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TURBINE SPEED GOVERNOR PARAMETERS VALIDATION IN ISLANDED PRODUCTION

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ABSTRACT

The transient behavior of hydroelectric power plants is of high interest for ensuring stability of islanded electrical power networks. Therefore, it is suitable to determine and validate the set of parameters of a turbine speed governor using a realistic simulation model taking into account the hydraulic circuit, the rotating inertias, the electrical installations and the control systems. This paper presents the modeling of a 4x250 MW Francis turbine hydroelectric power plant taking into account the dynamics of all the aforementioned components. The transfer function of the turbine is determined through a time domain simulation using white noise excitation for the determination of an appropriate set of parameters. The performance of the regulator parameters are assessed using two different models: (i) a hydraulic model and (ii) a full hydroelectric model including the model of an islanded power network. The stabilization effect of Standard Power System Stabilizer (PSS) is evidenced.

INTRODUCTION

Hydropower has an important role to play in the regulation and in the stability of electrical power networks as it is one of the only energy resources capable of quick changes of set points and featuring large operating range. Every hydroelectric power plant features a different layout, and consequently different time constants, therefore no standard set of regulation parameters can be used. The determination and validation of regulation parameters should be performed using realistic simulation models taking into account phenomena of major concerns according to the layout of the hydraulic circuit [12]. Thus, hydropower plants comprising long penstock, surge tank and operating in islanded production are subject to waterhammer, mass oscillation, hydromechanical and electromechanical phenomena. Consequently the analysis of such a system requires a simulation model including hydraulic, electrical, mechanical and control system high order models.

This paper presents the analysis of the transient behavior of an islanded power network comprising a 1 GW hydroelectric power plant and a 1.3 GW thermal power plant and 2 passive consumer loads, see Figure 1, under load rejection. First the modeling of the hydroelectric power plant is presented and the transfer function of the power plant is determined for control parameters determination. The set of parameters is validated with a hydraulic model. Then the modeling of the thermal power plant is briefly presented and the model of 2.3 GW islanded power plant is setup. Finally, turbine speed governors parameters validity is assessed in islanded production mode and stabilization effect obtained with a Power System Stabilizer (PSS) is demonstrated.

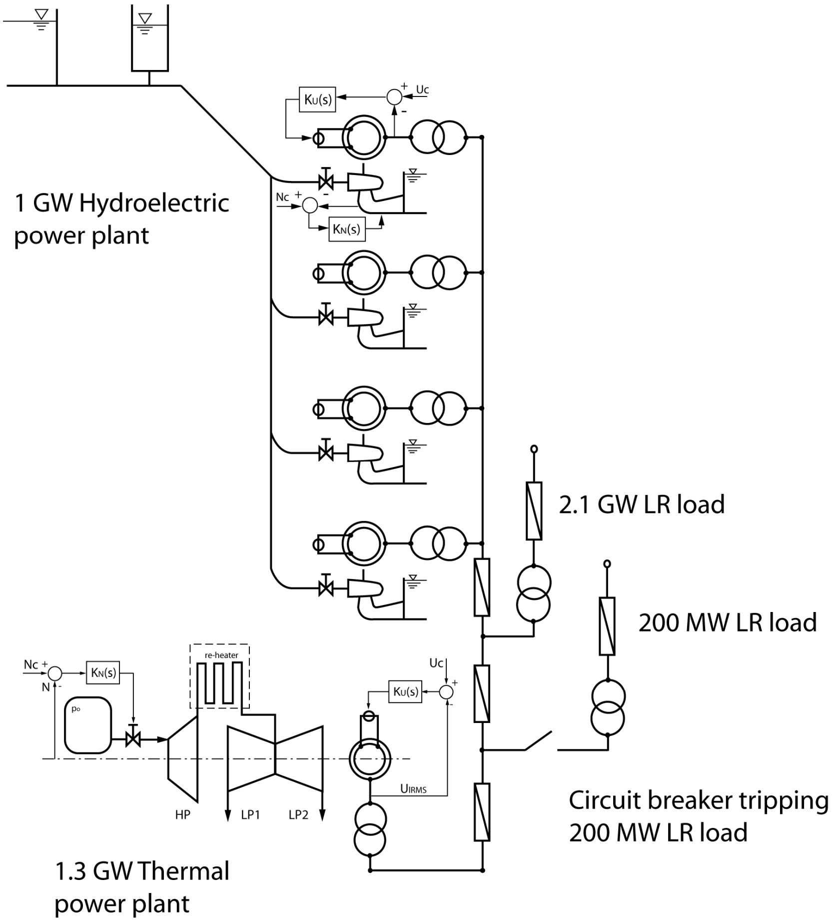

Figure 1. Islanded power plant of the case study.

MODELING OF THE HYDRAULIC INSTALLATION

Hydraulic system modeling

By assuming uniform pressure and velocity distributions in the cross section and neglecting the convective terms, the one-dimensional momentum and continuity balances for an elementary pipe filled with water of length dx, cross section A and wave speed a, see Figure , yields to the following set of hyperbolic partial differential equations [13]:

$$\begin{cases} \dfrac{\partial h}{\partial t} + \dfrac{a^2}{gA} \cdot \dfrac{\partial Q}{\partial x} = 0 \\ \dfrac{\partial h}{\partial x} + \dfrac{1}{gA} \cdot \dfrac{\partial Q}{\partial t} + \dfrac{\lambda |Q|}{2gDA^2} \cdot Q = 0 \end{cases} \quad (1)$$

The system (1) is solved using the Finite Difference Method with a 1st order centered scheme discretization in space and a scheme of Lax for the discharge variable. This approach leads to a system of ordinary differential equations that can be represented as a T-shaped equivalent scheme [2], [9], [11] as presented in Figure 3. The RLC parameters of this equivalent scheme are given by:

$$R = \frac{\lambda \cdot |\overline{Q}| \cdot dx}{2 \cdot g \cdot D \cdot A^2} \ ; \ L = \frac{dx}{g \cdot A} \ ; \ C = \frac{g \cdot A \cdot dx}{a^2} \quad (2)$$

where λ is the local loss coefficient. The hydraulic resistance R, the hydraulic inductance L, and the hydraulic capacitance C correspond respectively to energy losses, inertia and storage effects.

