A SIMULATION TOOL LINKING HYDROELECTRIC PRODUCTION SITES AND ELECTRICAL NETWORKS

J.-J. Simond, Ph. Allenbach, C. Nicolet, F. Avellan

***Abstract*— Since many years the EPFL Laboratory of Electrical Machines develops SIMSEN, a numerical software package for the simulation in transient and steady-state conditions of electrical power systems and adjustable speed drives, having an arbitrary topology. SIMSEN is based on a collection of modules, each corresponding to one system component (machines, converters, transformers, control devices, etc.). For more information, one may refer to: http//simsen.epfl.ch.**

This contribution presents the extension of SIMSEN to the hydraulic components of a hydroelectric power plant including pump-turbine, valve, penstock, surge tank, gallery, reservoir, etc. The basic idea is to define for each hydraulic component an equivalent electric component which can be introduced in the existing electric version of SIMSEN. Doing this, it becomes possible to use the modularity of the electric version to define the complete topology of the hydroelectric power plant and the connected electrical network.

This extension makes possible a numerical simulation taking precisely into account the interactions between the hydraulic and the electric parts of the system during transients. It is therefore useful for transient and stability analyses as well as for the design optimization.

***Index Terms*— hydroelectric power plants, electrical networks, modelling, transient behaviour**

I. INTRODUCTION

Since many years the EPFL Laboratory of Electrical Machines develops SIMSEN, a numerical software package for the simulation in transient and steady-state conditions of electrical networks and adjustable speed drives having an arbitrary topology. The main features of this SIMSEN electric version are the following:

- High-level modelling combined with advanced knowledge in computer sciences applied to complex electrical systems.
- Modular system with arbitrary topology.
- Electrical machines, network elements, power electronics, mechanical elements, regulation devices, analog / digital mixed-signals regulation systems, today more than 120 modules.
- Automatic generation of the set of differential equations according to the desired topology.
- Gathering in a common tool the modeling coming from different research projects.
- Evolutive system (permanent development).

SIMSEN is used by several well known manufacturers and electric power utilities in Switzerland and abroad. For more information, please refer to: http://simsen.epfl.ch.

J.-J. Simond, Ph. Allenbach are with the Laboratory for Electrical Machines of EPFL, Swiss Federal Institute of Technology Lausanne, Switzerland (e-mail:jean-jacques.simond@epfl.ch)

C. Nicolet, F. Avellan are with the Laboratory for Hydraulic Machines of EPFL, Swiss Federal Institute of Technology Lausanne, Switzerland (e-mail:francois.avellan@epfl.ch)

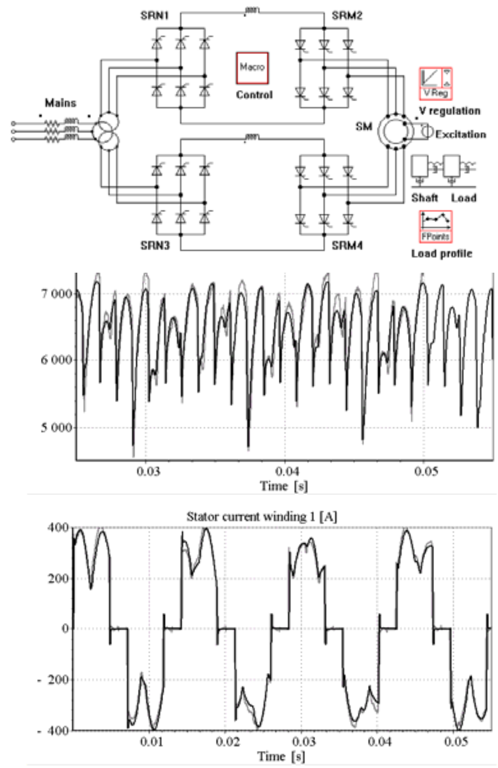


Fig. 1: Comparison measurement on the test shop (light color) – simulation (dark color); LCI12 drive; 2,94 MW; 4236 rpm; 2x3800 V; cos φ = 0,91.

Results provided by SIMSEN have been validated by comparison with measurements on test-platform or on site [1]. Fig. 1 illustrates an application of SIMSEN in the case of a LCI-12 fed synchronous motor driving a 20 MW gas compressor.

