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Determination of optimal supercapacitor-lead-acid battery energy storage capacity for smoothing wind power using empirical mode decomposition and neural network

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ABSTRACT

A new approach to determine the capacity of a supercapacitor-battery hybrid energy storage system (HESS) in a microgrid is presented. The microgrid contains significant wind power generation and the HESS is to smooth out the fluctuations in the delivered power to load. Using empirical mode decomposition (EMD) technique, historical wind power data is firstly analyzed to yield the intrinsic mode functions (IMF) of the wind power. From the instantaneous frequency-time profiles of the IMF, the gap frequency is identified and utilized in the design of filters which decompose the wind power into the high- and low-frequency components. Power smoothing is then achieved by regulating the output powers of the supercapacitors and batteries to negate the high- and low-frequency fluctuating power components, respectively. The degree of smoothness of the resulting power delivered to load is assessed in terms of a newly developed level of smoothness (LOS) criteria. A neural network model is then utilized to determine the storage capacity of the HESS through the minimization of an objective function which contains the costs of the HESS and that associated with the achieved LOS. Example of the design of a supercapacitor-lead acid battery HESS for an existing wind farm demonstrates the efficacy of the proposed approach.

1. Introduction

Research into microgrid (MG) has captured intense interest in recent years because of its potential environmental and economic advantages. However, the design and operation of a MG can be significantly different from that of a conventional power system due to the significant level of renewable generation often present in the MG. The amount of power generated from the renewable sources at any given time would depend on climatic conditions. As a result, the fluctuating renewable power could lead to unacceptable degradation in system reliability and security. In this connection, energy storage system (ESS) has been widely viewed as a necessary part of the MG for mitigating negative impact the renewable generation may bring to the power system [1,2].

In the context of wind power generation within a grid-connected MG, the ESS can function as a buffer to smoothen the output power of wind turbine generators. Conventionally, the power smoothing task can be achieved by controlling the pitch angle of the turbine blades [3]. However, this practice imposes additional mechanical stress on the blades which, if excessive, can shorten the useful lifetime of the turbines. Thus the use of ESS for power smoothing has attracted much research attention. For example, the authors of [4] have proposed a real-time battery power allocation method to extend the service life of the battery energy storage system (BESS). However, the authors have not considered whether the BESS would be the most appropriate choice. Specifically, batteries tend to have relatively high specific energy density, although their cycle life is comparatively less than that of supercapacitors (SCs) [5]. In contrast, SCs have a cycle life of the order of a million cycles and higher round-trip efficiency than the batteries but they have low specific energy density [5]. SCs would be suitable for smoothing out shorter-term and rapid fluctuating components of the wind power, while batteries can be used to buffer the lower frequency components. Thus, a judiciously designed supercapacitor-battery hybrid energy storage system (HESS) would be more suitable than the BESS in the smoothing of the renewable power. Indeed, the HESS is attractive as it can extend the lifespan of the batteries [6].

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An important issue concerning the design of the HESS is the determination of the storage capacities of the SCs and batteries. Jia et al. [7] have developed a control strategy to avoid small charging/discharging cycles of the batteries and in so doing, could prolong the lifetime of the batteries. The proposed control strategy requires the specification of threshold frequency levels which then leads to the segmentation of the operating state of the batteries into different regimes. However, it is unclear how the threshold frequencies are to be determined. The authors of [8] have investigated a wavelet-based method to determine the HESS capacities. Wavelet transform requires the use of predefined basis functions but different basis functions might lead to different bands and does not allow a unique reconstruction of the original waveform. In a study on efficient energy management of network consisting of wind-turbines and diesel generators, Tankari et al. [9] have considered the use of the HESS and a rain-flow counting method to quantify the battery lifetime. However, it is uncertain whether the capacity of the HESS so determined can lead to acceptable level of power smoothness in the network, a condition as required for the proper operations of the diesel generators. The authors of [10] have proposed to limit the ramp rate of the output power of the wind turbines. The determination of the limit is based on the average output wind power of the preceding minute and is therefore over restrictive. In contrast, the proposed design of the HESS in [11] uses filters to extract the relevant wind power components to control the power flows to the SCs and batteries. Unfortunately it is unclear how the cut-off frequencies of the filters are to be selected. In fact, there are no known reported works in the open literature concerning the determination of the cut-off frequencies for filters used in wind power smoothing.

