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Enhancing hydropower modeling in variable generation integration studies

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ABSTRACT

The integration of large amounts of variable renewable generation can increase the demand on flexible resources in the power system. Conventional hydropower can be an important asset for managing variability and uncertainty in the power system, but multi-purpose reservoirs are often limited by non-power constraints. Previous large-scale variable generation integration studies have simulated the operation of the electric system under different penetration levels but often with simplified representations of hydropower to avoid complex non-power constraints. This paper illustrates the value of bridging the gap between power system models and detailed hydropower models with a demonstration case. The United States Western Interconnection is modeled with PLEXOS, and ten large reservoirs on the Columbia River are modeled with RiverWare. The results show the effect of detailed hydropower modeling on the power system and its benefits to the power system, such as the decrease in overall production cost and the reduction of variable generation curtailment.

1. Introduction

Integrating large amounts of wind and solar energy into the electric system can increase the demand for flexible resources. VG (Variable generation), such as wind and PV (photovoltaic) solar power, is both variable and uncertain, that is, their output changes over time due to their dependency on weather phenomena and cannot be fully forecasted. As a result, the remainder of the electric generation mix needs to balance the more variable net load (load minus VG generation) [1,2].

Hydropower generation is already part of the generation mix and is particularly abundant in the western United States, the geographic focus of the example presented in this paper. However, electricity generation is commonly only one of many purposes of reservoirs, which include an ever-growing, complex mix of power and non-power objectives and constraints, including the Endangered Species Act and additional environmental objectives, navigation, flood control, water supply, and recreation, among others. Generally, these non-power objectives and constraints prevail over the generation of electricity and prevent utilization of the full physical flexibility that hydropower can provide.

Both the power system and hydropower basins are complex systems with competing objectives and numerous constraints. Capturing these complexities in one single model has not been achieved to date, especially on a larger scale. Thus, often a simplified version of the one model is included in the other. The purpose of this paper is to bridge the gap between two existing models with a systematic approach that takes full advantage of their strengths. The approach is applied to a large-scale system with hydropower and VG and demonstrates that hydropower can play a significant role in the integration of VG when it is correctly modeled.

Previous studies have developed methods aimed at improving the coordination of hydro operations with VG, particularly wind. One set of these methods optimizes bids into electricity markets from combined wind-hydro systems with stochastic wind inputs. The algorithms presented in Refs. [3] and [4] use hydro to meet the imbalance from wind forecast error and thus reduce imbalance

Abbreviations: BAU, Business-as-usual; BPA, Bonneville Power Administration; CC, Combined cycle; CT, Combustion turbine; DR, Demand response; PNW, Pacific Northwest; PV, Photovoltaic; TDG, Total dissolved gas; TEPPC, Transmission Expansion Planning Policy Committee; WECC, Western Electricity Coordinating Council; VG, Variable generation; WSIS-2, Western Wind and Solar Integration Study, Phase 2.

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penalties when such operations would improve the economic outcome of the combined system. In Refs. [5] and [6] transmission congestion is considered. The hydro producer can adjust its bid to relieve congestion and reduce wind curtailment in exchange for a payment from the wind producer. In Ref. [7] the optimization problem includes a constraint on the acceptable risk of not meeting a target payoff when scheduling combined wind and hydro.

Another set of methods coordinates hydro, wind and thermal resources to meet a specified power demand (load). The methodology in Ref. [8] commits available hydropower units if wind output is below a threshold and uses additional hydropower units for peaking when necessary in order to improve system reliability. A particle swarm optimization presented in Ref. [9] minimizes the cost of operating thermal units when meeting a load by coordinating wind, thermal and hydropower resources. The model is decomposed into two sub-problems with objectives of minimizing variation of thermal generation and maximizing the use of water available for hydro generation.

The aforementioned studies are designed to improve coordinated scheduling and operations of wind, hydropower and the thermal fleet in an operational context. As measured by their stated objectives all demonstrate improvements in the coordinated wind and hydropower systems, but do not provide an assessment of the performance of the wider electric system in the context of increased VG. These studies have not considered the effects of VG integration on an extensive grid scale, nor employed a representation of the complete power system including a full representation of other generating units, ancillary services and dynamic transmission constraints.

