NEW TOOL FOR THE SIMULATION OF TRANSIENT PHENOMENA IN FRANCIS TURBINE POWER PLANTS

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ABSTRACT

An analytical approach allowing modelling transient phenomena in pipes, valves, surge tanks and Francis turbines based on impedance method is developed. These models are implemented in a software called "SIMSEN", which simulates the behaviour of complex applications in the domain of adjustable speed drives and electrical power networks. This program is based on a modular structure, which enables the numerical simulation of transient modes of systems exhibiting arbitrary topologies. The numerical simulation for transient phenomena in hydropower plants with "SIMSEN" has the benefit of an algorithm that generates and solves an integrated set of differential equations. This algorithm solves simultaneously the electrical, hydraulic and control equations ensuring a proper interaction between the three parts of the system. The case of a Francis turbine power plant is studied. The model of the turbine is based on measured steady state characteristics. The simulation of the dynamic behaviour of the power plant under load variation is investigated.

RÉSUMÉ

Une approche analytique basée sur la méthode des impédances permettant la modélisation des phénomènes transitoires faisant intervenir des composants tels que conduites, vannes, cheminées d'équilibre et turbines Francis est développée. Ces modèles sont implémentés dans un logiciel nommé "SIMSEN". Celui-ci permet la simulation du comportement dynamique dans le cadre d'applications dans les entraînements électriques et les réseaux électriques. Ce programme à structure modulaire, permet la simulation numérique en modes transitoires de systèmes ayant une topologie arbitraire. La simulation de phénomènes transitoires dans les centrales hydroélectriques avec "SIMSEN" bénéficie d'un algorithme qui génère et résout le système d'équations différentielles. Cet algorithme résout simultanément les équations de nature électrique, hydraulique et de réglage assurant de ce fait la prise en compte de l'interaction entre les trois parties du système. Le cas d'une centrale hydroélectrique équipée d'une turbine Francis est étudié. Le modèle de la turbine est basé sur les caractéristiques statiques mesurées. La simulation du comportement dynamique de la centrale de production est étudiée dans le cas d'une variation de puissance requise par le réseau électrique.

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 coefficient	K	[-]
Electrical resistance	R_e	[ohm]

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 rotating speed	α	$\alpha = \omega/\omega_R$ [-]
Rated torque	β	$\beta = T/T_R$ [-]
Static turbine characteristic	θ	$\theta = \tan^{-1}(\upsilon/\alpha)$
Rated flow	υ	$\upsilon = Q/Q_R$ [-]

Term	Symbol	Definition
Electrical inductance	L_e	[H]
Electrical capacitance	C_e	[F]
Rotating speed	ω	[rad/s]
Torque	T	[Nm]

Term	Symbol	Definition
Rated head	h	$H = H/ H_R$ [-]
Density	ρ	[Kg/m^3]
Mechanical inertia	I	[$Kg \cdot m^2$]
Guide vane opening degree	y	[-]

INTRODUCTION

The power output of a hydroelectric installation changes constantly according to the network needs, generating variations of the turbine's rotating speed involving a reaction of the control system. That is why, the study of the stability of the whole power plant requires a full model considering the influence of every component.

A software called "SIMSEN" (Ref. 6, Ref. 8) has been developed by the EPFL Laboratory for Electrical Machines for the simulation of electrical power networks systems in transient or steady state modes and speed drive systems including the control systems. This software is based on a modular structure which enables to consider systems with arbitrary topology. It is composed of units, each representing a specific element in the network: electrical machine, mechanical system taking into account mechanical masses connected with damping and springs, transformers, voltage supplies, transmission lines, loads, static converters, controllers. The strength of this package lies within its ability to simulate electrical power networks involving semi-conductor units.

Each unit includes a set of differential equations based on the network element model. An original algorithm has been developed in order to generate the global set of differential equations solved by fourth order Runge-Kutta procedure. The variable time-step used for the integration of the governing equations allows to detect the exact sequence of events like the on-off switching of semi-conductors or circuit-breakers phase on-off switching.

The aim of this paper is to present the new hydraulic extension which has been implemented in SIMSEN, including the models of pipe, valve, surge tank and Francis turbine. This extension enables to study hydraulic installations alone or with the inclusion of both control devices and electrical units. Here, the case of a Francis turbine power plant under load variation is investigated. For the simulation of the Francis turbine transient behaviour the model based on the characteristic curves of the hydraulic machine is used. This model is the first step of the modelling of the Francis turbine and its unsteady behaviour using a parametrical approach.

