11th International Meeting of the Work Group on
THE BEHAVIOUR OF HYDRAULIC MACHINERY UNDER
STEADY OSCILLATORY CONDITIONS

Stuttgart, Germany

TRANSIENT PHENOMENA IN FRANCIS TURBINE POWER PLANTS: INTERACTION WITH THE POWER NETWORK

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ABSTRACT

Models of hydraulic components based on impedance method have been implemented in a software called "SIMSEN". This software allows the simultaneous solution of the electrical, hydraulic, mechanic and control equations ensuring a proper interaction between these four parts of a system. Using this tool, in this paper, the transient behavior of an islanded power network is investigated. This network comprises a 2 Francis turbines hydroelectric power station of 172 MW, a nuclear power station of 1300 MW and a consumer load. The nuclear power station modeling takes into account the rotating masses and stiffness, the rotational speed regulators, a first order steam turbine model and the generator. Two disturbances are simulated using SIMSEN: the hydroelectric power plant switch off and the load acceptance and rejection. The simulation results show how the power is balanced during such transients. This approach allows for the analysis of control command parameters of an islanded power network.

NOMENCLATURE

Term	**Symbol**	**Definition**
Piezometric head	H	$H = z + p/(\rho g)$ [m]
Flow rate	Q	[m^3/s]
Wave speed	a	[m/s]
Cross section area	A	[m^2]
Friction factor	λ	[-]
Singular losses	K	[-]

Term	**Symbol**	**Definition**
Hydraulic resistance	R	$R = R' \cdot dx$ [s/m^2]
Hydraulic inductance	L	$L = L' \cdot dx$ [s^2/m^2]
Hydraulic capacitance	C	$C = C' \cdot dx$ [m^2]
Rated head	h	$h = H/H_R$
Rated torque	β	$\beta = T/T_R$ [-]
Static turbine	θ	$\theta = \tan^{-1}(\upsilon/\alpha)$

Term	**Symbol**	**Definition**
coefficient		
Electrical resistance	R_e	[ohm]
Electrical inductance	L_e	[H]
Electrical capacitance	C_e	[F]
Rotating speed	ω	[rad/s]
Torque	T	[Nm]
Thermal time constant	τ_{th}	[s]

Term	**Symbol**	**Definition**
characteristic		
Rated flow	υ	$\upsilon = Q/Q_R$ [-]
Rated rotating speed	α	$\alpha = \omega/\omega_R$ [-]
Density	ρ	[Kg/m^3]
Mechanical inertia	I	[$Kg \cdot m^2$]
Guide vane opening degree	y	[-]
Regulator statism	bp	[%]

INTRODUCTION

The operation of an hydroelectric power plant is subject to several transient phenomenon due to group star-up and shut-down, modification of operating point, earth fault, out of phase synchronization during start-up, emergency stop and so on. A full model of the power plant taking into account the hydraulic, electric, mechanical and control device components is requested to investigate all the worst cases and to calculate control command parameters ensuring operating stability.

The EPFL Laboratory for Electrical Machines –LME– has developed a software called SIMSEN (Ref. 9, Ref. 10) for the simulation of electrical power networks systems in transient or steady state modes and adjustable speed drive systems. To be able to study the dynamic behavior of a whole hydroelectric power plant including electrical, hydraulic and control components, a hydraulic extension has been developed and implemented in SIMSEN (Ref. 6 and Ref. 7). This development is the result of the collaboration between the LME and the EPFL Laboratory for Hydraulic Machines. The extension includes the models of pipe, valve, surge tank and Francis turbine. To match the formalism of this software the impedance method (Ref. 1, Ref. 4 and Ref. 11) has naturally been chosen for the modeling of the hydraulic components. Thus, the corresponding governing equations can be implemented easily and the hydraulic extension benefits from the arbitrary topology feature allowing to model complex piping systems. The modeling of the hydraulic components is presented in Table 1.

Previous simulations already demonstrated the importance of fully taking into account the hydraulic and electrical part of a power system (Ref. 8). This paper emphasizes the need of a detailed modeling in the case of transient behavior simulations of an islanded power network. A network comprising a hydroelectric power station, a nuclear power station and a consumer load is modeled. Power balance is analyzed during/after hydroelectric power plant switch off and consumer load variations.

