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Power Management of Solar PV Battery and Supercapacitor in DC Microgrid

Bahri Bilgiç[1], Enes Ladin Öncül[1], Ozgun Girgin[1]
[1]Physics Engineering Departmant, Istanbul Technical University
ITU Ayazaga Campus, Istanbul, Turkiye
bahri.bilgic@itu.edu.tr; oncul17@itu.edu.tr; ogırgın@itu.edu.tr

Abstract - This paper presents an intelligent power management strategy for a DC microgrid integrating a solar photovoltaic (PV) system, battery storage, and a supercapacitor (SC) to ensure reliable and efficient energy distribution under fluctuating load and environmental conditions. The core challenge addressed is the coordination of diverse energy sources to maintain power balance and voltage stability. To optimize energy harvesting from the PV array, an Incremental Conductance (IC) Maximum Power Point Tracking (MPPT) algorithm is implemented, which accurately tracks the maximum power point (MPP) even under dynamic irradiance levels, achieving efficiencies of up to 99.9%. The battery functions as the primary energy buffer, absorbing excess energy during high solar generation and discharging during periods of low irradiance or high demand. The Supercapacitor complements the battery by handling transient load variations and providing immediate power support, thereby reducing stress and enhancing battery lifespan. A PI-based Power Management Control (PMC) dynamically adjusts the contribution from each source based on system parameters. Simulation results in MATLAB confirm that the proposed strategy maintains the DC bus voltage at a constant 400V and sustains a continuous load power of 1 kW, regardless of changes in solar irradiance. The battery and SC exhibit efficient and coordinated operation, ensuring uninterrupted power supply and improved energy efficiency. This proposed system is particularly suitable for remote or off-grid locations, offering a robust, scalable, and reliable solution for modern renewable energy-based microgrid.

Keywords**:** Solar PV, Battery Storage, Supercapacitor, DC Microgrid, Power Management, Incremental Conductance MPPT, Energy Coordination

1. Introduction

DC microgrids are used to integrate distributed energy resources like PV systems, batteries, and supercapacitors in response to the growing demand for renewable energy and the requirement for decentralized power networks. Benefits of DC microgrids include lower conversion losses, enhanced interoperability with contemporary electronic loads, and a more straightforward control architecture. However, sustaining power balance, voltage stability, and effective energy use is extremely difficult due to the sporadic nature of solar energy and fluctuating load needs. An efficient power management system that can coordinate various energy sources is necessary to overcome these problems.

Microgrids are ideally positioned to handle this shift by balancing supply and demand locally, maintaining stability in the face of increasing environmental and human-caused interruptions. However, overcoming regulatory obstacles and proving their economic feasibility via enhanced power quality and dependability are prerequisites for their broad implementation [1]. These elements are presently being examined in international markets as microgrids develop to satisfy technical and societal needs.

The rise of DC distribution networks, fueled by the expansion of DC-compatible components such as storage and renewable energy systems, is a major advancement in microgrid technology. By removing reactive power and frequency synchronization losses, DC networks are more efficient than conventional AC systems. DC microgrids have great potential, but their smooth integration into current infrastructure is hampered by standardization and unresolved technical concerns [2]. Additional complications arise when renewable energy is included into DC microgrids, namely in the areas of energy management, voltage regulation, and system inertia. To address these problems, a number of control techniques have been put forth, including centralized control, virtual inertia control, and droop control.

Nevertheless, there is still a lack of thorough knowledge regarding these methods and their long-term effects, which calls for more research to maximize the addition of non-conventional resources and improve dependability [3].

The efficient running of microgrids, especially in standalone systems, depends significantly on PMC. One method is to manage a hybrid system that consists of PV panels, FC batteries, and SCs using traditional PI management. This approach ensures effective power supply to loads by optimizing hydrogen consumption and keeping battery state of charge within reasonable bounds. The effectiveness of this strategy has been confirmed by simulations, yet, more research is necessary to explore potential cost optimization and other control strategies [4]. Advanced energy management system (EMS) approaches that make use of non-linear flatness control theory have been presented to overcome the drawbacks of conventional PI control. By minimizing overshoot and ripple, these techniques seek to maintain DC bus potential under various load and solar irradiation situations. The operation of PV scheme is improved by implementing particle swarm optimization for MPPT, which results in excellent power quality and increased system dependability [5]. To manage DC bus potential and lessen battery strain, a hybrid adaptive fractional-order PID (FOPID) control has been designed. By directing transient currents to supercapacitors, this technique ensures quick adjustment for power imbalances and increases battery longevity. Platforms such as OPAL-RT have shown that real-time simulations perform better than traditional PMS, especially in dynamic scenarios with varying renewable sources and loads [6].