A significant number of large-scale studies have simulated the operation of the electric system under different levels of VG penetration. In the United States, these include the Western Wind and Solar Integration Study [10,11], Eastern Wind Integration and Transmission Study [12], New England Wind Integration Study [13], and California's Integration of Renewable Resources [14]. All of these studies found that the integration of renewables is facilitated with a more flexible fleet of conventional generators. Yet, due to the complex mix of non-power constraints, hydropower representation in these electric sector models is typically simplified, leading to under- or over-constrained estimates of the flexibility available in reservoirs. In both cases, the results of the studies are influenced by these assumptions.

Results from the *International Energy Agency Task 24 Integration of Wind and Hydropower Systems Final Technical Report* are summarized in Ref. [15]. Case studies from seven countries show that hydropower systems can provide much of the flexibility required for integrating large amounts of wind generation. The report acknowledges, however, the need for improvement in the modeling the physical characteristics and operating constraints of hydro systems in wind integration studies.

The methodologies presented in Refs. [3–9] include basic constraints on the hydropower system, such as water balances, minimum and maximum storage volumes and minimum and maximum discharge rates. Limits on storages and discharges are included as constant values and typically represent the physical limitations of the system. Exceptions include [3] and [4] in which time-varying constraints on discharge represent non-power policy constraints. Also, a constraint on total discharge volume for the simulation period is included in Ref. [9] to represent limits due to non-power water uses. In all cases, these are hard constraints. However, the actual operating policies for most hydro systems include competing water management objectives at varying levels of priority. Modeling these objectives of the hydro system as hard constraints cannot capture the realistic complexity of these policies and the operations that they implement.

Modeling of hydro operations is a well-established field but has not been incorporated widely into the electric sector primarily because both electrical system models and hydropower models are complex and are used for different purposes. RiverWare [16], in particular, is a river and reservoir modeling tool developed by the Center for Advanced Decision Support for Water and Environmental Systems authors of this paper, sponsored by the Tennessee Valley Authority, Bureau of Reclamation, and the U.S. Army Corps of Engineers, and used by these agencies and many others [17,18]. Several RiverWare models are used on an ongoing basis for planning or operations such as models of the Tennessee River, Colorado River, the Upper Rio Grande River, the Truckee–Carson Basin, and the Colorado River in Texas. The Tennessee Valley Authority has used RiverWare to optimize hydropower while preferentially satisfying the non-power constraints of multi-purpose reservoirs [19]. Due to the complex nature of the electric system, proxies are often utilized with varying degrees of fidelity.

The work described in this paper is motivated by the desire to determine the extent to which a full-scale electricity production simulation is able to accurately capture the nuances of the hydro system's constraints and the potential for improvement of the electricity production modeling so that the impacts of VG can be more accurately captured. We present a novel approach that bridges the gap between the two worlds by combining the hydro modeling system RiverWare [16] with the power system production model PLEXOS [20]. The methodology herein presented can be extrapolated to any combination of hydro reservoir optimizer and power systems production cost model. The final objective is to optimize the participation of hydro power facilities in the electric sector while meeting the aforementioned non-power constraints, thus yielding a more realistic representation of the contribution of hydropower to the system flexibility, maximizing revenues to hydro operators, and enabling the integration of large amounts of VG energy. This paper shows the effects on the electrical system resulting from using RiverWare scheduling instead of a simplified hydro model as used in previous studies.

The remainder of the paper is organized as follows: Section 2 describes the methodology and software simulation tools used, Section 3 presents the case study in this paper, Section 4 summarizes the results, and Section 5 presents the conclusions.

2. Methodology

This section summarizes the steps in our proposed approach to integrate two simulation models, one that models the power system and one that optimizes the operation of a series of hydro facilities. Even though two particular software implementations are used in this paper, the methodology can be generalized to any pair of model implementations.

2.1. Production cost model of the power system in PLEXOS

PLEXOS [20] is a commercial production cost model that models the unit commitment and dispatch of generators in the electric power system. It is developed and commercialized by Energy Exemplar and used by industry and academia throughout the world. The optimization algorithm in PLEXOS seeks to minimize the overall cost of operating the system. The model uses a deterministic mixed integer linear program to minimize the cost to produce energy and serve all of the demand and ancillary services in the electric power system. The main decision variables are generation by generator, status (on/off), transmission flows, procurement or reserves, charging/discharging of storage (e.g., pumped-hydro, batteries). The generators on the system are committed using both day-ahead (for coal and nuclear generators) and 4-h-ahead