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Dynamic response of hydro power plants to load variations for providing secondary regulation reserves considering elastic water column effects

***Abstract**. In this paper, the dynamic response of a hydro power plant for providing secondary regulation reserve is studied in detail. Special emphasis is given to the elastic water column effects both in the penstock and the tailrace tunnel. For this purpose, a nonlinear model based on the analogy between mass and momentum conservation equations of a water conduit and those of wave propagation in transmission lines is used. The influence of the plant configuration and design parameters on the fulfilment of the Spanish Electrical System Operator requirements is analysed.*

Streszczenie.** W artykule analizowano odpowiedź dynamiczną elektrowni wodnej użytej jako wtórna rezerwa. Uwzględniono efekt elastycznej kolumny wodnej zarówno w rurociągu jak i w odpływie. W tym celu zaproponowano nieliniowy model bazujący na analogii równaniami zachowania masy i momentu a falową propagacją linii transmisyjnej. (**Odpowiedź dynamiczna elektrowni wodnej na zmiany obciążenia z uwzględnieniem elastycznych efektów kolumny wodnej)

Keywords: Dynamic Response of Hydro Plants, Water Hammer Effects, Secondary Regulation Reserve.
Słowa kluczowe: elektrownia wodna, odpowiedź dynamiczna.

Introduction

The integration of non-dispatchable energies in the electric grid may affect the reliability of the electric power supply, mainly due to their unpredictability and to the existing limitations for efficiently storing energy. An increase in the penetration of non-dispatchable energies may give rise to an increase in the needs for load-frequency regulation services [1], such increase being especially critical in isolated systems, where both regulating power and short-circuit power are in general smaller.

As it can be seen in Fig. 1, in the Spanish electric power system, there has been an increase both in renewable energy penetration and in the amount of energy required for certain load-frequency regulation services during last years. In addition, wind installed capacity is expected to increase in the next years. Said increase could have significant impacts on the electricity system operation if it is not accompanied with flexible generation and storage units [2].

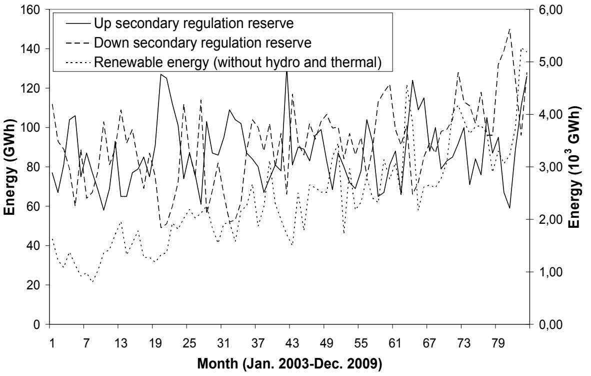

Fig. 1: Monthly energy.

In order to provide the above-mentioned services, power plants must adapt their operating point and vary the power output within very short time frames, in accordance with the requirements of the electric power system operator. In Spain, the response times required for load-frequency regulation range from a few seconds (primary reserve) to 15 minutes (tertiary reserve).

Hydro power plants can provide load-frequency regulation services in an efficient manner [3]. Nevertheless, the power plant dynamic response to load variations of different magnitudes should be studied in detail in order to guarantee the capability of the power plant for providing said reserves within the required response times, avoiding harmful pressure fluctuations and instabilities.

For that purpose, several models have been proposed in the technical literature. In outline, the hydro plant models can be classified as elastic or rigid water column models [4], according to whether or not the water compressibility and conduit elasticity are considered. The use of linear or non-linear models is usually dependent on the magnitude of the disturbances applied to the hydropower plant under study. Linear models are used for small disturbances [5], whereas non-linear models are used for large disturbances such as load rejection or start-ups. In [6] a non-linear rigid water column model is proposed for dynamic studies of a penstock supplying water to one or several hydro units.

As it is well known, mass and momentum conservation equations can properly describe the dynamic behaviour of a water conduit; in said equations, the convective terms can be neglected with respect to the propagative terms, due to the higher relative wave speed [7]. Several methods have been proposed to solve the resulting system of partial differential equations.