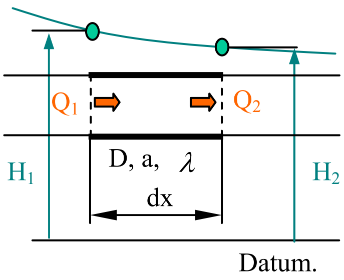
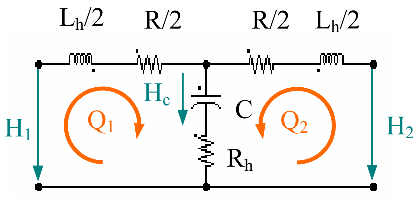
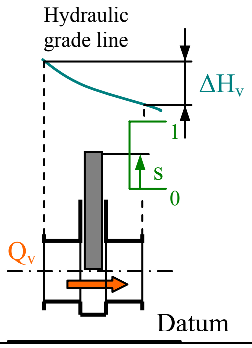
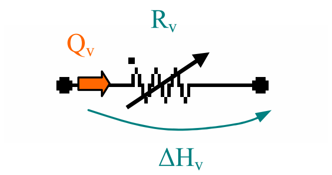
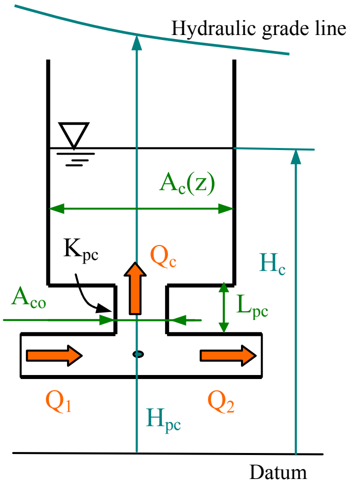
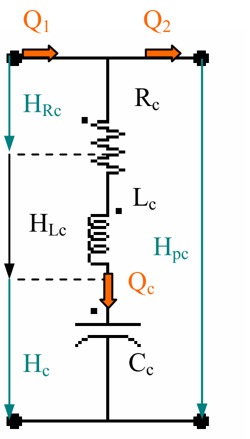
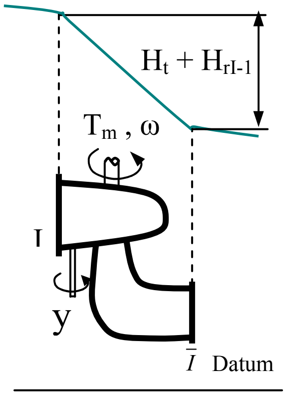
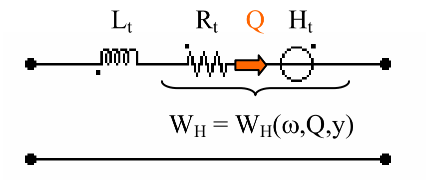
Component	Electrical equivalent	Equation set
		$\frac{dx\cdot g\cdot A}{a^2}\frac{dH_c}{dt}=C\frac{dH_c}{dt}=Q_1-Q_2$ $\Delta H_R=\frac{\lambda dx\lvert Q_1\rvert}{2DgA^2}Q_1=RQ_1$ $\Delta H_L=\frac{dx}{gA}\frac{dQ_2}{dt}=L\frac{dQ_2}{dt}$
		$\Delta H_v=\underbrace{\frac{\lvert Q_v\rvert}{2g\left(C_d(s)A_G(s)\right)^2}}_{R_v}Q_v$
		$\left(H_{pc}-H_c\right)=\underbrace{\frac{K_{pc}\lvert Q_c\rvert}{2gA_{co}^2}}_{R_c}Q_c$ $\underbrace{A_c(z)}_{C_c}\frac{dH_c}{dt}=Q_c$ $L_c=\frac{L_{pc}}{gA_{co}}$
		$W_B(\theta)=\frac{\beta}{\alpha^2+\upsilon^2}$ $W_H(\theta)=\frac{h}{\alpha^2+\upsilon^2}$ $\theta=\tan^{-1}\left(\upsilon/\alpha\right)$ $L_t=\int_I^{\bar{I}}\frac{1}{gA(x)}dx$

***Table 1** Modeling of the hydraulic components using impedance method.*

CASE STUDY

The system investigated is a 220 kV islanded power network comprising a 2 Francis turbine hydroelectric power plant, a nuclear power plant and a consumer modeled as an RL variable load (Figure 1). Hydroelectric unit switch off and load rejection and acceptance on this islanded network is investigated by simulating the transient behavior of the entire system. Interactions between the hydroelectric power plant and the rest of the system are presented.

