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Comparative Analysis of a DC-microgrid Incorporating Hybrid Battery/Supercapacitor Storage System Addressing Pulse Load

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Abstract. Renewable energy sources (RESs) have become the primary power source of microgrids with many merits. However, RESs depend on the climate (i.e., wind speed and solar irradiance), leading to intermittent power generation. Moreover, some of the particular loads, such as the pulse load, severely impact the microgrid performance. Therefore, energy storage systems (ESSs) are considered a vital solution to improve microgrid performance and overcome microgrid challenges. This paper presents a comparative analysis of the performance of a DC-microgrid incorporating a battery storage system (BSS) and a hybrid battery/supercapacitors storage system (B-SCSS). The study addressed the fluctuations of solar radiation and wind velocity on the system performance in the presence of both energy storage technologies. In addition, the sudden load disturbance is also investigated with particular attention to the pulse load. The overall microgrid components are designed and controlled based on the PI controller to enhance the system's stability. The photovoltaic and wind energy are utilized with maximum power tracking (MPPT) to get the full benefits from RESs. The B-SCSS is proposed to maintain the DC-bus voltage, load power, and frequency constant during various disturbance events. The obtained results using Matlab software prove the effectiveness of the proposed method.

Keywords. DC-microgrid; battery storage system; supercapacitor; pulse power load; renewable energy

1. Introduction

Recently, the integration of renewable energy sources (RESs) has increased significantly in the electrical power system. Moreover, most studies on power quality issues are related to continuous power loads. However, a few kinds of research deal with discontinuous power loads [1]. The most common type of discontinuous load is pulse power load (PPL), which is defined as a high-power load (from kW to MW) integrated into the power system quickly (a couple of seconds) with repeated pulses [2], [3]. The PPL is used in many applications, such as medical applications, military applications like electromagnetic guns, laser beam weapons, shipboard loads, electromagnetic launch systems, high electric pulse for food production, radar applications, particle accelerators, and a collection of electric vehicles during their charging time through a very short time [4,5]; however, it has various and more complex effects on the power systems compared to the traditional disturbance load. As a result of using PPL, a lot of challenges and issues can face the modern electrical power system, such as dynamic overvoltage, voltage sag, the cut-off among the generation and load, frequency fluctuation in the joint power system, high reactive power flow, interruption of other devices, and failure of the control system [6], [7].

RESs and PPL integration lead to a severe challenge in the electrical systems regarding the power quality issues and stability [8]. Until nowadays, few studies have been discussed and proposed solutions for the effects of the PPL on the modern power system, such as reference [9], which proposed a limit-based control (LBC) method to overcome the issues of the PPL. Meanwhile, in [10], the authors used a trapezoidal-based control (TBC), and generalized profile-based control (PBC) applied in [3]. One of the vital solutions to overcome such challenges and dilemmas is using energy storage systems such as batteries, supercapacitors (SCap), flywheels, and superconducting magnetic energy storage systems [11]. This paper presents a comparative analysis of DC-microgrids incorporating a hybrid battery-supercapacitor storage system (B-SCSS) to improve the DC-microgrid performance during various events such as variable solar radiation, variable wind velocity, sudden load change, and supplying a PPL. The main advantage of the BSS is high energy density, and on the other side, it has a limited lifetime, slow response [12]. Meanwhile, the SC have ability to release the energy very rapidly, so SCap is used to compensate the required high power during very short time. In order to obtain the great benefits from BSS and SCap, both elements can be merged and used together to overcome unfavorable effects of PPL applications and various wind speeds, and solar radiation. Moreover, another aim is to improve the BSS lifetime by reducing the stresses applied to batteries and to overcome the limitations of SCap.

The rest of this paper is organized as follows; Section 2 presents the system modelling and description; Section 3 exemplifies the proposed control techniques used for the hybrid B-SCSS, while Section 4 offers the important simulation results. Finally, Section 5 introduces the conclusion of the presented work.

2. System Modelling and Description

The schematic diagram of the examined energy system is demonstrated in Fig. 1, where a hybrid B-SCSS is integrated into a PV/Wind DC-microgrid. The generated power can be transported promptly to the different loads or the B-SCSS when the production exceeds the load requirements. The supply precedence is that the RESs fulfil the load demand while the B-SCSS activates when the RESs' output becomes inadequate to meet the loads. The modelling of the utilized battery and supercapacitor is introduced in the following subsection.

