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Real-time co-simulation of adjustable-speed pumped storage hydro for transient stability analysis

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ABSTRACT

Pumped storage hydro (PSH) based generation of electricity is a proven grid level storage technique. A new configuration i.e., adjustable speed PSH (AS-PSH) power plant is modeled and discussed in this paper. Hydrodynamic models are created using partial differential equations and the governor topology adopted from an existing, operational AS-PSH unit. Physics-based simulation of both hydrodynamics and power system dynamics has been studied individually in the past. This paper demonstrates a co-simulation of an AS-PSH unit between penstock hydrodynamics and power system events in a real-time environment. Co-simulation provides an insight into the dynamic and transient operation of AS-PSH connected to a bulk power system network. The two modes of AS-PSH operation presented in this paper are turbine and pump modes. A general philosophy of operating in turbine mode is prevalent in the field when the prices of electricity are high and in the pumping mode when prices are low. However, recently there is renewed interest in operating PSH to also provide ancillary services. A real-time co-simulation at sub-second regime of AS-PSH connected to the IEEE 14 bus test system is performed using digital real-time simulator and the results are discussed.

1. Introduction

Electric grids around the world are undergoing a progressive transition towards a more modernized, resilient, and self-governing architecture and operation. All three – generation, transmission, and distribution sectors are experiencing significant improvements and upgrades in terms of infrastructure development, increased penetrations by variable renewable generation, and novel management techniques. The generation sector of the future may be well characterized as a unique blend of conventional resources and non-conventional, non-dispatchable variable output resources. The optimum combination of generation resources is based on their capability to complement one another, and to supply real-time daily evolving demand according to established reliability criteria. The transmission sector is rapidly evolving with infrastructure upgrades of transmission line design and operation including extra high voltage alternating and direct current transmission lines, multi-phase designs, hi-fidelity measurement systems such as phasor measurement units, localized real-time capacity monitoring, dynamic line rating, high speed communications, and, deployment of flexible AC transmission devices (FACTS). In the context of deregulation, the Federal Energy Regulatory Commission (FERC) issued Order no. 888 that requires utilities to provide fair open-access of transmission resources to all market participants led a significant transformation [1]. The distribution sectors are adopting innovative concepts such as microgrids, distributed energy resources, reconfigurability and self-healing network.

Wide-band semiconductor based power electronic converters and their applications have a potential to provide a greater flexibility in all these three sectors of the grid. Prior to deregulation, power generation plants in bulk power electric grids were deterministic and dispatchable; hence they are predictable. However, the current and future trend of increasing penetration levels of wind and solar photovoltaic installations on the grid impart non-trivial stochas-

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Variable interpretation

x	location variable (m)
t	time variable (s)
U	flow velocity in (m/s)
H	head of the flow (m)
a	pressure wave velocity (m/s)
g	gravitational acceleration
D	internal diameter of pipe (m)
f	frictional factor
h	height (m)
k_{fp}	normalized friction coefficient
h	height (m)
$\bar{P}_m$	mechanical power (p.u.)
A_t, D_{turb}	turbine specific constants
$\bar{\omega}$	angular velocity (rads/s)
α	constants for simplification
C_1, C_2, C_3, C_4, C_5	boundary level constants (p.u.)
$T_{(s)}$	hydraulic circuit transfer function
h_{num}	per unitized head values
$\bar{u}_{num}$	per unitized flow values
T	time constant of hydro channel
Z	impedance of hydro channel
$i_{(ra)}$, $i_{(rb)}$, $i_{(rc)}$	rotor circuit currents in 3 phases
$i_{(rd)}$	direct axis rotor circuit current
$i_{(rq)}$	quadrature axis rotor circuit current
ψ	phase difference
P_{total}	total electrical power generated
P_{ms}, P_{mr}	stator and rotor power
$slip$	slip of the induction machine

ticity to the generation dispatch [2]. The renewable energy sources are connected in both aggregated and standalone configurations, thus, diversifying the portfolio. The increase in renewable energy sources coupled with the retiring of thermal power plants is leading to reduced inertia in the grid [3].