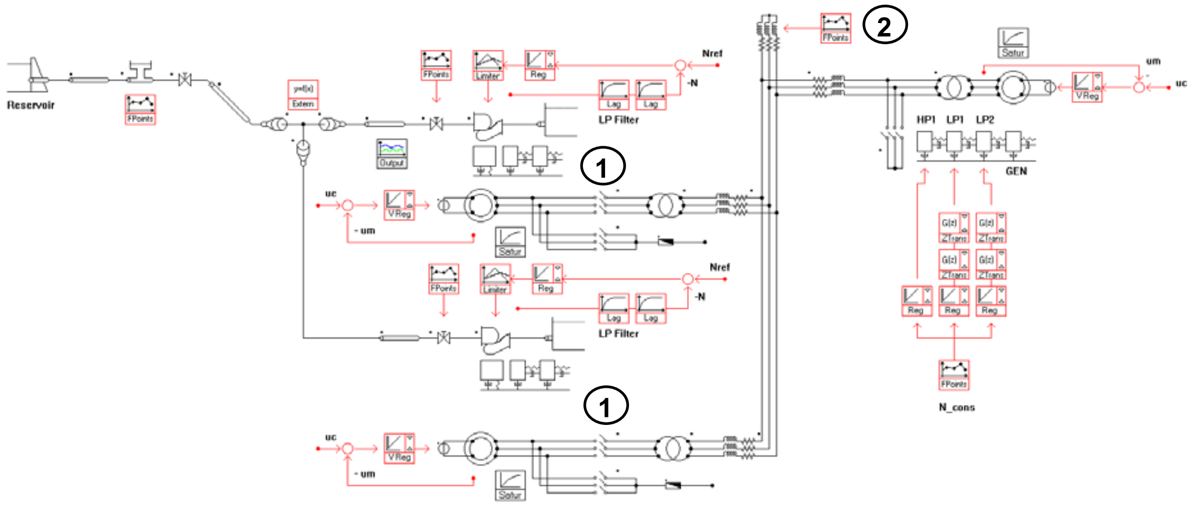


Figure 1 *Modeling of the power plant with SIMSEN.*

Hydraulic power plant modeling

The hydroelectric power plant comprises a tank, a gallery, a surge tank, 2 Francis turbines of 86 MW and 2 generators. The data corresponding to hydraulic power plant of this example are presented in Table 2 and the characteristic curves of the turbines are presented in Figure 2 with Sutter representation (Ref. 5). The rotating masses of the generator and the turbine are connected considering the stiffness of the shaft.

Gallery	Surge Tank	Pipe	Turbines	Generators
L = 4000 m D = 10 m λ = 0.03 a = 1000 m/s	$A(z<77) = 700\ m^2$ $A(77<z<87) = 400\ m^2$ $A(z>87) = 700\ m^2$	L = 125 m D = 5.5 m λ = 0.02 a = 1250 m/s	$H_{tR} = 82$ m $n_R = 200$ rpm $Q_{tR} = 114\ m^3/s$ $T_{tR} = 4.11e6$ Nm	$I_{t+g} = 1.767e6\ Kgm^2$ Sn = 98 MVA Un = 17.5 kV Pole pairs = 15 Fn = 50 Hz

Table 2 *Characteristics of the power plant.*

The trijunction, which distributes the flow rate to the turbines, is modeled by three singular losses parameterized using a coefficient function of the the flow rate repartition between the three branches. The losses coefficients are taken from Ref. 3.

PID controllers are used for:

- output voltage regulation acting on field voltage of the synchronous generators;
- rotational speed regulation acting on the guide vane opening degree of Francis turbine.

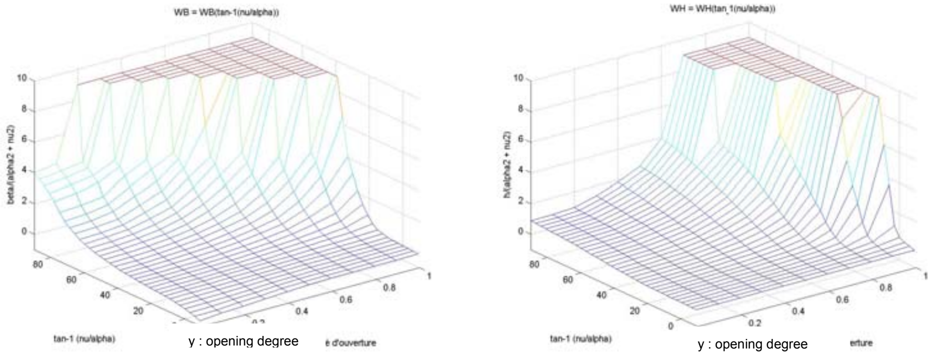


Figure 2 *Characteristics W_B and W_H of the turbines.*

Nuclear power plant modeling

The nuclear power plant is constituted of three 433 MW steam turbines (a high pressure turbine (HP1) and two low pressure turbines (LP1,2)) connected to a 1400 MVA generator (Figure 3) . The rotating speed of the 4 masses shaft is 1500 rpm. The 4 rotating masses and 3 connecting stiffness model is taken from Ref. 2 and summarized in Figure 4. The torque of the steam turbines is modeled by a first order transfer function taking into account the proportional regulation with a statism *bp* and a thermal time constant τ_{th} as described in Figure 5. The set of parameters of the transfer function is presented in Table 3. In addition, the steam transit time from the high pressure turbine to the low pressure turbine through the re-heaters, is taken into account by a time delay: $G(z) = z^{-b}$. The simulation results of a rotational speed set point change is presented in Figure 6. Although this operation is not realistic, it is used in order to illustrate the dynamic response of the unit.

