Advanced simulation of hydroelectric transient process with Comsol/Simulink

2010 IOP Conf. Ser.: Earth Environ. Sci. 12 012060

(http://iopscience.iop.org/1755-1315/12/1/012060)

Advanced simulation of hydroelectric transient process with Comsol/Simulink

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Abstract. In the study of hydroelectric system, the research of its transient process and the improvement of its simulation accuracy are restricted mainly by the precision mismatch among the hydraulic and power system models. Simulink provides a very rich control and automation model library system, thus electrical and mechanical conditioning control systems can be accurately simulated. However, it can only solve time but spatial integral problem. Due to that cause, the hydraulic system model often needs to be simplified in course of the simulation of hydroelectric transient process. Comsol, a partial differential equation (PDEs)-based multi-physics finite element analysis software, can precisely simulate the hydraulic system model. Being developed in the Matlab environment, it also can seamlessly integrate with Simulink. In this paper, based on the individual component model, an integral hydraulic-mechanical-electric system model is established by implementing Comsol code into the Simulink S-Function. This model helps to study the interaction between the hydraulic system and the electric system, and analyze the transients of a hydro plant. Meanwhile the calculation results are compared and analyzed with the general simulation system only by using Simulink.

1. Introduction

With the rapid construction and development of China large-scale hydropower stations, the associated security and stability issues among hydraulic, mechanical and electrical systems becomes increasingly prominent. In the past research, the three systems are often studied respectively by experts of each field. Among those researches , the coupled interaction is usually not considered and the model accuracy always can not meet the demand of research, which leads to simplification of the impacts among hydraulic, mechanical and electrical system. Under such condition, this paper takes a single-machine infinite-bus power system as an example by using Comsol/Simulink. Based on this model, the interaction between systems is studied and simulation results are given and analyzed. The hydraulic-mechanical-electric coupled system is shown in Fig. 1.

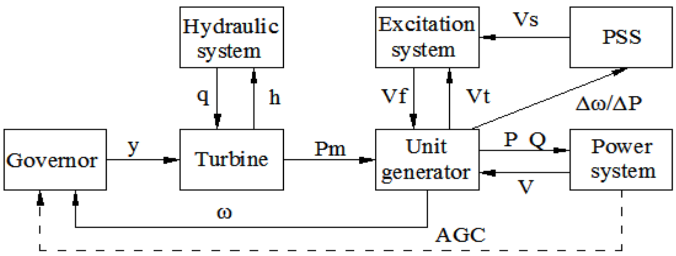

Fig. 1 Hydraulic-mechanical-electric coupled system

2. How Comsol works

Comsol (formerly FemLab) is a finite element analysis, solver and Simulation software package for various physics and engineering applications. It also offers an extensive interface to MATLAB and allows for entering coupled systems of partial differential equations (PDEs), 1-D, 2-D or 3-D, nonlinear and time dependent. The specified PDEs and boundary conditions can be represented by the general form:

$$e_a \frac{\partial^2 u}{\partial t^2} + d_a \frac{\partial u}{\partial t} + \nabla \cdot \Gamma = F \quad \text{in} \quad \Omega \tag{1}$$

$$-n \cdot \Gamma = G + \left(\frac{\partial R}{\partial u} \right)^T \mu \quad \text{on} \quad \partial\Omega \tag{2}$$

$$R = 0 \qquad\qquad \text{on} \quad \partial\Omega \tag{3}$$

Where eq. (1) is satisfied inside the domain Ω, eq. (2) (generalized Neumann boundary) and eq. (3) (Dirichlet boundary) are both on the boundary of $\partial\Omega$.

