2014 IEEE Conference on Control Applications (CCA)
Part of 2014 IEEE Multi-conference on Systems and Control
October 8-10, 2014. Antibes, France

Optimal Size of Battery Energy Storage and Monotonic Charging/Discharging Strategies for Wind Farms

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Abstract— **This paper focuses on the development of a monotonic charge/discharge strategy to optimize the capacity of a large-scale battery energy storage system (BESS) integrated with a large wind farm to smooth out the intermittent wind farm output for effective power dispatch to the electricity grid. Since a large-scale BESS is rather expensive, adopting such strategy for optimal sizing of the BESS has become critically important. The paper proposes a constraint-based monotonic charge/discharge strategy for multiple batteries of a BESS and determines the optimal capacity of each individual battery satisfying a set of given operating constraints. The effectiveness of the strategy is confirmed with data analysis taken from an actual wind farm. The strategy is generic enough to be applicable to other intermittent generation sources such as solar PV farms.**

I. INTRODUCTION

Renewable energy systems (RESs) either off-grid or grid-connected have the tremendous potential to reduce our dependency on fossil fuels, improve security of supply and reduce greenhouse gas emissions, delivering significant environmental benefits for societies [1]. Control and optimization of RESs, especially those of large-scale integrated with the electricity grids are key technological developments urgently needed to ensure high penetration of those systems is technically feasible without risking grid stability and performance. In particular, wind power is undergoing the fastest rate of growth of any form of electricity generation in the world [1]. However, high penetration of wind power could introduce technical challenges associated with power quality, reactive power and voltage control, reliability, availability, protection, generation dispatch to mention just few of them.

Given the non-controllable and stochastic nature of the renewable energy (RE) resources, a natural solution is the use of a battery energy storage system (BESS) which allows accumulating the surplus energy in those periods in which RE production is higher than the plant power commitment and delivering it back in the opposite situation. Today there are several battery energy storage technologies available in the market, though all of them are still expensive for wind power applications. Since the size of the BESS determines its cost [2], it becomes important that the control schemes for the BESS should be tailored to minimize the required BESS size and optimize BESS's operation within the given physical constraints. Obviously the BESS can easily be depleted or overcharged in the absence of additional control actions and it is not desired to deplete or overcharge the battery.

An optimum BESS sizing calculation combined with an optimized control strategy for the RES-BESS power plant are key issues for the future economic viability of these renewable power resources. In the technical literature, different proposals have been published to increase the penetration of wind generation systems in a power system; most of them used BESS to support RES power plants [3], [4], [5], [6], [7], [8], [9], [10]. However, most of them are focused on isolated grids and micro-grids or rely on basic control approaches which require a larger BESS. Since a large-scale BESS is rather expensive, adopting a control strategy for optimal use of the BESS is a critical design issue.

In this paper, we focus on the size optimization of a BESS comprising of a number of batteries and is integrated with a large-scale grid-connected wind farm. A constraint-based monotonic charging/discharging strategy is proposed to achieve a more efficient BESS operation. The proposed strategy originates from the fact that the consistent charging/discharging direction of batteries in the BESS reduces the battery ageing and prolongs the battery lifetime [11]. Secondly the monotonic charging/dischargng cycles are restricted within the physical and realistic operating constraints of the BESS so as to avoid overcharging of a battery or its depletion. The optimal capacity of each individual battery and consequently the total BESS size is determined by increasing the number of its batteries.

The remainder of the paper is organized as follows. Section II provides the brief background. The proposed BESS sizing methodology is described in III. The proposed control scheme is given in Section IV. Section V presents the simulation results and discussions. Finally, Section VI concludes the paper.

II. BACKGROUND

We consider a wind power farm integrated with a BESS. The use of BESS to compensate for the intermittent power output of the wind farm is illustrated in Fig. 1. The BESS is connected to the system at the point of common coupling and is charged/discharged through power electronics converters to smooth the new power injected to the grid. To date, different solutions have already been implemented to mitigate wind power intermittency [12], [13], [14], [15], [16], [17]. Recent advances in energy storage technologies provide an opportunity for increasing wind power use

This work was supported by the Australian Research Council.