In [8] the well-known characteristics method [9] is applied to calculate the hydraulic transients in a diversion hydropower plant consisting of reservoir, headrace tunnel, surge tank, penstock and tailrace tunnel; the water inertia of the tailrace tunnel was considered in the penstock.

In [10], the problem is formulated and solved in the frequency domain. Finally, the approaches proposed in [11] and [12] are based on the analogy between the above-mentioned equations and those of electromagnetic wave propagation in transmission lines; π- and T-equivalent circuits were used, respectively.

In this paper, the dynamic response of a hydro power plant for providing secondary regulation reserve is studied in detail. For this purpose, a nonlinear model based on the above-mentioned electrical analogy is used. The hydropower plant is supposed to be connected to an isolated power system represented by an equivalent inertial model. The dynamic response of the plant to load variations and changes in the operating point settings is studied. Special emphasis is given to the elastic water column effects both in the penstock and the tailrace tunnel. The influence of the plant configuration and design parameters on the fulfilment of the Spanish Electrical System Operator requirements is analysed.

Modelling hydraulic transients

Mass and momentum conservation equations properly describe transient-state flows in closed conduits [9]. By assuming uniform pressure and velocity distributions in the cross section and neglecting both the convective and the slope terms the above-mentioned equations can be expressed as follows:

$$\frac{\partial H}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial x}=0 \tag{1}$$

$$\frac{\partial Q}{\partial t}+gA\frac{\partial H}{\partial x}+\frac{fQ|Q|}{2DA}=0 \tag{2}$$

There exist several approaches to solve these equations [8-12]. In this paper, a lumped parameters approach (i.e. a finite difference method) has been used. This approach leads to a system of ordinary differential equations that can be represented as a series of Γ-shaped consecutive elements of length L_e. As described below, the "orientation" of the Γ-shaped elements may vary according to the upstream and downstream boundary conditions of the pipe.

Ancillary services

Ancillary services (AS) may be defined as the set of activities apart from the energy production, which are related to safety and reliability of a power system [13]. Five different AS are provided within the Spanish Electric Power System:

- Primary, secondary control and tertiary control (reserve) ancillary services
- Balancing ancillary service
- Voltage control ancillary service

Primary, secondary, tertiary and balancing AS provide the necessary equilibrium between generation and demand. Voltage control AS is designed to maintain an adequate voltage profile within the transmission grid. Reserve services differ from each other mainly in two different aspects:

- The response time required to provide the service
- The market mechanisms around which the service is organized or negotiated

The aim of the primary control ancillary service (PCAS) is preventing large variations of frequency. In order for a unit to provide the PCAS it must be capable of modifying 1.5% of its rated output before 15 s for frequency deviations lower than 100 mHz, and linearly up to 30 s for frequency deviations up to 200 mHz. PCAS is a mandatory non remunerable AS.

In turn, the main objective of the secondary control ancillary service (SCAS) is to bring the system frequency back to its scheduled value. In order for a unit to provide the SCAS, its output power must vary according to an established response criteria, begin before 30 s and be maintained for 15 minutes.

The aim of the tertiary control ancillary service (TCAS) is to replace the secondary reserve in use. In order for a unit to provide the TCAS its output power variation must be set in 15 min and sustained for at least 2 hours. This paper is focused on issues related to the provision of the PCAS and SCAS

Model description

The model used in this paper is composed of the following components:

i) Upstream reservoir: the head in the upstream reservoir is considered constant and equal to h_{ur}.

ii) Head-race tunnel: a rigid water column model (3) is used to represent the head-race tunnel behaviour.