2.1 Hydraulic system model

In the study of transient process in a hydropower station, the hydraulic system is generally calculated as one dimensional compressible unsteady flow. Considering head loss and compressibility of water and pipe wall, the basic equations of the water hammer pressure (including motion and continuity equations of unsteady flow) are as follows:

$$gA^2 \frac{\partial H}{\partial l} + Q \frac{\partial Q}{\partial l} + A \frac{\partial Q}{\partial t} + \frac{fQ|Q|}{2D} = 0 \tag{4}$$

$$Q \frac{\partial H}{\partial l} + A \frac{\partial H}{\partial t} + \frac{a^2}{g} \frac{\partial Q}{\partial l} = 0 \tag{5}$$

To be consistent with the transfer function in Simulink, eq. (4) ~ (5) should be into dimensionless form:

$$\frac{gAH_r}{LQ_r} \frac{\partial h}{\partial x} + \frac{Q_r}{AL}(q + q_0) \frac{\partial q}{\partial x} + \frac{\partial q}{\partial t} + \frac{fQ_r}{2DA} |q + q_0| (q + q_0) = 0 \tag{6}$$

$$\frac{Q_r}{AL}(q + q_0) \frac{\partial h}{\partial x} + \frac{\partial h}{\partial t} + \frac{a^2 Q_r}{gALH_r} \frac{\partial q}{\partial x} = 0 \tag{7}$$

$$h = \frac{H - H_0}{H_r}, q = \frac{Q - Q_0}{Q_r}, \quad x = \frac{l}{L} \tag{8}$$

In this case, the PDE model for the inside of the domain is given by eq. (6) ~ (7). The general form is here used for this type of non-linear problem. In Appendix 6.1 the corresponding part of Comsol code is provided.

2.2 Implement Comsol code into S-Function

Comsol has standard facilities to export models to Simulink. Being a non-linear model which can not be simulated efficiently by Simulink, a standard export of the hydraulic system model to Simulink is not very practical. A possible solution to this problem is to implement the Comsol code in the Simulink S-function. The S-function solves each time step the hydraulic system model using the FemLab solver. Depending on the input value of q from Simulink, after each time step the value of h from Comsol is exported. Appendix 6.2 shows details of how an S-function can be programmed for the use with this Comsol model and solver.

3. Models under Simulink environment

Simulink, developed by The MathWorks, is widely used for modeling, simulating and analyzing multi-domain dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. Simulink provides a very rich control and automation model library system, thus electrical and mechanical conditioning control systems can be accurately simulated.

3.1 Hydro turbine model

The characteristic of turbine is too complex to be accurately expressed by a mathematical expression due to the complexity of flow movement. In this paper, turbine characteristic curve is used and described by two tables, namely: 1) table of the relationship between unit speed, guide vane opening and unit discharge; 2) table of the relationship between unit speed, guide vane opening and unit torque. Look-up Table (2-D) in Fig. 2 is a two-dimensional look-up table module. According to the known unit speed, head and opening, the unit discharge and torque can be derived through interpolation calculation by this module.

3.2 Turbine governor model

The parallel PID governor is used in this paper, shown in Fig. 3.

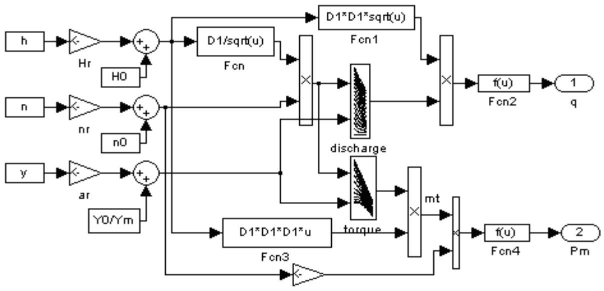

Fig. 2 Hydro turbine model

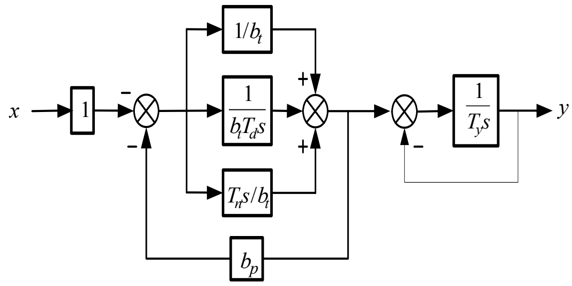

Fig. 3 Turbine governor model

3.3 Unit generator, Excitation system and PSS models

The three models are directly selected from the 'SimPowerSystems' in Matlab. The electrical part of the Unit generator model is sixth-order state-space and takes into account the dynamics of the stator, field, and damper windings. And the excitation system block implements a DC exciter, without the exciter's saturation function. The basic elements that form the excitation system block are the voltage regulator and the exciter. PSS can add damping to the rotor oscillations of the synchronous machine by controlling its excitation. The output signal of the PSS is used as an additional input (vstab) to the Excitation System block, and the input signal in this paper is the machine speed deviation.

