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Design and real-time test of a hybrid energy storage system in the microgrid with the benefit of improving the battery lifetime

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HIGHLIGHTS

- A new control method of the hybrid energy storage system is introduced.
- The battery lifetime has been proved to be extended in the real-time experiment.
- A new experiment method is proposed using the RTDS&HIL to give real-time verification.
- A battery lifetime prediction method is introduced.
- The RTDS&HIL scheme highlights a flexible real-time experimental approach.

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ABSTRACT

This study proposes a hybrid energy storage system (HESS) composed of the superconducting energy storage system (SMES) and the battery. The system is designed to compensate power fluctuations within a microgrid. A novel control method is developed to share the instantaneous power between the SMES and the battery. The new control scheme takes into account the characteristics of the components of the HESS, and the battery charges and discharges as a function of the SMES current rather than directly to the power disturbances. In this way, the battery is protected from the abrupt power changes and works as an energy buffer to the SMES. An new hardware-in-loop experiment approach is introduced by integrating a real-time digital simulator (RTDS) with a control circuit to verify the proposed hybrid scheme and the new control method. This paper also presents a battery lifetime prediction method to quantify the benefits of the HESS in the microgrid. A much better power sharing between the SMES and the battery can be observed from the experimental results with the new control method. Moreover, compared to the battery only system the battery lifetime is quantifiably increased from 6.38 years to 9.21 years.

1. Introduction

The microgrid concept, that is defined as a low-voltage system having a cluster of loads and generators capable of providing the stable electricity to the localised area, is regarded as an effective system formation to enhance the renewable power penetrations [1–3]. Due to the variable nature of renewables, the generated power profile may not be able to match the load requirement. Accordingly, much attention has been focused on the development of energy storage technologies to compensate the power disturbances and maintain the system stability [4–6].

The battery storage system (BSS) which has a relatively high level of maturity was reported to be used in the microgrid by many previous works [7–9]. A BSS has a relatively high energy density and a high efficiency [10–13], which makes it an effective method to tackle the power balancing issues in a microgrid [14]. Nevertheless, a BSS faces two challenges. First, the service lifetime of the battery is limited. Depending on the variable nature of the renewable energy source, the battery in a microgrid may experience many short-term charge/discharge cycles. Secondly, compared to short-term energy storage technologies such as a SMES, the power density of the battery is much lower, which makes it difficult for the battery to handle the high-

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frequency fluctuations. The SMES is characterised by an outstanding power density and is able to response to the power requirements very quickly [2,15–18]. However, the energy density of the SMES is much lower than that of the battery [19]. The concept of the SMES/battery hybrid energy storage is, therefore, proposed by combining two kinds of complementary energy storages. In this paper, a detailed scheme of the SMES/battery hybrid energy storage is presented, which has the advantages of both primary energy storage systems meanwhile complementing the disadvantages of each ESS.

The control of the battery and the SMES is the key factor to achieve the expected power distributions and complementary functions of the ESSs [20]. For the single energy storage technology used in the power system, the charge/discharge demands for the single ESS is straightforward [21]. However, in the hybrid energy storage scheme, the control task is much more complicated because the control needs to effectively combine the harmonious operation of two storage technologies such that they complement each other [22–24]. Fuzzy control, which can realize power management in nonlinear systems without accurate system modelling has been proven highly suitable for coordination of multiple energy sources [25]. Ise et al. [26] propose a fuzzy control based method in railway power systems, achieving effective power sharing between the battery and the SMES. However, some specific constraints and fuzzy regions used in this control are selected empirically, which sometimes may lead to sub-optimal design choices. Wang et al. in [27] proposed the conceptual control method that classifies the power requirements manually and distributes the power demands to the different energy storage systems based on their classification. However, the accuracy of this controller is highly dependent on the specific implementation. The filter based power control method which uses the inherent filtration characteristic of the SMES or supercapacitor to allocate low-frequency charge cycling to the battery has been applied in EVs [27–29] and renewable generations [30,31]. In this control scheme, the SMES and the battery are in parallel position and deal with the power fluctuation at the same time. Consequently, the battery may still experience the high-frequency power fluctuations which result in stinging charge/discharge of the battery. A modified fraction control method is, therefore, developed to share the power between the SMES and the battery. In the new method, the SMES and the battery are in series position, and the power disturbances are firstly dealt by the SMES. The battery works as the energy buffer to maintain the SMES current. Hence, the battery charges and discharges according to the SMES current rather than the instantaneous net power. The experiment shows that compared with the preceding fraction based HESS control, the new control scheme is able to protect the battery from abrupt power changes.