Data-driven, model-free control techniques are an achievable method to manage power fluctuations in freestanding PV-based DC microgrids. These techniques use a battery-SC hybrid energy storage system (HESS) to smooth power fluctuations and only use input-output data to adjust DC bus potential and satisfy load needs. The ability of this method has been shown by algebraic simulations with real-world data, providing a reliable solution that reduces the requirement for intricate system modeling [7]. These data-driven methods are especially useful in dynamic settings where conventional model-based controls will not be able to adjust.

Hybrid control techniques that combine rule-based systems with fuzzy logic have been investigated as a way to improve energy management in HESS. By allowing adaptive operation in both grid-linked and islanded modes, these solutions overcome the drawbacks of traditional control strategies. These techniques maximize supercapacitor use to prolong battery longevity while ensuring consistent DC bus voltage with little overshoot or undershoot by adjusting battery and supercapacitor charge levels. The potential of intelligent control systems in a variety of network settings is shown by simulation findings, which validate quick voltage recovery and improved system performance [8].

A powerful alternative for PI controllers, which are frequently restricted to a single operating state and have trouble regulating the voltage of supercapacitors, are non-linear control structures. One significant method combines a Finite Predictive Control for inner current management with an Assessment-Passivity Based Control for outer-loop voltage regulation. By efficiently controlling the DC-link and SC voltages, this arrangement gets around problems like controller conflicts and constrained stability zones. Its better performance and digitally friendly design are validated by simulation and experimental findings, especially to reducing the impact of repeated discharge cycles or supercapacitor self-discharge [9].

The performance of DC microgrids is greatly influenced by their structural design as well as creative control techniques. A unique control strategy based on voltage fluctuations is used in a proposed DC microgrid topology that combines PV generating, battery, and supercapacitor storage [10]. By using battery and supercapacitor storage simultaneously, this technique improves the microgrid's transient responsiveness and its capacity to manage sudden load fluctuations in both grid-linked and standalone modes. In standalone DC microgrids driven by PV systems, the function of HESS in reducing transient voltage fluctuations has been investigated further. Research comparing microgrid performance with and without supercapacitor banks shows that using HESS significantly lowers the amplitude of transient voltage. HESS efficiently adjusts for abrupt variations under varying load and irradiance circumstances, preserving DC bus voltage stability. These results highlight how important supercapacitors are for improving system resilience, especially in the event of breakdowns or abrupt changes in load [11].

Effective energy distribution between batteries and supercapacitors within HESS requires sophisticated management strategies. One approach utilizes a PI controller design augmented with a low-pass filter to steady DC bus voltage at a reference level while distributing energy between storage mediums. The filter directs peak currents to supercapacitors, reducing battery stress and extending lifespan. Simulation results indicate that adjusting the filter constant can significantly lower battery SOC consumption, with SOC reductions from 57.60% to 48.96% observed as the filter constant increases. This approach ensures stable voltage and optimizes storage utilization, offering a practical solution for standalone PV systems [12].

The contribution of this paper lies in the development of an intelligent PMC for a DC microgrid that integrates a PV system, battery and a SC to ensure stable and efficient energy delivery under varying environmental and load conditions. By implementing the Incremental (INC) MPPT, the system effectively tracks the MPP, maintaining high PV efficiency even under fluctuating irradiance. A layered PI-based PMC is employed to coordinate energy flow among the PV, battery, and SC, enabling the battery to handle long-term energy balancing while the supercapacitor provides rapid support during transient events. The proposed strategy ensures a constant DC bus voltage and stable power supply, lower stress on the battery, extends its lifespan, and enhances overall system reliability and performance, making it particularly suitable for remote and off-grid applications.

2. System Description

A hybrid energy system that merges a PV , battery, and SC to power a DC load using a centralized DC bus is shown in Fig. 1. A boost converter, which enhances the voltage from the PV module to a point appropriate for the DC bus, linked the PV module. This permits consistent power to the load and ensures the best possible power extraction from the PV module. The DC bus provides direct power to the DC load, which is powered by any or all of the three sources based on availability.

