Received: 10 August 2022 | Revised: 29 August 2022 | Accepted: 02 September 2022
DOI: 10.37917/ijeee.19.1.1 Vol. 19| Issue 1| June 2023

Open Access

Iraqi Journal for Electrical and Electronic Engineering
Original Article

Control Strategy for a PV-BESS-SC Hybrid System in Islanded Microgrid

Ali Almousawi*[1,2], Ammar A. Aldair[1]
[1] Electrical Engineering Department, College of Engineering, University of Basrah, Iraq
[2] Electrical Engineering Department, Faculty of Engineering, University of Kufa, Iraq

Correspondence
*Ali Q. Almousawi
Electrical Engineering Department
Faculty of Engineering, University of Kufa, Iraq
Email: ali.almousawi@uokufa.edu.iq

Abstract
In this paper, a control strategy for a combination PV-BESS-SC hybrid system in islanded microgrid with a DC load is designed and analyzed using a new topology. Although Battery Energy Storage System (BESS) is employed to keep the DC bus voltage stable; however, it has a high energy density and a low power density. On the other hand, the Supercapacitor (SC) has a low energy density but a high-power density. As a result, combining a BESS and an SC is more efficient for power density and high energy. Integrating the many sources is more complicated. In order to integrate the SC and BESS and deliver continuous power to the load, a control strategy is required. A novel method for controlling the bus voltage and energy management will be proposed in this paper. The main advantage of the proposed system is that throughout the operation, the State of Charging (SOC), BESS current, and SC voltage and current are all kept within predetermined ranges. Additionally, SC balances fast-changing power surges, while BESS balances slow-changing power surges. Therefore, it enhances the life span and minimizes the current strains on BESS. To track the Maximum Power Point (MPP) or restrict power from the PV panel to the load, a unidirectional boost converter is utilized. Two buck converters coupled in parallel with a boost converter are proposed to charge the hybrid BESS-SC. Another two boost converters are used to manage the discharge operation of the BESS-SC storage in order to reduce losses. The simulation results show that the proposed control technique for rapid changes in load demand and PV generation is effective. In addition, the proposed technique control strategy is compared with a traditional control strategy.
KEYWORDS: Islanded Microgrid, Hybrid System, PV array, Autonomous Control.

I. INTRODUCTION

Interconnections of Photovoltaic (PV) panels with supplemental energy sources which including Fuel Cell (FC), wind turbine, or microturbine should solve the intermittency issue in the islanded Microgrid (MG) [1].
In addition, several techniques use storage rather than energy sources, such as Supercapacitors (SC) or Battery Energy Storage Systems (BESS). As a result, a PV-BESS or PV-BESS-SC hybrid system are created in order to manage the load and PV power generation by supplying/storing the required/surplus loads power [2].
The BESS has a high energy density and a low power density while the SC has a low energy density but a high-power density. Therefore, a Hybrid Energy Storage System (HESS) combining SC and BESS becomes a common alternative for providing high power density as well as large energy capacity [3]. This application has been widely used in tramways [4], electric vehicles [5], wind/PV power production systems [6], Fuel Cell ships [7], and DC MGs [8].
Several researchers have presented strategies for implementing a HESS.
In [9], the proposed technique is based on the analysis of the frequency of electric energy demand into low and high frequency components. Low-frequency components are associated with elements that have a high energy density but a low power density (BESS), while high-frequency components are associated with HESS elements that have a low energy density but a high-power density (SC). The direct connection of the BESS in this study unavoidably exposes it to a rapidly rising charging/discharging current, reducing its life span.
In [10], the authors suggested an adaptive frequency technique as a new HESS power management approach for electric vehicles. A simpler digital adaptive filter was utilized in this technique to ensure solution convergence and to reduce the computational expense involved with real-time control. Using a half-bridge DC/DC converter, this power management method was successfully tested. In this study, improved the efficiency only when the load is low.

The state of power and the SOC for the HESS were calculated using the Kalman filtering technique in [11], and then used in the Fuzzy Logic Control (FLC) to compute the maximum power output to be generated by the BESS. When the State of Charging (SOC) of BESS is low in this approach, FLC is implemented and the SC charges the BESS to avoid low SOC situations and so expand the life span. When the SOC of BESS is high and the SOC of SC is low, the BESS charges the SC. In this work, when the BESS SOC reach to maximum value not discussed.

Optimization algorithm-based techniques seek to minimize an objective function. In general, minimizing this objective function has the goal of saving operational costs within a specific time period or extending the life span of the HESS component. Global optimization techniques are further classified as Dynamic Programming, Genetic Algorithms (GA), or Particle Swarm Optimization (PSO) [12]. When compared to traditional control systems, optimization algorithms-based approaches are more robust and efficient [13].

Power management using an Artificial Neural Network (ANN) was developed for an islanded PV/wind power system with a HESS consisting of an electrolyzer and a BESS. The implemented power management attempts to maintain the electrolyzer output in order to keep the SOC of BESS fixed. Simulated results proved that the proposed system had a faster response capability [14]. However, the BESS is used only with transient power and when the SOC of BESS reach to maximum value not discussed.

In [15] developed an ANN-based power management technique for electric vehicles. The system includes a HESS, with the BESS linked directly to the DC bus and the SC connected through a chopper circuit. The applied ANN aims to manage the SC current reference to support and increase the life span of the BESS. But, a rapidly rising charging/discharging BESS current reducing its life span when compared with the BESS is connected via DC-DC converter.

From the above literature review, some drawbacks with HESS are noticed in some papers such as: -

1) The BESS or SCs are connected directly across the loads.
2) The limitations of charge/ discharge of BESS-SC current are neglected.
3) The hybrid system is managed to operate in Maximum Power Point Tracking (MPPT) in all modes (not discussed if the PV power produced exceeds the power demand and when the charging of BESS reaches to its maximum value).
4) Unnecessary power losses through BESS-SC charging.
5) Single-loop control is used and a state machine or a programmed algorithm is proposed.

A power management control technique for PV-BESS-SC hybrid system under variable generation and load conditions is proposed in this paper. The main advantages of the proposed structure and control approach are listed below:

1) The control strategies can be implemented without the required programmed algorithms which required more switching or discrete states which required supervisory controller.
2) The limitation constraints of the BESS and SC charging current are included.
3) A dual-loop control technique is utilized to achieve the working of charging/ discharge HESS converters and PV converters.
4) The efficiency of the hybrid stand-alone system is increased by charging the HESS through one dc to dc converter instead of using two dc to dc converters.
5) PV panels can be operated at MPPT by using the Perturb and Observe (P&O) algorithm or curtail PV power without using another control loop. Also, the complexity of the controller scheme is avoided.
6) Reducing the cost when reducing the values of capacitors and inductors.

A description of the general topology of the HESS with advantages and drawbacks is explained in Section II. In Section III, the proposed system structure is discussed. The proposed control and energy management strategy is designed and illustrated in Section IV. This is followed in Section V by discussing of modeling and control design for PV, BESS, and SC. Section VI displays the simulation results under different variations in power demand and PV generation. Finally, conclusions are presented in Section VII.

II. Hybrid Energy Storage Systems (HESS)

When the comparison between the SC and the other energy storage systems, the SC offers many advantages such as high power density, extended lifetime and long shelf life (4-5 year), environmentally safe and no gas emissions, stop accepting energy when it becomes fully charging, and does not below up in case of accidental direct short connection [16-17]. These advantages are investigated for hybrid PV–BESS-SC.

