European Journal of Control ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

European Journal of Control

journal homepage: www.elsevier.com/locate/ejcon

Nonlinear model-based control for minimum-time start of hydraulic turbines

Hugo Mesnage [a,b], Mazen Alamir [b,*], Nicolas Perrissin-Fabert [a], Quentin Alloin [a]

[a] General Electric Power, R&D Process Control & Monitoring, 82 Avenue Leon Blum, BP 75 38041 Grenoble, France
[b] CNRS/Gipsa-lab, University of Grenoble Alpes, 11 Rue des Mathématiques, F38000 Grenoble, France

ARTICLE INFO

Article history:
Received 3 May 2016
Received in revised form
9 September 2016
Accepted 6 December 2016
Recommended by A. Astolfi

Keywords:
Hydraulic turbines
Fast start
Integration of renewable

ABSTRACT

Fast start of hydraulic turbines is mandatory for a successful integration of renewable sources of energy. Successful handling of this issue needs to operate close to the boundary of the admissible domain while fully exploiting the knowledge of the system dynamics. This paper introduces a simplified model of hydraulic turbines including the hydraulic nonlinear hill-chart and a first order model of the penstock. Based on the resulting reduced model, a graphical representation of the vector fields of the resulting controlled system is first obtained under the assumption of a band unlimited actuator. This ideal 2D-graphical representation enables an exact evaluation of the lower bound on the minimum achievable start-time as well as the time structure of the control profile. Based on this analysis, a real-life MPC scheme is proposed that takes into account realistic limitations on the actuator leading to feasible, almost time-optimal control design.

1. Introduction

In a pump storage plant (PSP), a sole runner enables both turbining water from an upstream tank to a downstream reservoir and pumping water from the downstream reservoir to the upstream tank (Fig. 1). Therefore PSPs provide an excellent energy storage solution that is necessary for a widespread use of renewable intermittent sources. The use of hydraulic storage induces however some new paradigms. The first that is widely addressed by hydraulic engineers is the conversion efficiency enhancement during steady flow operations, like in [14,12]. The second is the need for fast transient when switching between its different modes (see Fig. 2). The frequency of these switches increases when the hydraulic stored energy is used to compensate for intermittency of renewable sources [3]. This especially concerns the operations of start-up in turbine and pump modes.

This paper focuses on the start-up operation in turbine mode. This is the time necessary to drive the turbine from rest towards the connection-to-grid rotational speed. This sequence is critical because of the use of synchronous machines – without electric transformation – in the PSP. This topology is more often used for hydroelectric production because it is cheaper while providing best efficiency than configurations involving an asynchronous machine. But the design of synchronous machines prevents decoupling between output voltage frequency and rotational speed. Consequently, the coupling to the grid must be done carefully as any discrepancy between the grid voltage and machine's output voltage at connection time can result in strong current that may be harmful [7]. At General Electric (GE), and for such big machines, three criteria must be respected before coupling the machine to the grid:

1. The rotational speed Ω, that is proportional to the output voltage frequency, must be in a $\pm 0.2\%$ band around its final desired value.
2. The amplitude of the output voltage must be equal to the grid voltage amplitude.
3. The phase between the output voltage and the grid voltage, and its evolution have to be appropriately contained.

The voltage and phase equality being done on shorter time scales by an independent controller, only the first above-mentioned issue is addressed in this paper.

1.1. State of the art and contributions

In this contribution, a model-based start time-optimal design is proposed for turbine mode. The design is based on a simplified model of the penstock [2,5,6,8] and a full nonlinear model of the runner's dynamic through its hill-chart. The design method proposed in the present contribution shows two appealing properties: *First*, it gives, for the original nonlinear systems, a precise

* Corresponding author.
E-mail address: mazen.alamir@grenoble-inp.fr (M. Alamir).

http://dx.doi.org/10.1016/j.ejcon.2016.12.002
0947-3580/

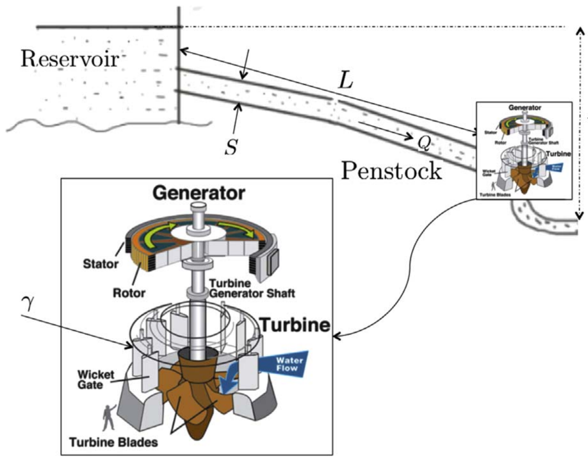

Fig. 1. Representation of the PSP.