The SIMSEN electric version takes the rotating mechanical systems into account according to the lumped masses model. For example, a pump turbine is a rotating mechanical mass on which a mechanical torque is acting. This paper describes the extension of SIMSEN to the hydraulic components of a hydraulic power plant including pump turbine, valve, penstock, surge tank, gallery and reservoir leading to the SIMSEN hydro version (Fig. 2).

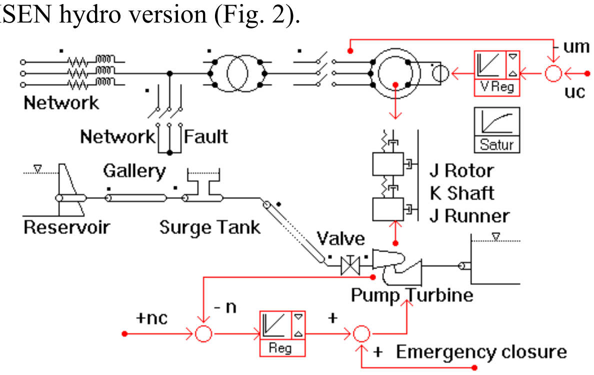


Fig. 2: A simple application example of SIMSEN hydro version

The basic idea is to define for each hydraulic component an equivalent electric component in order to use the modularity of the electric part of SIMSEN to define the complete topology of a hydraulic power plant and of the connected electrical network. This extension makes possible a numerical simulation in steady state or transient conditions taking precisely into account all the interactions between hydraulic, electrical and regulation parts of a given topology [2].

II. HYDRAULIC COMPONENTS

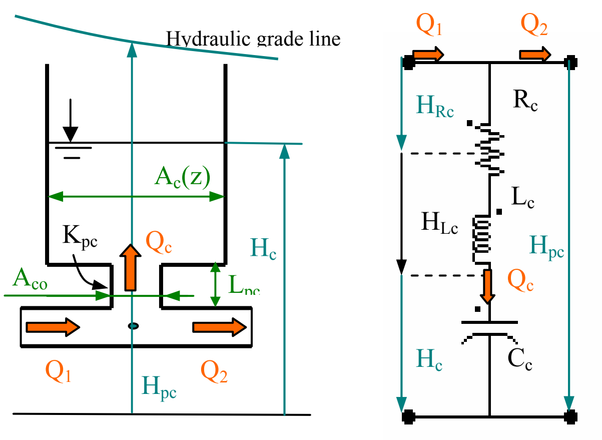


Fig.3: surge tank, hydraulic model and equivalent electrical circuit

Fig. 3 shows the hydraulic scheme and the equivalent electric circuits of a surge tank. The piezometric heads H and the flow rates Q on the hydraulic side are replaced on the electric side by voltages and currents. All the elements of the equivalent electrical circuits can be deduced from the hydraulic parameters. This procedure can be used for each hydraulic component as explained in [3]. Only the case of a pipe segment will be briefly described in this paper.

In the case of a pipe segment, the electric equivalent circuit can be obtained using the momentum and mass conservation equations:

$$\frac{\partial H}{\partial x} + \underbrace{\frac{1}{gA}}_{L'}\frac{\partial Q}{\partial t} + \underbrace{\frac{\lambda|Q|}{2gDA^2}}_{R'}Q = 0 \qquad (1)$$

$$\frac{\partial H}{\partial t} + \underbrace{\frac{a^2}{gA}}_{1/C'}\frac{\partial Q}{\partial x} = 0 \qquad (2)$$

with:
A = cross section [m^2]
λ = friction factor
D = pipe diameter [m]
a = wave speed [m/s]

L' [s^2/m^3], C' [m], R' [s/m^3] = hydro acoustic linear inductance, capacity, resistance

Equations (1) and (2) become the telegraphic equations (3) of an electrical transmission line if the piezometric head H and the flow rate Q are replaced by the voltage U and the current I:

$$\begin{aligned} &\frac{\partial U}{\partial x} + L_e\frac{\partial I}{\partial t} + R_e I = 0 \\ &\frac{\partial U}{\partial t} + \frac{1}{C_e}\frac{\partial I}{\partial x} = 0 \end{aligned} \qquad (3)$$

L_e [H/m], C_e [F/m], R_e [Ω/m] = linear inductance, capacity, resistance.