The model of a pipe of length *L* is made of a series of n_b elements based on the equivalent scheme of Figure 3. The system of equations relative to this model is set-up using Kirchoff laws. The model of the pipe, as well as the model of valve, surge tank, Francis turbine, etc, are implemented in the EPFL software SIMSEN, developed for the simulation of the dynamic behavior of hydroelectric power plants, [6], [10]. The time domain integration of the full system is achieved in SIMSEN by a Runge-Kutta 4th order procedure.

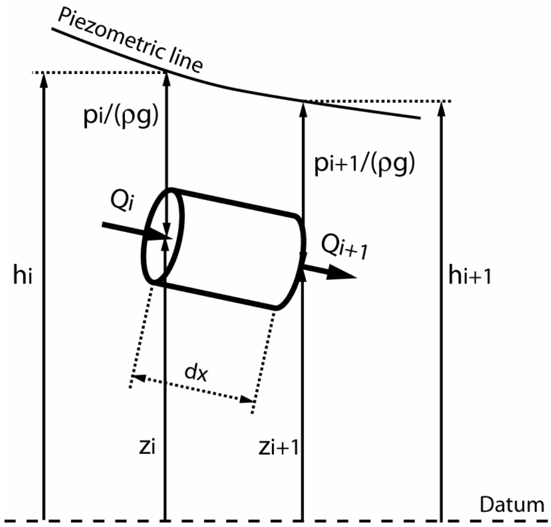

Figure 2. Elementary hydraulic pipe of length dx.

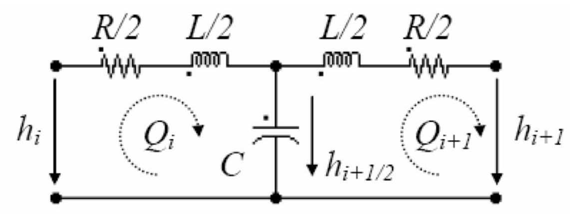

Figure 3. Equivalent circuit of an elementary pipe of length dx.

Hydraulic power plant model

The layout of the hydroelectric power plant presented in Table 1 is made of a 1'515 meters long gallery, a surge tank with variable section, a 1'388 meters long penstock and a manifold feeding 4x250 MW Francis turbines. The main parameters of the hydroelectric power plant are summarized in Table 1.

The gallery and the penstock are respectively discretized into 22 and 31 elements. The Francis turbine characteristics of discharge and torque factors versus the speed factor are presented for different guide vane opening values y, see Figure . The discharge, torque and speed factors are defined as follows:

$$N_{11} = \frac{N \cdot D_{ref}}{\sqrt{H}} ; Q_{11} = \frac{Q}{D_{ref}^2 \cdot \sqrt{H}} ; T_{11} = \frac{T}{D_{ref}^3 \cdot H} \quad (3)$$

The block diagram of the PID governor of the Francis turbine is presented in Figure . The governor structure includes both speed and power feedbacks. The network frequency feedback is neglected in this study because only islanded production modes are considered. The servomotor of the guide vanes is modeled through a first order transfer function with a time constant of $\tau sv = 0.1$ s.

Table 1. Hydraulic power plant characteristics.

Gallery	Length: 1'515 m Diameter: 8.8 m Wave speed: 1'000 m/s
Surge tank	Mid tank section: 133 m^2
Penstock	Length: 1'388 m Diameter: 8.8 / 7.15 m Wave speed: 1200 m/s
Francis turbine	Rated mechanical power: P_R = 250 MW Rated speed: N_R = 333.3 rpm Rated discharge: Q_R = 75 m^3/s Rated head: H_R = 350 m Specific speed: ν = 0.226 Reference diameter: D_{ref} = 2.82 m Inertia : $J_t = 1.7 \cdot 10^5$ kg*m^2
Generator	Rated apparent power: S_n = 270 MVA Rated phase to phase voltage: U_n = 18 kV Frequency: f = 50 Hz Number of pairs of poles: p = 9 Stator windings: Y Inertia: $J_G = 1.54 \cdot 10^6$ kg·m^2
Coupling shaft	Stiffness: $K = 3.62 \cdot 10^8$ Nm/rad Viscous damping: $\mu = 6.7 \cdot 10^3$ Nms/rad

Turbine governor parameters determination and validation

The transfer function of the turbine considering the guide vane as input variable and the rotational speed as output variable is determined using a Pseudo Random Binary Sequence (PRBS) signal [7]. The time evolution of both the rated rotational speed n and the rated guide vane opening y are presented in Figure 6. The time domain simulation is performed for T=2000s, with an integration time step dt=0.005s and a PRBS time constant of dt=0.05s. The resulting transfer function is presented in Figure 7.

The transfer function evidences the natural frequencies of the hydroelectric system pointing out the mass oscillation frequency with a period of T=115 s, a penstock first natural period of T=4.6 s and the harmonics of the penstock and piping system, the rotating inertia anti-resonance of a frequency of f=2.3 Hz, and a rotating inertia resonance of a frequency of f=7.7 Hz, [7].

