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Capacity allocation of a hybrid energy storage system for power system peak shaving at high wind power penetration level

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A B S T R A C T

High wind power penetration in power system leads to a significant challenge in balancing power production and consumption due to the intermittence of wind. Introducing energy storage system in wind energy system can help offset the negative effects, and make the wind power controllable. However, the power spectrum density of wind power outputs shows that the fluctuations of wind energy include various components with different frequencies and amplitudes. This implies that the hybrid energy storage system is more suitable for smoothing out the wind power fluctuations effectively rather than the independent energy storage system. In this paper, we proposed a preliminary scheme for capacity allocation of hybrid energy storage system for power system peak shaving by using spectral analysis method. The unbalance power generated from load dispatch plan and wind power outputs is decomposed into four components, which are outer-day, intra-day, short-term and very short-term components, by using Discrete Fourier Transform (DFT) and spectral decomposition method. The capacity allocation can be quantified according to the information in these components. The simulation results show that the power rating and energy rating of hybrid energy storage system in partial smoothing mode decrease significantly in comparison with those in fully smoothing mode.

1. Introduction

Power generation based on renewable energy sources is increasing significantly throughout the world due to growing concerns about the rapid depletion of conventional fossil fuel resources and global environmental issues. Among renewable energy sources such as wind, hydro, solar, geothermal, biomass and tidal, wind energy utilization is a promising power generation technology. The world wind power installed capacity gains rapidly with a growth rate of 18.8%–282.6 GW at the end of 2012 [1]. However, due to the intermittence and volatility of wind energy, new methods for balancing power production and consumption are needed in the power system with a high wind power penetration level. Hence, the integration of large scale wind energy is a significant challenge for the power system operation and dispatch [2].

In recent years, researchers and power system operators are now more interested in seeking new technologies to make the wind power controllable, such as the wind power forecasting tools and energy storage technologies. Energy storage system used in conjunction with wind energy can help offset the negative effects of wind power penetration in the electrical energy supply. The energy storage system can provide a wide range of power system security related applications such as spinning reserve, frequency control, peak shaving and power quality [3]. The energy storage technologies could be divided into four categories in terms of the mechanisms of energy storage process, which are mechanical energy storage, electro-magnetic energy storage, electro-chemical energy storage and phase change energy storage. Several publications regarding the review of energy storage technologies can be found in literature [4–6], in which the main technical indicators such as the energy rating, power rating, capital cost, round trip efficiency, response time and cycle life are provided.

Recently, lots of studies about the wind-energy storage system have been carried out, focusing on performance investigations [7,8], control strategies [9,10] and economic analysis [11]. However, it's known to all that introducing energy storage system into power system would increase the capital cost. So the capacity of energy storage system must be coordinated with the interacted power system in order to acquire the maximum benefits.

The earlier report on the capacity sizing issue of energy storage system was investigated by Korpaas et al. [12] in 2003. The dynamic programming algorithm was employed to determine the optimal energy exchange with the market considering transmission constrains for a specified scheduling period and the feasible energy

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Abbreviations

BESS	battery energy storage system
CAES	compressed air energy storage
FESS	flywheel energy storage system
HESS	hydrogen-based energy storage system
LA	lead-acid battery
Li–ion	lithium–ion battery
NaS	sodium–sulfur battery
Ni–Cd	nickel–cadmium battery
PHS	pumped hydro storage
SESS	supercapacitor energy storage system
SMES	superconducting magnetic energy storage system
VRB	vanadium redox battery
ZBB	zinc–bromine flow battery

storage system sizing was also emphasized by concerning about the economic issue. Henceforth, the problem of optimization sizing of energy storage device was formulated as maximization or minimization of an objective function taking into account the economic benefit, which were adopted in large amount of published works. Wang et al. [13] achieved the optimized rated power and rated energy of compressed air energy storage (CAES) system by maximizing the economical profit. Brown et al. [14] reported the optimized capacity of pumped hydro storage (PHS) in a small island system by solving a linear programming optimization problem. The objective function of this problem was minimization the expected daily cost of operation and amortization. Wang et al. [15] studied a method for determining battery storage capacity in energy buffer for smoothing wind farm fluctuations through the maximum economic profit. However, Bludszuweit et al. [16] proposed a novel probabilistic method for energy storage device sizing for reducing the wind power forecasting uncertainty. This approach obtains the influences of the wind power forecasting conditions on the distribution of the state of charge (SOC) of the energy storage system, in terms of the statistical behavior of the wind power forecasting error and SOC, and thus the optimized sizing of energy storage system can be determined with a well-defined uncertainty limit.