The two energy storage units of HESS are commonly linked to a central AC or DC bus. Connecting across a common DC bus is the preferred solution for RESs based islanded microgrids with an Energy Storage System (ESS) for a variety of purposes [18-19]. Firstly, the majority of popular RESs (PV, FC, etc.) and ESS elements work in DC voltage. Therefore, reducing the number of inverters is used, and has lower power losses (more efficiency) [20]. Second, the DC bus does not need synchronization, which considerably simplifies the overall system and controller complexity [21]. Generally, HESS can be divided into three types based on their connection topology to the DC bus: active, semi-active, and passive. Active HESS occurs when two storage devices are connected to a DC link via a bidirectional DC-DC converter. Semi-active occurs when one storage device is connected to a DC link via one converter for the BESS or the SC. Passive HESS refers to storage devices that are directly connected to the DC link. These types of topologies are shown in Fig. (1).

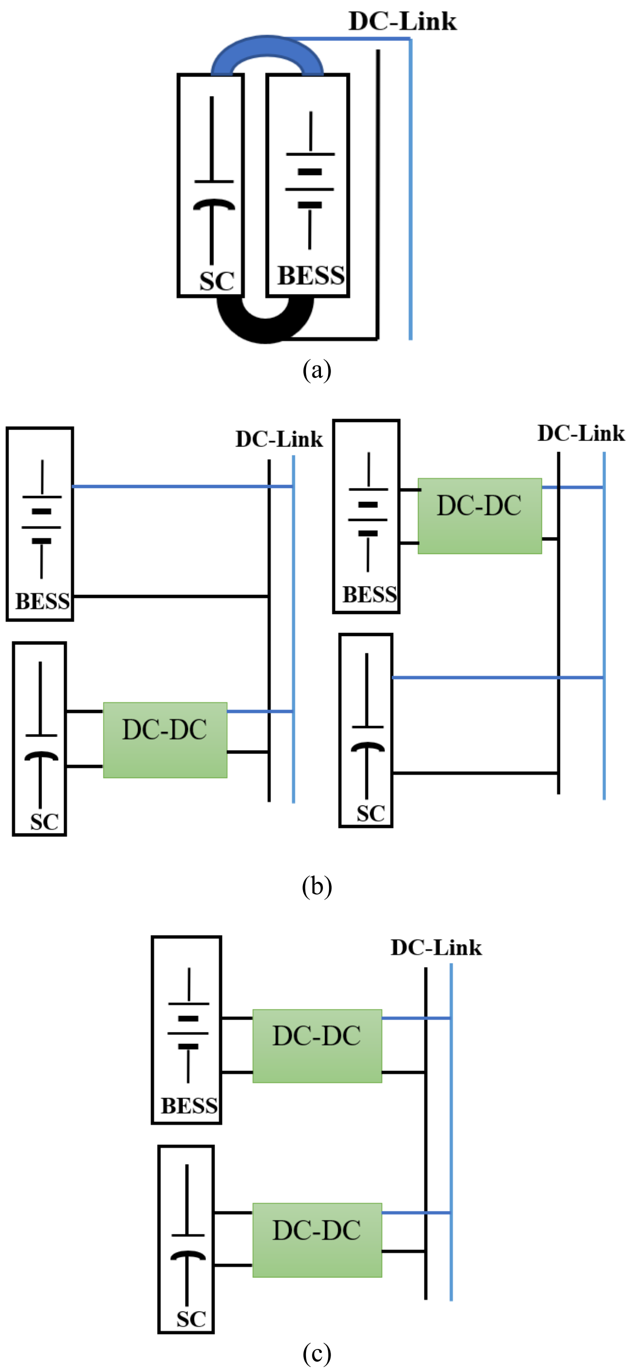


Fig. 1: HESS for (a) Passive structure (b) Semi-active structure (c) Active structure.

The passive link is the least expensive and simplest HESS structure. Also, reduce transient current under load variation, minimize internal losses, and maximize the peak power [22]. The output voltage of the SC and BESS must be the same. When dealing with an unregulated power flow, the BESS may have rapid fluctuations in charging/discharging currents in the event of sudden power requirements. It will result in BESS functioning degeneration and a significant loss in a lifetime. As a result, SC's power handling potential is underutilized because the voltage change of the battery terminal is low, and the SC will not operate at its full SOC range, resulting in poor volumetric efficiency [23].

To solve the disadvantages of HESS passive connection, DC-DC converters are interfaced between ESS and DC link to actively manage power flow from and to ESS [24]. Only one of the two ESS components is actively regulated in a semi-active HESS configuration. When only the BESS is directly linked to the DC link, the SC will work along with a greater voltage range, significantly enhancing volumetric efficiency. The battery's direct link also ensures stable Bus voltages [25]. The direct connection of the BESS, on the other hand, unavoidably exposes the BESS to a rapidly rising charging/discharging current, which reduces its life span [26].

When only the SC is connected to the DC-link [27], the BESS current can be kept in a relatively softer way despite power demand fluctuations, and the voltage output is not required to fit the DC link voltage, enabling for more efficient and flexible battery sizing and configuration [28]. The volumetric efficiency of the battery, on the other hand, is low since most systems do not let the SC run in its wide SOC range. SC's linear charge/discharge feature also creates significant variation in the DC link, which can lead to poor power quality and system stability. To keep the DC link voltage generally stable, the SC must be exceedingly large, which is not cost-effective.

Bidirectional DC-DC converters manage the power flow between BESS & SC in active HESS. A properly planned control technique improves DC bus stability and cycle life to further improve the HESS's flexibility and performance [26]. DC-DC converters, for example, can adjust the Bus voltage to preserve Bus voltage stability. Also, the SC can be programmed to respond to high-frequency surge power, but the BESS with a high energy density is designed to meet low-frequency power transfer. The separating of the BESS and the SC enables both elements to work at a wider range of SOC, considerably enhancing the volumetric efficiency of the HESS. The total efficiency of the HESS will decrease as the number of power converters increases because of power losses in the converters.

III. Proposed System Structure

Fig. (2) describes an islanded microgrid PV system consisting of a PV panel, BESS, and SC configurations. A unidirectional boost converter ties the PV panel to the DC link. By using the P&O algorithm as an MPPT algorithm [29]. The unidirectional boost converter is used to extract the maximum power from the PV array by regulating the PV panel terminal's input voltage. Instead of employing a single huge capacitor for the DC link, each converter terminal is coupled to a small filter capacitance as demonstrated (C_{o1}, C_{o2}, and C_{o3}).

The power efficiency is improved by employing the new topology depicted in Fig. (2) because of using one converter to charge BESS or SC and reducing the unnecessary power losses. This arrangement employs four separate DC-DC converters for the BESS-SC charging/discharging scenario. Due to a mismatch between load and generation, HESS is employed to ensure a constant output voltage level (V_{DC}). When the load exceeds a production, V_{DC} drops from its set point. As a result, HESS will discharge to meet the surplus load. Consequently, when generation exceeds load, V_{DC} rises over its reference value, and HESS charges to receive the excess power. The discharge/charge HESS current is controlled by the four converters using a double loop control scheme to avoid overlap appearing in [30].