The set of parameters of the PID turbine governor is determined according to the transfer function in order to ensure 60-90° of phase margin, 6-9 dB of gain margin and a slope of -20dB/decade at the cut-off frequency selected to be f_c=0.02 Hz. The cut-off frequency is selected in order to ensure not amplifying any natural frequency of the system. The resulting set of parameters is given in Table 2 where Kp, T_I, T_D and are respectively the proportional gain, the integral, derivative and tachometer time constants.

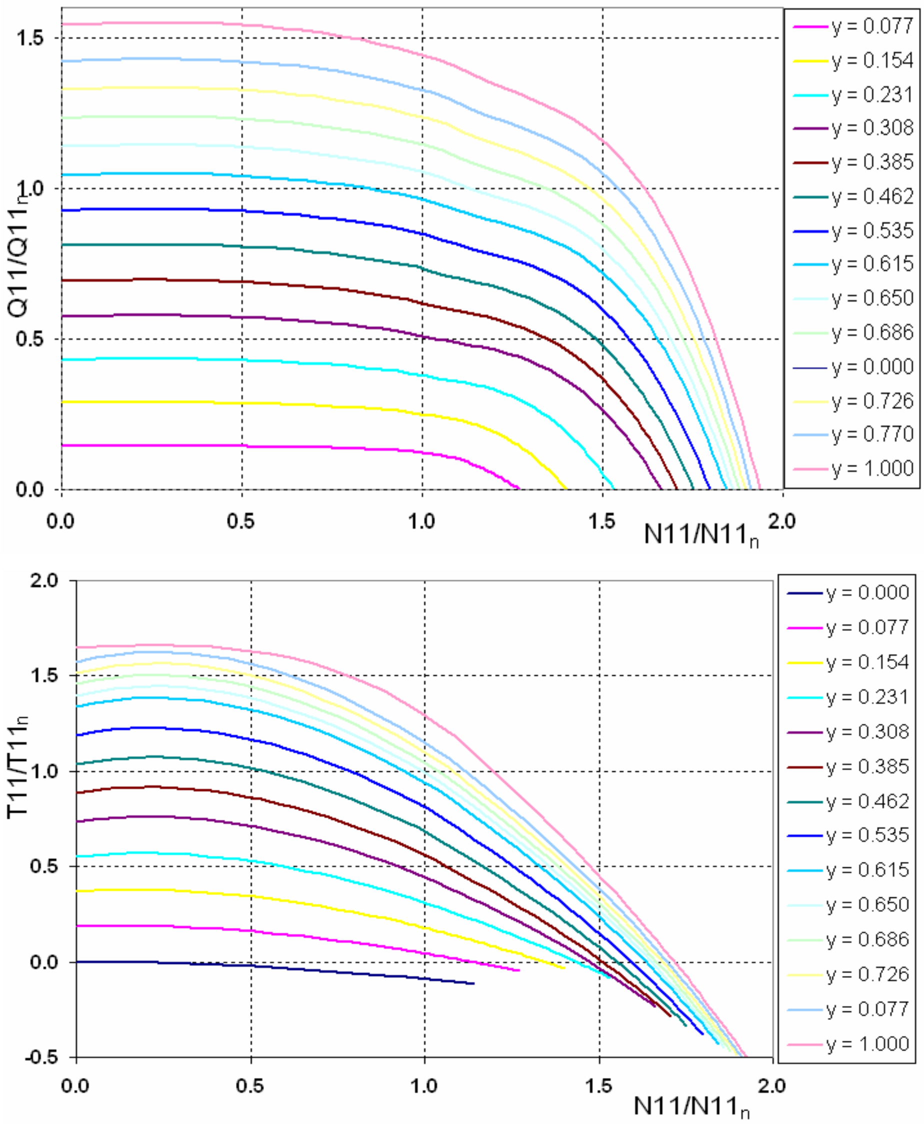

Figure 4. Turbine characteristics $Q_{11}=Q_{11}(N_{11})$, left, and $T_{11}=T_{11}(N_{11})$, right, for different GVO opening y.

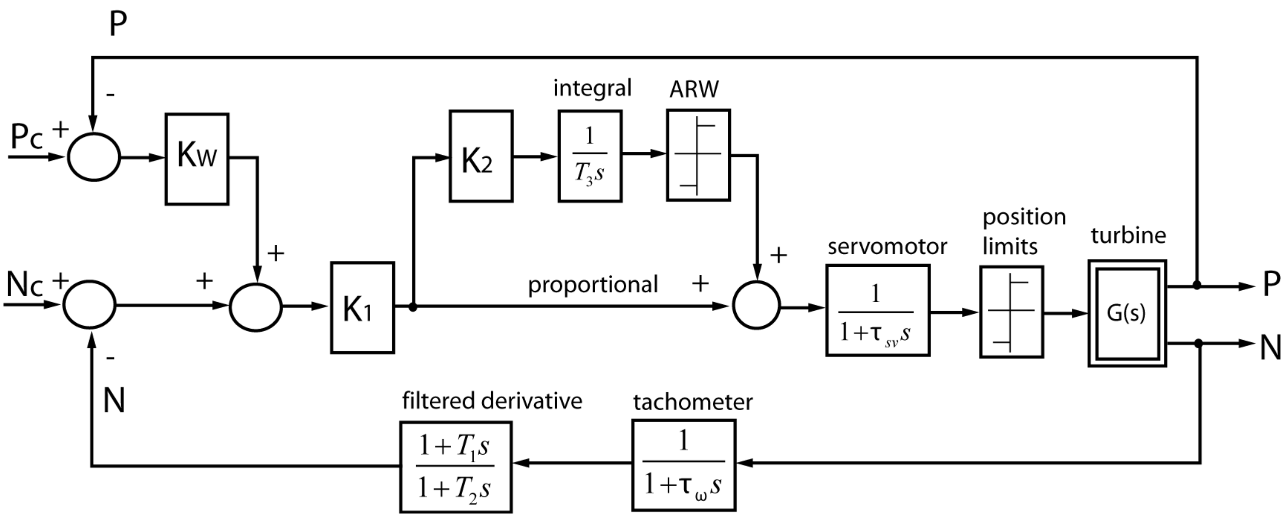

Figure 5. Block diagram of the turbine speed governor.

