2022 IEEE International Conference on Power Electronics, Smart Grid, and Renewable Energy (PESGRE)

Adaptive power management in PV/Battery integrated hybrid microgrid system

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***Abstract* — The fundamental goal of power management in a hybrid microgrid is to maintain the active power balance between renewable sources, storage batteries, loads, and the distribution grid. This paper proposes an adaptive power flow management technique for a standalone hybrid renewable energy system (HRES) that includes a photovoltaic cell, battery energy storage (BES), and load management. A multi-stage fractional order proportional integral derivative (multi-stage FOPID) controller is proposed in the voltage controlled loop of bidirectional dc-dc converter which is optimized by modified sine cosine algorithm (m-SCA). This controller aims to stabilize the dc bus voltage and power flow in islanded mode.**

***Keywords*— Hybrid microgrid system (HMG), Battery energy system, Power management system, multi-stage fractional order proportional integral derivative (multi-stage FOPID), modified sine cosine algorithm (m-SCA).**

I. INTRODUCTION

The microgrid is a complicated power distribution network that generates electricity using local resources. The uncertainty and intermittency of renewable energy sources such as wind and solar, which are highly dependent on diurnal and seasonal variations, are important concerns that must be addressed before the resources' full potential can be realized. Energy storage systems are utilized in microgrids to overcome power shortages or surplus generation. Furthermore, advanced control techniques are necessary to manage power flow and maintain constant voltage at the consumer side, regardless of generation and/or load fluctuations. During power system contingencies, it is vital to maintain constant DC bus voltage and provide optimum power flow between generation, load, and energy storage devices to ensure stable and uninterrupted power system operation. In [1–3], there are a few works on uninterruptible power management and voltage stability in hybrid energy resource-based DC microgrids. [4] uses an energy storage system as a smoothing agent to eliminate power variations in a wind/PV hybrid system by managing the state of charge (SoC) of the battery to extend the ESS's service life. Smoothing targets and initial overshoot are not taken into account in this paper. [5] provides a comprehensive overview of various energy management approaches utilized in microgrids using renewable energy sources. Recent research has shown that current control and power control loops can be used to regulate power flow [6]. An energy management controller controls the charging and discharging of the battery in [8]. The trial-and-error method is used to determine the PI controller parameters used for DC-link control. Because of their robustness and ease of construction, PI controllers are the most often utilized. It takes more time while tuning the PI controller's parameters by trial and error method and Zeigler–Nichols method [9]. Because of the uncertainty in the optical selection of the parameters, power systems may have reduced dynamic response and instability. To increase the steady-state and transient response of the control system, the gains of the PI controller must be properly tuned. As a result, soft computational algorithms are currently being utilized to choose the efficient parameters while ensuring less overshoots, minimum settling time, and improved dynamic response under changing load conditions, and a smoother RES and battery power flow. Particle swarm optimization (PSO), improved PSO, and the grasshopper optimization method (GOA) have all been used in recent research on microgrid power flow control employing soft computational tools [10 - 11]. However, the fundamental disadvantage is that the algorithms described above tend to become stuck in local minima and have ambiguity in parameter selection. Many soft computing techniques, such as the genetic algorithm (GA) [14], ant colony optimization (ACO) [15], firefly algorithm (FA) [16], and bees algorithm (BA) [17], are also shown in the literature for the optimal selection of controller parameters. To achieve optimal power regulation, all of the above soft computational methods were applied to optimise the gain settings of the PI controller. Researchers use controllers such as sliding mode controllers [18] and predictive controllers [19] which consist of complex advanced mathematical analysis. For many hybrid energy system difficulties, intelligent controllers such as fuzzy logic controllers provide better results with good steady-state response [20]. However, the main disadvantage of fuzzy is that the error signal changes in response to changes in the reference value, making membership function selection problematic [20]. In [25], hybrid energy storage devices that employ an ultra capacitor and a battery are proposed, with a fuzzy logic controller replacing the PI, resulting in reduced stress and improved battery life while regulating DC-link voltage. The neural fuzzy adaptive PID controller was proposed in [26] to determine the switching signal to ensure DC-link stability during steady-state and improve transients in the PV system.

