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Design/test of a hybrid energy storage system for primary frequency control using a dynamic droop method in an isolated microgrid power system

Jianwei Li [a,*], Rui Xiong [b], Qingqing Yang [a], Fei Liang [a], Min Zhang [a], Weijia Yuan [a,*]

[a] University of Bath, Bath BA2 7AY, United Kingdom

[b] National Engineering Laboratory for Electric Vehicles and Collaborative Innovation Center of Electric Vehicles in Beijing, Beijing Institute of Technology, Beijing 100081, China

HIGHLIGHTS

- A MG with the HESS is developed based on the case of Uligam Island of Maldives.
- A new dynamic droop control for the HESS is proposed and proved effectively.
- The SMES integrated HESS scheme for PFC is designed/tested for the first time.
- The performances of the preceding control and the new control are compared.
- Extensions of battery lifetime in different scenarios are quantified and analyzed.

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ABSTRACT

Frequency dynamics, occurring due to the high penetration of the renewable energy in the microgrid (MG) are of great concern to the system dynamic stability. The battery energy storage systems are reported to have a good frequency regulating ability in the off-grid microgrid systems. However, to compensate the power irregularities, the battery is needed to charge and discharge at a high frequency, which degrades its lifetime significantly. In addition, in the primary frequency control (PFC) the battery needs to deal with the abrupt power changes, which will also accelerate the battery degradation process. In this regard, this paper presents a new concept of primary frequency control by integrating the superconducting magnetic energy storage (SMES) with battery, thus achieving the ability of not only performing a good frequency regulating function but also extending the battery service time. A novel power sharing method using the dynamic droop factors to control charge/discharge prioritization between the SMES and the battery is proposed and has been proved to have a better operation than the preceding droop control. A microgrid system based on the case of Uligam Island of Maldives is developed in the PSCAD, verifying the performance of PFC with the hybrid energy storage system (HESS) using the dynamic droop control. The results show that the HESSs have a better frequency regulating ability and the proposed dynamic droop control is capable of exploiting the different characteristics of both SMES and battery, forming a kind of complementary hybrid energy storage system. Moreover, the battery in the new control scheme is better protected from the short-term frequent cycles and abrupt currents, hence has been proved to have a longer lifetime extension.

1. Introduction

A stable electricity power supply is an essential requirement for the human activities. However, many people living in the remote islands still have no access to electricity [1]. As the fossil fuel resources are becoming increasingly insufficient, inhabitants in the remote island are faced with the high cost of diesel bills [2,3]. The Republic of Maldives which is one such island nation is suffering from such problem [4]. Renewable power generations in conjunction with conventional diesel generators would help in bringing down the electricity cost. With the continuous development of the renewable power generation technology, the cost of renewable energy devices and technologies have declined significantly over

* Corresponding authors.
E-mail addresses: jl977@bath.ac.uk (J. Li), w.yuan@bath.ac.uk (W. Yuan).

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the past decade. Therefore, it is economical and technically attractive to build a microgrid using renewable energy in the remote islands.

A microgrid is defined as a low voltage power system and capable of providing the continuous electricity to a specific localised area [5]. However, due to variable nature of renewable sources and fluctuating load profiles, the power supply in the MG sometimes cannot match the load demands. The unbalance between generation and load will result in system frequency fluctuation. The situation in MG is much worse because of the low inertia and small time constant of the system [6]. In addition, the various forms of small-scale generations (solar panels, wind turbines, etc.) mean many of the power electronic interfaces are required [7]. These power electronic devices are more sensitive to the frequency changes hence making the MG more sensitive to the power disturbances. In the grid-connected mode, MGs are able to exchange the power with the main grid, which helps in maintaining the system frequency [8]. However, because of the high investment of the power transmission system, MGs in remote islands are usually designed as off-grid systems [1,9]. Therefore, the primary frequency control is critical in the island MG.