A pipe must always be divided into a series of N elementary pipe segments with the length dx; in that respect it is necessary to reformulate the equations (1) and (2) by choosing as state variables the piezometric head in the middle of the segment $H_{i+1/2}$ and the input / output flow rates Q_i / Q_{i+1}. The input / output piezometric heads H_i / H_{i+1} become boundary conditions for this pipe segment. The first derivatives of H and Q in the middle of the pipe element i can be written according to Fig. 4:

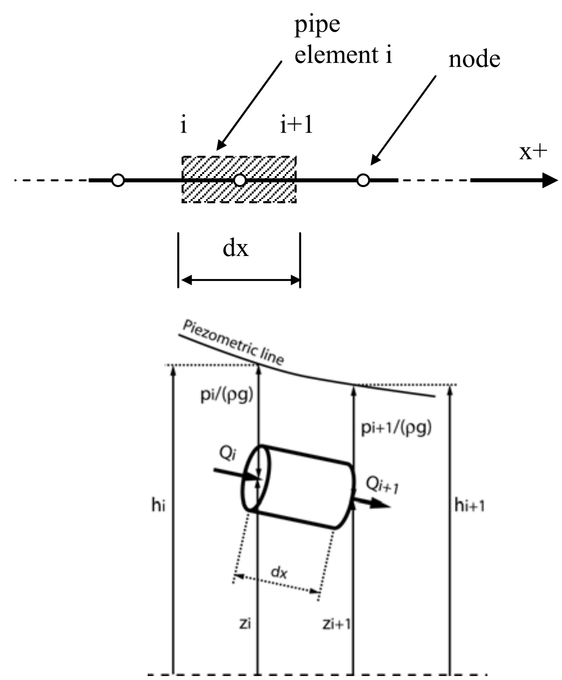


Fig.4: Discretization of a pipe into n elements

$$\left.\frac{\partial H}{\partial x}\right|_{i+1/2} = \frac{H_{i+1} - H_i}{dx} \qquad (4)$$

$$\left.\frac{\partial Q}{\partial x}\right|_{i+1/2} = \frac{Q_{i+1} - Q_i}{dx} \qquad (5)$$

Using these derivatives, equations (1) and (2) take the form:

$$\frac{dH_{i+1/2}}{dt} + \frac{1}{C'} \cdot \frac{Q_{i+1} - Q_i}{dx} = 0 \qquad (6)$$

$$\frac{H_{i+1} - H_i}{dx} + L' \cdot \frac{dQ_{i+1/2}}{dt} + R' \cdot Q_{i+1/2} = 0 \qquad (7)$$

with: $Q_{i+1/2} = \dfrac{Q_{i+1} + Q_1}{2}$

the equations (6) and (7) become:

$$C' \cdot dx \cdot \frac{dH_{i+1/2}}{dt} = -\left(Q_{i+1} - Q_i\right) \qquad (8)$$

$$\underbrace{H_{i+1} + \frac{L' \cdot dx}{2} \cdot \frac{dQ_{i+1}}{dt} + \frac{R' \cdot dx}{2} \cdot Q_{i+1}}_{H_{i+1/2}} = \underbrace{H_i - \left(\frac{L' \cdot dx}{2} \cdot \frac{dQ}{dt} + \frac{R' \cdot dx}{2} \cdot Q_i\right)}_{H_{i+1/2}} \qquad (9)$$

R = R'.dx ; L = L'.dx ; C = C'.dx, equations (8) and (9) lead to the electrical equivalent circuit in Fig. 5, which can be used in the SIMSEN electric version for modelling a pipe segment.