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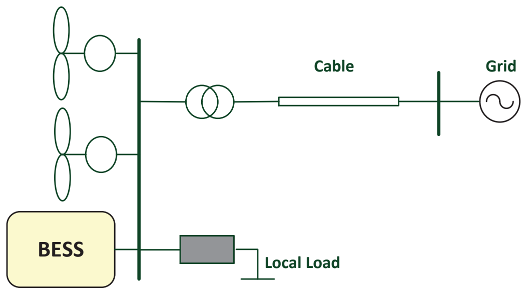


Fig. 1. A grid-connected wind farm with a BESS.

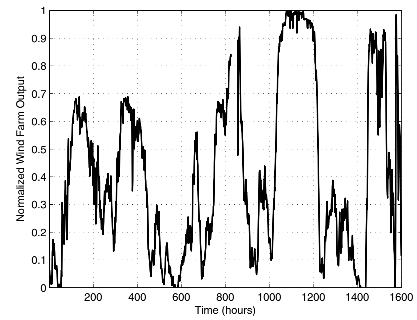


Fig. 2. Typical wind farm's power profile.

and reducing wind energy intermittency [18]. A variety of energy storage technologies have been investigated for renewable energy power generation, such as flywheels, superconducting magnetic energy storage, electrolytic hydrogen, super-capacitors, and battery storage technologies [19], [20], though all of them are still expensive for RESs applications due to over-dimensioning of storage system and/or poor operation strategy. For example, frequent charge/discharge cycles may seriously affect the health of the batteries by shortening the lifetime of batteries.

Fig. 2 shows the actual wind power profile of a 65MW wind farm over a time interval of more than two months. The figure shows that the wind power output exhibits steep rises, sudden drops and hence highly fluctuating for most of the time. Integrating such a highly intermittent power resource into the grid, especially into a weak one, can pose serious challenges [21] and it can be seen that a quite large BESS is required for an effective power dispatch, even assuming 90% accurate forecast of the average wind power output and an ideal BESS, to compensate for the differences between the dispatch level and the actual power output. This paper focuses on the sizing of BESS and in particular addresses the critical issues such as minimizing the size of the BESS, limiting the number of charge/discharge cycles of the BESS, and optimizing the BESS operation for grid connected wind farm.

III. BESS Sizing Methodology

Let $p(t)$ denote the energy production of the wind farm at time t, and let $g(t)$ denote the amount of energy sent to the grid at time t. Furthermore, let $e(t)$ denote the difference

$$e(t) = p(t) - g(t) \tag{1}$$

which is sent to the battery energy storage assuming that the conversion stages are lossless. If $e(t) > 0$ the BESS is charged, if $e(t) < 0$ the BESS is discharged.

We assume that $e(t)$ is bounded piecewise continuous function satisfying the following constraint:

$$-a \leq \int_0^T e(t)dt \leq a \qquad \forall T > 0 \tag{2}$$

where $a > 0$ is a given constant.

We assume that the BESS consists of several identical batteries and each battery has capacity $c > 0$. Let $x_i(t)$ denote the amount of energy at time t in the battery i. To prolong the battery's life and reduce the cost of the BESS, we require the following two constraints.

C1: Let $0 < \alpha_m < \alpha_M < 1$ be given constants. Then

$$\alpha_m c \leq x_i(t) \leq \alpha_M c \qquad \forall t \geq 0 \quad \forall i.$$

C2: For any i there exists a sequence of times $t_0^{(i)} = 0, t_1^{(i)}, t_2^{(i)}, t_3^{(i)}, \ldots,$ such that for any $k = 0,1,2,3,\ldots,$ either

$$x_i(t_k^{(i)}) = \alpha_m c, x_i(t_{k+1}^{(i)}) = \alpha_M c,$$
$$\dot{x}_i(t) \geq 0 \quad \forall x_i(t_k^{(i)}) < t < x_i(t_{k+1}^{(i)}),$$

or

$$x_i(t_k^{(i)}) = \alpha_M c, \quad x_i(t_{k+1}^{(i)}) = \alpha_m c,$$
$$\dot{x}_i(t) \leq 0 \quad \forall x_i(t_k^{(i)}) < t < x_i(t_{k+1}^{(i)}).$$

In other words, the battery is monotonically charged from $\alpha_m c$ to $\alpha_M c$, and then is monotonically discharged from $\alpha_M c$ to $\alpha_m c$ and so on as shown in Fig. 3a.