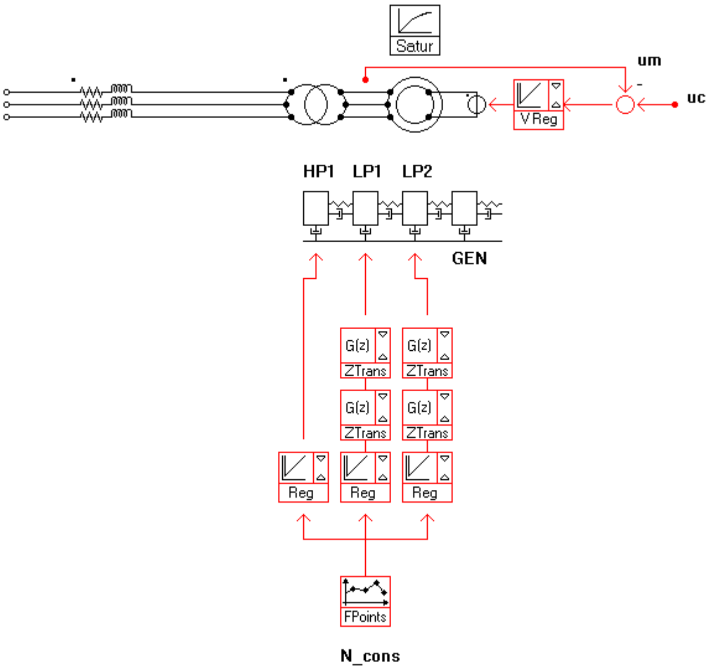
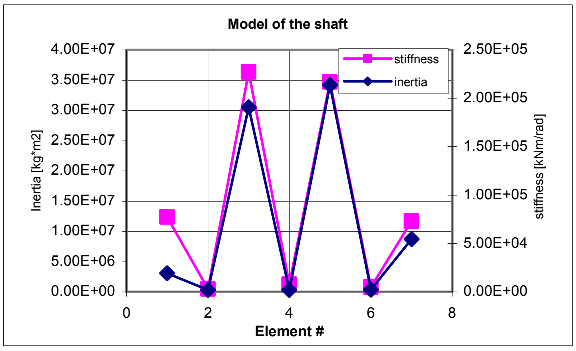
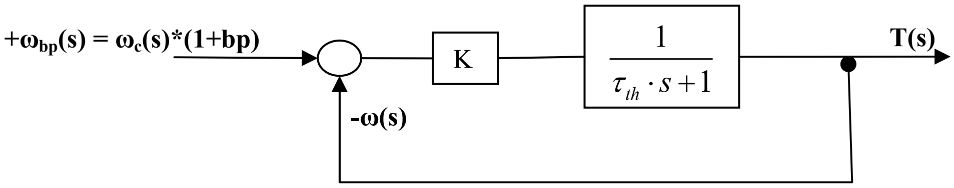


Figure 3 *Model of the nuclear power plant.*



Component	Inertia [kg·m^2]	Stiffness [Nm·rad^{-1}]
HP1	19036	12401000
coupling	2008	497792
LP1	190749	36369200
coupling	2008	1287170
LP2	213575	34719900
coupling	2160	794565
Gen	54719	11685200

Figure 4 Inertia and stiffness of the nuclear power plant rotating shaft (Ref. 2).



$$G(s) = \frac{T(s)}{\omega_{bp}(s) - \omega(s)} = K \cdot \frac{1}{\tau_{th} \cdot s + 1}$$

Figure 5 Transfer function of the proportional regulator of the steam turbine including thermal time constant τ_{th}.

	τ_{th} [s]	bp [%]	b [s]
HP1	0.5	4	0
LP1,2	15	12	3.8

Table 3 Parameters of the steam turbines models.