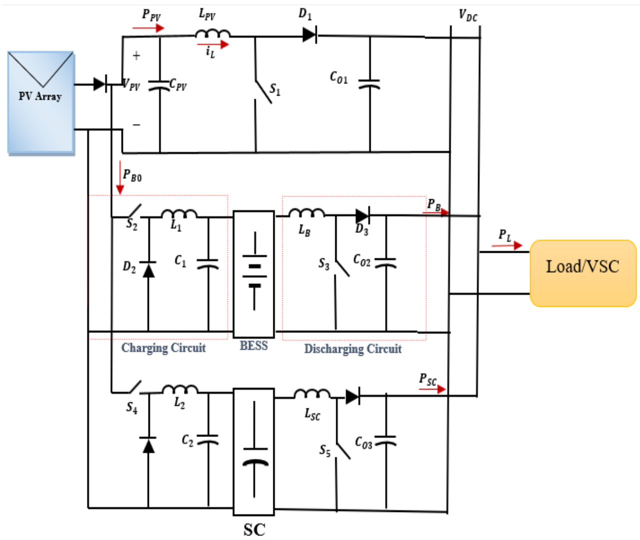
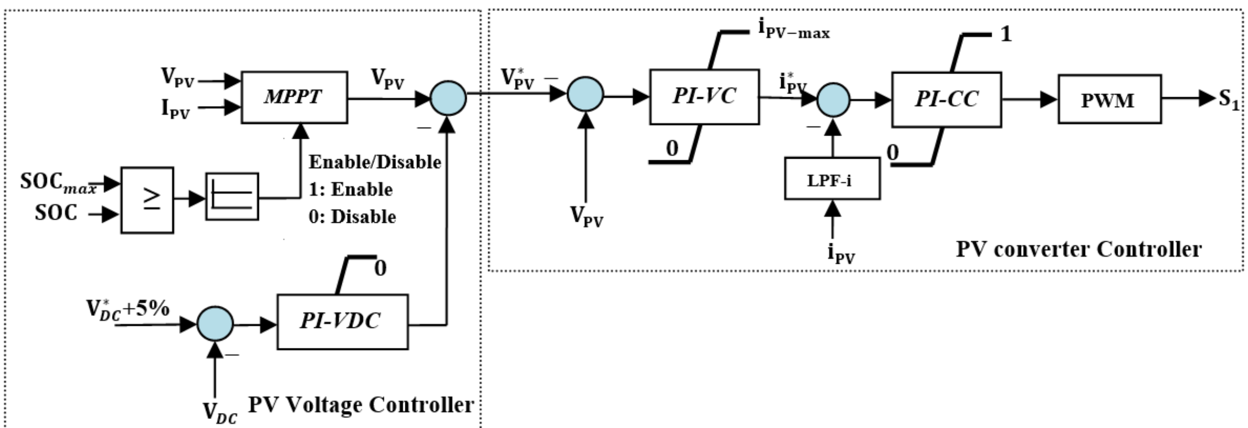


Fig. 2: PV-BESS-SC Hybrid System

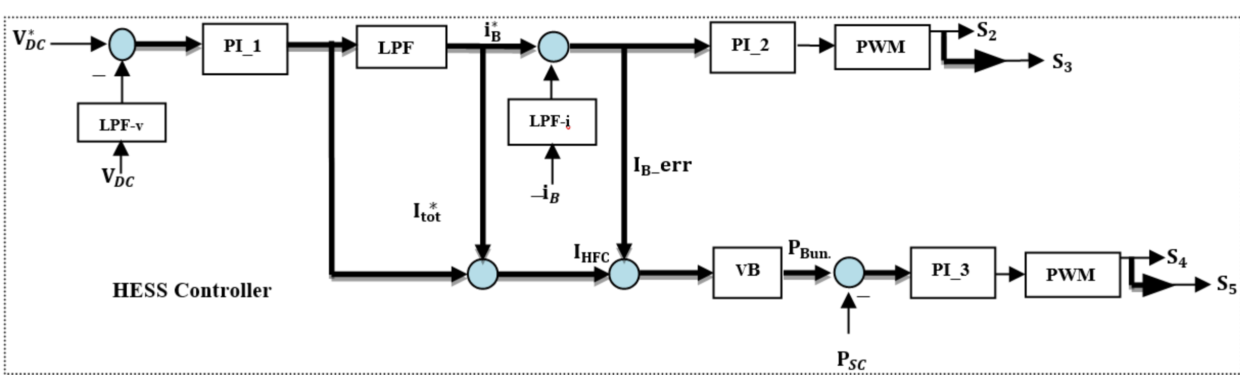
The HESS charge/discharge mechanism is regulated by the P_{PV} output and the specific P_{load}. The buck charging converters redirect the excess P_{PV} to charge the HESS, while the boost discharging converters supply the HESS's necessary power. V_{SC}, V_{BESS}, and V_{PV} in Fig. (2) represent the voltages of a SC, a BESS, and a PV panel, respectively. SC, BESS, and PV panel currents are represented by the variables I_{SC}, I_B, and I_{PV}. L_{PV} indicates the filter inductance of the PV panel's boost converter. L_{SC} and L_B are the filter inductances of the SC and BESS boost converters, respectively, while R is the load resistance. S_1, S_2, S_3, S_4, and S_5 are the control switches.

IV. Proposed Control and Energy Management Strategy

The block diagram of the control strategy used in this paper is shown in Fig. (3). Because of its higher noise protection, average current mode control is used for the BESS, SC, and PV panels, and it offers additional robust voltage regulation. A first-order Low Pass Filter (LPF) is used for BESS current, PV inductor current, and DC load voltage to reduce switching noise, measurement noise, and current ripple.



(a)



(b)

Fig. 3: Control System Structure for (a) PV Panel (b)-HESS.

The maximum P_{PV}, P_{Load}, and SOC of BESS obtain the optimal reference voltage (V_{PV}^{*}) of the PV panel generated by the control schemes. From these variables, the power coordinate in the PV-BESS-SC hybrid system can be classified into two employment environments: normal and SOC regulations. These variables are detailed in the previous work [31]. The goal of this control is to minimize the charging/discharging stresses on the BESS, thereby raising the battery's lifetime. Throughout the work, it is assumed that the SOC of BESS is within acceptable limits.

The average value of V_{DC} is compared with a reference voltage of DC link (V_{DC}^{*}) in this HESS control strategy, and the error is given to the PI controller (PI_1). The total current required (I_{tot}^{*}) is developed by the (PI_1) controller from ESS. This I_{tot}^{*} is divided into high frequency components (I_{HFC}) and low-frequency components (via LPF), yielding a reference battery current (I_{B}^{*}). I_{B}^{*} is compared with the actual BESS current (I_B), and the difference is sent to the (PI_2) controller, which generates PWM to generate switching pulses for BESS switches (S_2, S_3). The component with the high frequency is defined as:-

$$I_{HFC} = I_{tot}^{*} - I_{B}^{*} \qquad (1)$$

BESS may not track the I_{B}^{*} immediately because of the slow dynamics. As a result, the uncompensated BESS power is given as:-

$$P_{B\_uncompensated} = V_B * \left(I_{HFC} + I_{B_{err}}\right) \qquad (2)$$

SC will compensate for this uncompensated battery power.

$$P_{B\_uncompensated} = P_{SC} \qquad (3)$$

and the difference of power is sent to the (PI_3) controller, The PI_3 controller, generates PWM to control the SC switches (S_4, S_5).

V. Modeling and Control Design

Mathematical Models and control designs for the PV panel, BESS, SC, and DC-DC converters are shown in this section. TABLE I represented the parameters of the PV-BESS-SC hybrid system.

TABLE I

Electrical System Parameters

Design Parameters	value
PV Input Capacitor, C_{PV}	470 µF
PV Inductor, L_{PV}	880 µH
Output Capacitor, $C_{O1}, C_{O2}, and\ C_{O3}$	1200 µF
Buck Capacitor for BESS, C_1	470 µF
Buck Inductor for BESS, L_1	550 µH
Boost Inductor for BESS, L_B	880 µH
Buck Capacitor for SC, C_2	470 µF
Buck Inductor for SC, L_2	550 µH
Boost Inductor for BESS, L_{SC}	880 µH
DC-Link Voltage, V_{DC}	400 V
Nominal BESS Voltage, V_B	192 V
Nominal SC Voltage, V_{SC}	220 V

The equivalent circuit of a PV panel with an equation was explained in [32]. Also, the mathematical model for BESS is described in [31]. The mathematical model for SC is described in [33]. In this paper, the PV array consists of 4 strings connected in parallel, with each string containing 12 panels in series. This arrangement is used to obtain a power of 5790 W as shown in Fig. (4). The relations between time and voltage characteristics of BESS with different current discharge is shown in Fig. (5).