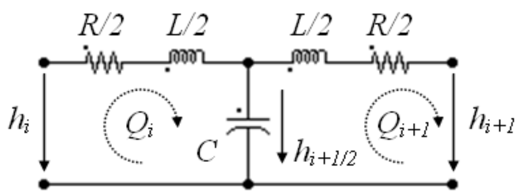


Fig.5: Electrical equivalent circuit of a pipe segment

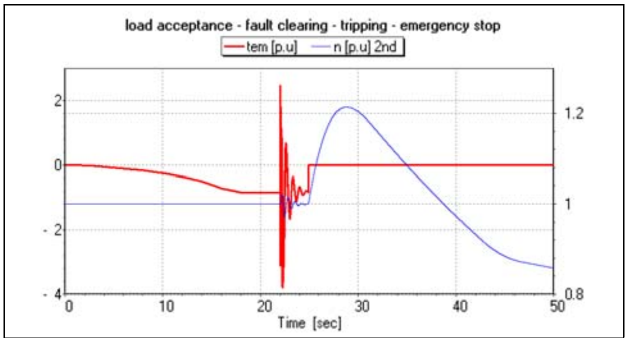
This procedure can be used to define an equivalent electrical circuit for each hydraulic component (valve, surge tank, pump turbine …) [2].

III APPLICATIONS

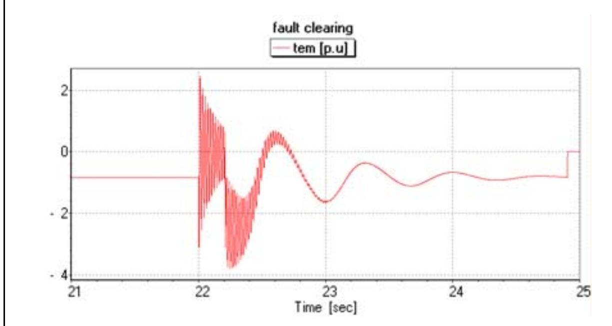
The applications described in this section are related to the power plant configuration given in Fig. 2. The rated data of the synchronous motor-generator are: apparent power S_N = 250 MVA, nominal voltage U_N = 17,5 kV; number of poles 2p = 16, Frequency F_N = 50 Hz. The main hydraulic data are given by the following table (L = length, D = diameter):

Gallery	Surge tank	Penstock	Turbine	
L=5000m D=5m	A=80m^2 A$_o$=12.5m^2	L=1100m D=5m	H_N=309m N_N=375rpm	Q_N=85.3m^3 P_N=230MW

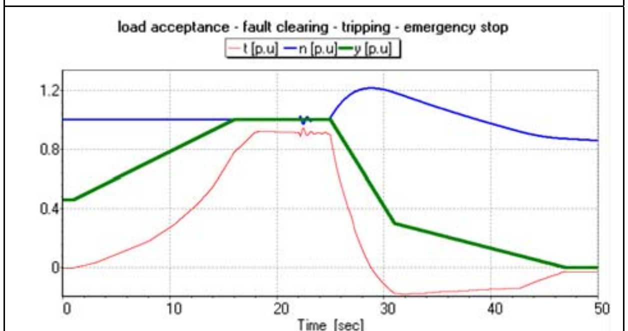
Fig. 6 illustrates the behavior of the power plant during the following operation steps:



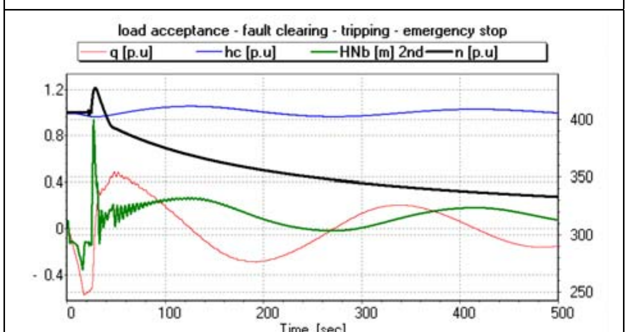
a) Electromagnetic torque tem and speed n of the hydro-generator



b) Electromagnetic torque during 3 phase fault and fault clearing



c) turbine torque t, speed n, turbine guide vane opening y



d) surge tank inlet discharge q, surge tank level hc, turbine inlet piezometric head HNb, speed n

Fig. 6: Numerical simulation of a hydroelectric production site under transient conditions.

- Initial conditions: unit connected to the network under no-load operation during 1 s.
- Turbine guide vane opening in 15 s, load acceptance.
- Steady-state operation since t = 16 s.
- At t = 22 s a 3 phase fault occurs on the HV side of the unit transformer with successful fault clearing 200 ms later.
- At t = 24,9 s the circuit breaker of the unit is switched off, tripping of the unit.
- At t = 25 s the turbine emergency closure is switched on according to a closure law divided into two linear steps.