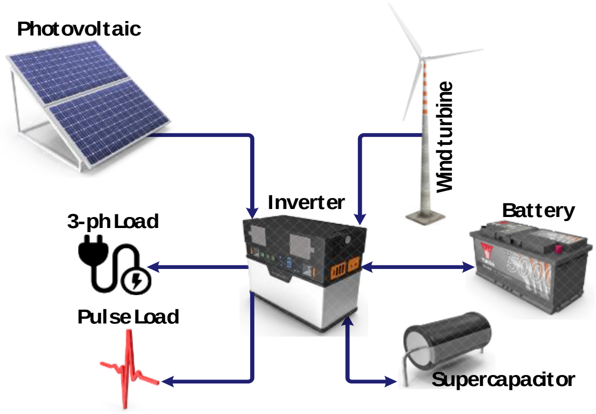


Fig. 1 Description of the investigated system

2.1 Battery storage system

The general battery mathematical representation is given in [13], in which a controlled voltage source is utilized, as displayed in Fig. 2 and described in terms of Eq.1 [14]. The battery output voltage (V_{BAT}) and battery power (P_{BAT}) are conveyed by Eqs. 2 and 3, respectively [14].

$$E_{BAT} = E_0 - \frac{KQ}{Q - \int_0^t idt} + A\exp(-B\int_0^t idt) \tag{1}$$

$$V_{BAT} = E_{BAT} - R_i.I \tag{2}$$

$$P_{BAT} = R_i I^2 \tag{3}$$

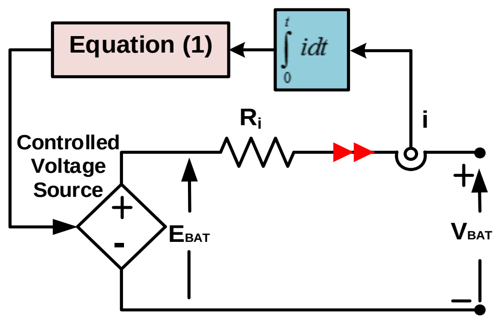


Fig. 2 Basic equivalent circuit of a typical battery

A lead-acid battery pack of 265 Ahr is employed in this work on which this capacity of the battery storage system (C_{BAT}) can be evaluated by Eq. 4 [15], where E_d represents the energy essential from the battery to secure a load demand in watts for one hour, and *DoD* is the depth of discharge. In this work, V_{BAT} and *DoD* are assumed to be 400 V and 60%, respectively.

$$C_{BAT} = \frac{E_d}{V_{BAT} \cdot \mathrm{DoD}} \tag{4}$$

2.2 Supercapacitor

This work's model employed to represent the SCap is driven by Stern's principal arrangement of Helmholtz and Gouy–Chapman models [16], [17]. The typical representation of the supercapacitor equivalent circuit is displayed in Fig. 3. The capacitance of the SCap can be designed as examined in [18] by Eq. 5, in which the values of the C_{GC} and C_H capacitances can be found in [18]. Besides, a pattern of interrelated series (N_s) and parallel (N_p) capacitance units is used to achieve the overall capacitance (C_{Scap}) and the essential ratings. Moreover, the output voltage (V_{sc}) can be defined by Eq. 6 [18].

$$C^{-1} = \left[\frac{1}{C_{GC}} - \frac{1}{C_H}\right], C_{Scap} = C\frac{N_p}{N_s} \tag{5}$$

$$V_{SCap} = \frac{Q_T}{C_{SCap}} - R_{SCap} \cdot i_{SCap}, \quad \text{where } Q_T = N_P Q_c \cdot \int i_{SCap}\, dt \tag{6}$$

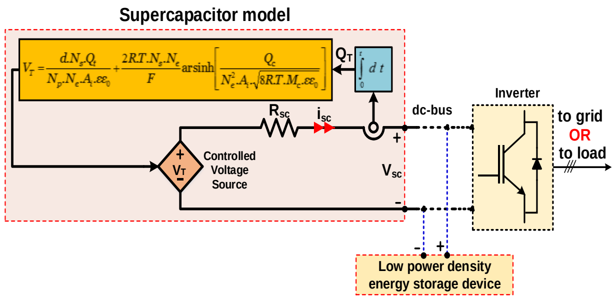


Fig. 3 Equivalent circuit of a typical Supercapacitor

The integration between batteries and supercapacitors become essential under high pulse load power demands due to the degradation which occurs to the batteries causing high stress on the different parts of the battery and lessening their lifetime [19]. Thus, including a SCap can serve as a fast energy storage element of high-power density, which can aid the battery in the power-sharing operation; hence, it is enhancing the dynamic performance of the energy storage system, saving battery power, reducing the possible stresses on the battery portions, and consequently increasing its lifespan [19], [20].