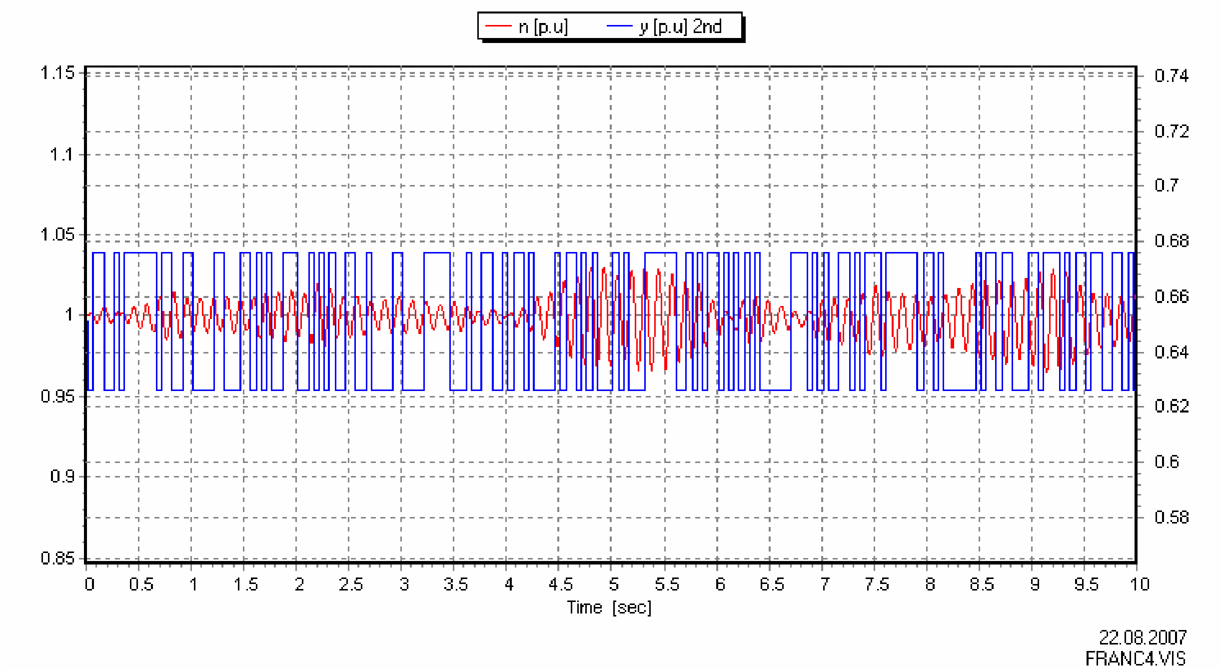

Figure 6. PRBS excitation at the guide vane opening y and resulting rotational speed n of duration T=2000 s with integration time step dt = 0.005 and PRBS basic time constant Tau = 0.05 s.

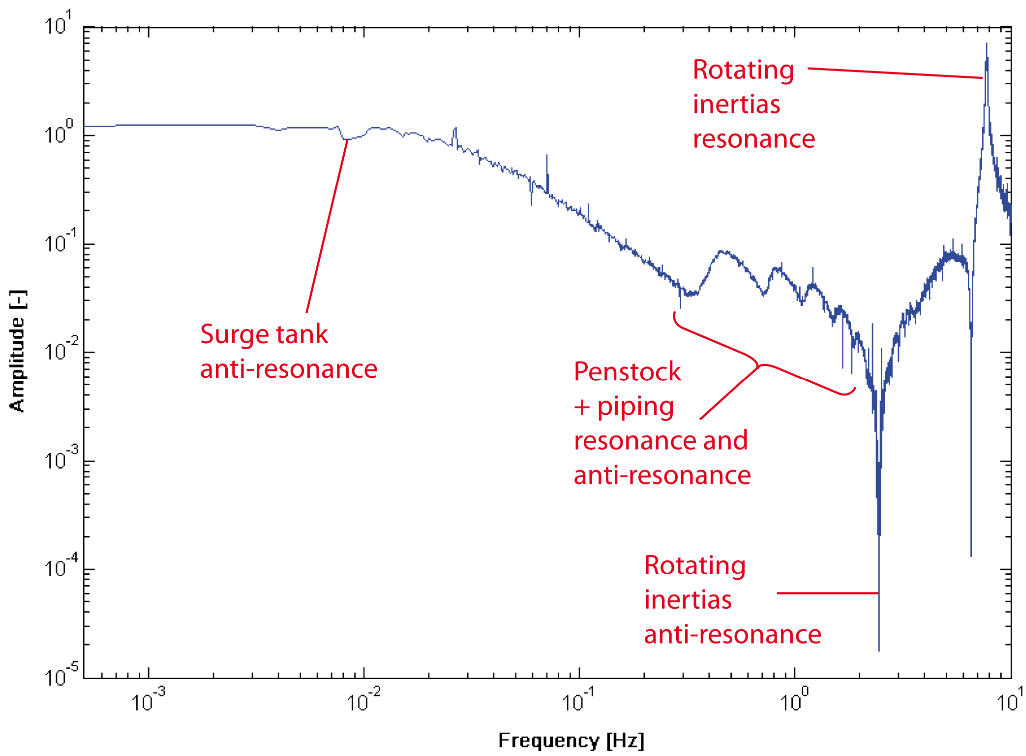

Figure 7. Turbine transfer function resulting from the PRBS excitation of Figure 6.