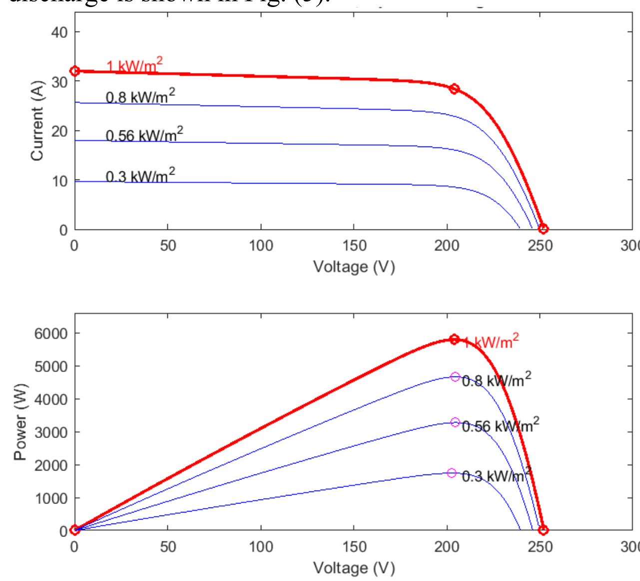


Fig. 4: Output of V-I & V-P Characteristics Under Different Radiation

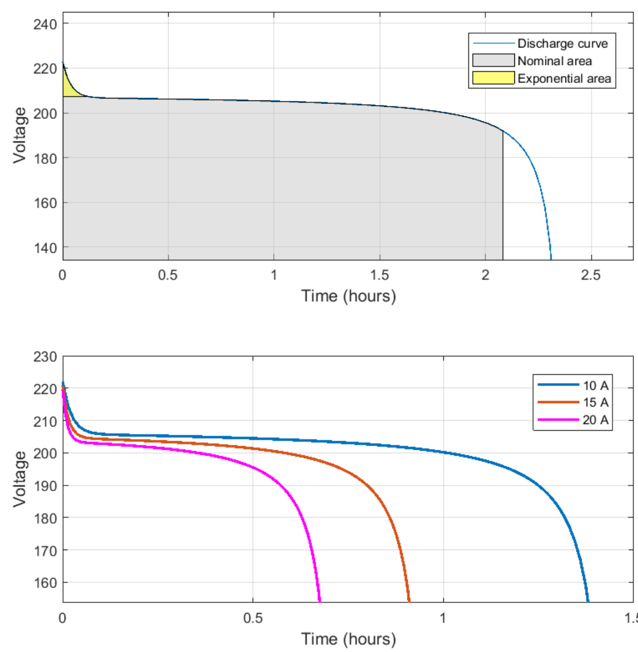


Fig. 5: Characteristics of BESS with Different Discharge Current.

In this paper, the Artificial Bee Colony (ABC) algorithm is used as an optimization technique to achieve the optimized gains of the five PI controllers with the parameters shown in Table II [34]. The cost function is represented the saving operational costs and extending the life span of the HESS components. The dimension is represented the number of parameters that required to tune, limit (local optimization) is represented the number of trails to find the new solution for each parameter, and a scout production period (global optimization) is represented another control parameter to find the new solution randomly. The best cost function illustration is in Fig. (6). the flowchart of ABC is illustrated in Fig. (7).

TABLE II:
ABC PARAMETERS

Parameters	value
Number of bees	40
Maximum iteration number	50
Dimension	10
Limit	5
Scout production period	5

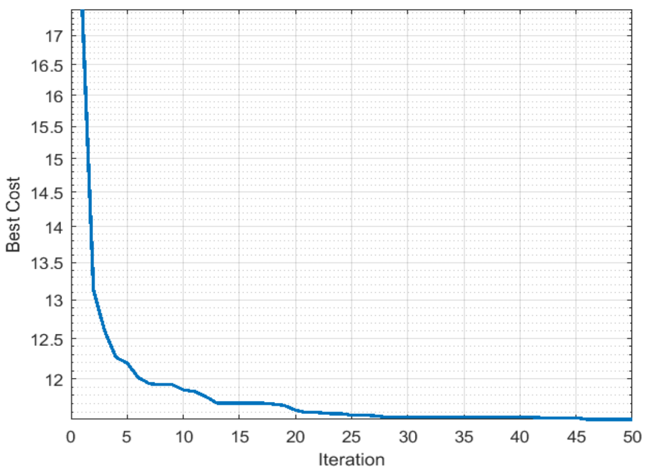


Fig. 6: The Best Cost Function of ABC Algorithm.

The result of PI controllers is given as: -

$$PI\_VC = \frac{0.0124s + 87}{s}$$

$$PI\_CC = \frac{0.01s + 69}{s}$$

$$PI\_1 = \frac{1.463s + 837}{s}$$

$$PI\_2 = \frac{0.043s + 0.65}{s}$$

$$PI\_3 = \frac{0.35s + 973}{s}$$

VI. SIMULATION RESULT

The proposed control strategy and energy management are tested using MATLAB simulation. To demonstrate the compensated power produced by SC, it is first compared to a conventional control strategy in [35] as shown in Fig. (8), the power density increases by more than 56% and DC link voltage operating with prelimited range (±2%). Then, tested the system operation using four scenarios; increasing in power requirement; decreasing in power requirement; increasing in PV generation, and decreasing in PV generation. Additionally, the SOC regulation is examined.

A. First Scenario: Increasing in Power Requirement

The hybrid system is simulated for 9 s and the controller examined with power demand increasing as shown in Figure (9a). SOC is set to 50%.

It can be noted that the three cases of the hybrid system ($P_{PV} > P_{load}$, $P_{PV} = P_{load}$, $P_{PV} < P_{load}$) with the normal operation are explained as active power, and SOC of BESS as shown in Fig. (9b). At the second step (between 3 and 6 s), the small difference between P_{load} and P_{PV} indicates that the HESS losses are very low. In Fig. (9c), the SC is discharged when the power load is increased according to the HFC in the proposed controller. According to Fig. (9d), the V_B is decreased when the power demand increases because the BESS is discharged while the V_{SC} small change and returns to the nominal value.

B. Second Scenario: Decreasing in Power Requirement

The controller tested with power demand decreasing as shown in Fig. (10a). It can be noted that the three cases of the hybrid system with the normal operation are explained as the active power, and SOC of BESS as shown in Fig. (10b). In Fig. (10c), the SC is charged when the power load is decreased according to the HFC in the proposed controller. According to Fig. (10d), DC voltage is operated with nominal value (400V). The V_B is increased when the power demand decreases because the BESS is charged as illustrated in Fig. (10e).

C. Third Scenario: Increasing in PV Generation

When the irradiance changes, that effect on the power produced from the PV array. Fig. (11a) depicted the simulation outcome when the PV irradiance was adjusted in four steps within 12 s.

According to Fig. (11b) shows that the $P_{PV} < P_{load}$ through the first 6 second. As a result, the BESS is discharged to regulate the DC link voltage as illustrated in Fig. (11c). $P_{PV} = P_{load}$ during the third step, thus, the BESS converters are turned off for charging/discharging. The small difference between P_{load} and P_{PV} indicates that the HESS losses are very low. The solar radiation increases further during the fourth step. So, the BESS will absorb the power via charging converter.