3. Proposed Control Techniques

The applied control technique for the hybrid B-SCSS employs two consecutive control loops for voltage and current, in turn, to supervise the operation of each energy storage device operation and preserve the coupling dc-bus voltage constant during the distinct climatic and load instabilities. Fig. 4 illustrates the proposed control technique of the hybrid B-SCSS. Besides, the PV and wind systems are provided with maximum power point tracking techniques to attain the maximum possible power from solar and wind energies, respectively. The control system of the PV is based on the incremental conductance control technique, while for the wind system, the wind speed measurement technique is used for the maximum power point tracking control [21]. Moreover, the system inverter can be controlled using different control techniques based on the switching frequency [22]. In the current study, the system's primary inverter is controlled using an adjustable pulse width modulation index to stabilize the load voltage/frequency during the different instabilities [15].

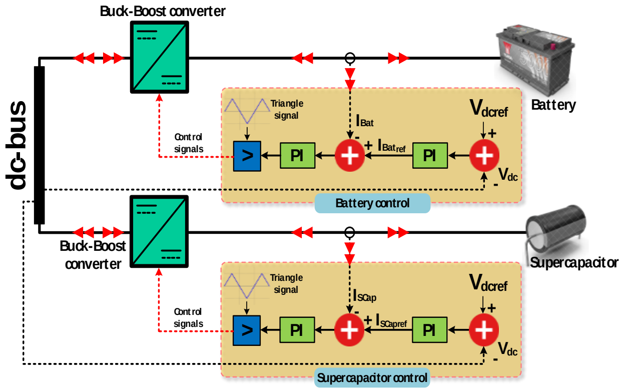


Fig. 4 Proposed control technique of the hybrid B-SCSS

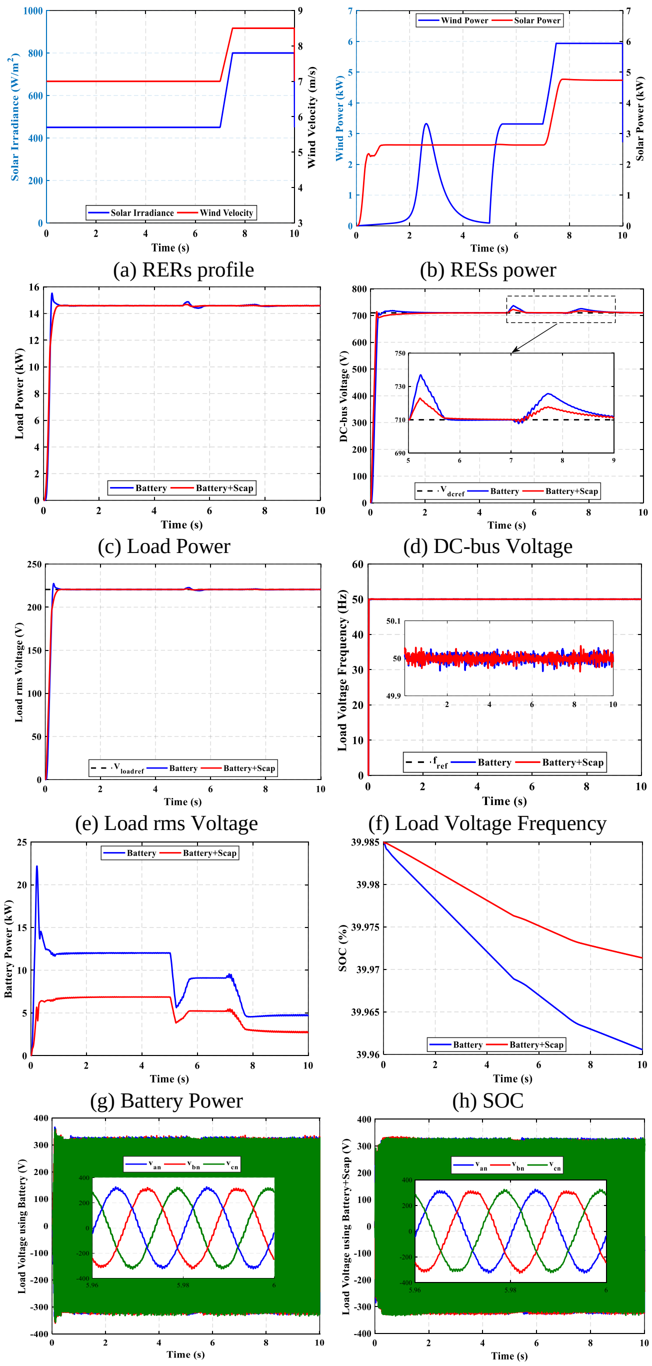
The desired goals of the proposed control techniques can be attained by employing controlled buck-boost converters for each of the batteries and the supercapacitors. For the buck-boost converters, the voltage level of the energy storage device can be decided to be lower than the required reference value [23], [24]. The control objectives of the employed converters are to modify, monitor and supervise the battery and supercapacitor operation continuously. The charging/ discharging mode of operation is determined based on the controlled act. The first control loop (voltage loop) is accountable for producing the reference signal of the current loop by monitoring the change occurring in the coupling dc-bus voltage. In the charging mode, the dc-bus voltage becomes greater than the reference value (i.e., the energy produced from RESs is higher than the load requirements). In this case, the extra power is transferred from the microgrid to the energy storage device. For the discharging mode, the dc-bus voltage becomes lower than the reference value (i.e., the energy produced RESs is insufficient to fulfil the load demand). Hence, the necessary power is transferred from the energy storage device to the load/s to overwhelm scarcity. In the second control loop (current loop), the real current of either the battery or the supercapacitor is compared with the previously-defined reference signal. The control system generates the essential duty cycle for adjusting the operation of the buck-boost converter of each energy storage element.

