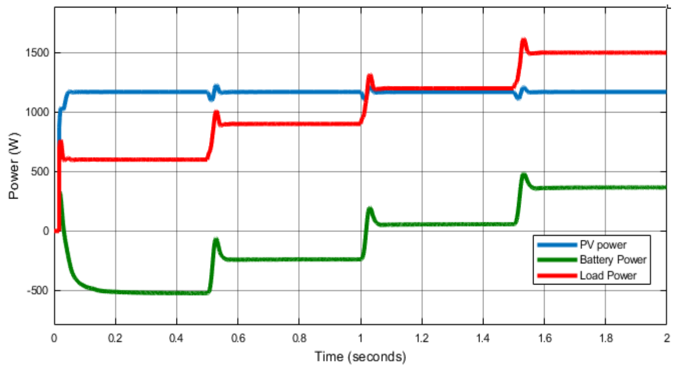

Figure 13. Power responses of PV batteries and load with variable load

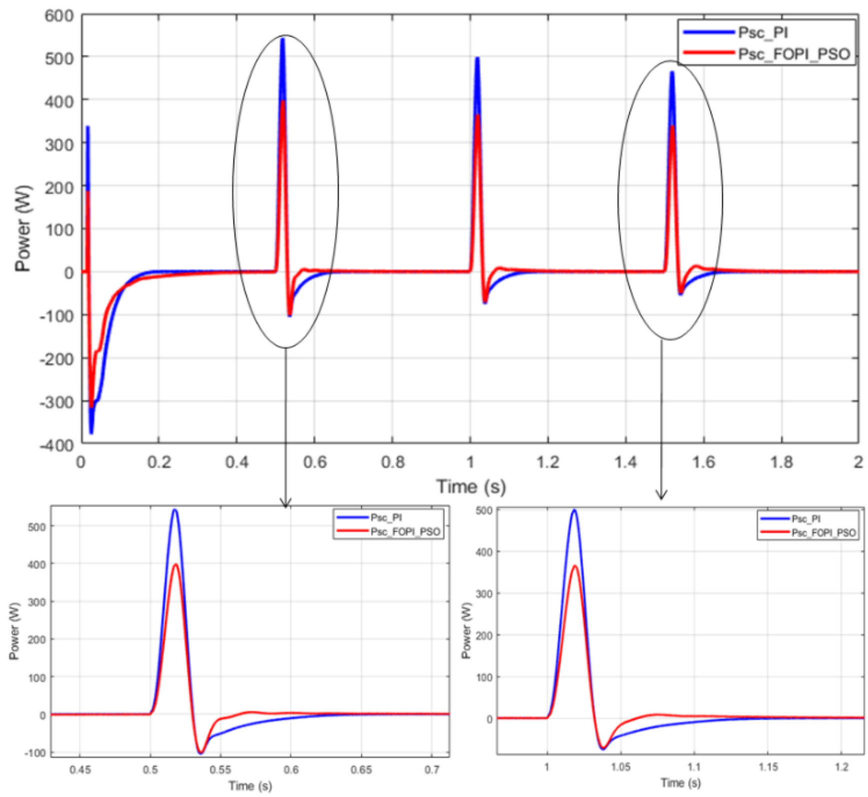

Figure 14. Power responses of SCs for variable load with PI and FOPI-PSO controllers

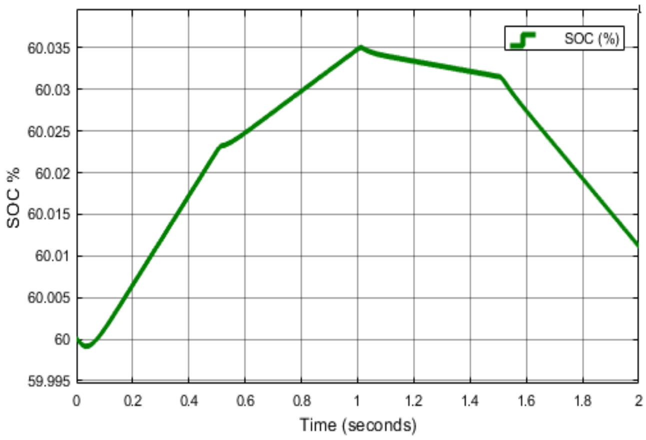

Figure 15. Battery state of charge with variable load

5.3 Test of robustness

Table 2 displays the results of the proposed approach and the conventional PI technique when load variations are present.