The analysis of the results given in Fig. 6 leads to the following remarks:

- The 3 phase short-circuit on the HV side of the transformer unit and its clearing 200 ms later represent strong constrains for the electric part of the configuration (Fig. 6b), however they have no significant influence on the hydraulic quantities.
- As expected the constraints acting on the hydraulic components are most severe during the turbine emergency closure (Fig. 6d), the turbine inlet piezometric head increase is bigger than 40%.
- The surge tank is properly taken into account; the time variations of the surge tank inlet discharge q and of the level hc appear clearly in magnitude and phase in Fig. 6d.
- The long time simulation in Fig. 6d shows the low frequency mass oscillation in the surge tank compared to the pulsating component of the turbine inlet piezometric head due to the waterhammer effect.

The second application is also related to the configuration illustrated in Fig. 2 but with a supplementary passive load connected in parallel with the network on the HV side of the transformer unit.
The initial steady-state conditions are the following concerning the active and reactive powers delivered to the network and to the passive load:
-Network: active power: 30 MW; reactive power: 20 MVar
-Pas. load: active power: 120MW; reactive power : 80 MVar.
Neglecting the losses, this means the following operation point for the hydro-generator: active power 150 MW, reactive power 100 MVar.
At time t = 10 s the configuration is disconnected from the network and goes over into an islanded operation controlled by the voltage and turbine regulators.

Fig. 7 compares the results obtained in two different simulations. The first one takes into account the complete configuration (Fig. 2). The second one considers only the hydraulic part and replaces the electric part trough a reduction in the ratio 120 / 150 of the mechanical counter torque acting on the turbine shaft. The results of these two simulations are quite different with respect to the turbine torque- and speed oscillations and dampings. This simple example demonstrates how important it is to consider the complete hydroelectric configuration and not only its hydraulic part. Reference [4] describes and analyses other important interactions between electric and hydraulic parts of a hydroelectric production site with respect to the stability of the entire site.

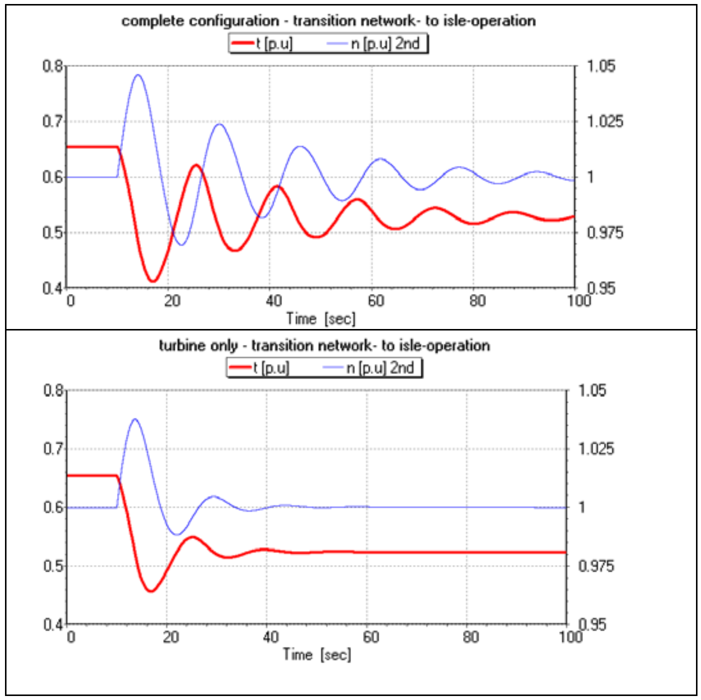


Fig. 7: Simulations taking the electric part into account or not.
t = turbine torque [p.u.], n = turbine speed [p.u.]

IV CONCLUSIONS

A numerical software package initially developed for the simulation of electrical power systems and adjustable speed drives has been extended to the hydraulic components of a hydroelectric production site having an arbitrary topology. This new simulation tool is able to take into account all the important interactions between both parts of a hydroelectric production site, it is therefore very useful for stability analysis as well as a design optimization tool.

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