4. Results and Discussion

The DC-microgrid was examined under three different case studies: i) climatic changes in solar irradiance and wind velocity, ii) unpredictable load change, and iii) under sudden pulse load events. In all cases, the wind turbine is assumed to be connected to the system after 5 s, the time required for the voltage building up procedure in the permanent magnet synchronous generator. The three tests are illustrated and analyzed in the following subsections.

4.1 RERs variation and constant load

In this case, the solar irradiance and wind velocity were changed, as displayed in the profiles shown in Fig. 5-a, while the load power was kept constant at 14.52 kW. The corresponding power generated from both PV and wind turbine systems is illustrated in Fig. 5-b. Thanks to the proposed control techniques, the load power has been successfully provided using either the battery or the hybrid B-SCSS as indicated in Fig. 5-c. The microgrid steadiness can be clarified from Fig. 5-d, in which the dc-bus voltage is successfully preserved constantly with a better performance using the hybrid B-SCSS over the battery. As a result of enhancing the dc-bus voltage and thanks to the inverter control system, the load rms voltage and frequency were kept constant as displayed in Fig. 5-e and Fig. 5-f, respectively. The constructive impact of integrating the supercapacitor into the microgrid system can be recognized in Fig. 5-g. The battery's dynamic behaviour was greatly enhanced, and about 47% of the battery power was saved due to the integration of the supercapacitor. This impact can also be distinguished from the SOC shown in Fig. 5-h. The instantaneous load voltage using both battery and B-SCSS was almost the same as shown in Fig. 5-i and Fig. 5-j.



(a) RERs profile (b) RESs power

(c) Load Power (d) DC-bus Voltage

(e) Load rms Voltage (f) Load Voltage Frequency

(g) Battery Power (h) SOC

(i) Load voltage using battery (j) Load voltage using B-SCSS

Fig. 5 Obtained results during the RERs variation

4.2 Pulse load event

Fig. 6-a displays the pulse load profile of 14.52 kW, which is connected at t = 7 s for only 0.3 s. The wind velocity and solar irradiance were assumed constant at 6 m/s and 1 kW/m^2, respectively. The performance of the microgrid system can be displayed in terms of the dc-bus voltage (Fig. 6-b), the load voltage (Fig. 6-c), the battery power (Fig. 6-d), the battery SOC (Fig. 6-e), and the load voltage frequency (Fig. 6-f). The obtained results confirmed the efficacy of the hybrid B-SCSS and the employed control techniques over the utilization of the battery individually. The hybrid B-SCSS profitably damped the transient overshoot caused by the transitory restraint of the battery, lessened the maximum undershoot in the dc-bus voltage by 47.3%, and saved the power battery by 55.3%. Also, the load voltage and frequency were efficiently alleviated due to the stabilization of the dc-bus voltage and the inverter control system.