This paper proposes adaptive power management for the hybrid microgrid system. The major goal of the power management scheme is to manage the generation and demand to maintain the dc-link voltage within the limits. A multi-stage FOPID controller is used in the voltage-controlled loop in the bi-directional converter, whose work is to improve dc bus voltage stability and provide optimal power flow between generation sources, load, and battery. The proposed controller is capable of good set-point tracking and disturbance rejection. The system's performance is evaluated for variations in renewable energy generation as well as load demand.

The paper is structured as follows: Section II consists of the general structure of the system. The power management scheme is described in Section III. Section IV represents the simulation results and discussion of the proposed work and the conclusion part of this work is described in Section V.

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II. SYSTEM CONFIGURATION

A. *PV/battery integrated microgrid system*

Fig. 1 depicts the hybrid microgrid's system configuration, which includes a PV system, a battery bank, and loads. A dc-dc boost converter with MPPT ties a 12 kW PV array to the dc bus. A dc-dc bi-directional converter connects a 24 Ah lithium-ion battery to the dc grid. The dc bus has a rated voltage of 240 V.

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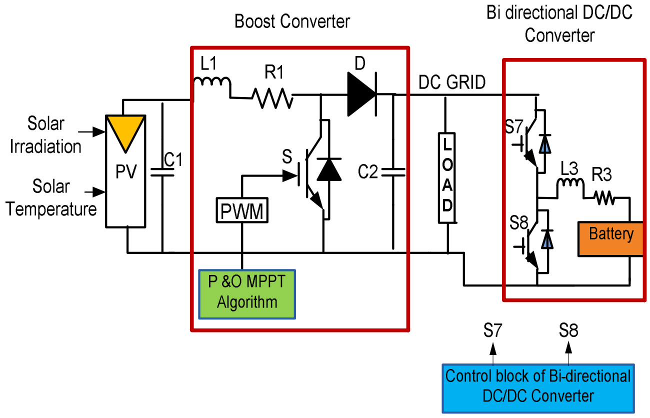


Fig. 1. Structure of PV/Battery integrated hybrid microgrid system

B. *Battery Management System*

Many distributed generators have a large time constant, and they are also intermittent and unstable. Many distributed generators (DGs) are intermittent and have a large time constant. As a result, in the microgrid, a battery storage system is required to accommodate changes in power output and load. The state of charge (SoC) and current direction of the battery govern how it charges and discharges. The SoC is the difference between the maximum battery capacity consumed and the total capacity available from the battery.

$$SoC = 100\left(1 + \frac{\int I_{bat}\,.dt}{q}\right) \tag{1}$$

$$SOC\min \leq SOC(t) \leq SOC\max \tag{2}$$

Where I_{bat} is the charging current of the battery. The minimum and maximum of the SoC's ampere-hour capacity are set at 20% and 80%, respectively.

C. *Bi-Directional dc-dc Converter*

This converter connects the battery bank to the dc bus. The circuit design of this converter is shown in Fig. 2, and the control method for a bidirectional dc-dc converter is shown in Fig. 3. There are two controlled loops in this control method. The outer loop is a voltage-controlled loop that regulates the dc bus voltage and battery voltage. The current controlled loop is the inner loop, which regulates power to and from the battery to control battery and PV power changes. Previously, in this current-controlled approach, a typical PID controller was employed, which did not successfully stabilize the dc bus voltage. This paper proposes a multi-stage FOPID controller to properly regulate the dc bus voltage.