In Fig. (11d), the SC is charged when the PV generation is increased according to the HFC in the proposed controller. The BESS voltage is increased when the BESS is charged as illustrated in Fig. (11d). According to Fig. (11f) the DC link voltage small decreased at each step within the prelimited values and return to specified reference with less than 20 ms.

D. Fourth Scenario: Decreasing in PV Generation

Fig. (12a) showed the simulation outcome when the PV irradiance was decreased in four steps within 12 s. According to Fig. (12b) shows that the $P_{PV} > P_{load}$ through the first 6 s. As a result, the BESS is charged to regulate the DC link voltage as shown in Fig. (12c). The $P_{PV} = P_{load}$ during the third step. Thus, the BESS converters are turned off for charging/discharging current.

The small difference between P_{load} and P_{PV} indicates that the HESS losses are very low. The solar radiation decreases further during the fourth step. So, the BESS will supply the power via discharging converter. According to Fig. (12d), the DC link voltage small increased at each three steps within the prelimited values and return to setpoint. V_{PV} operating with MPPT and small change with each step to satisfied the maximum P_{PV}.

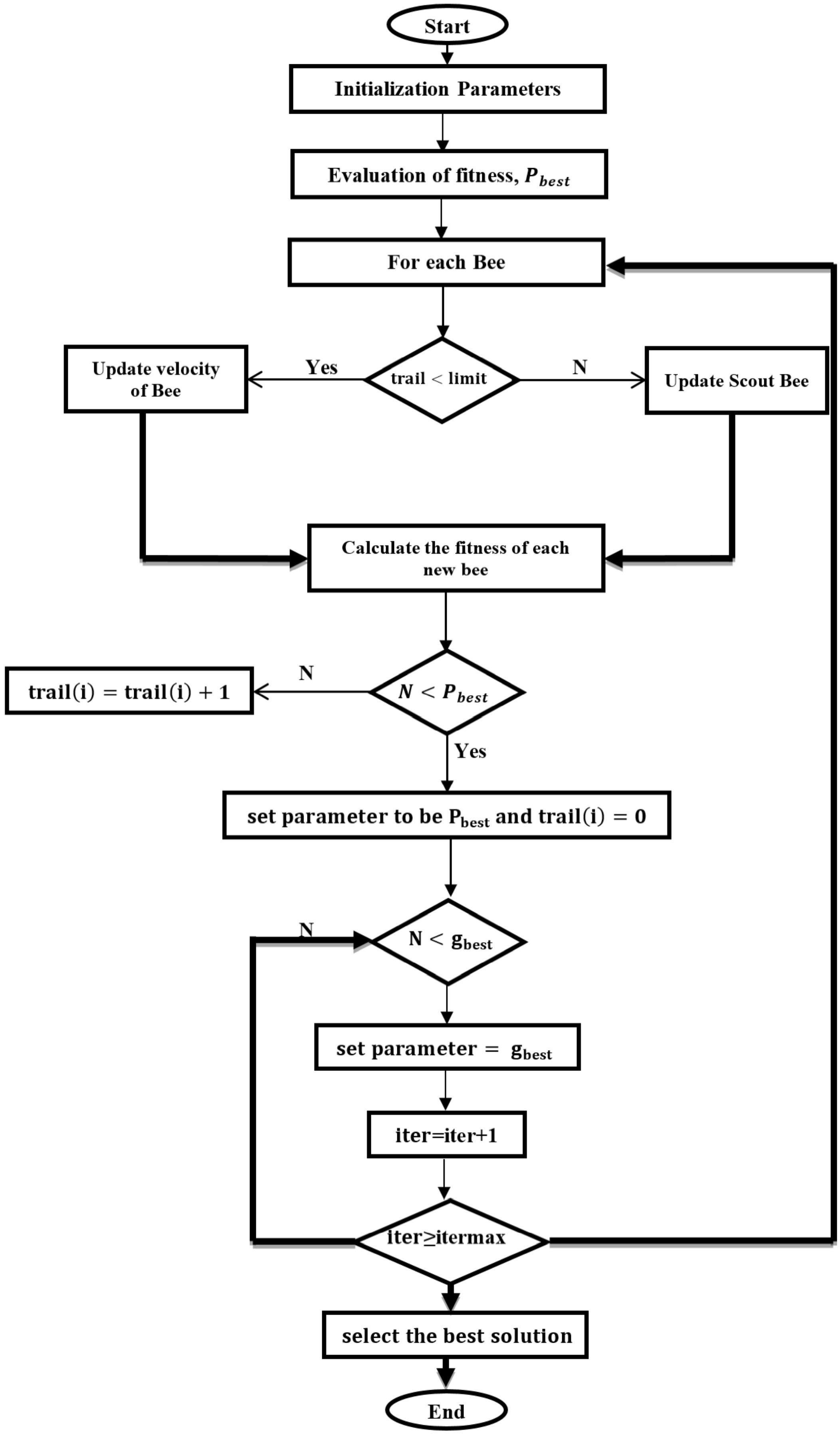
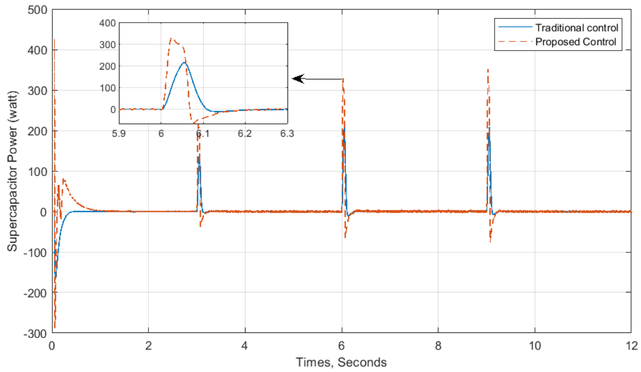
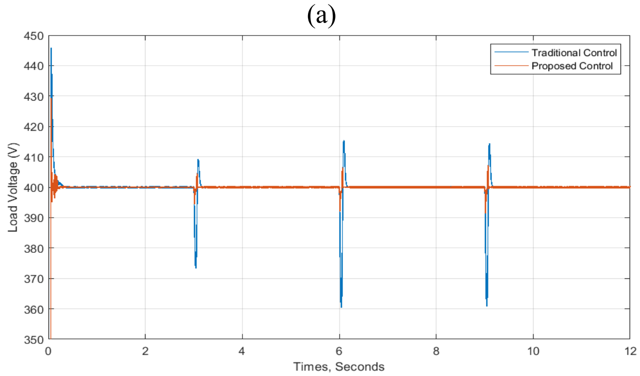


Fig. 7: Flowchart of ABC Algorithm.