HYDRAULIC COMPONENTS

In order to be able to study the dynamic behaviour of a whole hydroelectric power plant including electrical, hydraulic and control components, a hydraulic extension has been developed and implemented in the software SIMSEN. To fit to the formalism of this software the impedance approach has naturally been chosen for the modelling of the hydraulic components. Thus, the corresponding governing equations can be implemented in an easier manner. Therefore the hydraulic extension benefit from the arbitrary topology feature which allows modelling complex piping systems.

MODELLING OF HYDRAULIC COMPONENTS

According to the impedance method (Ref. 2), hydraulic elements are modelled as a RLC electrical circuit and the whole system is interpreted as a network where the variables are: (1) the piezometric head H at the node and (2) the discharge Q through each component – respectively corresponding to potential U and flux I. Thus, the differential equations can be generated by "SIMSEN" using Kirchhoff's law. The differential set of equations contains electric, hydraulic and control equations that are solved simultaneously ensuring to take into account the interaction between each part of the system.

One has chosen to focus, first, on the modelling of basic components which constitute a hydroelectric power plant, such as:

- pipe
- singular losses
- valve
- surge tank
- Francis turbine

The modelling of these hydraulic components is described below.

Pipe model

The conservation of mass and motion equations applied to the cross-flow section of fluid in a pipe can be written (Ref. 9), after linearization, as follows:

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

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

The hyperbolic set of equations above can be written by introducing the corresponding impedance:

$$\frac{\partial U}{\partial t} + \frac{1}{C_e}\frac{\partial I}{\partial x} = 0$$

$$\frac{\partial U}{\partial x} + L_e\frac{\partial I}{\partial t} + R_e I = 0$$

A capacitance C', an inductance L' and a resistance R' per meter (Ref. 1) can be identified, allowing to establish the following equations:

$$\underbrace{dxC'}_{C}\frac{dH_c}{dt} = Q_1 - Q_2 \qquad \Delta H_R = \underbrace{dxR'}_{R}Q_1 \qquad \Delta H_L = \underbrace{dxL'}_{L_h}\frac{dQ_2}{dt}$$

The Fig. 1 presents the impedance model for a pipe of length dx:

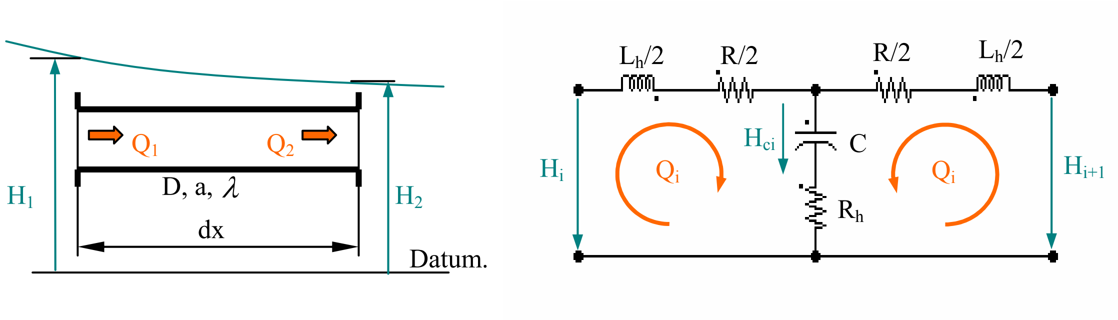


Fig. 1 Crossflow section of a pipe modelled using impedance method.

The capacitive, inductive and resistive RLC terms respectively correspond to the storage, inertial and losses effects. A whole pipe is constituted of *n* RLC circuits.

Valve model

The discharge equation of a valve can be expressed as:

$$\Delta H_v = \underbrace{\frac{|Q_v|}{2g\left(C_d(s)A_G(s)\right)^2}}_{R_v} Q_v$$

Where C_d is the discharge coefficient and A_G is the area of opening and *s* is the obturator course. A valve corresponds to a variable resistance as shown in the Fig. 2.