Various solutions have been investigated to tackle the frequency fluctuation problems in the microgrid system. These solutions include, adding extra rotating masses and increase the inertia of the MG, hence to maintain system frequency [10,11]; additional use of reserve power generations such as gas engines and diesel generators, in order to improve system frequency stability [12]. Many works [13–15] also investigated the variable-speed wind turbines to be used in the microgrid for the frequency control. However, all the methods discussed in the literature have a similar weak point that the dynamical response speed of the additional devices is too slow, hence unable meet the frequency regulation requirement very well in the MGs [6,16,17]. Battery energy storage systems which have high efficiency and large energy density [18] are believed to be an effective solution for power balancing in the island MGs. Many preceding reports have already studied the integration of battery energy storage into the microgrid with the purpose of primary frequency control. To optimize the battery system for the frequency control in an island power system, Mercier et al. [17] introduced an adjustable state of charge limits. A dynamic frequency control method is used in the French island of Guadelope with the aim of enlarging renewable power penetration in the MG systems [16]. The batteries in the plug-in electric vehicles are investigated to be used in a microgrid and have been proved to have a good frequency regulating ability [19]. A three-phase battery system scheme is introduced by [20] achieving the power balancing function in the MG without load shedding. However, there are two disadvantages that limit the usage of battery. Firstly, the battery has a limited service life. The situation is worse when the battery is used in renewable power, because the battery undergoes a great deal of many short-term cycles [21]. Secondly, compared with the other energy storage systems (ESS) such as supercapacitor and SMES, the battery has lower power density, which means the battery cannot respond as quickly as the short-term ESSs. Although the power capacity of the battery bank can be made high enough to handle the high-frequency power changes, a larger battery cell matrix is needed [22]. Moreover, the large battery bank still undergoes many short-term charge/discharge processes which could cause serious battery lifetime degradation [21]. The advantages that large power density, unlimited cycles, and high charge/discharge efficiency [23] make the superconducting magnetic energy storage an ideal supplement for the battery. Many previous works have introduced SMES/battery HESS in different applications: improving overall system efficiency in wind applications [24], compensating fluctuating loads in railway system [25], extending battery lifetime in electrical buses [26], etc. However, none published literature has been found that introduces the SMES/battery HESS in the MG with the frequency control function. Hence, to tackle the issues mentioned above, a new concept of a SMES/battery hybrid energy storage system used for primary frequency control is proposed in this paper.

The droop control has been studied in many previous works to be used in the microgrid, [7,27–33]. To share the power between various power units in the multi-terminal DC system, the droop control is introduced in [29,30]. Using the droop characteristics of the micro-sources, the stability of the microgrid has been tested to be improved in [28,32]. The energy management strategy of the microgrid has been designed and proved to be capable of optimizing the generator output by [7] using the stability-constrained droop control. The parallel power devices in the microgrid are managed by the droop controller archiving an optimal matching between the power sources and load demands [27,33]. The battery energy storages with the droop controllers have been described in [31,33]. However, there is no such published work that considers both the droop characteristics of the SMES and the battery, in regulating the system frequency of the microgrid.

The main challenge of using the droop control in the microgrid is to determine the optimal droop factors for different units. The small-signal technique is introduced in [7,34] to select the droop parameters in the microgrid with the robust performance. The small-signal studies also highlight that the frequency droop factors have the great impact on the dominating frequency eigenvalues [34], hence affects both system stability and transient performance [7]. Lu et al. presented a low bandwidth-based method to describe the droop gains [31,33]. Goya et al. also introduced an improved droop control with the optimal droop factor determining method, based on an infinity H formulation, Goya et al. [33] introduced an improved droop control with the optimal droop factor determining method. The droop factors are always given as constant values by the existing algorithms that have been reviewed. In the hybrid energy storage system, the SMES has high power capacity but low energy destiny and as a result, the SMES should be controlled to meet the short-term high power requirement at the very beginning of its functional actions. The sharing power of SMES then needs to be controlled to decrease while the sharing power of the battery should increase. The constant droop factors, therefore, cannot meet the requirement of synergetic operation of the two kinds of energy storages because of the different inherent characteristics of the SMES and battery. To fulfill this gap a new method using the dynamic droop factors is proposed in this paper.

A microgrid system is developed in the PSCAD to verify the hybrid energy storage design with the new droop control method. The Uligam Island in Maldives is selected as the case to build the microgrid. The battery lifetime extension is one of the key indicators, evaluating the hybrid energy storage system. Therefore, the battery lifetime of HESS is predicted and compared to the battery only system. The simulation results show that compared with the battery only system, the SMES/battery HESSs have a faster frequency disturbance regulation. Compared with the HESS using the preceding constant droop control method, the new dynamic droop control achieves a complementary power-share between the battery and the SMES. In addition, the battery lifetime has been proved to extend from 5.7 to 9.2 years by using the HESS design with the new control method.

2. System configuration and modeling

The Uligam, one of the islands of the Republic of Maldives, located at 7′ 05″ N, 72′ 55″ W, is rich in the renewable resources and therefore is selected as the case that studied in this paper. Fig. 1 gives the Aerial view of the Island and as it can be seen from