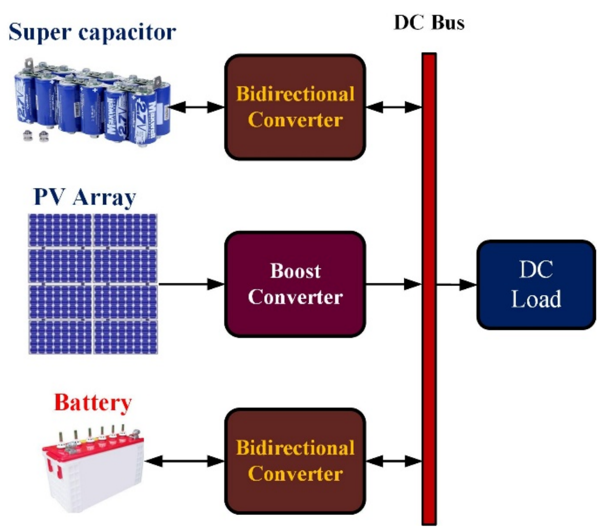

Fig.1: Architecture of DC Microgrid

The system consists of a PV , battery and a Supercapacitor, all of which are coupled to the DC bus using separate bidirectional converter. Depending on the needs of the system, the battery and SC will either charge or discharge through converters, which allow electricity to flow both ways. Long-term energy storage from the battery supports the load during times when PV output is low, while the SC can quickly charge and discharge to manage transient loads and short-term power swings. This combination improves the overall energy management efficiency, responsiveness, and dependability of the system.

2.1. PV Model

A 2 kW PV module is used in this work. The PV cell circuit is represented in Fig.2, where I_{in} is the current generated by PV.

$$I_{pv} = I_{in} - I_o\left(exp\left(\frac{V_{pv} + IR_{se}}{\alpha V_T}\right) - 1\right) - \frac{V_{pv} + IR_{se}}{R_{sh}} \quad (1)$$

where I_{pv} and I_o are output current and diode saturation current, V_{pv} and V_T are output and thermal voltage. Compared to the series resistance, the value of the shunt resistance (R_{sh}) is necessary when solving Equation (1) for the short-circuit current. The following formula allows for the direct calculation of the current as a function of temperature.

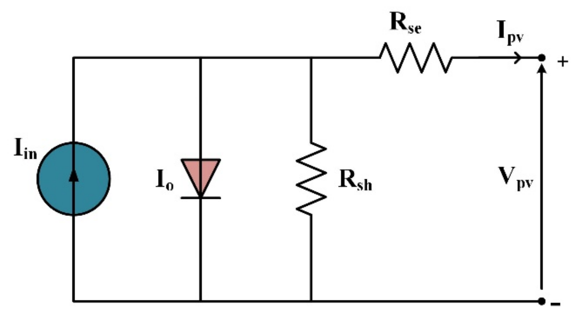

Fig.2: Equivalent circuit of PV

$$I_o = I_{o.ref}\left(\frac{T_{ref}}{T}\right)^3 exp\left\{\frac{qE_g}{ak}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right\} \quad (2)$$

where E_g represents the energy gap and T_{ref} and T stand for the reference and surrounding temperatures, respectively. The current produced by photons is given by,

$$I_{in} = \frac{G}{G_a}(I_{L.ref} + V_{sc}\Delta T) \quad (3)$$

Where, G and G_a represents the actual and reference irradiance, ΔT is the difference between the actual operating temperature and V_{sc} refers to the temperature coefficient.

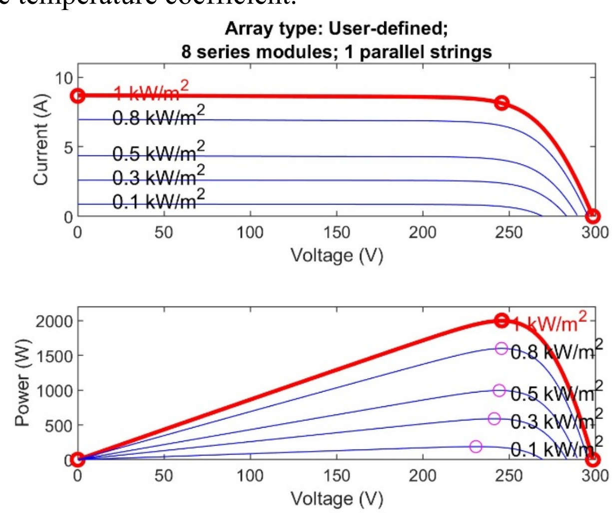

Fig.3 Characteristics of PV module

The INC MPPT is used to track MPP from the PV, the pseudocode of the method is given as follows,

Step 1: The INC MPPT algorithm begins with an initialization step; this step sets up the algorithm to track the MPP and ensures that all required parameters are ready for processing.