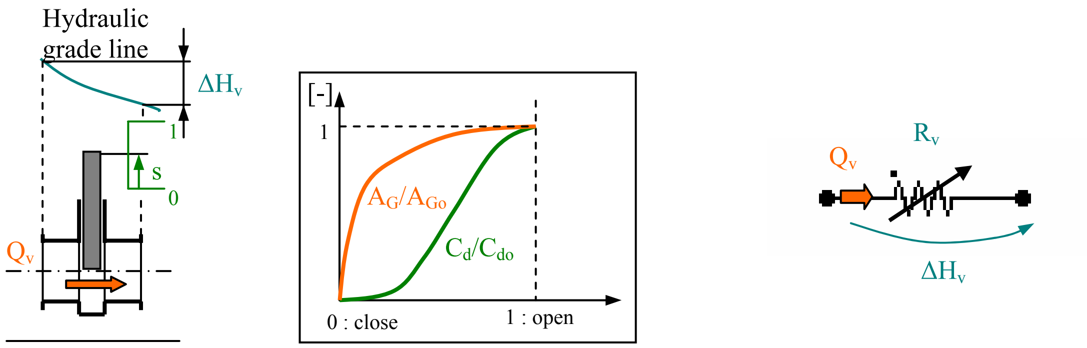


Fig. 2 Valve modelled using impedance method.

Surge tank model

A surge tank is described by singular losses at the inlet, a level variation and inertia. According to hydraulic laws, the following expressions can be written:

$$\left(H_{pc} - H_c\right) = \underbrace{\frac{K_{pc}|Q_c|}{2gA_{co}^{\,2}}}_{R_c} Q_c \qquad \underbrace{A_c(z)}_{C_c}\frac{dH_c}{dt} = Q_c \qquad L_c = \frac{L_{pc}}{gA_{co}}$$

Since these terms are related to the discharge Qc incoming in the surge tank, the three components $R_cL_cC_c$ are placed in series (Fig. 3).

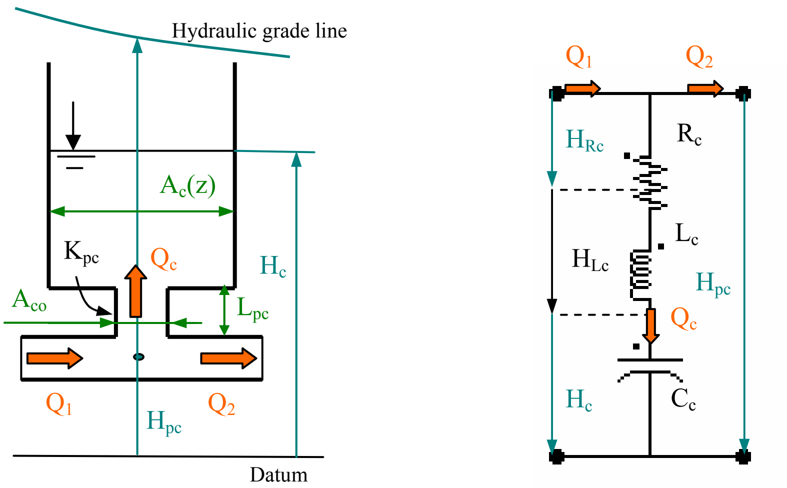


Fig. 3 Surge tank modelled using impedance method.

Francis turbine model

Assuming that the transition between two operating points of a turbine corresponds to a succession of steady state operating points, the transient behaviour of this hydraulic machine can be modelled using static characteristic curves. The dimensionless relations formulated by Marchal, Flesh and Suter (Ref. 3) are suitable for the computation and expressed as:

$$W_B(\theta) = \frac{\beta}{\alpha^2 + \upsilon^2} \qquad W_H(\theta) = \frac{h}{\alpha^2 + \upsilon^2} \qquad \theta = \tan^{-1}\left(\upsilon / \alpha\right)$$

The dimensionless characteristics are given by:

$$\alpha = \frac{\omega}{\omega_R} \qquad \upsilon = \frac{Q}{Q_R} \qquad \beta = \frac{T}{T_R} \qquad h = \frac{H}{H_R}$$

Where the subscript *R* indicates the rated quantities and corresponds to the best efficiency point. Knowing the parameter Q, y and ω, T and H can be deduced from W_H and W_B.

The equivalent model of a turbine, which is composed of an inductance term L_t, a resistance R_t and a source H_t, is presented in the Fig. 4.

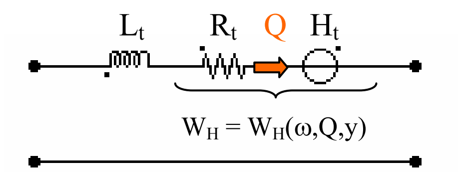


Fig. 4 Simplified impedance model of the Francis turbine.

We can notice that the two last terms are directly taken into account by the characteristic curve $W_H(\theta)$, whereas the inductance term depends on the geometry of the turbine, given by:

$$L_t = \int_{l}^{\bar{l}} \frac{1}{gA(x)} dx$$

One of the further evolution of this model will be to take into account the excitation source of the turbine as well as the effect of the vortex rope compressibility at part load with a model similar to the Philibert and Couston model (Ref. 5).

