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Modeling and static optimization of a variable speed pumped storage power plant

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ABSTRACT

Pumped storage power plants are key components to stabilize electric distribution networks with high amount of intermittent power sources as, e.g., solar and wind power plants. Tailored mathematical models are important for the transient and the stationary analysis of such plants. A comprehensive mathematical model of a variable speed operated pumped storage power plant, which incorporates reversible pump turbines in combination with doubly fed induction machines, is developed in this paper. Special emphasis is laid on an accurate description of important dynamic effects (e.g., water hammer) and of the energy losses of the system. Based on this model, optimal stationary operating points are determined, which minimize the overall system losses and systematically take into account the operating constraints.

1. Introduction

Electric power industry is currently faced with environmental issues, increasing energy consumption and limited resources of fossil fuels. These challenges are, amongst others, tackled by an intensified usage of renewable energy sources, in particular wind and sun. The intermittent nature of these energy sources calls for a sufficient amount of large scale energy storage capabilities in order to ensure a generation-load balance and thus grid stability. The well-established pumped storage power plants (PSPPs) still represent the most attractive way of large scale energy storage, having a worldwide installed capacity of approximately 130 GW [1]. In particular variable speed operated PSPPs with reversible pump turbines offer distinct advantages in comparison to conventional fixed-speed PSPPs, including: (i) increased efficiency (especially during part-load operation) and an enhanced operating range in turbine mode, (ii) improved network frequency regulation capabilities due to rapid injection of active power (flywheel effect) as well as (iii) improved active power regulation capability during pump operation, see, e.g., [2–5].

Together with the ability of reactive power control, these features make variable speed PSPPs an excellent aid for improving grid stability, e.g., by primary frequency control. Two types of variable speed PSPPs are typically considered in literature: the doubly fed induction machine (DFIM) with a part-load converter at the rotor terminals and the synchronous machine with a full-load converter at the stator terminals [5–7]. The converter fed synchronous machine inherently offers some advantages over the DFIM, including a much larger possible speed range and a lower start-up time [7]. While power electronics components typically limit the power range of a full-load converter, the recent advances in power electronics technology allow to build such PSPPs with ever increasing power, see, e.g. [8], where a commissioned PSPP applying a 100MW full-load converter is described.

Nevertheless, the usual restriction of the speed range to approximately ±10% around the synchronous speed allows to size the part-load converter of the DFIM topology to only a small portion of the rated machine power. This constitutes a decisive economic advantage of the DFIM topology, currently making it the predominant technology for high power ($\gtrsim$100MW) applications, with several examples of commissioned power plants, see, e.g., [9–11]. Hence it is a variable speed PSPP employing the DFIM topology that is considered in the present contribution.

Mathematical models of the PSPP are required for the dynamic simulation, the controller design and the optimization of the operation of PSPPs. Thus, one goal of this contribution is the derivation of a comprehensive mathematical model of a variable speed PSPP. In particular, special focus is laid on the accurate description of the dynamic behavior as well as of the losses of the overall plant,

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incorporating both the mechanic as well as the electric key components. In literature, see, e.g. [10,12,13], simplified pump turbine models are often used, which are not suitable to properly reflect pump turbine losses in a larger operating range. A more sophisticated PSPP model intended for power system simulations is presented in Ref. [14]. Here, the hydraulic system is modeled in a similar way as in this paper, i.e. modeling the pump turbine in a quasi-stationary manner by its characteristics and numerically solving the pipe model's partial differential equations (PDEs) by the Method of Characteristics (MOC). The mathematical model of the electric system, however, is not described in detail. This might be reasonable for power system simulations, but is not appropriate for controller design and optimization. In Ref. [4] a variable speed PSPP is modeled based on the hydraulic modeling approach of [15,16], which applies a finite difference scheme for the numerical solution of the pipe PDEs. The simulation builds upon an existing software tool, which was originally developed for the simulation of electric systems [16]. Thus, also the hydraulic components are described by equivalent electric models. As the pump turbine characteristics are interpolated with continuity of order 0, it is, however, difficult to directly use this model for optimization purposes. In Ref. [17] a simulation model based on the MOC and a continuously differentiable surface interpolation of the pump turbine characteristics [18] is applied for water hammer studies. This modeling approach is also described in Ref. [19]. A continuously differentiable interpolation of the pump turbine characteristics allows for the application of numerically efficient gradient based optimization methods. Therefore, a similar interpolation scheme is also provided in the present work, combining a state-of-the-art modeling approach of the hydraulic system with a detailed model of the electric system, particularly modeling the energy losses of the electric subsystem in more detail compared to above mentioned works.

