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Integrating variable wind power using a hydropower cascade

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Abstract

In this paper, we examine the ability of a hydropower cascade to balance variability from wind power. We consider a coordinated hydro-wind system that satisfies a single power balance, and we use a real-time control scheme to optimize system operations such that wind and load curtailment is minimized. The control scheme considers system hydraulics (including dynamic tailrace elevations and water travel times) and system constraints. Generation from an individual hydropower plant is modeled using a convex piecewise planar approximation. We give results from a case study involving hydro and wind power in the Pacific Northwest region of the United States. The objective of this paper is to present a framework for evaluating how the regulation of wind generation affects hydropower operations. Our intention is to use this framework in future work to perform a systematic study of balancing capability across different hydraulic conditions, system constraints, and wind generation scenarios.

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Keywords: hydropower, wind power, renewable generation, optimization, model predictive control, quadratic programming

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1. Introduction

In recent years, there has been a sustained push to supplement and replace conventional thermal generation with wind and solar power. However, renewable generation is both intermittent and variable, and output power can only be forecasted with a certain degree of accuracy. As more wind power comes online, the variability from wind generation dominates the variability from electricity demand and stresses the power system's ability to remain balanced [1]. Methods to address this variability include the implementation of grid-scale storage, more active demand response, and increased deployment of fast ramping and cycling natural gas generation. However, in regions with the necessary water resources, flexible hydropower plants are viewed as an ideal counterpart to variable renewable generation [2]. There are examples in the literature demonstrating the benefits of operating hydropower and wind power symbiotically to increase economic profit [3], mitigate transmission congestion [4], and reduce wind curtailment [5]. Broader, system level studies have demonstrated repeatedly that “flexibility in the scheduling of hydro generation is clearly beneficial to the integration of wind and solar resources” [1,2,6].

This paper is focused on assessing the capability of a hydropower cascade to integrate different levels of wind penetration. Specifically, we look at the sub-hourly optimization and dispatch of hydropower and wind resources in order to identify how the performance of the hydropower cascade is affected by the variability and intermittency of

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wind power. Previous studies have indicated that the point where wind penetration begins to adversely affect the total value of an integrated hydro-wind system is between 20% and 30% [1,2,7]. However, these studies have also identified the need for more detailed modeling of minute-by-minute system hydraulics and real-time constraints in order to better characterize the relationship between wind penetration and the balancing performance of the hydropower system.

The paper is organized as follows. Section 2 presents optimization and system modeling for the hydropower cascade. Section 3 introduces the Mid-Columbia hydropower system and associated dataset. Section 4 presents the results from a case study used to illustrate our methods. Section 5 concludes the paper.

2. Modeling and optimizing the hydropower cascade

Our control scheme employs model predictive control (MPC), a type of receding horizon optimal control in which a linear state space model is used to predict the reaction of a system to a set of control inputs [8]. This section discusses the optimization scheme that we developed using the MPC framework (including the hydraulic model), the approximation of power production from a hydropower plant, the objective function, and the formulation of a combined hydro-wind system power balance.

2.1. Hydraulic model

Linear, time-discrete MPC models have the general form

$$\mathbf{x}(k+1) = A\mathbf{x}(k) + B\mathbf{u}(k) \tag{1}$$

for $k = 0, \ldots, K-1$ where $\mathbf{u}(k)$ is the vector of control variables and $\mathbf{x}(k)$ is the vector of state variables. The A and B matrices describe the relationship between the control inputs, current system state, and future system state. K is the discrete time-horizon over which the system is optimized. Constraints on state and control variables are explicitly incorporated into the MPC model. Additionally, since the state variable cannot change instantaneously, $\mathbf{x}(0)$ is a fixed value reflecting the initial system state.

In a cascaded hydropower system, hydraulic coupling of reservoirs can be modeled with a water balance equation in which water from the upstream hydropower plant (HPP) arrives in the forebay of the downstream HPP after some travel time. Mathematically,

$$x_j(k+1) = x_j(k) - \frac{t_k}{\Psi_j}\Big(q_j(k) + s_j(k)\Big) + \frac{t_k}{\Psi_j}\Big(w_j(k-\tau_j) + q_{j-1}(k-\tau_j) + s_{j-1}(k-\tau_j)\Big) \tag{2}$$

where the natural inflow into the reservoir behind dam j is denoted by $w_j(k)$; turbine discharge and spill through dam j is denoted by $q_j(k)$ and $s_j(k)$, respectively; and the water level behind dam j is denoted by $x_j(k)$. There are a total of J dams in the cascade. Ψ_j is the effective surface area of the reservoir behind dam j. The model is discretized by t_k, the length of the optimization interval. The t_k/Ψ_j term in (2) maps water flow into or out of reservoir j to a proportional increase or decrease in the elevation of reservoir j. For hydropower cascades with multiple upstream reservoirs, the water balance equation (2) could be modified to account for inflows from all upstream HPPs [4].

The travel time τ_j between dam $j-1$ and dam j is normalized by the optimization time step t_k. Water travel times on the Mid-Columbia are on the order of tens of minutes. In our previous work, we implicitly set $\tau_j = 0$ [9]. For modeling simplicity, we set the delay times for natural inflow, turbine discharge, and spill to be equal. Since natural inflows on the Mid-Columbia are relatively small, this assumption does not affect our modeling results. However, for other systems, the time delay for natural inflow could be different than the time delay for turbine discharge and spill. We also considered using river routing equations to model hydraulic coupling [10], but we elected not to use such a formulation because flow and elevation measurements were too noisy to fit accurate routing equations.

The state space model used in MPC relates the system state and control inputs at time k with the system state at the next time step $k+1$. Since the travel time between each dam is several times the length of the optimization time step, the formulation in (2) must be modified by introducing additional state variables that retain this information across multiple time-steps. By integrating these variables, the time delay $\tau_j \neq 0$ is modeled while only relating the state variables at intervals k and $k+1$. This procedure is similar to the one used when constructing the state-space equations for a transfer function with multiple zeros [11].