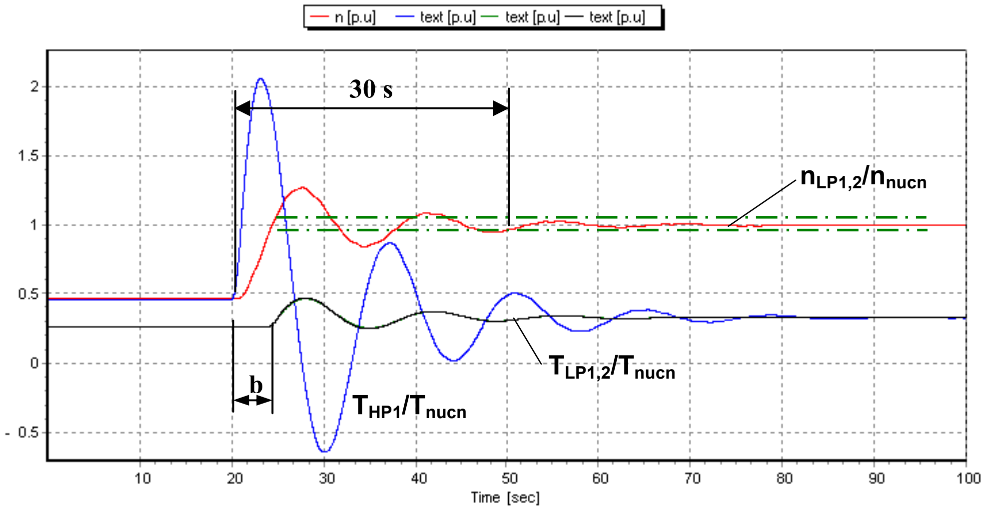


Figure 6 Dynamic response of the nuclear unit to a change of the rotational speed set point from 0.5·n_n to n_n.

LOAD PERTURBATION

Hydroelectric units switch off

The first investigation concerns the tripping of the hydro-generators where the circuit-breaker between the transformer and the generator are switched off ((1) in Figure 1), while the power set point of the nuclear unit remains constant. Simultaneously, the distributor of the two Francis turbines are closed linearly in 7 seconds. The evolution of the main variables during and after the total load rejection is presented in Figure 7 and Figure 8.

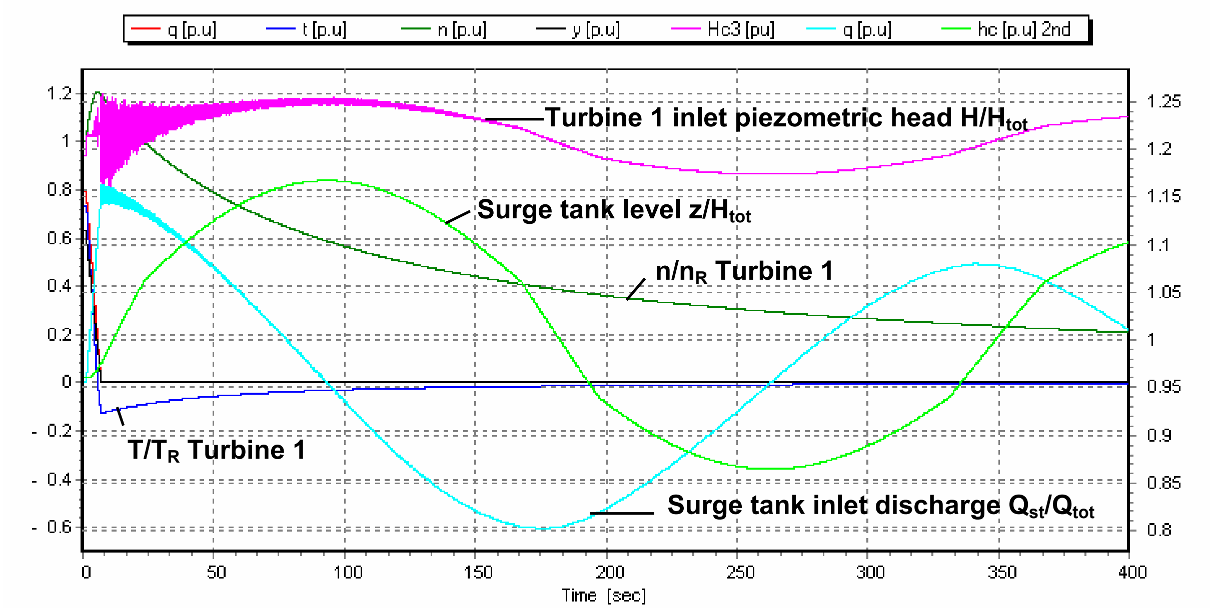


Figure 7 *Evolution of the main variables of the hydroelectric power plant during the switch off of the two hydraulic turbines.*