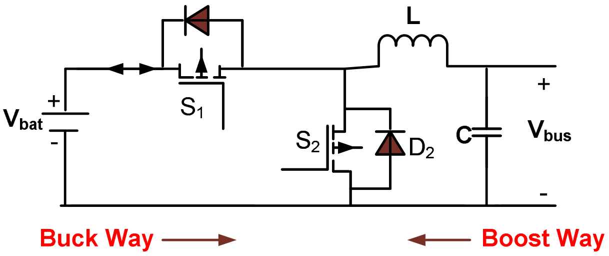


Fig. 2. Circuit diagram of DC-DC bidirectional converter

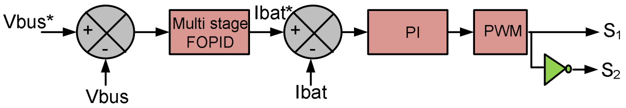


Fig. 3. Control scheme of DC-DC bidirectional converter

D. *Proposed Controller Structure*

Earlier, control engineers have mostly preferred proportional integral derivative controllers because of their simplicity and dependability. However, they are increasingly turning to FOPID controller because of its versatility in tuning, as it has five parameters to consider throughout the tuning process. A PID controller can be used in any mode, such as proportional, integral, or derivative, although it can be challenging to use a PID controller to get the best results at times. The goal of an integral controller is to reduce steady-state error. However, it has the disadvantage of causing undesirable spikes in the transient part of the response, which is a cause for concern. The solution is to make the integral part active after the system has passed through its transient state. To diminish the settling time and disturbance, the transient part can be handled by a proportional derivative (PD) controller. The integral controller can then be used to reduce the steady-state error. The fractional-order PD controller cascaded to fractional-order PI controllers, named as multi-stage FOPID controller is employed to produce this efficient control scheme.

Fig. 4 depicts the design of a multi-stage FOPID controller.The proportional, integral, and derivative gains are denoted by Kp, Ki, and Kd, respectively; λ and ϒ are the integral and derivative gain, N is the filter co-efficient. *E(s)* and *U(s)* are the error input and output of the controller.

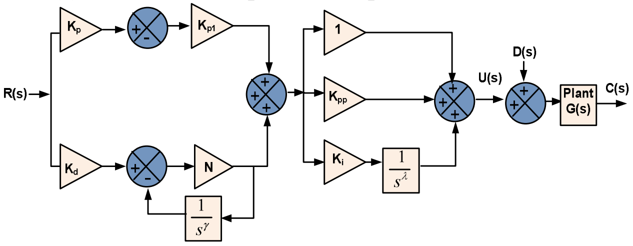


Fig. 4. Controller structure of multi-stage FOPID

E. *Proposed m-SCA Algorithm*

Metaheuristic optimization techniques have been popular in recent years due to their specific benefits over conventional algorithms. Multiple-objective and nonlinear formulations can be solved using metaheuristic optimization. Modified sine cosine algorithm is a novel meta-heuristic algorithm. It has a faster convergence time to global (or nearly global) optimal. Fig. 5 represents the flow chart of the m-SCA algorithm.

The formula of the fitness function is described as per the following equations:

$$\begin{array}{l} r_1X_i^k + c_1\times\sin(r_2)\times\left(P_{best-i}^{\ k} - X_i^k\right) + c_2\times\sin(r_2)\times\left(E_{best}^{\ k} - X_i^k\right), r_3 \prec 0.5 \\ r_1X_i^k + c_1\times\cos(r_2)\times\left(P_{best-i}^{\ k} - X_i^k\right) + c_2\times\cos(r_2)\times\left(E_{best}^{\ k} - X_i^k\right), r_3 \succ 0.5 \end{array} \quad (3)$$

Where X_i is location of the present optimal solution, k is the number of present iterations, P_i is the optimal solution, r_1 is the convergence factor, r_3 is a random number, $c1$ *and* $c2$ are constants that can be changed to fit specific problems, E stands for empirical parameters that are utilized to improve the search path and reduce the error rate.

The following is the definition of the modified convergence factor:

$$r_1 = r_{\max} - (r_{\max} - r_{\min})\frac{t}{T} \quad (4)$$

Where r_{max} and r_{min} are constants that can be adjusted to fit a particular problem, t is the present iteration and T is the maximum iteration.