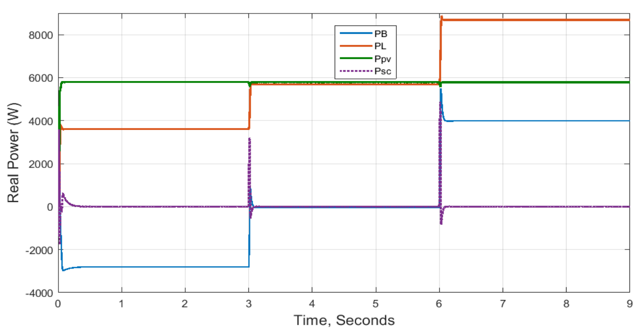


(a)

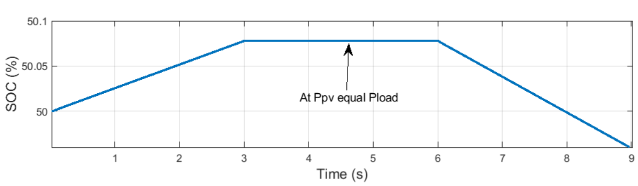


(b)

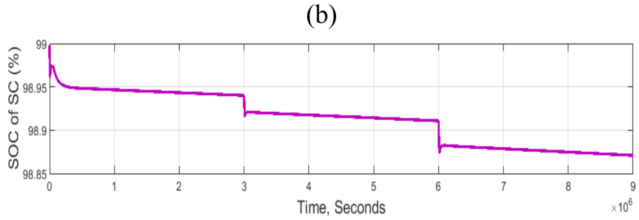
Fig. 8: Proposed and Conventional Controller for (a) P_{SC} (b) DC Voltage



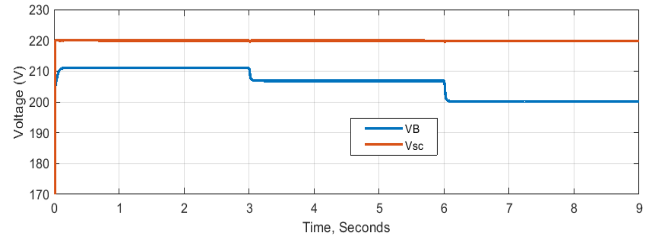
(a)



(b)

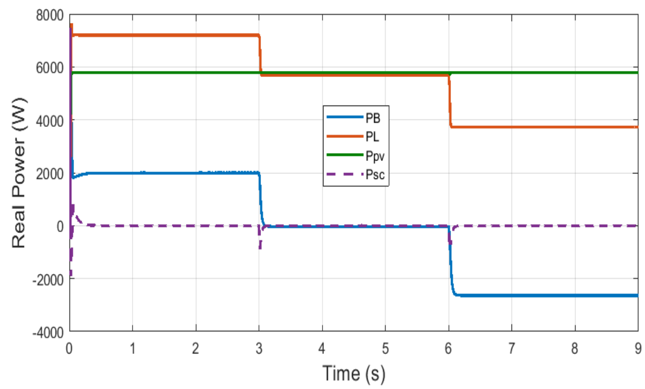


(c)

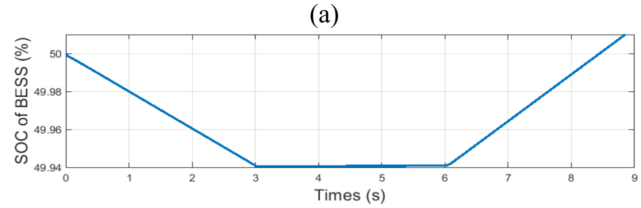


(d)

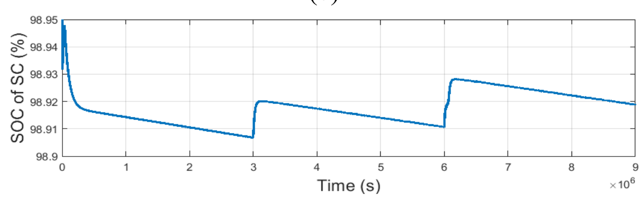
Fig. 9: Simulation results for increasing load (a) Active power (b) SOC of BESS (c) SOC of SC (d) Voltage of BESS & SC



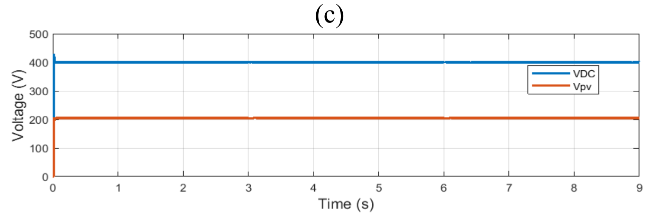
(a)



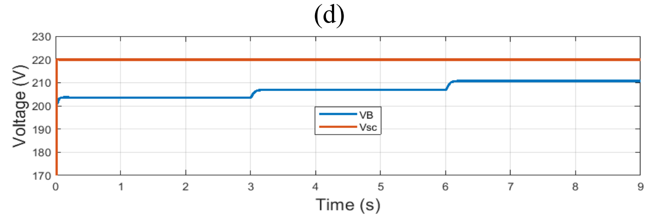
(b)



(c)

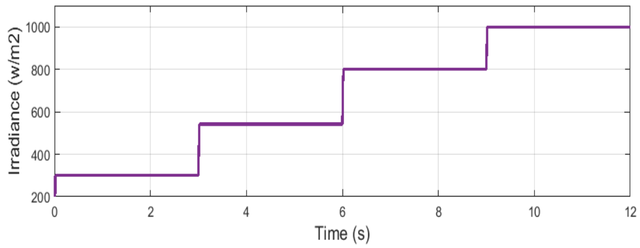


(d)

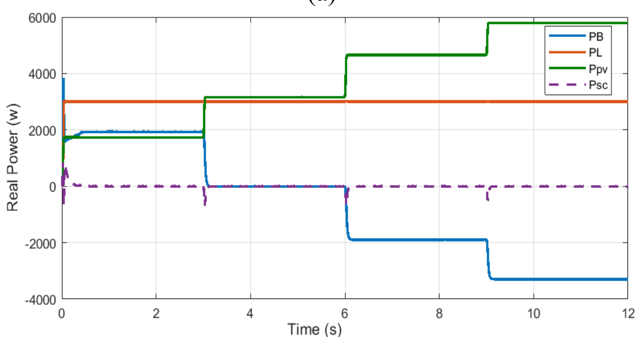


(e)

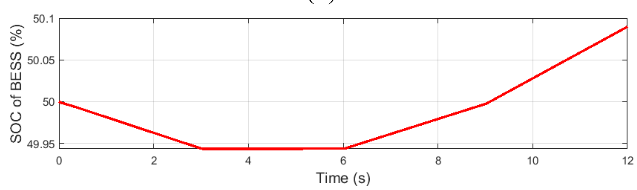
Fig. 10: Simulation results of decreasing load (a) Active power (b)SOC of BESS (c) SOC of SC (d) Voltage of BESS & SC(e) Voltages of DC Bus & PV.



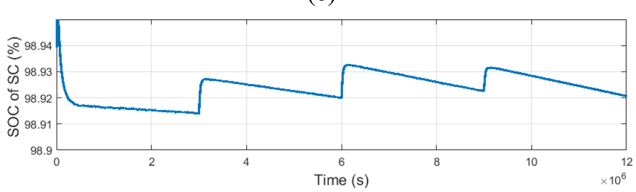
(a)



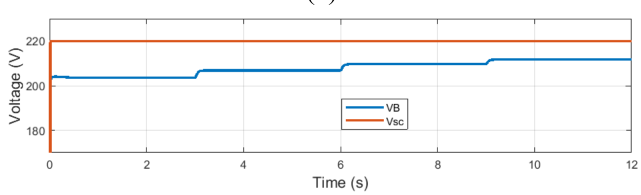
(b)



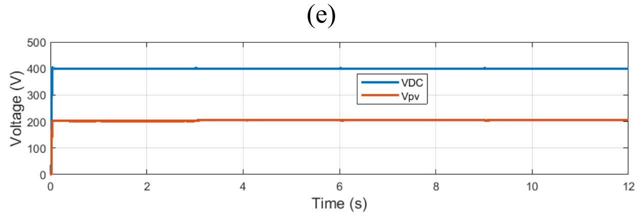
(c)



(d)

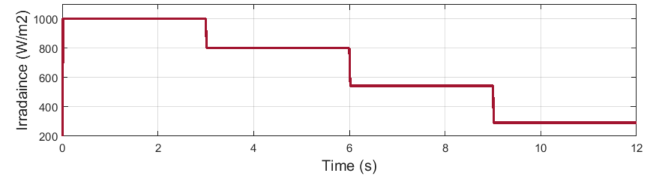


(e)