Table 2. PID turbine speed governor parameters.

Kp	T_I	T_D	$\tau\omega$
0.59	17.50 s	1.89 s	0.05 s

To validate the set of parameters, a 6% successive load rejection and acceptance is simulate in the time domain with the hydraulic model of the power plant with a power level of 40% of the nominal power.

The resulting time evolution of the rotational speed and guide vane opening shows that stability of the rotational speed is quickly recovered after perturbation even if there is a small oscillation of the guide vanes at the mass oscillation period of T=115 s. The validity of the regulator parameter set was also checked for 70%, 100% and 115% of the nominal power.

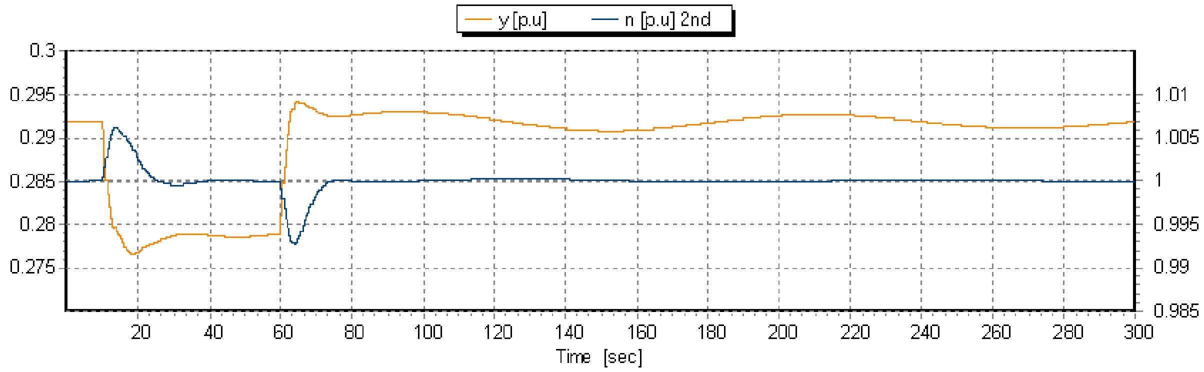

Figure 8. Time evolution of the turbine rotational speed and guide vane opening resulting from 6% load rejection and acceptance.

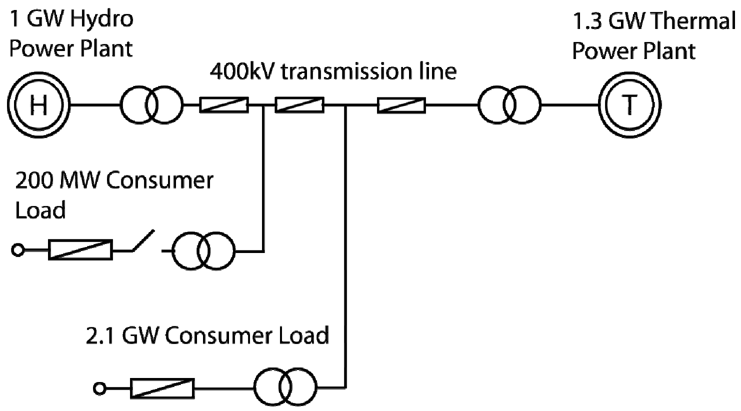

Figure 9. Islanded power network configuration.

MODELING OF THE THERMAL POWER PLANT

The model of the 1 GW thermal power plant is based on steam flux and takes into account a constant pressure steam vessel, a regulating valve, a high pressure steam turbine, then the steam transit through a re-heater and then feed two low pressure steam turbines as presented in Figure 1. The model is based on valve and torque characteristics deduced from [1], on first order transfer functions for the turbine dynamics with τ_{HP}, τ_{LP} time constants, a re-heater modeled by a time delay b, and a proportional regulator of constant Kp. The shaft line comprises 4 rotating inertias connected by 3 shaft with given stiffness and damping. And finally a 2 pole pairs generator is also included in the model with ABB unitrol voltage regulator. The parameters of the model are given in Table 3 and details of the model can be found in [7].

MODELING OF THE ISLANDED POWER NETWORK

A model of an islanded power network is setup using the model of the 1 GW hydroelectric power plant and the model of the 1.3 GW thermal power plant and including 2 passive consumers loads: one of 2.1 GW and one on 200 MW as presented in Figure 9. The producers and consumers are connected through a 400 kV transmission network.

Table 3. Thermal power plant characteristics.

Steam turbines model	τ_{HP} = 0.5 s τ_{LP} = 12 s b = 4 s Kp = 25
Mechanical masses inertia	JHP = 1.867.10^4 Kg*m2 JLP1 = 1.907.10^5 Kg*m2 JLP2 = 2.136.10^5 Kg*m2 JGEN = 5.223.10^4 Kg*m2
Mechanical shaft stiffness and damping	K1 = 3.614.10^8 Nm/rd K2 = 8.206.10^8 Nm/rd K3 = 4.116.10^8 Nm/rd μ1 = 6.719.10^3 Nms/rd μ2 = 7.06.10^3 Nms/rd μ3 = 7.06.10^3 Nms/rd
Generator	Rated apparent power: 1400 MVA Rated phase to phase voltage: 28.5 kV Frequency: 50 Hz Number of pairs of poles: 2 Stator windings: Y

To include the hydroelectric power plant in the islanded power network, the model of the synchronous generator is also taken into account. The main parameters of the generators are given in Table 1.

