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Development of hybrid battery–supercapacitor energy storage for remote area renewable energy systems ☆

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HIGHLIGHTS

- A hybrid battery–supercapacitor energy storage was proposed for standalone renewable energy systems.
- The operation of a passive connected HESS was examined via both theoretical analysis and numerical simulation.
- An experimental test bench was developed to validate the simulation results.

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ABSTRACT

In this study, a hybrid energy storage system (HESS), which combines battery for long-term energy management and supercapacitor for fast dynamic power regulation, is proposed for remote area renewable energy power supply systems. The operation of a passive connected HESS was examined via both theoretical analysis and numerical simulation using Matlab/Simulink. An electric inductor was further introduced to improve the performance of the HESS. An experimental test bench was developed to validate the simulation results. It was demonstrated that the HESS can stabilize energy provision, not only for the intermittent renewable energy (RE), but also for fluctuating load applications.

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1. Introduction

Energy generated by renewable sources for remote areas has many advantages over conventional supplies, but a negative aspect is that the supply that it is stochastic in nature and consequently difficult to control. To regularize an intermittent RE output, an appropriate energy storage component with high specific power and at the same high specific energy over periods minutes or hours is required [1,2]. The pumped hydro storage system [3–6] offers a good solution for remote area renewable energy integration, but subject to site limitation in respect of available water elevations. In addition, compressed air energy storage is normally used for long-term energy storage [7], and a flywheel is usually incorporated to cope with the short-term peak power demand [8]. The battery energy storage could be a good solution for remote RE projects because of its technical maturity and wide availability [9–11]. However, on one hand, batteries are only efficient at supplying low and steady loads, and on the other hand, RE outputs are not ideal for battery charging as the output fluctuates greatly depending on weather conditions [12,13]. It is difficult for batteries to recover from rapid power fluctuations without a dramatic reduction in their lifetime. In addition, the charge/discharge rate of battery is limited because of its low power density [14]. This imposes severe stress on the batteries under conditions of quick power supply/load fluctuations, resulting in extended periods of low state of charge and also in more charge/discharge cycles. The lifespan of the battery is, thereby, significantly reduced [15,16]. Furthermore, high startup currents are required by some typical appliances. Water pumps, for example, its starting current can be 6–10 times greater than the rate current [17]. Even though these large current spikes only exist for a short duration, the battery must be sized large enough to supply the current spike, leading to the necessity for an excessively high battery storage capacity.

A promising energy buffer device, the supercapacitor (also known as an ultracapacitor or electronic double layer capacitor) has become increasingly interesting in the above regard because of its higher power density, longer cycle life and higher

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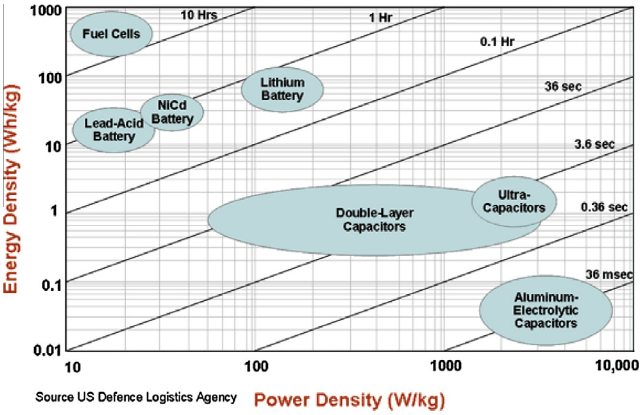

Fig. 1. Ragone plot of energy storage technologies [19].

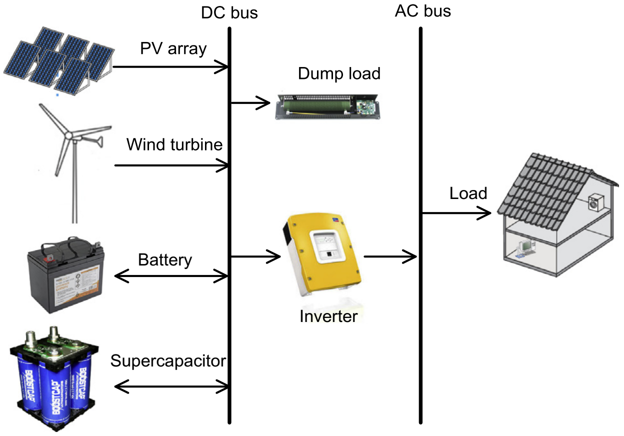

Fig. 2. Standalone RE system with passive hybrid energy storage system.

charging–discharging efficiency compared with that of the traditional battery. Its only disadvantage is a low energy density [18]. Since the supercapacitor and the battery are complementary in technical characteristics, it is reasonable to combine them to create a hybrid energy storage system (HESS) where the battery absorbs/supplies long term continuous power and the supercapacitor responds speedily to the dynamic and instantaneous power demands.