Now we assume that the BESS consists of $2n$ batteries where $n = 1,2,3,\ldots,$ and the first n batteries are initially charged to minimum allowed level, and the other n batteries are initially charged to the maximum allowed level as in Fig. 4, i.e.,

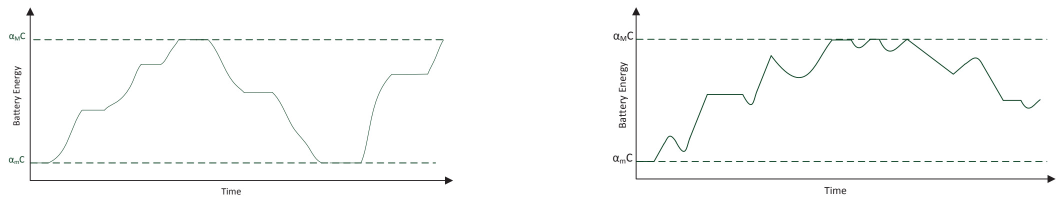
$$\begin{aligned} x_i(0) &= \alpha_m c \qquad \forall i = 1,2,\ldots,n, \\ x_i(0) &= \alpha_M c \qquad \forall i = n+1,2,\ldots,2n. \end{aligned} \tag{3}$$

We will consider charge/discharge strategies of the form

$$\begin{aligned} \dot{x}(t) &= u(t), \\ u(t) &= \mathscr{U}[x(\cdot)\mid_0^t, e(\cdot)\mid_0^t]. \end{aligned} \tag{4}$$

Here $x(t) := (x_1(t), x_2(t), \ldots, x_{2n}(t))'$, $u(t)$ is the control input vector of dimension $2n$, $\mathscr{U}[x(\cdot)\mid_0^t, e(\cdot)\mid_0^t]$ is an arbitrary function. Notice that this function is based on the past values of $x(t), e(t)$ and does not use any future values. Our goal is to find the optimal battery capacity $c(n)$ and derive a monotonic charge/discharge strategy for the battery capacity $c(n)$. We propose the following theorem:

Theorem 3.1: Let n, a, α_m, α_M be given. Consider the BESS consisting of $2n$ batteries of capacity c and suppose that (3) is satisfied. Then the following two statements hold:



(a) (b)

Fig. 3. Charging/discharging characteristics of a BESS (a) A monotonic charge/discharge. (b) A charge/discharge without the monotonicity requirement.

(i): If $n = 1$, then $c(n) = \infty$. In other words, there does not exist any monotonic charge/discharge strategy with two batteries.

(ii): If $n > 1$, then

$$c(n) = \frac{a}{(\alpha_M - \alpha_m)(n-1)}. \tag{5}$$

Furthermore, if the BESS consists of $2n$ batteries with capacities $c = c(n)$ each, where $c(n)$ is defined by (5), then the proposed charge/discharge strategy is monotonic.

The proof of this theorem is given in the journal version of this paper.