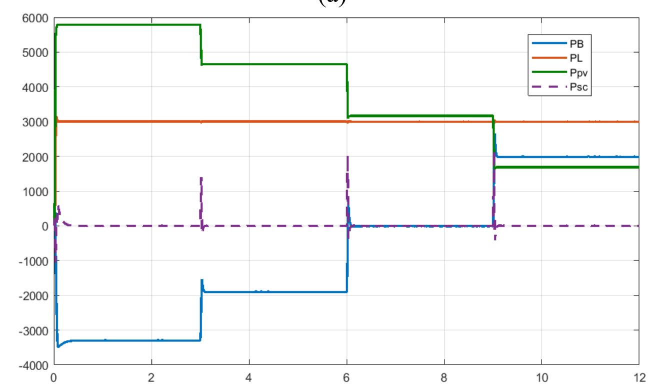


(f)

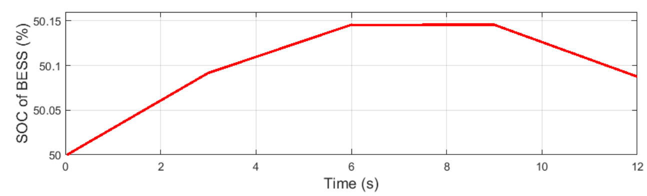
Fig. 11: Simulation results for increasing PV generation (a) Irradiation (b) Active power (c) SOC of BESS (d) SOC of SC (e) Voltage of BESS & SC (f) Voltages of DC Bus & PV.



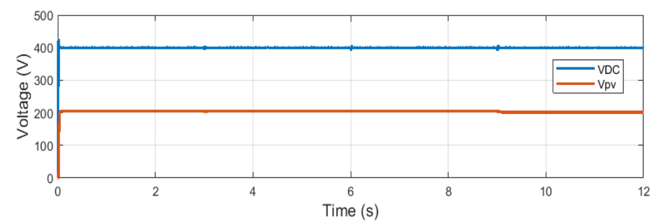
(a)



(b)



(c)

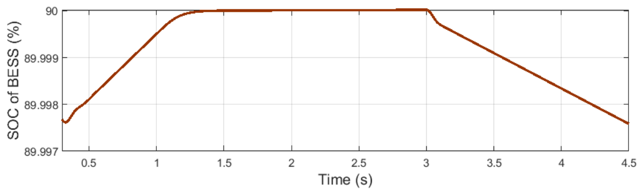


(d)

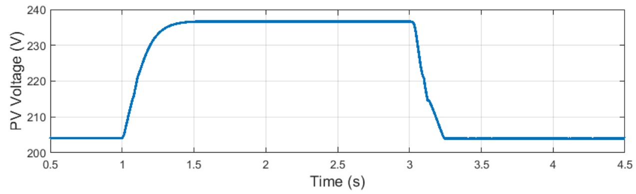
Fig. 12: Simulation results for decreasing PV generation (a) Irradiation (b) Active power (c) SOC of BESS (d) Voltages of DC Bus & PV.

E. Fifth Scenario: SOC Regulation

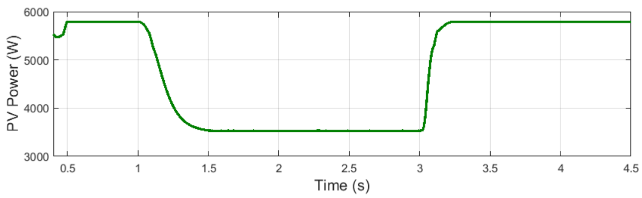
If the SOC reaches its maximum value (90%) as shown in Fig. (13a), the operation of the controller focuses on regulating the V_{PV}^{*} away from the MPPT as illustrated in Fig. (13b). It is noted that the V_{PV}^{*} rises from 204 V to 236.6V. Corresponding to the new reference voltage, the P_{PV} as illustrated in Fig. (13c) decreases to 3528 W to achieve the power balance in the hybrid system as well as discontinuing the BESS from charging. The BESS reacts quickly when the load power increases, to accommodate the new load. Therefore, the SOC is reduced to less than its maximum value and the PV panel is forced to operate back with MPPT.



(a)



(b)



(c)

Fig. 13: Plots of (a) PV Power (b) SOC of BESS (c) PV Voltage.

VII. Conclusions

The proposed control strategy is focused on the analysis of the high and low-frequency power components of electrical energy demand mismatch and regulates the SC using the error component of BESS current for the HESS. The configuration is simple to implement and needs fewer processing than systems such as state machines, or programmed algorithms. When the proposed control strategy is compared to the traditional strategy, the simulation results demonstrate that the compensated power delivered by the SC is improved by more than 56%. As a result, the BESS experiences less current stress, has lower charge and discharge current rates, and has a longer life span.

In the existence of a predefined limit, the proposed energy management strategy regulates the P_{PV}, BESS, and SC converters. The PV-BESS-SC hybrid system operation is separated into normal operation (the PV panel works at MPPT in all situations) and SOC control (restricting the P_{PV} when the SOC reaches maximum value) methods to easily control the power transfer within the hybrid system.

The following are the benefits of the proposed PV-BESS-SC hybrid system instead of using a state machine, which needs more switching, autonomous regulation is used to create a smooth shift between MPP and SOC regulation. HESS charging needs minimal switches, leading to lower power losses. The transfer of power between HESS and load is smooth. The proposed strategy and control configuration have been identified and validated in the PV-BESS-SC hybrid system under various power demand and irradiation conditions.

List of Abbreviation

Battery Energy Storage System.	BESS
Fuel Cell	FC
Fuzzy Logic Control	FLC
Genetic Algorithms	GA
Hybrid Energy Storage System	HESS
Maximum Power Point Tracking	MPPT
Microgrid	MG
Supercapacitor	SC
State of Charging	SOC
Particle Swarm Optimization	PSO
Photovoltaic	PV

Conflict of Interest

The authors have no conflict of relevant interest to this article can be used.

References

[1] C. Ghenai, T. Salameh and A. Merabet, “Technico-economic analysis of off grid solar PV/Fuel cell energy system for residential community in desert region”, International Journal of Hydrogen Energy, Vol. 45, pp.11460-11470, 2020.

[2] Jing, Wenlong et al. “Battery-supercapacitor hybrid energy storage system in standalone DC microgrids: areview”, IET Renewable Power Generation, Vol. 11, pp. 461-469, 2017.

[3] Jarno D. Dogger, Bart Roossien, Frans D. J. Nieuwenhout, “Characterization of Li-Ion Batteries for Intelligent Management of Distributed Grid-Connected Storage”, IEEE Transactions on Energy Conversion, Vol. 26, No.1, pp. 256-263, 2011.

[4] Ying Han, Qi Li, Tianhong Wang, Weirong Chen, Lei Ma, “Multisource Coordination Energy Management Strategy Based on SOC Consensus for a PEMFC–Battery–Supercapacitor Hybrid Tramway”, IEEE Transactions on Vehicular Technology, Vol. 67, No.1, pp. 296-305, 2018.

[5] Burin Yodwong, Phatiphat Thounthong, Damien Guilbert, Nicu Bizon, “Differential Flatness-Based Cascade Energy/Current Control of Battery/Supercapacitor Hybrid Source for Modern e–Vehicle Applications”, Mathematics, Vol. 8, 2020.

[6] Wenlong Jing, Chean Hung Lai, Wallace S.H. Wong, M.L. DennisWong, “A comprehensive study of battery-supercapacitor hybrid energy storage system for standalone PV power system in rural electrification”, Applied Energy, Vol. 224, pp. 340-356, 2018.