Step 2: Measure Voltage V(t) and Current I(t). These measurements are essential for determining the operating point of the PV system and deciding whether adjustments are required to track the MPP.

Step 3: Calculate Changes in voltage (*d*V) and current (*d*I) are computed using the differences between the present and previous values. These changes are given by:

$$dV = V(t) - V(t-1) \tag{4}$$

$$dI = I(t) - I(t-1) \tag{5}$$

These values help in analyzing the power variation in the system and determining whether the PV module is operating at the MPP.

Step 4: Checks if dV=0. This condition helps determine whether the voltage is stable, which affects the next steps in the decision-making process.

Step 5: If dV=0, the algorithm evaluates dI = 0, the system is already at the MPP, and no changes are made to the duty cycle. This ensures that the power extraction remains optimal without unnecessary adjustments.

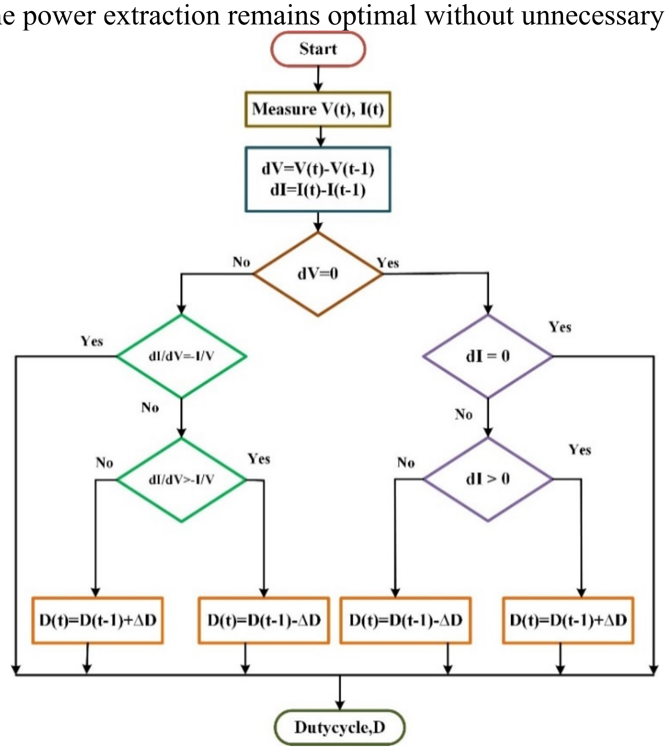

Fig.4 Flow diagram of INC

Step 6: Adjust Duty Cycle Based on Current Change If dI>0dI > 0, it indicates that the power is increasing, meaning the system should increase the duty cycle by a small step Conversely, if dI<0, the power is decreasing, so the duty cycle is decreased This ensures that the system dynamically adjusts its operation to maintain maximum power extraction.

Step 7: If dV≠0, the algorithm computes the INC dI/dV and compares it with the instantaneous conductance −I/V. These values help in determining whether the sys-tem is operating at, to the left or to the right of the MPP.

Step 8: The algorithm first checks if dI/dV=−I/V. If this condition holds, it means the system is at the MPP, and no change is required in the duty cycle. This prevents unnecessary adjustments and maintains stable operation at the MPP.

Step 9: If dI/dV>−I/V, it indicates that the system is operating to the left of the MPP, meaning the voltage needs to increase. To achieve this, the duty cycle is decreased, allowing the system to move towards the MPP.

2.2. Battery

The primary goal of utilizing and combining a battery and a SC with the configuration of non-conventional resources is to collect the excess power generated from the other sources and utilize it if energy becomes restricted. The 48 Ah lithium-ion battery served as the foundation for the suggested design in this research.

Battery modeling can generally be categorized into 3 main categories, mathematical, electro-chemical and equivalent circuit models. Among these, the equivalent circuit model is considered the most practical and broadly used approach for real-world applications. This preference arises because mathematical models often lack applicability in dynamic scenarios, and electro-chemical models are typically too complex for routine system integration.

