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The Ragone plots guided sizing of hybrid storage system for taming the wind power

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ABSTRACT

The fluctuant behaviors of wind power, and so as their effects on the stability of grid, span across different time scales. Hence, single type of electrical energy storage (EES) cannot level the fluctuation effectively. The high energy density sources (*e.g.* lead-acid batteries) and high power density sources (*e.g.* supercapacitors) are complementary in merits such as power density and energy density. As a result, the employment of the hybrid EES (HEES) is hoped to level wind power output more effectively. This work proposes a sizing strategy for determining the capacity allocation between the high energy density sources and high power density sources. The traits of this employed strategy are the introduction of energy-power relationships (Ragone plots) of EES as constraints and taking of the minimization of life cycle cost (LCC) of HESS as objective function; which respectively considers the power and energy storage characteristics of EES integrally, and reflects the economic need of renewable energy integration. The analytical process of the sizing strategy is described in detail. A case study for an analysis of specific wind power output, with the types of EES we adopted in project, is illustrated graphically based on the developed programming software platform.

Introduction

As the increasing prosperity and economic growth, the capability to access to clean and reliable energy has been treated as a cornerstone of the world [1]. This requirement is more demanding especially in developing nations, such as China, which has sawn an extended period of double-digit annual increases in economic growth and energy consumption. With the wind power estimated of 3000 GW or so, available for covering nearly all of the electricity demand [2], China is increasingly swinging around and embracing this kind of clean energy [3] However, the common challenges facing the employment of wind power are cost and the ability of integrating this kind of renewable source into the grid. The situation of far from existing high capacity transmission lines and their difficulties in matching the electricity production with demand, as well as the variable and unpredictable characteristics of wind power, the before mentioned high wind potential cannot be utilized completely for electricity production.

Currently, there are several options existed that can be implemented in order to obtain a larger wind energy contribution, including: (1) Grid reinforcement (*i.e.* transmission upgrades); (2) Fossil fuel utilities dispatch; and (3) Employment of energy buffer (*i.e.* energy storage). Grid reinforcement expands the capacity of the grid through increasing the cross section of the cables, which is usually done from erecting a new line parallel to the existing line for some part of the distance. However, this approach can be very costly and sometimes impossible due to planning restrictions [4]. Fossil fuel utilities dispatch is the measure that uses slow responding base and intermediate load generators with fast responding peak load generators to capture the chaotic behavior of wind sources [5]. However, there are increased costs associated with the additional needs for providing short-term ramping (for fulfilling frequency regulation) and hourly ramping (for satisfying load following requirements) [6,7], as well as the less efficiently operate

Abbreviations: EES, electrical energy storage; HESS, hybrid electrical energy storage; LCC, life cycle cost; $E_{Loadmax}$, the maximum value of the energy that the electrical energy storage needs to undertake; E_ρ, the energy density (with unit of J kg^{-1}); m_b, amount of the lead-acid batteries that need to be employed; m_{sc}, amount of the supercapacitors that need to be employed; *PoB*, unit price of lead-acid batteries; *PoSC*, unit price of the supercapacitors; $P_{Level}(t)$, power needs to be taken by hybrid electrical energy storage; $P_b(t)$, power demands of lead-acid batteries; $P_{sc}(t)$, power demands of supercapacitors; $P_{Loadmax}$, the maximum value of the power that the electrical eneroogy storage needs to undertake; P_ρ, the power density (with unit of W kg^{-1}); τ, the filtering time constant.

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results from having a suboptimal mix of units online because of errors in the wind forecast [8,9]. Electrical energy storage (EES) is another choice that has been proposed to enable the greater use of wind power through leveling its fluctuations; and is characterized in terms of its fast response over diverse timescales and control flexibility [8,10,11]. Compared with the grid reinforcement and fossil fuel utilities dispatch, EES employment solutions are likely to be more economical and technical feasible [12–14]. Currently, there are numerous literatures reviewing and discussing the employment of suitable storage technologies for wind power integration [5,15–19].