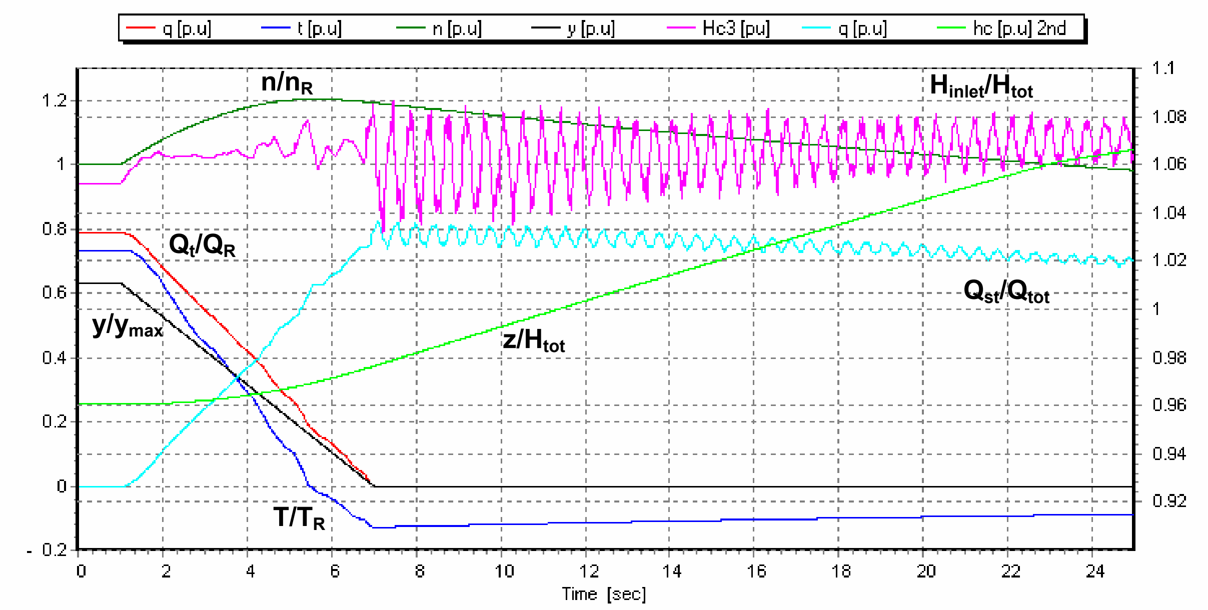


Figure 8 *Evolution of the hydraulic turbine 1 variables during the switch off.*

At the outset, the electromagnetic torque of the generators drops to zero instantaneously, as a consequence the rotational speed of the groups increase. The closure of the distributor reduces the hydraulic torque quickly, limiting the rotational speed. The distributor closure induces a Waterhammer effect in the adduction part of the power plant and a mass oscillation between the reservoir and the surge tank. Moreover, the effect of non-uniform surge tank cross-section is properly taken into account. The electromagnetic torque drop of the hydro-generators induces a rotational speed diminution of the nuclear unit which compensates partially the lack of power on the network. However, due to the proportional structure of the rotational speed regulation, the nominal speed is not recovered after the transient as shown in Figure 9. Because the power network is not interconnected, the nominal frequency of 50 Hz could not be recovered without changing the power set point.

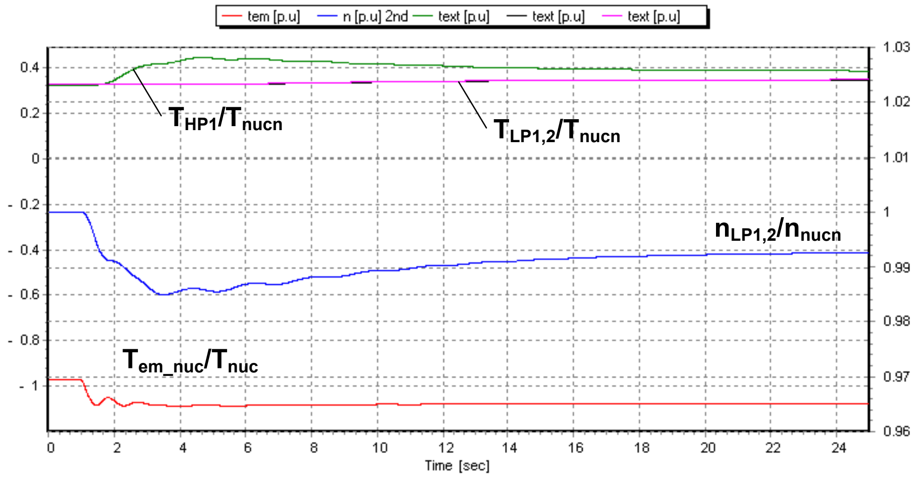


Figure 9 Dynamic response of the nuclear unit due to hydro unit switch off.