$$\frac{dq_{hr}}{dt}=\frac{1}{T_{hr}}(h_{ur}-h_s-\frac{r_{hr}}{2}q_{hr}^2) \tag{3}$$

iii) Surge tank: a surge tank is located between the head-race tunnel and the penstock. The surge tank dynamics is modelled as follows:

$$F_s\frac{dh_s}{dt}=q_{hr}-q_{p1} \tag{4}$$

iv) Penstock: a lumped parameters model has been used to represent the penstock behaviour. A scheme of the model can be seen in Fig. 2. The set of equations of the penstock dynamics are as follows:

$$\frac{dq_{p,i}}{dt}=\frac{ne_p}{T_p}(h_{p,i-1}-h_{p,i}-\frac{r_p}{2ne_p}q_{p,i}^2)\ ;\ \forall i=1,\dots,ne_p \tag{5}$$

$$\frac{dh_{p,i}}{dt}=\frac{T_p ne_p}{(L_p/a_p)^2}(q_{p,i}-q_{p,i+1})\ ;\ \forall i=1,\dots,ne_p \tag{6}$$

v) Turbine: the turbine has been modelled according to (7)-(8), following the recommendations of [5]:

$$q_t=z\sqrt{(h_t-h_{tr})} \tag{7}$$

$$p_t=A_t h_t(q_t-q_v)+Bz(n_0-n) \tag{8}$$

vi) Tail-race tunnel: a lumped parameters model has been used to represent the tail-race tunnel behaviour. The model scheme is analogous to that of the penstock model, but the configuration of the circuit terminals are interchanged because of the different end conditions; i.e., in the left end the flow must fit the turbine flow, q_t, and in the right end the head is given by the tail-race level.

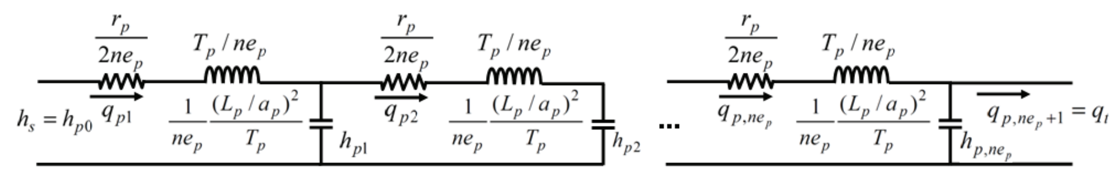

Fig.2. Scheme of the penstock model.

vii) Turbine governor - PI controller: The proposed governor model is shown in Fig. 3 and it is based on [14], [15]. The main function of this regulator is to control the speed and load through the feedback signals of the speed error and the power variation, modifying the wicket gate position and regulating the water flow through the penstock. The action of this governor allows eliminating the power-frequency error under electrical load variations.

The error signal is processed by a conventional proportional-integral (PI) controller and then the output of this block is applied to a hydraulic servomotor (with T_s time constant) to produce a change in the wicket gate position.

The limits in the gate position and its rate of change are considered in the model.

viii) Power system: The modelled hydroelectric station is supposed to belong to an isolated network representing a secondary regulation area [10,13], where it is the only plant providing secondary regulation.

The unit speed response Δn (p.u.) is obtained from the unbalance between the shaft power and the generated power according to the equation [10,14]:

$$\Delta P_m - \Delta P_g = \left(M_h s + D_h\right)\Delta n \tag{9}$$

The generated power P_g is the power transmitted through the interconnection line, which depends on the phase difference between the internal voltages of the generators connected at the line terminals [10].

Therefore an inertial model similar to the one represented by the previous equation should be added; the inertia constant should include the equivalent inertial effects of all connected machines and the damping constant represents the sensitivity of the frequency to load changes. The primary regulation in the external system is also considered by the corresponding speed-droop R_s (p.u.); thus the power-balance equation in the external subsystem results:

$$\Delta P_g - \frac{1}{R_s}\Delta n_s - \Delta P_L = \left(M_s s + D_s\right)\Delta n_s \tag{10}$$

Finally, the angle difference is obtained from the time integral of the relative frequency deviations:

$$\Delta\delta - \Delta\delta_s = \frac{\omega_0}{s}\left(\Delta n - \Delta n_s\right) \tag{11}$$

where ω_0 is the base system frequency and is introduced to obtain the angles in radians.

The action of secondary regulation can be introduced by the corresponding change in the set-point of the turbine governor.

Case study

The model described in the previous section has been used to analyze the dynamic response of a hydro power plant that is currently in the pre-planning stage. Some already decided design parameters of the hydropower plant are included in Table 1. It should be noted that the hydropower plant is planned to be located between two existing reservoirs; thus, some design parameters, such as the head or the total length of the conduits, are forced.