CASE STUDY

A rejection of load perturbation in a power plant constituted of a tank, a pipe, a Francis turbine and a generator is illustrated in Fig. 5. A 30% torque's decrease in a time period of 0.1 second is studied. The data corresponding to this example are presented in Table 1 and the characteristic curves of the turbine shown in Fig. 6 are taken from Wylie & Streeter (Ref. 9).

Tank	Pipe	Turbine	Generator	Controller
H_o = 82 m	L = 125.27 m D = 5.48 m λ = 0.1 a = 1250 m/s	H_{tR} = 82 m ω_R = 20.94 rd/s Q_{tR} = 114 m^3/s T_{tR} = 4.11e6 Nm	I_{t+g} = 1.5e6 Kgm^2 T_{gi} = 2.947e6 Nm T_{gf} = 2.14e6 Nm t_{ch} = 0.1 s	T_d = 3.7 s T_α = 0.325 s δ = 0.18

Table 1 Characteristics of the power plant with Francis turbine.

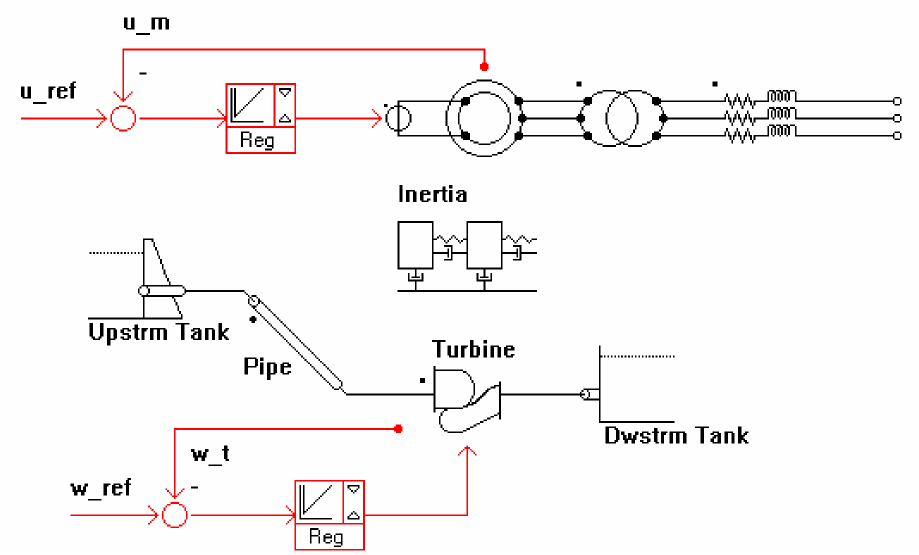


Fig. 5 Modelling with SIMSEN of a power plant including a Francis turbine coupled to a generator.

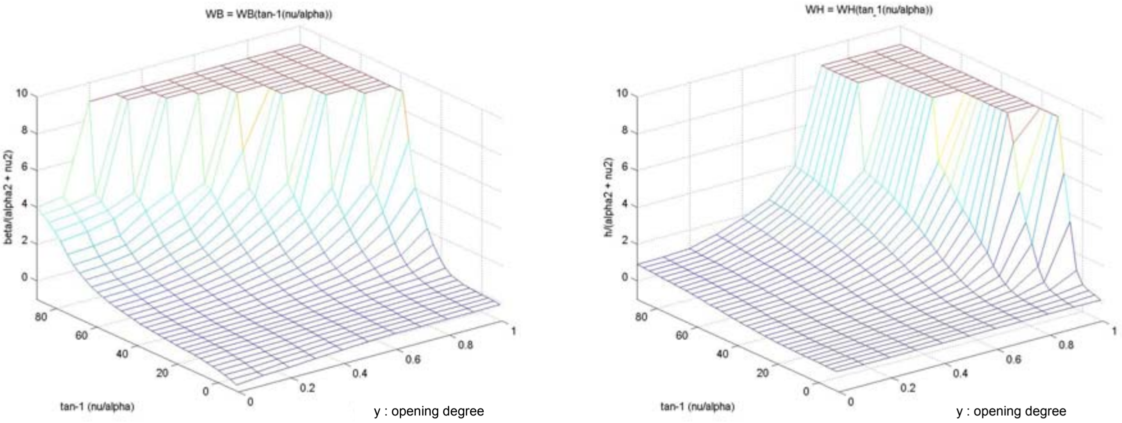
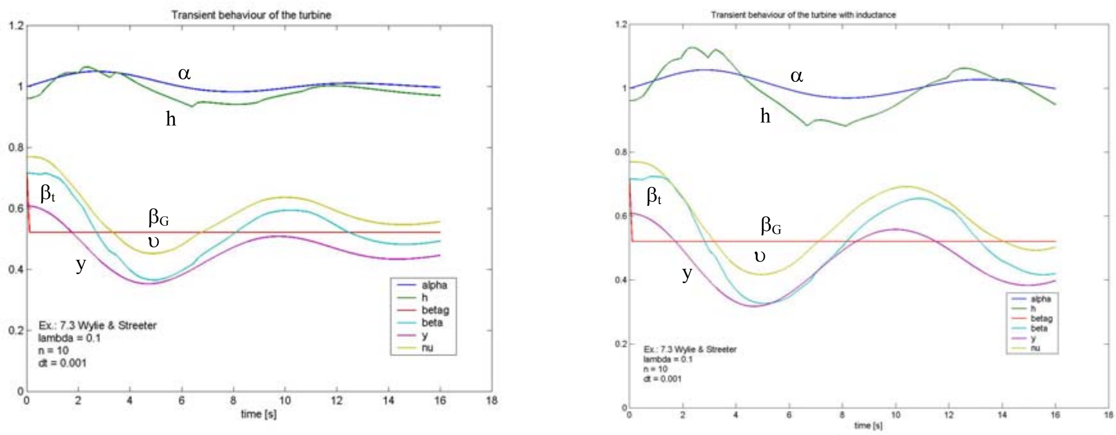