It can be seen that the methods mentioned above can only determine the sizing of independent energy storage system.

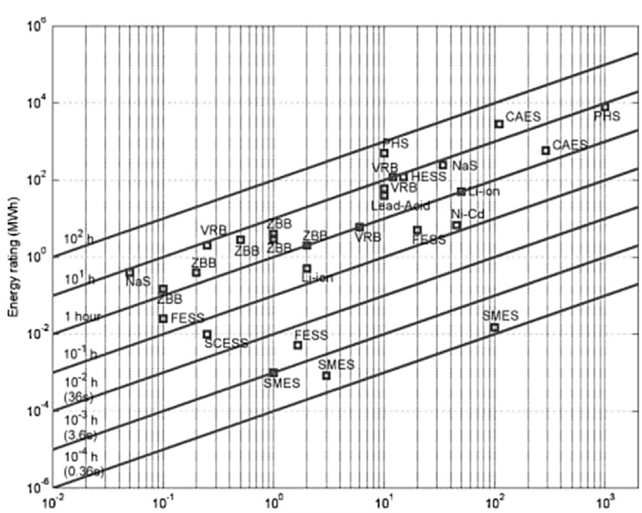

Fig. 1. The duration time at rated power of different energy storage technologies [5].

However, the fluctuations of wind power contain various components with different periods and amplitudes according to its power spectral density [17]. On the other hand, each energy storage technology has different characters, and is suitable for different applications in wind energy area. Fig. 1 shows the duration time at rated power of different energy storage technologies. Table 1 and Table 2 exhibit the characteristics and various applications of energy storage technologies in wind energy area. Obviously, the bulk energy storage systems such as CAES and PHS have higher energy rating, higher power rating but slower ramp rate. The small energy storage systems have lower energy rating and lower power rating but faster ramp rate, including flywheel energy storage system (FESS), flow battery system (FBS), battery system, supercapacitor energy storage system (SESS) and superconducting magnetic energy storage (SMES). Therefore, the different components of wind power fluctuations must be smoothed out by the energy storage systems with different features. It means that the fast ramp rate energy storage system with lower power rating would match the low amplitude, short period fluctuation. On the contrary, the energy storage system with slower ramp rate and higher power rating would match the higher amplitude, longer period fluctuation. Hence, the hybrid energy storage system by combining several different energy storage systems is needed for smoothing out wind power fluctuations effectively. Determination capacity of the hybrid energy storage system is a significant mission for system design and optimal operation.

To the author's knowledge, few research papers about the sizing method of hybrid energy storage system have been published. Makarov et al. [18] employed discrete Fourier transform to acquire the different time scale components from the required balancing power in a power system control area. The capacities of independent energy storage systems in hybrid energy storage system can be quantified by the decomposed time scale components.

In present study, a preliminary scheme for capacity determination of hybrid energy storage system in purpose of peak shaving is proposed by using spectral analysis method. The proposed hybrid energy storage system consists of a small energy storage system and a bulk energy storage system. The former system represents low power rating, fast ramp rate device, while the latter one stands for high power rating, slow ramp rate device.

This paper is structured as follows: first the nature of wind and the spectrum of wind power are given in Sec. 2. Then the wind power smoothing strategies are suggested in Sec. 3. The method of sizing hybrid energy storage system is described in Sec. 4, after which the simulations and discussions of a case study is performed in Sec. 5. Finally the conclusions are given in Sec. 6.

Table 1
The characteristics of the energy storage technologies [5].

Energy storage technology	Energy rating/MWh	Power rating/MW	Response time	Efficiency/%	Cycle	Life/year
PHS	500–8000	10–1000	min	70–85	10k–30k	30–60
CAES	200–2860	5–350	sec–min	57–85	8k–12k	20–40
FESS	0.0052–5	0.1–20	<1cycle	70–95	20k–100k	15–20
Li–ion	0.0015–50	0.015–50	<1/4cycle	85–98	1k–10k	5–15
LA	0.001–40	0.05–10	<1/4cycle	70–82	100–2k	3–20
NaS	0.4–244.8	0.05–34	<1/4cycle	70–90	2.5k	5–15
Ni–Cd	6.75	45	<1/4cycle	60–70	800–3.5k	5–20
ZBB	0.1–4	0.1–1	<1/4cycle	60–75	2k	5–10
VRB	2–120	0.2–10	<1/4cycle	60–85	12k–14k	5–15
HESS	120	0.1–50	<1/4cycle	20–50	1k+	5–20
SESS	0.01	0.05–0.25	<1/4cycle	60–70	50k	5
SMES	0.00083–0.015	1–100	<1/4cycle	90–98	100k	20–30