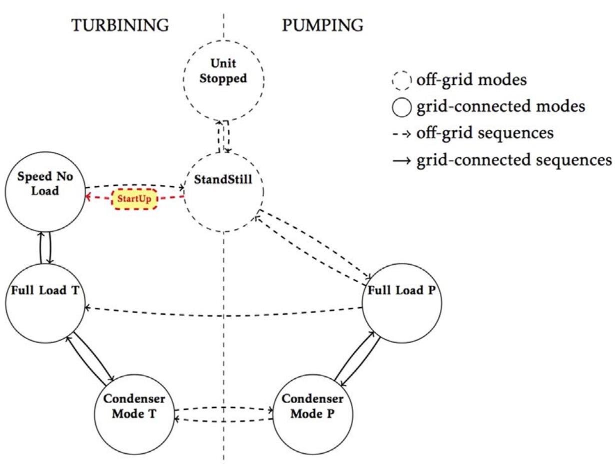

Fig. 2. Sequences and operating modes of a Pump Storage Plant. In this paper, the optimization of the start-up in turbine mode sequence (in red) is addressed. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

computation of the lower bound on the minimum start time together with the time structure of the optimal control profile which is independent of the actuator capacity. Namely, the start time is only limited by the hydraulic part that shows maximal acceleration feature. *Then*, it uses the deep understanding of the resulting ideal profile in order to derive a realistic constraints-aware feedback design that approaches the time-optimal profiles as close as the actuator limitations permit.

Regarding the novelty and the contribution of the paper, let us first mention that few papers addressed the control design of the turbine's start maneuver in an extensive and rigorous way. Rather, contributions focused on the control of grid-connected mode [5,11,15]. This is because as explained above, in traditional operation of hydraulic plants as the main energy providers, this start mode was rarely visited and can take a rather long time to settle without harm. It is the use of this mode repeatedly in a context where the hydraulic plant serves as support to renewable sources that emphasized the need to work out advanced control methods and performance assessment.

When compared to existing methods commonly used by GE's operators, the contributions and the novelty of the paper can be summarized as follows:

1. Traditional starting controllers are commonly based on heuristic tuning of multiple simple PID controllers with switching rules among them based on the value of the rotational speed being reached. These controllers receive a ramp-like reference signal that is heuristically defined between $\Omega = 0$ and $\Omega = \Omega_d$. Beside the fact that this tedious tuning is to be restarted from scratch at each new project, the difficulty is precisely to *guess* what is the time-optimal profile that the turbine under study is able to track.
   The control design proposed in this contribution does the exact opposite. It starts from the problem's known parameters (the nonlinear hill charts, the penstock and the actuator characteristics) and delivers simultaneously the almost optimal achievable time together with the associated trajectory of the rotational speed $\Omega(\cdot)$.
2. In addition to the appealing feature mentioned above, the proposed algorithm is generic as it uses the hill charts in a rather black-box way. This makes the computation of the optimal operational starting trajectory quite systematic and trivial.
3. This contribution theoretically shows (by analyzing the vector field of the simplified model) that there is hydraulic limitation on the decrease of the start time regardless of the actuator limits and the control law being used. Moreover, the proposed controller design explicitly pushes the system towards this limit in order to produce the almost minimum start time.

This paper is organized as follows: The dynamic model of the plant that is used in the computation and the feedback design is first derived in Section 2. The control problem is stated in Section 3. The control design is proposed in Section 4 following two steps: first, the ideal feedback design in the case where no actuator limitations are considered is derived in Section 4.1 by analyzing the vector field in an appropriate state space. Then a realistic saturation-aware feedback law is proposed and the resulting closed-loop performance are assessed in Section 4.2. Finally Section 5 summarizes the paper and gives hints for further investigation.

2. Mathematical modeling

We consider the PSP depicted in Fig. 1. It is assumed that the hydroelectric machinery is located along a linear and constant section penstock. In most cases, this approximation can be made true by computing an equivalent linear and constant section penstock (see [1] for more details). The full hill-chart characteristic described as in [10] is used to provide the hydro-turbine behavior. This includes the expression of the resulting mechanical torque as well as the implicit equation linking the flow rate to the remaining state and control variables. The whole plant works under a constant head H_b (see Fig. 1), and the electric machine – which is linked to the runner through a rigid shaft – is only taken into account for its inertia. Indeed, the start-up sequence occurs off-grid. The only actuating body is the guide vanes opening γ that enables the control of the hydraulic flow in the runner and in the pipes. In what follows, the elementary models of each part of the PSP are introduced.

2.1. Penstock dynamic

Let us denote by $h(x,t)$ and $Q(x,t)$ the water-hammer pressure and the flow rate respectively at instant t and abscissa x along the penstock. According to [13], these two quantities are linked through the following nonlinear transfer function:

$$h(s) = \left[-\frac{H_0}{Q_0}\frac{t_w}{t_e}\tanh(s \cdot t_e) \right] Q(s) \tag{1}$$

Please cite this article as: H. Mesnage, et al., Nonlinear model-based control for minimum-time start of hydraulic turbines, European Journal of Control (2016), http://dx.doi.org/10.1016/j.ejcon.2016.12.002