4. Simulation of hydraulic-mechanical-electric coupled system

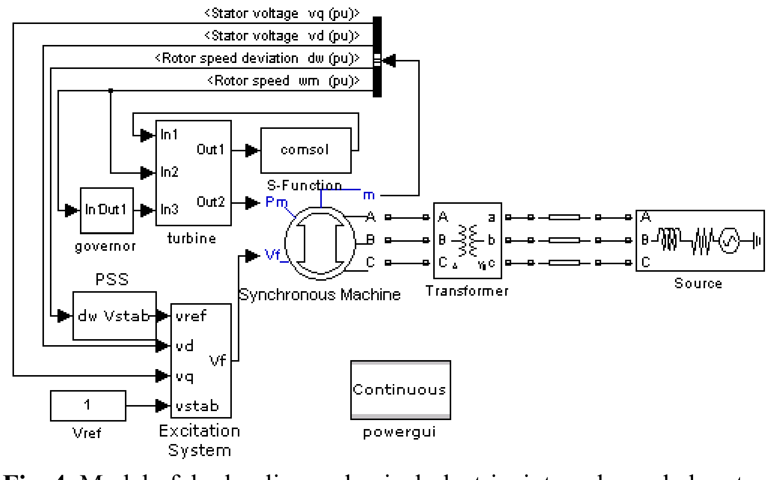

Fig. 4 Model of hydraulic-mechanical-electric integral coupled system

By combining each part of above models, the model of hydraulic-mechanical-electric integral coupled system is built, as shown in Fig. 4.

4.1 Application example

According to the established coupling system model, an actual Hydropower plant is simulated. The calculation data of the plant are as follows: $L=780m$, $D=14.5m$, $a=1000m/s$, $f=0.02$, $D_1=8.15m$, $H_r=106m$, $Q_r=624.5\ m^3/s$, $P_{mr}=605MW$; $b_t=0.4$, $T_d=7s$, $Ty=0.02s$. The parameters of excitation and PSS model can be found in reference 4.

Calculation conditions:

1) Three-phase short circuit: T=5.0s, it suddenly happens three-phase short-circuit at the terminal outlet of generator with nominal output, the fault is removed at T= 5.1s.

2) Load rejections: The plant with nominal output rejects 80% load at T=5.0s.

4.2 Results analysis

Figure 5 and 6 shows the calculation results of above two calculation conditions and comparison with the system of simplified elastic water hammer model:

$$G_h(s) = \frac{h(s)}{q(s)} = -\frac{T_w s}{1 + 0.125 T_r^2 s^2} \quad (T_w = LQ_r / gH_r A,\ T_r = 2L/a) \tag{9}$$

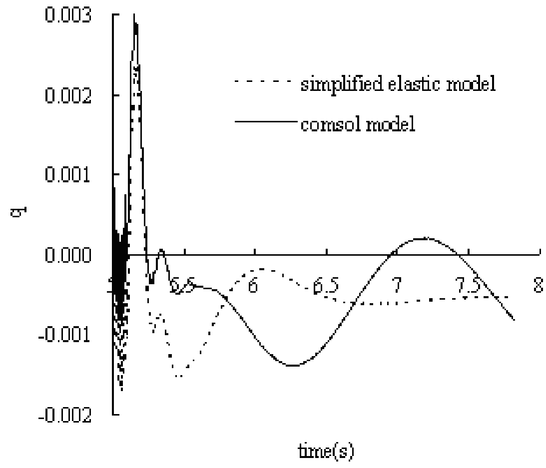

Fig. 5a Relative change of discharge (condition 1)

