Battery Energy Storage Station (BESS)-Based Smoothing Control of Photovoltaic (PV) and Wind Power Generation Fluctuations

Xiangjun Li, *Senior Member, IEEE*, Dong Hui, and Xiaokang Lai

***Abstract*—The battery energy storage station (BESS) is the current and typical means of smoothing wind- or solar-power generation fluctuations. Such BESS-based hybrid power systems require a suitable control strategy that can effectively regulate power output levels and battery state of charge (SOC). This paper presents the results of a wind/photovoltaic (PV)/BESS hybrid power system simulation analysis undertaken to improve the smoothing performance of wind/PV/BESS hybrid power generation and the effectiveness of battery SOC control. A smoothing control method for reducing wind/PV hybrid output power fluctuations and regulating battery SOC under the typical conditions is proposed. A novel real-time BESS-based power allocation method also is proposed. The effectiveness of these methods was verified using MATLAB/SIMULINK software.**

***Index Terms*—Adaptive smoothing control, battery energy storage station (BESS), solar power generation, state of charge (SOC), wind power generation.**

NOMENCLATURE

Modeling of Power Sources:

WPGS	WP generation system.
PVGS	PV power generation system.
$V_{\rm bat}$	Terminal voltage of battery energy storage system (V).
$I_{\rm bat}$	Current of battery energy storage system (A).
$V_{\rm ocv}$	Open circuit voltage of battery (V).
$R_{\rm bat}^{\rm int}$	Internal resistance of battery energy storage system (Ω).
$R_{\rm ch}$	Internal resistance of charge (Ω).
$R_{\rm dis}$	Internal resistance of discharge (Ω).
SOC	State of charge (%).
$\rm SOC_{ini}$	Initial value of SOC (%).
η	Charging/discharging efficiency (%).
$\eta_{\rm ch}$	Efficiency of charge (%).
$\eta_{\rm dis}$	Efficiency of discharge (%).
$Q_{\rm bat}$	Battery energy storage system capacity (kWh).

SOC-Based Smoothing Control Strategy:

u_i	Start–stop status of unit i.
$\rm SOC_{\it i}$	SOC of unit i (%).
$\rm SOD_{\it i}$	State of discharge of unit i (%).
L	Total number of PCS.
M	Total numbers of violating the maximum allowable power limit constraints.
T	Investigated time period (Sec).
n	Number of samples.
Δt	Control cycle (Sec).
$\hat{P}_j^{\rm maxdisch}$	Allowable maximum discharge power of unit j (kW).
$\hat{P}_j^{\rm maxch}$	Allowable maximum charge power of unit j (kW).
$\delta_{\rm WPPV}$	Appointed power fluctuation rate limit value (%/min).
A_i	Modified power factor for unit i.
$\rm SOC_{ref}$	Reference value of SOC (%).
$\rm SOC_{\it i}^{max}$	Allowable maximum SOC of unit i (%).
$\rm SOC_{\it i}^{min}$	Allowable minimum SOC of unit i (%).
$f_{\rm LT}$	A one-dimensional lookup table (LT) block for which the input is the battery $\rm SOC_{\it i}$ and the output is A_i.
$f_{\rm WPPV}$	A function to calculate original wind and PV power fluctuation rate.
$f_{\rm hybrid}$	A function to calculate wind/PV/BESS hybrid power fluctuation rate.
$r_{\rm (WPPV)}^T$	Original wind and PV generation power fluctuation rate during the investigated time period T (%/min).

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The authors are with the Electrical Engineering and New Material Department, China Electric Power Research Institute, Beijing, 100192, China, China (e-mail: lixiangjun@epri.sgcc.com.cn; li_xiangjun@126.com).

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$r^{T}_{(\text{hybrid})}$	Wind/PV/BESS hybrid power fluctuation rate during the investigated time period T (%/min).
$P^{\max}_{(\text{WPPV})}$	Maximum power value (KW).
$P^{\min}_{(\text{WPPV})}$	Minimum power value (KW).
$P^{\text{rated}}_{(\text{WPPV})}$	Total rated power of wind and PV generation (KW).
u^{WP}_{k}	Start–stop status of WPGS k.
u^{PV}_{k}	Start–stop status of PVGS k.
$P^{\text{rated}}_{\text{WP}\_k}$	Rated power of the WPGS k (KW).
$P^{\text{rated}}_{\text{PV}\_k}$	Rated power of the PVGS k (KW).
$P^{\text{ini}}_{\text{BESS}}$	Initial power of the BESS (KW).
P_{WPPV}	Total power of WP and PV generation (KW).
T_{WPPV}	Time constant for smoothing control (Sec).
s	Complex variable.
$r_{\text{WPPV}}(t)$	Original total power fluctuation rate of PV and WP generation at time t (%/min).
$K^{\text{rise}}_{\text{WPPV}}$	Rise rate limit value (kW/Sec).
$K^{\text{drop}}_{\text{WPPV}}$	Drop rate limit value (kW/Sec).
$P^{\text{DRL}}_{\text{WPPV}}$	Output power for the proposed dynamic rate limiter (DRL) (KW).
PCS	Power converter systems.
P_i	Target power of PCS i (kW).
P_{BESS}	Target power of the BESS (kW).
$P^{\text{smooth}}_{\text{WPPV}}$	Target smoothing power (kW).
δ_{WPPV}	Appointed power fluctuation rate limit value.

