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Dispatchability of Wind Power with Battery Energy Storage in South Australia

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Abstract

In fiscal year 2016, 42% of electricity generated in South Australia came from intermittent renewable energy sources — a level of penetration that presents challenges to the economic supply of baseload power of acceptable quality. This study measures the improvement in the dispatchability of intermittent renewable energy from an SA wind farm coupled with a utility-scale battery using model predictive control and real-world data published by the Australian Energy Market Operator. The process of wind power dispatch with battery energy storage is represented as an incremental state-space model. The state-space model properly accounts for battery charge/discharge efficiency, and its incremental formulation allows the controller to penalise control effort.

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Keywords: Wind power dispatch, battery energy storage, baseload power, time shifting, model predictive control, state-space model.

1. Introduction

The Australian Energy Market Operator (AEMO) reports that of the electricity generated in the state of South Australia (SA) in fiscal year 2016, 35% and 7%, respectively, came from wind and solar photovoltaic [1]. At this level of intermittent renewable energy penetration the challenge is to economically supply baseload power of acceptable quality. This paper examines the dispatchability of wind power with battery energy storage in SA using state-space model predictive control (MPC). Improving dispatchability would permit time shifting of wind power dispatched to the electricity grid, enabling wind generators to supply baseload power, exploit energy arbitrage and provide ancillary services.

The contribution of this research is both theoretical and empirical. Our theoretical contribution represents the process of wind power dispatch with battery energy storage as an incremental state-space model.

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The state-space model properly accounts for battery charge/discharge efficiency, and its incremental formulation allows the MPC controller to penalise control effort. On an empirical level, we demonstrate the improvement in the dispatchability of intermittent renewable energy by simulating power dispatched to the grid by an SA wind farm coupled with a utility-scale battery at varying levels of confidence. Using unconstrained intermittent generation forecasts (UIGF) produced by the Australian Wind Energy Forecasting System (AWEFS) and published by AEMO, we find that the probability of power dispatched to the grid supplying a target baseload power is moderately higher with battery energy storage than no energy storage.

A number of recent studies use state-space MPC to demonstrate the improvement in wind power dispatch with battery energy storage. Their common objective is to minimise the tracking error of actual power dispatched to the grid relative to set points generated using, among other data, wind power forecasts. They implement MPC controllers that enable wind farms to: schedule power dispatched to the grid [2, 3]; minimise cost by prolonging battery life [4, 5]; maximise revenue by exploiting energy arbitrage [6]; or supply quality power through the provision of ancillary services [7]. The state-space models developed in prior papers are not of the incremental type, and do not penalise control effort. Nor do they properly account for battery charge/discharge efficiency, instead, either assuming 100% efficiency or approximating energy losses independent of the power stored or discharged during the dispatch interval.

2. State-Space Model Predictive Control of Wind Power Dispatch with Battery Energy Storage

Our research examines the dispatchability of intermittent renewable energy by simulating power dispatched by an SA wind farm coupled with a utility-scale battery using state-space *model predictive control* (MPC). A *state-space model* represents a physical process by describing its outputs as a function of state variables, which depend on control signals or process inputs. The MPC controller determines a sequence of control signals over a given control horizon that results in a sequence of predicted process outputs over a specified prediction horizon, which tracks a sequence of set points or reference signals. The resulting trajectory of predicted process outputs is an outcome of optimising a *performance index*, or minimising a cost function, that penalises the tracking error of the predicted process outputs relative to their set-point trajectory and the control effort involved in tracking the set-point trajectory.

2.1. Incremental State-Space Model

In the incremental formulation of the state-space model, the control signals become internal state variables augmenting the observable state variables, and control increments serve as process inputs. We begin by formulating a single-period incremental state-space model in the standard notation typically used to represent an abstract process. Then, we define the process outputs, state variables and control signals that capture the process dynamics of wind power dispatch with battery energy storage, and formulate the representative incremental state-space model for a single period.

Time in the incremental state-space model is represented as discrete time steps, or intervals, $t \in \mathbb{N}$. Suppose that discrete times $t-1$ and t, respectively, translate to clock times ς and τ. Then, "at time t" refers to clock time τ, and "during time interval t" refers to clock time interval $(\varsigma, \tau]$.

Let $\boldsymbol{y}(t) \in \mathbb{R}^m$ be the process output vector at time t, $\boldsymbol{x}(t) \in \mathbb{R}^{s-q}$ the observable state vector at time t, and $\boldsymbol{u}(t) \in \mathbb{R}^q$ the control signal vector at time t. Denote by $\boldsymbol{z}(t) \in \mathbb{R}^s$ the augmented state vector at time t, and $\boldsymbol{\Delta u}(t) \in \mathbb{R}^q$ the control increment vector at time t. Then, the single-period incremental state-space model representing an abstract process may be expressed as

$$\boldsymbol{z}(t+1) = \begin{bmatrix} \boldsymbol{x}(t+1) \\ \boldsymbol{u}(t) \end{bmatrix} = A \begin{bmatrix} \boldsymbol{x}(t) \\ \boldsymbol{u}(t-1) \end{bmatrix} + B\,(\boldsymbol{u}(t) - \boldsymbol{u}(t-1)) = A\boldsymbol{z}(t) + B\boldsymbol{\Delta u}(t), \quad (1)$$

$$\boldsymbol{y}(t+1) = C\boldsymbol{z}(t+1) = CA\boldsymbol{z}(t) + CB\boldsymbol{\Delta u}(t), \quad (2)$$

where $A \in \mathbb{R}^{s\times s}$, $B \in \mathbb{R}^{s\times q}$ and $C \in \mathbb{R}^{m\times s}$ are matrices defining the incremental state-space model.

Our incremental state-space model for wind power dispatch with battery energy storage includes two process outputs, four state variables and three control increments. Let $e(t) \geq 0$ be the state of charge (SOC) of the battery at time t, $p_{b+}(t) \geq 0$ the battery charge control signal at time t, and $p_{b-}(t) \geq 0$ the battery