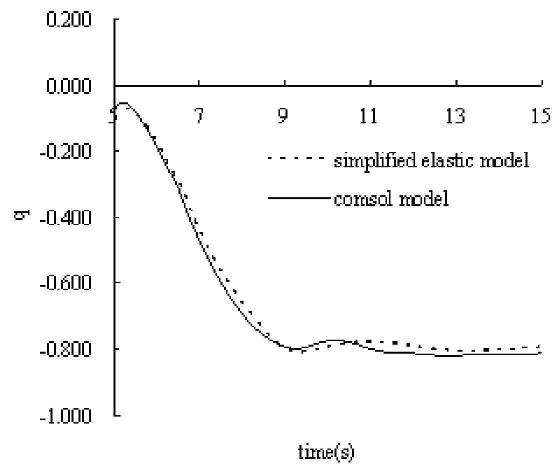

Fig. 6a Relative change of discharge (condition 2)

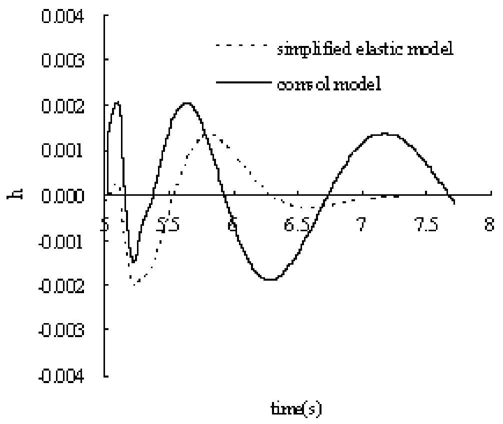

Fig. 5b Relative change of head (condition 1)

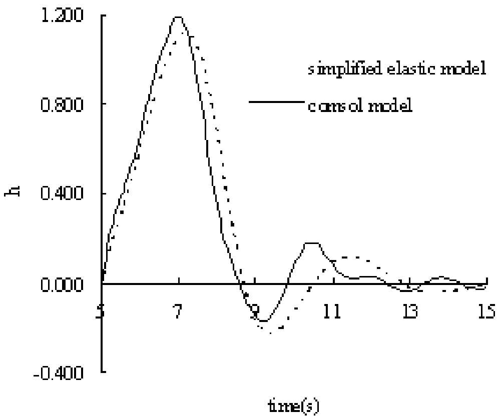

Fig. 6b Relative change of head (condition 2)

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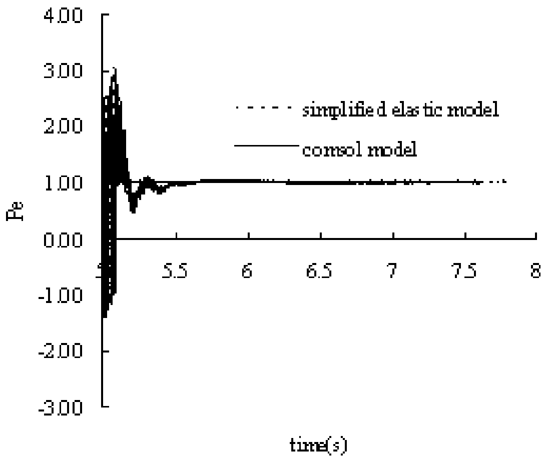

Fig. 5c Electromagnetic power/p.u. (condition 1)

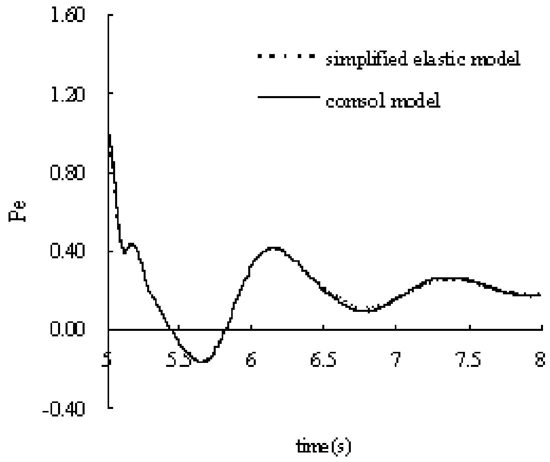

Fig. 6c Electromagnetic power/p.u. (condition 2)