System operators and utilities need adequate flexible resources such as hydropower, to dispatch within quick time during contingencies and sudden loss of renewable energy generation. Procedures to account for generation outages (N-1 contingencies) exist with the system operators since the advent of interconnections and are developed to adopt the relevant North American Electric Reliability Corporation (NERC) standards to maintain reliability of the grid. FERC has approved NERC's agreement with the eight regional reliability organizations to ensure and enforce the compliance of operations with the reliability standards [4]. These procedures are based on theory of interconnected networks, physics of power systems and their control, and practical experiences in grid operation. The generation variability introduced by interconnection of renewable variable output energy sources requires a different approach as compared to the one based on dispatchable generator units [5,6].

Hydroelectric generation can be very effectively utilized in an optimization framework to accommodate the increasing penetration of renewable energy resources [5,6,8–10]. The pattern of electricity generation using hydroelectric generation and other renewable sources in the U.S. is shown in Fig. 1. The inference that can be drawn is that hydropower technology is the largest producer of clean energy in the U.S. It is expected, that renewable generation will continue to increase for the foreseeable future. Coordinated hydro power generation can improve the grid reliability [11]. In general, the growth in installed hydropower generation has fluctuated in the past few decades but it is projected to increase in the near future as noted in the Hydropower Vision by the Department

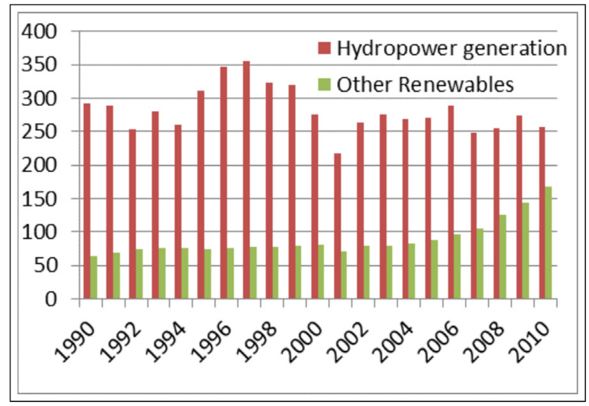

Fig. 1. Electricity generation by hydro and renewable energy sources in the U.S. (*X*-axis: year and *Y*-axis: electricity generated in million MWh).

of Energy (DOE) [12]. Fig. 2 shows the fraction of electricity generated by all hydropower technologies (including PSH) for leading hydropower producing countries of the world [7]. According to the National Hydropower Association (NHA) in the U.S. PSH plants exist at 40 locations with installed capacity of approximately 22,000 MW and future plants at 60 new locations with a total of 51,130 MW are pending approvals [13]. The magnitude of storage potential using PSH technologies is of significant value. Other potential attributes of AS-PSH are frequency regulation in both pumping and generating modes, grid scale inertial response based storage, part load pumping and ancillary services (load following, voltage support, and flexible spinning reserve). The utilities in Japan were the first to realize the benefits of adjustable speed pumped storage [14].

Specific benefits of AS-PSH operation include improvement of system stability, better dynamic performance, use of multi-level converters to enhance operational efficiency, enhanced market prices, and smoothing of renewable energy are demonstrated for the European and Asian grids in [15–20]. However, the aforementioned benefits are applicable to any grid interconnections and are generalizable. Besides generating dispatchable power, hydroelectric power plants were historically utilized to provide regulation services and they can act as sources of spinning reserves. PSH can also serve as a critical resource for black start procedures and system restoration hence is an added advantage. The fast ramp rates and quick response of hydroelectric power plants make them a viable source as providers of balancing services and daily load following [16]. The quantification of value of AS-PSH to the grid as a critical task was identified and presented in [21,22]. For the quantification of value, especially rotational inertia-like response that the AS-PSH can provide to the grid, accurate modeling is necessary for simulation, assessment, and market frameworks. After a rigorous assessment of existing models in hydroelectric power engineering a DOE report identified two major research gaps namely, research and modeling of AS-PSH and modeling of Ternary PSH units [23]. The challenges associated with PSH are high investment cost, licensing procedures, and availability of water especially with power generation being a lower priority.

Dynamic models for AS-PSH available for power system stability analysis are presented by treating the water column as a rigid (transient) and elastic (long term dynamics) body both described in [24,25]. The model proposed uses conventional hydro turbine and pump head-flow curve with gate control for generation and pump mode respectively. Models are also proposed based on combinations whether the plants have a common tunnel and multiple penstocks [26,27]. One of the fundamental publications in analyzing the transient response of AS-PSH based on a Hitachi design that is operational in Japan is presented in [28]. The operational and