In view of the above, the present investigation aims to develop a new approach to determine the energy storage capacity of supercapacitor-battery HESS intended for use in a MG. The role of the HESS is to smoothen the fluctuations in the output power $P_G(t)$ of the wind farm shown in Fig. 1. In this connection, standards and operational guidelines developed for modern power systems often include statements pertaining to the maximum allowable MW ramp rate from a generating station. For example, the maximum MW changes over 1- and 10-min intervals a wind farm can introduce into a grid system have been stipulated by the State Grid of China in [12]. Hence, the determination of the capacity of the HESS is to take into consideration the level of smoothness of the net output power $P_L(t)$ shown in Fig. 1. Accordingly, Section 2 provides a description of the power smoothing task and the proposed approach to solve the design problem. Empirical mode decomposition (EMD) shall be used to identify the frequency components of $P_G(t)$ in Section 3. It leads to the development of a new method to segregate $P_G(t)$ into components which shall be independently and efficiently dealt with by the SCs and batteries through a filtering scheme. The filters used in the proposed scheme are designed based on the outcome of an analysis on the frequency-time characteristics of $P_G(t)$. As a result, the proposed technique removes the ambiguity seen in [11] with regard to the selection of the filter cut-off frequency. The output power of the aggregated wind farm-HESS system can then be assessed using a newly developed level of smoothness (LOS) criteria described in the section. The new LOS measure is a refinement of that shown in, e.g., [12]. In Section 4, a neural network model is developed to establish the relationship between the HESS capacity and the LOS. By extending the study to include long-term operations of the wind farm, genetic algorithm is then used to determine the optimal capacity of the HESS by minimizing a proposed objective function. The example in Section 5 is utilized to demonstrate the proposed approach in designing the HESS, based on data obtained from an existing wind farm.

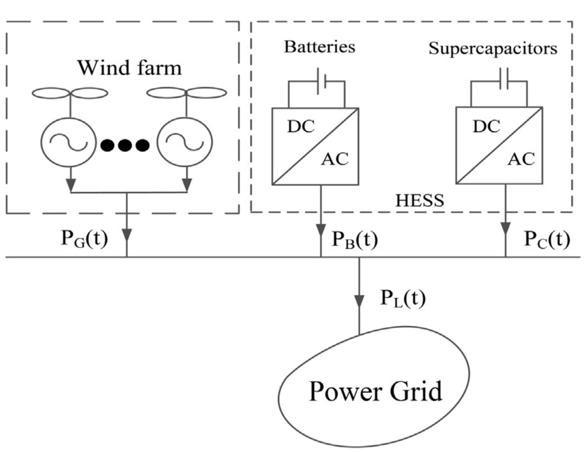

Fig. 1. Schematic diagram showing power flows within a MG consisting of wind generation and HESS.

2. Objective and design methodology of the supercapacitor-battery HESS

2.1. Problem statement

Fig. 1 is used herewith to study the role of the supercapacitor-battery HESS in the MG. $P_G(t)$ is the aggregated output power of the wind farm which is shown to consist of a number of wind turbine generators. The present work investigates the use of the HESS to smoothen the net wind farm-HESS power $P_L(t)$ through the control of the batteries' and SCs' output powers $P_B(t)$ and $P_C(t)$, respectively. The HESS is to act as an energy-buffer between $P_G(t)$ and $P_L(t)$.

In the power smoothing scheme considered in this work, and in line with the observations contained in Section 1, the batteries and the SCs in the HESS shall be used to smooth the lower and higher frequency components of $P_G(t)$, respectively. The design problem in hand is to determine the capacities of the SCs and batteries to achieve desired LOS in $P_L(t)$. Although the HESS does incur losses, in this work, the performance measure which determines the HESS capacity is formulated in such a way that the losses are not considered. A general description of the proposed approach shall be described, as follows.

2.2. General description of the proposed design methodology

To start off the design process, one shall assume there is sufficient historical data on $P_G(t)$. Next, $P_G(t)$ is analyzed using the EMD technique. EMD can decompose a non-stationary dataset adaptively and in a data-driven manner. It allows a unique reconstruction of the original signal. The technique has found applications in many branches of engineering, e.g. on electric load forecasting [13], and detailed theoretical development of EMD can be found in [14]. Central to the EMD approach is a sifting process which, for the problem in hand, allows $P_G(t)$ to be decomposed into a family of intrinsic mode functions (IMF), denoted herewith as $c_i(t)$, $i = 1,\ldots,m$ and a trend function called the final residue $r_f(t)$. While the procedure to determine $c_i(t)$ and $r_f(t)$ shall be described in the next section, it is sufficient to state herewith that each IMF represents an oscillatory mode embedded in $P_G(t)$ while $r_f(t)$ is a monotonic function. Also, $c_i(t)$ shall be of higher frequency than the next higher order IMF $c_{i+1}(t)$ and using Hilbert Transform, the instantaneous frequency-time plot of each IMF can be determined. An attractive feature of the present approach is that it allows the so-called gap frequency f_g be identified in such a way that at this gap frequency, there is minimal overlap energy between two consecutive IMF, $c_g(t)$ and $c_{g+1}(t)$. The significance of using f_g in the HESS