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Minimization and control of battery energy storage for wind power smoothing: Aggregated, distributed and semi-distributed storage

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ABSTRACT

A battery energy storage system (BESS) is usually integrated with a wind farm to smooth out its intermittent power in order to make it more dispatchable. This paper focuses on the development of a scheme to minimize the capacity of BESS in a distributed configuration using model predictive control theory and wind power prediction. The purpose to minimize the BESS capacity is to reduce the overall cost of the system as the capacity of BESS is the main cost driver. A new semi-distributed BESS scheme is proposed and the strategy is analyzed as a way of improving the suppression of the fluctuations in the wind farm power output. The scheme is tested for similar and dissimilar wind power profiles, where the turbines are geographically located closer and further from each other, respectively. These two power profiles are assessed under a variety of hard system constraints for both the proposed and conventional BESS configurations. Based on the simulation results validated with real-world wind farm data, it has been observed that the proposed semi-distributed BESS scheme results in the improved performance as compared with conventional configurations such as aggregated and distributed storage.

1. Introduction

In recent years there has been a growing demand for wind power worldwide [1]. However, the intermittent nature of such power poses challenges for its integration into electricity networks with conventional generators. Industry must overcome a number of technical issues to deliver wind power in significant quantities without creating reliability, stability, and power quality problems in the main electrical grid. Firstly, advanced control techniques are a key enabling technology for the deployment of such renewable energy systems. Therefore, wind power requires effective use of such advanced control strategies that can cope with technical issues to improve the performance and to decrease the cost per kilowatt-hour generated. Secondly, a battery energy storage system (BESS) is usually necessary to maintain the power and energy balance as well as to improve the power quality. Since the cost of energy storage units per power unit is a strong function of their capacity, and too high cost is prohibitive to industrial and commercial acceptance, a method for optimizing the size and operation of such storage systems to fit application constraints is a crucial task.

The emergence and subsequent growth of distributed generation has been widely accepted worldwide. A significant percentage of currently installed distributed generation is from wind generation connected to rural distribution systems and the trend is towards its continued growth. The demand for a more secure, reliable, and efficient power system using non-dispatchable resources like wind is increasing rapidly. However, the integration of non-dispatchable renewable energy resources into the existing design and operational practices of the electrical power grid is not easy [2]. The distributed energy storage system is a key to the future development of all non-dispatchable renewable energy resources in the electrical power grid [3]. The use of distributed energy storage systems was justified with proper control, intelligent monitoring, and communications with net overall benefits as compared with conventional power solutions [4].

A schematic diagram of a general generation-storage system with wind power is shown in Fig. 1 whereas the 'aggregated' and 'distributed' are the well known BESS configurations in a distributed fashion. The aggregated BESS configuration has been considered to be superior because of less storage units. However, the distributed generation and storage is now becoming more popular because of the associated advantages. Distributed generation within the existing power network is utilized in order to meet the

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growing load demand of particularly rural and remote areas. Thus the need to minimize the capacity of distributed energy storage systems and to realize the maximum benefits and reduce losses, optimal operation and management of distributed energy storage devices in a distribution system with wind generation has become extremely important [5,6].

Therefore, the goal of this study is to propose such a scheme that offers the operation of wind power smoothing with optimized capacity of distributed BESS and consequently minimizes the cost of the overall storage system and maximizes the profit for potential BESS owner. It can be achieved if BESS can be used in a best configuration and overall system can be operated under certain feasible bounds, constraints, and limitations. A semi-distributed BESS configuration is proposed in this study along with predictive control theory to optimize BESS operation under certain limitations, conditions, and constraints associated with a wind power smoothing model [7]. Firstly, the scheme is tested for similar power profiles of turbines where the turbines are located geographically closer to each other in a given wind farm site. Secondly, the results are validated with dissimilar power profiles of the turbines located further from each other geographically. It was observed that the amount of storage required for the given wind power smoothing is smaller in case of the proposed semi-distributed scheme as compared with aggregated and distributed configurations.

The remainder of the paper is organized as follows. Energy storage and related configurations are demonstrated in Section 2. The proposed methodology is described in Section 3. The information about databases is given in Section 4. Section 5 presents the results and discussions.