In turn, main parameters of the power system to which the power plant is connected are included in Table 2. These parameters could correspond to a single regulation zone within the Spanish control area.

Table 1. Main plant design parameters.

Q_b	178.4 m^3/s	r_p	0.0075 p.u.
H_b	133.07 m	a_p	1000 m/s
L_{hr}	1588.47 m	L_{tr}	548.12 m
F_{hr}	38.48 m^2	A_t	1.0526
r_{hr}	0.0413 p.u.	B	2.0 p.u.
F_s	201.06 m^2	q_v	0.05 p.u.
L_p	123.23 m	P_b	225 MW
F_p	23.76 m^2		

Table 2. Main power system parameters.

M_s	26.67 s	R_s	0.0045 p.u.
D_s	8.89 p.u.	P_s	1000 MW

Several simulations have been done in order to analyze the influence of some parameters on the plant and power system dynamic responses. The number of Γ-shaped elements used to model the penstock behaviour, ne_p, has been set equal to 2 in all simulations. In all cases analyzed, a demand step of 5% of P_s has been simulated at time t=10 s; then, at time t = 160 s, a change in the set-point of the turbine governor is introduced in order to bring the system back to its nominal frequency, 50 Hz. It is important to note that the hydropower plant is assumed to be the only power plant of the system providing the SCAS.

The first parameter analyzed has been the number of Γ-shaped elements, ne_{tr} used to model the behaviour of the tail-race tunnel, which is considerably longer than the penstock. In Fig. 4, it is shown the frequency and plant power output for different ne_{tr}, under the above-mentioned conditions. On the one hand, from this Fig. it can be stated that the influence of ne_{tr} on the plant and power system responses is negligible in the case analyzed.

On the other hand, it can be seen how the power plant contributes to providing both the PCAS and SCAS. According to the Spanish TSO requirements previously mentioned, the plant should be capable of modifying 1.5% of its rated output before 15 s for frequency deviations lower than 100 mHz. As it can be seen in the figure, the power plant modifies its power output from 0.68 to 0.72 p.u. within the first 15 seconds after the load variation; in turn the frequency deviation is lower than 100 mHz and the power plant achieves to bring the system frequency back to its nominal value as a result of the change introduced in the governor set-point (SCAS).

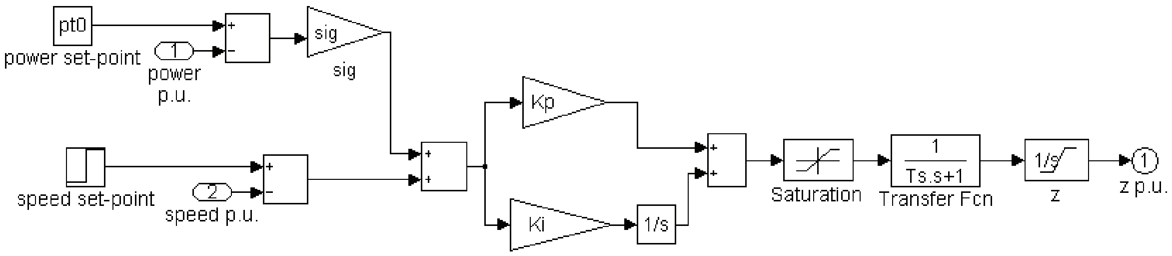

Fig. 3: Governor model.

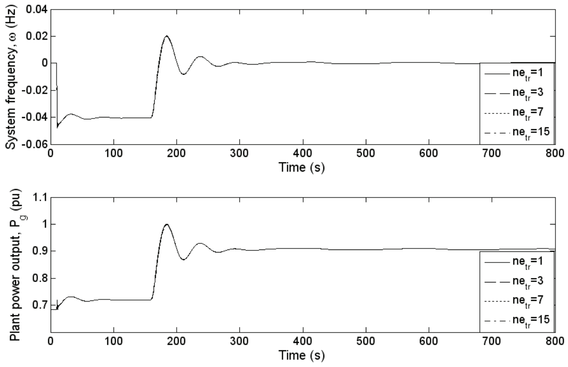

Fig. 4. System frequency and plant power output for different ne_{tr}.