TRANSIENT BEHAVIOR OF THE POWER NETWORK

Transient behavior in islanded production mode

The turbine speed governor parameter set is validated using a hydraulic model of the power plant. However, this power plant has to operate into an islanded power network which dynamics affect the dynamic behaviour of the turbine. The turbine transfer function is therefore re-identified using again a PRBS signal but operating in the islanded power network of Figure 9. The new transfer function is presented in Figure 10. Comparing the new transfer function of the turbine with the previous one obtained only with the hydraulic model, see Figure 7, it can be noticed that:

- there is a stabilization effect due to the power network at low frequencies;
- there is a new natural frequency at f=1.36 Hz corresponding to the electromechanical mode so called the generator natural frequency [4], [8].

If the new natural frequency of the system which is the natural frequency of the generator is not taken into account, resonance between the turbine governor and the generator can occur. To avoid such resonance, the tachometer filter time constant should be reduced in order to ensure that the electromechanical mode is not excited by the turbine speed governor.

The time domain simulation of the tripping of the consumer load of 200 MW is undertaken using the power distribution given in Table . The difference in the active power balance is due to losses of electrical lines and transformers and the difference in reactive power balance is due to electrical lines capacitances. Figure 11 and Figure 12 present the time evolution of respectively the rotational speed and the active power of the Unit 4 for two cases:

- the case with the initial filter time constant τ_ω=0.05 s leading to unstable behaviour due to the resonance at 1.36 Hz of the generator;
- the case with modified filter time constant τ_ω=0.3 s leading to a stable operation.

It can be also noticed that the tripping of the 200 MW consumer load induces in both cases speed deviation of 3% after 6 seconds.

Table 4. Power distribution in the islanded power network of Figure 9.

Element	Active power P [MW]	Reactive power Q [MVAR]	Power flow
Hydropower plant	-239.8	-20.6	Production
Thermal power plant	-1262	-173.9	Production
Load 1	2013	365	Consumption
Load 2 (Tripped)	194.7	70	Consumption

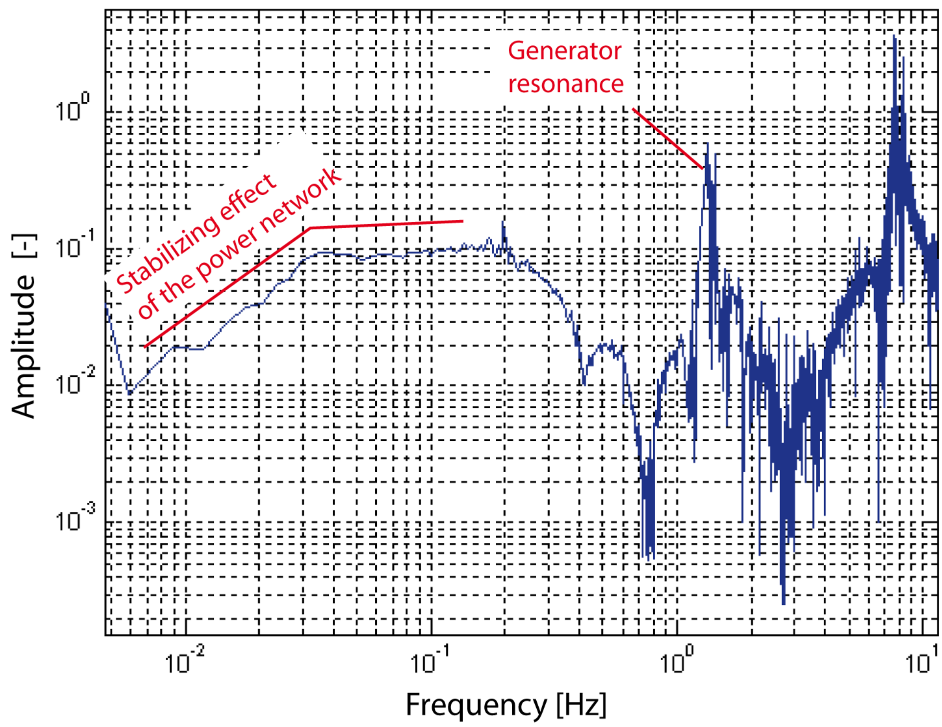

Figure 10. Turbine transfer function with the full hydroelectric model.

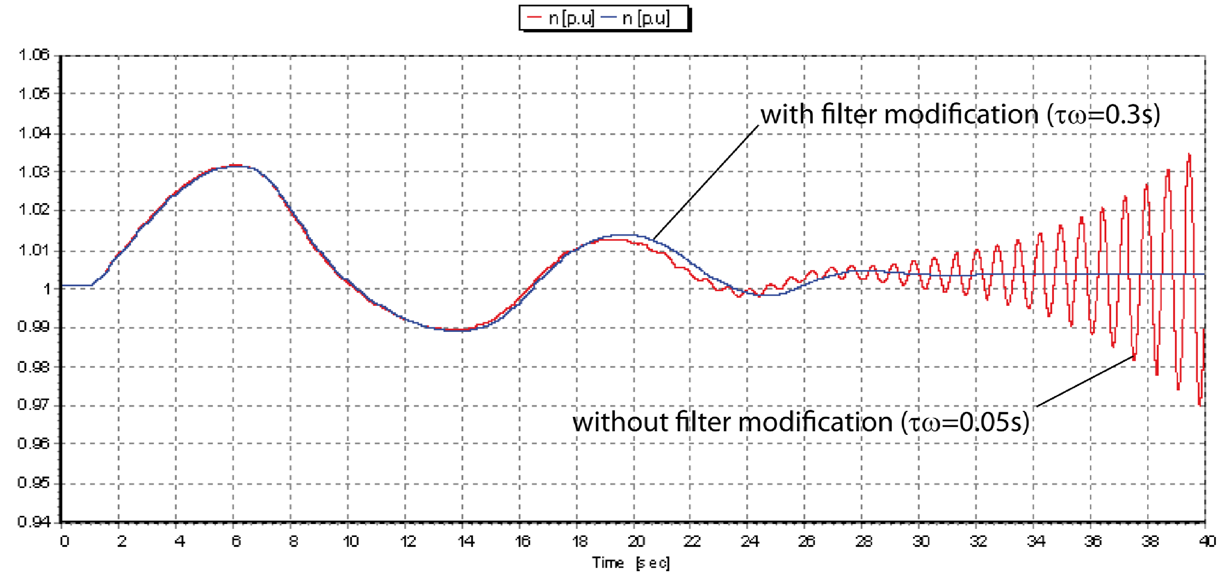

Figure 11. Time evolution of the rotational speed of the turbines with and without modification of the tachometer filter time constant.

