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An optimal operation of wind energy storage system for frequency control based on model predictive control

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ABSTRACT

A method for an efficient operation of a battery energy storage system (BESS) associated with frequency control problem is presented in this paper. A control system model is proposed to simulate the operation of BESS, and a controller is designed. The strategy is based on model predictive control to ensure the optimal operation of BESS in the presence of system constraints. A frequency prediction model based on Grey theory is also designed to optimize the performance of the predictive controller. The method is tested using real measurements from a power grid. The simulation results depict the effectiveness of the proposed approach.

1. Introduction

Energy storage technology has become an attractive option to cover a wide spectrum of applications ranging from short term power quality support to long term energy management. Various technologies such as battery energy storage systems (BESS), compressed air energy storage (CAES), pumped storage, and superconducting magnetic energy storage (SMES) are used for this purpose. The devices such as batteries, ultracapacitors, super inductors, flywheels, and fuel cell systems are normally utilized for storage purposes [1]. A principal diagram of BESS is shown in Fig. 1.

As the world is moving towards renewable energy sources such as wind and solar. In particular, wind energy is becoming the fastest growing energy technology in the world. It provides a clean opportunity for future power generation and many countries have started harnessing it [2]. Due to the intermittent nature of these sources, significant problems such as frequency control, voltage support, excessive peak loads on transmission lines, and power quality may arise [3]. Therefore, energy storage is critical to act as a buffer for the grid. The role of energy storage is also significant in different applications. For example, load leveling, load frequency control, peak shaving, wind power smoothing, and power quality control; see, e.g., [4–7] and references therein. It can also be used in primary frequency control (the frequency regulation during first few seconds of deviation) and secondary frequency control (the frequency regulation up to a few minutes after the primary control).

Model predictive control (MPC) has gained popularity in the industry since the 1990s and there is a steadily increasing attention from control practitioners and theoreticians. MPC has been a major success story in the modern control engineering. Thousands of industrial applications have been reported in the literature, especially in the petrochemical area; see, e.g., [8,9]. The advantage of MPC is mainly due to the fact that today's processes need to be operated under tight performance specifications and more and more constraints need to be satisfied. These demands can only be met when process constraints are explicitly taken into account in the controller design. MPC is an effective solution for that due to its intrinsic constraints handling capability.

Clearly BESS has certain constraints to satisfy in order to regulate the frequency at a nominal value. The constraints associated with BESS are expressed in terms of battery capacity, battery power, state of charge, and charging/discharging rate. For frequency control, certain constraints need to be satisfied as specified in the grid code; e.g., nominal frequency, maximum frequency deviation and non-critical window of frequency.

In this study, a control system model to simulate the operation of BESS is proposed along with the design of its controller. As a case study, the controller has been tested with real data from a power grid. In addition, a frequency predictor based on the Grey model has been designed to improve the performance of the predictive controller. The prediction model involved is capable of predicting

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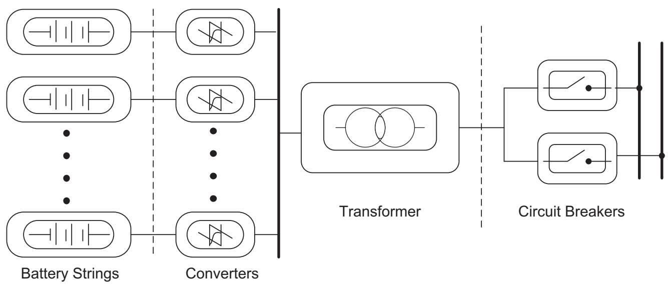

Fig. 1. A principal BESS.

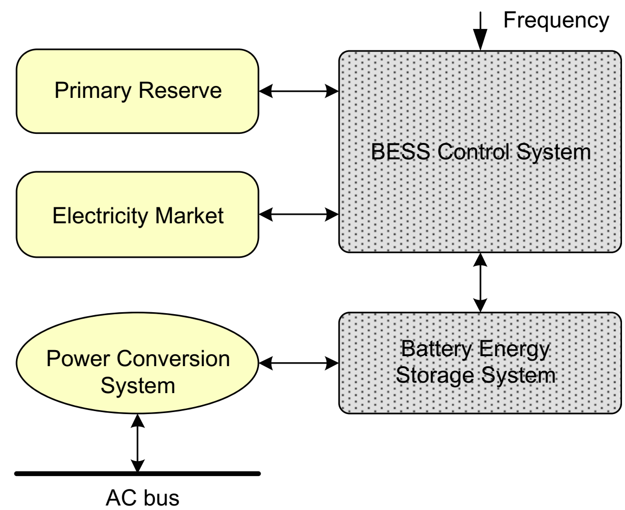

Fig. 2. Schematic diagram of the system.

frequency multi-step ahead which is used in the optimization part of the controller.