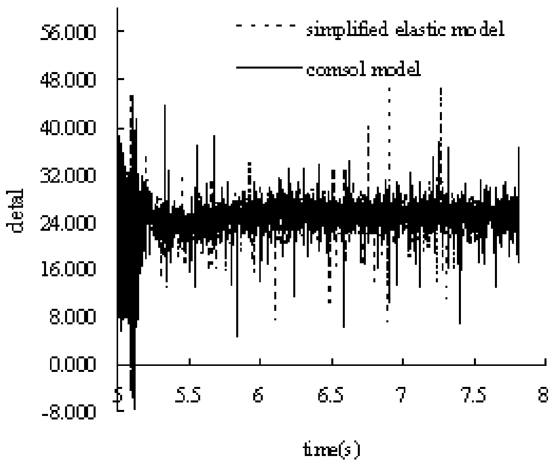

Fig. 5d Load angle/deg (condition 1)

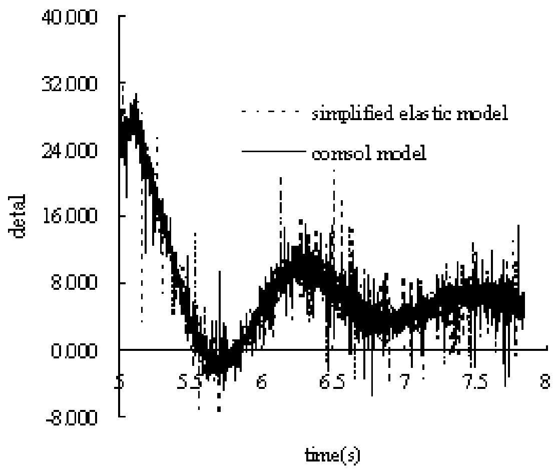

Fig. 6d Load angle/deg (condition 2)

1) As can be see from Fig. 5c, d and 6c, d, by using Comsol and simplified models, the results of electromagnetic power and load angle under two conditions are nearly the same. However, these two models did obvious impacts on the result of discharge and head. The maximum differences of discharge and head between two models are about 3%.

2) When it had a large disturbance at electrical system side (condition 1), the changes of turbine discharge and head are very small. The biggest changes are only 0.003 and 0.002 respectively. On the contrary, the electromagnetic power of generator and the load angle had great changes. Particularly, the change of the electromagnetic power had amounted to 2 after the disturbance. From the simulation results, we can see that effects of electrical system disturbance on itself are relatively larger than hydraulic system. In theory, the reason is that in the transient process short-circuit recovery of the electric power system takes quickly while the turbine governor is too late to respond in such a short period, which leads to little change to hydraulic system.

3) When it occur a large disturbance at hydraulic system side (condition 2), the changes of turbine discharge and head are very rapid and great. From Fig. 6c and 6d it can be seen that the disturbance to the electrical system is also very large and the electromagnetic power of generator had a significant oscillation. We can say that the impact of hydraulic system disturbance on the electrical system is relatively larger.

5. Conclusions

According to the electromechanical components of Hydropower Station, hydraulic-mechanical-electric integral coupled system model of single-machine infinite-bus power system is built in this paper. The model considers a more comprehensive interaction between hydraulic and electrical system. With the help, we can analysis many kinds of hydraulic-mechanical-electric transition process and get the main conclusions as follows:
1) The accuracy of hydraulic model has little impact on the electrical system in a single-machine infinite-bus power system. But it did obvious difference to the hydraulic system.

The Comsol model is more desirable in the study of hydraulic transient process.
2) The impact of hydraulic system and electrical system on each side will be different. The disturbance from hydraulic system side makes a bigger effect on electrical side. In short, the hydraulic system disturbance will make significant changes of head and discharge, which finally leads to the rapid and great vibration of the generator mechanical torque.

However, the inter-coupling relations of hydraulic system, mechanical system and electrical system are very complex. Only a simple machine infinite-bus system had been studied in this paper. In terms of the station with more than one machine and a surge tank, isolated power network, the interactions are so complicated that a further study is still needed.