Since PSPPs involve remarkable investments, suitable building sites are limited and due to liberalized energy markets, efficient operation is becoming increasingly important. In particular, the additional degree of freedom gained from variable speed operation is utilized to increase the efficiency of hydraulic machines. Reference [20] briefly describes the determination of optimal stationary operating points of a hydro power plant, where the hydraulic components and the generators are taken into account in a special software tool. Stationary operating points of maximum efficiency are determined by an iterative process. Since the generators are modeled as active power-depending efficiencies, their operating constraints are not systematically considered in the optimization process. In Ref. [4] control strategies for the optimized stationary operation of variable speed pump turbines are suggested. In turbine mode, the optimal set point of the turbine speed is determined for a given net head and a desired output power from a lookup table. Similarly, in pumping mode an optimal guide vane opening is calculated for a given rotational velocity and a given net head by a stationary law. In these cases, operating constraints are not explicitly taken into account and in Ref. [4] optimality is solely based on the pump turbine characteristics.

The mathematical model proposed in this paper is intended to serve as a basis for the analysis of the static and dynamic system behavior (e.g., water hammer studies), the design and test of control strategies and the determination of optimal system operation. Special emphasis is placed on a stringent physics-based mathematical description of the relevant parts of the system. This approach can thus be easily extended to or adapted for different plant topologies. It combines and extends existing mathematical models of the system components to an overall comprehensive system model. In this paper, the model is used to calculate optimal stationary operating points of the PSPP for different modes of operation, which yield minimal energy losses of the overall system while adhering to operating constraints.

The paper is organized as follows: Section 2 introduces the considered variable speed PSPP and summarizes the mathematical models of its components. In Section 3, the dynamic behavior of the PSPP is analyzed by simulation studies. Section 4 describes the optimization problem for optimal stationary operating points and presents its numerical results. Finally, Section 5 gives some conclusions.

2. Mathematical model

The overall system, depicted in Fig. 1, consists of two plant units *A* and *B*, which are coupled by a common pipe system. Assuming constant grid voltage amplitude and frequency, the coupling over the common electric grid segment can be neglected. Further, it is assumed that both plant units have an identical configuration, which allows to apply the same mathematical model to both plant units. If necessary, the superscripts *A* and *B* are utilized to distinguish the different plant units. Subsequently, quantities in per unit representation are often used, which will be marked by $\widetilde{(\cdot)}$.

2.1. Electric subsystem

The equations of the electric system are given in a per unit dq-representation, normalized with respect to the stator of the DFIM. The reference frame is synchronously rotating with the constant grid frequency $\omega_{grid} = 2\pi 50\text{rad/s}$, which is also used as the base frequency ω_b in the per unit representation, i.e. $\omega_b = \omega_{grid}$, see Table 1. The respective 0-components are not taken into

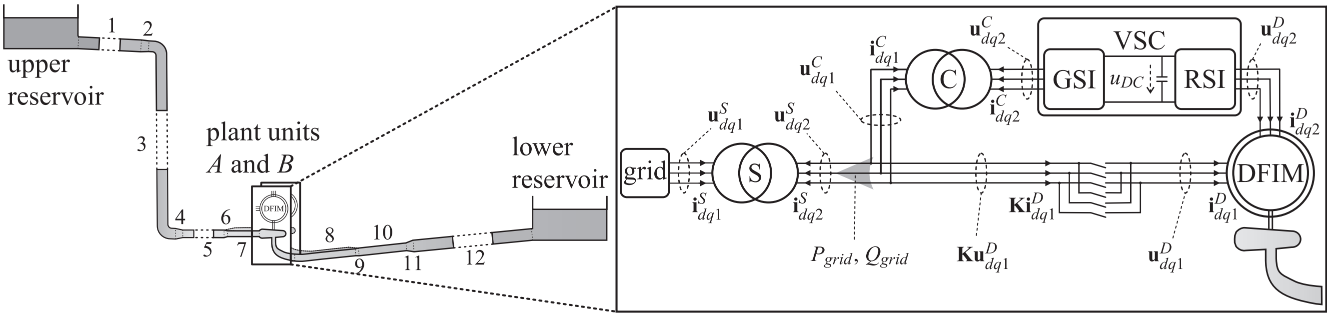

Fig. 1. Setup of the considered variable speed pumped storage power plant (PSPP). The pipe segment numbering corresponds to Table 3. The electric system of each plant consists of a DFIM, a step-up transformer (S), a converter transformer (C) and a voltage-source converter (VSC), comprising a grid side inverter (GSI) and a rotor side inverter (RSI). Vector notation is applied for the respective dq-quantities, e.g., $\mathbf{u}^D_{dq1} = [u^D_{d1}\ u^D_{q1}]^{\mathrm{T}}$.