Load rejection and acceptance

The second investigation is the simulation of the transient behavior of the whole system due to a successive increase and decrease of the consumer load ((2) in Figure 1). The evolution of the power at the consumer load is presented in Figure 10. The dynamic response of the hydro units and the nuclear unit are presented in Figure 11 and Figure 12.

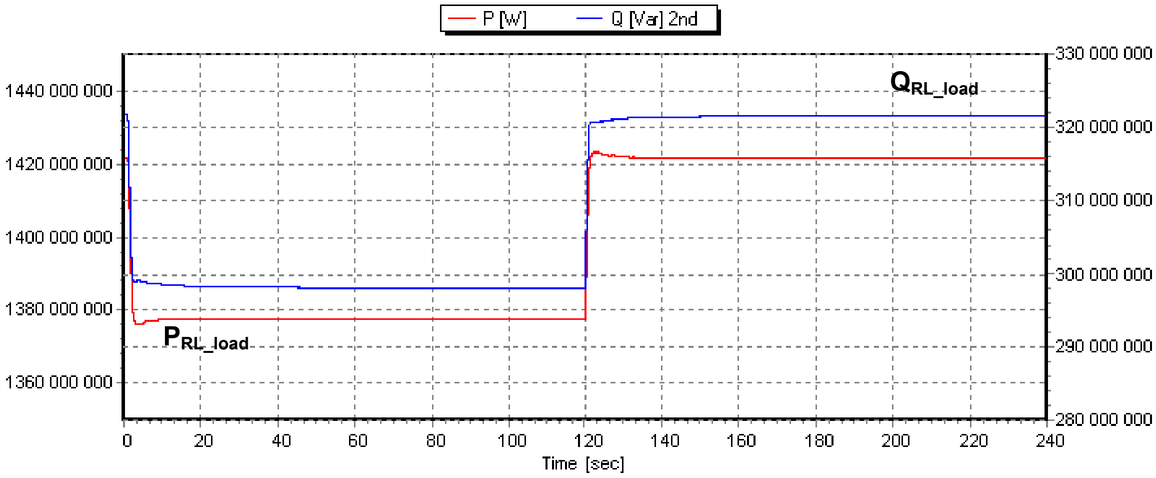


Figure 10 Power variation of the RL load modeling the consumer.

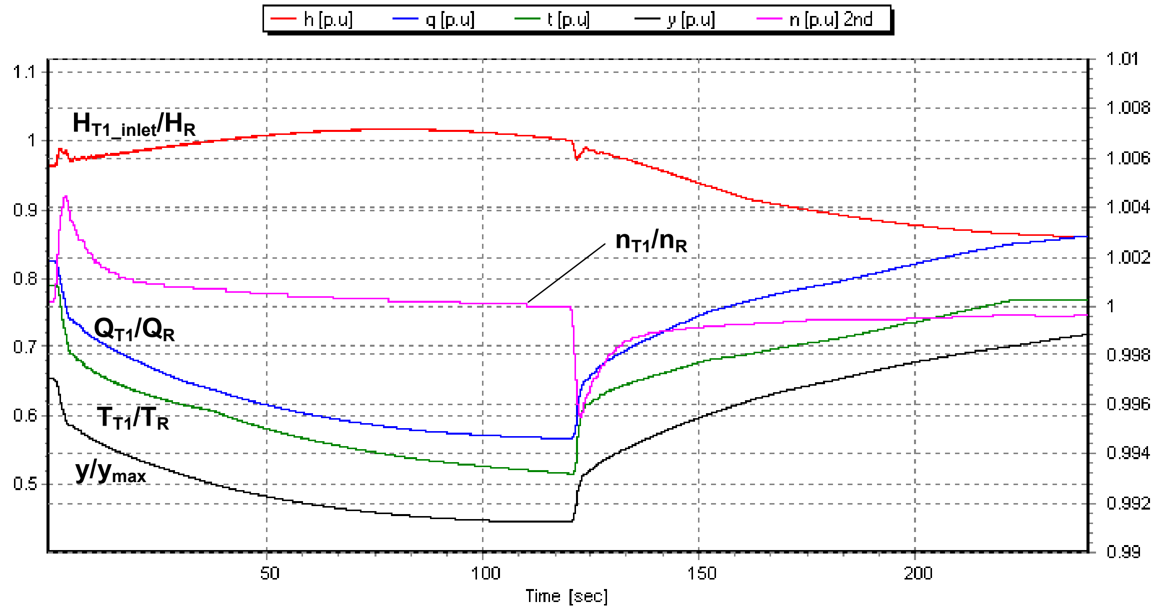


Figure 11 Dynamic response of the hydraulic turbine 1 due to the successive load rejection and acceptance.