Regarding the SCAS, according to the TSO requirements, the plant power output should resemble to the possible extent an exponential of time constant equal to 100 s. This implies that it should reach the 63 % of the load variation ($0.63 \cdot 0.05 \cdot P_s/P_b = 0.14$ p.u.) at time t = 260 s (100 seconds after the change in the governor set-point) and the final value at time t = 560 s. As it can be seen in Fig. 4, both conditions would be fulfilled in this case.

The second parameter analyzed has been the tail-race tunnel cross section, F_{tr}. A first estimation of this design parameter is based on a conservative value of the flow velocity, V_{tr} = 1 m/s for $Q = Q_b$. Fig. 4 was obtained with this value of F_{tr}. The PI controller gains are adjusted using the expressions given in [10], taking as water starting time (T_w) the total value obtained by adding the contributions of the two inertial elements: penstock and tail-race tunnel ($T_p + T_{tr}$). In Fig. 5, the head at the tail-race tunnel inlet (or turbine outlet), h_{tr1}, (upper part) and the plant power output (lower part) have been depicted for different cross sections, corresponding to the flow velocities 1, 3 and 5 m/s; the controller gains have been maintained in their original values adjusted for V_{tr} = 1 m/s. As it can be seen in this figure, harmful low pressures appear at the turbine outlet, except in the case corresponding to the smaller velocity (i.e. the greater cross section). It is important to note that the effects of the observed low pressures could be significantly more evident for higher load variations. Also, it is worth mentioning that both pressure fluctuations and low pressures can have harmful effects both in the tail-race tunnel and the turbine, where cavitation could even appear. In addition, the power response is poorly damped in the case with the smaller cross-section.

In order to avoid these undesirable responses, the controller gains should be changed as the cross-section and so the water starting time change. Fig. 6 shows the results of the simulations conducted in that way. No dangerous low pressures appear as the cross-section diminishes (i.e. as the flow velocity increases), but the slope of the power response after the step inputs becomes lower. This slower power response could limit the capability of the plant to provide SCAS. Moreover, after the transient caused by the step in the governor set point has practically extinguished, a persistent oscillation in the responses is observed in the cases with higher design velocity. Although, with respect to the previous case, the damping of the power response improves significantly, this oscillation may prevent the plant from providing the SCAS, since the resulting settling times are considerable higher than those required by the Spanish TSO. Said oscillation is a consequence of the surge tank dynamics; usually it is not observed, because the load-frequency regulator filters it out by modifying the wicket gates position in opposition to the surge tank level deviation. However in the cases with the smaller cross-section (higher fluid inertia), the adjustment of the controller gains results in a weak control action which is unable to counteract the changes in the surge tank level. It could be expected that an increase in the controller gains was adequate in these cases, provided that acceptable limits in the pressure at the tail-race inlet as well as in the settling time can be ensured. Nevertheless, further research is therefore needed in order to find a compromise solution between a small and therefore cheaper tail-race cross section and one that allows providing the above-mentioned ancillary services and that do not jeopardize the plant time life.

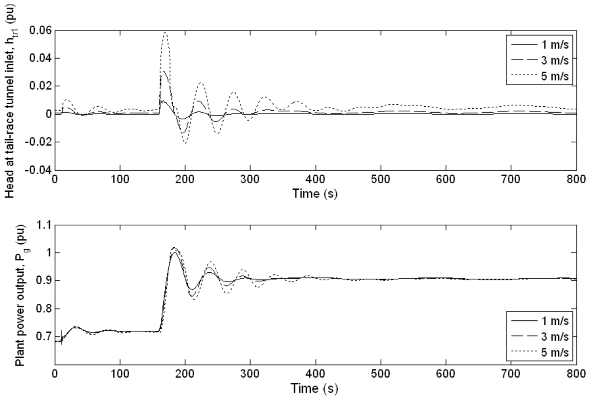

Fig. 5: Head at the tail-race tunnel inlet and plant power output for different F_{tr}. Constant controller gains.