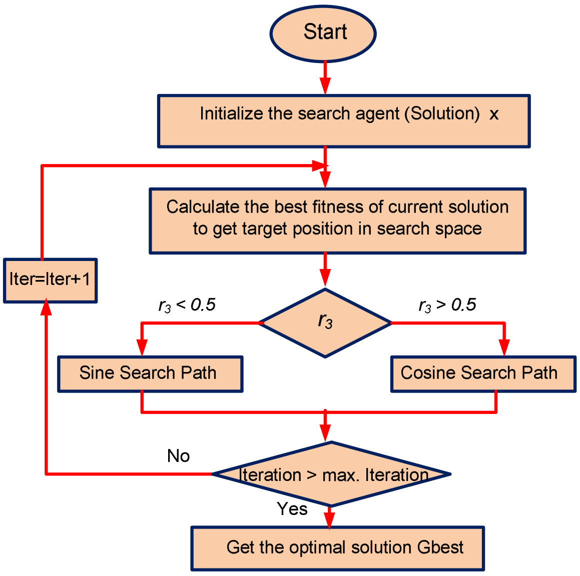


Fig. 5. Flow chart of m-SCA algorithm

III. POWER MANAGEMENT SYSTEM

The goal of power flow management is to maintain the power balance of the system by smoothing out power demands.

$$P_{pv} \pm P_{bat} = P_{load} \quad (5)$$

Where P_{pv}, $P_{bat,}$ *and* P_{load} are the PV, battery, and load powers respectively.

The charging and discharging function of the battery storage system is controlled by a bidirectional dc-dc converter. Fig. 6 depicts the block diagram of the proposed power management scheme for the battery power management system. The difference between the measured and reference dc voltage is fed into the outer PI controller, which then outputs the reference current for the inner current loop. The difference between battery current and battery reference current generates the dc current. The outer voltage control loop generates a negative current reference. if the dc bus voltage is greater than the reference voltage, and vice versa. As a result, the dc grid voltage drops to the reference voltage, and the battery absorbs extra energy during input and output power changes, drawing a stable dc current. The proposed m-SCA method is utilized to modify the gain of the multi-stage FOPID controller used for the inner current loop to reduce overshoot and settling time, which would otherwise cause system instability. Fig. 7 represents the flow chart of the power management scheme.

