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Finite-time convergence robust control of battery energy storage system to mitigate wind power fluctuations

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ABSTRACT

Wind energy is envisioned to be one of the most promising clean and renewable energy to drive our future society. Due to its intermittency nature, wind power may change rapidly and frequently. Wind power fluctuations pose great challenges on power quality, reliability and raise many other issues like frequency and voltage regulation. This paper proposes a finite-time convergence robust control algorithm of battery energy storage system (BESS) to mitigate the wind power fluctuations. The major advantages of the proposed algorithm include, being insensitive to uncertainty and disturbance, enabling adjustable convergence time to accommodate different operating conditions and maintaining the state of charge (SOC) within a proper range for regulation capability reserve. Finite-time convergence of the proposed algorithm is derived through rigorous analysis. Simulation results demonstrate the effectiveness of the proposed algorithm.

1. Introduction

Driven by the ever growing energy demand from industrial load, commercial load, residential load and electrical vehicles, the worldwide energy demand is expected to steadily increase in future years [1]. In traditional power grid, electricity is centrally generated and then transported over long distances to the end users in dispersed locations. Such complicated structure with increasing probability of grid instability and outages will confront great challenges to accommodate the demand growth, as evidenced by the recent outages in North America that cost millions of dollars [2].

As a new paradigm to provide clean and inexhaustible energy source, renewable generation (RG) like wind power, is gaining significant attention and becoming an important complement of centralized energy production. However, fluctuations of the wind power generation, which is caused by the intermittency and uncertainty of wind, poses new challenges to the existing power system such as frequency and voltage regulation, grid interconnection, power quality and reliability [3]. Several de-loading methods [4–6] based on wind generator pitch angle control and rotor control have been developed to smooth the fluctuations of wind power at the cost of lowered utilization efficiency. Wind generators are usually controlled under the maximum power point tracking (MPPT) mode [7–9] to emphasize the utilization efficiency when they are connected to the main grid system for most of the time.

Recently, novel energy storage techniques provide effective solutions to mitigate wind power fluctuations and improve the power quality. As the promising wind power storage options, different energy storage devices such as flywheels [10–12], supercapacitors [13–15], and BESS have been investigated [16–20]. As power electronics-based device, BESS is among the candidates with the highest potential for wind power mitigation due to its fast response time, high energy efficiency, and promising large scale grid applications [16].

Since BESS with large capacity is quite an expensive option, adopting advanced control strategy for the optimal utilization of the available BESS becomes essential. There exist abundant literatures on using BESS as a buffer to reduce renewable power fluctuations and enhance power quality while enabling MPPT generation. Abbey et al. [17] proposed a knowledge-based artificial neural network control approach for the coordinated operation of a two-level energy storage system and the wind generator. The proposed control approach [17] comprehensively used lead-acid battery and supercapacitor to produce dispatchable wind power. This control approach effectively exploited the storage capacity while detail models of lead-acid battery and supercapacitor could be further investigated. Li [18] proposed a fuzzy logic control

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approach using a first-order Kalman filter with the feedback control of SOC. However, the internal resistance of battery was based on look-up tables with experimental data. The authors in [19–22] adopted low-pass filter (LPF) based methods to eliminate the high-frequency components to achieve a smoother wind power output profile, which are easy to implement and suitable for real-time operations. Considering the uncertainty of wind generation output, a two-time scale coordination control algorithm based on an improved LPF method was proposed in [23] to accommodate the mitigation requirements for constantly changing wind power. Recent works also investigate the SOC regulation, which enable the BESS to have efficient capacity to smooth wind power fluctuations in a finite period of time in future. In [24], the authors proposed a SOC feedback control strategy in real time to maintain the SOC in a proper range to provide ramp up and down energy reserve. In [25], a genetic algorithm based approach was proposed to find the optimal parameters of the electrical equivalent circuit based battery model which minimized the errors between the measure battery terminal voltage and the voltage calculated by the battery model. Although existing approaches have achieved satisfying results for their formulated objective functions, there still exist some significant drawbacks, which are discussed as follows.

First, quite a number of literatures [26,27] consider the BESS model with a constant charging/discharging efficiency, which may not be a reasonable assumption due to the internal resistance of the BESS. As demonstrated in [28,29], the charging/discharging efficiency of BESS will change with the charging/discharging power. Therefore, a proper BESS model considering energy efficiency is required for more accurate estimation of the SOC level.