A variety of load variation situations were taken into consideration during the simulations, which expanded the analysis's scope. These simulations were essential for testing both approaches' efficiency and robustness in dynamic environments. We were able to obtain greater knowledge of the performance of both strategies by including different load variations. This strategy also makes it easier to evaluate how well the techniques adapt to new conditions and continue to operate at their best. In comparison to the PI controller, all performance criteria were improved by the suggested FOPI-PSO controller. Our results align with the study [37], which employed the Particle Swarm Optimization technique and Fractional Order Proportional Integral controller in the context of a dual-star induction motor controlled by Direct Torque Control.

Table2. Robustness of the control system for variable load

	Peak Overshoot %	Rise Time	Setting Time	Steady State Error
PI	20.41%	3.87e-3	3.094 e-3	3%
FOPI-PSO	9.37%	3.58 e-3	2.541 e-3	Negligible

6. CONCLUSION

In conclusion, this paper proposes and simulates a standalone PV system incorporating a hybrid battery/supercapacitor HESS controlled by an EMS that uses a Fractional Order Proportional Integral (FOPI) controller. The introduced FOPI-PSO controller, distinguished by its increased parameter flexibility, has demonstrated superior performance compared to the conventional PI controller. Exploiting the PSO optimization technique for simultaneous adjustment of multiple parameters, the proposed FOPI-PSO controller was fine-tuned to achieve optimal settings.

Through various simulation scenarios with load fluctuations and irradiance conditions, the efficacy and robustness of both the PI controller and the novel FOPI-PSO controller for synchronizing batteries and supercapacitors were thoroughly evaluated. Results indicate that the use of PSO-based FOPI in the control strategy consistently outperformed the PI controller, demonstrating superior robustness and overall system performance.

This research contributes to the enhanced adaptability and effectiveness of the FOPI-PSO control approach, showcasing its potential for optimizing standalone PV systems with hybrid energy storage.

The study and proposed approach are subject to some limitations. These include:

- Initial conditions dependency: The PSO algorithm used for controller parameter optimization may be sensitive to initial conditions and configuration parameters. Additional trials with different initial setups may be necessary to ensure result reliability.
- Impact of real environmental variations: Our study may not comprehensively account for real-time environmental variations such as sudden climate changes or shading, which can affect the system performance under real conditions.

We recommend exploring the following ideas in future research:

- Experimental validation: Conducting experimental tests on a real system to validate the effectiveness of the approach under real-world conditions.
- Incorporation of machine learning: Exploring the use of machine learning techniques to enhance controller performance by dynamically adapting to system and environmental variations.
- Multi-objective optimization: Extending the strategy to take into account several goals at once, including reducing operating costs.

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NOMENCLATURE

PV	Photovoltaic
PSO	Particle swarm optimization
PI	Proportional integral controller
FOPI	Fractional Order PI Controller
HESS	Hybrid electrical energy storage
ESS	Electrical energy storage
DC	Direct current
EMS	Energy management strategy
MPPT	Maximum power point tracking
PWM	Pulse width modulation
IAE	Integral Absolute Error
Ppv	Photovoltaic power, W
Pbat	Batteries power, W
Psc	Supercapacitor power, W
Pload	Load power, W
SC	Supercapacitor
SOC	State of charge, %
Isc	Supercapacitor current, A
Ibat	Batteries current, A
LPF	Low pass filter
Vbat	Batteries voltage, V
Vsc	Supercapacitor voltage, V
SW1,SW2	Battery converter switches
SW3, SW4	Supercapacitor converter switches
VDC	DC voltage, V
VESS	ESS voltage, V