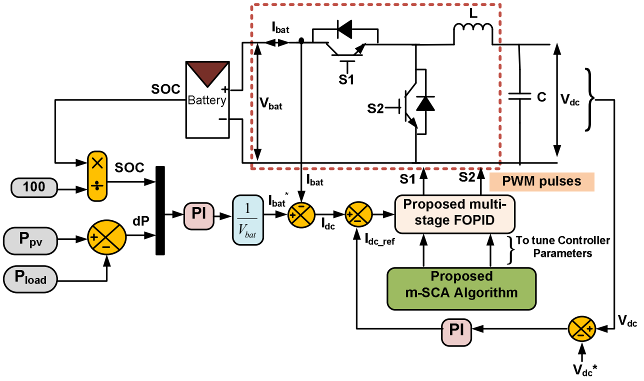


Fig. 6. Control scheme of battery power management

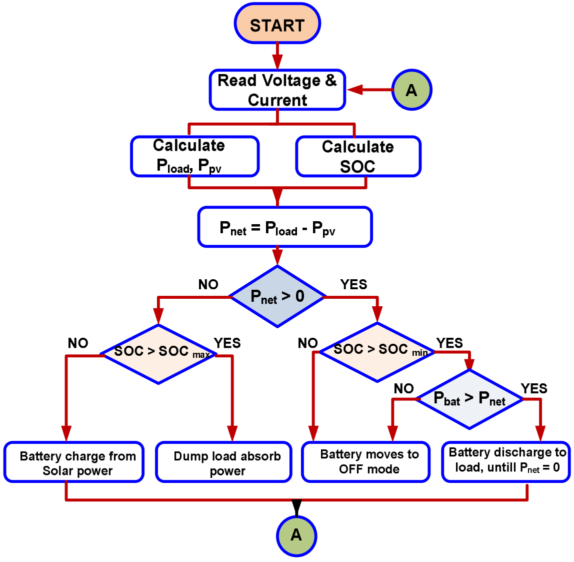


Fig. 7. Flow chart of power management scheme

IV. SIMULATION RESULTS AND DISCUSSION

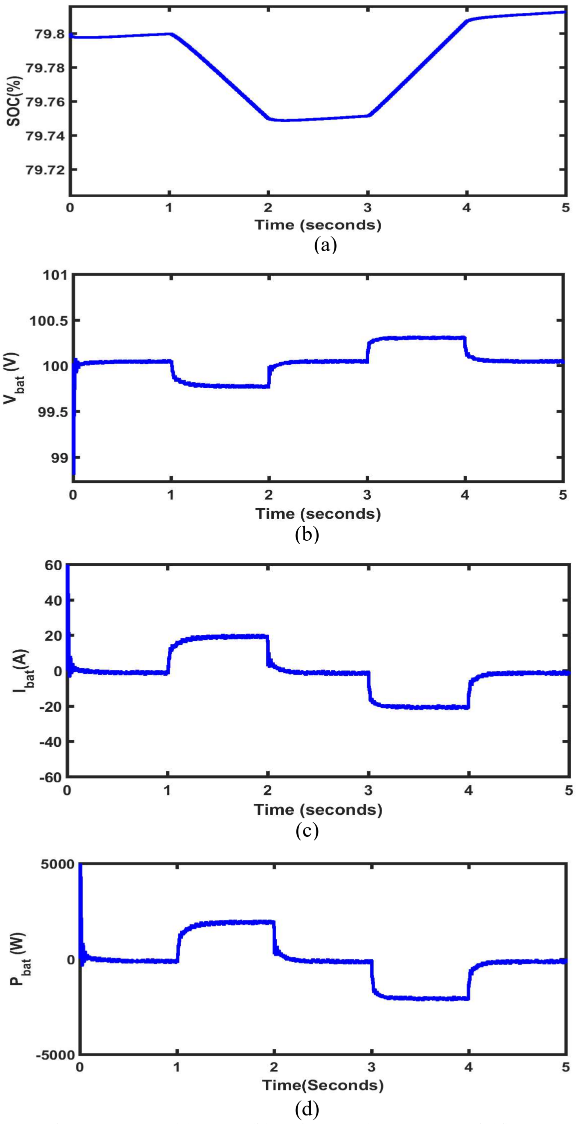
Case 1: System performance under variable load power demand and constant generation

The PV system is kept at constant insolation to provide constant power, and demand is varied at various times to test the effectiveness of the proposed system. Fig. 8(a–d) depicts the state of charge, battery voltage, current, and power for case 1 respectively. The battery's performance is analyzed depending on demand and generated power variations. When the load demand rises to 13 kW for 1–2 seconds, the generated power remains constant at 11 kW. As the generation is insufficient for load, the duty cycle of the battery's bidirectional converter is set to discharge to meet only the demand while the solar panels continue to produce constant voltages. As shown in Fig. 8(a), the SoC decreases as the battery provides power to the load. The bidirectional converter, on the other hand, charges the battery and raises SoC when demand drops to 9 kW between 3 and 4 s. Fig. 9(a) depicts the power management between generated PV, battery power, and load demand for case 1. It shows that, from 1 – 2 s, the load power is increased from 13 kW while keeping solar at 11 kW and the battery discharges the extra 2 kW required by the system. When the load demand drops to 9 kW from 11 kW between 3 and 4 seconds, the remaining 2 kW power is stored in the battery. At other times, the generation is sufficient to fulfill demand, therefore the battery remains constant. Fig. 9(b) represents the dc bus voltage in case1. TABLE I represents the system performance under variable load demand.