Owning to the fluctuation characteristics of wind speed and direction, it would result in the random combinations of power fluctuations with time scales ranging from cycles of several tens of seconds, cycles of several minutes, to cycles of several tens of minutes and cycles of hours [20]. Meanwhile, each type of EES has its own traits (*i.e.* response characteristics, storage capacity, cycle life, capital cost) and so the preferred niche applications. As a result, employing single type of EES for steering wind power cannot technologically or economically satisfies the power system requirements. The high energy density sources (e.g. lead-acid battery, lithium-ion battery) and high power density sources (e.g. supercapacitor, flywheel) are highly complementary in power density, energy density and life cycle. The employment of the hybrid of these two types of EES is hoped to have capability for leveling wind power output effectively and economically. Until now, there have been plenty of works being tried to employ hybrid (or composite) energy storage, accompanying with relevant devices and suitable charging/discharging strategies, to mitigate the intermittent characteristic of wind power and the like renewable [21–35]. Here, a strategic question arisen is how large the hybrid EES (HEES) capacity should be assigned; as well as how to distribute the total capacity, that the HEES needs to undertake, between the hybrid sources in order to fulfill the in-grid requirement economically. Currently, Li et al. [36] used one type of hybrid energy storage system, composing of supercapacitor and lithium-ion battery, to enhance wind power predictability; and so the grid stability. Within their work, an artificial neural network (ANN) based control algorithm was proposed to control the input/output of the storage system, in order to ensure the rated storage system capacity could satisfy the wind farm's running life. Chen et al. [37] employed one type of HEES including batteries and supercapacitors to smooth the fluctuation of wind power. They firstly based on the predictive output power of wind farm, and employ particle swarm optimization (PSO) algorithm to derive the desired power schedule of wind farm. From that the desired power compensation of the HEES can be derived. The PSO algorithm was implemented again to calculate the power contribution from the battery, in which reducing the state transitions of the battery is considered in order to extend the lifetime of the battery. The rest part of power compensation of HEES, contributed by supercapacitor, can be derived.

However, both of these studies stood at the point that the employment of supercapacitors is aimed to prevent the batteries from frequent charge/discharge state transitions; and so the capacity of employed batteries can be decreased, or the lifetime can be extended. It is worth noting that the power/energy mutual constraints of the supercapacitors, as well as of the batteries, are not taken into account. Furthermore, it is well known that the price of supercapacitors are always much higher than that of the batteries; as a result, employing supercapacitors to 'protect' the batteries not necessarily reducing the total cost of the HEES. In this study, we propose a strategy that applying Ragone plots to allocate the capacity within HEES. Ragone plot is the curve that displays the energy available to load as a function of the power, which differentiate energy storage devices by means of the available energy and power [38]. As mentioned by Christen and Ohler [39], this kind of method has a two-fold advantage for EES optimization including rigorously defined for any kind of EES [40] and readily display the two parameters with cost impact.

System formulation

Stems from the stochastic nature of the wind speed, the total captured wind power is highly time-varying. Fig. 1 shows the one-day wind power output profile of a medium size wind farm (11 MW capacities) in China, whose fluctuation rate reaches 1.9 MW min^{-1}; and would severely affect the stability of the power system. Due to that reason, system operators sometimes set instructions of power variation to wind farms, and demand them to follow the defined generator profiles (*i.e.* desired power schedule). A schematic diagram of the studied system is shown in Fig. 2, which depicts the employment of HEES for mitigating wind power fluctuations and variability. The batteries (lead-acid) and supercapacitors are together connected to the grid at the common coupling point, which are charged and discharged through bi-directional DC/AC power converters to level the wind power for satisfying the specified generator profiles.

Here, we will use the historical data to estimate the required capacity assignment; and the following section will present the detailed sizing strategy that would hopefully enable the wind farm outputs to meet the power system requirements, with minimum investment.

HEES sizing strategy

The optimized sizing of HEES, in this work, treats the capacity allocation of lead-acid batteries and supercapacitors, with the fulfillment of enabling the wind farm power output to follow the defined generator profiles. As said by Irving and Song [41], one optimization problem is a kind of mathematical model where to minimize numerical values that represent something undesirable, or maximize something which is desirable, under certain constraints.

In this study, due to "…this often-characterized 'need' for energy storage to enable renewable integration is actually an economic question", as said by Denholm et al. [8], we take the minimization of *life cycle cost* (LCC) of the hybrid EES as the objective for this optimization process, while considering the leveling requirement and technical characteristics of both types of EES (*viz.* lead-acid batteries and supercapacitors) as constraints. The following sections of this part entail the objective function and constraints, as well as the optimization strategy.

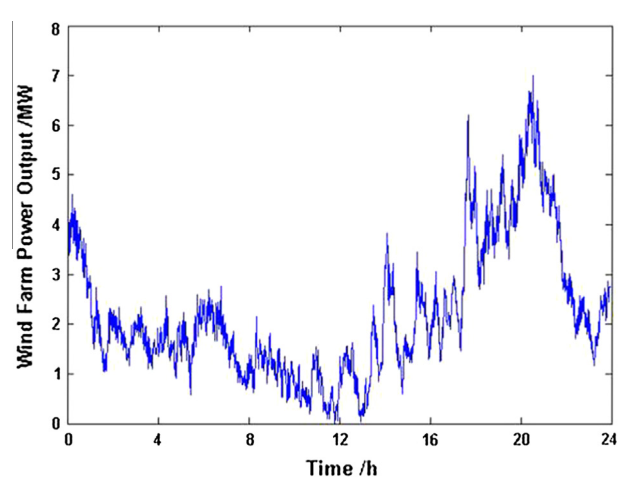

Fig. 1. Daily wind power output profile of one wind farm in China.