Generally, it is difficult to test the new control scheme used in the power system in the real experiments [32,33]. Hence, it comes to another novelty of this work that introduces a RTDS and HIL experimental to verify the hybrid design in a power system level. The RTDS which has real-time computing capability, is regarded as a very effective tool for the experimental verification of power systems. Also, the signals and measurements in the RTDS are real-time data, which make it possible to interface with the external hardware/devices. By adopting these advantages, an external circuit consisting of the digital signal processor (DSP) and the analogue/digital interfaces, is integrated with the RTDS forming a HIL test system.

Additionally, batteries have a significant impact on the budget when taking the whole life cost, replacement and maintenance into account. Hence, the quantitative analysis of the battery lifetime improvement is an essential process to evaluate the effectiveness of the SMES/battery HESS. A battery lifetime prediction method is also introduced in this study. The results show that the battery lifetime is predicted as 6.38 years in the battery only system, whereas in the same application the battery service time can be improved to 9.21 years by using the SMES/battery hybrid scheme.

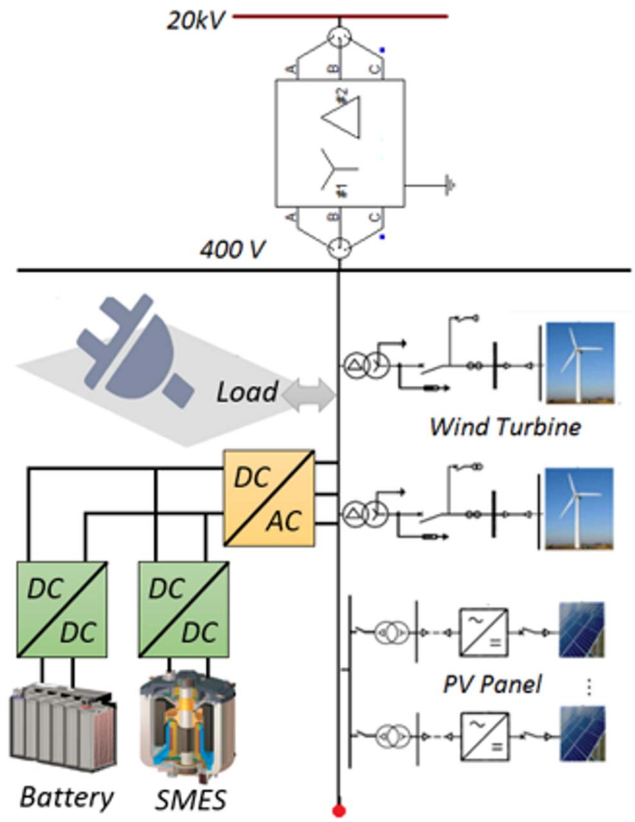

Fig. 1. The system configuration.

2. Methodology

2.1. System description

As shown in Fig. 1, a microgrid system based on the benchmark scheme [2,34] with renewable generations and the SMES/battery HESS, is established in the RTDS. The battery model in the RSCAD which works a controlled voltage source with a series resistor is used in this paper. Since the battery is protected from the short-term frequency charge/discharge processes in this study, so the simple model in the RDCAD software is good to reflect/count the decrease of the short-term frequency charge/discharge cycles. The SMES and the battery are modelled using the methods presented in [31]. Tow DC/DC converters and an AC/DC converter are used to interface the energy storage systems into the AC bus. The converters are modelled using the small-time-step model in the RSCAD software. The hybrid energy storage control algorithm is implanted in the external circuit using a DSP TMS320F28335. A more detail introduction of this RTDS&HIL test system is presented in Section 3.

2.2. Control method

The system control scheme consists of two parts: the voltage source control (VSC) of the AC/DC converter and the new power sharing control of the DC/DC converters is shown in Fig. 2. In this scheme, the HESS is modelled as the voltage source to compensate the system power fluctuations.

2.2.1. Voltage source control

In a grid connected microgrid system, the energy storage units could get the power and active power reference from the main grid [35,36]. However, in the off-grid system, there are no power and active power references [29,37,38]. Hence, as shown in Fig. 2, the current references in d-q axis (I_{d_ref} and I_{q_ref}) is generated based on the instantaneous