I. Introduction

IN RECENT years, electricity generation by photovoltaic (PV) or wind power (WP) has received considerable attention worldwide. The State Grid Corporation of China (SGCC) is building the National Wind/PV/battery energy storage station (BESS) and Transmission Joint demonstration project and it is located in the region of Zhangbei, Hebei, China. The Zhangbei belongs to one of the country's 10 million kilowatts of wind power base. The demonstration project is scheduled in three stages. Now, it is in the first stage and at the end of December, 2011, a 100-MW wind farm, a 40-MW PV farm, and 14-MW/63-MWh lithium–ion BESS have been built at Zhangbei.

The battery energy storage system can provide flexible energy management solutions that can improve the power quality of renewable-energy hybrid power generation systems. To that end, several control strategies and configurations for hybrid energy storage systems, such as a battery energy storage system [1]–[5], [13]–[19], a superconducting magnetic energy system (SMES) [6], a flywheel energy system (FES) [7], an energy capacitor system (ECS) [8]–[12], and a fuel cell/electrolyzer hybrid system [20], [21], have been proposed to smooth wind power fluctuation or enhance power quality. Thanks to the rapid development of batteries, battery energy storage systems recently have begun to be utilized for multiple applications such as frequency regulation, grid stabilization, transmission loss reduction, diminished congestion, increased reliability, wind and solar energy smoothing, spinning reserve, peak-shaving, load-leveling, uninterruptible power sources, grid services, electric vehicle (EV) charging stations, and others.

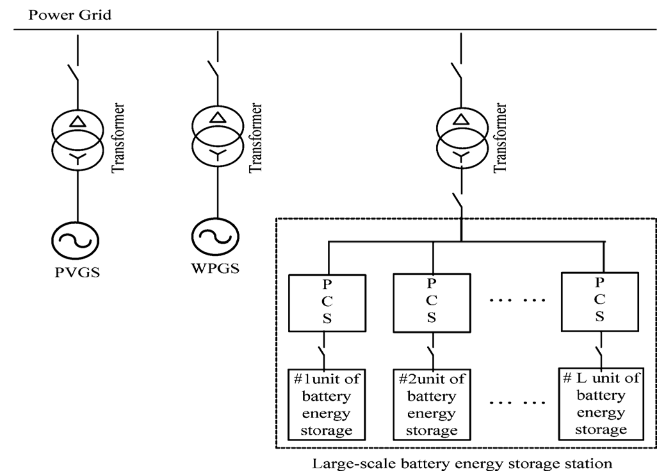

Fig. 1. Wind/PV/BESS hybrid power generation system.

These days, the issue of how power fluctuations in PV and wind power generation are to be smoothed has attracted widespread interest and attention. And even as this issue is being resolved, another one, that of the application of an energy storage system such as BESS, has arisen. When using BESS to control PV and wind power fluctuations, there is a trade-off between battery effort and the degree of smoothness. That is, if one is willing to accept a less smooth output, the battery can be spared some effort. Thus far, although various effective BESS-based methods of smoothing power fluctuations in renewable power generation systems have been proposed [2], [3], [5], smoothing targets for grid-connected wind and PV farms generally have not been formulated. Smoothing control by way of power fluctuation rate limits, for such systems, has rarely even been discussed. The control strategies published in [1]–[5], [13]–[19], [25], [26] were formulated mainly for small-scale BESS-based smoothing; hence, they did not consider power allocation among several BESS. A suitable and effective control strategy for large-scale BESS, therefore, remains an urgent necessity.

In the present study, under the assumptions that the capacities of the WP and PV hybrid generation system (WPPVGS) and BESS had already been determined and that we do not have ability to adjust the WPPVGS output power, a large-scale BESS was used to smooth the WPPVGS output power fluctuation. More specifically, Wind/PV/BESS hybrid power generation system (Fig. 1) along with a state of charge (SOC)-based smoothing control strategy was utilized to instantaneously smoothen WP and PV power fluctuations. This was accomplished by modifying smoothed target outputs adaptively and making flexible use of feedback adjustments of battery SOC in real-time. The detailed procedure is explained in Section III.

This paper is organized as follows. Section II presents the modeling of each power source. Section III describes