[7] Hui Chen, Zehui Zhanga, Cong Guan, Haibo Gao, “Optimization of sizing and frequency control in battery/supercapacitor hybrid energy storage system for fuel cell ship”, Energy, Vol. 197, pp. 117285, 2020.

[8] Carlet M. Enang and Brian K. Johnson, “Bidirectional dc-dc Converter Control in Battery-Supercapacitor Hybrid Energy Storage System”, 2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), pp. 1-5, 2020.

[9] A. Tani, M. B. Camara, B. Dakyo, “Energy Management Based on Frequency Approach for Hybrid Electric Vehicle Applications: Fuel-Cell/Lithium-Battery

and Ultracapacitors", IEEE Trans. Vehicle Technol., Vol. 61, No.8, pp. 3375–3386, 2012.

[10] Li Sun, Kaiwu Feng, Chris Chapman, Nong Zhang, "An Adaptive Power-Split Strategy for Battery-Supercapacitor Powertrain-Design, Simulation, and Experiment", IEEE Trans. Power Electron, Vol. 32, pp. 9364–9375, 2017.

[11] Zhou Shengzhe, Wang Kai, Xue Wen, "Fuzzy Logic-Based Control Strategy for a Battery/Supercapacitor Hybrid Energy Storage System in Electric Vehicles.", In Proceedings of the 2017 Chinese Automation Congress (CAC), Jinan, China, Vol. 1, pp. 5598-5601, October 2017.

[12] Nabil J. Aklo and Mofeed Turky Rashid, "Reinforcement Learning Based Energy Storage Units Scheduling Considering Point of Common Coupling Constraint," 2021 3rd International Symposium on Material and Electrical Engineering Conference (ISMEE), pp. 1-8, 2021.

[13] Lee Wai, Chong Yee, Wan Wong Rajprasad, Kumar Rajkumar Rajpartiban, Kumar Rajkumar, Dino Isa, "Hybrid Energy Storage Systems and Control Strategies for Stand-Alone Renewable Energy Power Systems", Renew. Sustain. Energy Rev., Vol. 66, pp. 174-189, 2016.

[14] R. Yumurtaci, "Role of Energy Management in Hybrid Renewable Energy Systems: Case Study-Based Analysis Considering Varying Seasonal Conditions." Turkish Journal of Elec. Eng. and Comp. Sci., Vol 21, pp. 1077-1091, 2013.

[15] J. Shen, A. Khaligh, "A Supervisory Energy Management Control Strategy in a Battery Ultracapacitor Hybrid Energy Storage System", IEEE Trans. Transp. Electr. Vol. 1, pp. 223–231, 2015.

[16] M. E. Glavin, William Gerard Hurley, "Optimisation of a photovoltaic battery ultracapacitor hybrid energy storage system", Solar Energy, Vol. 86, pp. 3009-3020, 2012.

[17] W. L. Jing, C. H. Lai, W. S. Wong, M. D. Wong, "Cost analysis of battery-supercapacitor hybrid energy storage system for standalone PV systems", In Proceedings of the 4th IET Clean Energy and Technology Conference, Kuala Lumpur, Malaysia, 14–15 November 2016.

[18] Ali M. Jasim, Basil H. Jasim, "Grid-Forming and Grid-Following Based Microgrid Inverters Control", IJEEE, Vol. 18, No.1, pp. 111–131, June 2022. DOI:10.37917/ijeee.18.1.13

[19] A. Etxeberria, I. Vechiu, H. Camblong, J. M. Vinassa, H. Camblong, "Hybrid Energy Storage Systems for renewable Energy Sources Integration in microgrids: A review", 2010 Conf. Proc. IPEC, pp. 532–537, 2010.

[20] Yunjie Gu, Xin Xiang, Wuhua Li, Xiangning He, "Mode-Adaptive Decentralized Control for Renewable DC Microgrid with Enhanced Reliability and Flexibility", IEEE Trans. Power Electron., Vol. 29, No. 9, pp. 5072–5080, 2014.

[21] Jackson John Justo, Francis Mwasilu, Ju Lee, Jin Woo Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review", Renew. Sustain. Energy Rev., Vol. 24, pp. 387–405, 2013.

[22] J. P. Zheng, T. R. Jow, M. S. Ding, "Hybrid power sources for pulsed current applications", IEEE Trans. Aerosp. Electron. Syst., Vol. 37, No. 1, pp. 288–292, 2001.

[23] R. A. Dougal, S. Liu, R. E. White, "Power and Life Extension of Battery– Ultracapacitor Hybrids", IEEE Trans. components Packaging Technol., Vol. 25, No. 1, pp. 120–131, 2002.

[24] Ziyou Song, Heath Hofmann, Jianqiu Li, Xuebing Han, Xiaowu Zhang, Minggao Ouyang "A comparison study of different semi-active hybrid energy storage system topologies for electric vehicles" J. Power Sources, Vol. 274, pp. 400–411, 2015.

[25] Wei Li, Geza Joos, "A power electronic interface for a battery supercapacitor hybrid energy storage system for wind applications", PESC Rec. IEEE Annual. Power Electron. Spec. Conf., pp. 1762–1768, 2008.

[26] A. Etxeberria, I. Vechiu, H. Camblong, J. M. Vinassa, "Comparison of three topologies and controls of a hybrid energy storage system for microgrids", Energy Conversion and Management, Vol. 54, pp. 113–121, 2012.

[27] A. Khaligh, Z. Li, "Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: State of the art", IEEE Trans. Veh. Technol., Vol. 59, No. 6, pp. 2806–2814, 2010.

[28] A. Kuperman, I. Aharon, S. Malki, A. Kara, "Design of a semiactive battery-ultracapacitor hybrid energy source", IEEE Trans. Power Electron., Vol. 28, No. 2, pp. 806–815, 2013.

[29] Selman, Nasir Hussein, Jawad Mahmood, "Comparison Between Perturb & Observe, Incremental Conductance and Fuzzy Logic MPPT Techniques at Different Weather Conditions", IJIRSET, Vol. 5, No. 7, pp. 12556-12569, 2016.

[30] Bhule Deeksha, S. Jain, Subhojit Ghosh, "Power Management Control Strategy for PV-Battery Standalone System", 2020 IEEE 9th Power India International Conference (PIICON), pp. 1-6, 2020.

[31] Ali Q. Almousawi, Ammar A. Aldair, "A New Power Management Control Strategy for PV-BESS Hybrid System", international journal of computing and digital systems, Vol.12, Issue 01, pp. 427-437.

[32] Ali K. Almousawi, Ammar A. Aldair, "Control Strategy of Reactive Power Sharing in an Islanded Microgrids", 3D SCEEER Conference, (2020), p.p 112-118.

[33] Wenlong Jing, Chean Hung Lai, Wallace S. H. Wong, M. L. Dennis Wong, "A comprehensive study of battery-supercapacitor hybrid energy storage system for standalone PV power system in rural electrification", Applied Energy, Vol. 224, pp. 340-356, 2018.

[34] Atheel K. Abdual Zahra, and Turki Y. Abdalla. "An ABC Optimized Adaptive Fuzzy Sliding Mode Control Strategy for Full Vehicle Active Suspension System", IJEEE, Vol. 18, No.1, pp. 151–165, Sep. 2021. DOI:10.37917/ijeee.17.2.17

[35] R. Sathishkumar, Sathish Kumar Kollimalla, Mahesh K. Mishra, "Dynamic energy management of micro grids using battery super capacitor combined storage", in Proc. Annual IEEE India Conf. (INDICON), pp. 1078–1083, 2012.