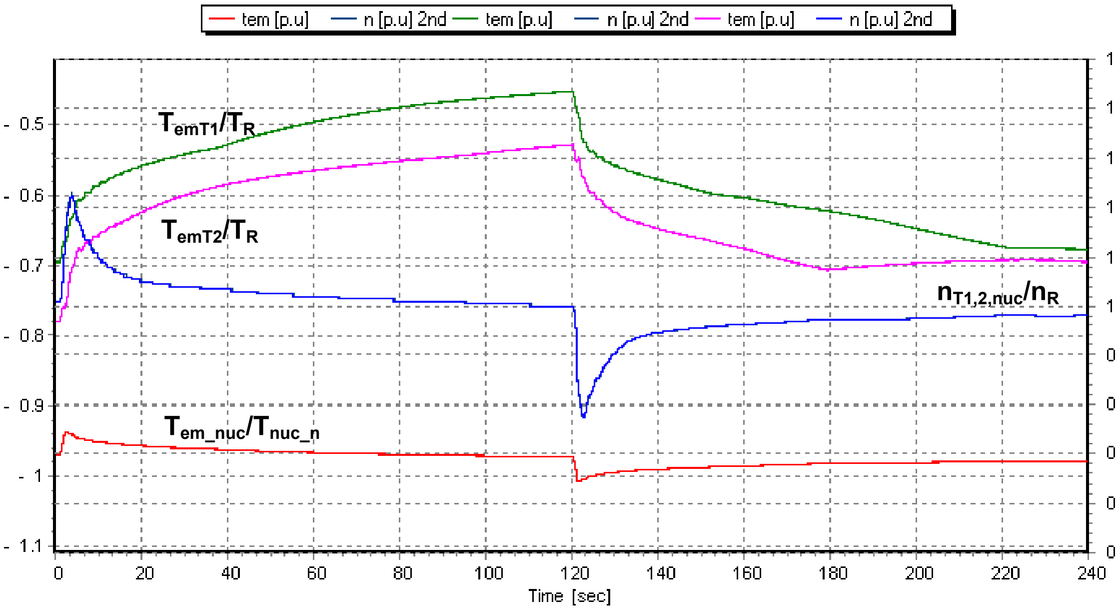


Figure 12 Electromagnetic torque of the 2 hydro units and of the nuclear unit during the successive load rejection and acceptance.

The decrease of 3% of the load induces a rotational speed increase of all the units. The rotational speed regulators of the hydraulic turbines act quickly on the wicket gate to reduce the torque. After 20 seconds the rotational speed error is reduced to 1‰. The nuclear unit reacts in the same time span but recovers its nominal power level after 2 minutes; when the 45 MW load variation is fully compensated by the hydro units. The dynamic response of the system is similar when the load increases. However, the first transient has induced a mass oscillation between the reservoir and the surge tank and this affects the head at the turbine inlet reducing the maximum power of the turbines. This simulation shows clearly how the power balanced is affected in such a small network during transients. When the load changes, all units act to compensate the rotational speed variation, but when steady state conditions are recovered, the power change is absorbed by the hydraulic units while nuclear unit does not change its power level.

CONCLUSION

A transient behavior due to load perturbations in an islanded power network has been investigated. The network is comprising a 2 Francis turbines hydroelectric power plant, a nuclear power plant and a consumer modeled as a RL load. First, the modeling of the hydroelectric power plant, based on the impedance method, is described. Then, the modeling of the nuclear power plant taking into account the rotating masses and the stiffness of the shaft, the proportional regulators, a first order transfer function for steam turbines and the generator is presented.

The simulation of the transient behavior of the whole islanded network has been performed using the software SIMSEN. Two disturbance cases have been simulated: a 2 hydroelectric units switch off and a load rejection and acceptance. The simulation results of the hydroelectric power plant switch off exhibits a decrease of the network frequency while the hydroelectric units are affected by waterhammer and mass oscillations effects. The simulation of the successive load rejection and acceptance show that both power stations, hydraulic and nuclear, acts to keep the network frequency constant. However, when steady state conditions are recovered, the power variation is provided by the hydraulic power plant while the nuclear station remains at its previous power level.

The optimization of the control command parameters and a stability assessment of an islanded network require modeling properly every power source to study the network frequency fluctuations. With an equivalent source instead of a detailed model, it would not be possible to perform such an analysis.

ACKNOWLEDGMENTS

We want to thank sincerely Nadine Pajean-Wassong and Laurent Bellet from EDF-CIH and Dr. Tu Xuan from EPFL-LME for their collaboration in the development phase.

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