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Nonlinear Control of a Fully-Fed Variable Speed Pumped Storage Plant

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Abstract: This paper presents the nonlinear control of a Fully-Fed Synchronous Machine based Variable Speed Pumped Storage Plant (FFSM PSP). First, a model is developed and the control objective is established followed by the control design. The control algorithm is designed using Feedback Linearization robustified by a Second Order Sliding Mode Control (SOSMC). Using both techniques allows a fast response of the system while relaxing the conditions on the Sliding Mode Control and avoiding the known chattering problem. The control is compared with the industrial standard PI controller from the dynamic response point of view and also during short-circuits.

Keywords: Application of power electronics, Control system design, Control of renewable energy sources, Power systems stability, Modeling and simulation of power systems.

1. INTRODUCTION

Pumped storage plants (PSP) are one of the most reliable and well-known large storage solutions in the power grid (Ibrahim et al. (2008)). Pumping water to the upper reservoir during low consumption periods and producing energy during peaks of consumption for hundreds of years (see Fig. 1). They are, however, reaching the limit of the exploitable sites (Deane et al. (2010)) while at the same time new challenges in the power system require more flexibility than the past decades. Nowadays, with the insertion of intermittent renewable energies, the response of a PSP needs to be faster than before (Ngoc et al. (2009)). Another challenge for the PSP is to increase their penetration knowing that the best economic exploitable sites are already taken (Deane et al. (2010)).

The Variable Speed PSP is seen today as the answer for both problems: it can increase PSP insertion. The speed variation allows a bigger operation range, increasing the number of technically feasible and economically attractive sites (Belhadji et al. (2013)). From the dynamic point of view, using the power electronics to control the power output of the turbine allows the PSP to react rapidly to any perturbation in the network (Pannatier (2010)).

Concerning the control of a Variable Speed PSP, few works have addressed this problem. In Hodder (2004), a controller for the whole chain of a PSP was designed for a Doubly-Fed Induction Machine based Variable Speed PSP (DFIM PSP). The author used two cascaded control loops: an inner control loop that controls either the current of the machine or the current in the transformer, and an outer control loop. The outer control loop controls an internal DC link while the inner controls: the reactive power and either the active power or the turbine's speed. The control design performed by Hodder (2004) is based on the transfer function approach using Méplat and Symmetric optimum criteria. Pannatier (2010) used the controllers developed in Hodder (2004) to assess the different strategies and its impacts on the operation of the DFIM PSP and their capability to provide services to the power grid.

DFIM PSP uses a wounded rotor induction machine with an Alternate Current (AC) excitation system. When using this technology, part of the power proportional to the speed variation goes through the excitation. The speed variation of this solutions is then limited by the rated power of the excitation system. Compared to the DFIM PSP, the Fully-Fed Synchronous Machine based Variable Speed PSP (FFSM PSP) is more flexible and robust. Synchronous Machine are the most used machines for power generation and is, thus a mastered technology. Additionally, for the FFSM PSP, the maximum speed variation is determined by the mechanical limits of the pump-turbine. However, due to higher prices and size of the converters, FFSM PSP is mostly used in low power applications. Nevertheless, due to tighter requirements from power system operators, the use of FFSM PSP is increasing since the machine is decoupled from the power system (Steimer et al. (2014)).

The present work focuses on the nonlinear control of the converters in a FFSM PSP. The chosen control approach is a cascaded one. Hence, the objective here is not to change the control methodology developed by Hodder (2004) and Pannatier (2010), but give a different way to design the controllers. Also, the cascaded control allows the use of

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different time scales in the systems as well as the plug and play characteristic (see Chen (2015)). Controllers were implemented in SIMSEN and simulated using turbine data from software library. SIMSEN is a software developed by the Ecole Polytechnique Federale de Laussanne (EPFL) which simulates hydraulic and electromagnetic phenomena.

From the control point of view, the FFSM PSP is controlled by the voltages in its two converters. One of them is connected to the power grid through a transformer (Grid Side Converter - GSC) and the other to the machine (Machine Side Converter - MSC). The converters are connected through a DC capacitance in what is called back-to-back connection to each other. Since the voltage output of the converters depends on the DC Voltage of the capacitor (which is also a state), the relation between control input and state is not linear. Simulation results in accordance to theory show that the nonlinear approach is more suitable for the FFSM PSP.

2. FFSM PSP MODEL AND CONTROL PROBLEM

The original complete model of the system is obtained from the different subsystems present in the FFSM PSP (see Fig. 1). A change of variables can be applied (as shown in the following) to the original model in order to ease the control design and highlight interesting properties from the control point of view. The subsystems to be taken into account when modeling the FFSM PSP are:

- The grid side converter (GSC) also called front end converter
- The machine side converter (MSC) also called the back end converter
- The DC link voltage dynamics
- The Machine rotational speed
- The Hydraulic circuit

The model shown here will concern the electric part of the system, i.e., both converters and the DC link between them, as well as the speed of the machine (see Fig. 1). Since no control is developed for the turbine, the hydraulic part is not modeled nor discussed in this paper. Nevertheless it is considered, for control purpose, that there is a control input in the turbine represented by the water gate opening. For more details on the hydraulic part, consult Pannatier (2010) or Nicolet (2007).