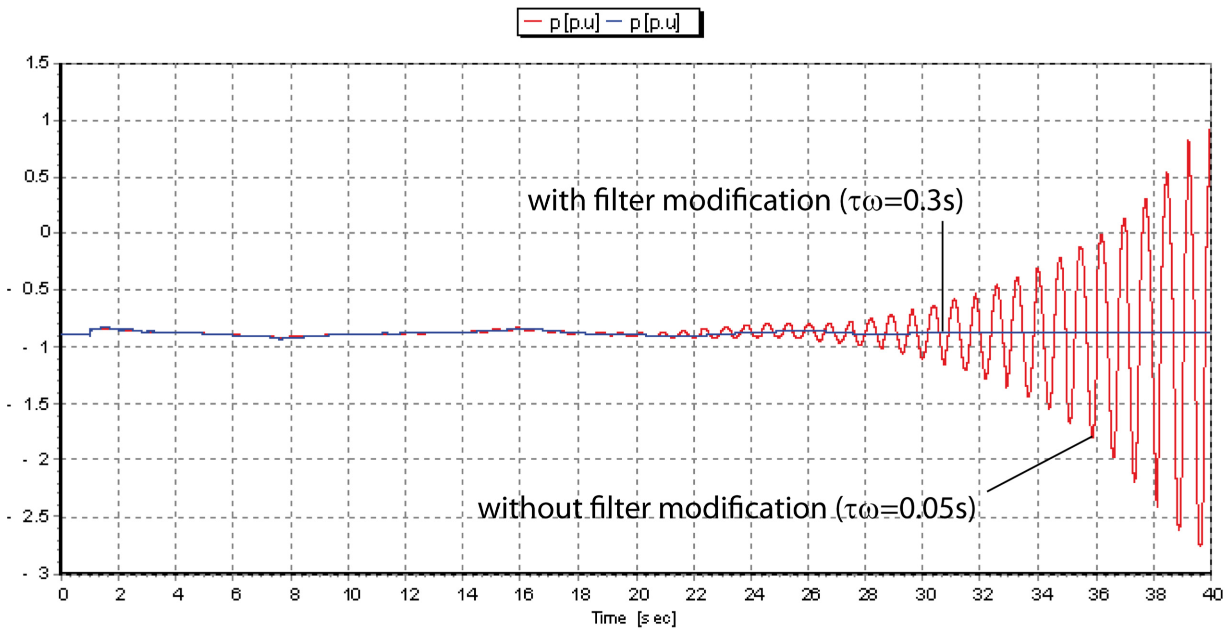

Figure 12. Time evolution of the active power of the turbines with and without modification of the tachometer filter time constant.

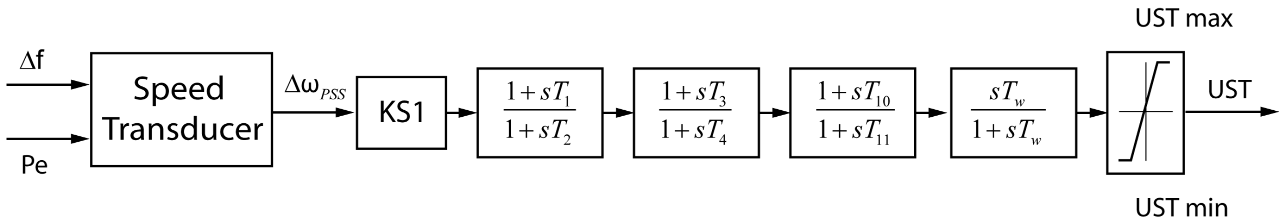

Figure 13. Block diagram of the Power System Stabilizers (PSS).

Transient behavior in islanded production mode with PSS

It is well know that Power System Stabilizers (PSS) can operate well in islanded power network enabling to reduce considerably speed deviations during load rejections and acceptances [3]. The PSS has for inlet values the network frequency deviation and the electrical active power, the output value is a correction of the voltage regulator set point. The block diagram of the PSS IEEE-PSS2B is presented in Figure 13. It corresponds, except for the speed transducer, to a series of filtered derivative regulators. The block diagram of the speed transducer can be found in [3]. The parameter set of parameters of the PSS2B is taken from [5].

The simulation of the tripping of the 200 MW consumer load is performed for the same operating conditions as previously but the PSS2B is included for the 4 voltages regulators of the 4 hydrogenerators keeping the modification of the tachometer filter time constant (τ_ω=0.3 s). The time evolutions of the rotational speed and of the active power are presented respectively in Figure 14, Figure 15 for the cases with and without PSS. It can be noticed that the speed deviation is considerably reduced, by a factor 3, and that also active power fluctuations are strongly damped, demonstrating the effectiveness of the PSS in islanded operation.