The Ragone plot, i.e. specific power versus specific energy ranges of various energy storage technologies, is displayed in Fig. 1. The plot shows the lead-acid batteries have high energy density of the order of 10–100 W h/kg, while the power density is low at around 100 W/kg, resulting in long charging/discharging times of 0.3–3 h in microgrid RE systems. Thus batteries cannot respond immediately under severe load fluctuations. In contrast, supercapacitors possess high power densities in the range of 1000–5000 W/kg and long life of around 500,000 cycles at 100% depth-of-discharge. The charge/discharge efficiency is very high (95%), at a fast rate over a time in the range of 0.3–30 s. Hence, supercapacitors are usually used for dealing with the quick power fluctuations [15,20,21]. The proposed HESS, therefore, is a good combination of the high energy density of the battery with the high power density of the supercapacitor. The combination in fact, can yield benefits greater than if the two components were to act separately [22].

In the literature, hybrid battery–supercapacitor energy storage was first explored as an alternative to the traditional battery system when subjected to pulsed loads in digital communication applications [23], and is now popularly applied in electric vehicles since they have frequent motor startups and braking events. The addition of the supercapacitor has the potential to reduce the size and improve battery life [24–26]. The HESS is also being considered for standalone renewable energy applications [22,24,27–29], as such battery–supercapacitor combinations result in better reliability and a longer battery life.

This study aims at exploring the advantages of both batteries and supercapacitors, to make the hybridization of two technologies able to cope with long duration power charging/discharging and short duration peak power surges in renewable energy system, and further extending the lifetime of the energy storage devices.

2. Passive connected HESS

There are three basic configurations of a hybrid battery–supercapacitor, i.e. passive, semi-active and fully active connection [30]. In the passive connection, battery and ultracapacitor are connected in parallel with each other. For a semi-active connection, usually a DC–DC converter is employed in addition to the battery and ultracapacitor, including battery semi-active, capacitor semi-active and load semi-active. In the active connection, two DC–DC converters are employed. Similarly the active connection also has three possible configurations: capacitor series active, battery series active and parallel active. Among the three configurations, the passive hybrid is the simplest and cheapest arrangement, which can achieve a better system performance than a single energy storage technology, although the power flow in and out of the HESS is not controlled.

A schematic diagram of a micro-grid RE system with HESS is presented in Fig. 2. The major components are renewable energy generator, HESS, inverter, controller, and load. The supercapacitor is directly connected in parallel with the battery bank, which is the so-called passive connection. In the standalone RE system with HESS configuration, the batteries provide the primary energy buffer for long duration, and super-capacitors only serve for peak power smoothing. It is expected that this system can not only meet stable RE output and load requirements, but can also meet sudden peak power output and peak load demands.

3. Mathematical models

In this study, the mathematical models of the battery and supercapacitor are simplified to make the analysis tractable. The battery is represented by an ideal voltage source V_b and an internal resistance R_b, and the supercapacitor is represented as a single lumped constant capacitance C together with an internal lumped resistance R_c [31]. The equivalent circuit of the direct connection is displayed in Fig. 3(a), and its equivalent circuit in the Laplace domain and its Thevenin equivalent are presented in Fig. 3(b) and (c), respectively.

Based on the analysis presented in [31,32], the equivalent circuit is transformed into the frequency domain using the Laplace transform.

$$V_{\text{Th}}(s) = V_b \frac{R_c}{R_b + R_c} \frac{s + \alpha}{s(s + \beta)} + V_{c0} \frac{R_b}{R_b + R_c} \frac{1}{s + \beta} \tag{1}$$

$$Z_{\text{Th}}(s) = \left(R_b + \frac{1}{sC}\right) \| R_b = \frac{R_b R_c}{R_b + R_c} \frac{s + \alpha}{s + \beta} \tag{2}$$

where s is the complex frequency, V_{c0} is the initial voltage of the supercapacitor, and

$$\alpha = \frac{1}{R_c C} \tag{3}$$

$$\beta = \frac{1}{(R_b + R_c)C} \tag{4}$$

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