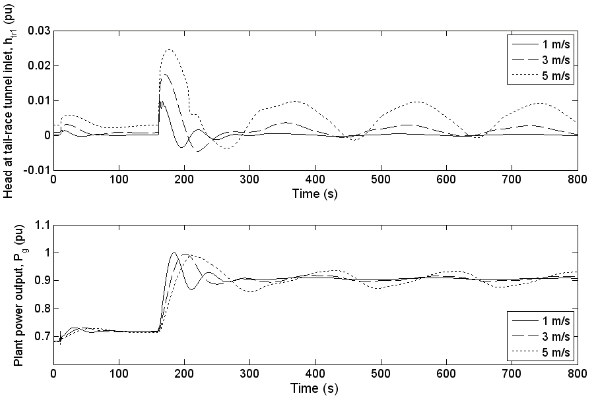

Fig. 6: Head at the tail-race tunnel inlet and plant power output for different F_{tr}. Readjusted controller gains.

Conclusions

A detailed dynamic model of a hydroelectric power plant has been used to assess its contribution to load-frequency regulation. The aspects related to the plant dynamic response have been studied in relation with the requirements of the Spanish Electrical System Operator.

The developed model may be applied for many possible plant configurations, including head-race tunnel, surge tank and tail-race tunnel. The elasticity of water and pipe has been considered by dividing the conduit in several elements. The results indicate that a short number of elements may be sufficient to adequately consider the pressure waves effects.

The influence of some critical plant design parameters in the quality of dynamic response has been studied. The results obtained in the practical case highlight the strong importance that should be given to the consideration of the dynamic response aspects in early design phases.

The section of the tail-race tunnel plays an important role in the stabilization of the response following a sudden change in the plant set-point. Thus, during the design phase, the need to satisfy determined requirements concerning the plant dynamic response, may lead to a substantial increase in the plant budget.

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Appendix - Notation

a	Wave speed (m/s)
a_p	Wave speed in the penstock (m/s)
A	Pipe cross section (m^2)
A_t	Turbine parameter
B	Turbine parameter
D	Pipe diameter (m)
D_h	Hydro plant damping constant (p.u.)
D_s	Power system damping constant (p.u.)
f	Darcy-Weisbach coefficient
F_{hr}	Head-race cross section (m^2)
F_p	Penstock cross section (m^2)
F_s	Surge tank cross section (m^2)
g	Gravity acceleration (m/s^2)
H	Head (m)
h_{dr}	Head at the downstream reservoir (pu)
$h_{p,i}$	Head at the end of the i-th Γ element of the penstock (p.u.)
h_s	Head in the surge tank (p.u.)
h_t	Head at the turbine inlet (p.u.)
h_{tr}	Head at the turbine outlet (p.u.)
h_{ur}	Head in the upstream reservoir (p.u.)
L_{hr}	Head-race tunnel length (m)
L_p	Penstock length (m)
L_{tr}	Tail-race tunnel length (m)
M_h	Hydro plant inertia constant (s)
M_s	External power system inertia constant (s)
ne_p	Number of Γ elements used to model the penstock
ne_{tr}	Number of Γ elements used to model the tail-race tunnel
n	Turbine speed
n_0	Turbine speed set point (p.u.)
n_s	External system frequency (p.u.)
p_t	Plant output power (p.u.)
P_b	Base plant power output
P_m	Turbine mechanical power (p.u.)
P_g	Generated power (p.u.) (the generator losses being neglected)
P_L	Demand power (p.u.)
Q	Flow (m^3/s)
q_{hr}	Flow in the head-race tunnel (p.u.)
$q_{p,i}$	Flow in the i-th Γ element of the penstock (p.u.)
q_t	Flow through the turbine (p.u.)
q_v	No-load flow (p.u.)
r_{hr}	Losses coefficient of the head-race tunnel (p.u.)
r_p	Losses coefficient of the penstock (p.u.)
R_s	External power system equivalent speed-droop (p.u.)
T_{hr}	Water starting time in the head-race tunnel (s)
T_p	Water starting time in the penstock (s)
z	Wicket gates opening (p.u.)
δ	Load angle of hydro plant generator (rd)
δ_s	Load angle of external system equivalent generator (rd)
ω_0	Base system frequency (rd/s)

(Base power for all p.u. magnitudes is the hydro plant rated power).

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