Remark 3.1: Let $C(n)$ denote the common capacity of $2n$ batteries with the optimal capacity each. It immediately follows from Theorem 3.1 that

$$C(n) = \frac{2na}{(\alpha_M - \alpha_m)(n-1)} = \frac{2a}{(\alpha_M - \alpha_m)}(1 + \frac{1}{n-1}). \tag{6}$$

Therefore, it is obvious that $C(n)$ is decreasing with n and

$$C(n) \to \frac{2a}{(\alpha_M - \alpha_m)} \quad as \quad n \to \infty.$$

IV. The Control Scheme

In this section, we describe our Model Predictive Control (MPC) based algorithm to smooth a wind farm output. This algorithm is a modification of the MPC algorithm developed in [13]. Let $p(k)$ be the actual wind power output of a wind farm, $g(k)$ be the smoothed power or grid power sent to electricity grid which we need to calculate according to our algorithm. The difference between the actual and smoothed power $e(k)$ is sent to BESS. We propose the following model for wind power smoothing and BESS.

$$\begin{aligned} e(k+1) &= p(k) - g(k) \\ x(k+1) &= x(k) + e(k) \end{aligned} \tag{7}$$

$$y(k) = \tau x(k) \tag{8}$$

where $x(k)$ is the energy state of the BESS. The τ is the constant multiplier and it is based on the given system's time period, and $y(k)$ is the net energy state of BESS.

The cost function associated with the system is

$$J := \sum_{k=0}^{M-1} e(k)^2 \to \min \tag{9}$$

where the integer k represents the time instant and M is the control horizon.

The system is subjected to the following constraints

$$0 < g(k) \le g_{max};\ k = 0, 1, \cdots, M-1 \tag{10}$$

$$-r_{min} \le g(k+1) - g(k) \le r_{max};\ k = 0, 1, \cdots, M-1 \tag{11}$$

where g_{max}, r_{min} and r_{max} are the given constraints. We refer to [22] and [4] for further details and a brief physical interpretation of constraints associated with any energy storage system.

The solution of the proposed wind power smoothing model is based on MPC theory. MPC is one of the most frequently employed control algorithms in current industrial practice. It is applied in numerous industrial, medical, and financial applications, e.g., chemical process control, power plant operations, smart energy systems, subsurface oil recovery, engines, and dynamic portfolio optimization (see, e.g., [23], [24] and references therein). MPC is now widely used in renewable energy systems [25] and power systems [26]. MPC is preferred mainly because most processes need to be operated under tight performance specifications. These specifications can be met when process constraints are explicitly taken into account in the controller design. The proposed control technique is very effective for this problem particularly due to its intrinsic constraint-handling capability, direct handling of multi-input multi-output problems, and easy development and implementation in real time.

In this paper, we define the control signal as $\tilde{u} := g$ and our proposed model is standardized such that techniques in [24] can be applied, where the optimal solution of the form

$$\tilde{U}^{Opt} = [\tilde{u}^{OPT}(0), \tilde{u}^{OPT}(1), ..., \tilde{u}^{OPT}(M-1)]^T \tag{12}$$

can be numerically solved as static-optimization problem of the form

$$\tilde{U}^{OPT} = \arg \min_{\substack{\tilde{U} \\ L\tilde{U} \le K}} \tilde{U}^T W \tilde{U} + 2\tilde{U}^T V \tag{13}$$

where W and V are functions of system matrices in our system (7), (8).

The magnitude and rate constraints can be easily expressed as linear constraints on $\tilde{U}$ of the form

$$L\tilde{U} \le K \tag{14}$$

and the convex optimization problem with quadratic cost function and linear constraints can be solved using standard numerical procedures like Quadratic Programming (QP) algorithms using MATLAB.

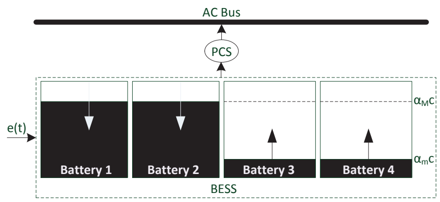


Fig. 4. The charging/discharging structure of the BESS.