6. Appendix

6.1 Main corresponding Comsol code

```
%variables: u1=q; u2=h; u1x=du1/dx etc.
g1=solid1([-0.0,1.0]);                % Geometry
fem.mesh=meshinit(fem);               % Initialize mesh
fem.mesh=meshrefine(fem, ...
    'mcase',0);                       % Refine mesh
% Application mode 1                  % PDE model of Equation (6)
bnd.r = {'-u1','-t/t0-u1'};          % specify boundary coefficient r
bnd.type = 'dir';                     % boundary type
equ.f = '-(A*Hr*g/L/Qr)*u2x-(Qr/A/L)*u1*u1x-(f*Qr/2/D/A)*(u1+q0)*abs(u1+q0)';
equ.init = {{0;0}};                   % specify initial value
equ.ga = q0*Qr/A/L;                   % specify PDE coefficient ga
equ.da = 1;                           % specify PDE coefficient da
% Application mode 2                  % PDE model of Equation (7)
bnd.r = {0,'hw0/Hr-u2'};              % specify boundary coefficient r
bnd.type = 'dir';                     % boundary type
equ.f = '-(Qr/A/L)*u1*u2x-(a*a*Qr/g/A/L/Hr)*u1x';
equ.init = {{'(1-x)*hw0/Hr';0}};
equ.ga = q0*Qr/A/L;
equ.da = 1;
fem.sol=femtime(fem, ...
                'init',init, ...
                'solcomp',{'u2','u1'}, ...
                'outcomp',{'u2','u1'}, ...
                'blocksize','auto', ...
                'tlist',[0:0.02:3], ...
                'tout','tlist');          %solving
```

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6.2 Implementation of a Comsol model in S-function

```
function[sys,x0,str,ts]=dsfun1D(t,x,u,flag)
global Outfem OutT Outsol
%Specify variable 'fem': the Comsol model geomtry, mesh,
% PDE coefficents and boundary conditons
tstap=0.02;   %time stepping
u0=0;         %initial value of input vector
switch flag,
    case 0
        [sys,x0,str,ts]=mdlInitializeSizes(fem,tstap,u0);
    case 2
        sys=mdlUpdate(t,x,u,fem,tstap);
    case 3
        sys=mdlOutputs(t,x,u,fem,tstap);
    case 9
        Outfem=fem;
        Outfem.sol=femsol(Outsol,'tlist',OutT);
        save OutData Outfem;
        sys=[];
    otherwise
        error(['unhandled flag =',num2str(flag)]);
end
function sys=mdlUpdate(t,x,u,fem,tstap)
global Outfem OutT Outsol
    fem.appl{1}.bnd.r={0,'u(1)-u1'};%bounadry value
    tijd=[t;t+tstap/2;t+tstap];      %calculate simulate time
    OutT=[OutT (t+tstap)];           %update time
function sys=mdlOutputs(t,x,u,fem,tstap)
global Outfem OutT Outsol
    sys=postinterp(fem,'u2',1);      %output
```

Nomenclature

e_a, d_a	Mass and damping coefficients in Comsol	P_{mr}	Nominal mechanical power [MW]
Γ,F,G,R	Comsol coefficients	h	Relative change of head
L	Length of penstock [m]	q	Relative change of discharge
A	Cross section area of penstock [m^2]	y	Guide vane relative opening
D	Cross section diameter of penstock [m]	p_e	electromagnetic power [p.u.]
a	Wave speed[m/s]	*delta*	Load angle [deg]
f	Head loss coefficient	b_t	Temporary speed droop
H, Q	Pressure[m] and discharge[m^3/s] at section l and time t	b_p	Permanent speed droop
		T_d	Time constant of damping device [s]
H_0,Q_0	Initial values of Pressure[m] and discharge [m^3/s]	T_n	Derivative time constant
H_r,Q_r	Unit nominal Pressure[m] and discharge[m^3/s]	T_y	Servomotor response time constant [s]
D	Nominal diameter of turbine [m]		

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