TABLE I

SYSTEM PERFORMANCE ON VARIABLE LOAD DEMAND

Power (kW)			
Time(Seconds)	**Demand**	**solar**	**battery**
0 - 1	11	11	0
1 - 2	13	11	2 (dis-charging)
2 - 3	11	11	0
3 - 4	9	11	2 (charging)
4 - 5	11	11	0



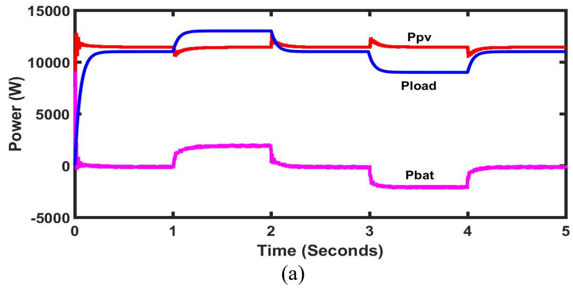
(a)

(b)

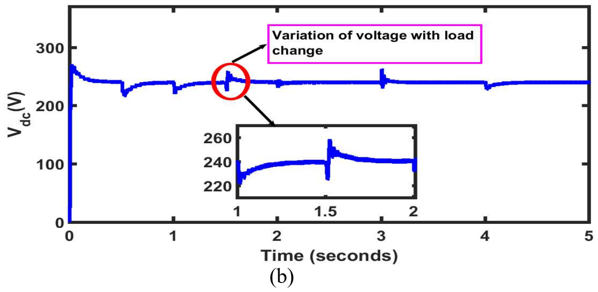
(c)

(d)

Fig. 8. Battery (a) SoC, (b) voltage, (c) current, and (d) power



(a)



(b)

Fig. 9. (a) Power flow management between PV, battery and load (b) DC grid voltage

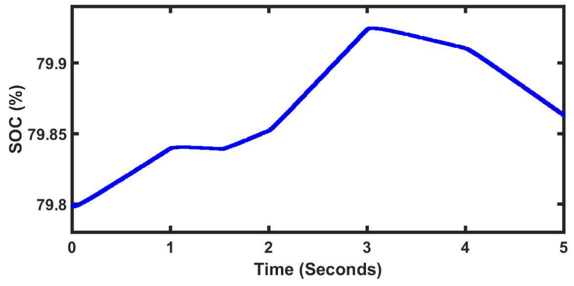
Case-2: System performance under variable solar irradiations and constant load power

For a constant load, the proposed approach is evaluated with a varying input. TABLE II provides the simulation parameter specifications as well as variable solar irradiations. The solar irradiation is changed at different time intervals to replicate the changeable input. The load is kept at 9 kW. Fig. 10 (a-d) represents the SoC of the battery, output current, voltage, and power delivered by the battery in response to variations in input. Fig. 10(a) depicts the percentage SoC of the battery. The solar irradiation variation is shown in Fig. 11(a). The power management between generated PV, battery power, and load demand for case 2 is shown in Fig. 11(b). Between 3 to 4 s and 4 to 5 s, when generated power is insufficient to satisfy demand, the battery discharges power in response to the change in PV power output, providing continuous power of 9 kW at load. When PV power generation increases between 0 to 1s and 2 to 3 s, the hybrid system produces more power than the load demand. The battery is charged by the excessive power of 2 and 0.5 kW, respectively. The DC voltage is kept constant at 240 V as shown in Fig. 11(c).