2. Energy storage configurations

The output power of wind turbines fluctuates. These power fluctuations make the wind power un-dispatchable. Furthermore, they can cause frequency deviations and power outage particularly when wind power penetration is significant. Thus any power grid intending to use large amounts of wind normally needs to use power storage units and/or backup generation to smooth fluctuations in the output. Generally, a wind farm consists of a wind power plant and an energy storage system. The storage units can be distributed in two well known configurations. Fig. 2a and b shows the conventional aggregated and distributed configurations respectively.

Most electricity grids were constructed to supply dispersed loads from centralized plants where power is generated on a large scale. Power losses from source to end use can be high at both distribution and transmission levels, depending on the layout of the grid and the distance between the power plants and the loads. Installation of small, distributed generating units near the loads will therefore reduce power flow from the central plants and losses. Many studies have concluded that dispersed and properly sized wind turbines and distributed wind power plants reduce losses [8,9]. However, since wind is a highly intermittent energy source, such benefits are likely to be small and site-specific. Installation of local energy storage could enhance wind farm performance and is a promising technology for optimal operation of a distribution network [10,11].

The cost of a BESS per power unit is a strong function of its capacity, i.e., the maximum discharge time. The total BESS cost over the complete lifetime is calculated by adding the cost of power conversion system and the net present value of costs of BESS type [12]. In most cases, its contribution to the total operational cost is found to be dominant, discouraging further penetration of the available wind resource [13,14]. Therefore, the goal is to minimize the capacity of distributed BESS to make a wind farm more dispatchable.

3. Proposed methodology

3.1. Semi-distributed BESS configuration

The proposed semi-distributed BESS configuration is shown in Fig. 3. It consists of a separate BESS unit at each individual turbine and an aggregated BESS unit. The key idea of the proposed semi-distributed scheme is to partially suppress the wind power fluctuations at the individual turbines with comparatively smaller capacities of BESS. As a result the aggregated BESS in the proposed scheme receives less variable power at its input and the required wind power smoothing can be achieved with a smaller capacity. The objective to minimize the total capacity of the proposed configuration is achieved with the careful selection of system parameters, a control system model, a predictive controller along with wind power prediction system where the system for the prediction of power generation is based on measurements from multiple observation points [15]. These measurements are transmitted over communication channels to our designed predictor. In fact, this system is an example of a networked control system. In recent years, such systems have been gaining popularity with their high potential in widespread applications [16–18].

3.2. Control system model

Consider the following model for wind power smoothing and battery energy storage system,

$$\begin{aligned} x_1(k+1) &= r(k) - u(k) \\ x_2(k+1) &= x_1(k) + x_2(k) \end{aligned} \tag{1}$$

$$y(k) = k_1 x_2(k) \tag{2}$$

with the following cost function

$$J := \sum_{k=0}^{M-1} (r(k) - u(k))^2 + \alpha (x_2(k))^2 \rightarrow \min \tag{3}$$

subject to the following constraints

$$0 < u(k) \le P_{\text{rated}}; \quad k = 0, 1, \cdots, M-1 \tag{4}$$

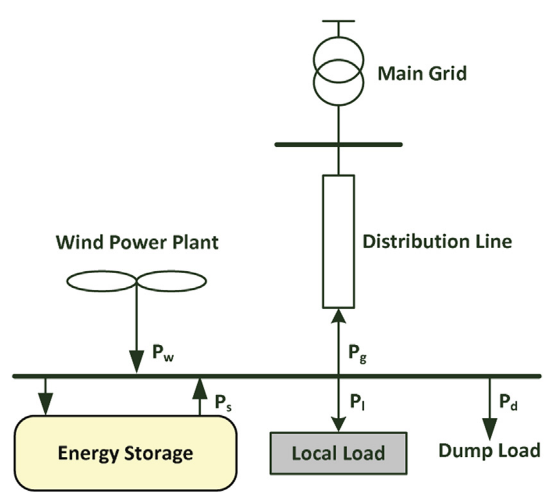

Fig. 1. Local energy storage and wind power generation.