2.1 Grid Side Converter (GSC) Model

This model can also be found in Hodder (2004) and is based on the XR model of the transformer connected to the GSC (see Fig. 1) in pu:

$$\frac{di_t}{dt} = \omega_b \left(V_{tr} - \frac{R_{SC}}{X_{SC}} i_t + j\omega_j i_t - \frac{1}{X_{SC}} M_t \cdot V_{DC} \right) \quad (1)$$

Where i_t is the complex current through the transformer ($i_t = i_{td} + ji_{tq}$). The nominal frequency of the network in rad/s is represented by ω_b. R_{SC} and X_{SC} are respectively the short-circuit resistance and reactance of the transformer. ω_j and V_2 are the frequency and the voltage of the transformer at the converter side. M_t is the duty cycle of the PWM, i.e., the control variable at the converter. V_{DC} is the DC voltage in the capacitance.

2.2 Machine Side Converter (MSC) Model

The model of the MSC is given by the equations of the machine and is represented in Fig. 1. In Damm (2001) a complete model of the synchronous machine is developed with different number of states for different purposes. For the control design it was chosen the third order model taking into account direct and quadrature axis flux as well as the excitation. However, for simulation, it was considered a fifth order model with damper windings in quadrature and direct axis. From the stability point of view, this simplification is not a concern since the damper winding improve the stability of the synchronous machine (see Damm (2001)).

$$\begin{aligned} v_d &= r_s i_d + \frac{1}{\omega_N}\frac{d\Phi_d}{dt} - \omega\Phi_q \\ v_f &= r_f i_f + \frac{1}{\omega_N}\frac{d\Phi_f}{dt} \\ v_q &= r_s i_q + \frac{1}{\omega_N}\frac{d\Phi_q}{dt} + \omega\Phi_d \end{aligned} \quad (2)$$

$$\begin{aligned} \Phi_d &= x_d i_d + x_{df} i_f \\ \Phi_f &= x_{df} i_d + x_f i_f \\ \Phi_q &= x_q i_q \end{aligned} \quad (3)$$

Where the indexes s, d, q, N and f are referred, respectively, to the stator, the d and q axis, the nominal value and field circuit. The variables v, r, i, ω and Φ are, respectively, the voltages, electric circuit's resistance, current, speed and electromagnetic fluxes.

Since current is a measurable variable and it will be used for the first control loop it was explicitly put as a state. A change of variables is made using equations 3. Additionally, the index m is added to the machine side current in order to differentiate it from the current in the transformer (i_t).

$$\begin{aligned} \frac{di_{md}}{dt} &= \frac{\omega_N}{x_f\left(x_d x_f - x_{df}^2\right)} \left(\left(r_f x_{df}^2 + r_s x_f^2\right) \cdot i_{md} \right. \\ &\quad + x_{df} x_f \cdot V_{exc} - r_f x_f \cdot \Phi_{exc} - x_q x_f^2 \cdot \omega \cdot i_{mq} \\ &\quad \left. - x_f^2 \cdot M_d \cdot V_{DC} \right) \\ \frac{di_{mq}}{dt} &= \omega_N \left(\left(-\frac{x_d}{x_q} + \frac{x_{df}^2}{x_q x_f} \right) \cdot \omega \cdot i_{md} - \frac{r_s}{x_q} i_{mq} \right. \\ &\quad \left. + \frac{1}{x_q} M_q V_{DC} - \frac{x_{df}}{x_q x_f} \cdot \omega\Phi_{exc} \right) \\ \frac{d\Phi_{exc}}{dt} &= \omega_N \left(\frac{r_f x_{df}}{x_f} i_{md} - \frac{r_f}{x_f}\Phi_{exc} + V_{exc} \right) \end{aligned} \quad (4)$$

It can be seen that the field current is not used as state variable. This because it is considered that the excitation of the machine is regulated by a classical excitation controller (not developed in this paper).

2.3 DC Link Model

The DC link is represented by the capacitance and its dynamics (see Fig. 1) in pu:

$$\begin{aligned} \frac{dV_{DC}}{dt} &= \frac{1}{2H_c} \left(-i_{td} \cdot M_{td} - i_{tq} \cdot M_{tq} \right. \\ &\quad \left. + i_{md} \cdot M_{md} + i_{mq} \cdot M_{mq} \right) \end{aligned} \quad (5)$$

Where H_c is the electrostatic inertia of the DC link in seconds given by $H_c = C_{tot}V_0^2/2S_N$. M_{td}, M_{tq}, M_{md} and