Fig. 6 Characteristics W_B and W_H of the turbine.

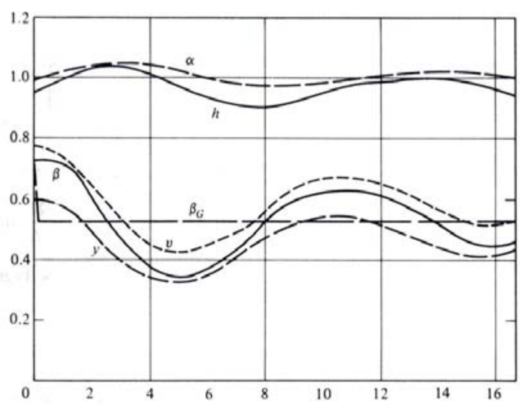
The controller equation used for the simulation is given by:

$$T_d T_\alpha \frac{d^2 y}{dt^2} + (T_\alpha + \delta \cdot T_d)\frac{dy}{dt} + (\alpha - 1) + T_d \frac{d\alpha}{dt} = 0$$

Simulation results of transient behaviour of the power plant due to the load rejection of 30% are presented in Fig. 7. First, hydraulic inductance L_t of Francis turbine is neglected. Afterwards, the inductance is estimated to be 0.36 s^2/m^2 using the statistical dimensions of Francis turbine provided by Servio de Leva (Ref. 7).



- a -   - b -



- c -

Fig. 7 Simulation results of the transient behaviour of the Francis turbine power plant.

a.) Without considering the inductance of the turbine.

b.) Considering the inductance of the turbine.

c.) Wylie & Streeter (Ref. 9).

The 30% decrease of the rated torque β_G of the generator induces an increase of the rated speed α which induces itself the reaction of the controller which commands the closure of the guide vanes. As a result, the torque delivered by the turbine follows the rated discharge υ and decreases under the torque of the generator. Then, the controller acts until the stabilisation of the rated speed α is reached, that is when the torque of the turbine is equal to the torque of the generator. The simulation performed with SIMSEN exhibits a good agreement with the simulation results obtained by Wylie & Streeter (Ref. 9, Fig. 7 b.) presents the effect of the inductance on the transient behaviour simulated and shows that the inductance increases the amplitude of all of the fluctuations. It means that the time required by the power plant for the stabilisation of the rotating speed increases as well.

CONCLUSION

Based on the impedance method, analytical models of a pipe, a vane, a surge tank and a Francis turbine are developed. These models, implemented in the software SIMSEN, have already proved a good agreement for mass oscillations and wave propagation modelling (Ref. 4). They demonstrate here their capability to reproduce the transient behaviour of a Francis turbine described by its measured characteristic curves. For example, the simulations show the increase of the time response of the power plant due to a perturbation if the inertia effect of the Francis turbine is considered. These developments constitute the first step for the modelling of the Francis turbine dynamic behaviour in order to be able to consider the excitation source and the vortex rope compressibility of the hydraulic machine and analyse its effect on the whole power plant.

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