The equivalent circuit model effectively captures the key electrical characteristics of a battery by representing it as a combination of its open-circuit (OC) potential and internal resistance. A typical configuration includes the open-circuit voltage, which varies as a function of the battery's SOC, along with internal resistance and a parallel RC network to model battery polarization effects. The voltage equation is shown as follows for discharge mode.

$$V_{battery} = E_o - K\left(\frac{Q}{Q - it}\right)i^* - K\left(\frac{Q}{Q - it}\right)it + Ae^{-Bit}(i^* > 0) \quad (6)$$

The battery voltage equation is shown as follows for charging mode:

$$V_{battery} = E_o - K\left(\frac{Q}{it + 0.1Q}\right)i^* - K\left(\frac{Q}{Q - it}\right)it + Ae^{-Bit}(i^* < 0) \quad (7)$$

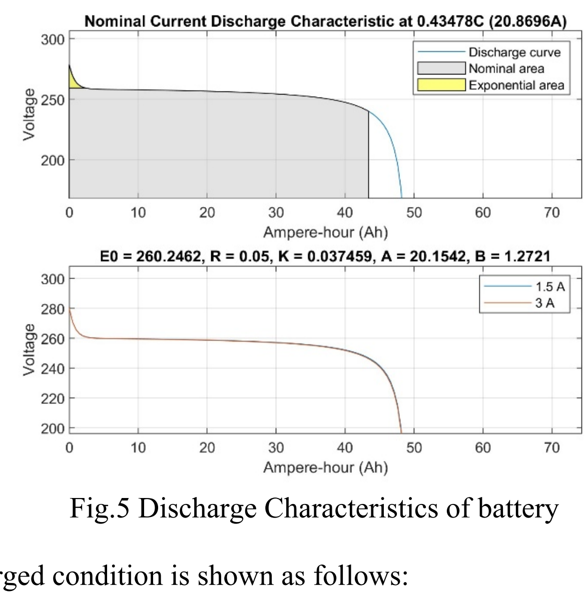

Fig.5 Discharge Characteristics of battery

The voltage in the fully charged condition is shown as follows:

$$V_f = E_o - Ri + A \quad (8)$$

where A stands for exponential voltage, B for exponential capacity, i^* for low frequency current dynamics, Q for maximum battery capacitance, E_0 for constant voltage, and K for polarization constant. The discharge characteristics of the battery is represented in Fig.4.

2.3. Super Capacitor

The SC is integrated with the battery to reduce the current stress on the battery during periods of highly fluctuating load demand. This is due to the SC's high specific power, which enables it to respond quickly to rapid power requirements that the battery alone cannot efficiently handle. While the battery is better suited for delivering average power over longer durations, the SC complements it by covering sudden power shortages.

SC are perfect for frequent and quick energy cycling because of their high efficiency, which is close to 100% charge-discharge cycle efficiency. Compared to batteries, they can supply energy considerably more quickly and withstand a greater number of charge/recharge cycles. Due to these features, SCs are frequently employed in conjunction with other energy storage devices that have lower energy delivery rates or slower dynamic reactions.

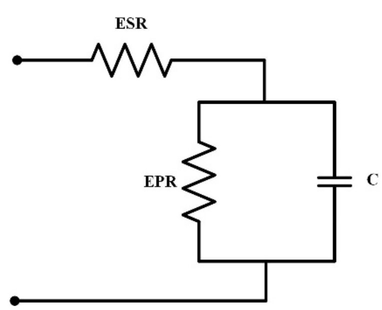

Fig.6: Equivalent circuit of SC

With C representing the SC's capacitance, EPR and ESR represents the equivalent parallel and series resistances respectively. Fig.6 depicts the electrical equivalent circuit for the SC.

$$E_{sc} = \frac{1}{2} C (V_i^2 - V_f^2) E_{sc} \tag{9}$$

where $(V_i^2 - V_f^2)$ is the voltage difference between the beginning and final voltages,

$$R_t = n_s \frac{ESR}{n_p} \tag{10}$$

$$ESR = \frac{\Delta V_d}{I_d} \tag{11}$$

$$C_t = n_p \frac{C}{n_s} \tag{12}$$

$$C = I_d \frac{(t_2 - t_1)}{(V_2 - V_1)} \tag{13}$$

where n_s and n_p is the number of capacitors linked in series and parallel, and I_d is the discharging current.