Second, most existing works consider the BESS as a deterministic model, while some important factors are overlooked for the model simplification. Since the BESS needs to be charged and discharged very often, the internal parameters will change due to the thermal effect and other unmodeled environmental factors. The control performance can be considerably degraded if the BESS model uncertainty is ignored.

Third, although traditional robust control algorithms can effectively adapt to the uncertainty and disturbance, they mainly provide asymptotical convergence. In [30,31], the applicability and effectiveness of the robust control algorithms with asymptotical convergence have been demonstrated in conventional power system applications with less frequently changing operating conditions. However, in the application with a high penetration level of renewable source energy, a finite-time convergence robust control algorithm is desired to address the highly intermittent nature of the wind power and enable the real-time coordinated control of wind generator-BESS devices. In [32], a finite-time convergence robust control algorithm is proposed to restore the voltage and frequency of a microgrid. However, the finite convergence time is predetermined by the system, which is difficult to adjust according to the operating condition and dynamic performance criteria.

To address the afore-mentioned drawbacks, this paper proposes a finite-time convergence robust control algorithm for the BESS to smooth the wind power output in a real-time manner. It is convenient to adjust the convergence time during fast changing wind speed period to improve the dynamic performance. The proposed algorithm is flexible, robust, and its validity is proved through rigorous analysis. The effectiveness of the proposed algorithm is demonstrated through simulations with a wind generator-BESS system. The major merits of the proposed control algorithm are summarized as follows:

(1) A more accurate BESS model is adopted instead of using a constant charging/discharging efficiency model;
(2) The SOC of BESS is regulated in a proper range, which enables the BESS to have enough capability to smooth the future power fluctuations without being over-charged or over-discharged in a long time period;
(3) A finite-time convergence robust control strategy is proposed in this paper, which enables flexible convergence time adjustments according to different situations or the preferences of various users.

The rest of the paper is organized as follows. Section 2 describes the problem of mitigating the wind power fluctuations. Section 3 introduces the BESS model. Section 4 presents the proposed finite-time convergence robust control algorithm and the convergence proof. Section 5 discusses the simulation results of the proposed algorithm, and Section 6 provides the conclusion.

2. Wind power fluctuations mitigation

Power system with high penetration level of wind power encounters significant challenges for its operation and control. Limiting the ramp-rate of the wind turbine's output power is useful when wind power output fluctuates up. However, the wind power output would not only fluctuate up but also fluctuate down. Limiting the ramp-rate of the wind turbine is conductive to restrict the ramp-up wind power fluctuations while it may not be able to compensate the ramp-down wind power fluctuations. Integration of the BESS can be an effective energy management means to improve the power quality of renewable energy hybrid power generation systems, specifically in terms of power output smoothing. Previous literature [33] shows that the power systems are subjected to the medium frequency power fluctuations (between 0.01 Hz and 1 Hz), because the generator inertia can absorb the high-frequency power fluctuations and the secondary control-automatic generation control (AGC) can alleviate the low-frequency fluctuations. Therefore, the BESS is designed to mitigate the fluctuations located in the medium frequency range.

Fig. 1 illustrates the topology of a hybrid wind generator-BESS system implemented in grid-connected mode adopted in this paper. BESS and wind generator are connected to the main grid at the point of common coupling (PCC). To smooth the wind power injected into the main grid, the real-time voltage (v_{abc}) and current (i_{abc}) output of the wind generator are sampled and its active power (P_w) is calculated. The high-frequency fluctuations component of P_w is filtered out by a first-order LPF, which becomes P_w^L. The filtering time constant T_{c1} is equivalent to $1/(2\pi f_{c1})$, where f_{c1} is the cut-off frequency. The cut-off frequency is set to 0.01 Hz in this paper, to remove the high-frequency component. The difference between the pre- and post-filtered wind power becomes a target signal (P_b^*) for the charging/discharging power output of BESS. Other smoothing filter approaches such as moving average filter (MAF) and Kalman filter (KF) can be easily applied based on this structure.

The transfer s-function of the LPF is given in Eq. (1) and the relationship between P_w and P_b^* is provided in Eq. (2).

$$G_{LPF}(s) = \frac{P_w^L}{P_w} = \frac{1}{T_{c1}s + 1} \tag{1}$$

$$P_b^* = \frac{-T_{c1}s}{T_{c1}s + 1} P_w \tag{2}$$

Although the main objective of the proposed control strategy is to mitigate the wind power fluctuations, practical constraints on SOC and the charging/discharging rate of BESS need to be satisfied all the time. If there is no effective control method for the regulation of SOC and rate limit, BESS with a large capacity and high per-