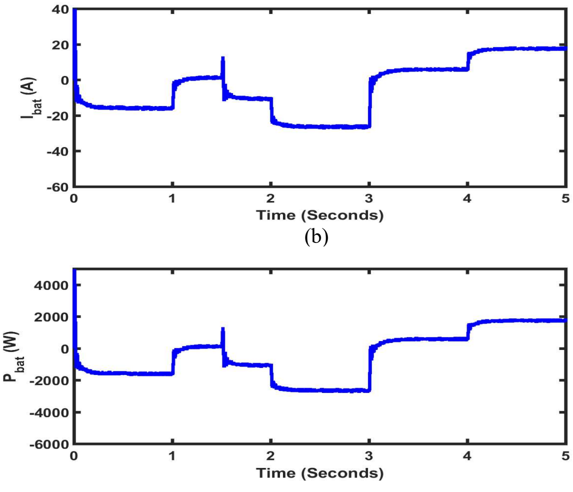
TABLE II

SYSTEM PERFORMANCE ON VARIABLE SOLAR IRRADIATION

Power (kW)				
Time(Seconds)	**Demand**	**solar**	**battery**	**Solar irradiation (W/m^2)**
0 - 1	9	11	2 (charging)	1000
1 – 1.5	9	9	0	800
1.5 - 2	9	10.5	0.5 (charging)	950
2 - 3	9	12	3 (charging)	1100
3 - 4	9	8.5	0.5 (discharging)	800
4 - 5	9	7	2 (discharging)	700



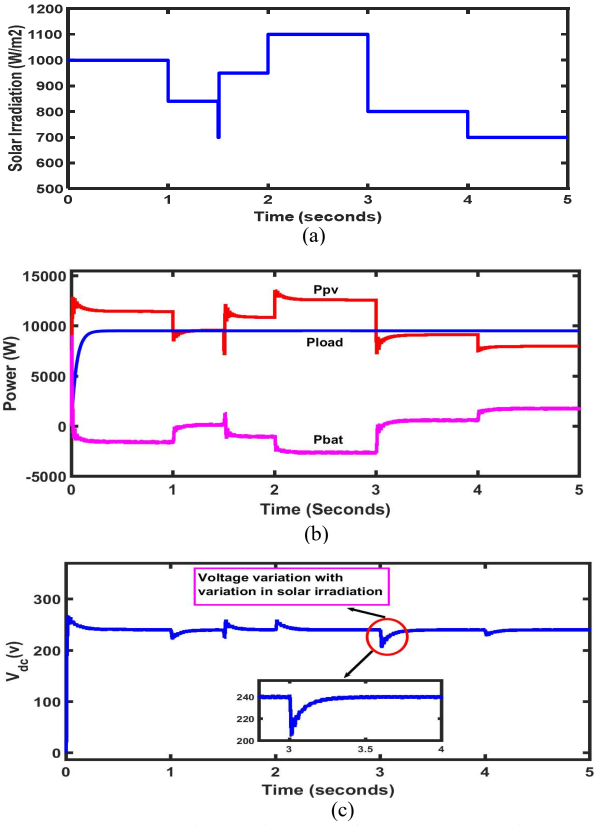
(a)



(b)

(c)

Fig. 10. Battery (a) SoC, (b) voltage, (c) current, and (d) power



(a)

(b)

(c)

Fig. 11. (a) Solar irradiation (b) Power flow management between PV, battery and load (c) DC grid voltage

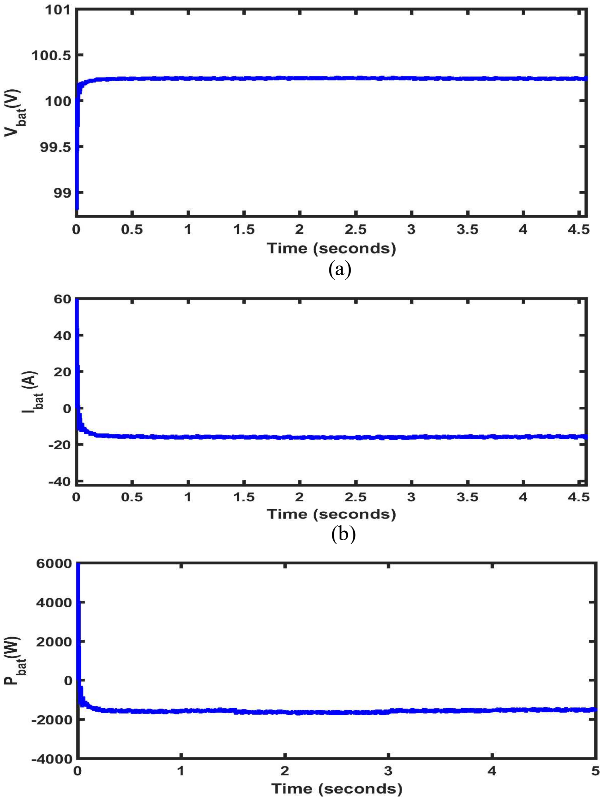
Case-3: System performance under variable solar temperature and constant load power