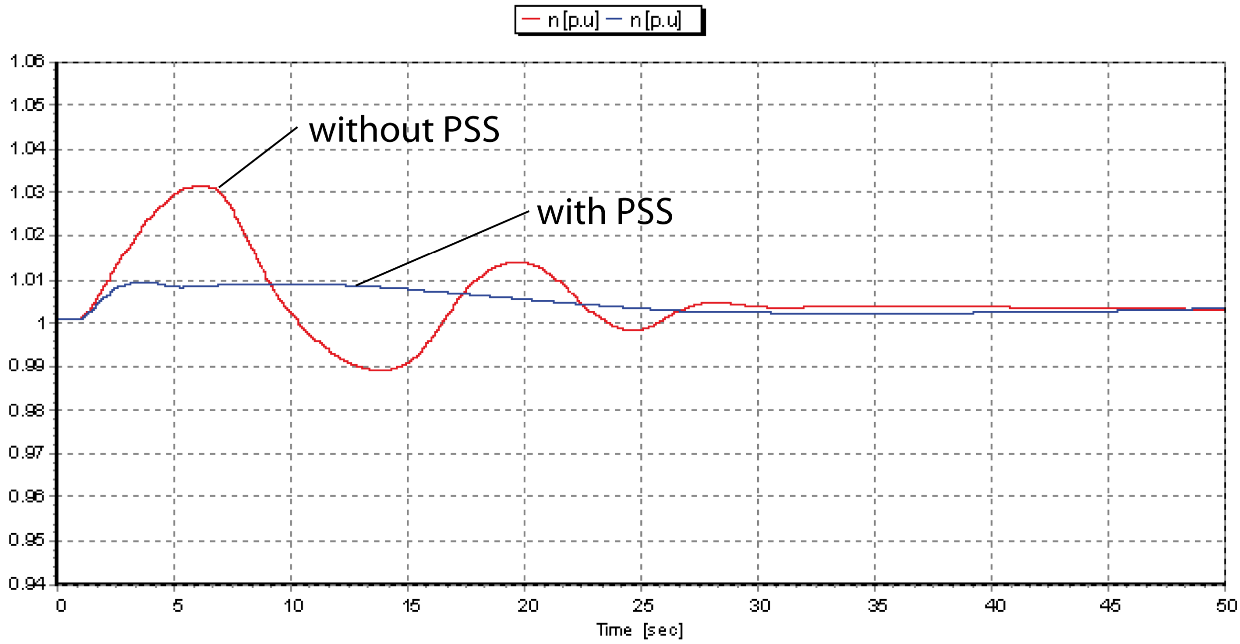

Figure 14. Time evolution of the rotational speed of the turbines with and without Power System Stabilizers (PSS).

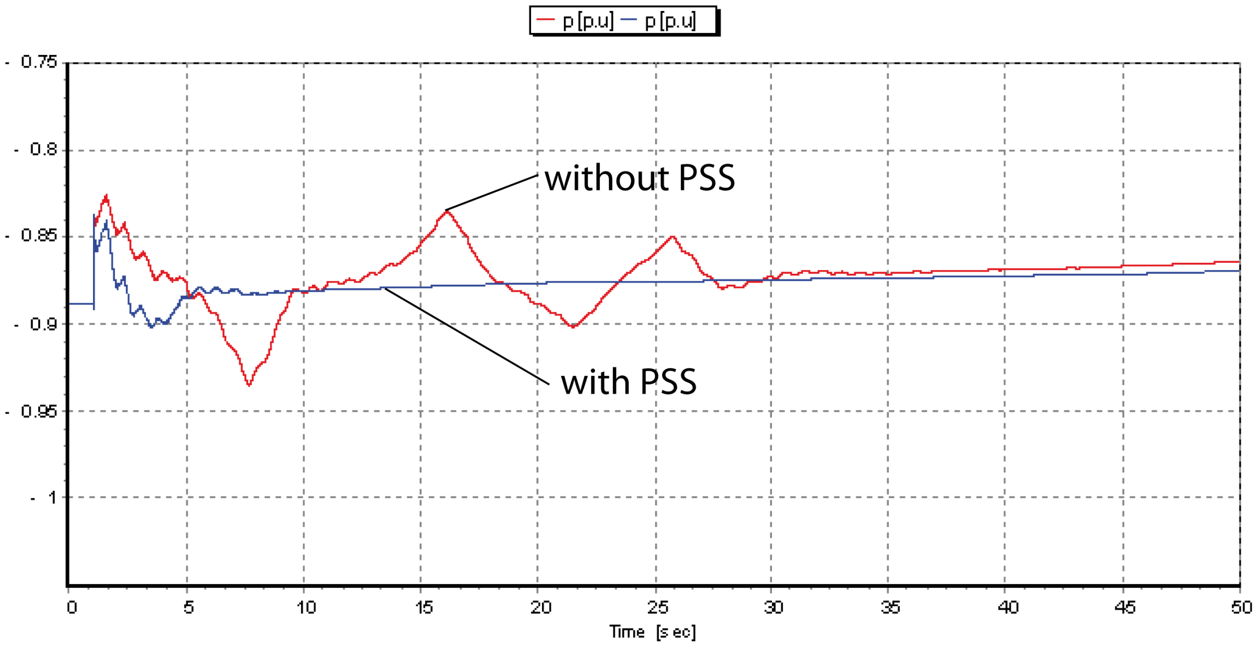

Figure 15. Time evolution of the active power of the turbines with and without Power System Stabilizers (PSS).

CONCLUSIONS

The modeling of a 2.3 GW islanded power network comprising a 1 GW hydroelectric power plant, a 1.3 GW thermal power plant and 2 passive consumer loads is presented. The parameters of the turbine governor are determined according to the turbine transfer function determined from a time domain simulation using a PRBS excitation. It is shown that it is not sufficient to validate the turbine governor parameters using a hydraulic model of the power plant, as electrical machines and power network can considerably affect the turbine transfer function and lead to unexpected unstable operation, at least in islanded production mode. In addition, it is demonstrated that Power System Stabilizers can contribute significantly to reduce speed deviations during load rejections.

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