3. Control Methods

3.2. Power Management Control using Battery and SC

The control circuit of a PV module with an INC MPPT technology and a boost converter incorporated is shown in Fig. 7. The PV inputs which are continually measured and sent into the INC MPPT controller, this data is processed by the INC MPPT algorithm to identify the ideal duty cycle that matches the PV system's MPP. The PWM Generator then uses the calculated duty ratio to provide the proper gate signals that regulate the switch S_b in the boost converter.

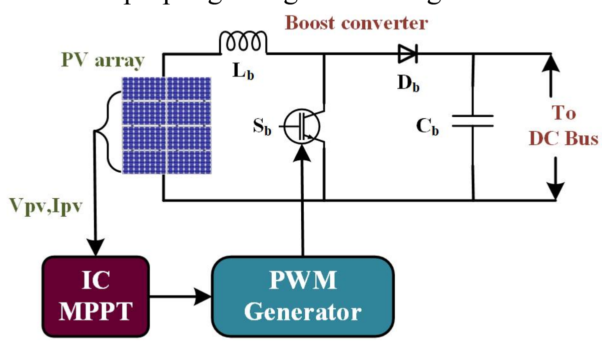

Fig.7 PV control with IC MPPT

The boost regulator enhances the PV array's output voltage to a greater level while maintaining compliance with the system's DC bus voltage needs. It is made up of the inductor L_b, switch S_b, diode D_b, and output capacitor C_b. While C_b smoothes the output voltage, S_b controls energy transfer through Lb, storing energy while on and releasing it through D_b when off when switched on and off at high frequency by the PWM signals. The DC bus then receives this controlled and optimized power, ensuring optimal solar energy use while preserving a steady voltage for the load.

3.2. Power Management Control using Battery and SC

A PMC method employing PI controllers to coordinate the operation of a battery and a SC in a hybrid scheme is shown in Fig. 8. Controlling the V_{dcbus} to equal the V_{ref} is the main goal of this control system. After comparing V_{ref} and V_{dcbus}, the first step of the control loop sends the error to a PI controller, which creates a reference current I_{ref}. A current limiter processes this reference current and divides I_{ref} among the battery and the SC according to their respective capacities and current requirements.

The distributed current is compared with the real current of the SC and battery independently. Dedicated PI controllers for the battery and SC process the difference between the reference and real currents. PWM signals are produced from the outputs of these controllers to regulate the power electronic converters connected to each storage device. By controlling the battery's and SC converters' charging and discharging behavior, these switching signals preserve the DC bus voltage within predetermined bounds and guarantee effective power sharing, stability, and storage system lifespan.

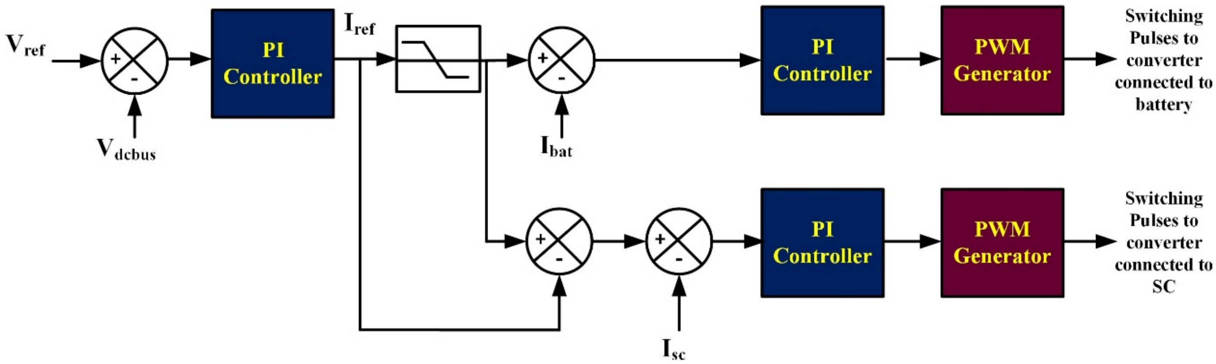

Fig.8 Power Management control for SC & Battery

4. Result & Discussions

The DC microgrid simulation is implemented using MATLAB. The results PV parameters operated at different irradiance is represented in Fig.9. The PV is operated with the irradiance of 1000,800,500,300 and 100 W/m^2.