TABLE III consists of the simulation parameter specifications as well as variable solar temperature. The load is kept at 9 kW. To imitate the variable input, the sun temperature is varied at different time intervals. Fig. 12(a) depicts the percentage SoC of the battery. The output voltage, current, and power produced by the battery in response are represented in Fig. 12(b - d). The solar temperature variation with respect to time is in Fig. 13(a). The power management between generated PV, battery power, and load demand, and dc-link voltage for case 1are shown in Figure 13 (b) and (c) respectively. When PV power generation increases, the hybrid system produces more power than the demand. The battery is charged by excessive power.

TABLE III

SYSTEM PERFORMANCE ON VARIABLE SOLAR TEMPERATURE

Power (kW)				
Time(Seconds)	**Demand**	**Solar**	**battery**	**Solar Temperature (^{0}C)**
0 - 1	9	11	2 (charging)	25
1 – 1.5	9	10.9	1.9 (charging)	18
1.5 - 2	9	11.5	2.5 (charging)	42
2 - 3	9	11.2	2.3 (charging)	37
3 - 4	9	10.9	1.9(charging)	18
4 - 5	9	10.8	1.8 (charging)	12

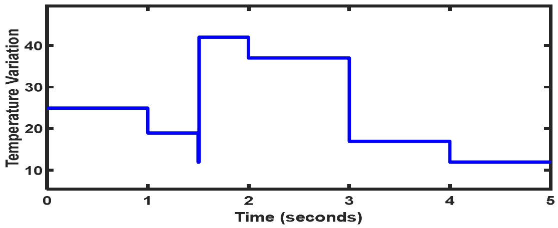


(a)

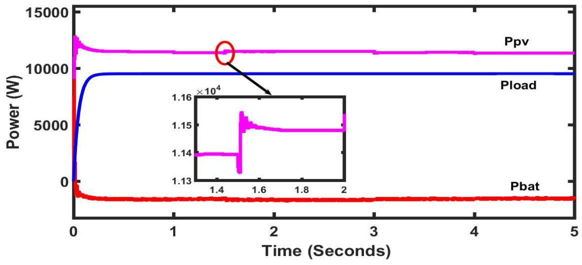
(b)

(c)

Fig. 12. Battery (a) SoC, (b) voltage, (c) current, and (d) power



(a)



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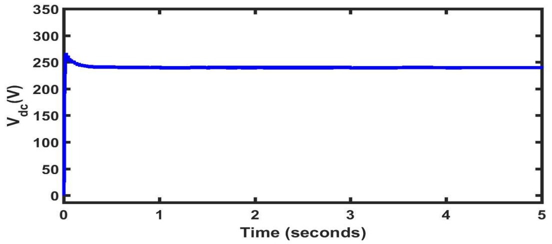

(c)

Fig. 13. (a) Solar temperature (b) Power flow management between PV, battery, and load (c) DC grid voltage

V. CONCLUSION

In this paper, an efficient power management technique for a hybrid renewable energy system is developed to improve dc-link voltage dynamics and power flow between load and generations. The proposed model is built using the MATLAB/SIMULINK software. A novel proposed modified sine cosine algorithm (m-SCA) based multi-stage fractional order proportional integral derivative (multi-stage FOPID) controller is used in the voltage controlled loop of the bi-directional dc-dc converter. From the simulation results, it is concluded that the proposed power management scheme with novel m-SCA optimized multi-stage FOPID stabilizes the dc bus voltage and power flow effectively.

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