The remainder of the paper is organized as follows: Section 2 briefly describes the problem description and associated requirements. Section 3 describes the proposed model. The information about data under study is given in Section 4. Section 5 presents the simulation results. Finally, Section 6.1 concludes the paper with the future works in Section 6.2.

2. Problem description

A basic schematic diagram of system is shown in Fig. 2. The objective of this study is to propose a control system model and to design a controller for the efficient operation of BESS facility for the frequency control application under variety of constraints imposed by both BESS and the grid. The overall goal of the study is to minimize the cost associated with BESS which can be achieved either by minimizing the capacity of BESS or by optimizing it's operation. A brief description, requirements, and limitations of the main components of the system are briefly described in the following sub-sections.

2.1. Battery energy storage system

Indeed the battery energy storage can provide the frequency regulation [10–12]. The basic principle of BESS is that it discharges the energy into the grid when the system frequency is below a nominal value and absorbs the energy when the system frequency is above that value. The important factor associated with BESS is the total cost, therefore, cost can be reduced either by minimizing the capacity of the storage unit [13] or by optimizing its operation. A simple control algorithm based on MPC for the optimal operation of BESS is proposed in this research. For an overview of other techniques; see, e.g., [14,15] and references therein.

The mathematical relation between storage content and the power flow of the storage device can be expressed as,

Charging case: absorbing power

$$S(t+1) = S(t) + \eta_c P_s(t)\Delta t; \ (P_s(t) \geq 0) \tag{1}$$

Discharging case: supplying power

$$S(t+1) = S(t) + \frac{1}{\eta_d} P_s(t)\Delta t; \ (P_s(t) \leq 0) \tag{2}$$

with the following constraints,

$$S^{\min} \leq S(t) \leq S^{\max} \tag{3}$$

$$P_s^{\min} \leq P_s(t) \leq P_s^{\max} \tag{4}$$

where P_s is the power flow in and out of the battery, S is the actual storage content or energy, η_c and η_d are the efficiencies of charging and discharging respectively and Δt is the time interval.

A reliable control system is required in order to approximate the efficient operation of battery such that the battery should neither be completely discharged nor overcharged, the BESS should operate between desired state of charge (SoC) levels, and the rate of charge/discharge of battery should be within the range in order to ensure maximum lifetime of battery.

2.2. Frequency control

The power production and consumption must be matched instantaneously and continuously in the power system. However, some factors as discussed in Section 1 may cause a deviation of system frequency from a set-point value and reduce the power quality. Therefore, a sufficient amount of active power is maintained in reserve to compensate for the mismatch. This is known as frequency control reserve and BESS serves this purpose. In any electric system, a constant equilibrium must be maintained between power generated and power demanded/consumed. A deviation of the system frequency f from it's nominal value f_o occurs due to any disturbances in this balance. As soon as frequency deviation ($\Delta f = f - f_o$) occurs, the controller must respond instantaneously within a few seconds to regulate the frequency inside the allowed tolerance band around the nominal frequency value as specified in the grid code, utilizing the BESS power.

The nominal frequency value is typically 50 Hz and the controller activation is triggered as soon as the frequency deviation towards the nominal frequency exceeds tolerance band of 20 mHz. The transformation of the frequency deviations into a required power in/out is based on power-frequency (*p-f*) characteristics as shown in Fig. 3. For further details, specific rules and requirements, the reader is referred to the Union for the Co-ordination of Transmission of Electricity (UCTE) handbook [16].

2.3. Economic optimization

In brief, the profit associated with BESS application is defined by the equation [13],

$$\text{Net profit} = \text{NPV}_{\text{Res}} - \text{NPV}_{\text{BESS}} \tag{5}$$

where the net present value of the reserve (NPV_{Res}) and net present value of the BESS (NPV_{BESS}) are defined over the life cycle T of BESS with discount rate r as follows,