Table I Power extraction from PV using INC MPPT

Irradiance (W/m^2)	Theoretical Power (W)	PV Power Obtained (W)	Efficiency (%)
1000	2001.6	1996	99.7
800	1600	1599	99.9
500	995.2	995	99.9
300	589.2	588.8	99.9
100	187.8	187.7	99.9

Table I presents the working of a PV module using the INC MPPT technique at different levels of PV irradiance. The table compares the theoretical power output of the PV with the actual power attained when the INC MPPT algorithm is applied. At an irradiance of 1000 W/m², the theoretical power is 2001.6 W, and the actual extracted power is 1996 W, resulting in an efficiency of 99.7%. As the irradiance decreases, both the theoretical and obtained power values reduce proportionally, yet the efficiency remains consistently high (99.9%) for irradiance levels of 800 W/m², 500 W/m², 300 W/m², and 100 W/m².

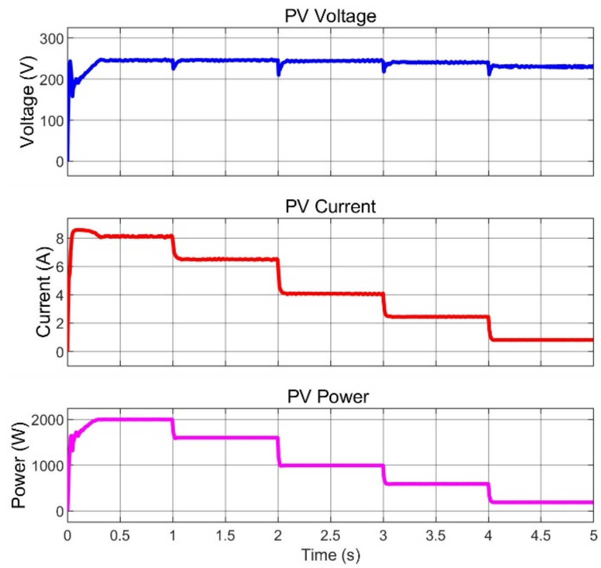

Fig.9 PV parameters with INC MPPT control

The battery parameters are represented in Fig.9. When the irradiance of PV is high, the battery is in charging state from 0 to 2s, the charging slowly decreases to discharging state as the irradiance of the PV drops, hence from 2s the battery discharges to the load linked to DC bus. The variation in SOC of the battery is given in Fig.10

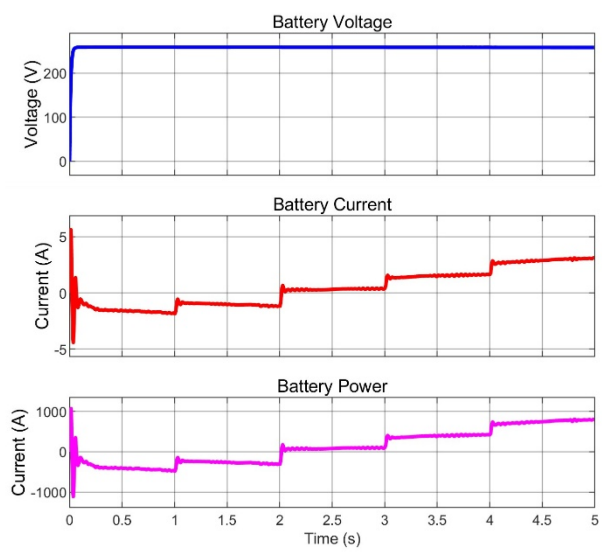

Fig.10 Battery Parameters with PMC

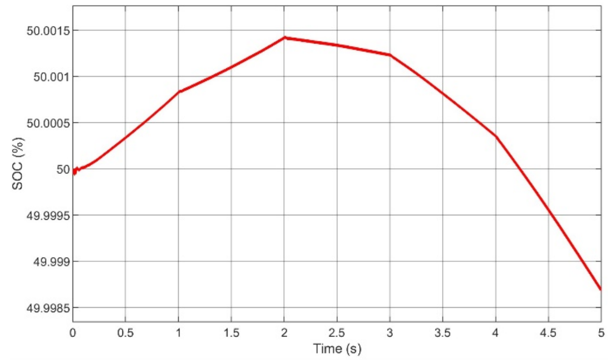

Fig.11 SOC of the battery

The SC parameters are shown in Fig.12. As like battery, the SC is in charging state, after 2s the SC supports battery when supplying the DC bus through PMC employed in this work. Whenever there is sudden change in the irradiance the battery must supply the load, during that condition the transient change occurs, Due to proper PMC SC will provide optimal power to the load to balance the battery.