V. Simulation Results

The proposed strategy has been tested by simulations using actual data from a wind farm of capacity 65MW. The wind farm observation data used consists of output power of the Roaring 40s Woolnorth wind farm in Tasmania, Australia. The first and a very important step in our proposed methodology is to find the value of the constant a from (2), which is the upper limit of the difference signal defined by (1). Secondly, we find the optimal capacities of BESSs consisting of 4, 6, 8, 10 and 12 batteries. The optimal capacity c of each battery in the BESS has been determined using the formula (6) for a particular value of a calculated as the minimum upper limit for difference signal $e(t)$. It can be observed from Fig. 5 that the optimal capacity of an individual battery decreases with an increase in the number of batteries in a BESS. Consequently, it also reduces the corresponding overall BESS capacity in each case as shown in Fig. 5. The final goal is to achieve the monotonicity of each individual battery in a given BESS for pre-calculated optimal battery capacity and for given lower and upper bounds. It can be observed that the proposed strategy ensures the monotonic behavior of the BESS with slow and fast charge/discharge rates with same optimal battery capacity c for the chosen data set as shown in Figs. 6 and 7. Ideally optimal capacity of each individual battery of the BESS must be found using historical data of fairly time long duration like one year, but due to unavailability of continuous data of such long time duration the algorithm was tested using the data period of one month.

VI. Conclusion

Optimal capacity of a large-scale BESS integrated with a grid-connected wind farm has been determined. It has been shown that the optimal size of all the batteries of the BESS decreases as the number of batteries increases. Furthermore, the optimal size of all the batteries of the BESS tends to some positive limit as the number of batteries approaches to infinity. We have proposed a constraint-based monotonic charge/discharge strategy of individual batteries of BESS with optimal capacity each. The two-fold benefits of the strategy lie in determining the overall optimal size of the BESS along with a strategy for charging and discharging of each individual battery of the BESS satisfying the given operating constraints. Simulation results prove the effectiveness of the proposed strategy. It has also been observed that the proposed strategy is robust against the variations in the system parameters.

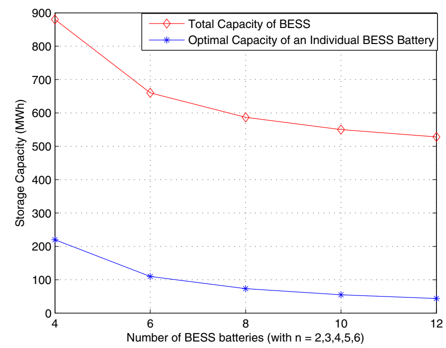


Fig. 5. The optimal BESS capacity trend vs number of batteries in a BESS.

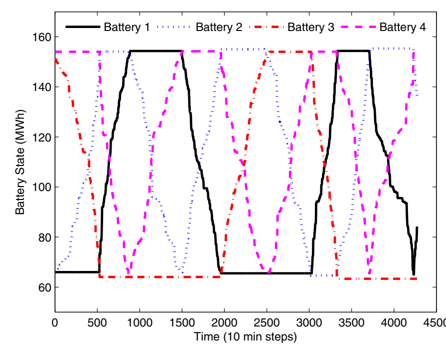


Fig. 6. Monotonic charging/discharging of BESS batteries within 30% - 70% operation band of optimal capacity each with fast rates.

VII. Acknowledgment

We would like to thank Hugh Outhred, Iain MacGill, Merlinde Kay, Nicholas Cutler, and Peerapat Vithayasrichareon at the Centre of Energy and Environmental Markets (CEEM) at the University of New South Wales (UNSW) for their assistance in getting the required wind power data to carry out this research. We would also like to thank Roaring40s for the use of their data.

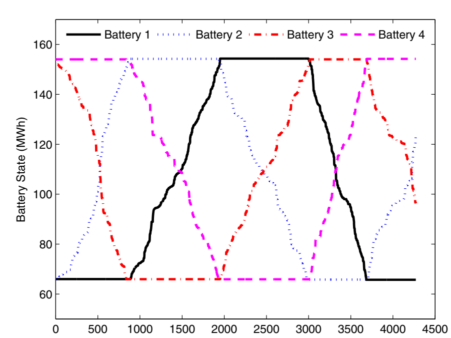


Fig. 7. Monotonic charging/discharging of BESS batteries within 30% - 70% operation band of optimal capacity each with slow rates.

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