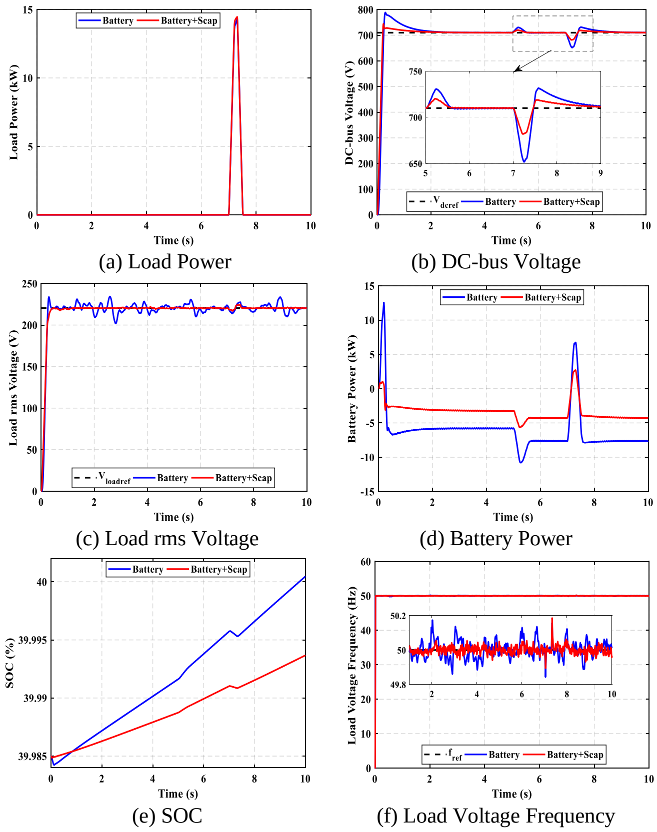


Fig. 6 Obtained results of the pulse load event

4.3 Sudden load change

The obtained results, in this case, are demonstrated in Fig. 7. The system started supplying a constant load of 14.52 kW until the load was suddenly doubled after 7 s. As in the previous test, the solar irradiance and wind velocity were assumed constant at 1 kW/m2 and 6 m/s, respectively. This figure shows that the DC-microgrid operated efficaciously in the presence of the hybrid B-SCSS compared to the battery individually. This can be clarified from the smoothed dc-bus in terms of the overshoot and undershoot in both dc-bus and load voltages, the constant load voltage frequency, the battery power, and battery SOC.

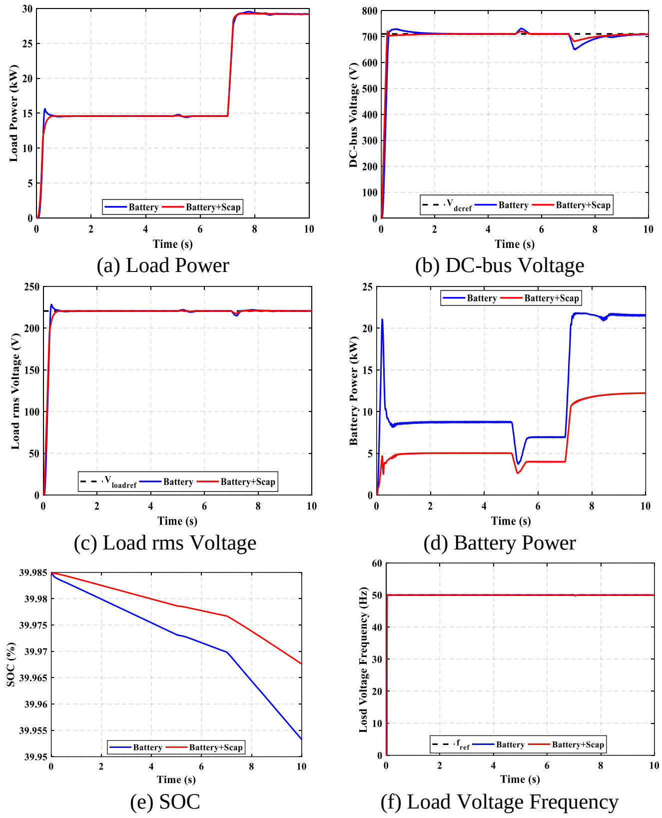


Fig. 7 Obtained results of the sudden load increase event

5. Conclusion

The proposed study offered a developed control approach to validate the microgrid's performance during various events such as pulse load and various wind speeds and solar radiation. The comparison between BSS and hybrid B-SCSS based on PI controller is presented and analyzed. The simulation results validate the effectiveness of the proposed method in mitigating the dc voltage, load power, and frequency during various events. The significant outcome of this work is providing a power management system between various types of ESSs to increase the stability and flexibility of microgrid and ESSs. This work will open the area of the research to provide a vital function for the PPL and reduce the impact of intermittent generation from RESs using the hybrid ESSs based on advanced control techniques.

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