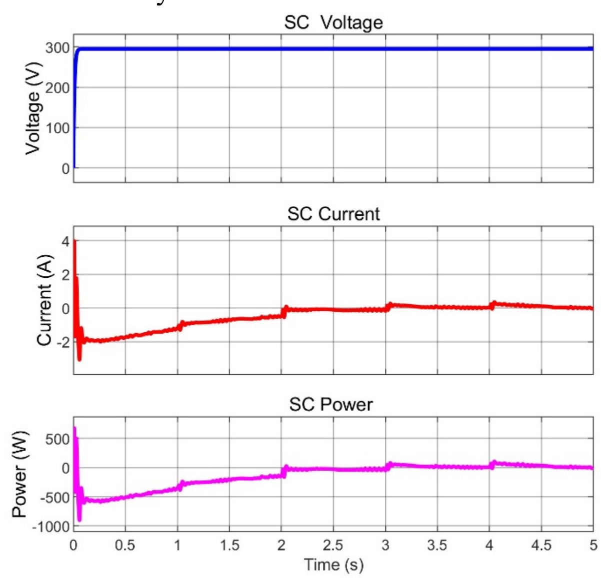

Fig.12 SC Parameters with PMC

The DC bus parameters are considered as load parameters, As the DC load is linked with the DC bus. The voltage of the DC bus is maintained constant at 400V. The DC bus power is retained at 1 kW irrespective of change in irradiance, this is due to optimal PMC employed between battery and SC. Fig.13 Shows the DC bus parameters.

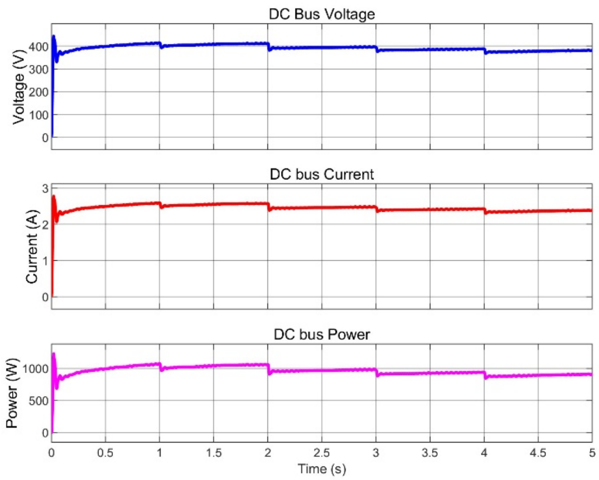

Fig.13 DC bus parameters

The battery serves as the primary energy buffer, while the SC handles transients to reduce battery stress. Simulation results demonstrated stable DC bus voltage (400V) and load power (1 kW), even during irradiance fluctuations. The coordinated control enhances energy flow, improves system reliability, reduces losses, and extends battery life, making it suitable for off-grid applications.

4. Conclusion

The intelligent power management strategy proposed in this work effectively coordinates the operation of a PV system, battery, and SC in a DC microgrid. The integration of the INC MPPT algorithm enables accurate tracking of the MPP, even under varying irradiance conditions, leading to high PV utilization efficiency (up to 99.9%). The use of a PI-based PMC allows dynamic allocation of power concerning the battery and the SC based on system requirements. The battery manages energy mismatch over longer durations, whereas the supercapacitor effectively supports rapid power transients, thereby minimizing stress on the battery. Simulation results reveal that during high irradiance conditions, the battery remains charging, and upon irradiance drop, it discharges to meet the load demand. The supercapacitor quickly responds during transient load fluctuations, stabilizing the DC bus voltage and ensuring uninterrupted power delivery. The SOC behavior of the battery and SC shows coordinated energy exchange, improving system efficiency and reducing wear on the battery components. The DC bus maintains a stable 400V output and 1 kW load power irrespective of environmental changes. The proposed control strategy improves the reliability, longevity, and performance of the DC microgrid system, ensuring efficient energy management for remote and off-grid applications

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