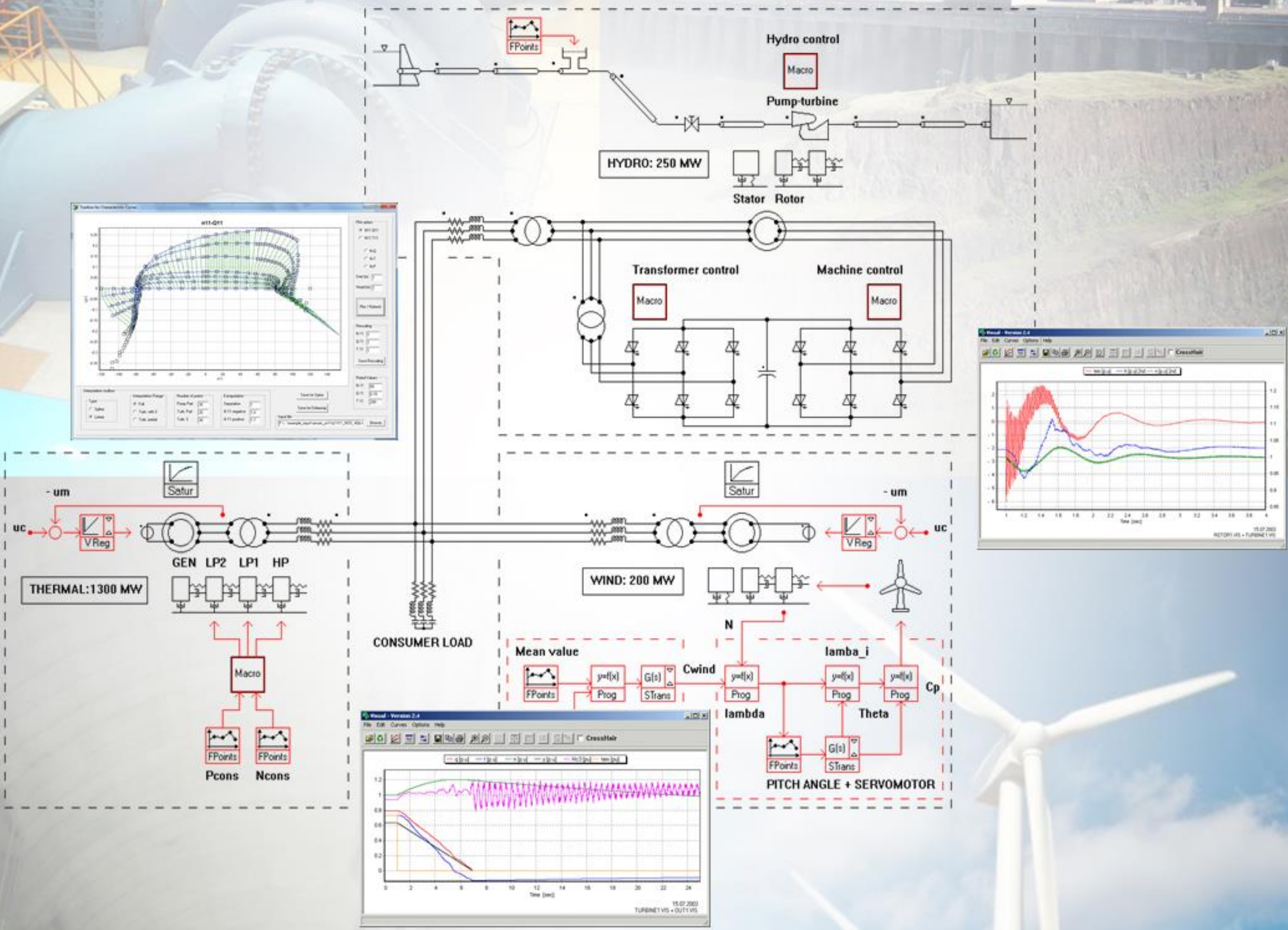
SIMSEN

Simulation Software for the Analysis of Electrical Power Networks, Adjustable Speed Drives and Hydraulic Systems

Quick User Guide



Electrical and Hydraulic Transients
Water Hammer Calculation
Hydroelectric Systems
Power Network Stability
Complex Drives Control
Load Flow

Table of Contents :

1 General information

SIMSEN software enables to simulate power systems dynamics, with a strong emphasis on the hydropower station dynamics. Indeed, SIMSEN takes into account complex hydraulic machinery and waterways, as well as electrical machines, power electronics and the control systems.

The development of this software started in 1992. The idea was to develop a modular system able to do fast simulations of electrical power systems including semiconductors and regulation parts. The whole development has been based on practical examples from power networks and industrial drives. In both domains, the customer came with problems requiring the study of complex systems. In 1994, it was decided to develop a first graphical user interface. From 1996 to 1998, the system has been extended to simulate the digital behavior of the regulation part, which made SIMSEN able to simulate correctly mixed-signals systems (systems with analog and digital elements).

In 2001, the development of a new Hydraulic Library was initiated and a first version of SIMSEN including hydraulic and electrical libraries was made available in 2006. This version included the main hydraulic components such as reservoir, elastic pipes, valves, surge tanks, Pelton, Francis and doubly regulated Kaplan turbines as well as reversible regulated Francis pump-turbine and centrifugal pumps. This version made possible the simulation of an entire hydroelectric power plant from water to wire including waterways, hydraulic turbines, rotating trains, electrical machines and control system for turbine and generator. Since then the hydraulic library was continuously enhanced including air vessels, cavity compliance, discrete losses, etc. From 2011 to 2016, development projects performed in collaboration with VOITH, ALSTOM and ANDRITZ Hydro enabled to develop the SIMSEN Advanced version including eigenvalues and eigenmodes calculation and representation, free surface open channel models, differential surge tanks, generalized surge tanks including inertia effects overflow and inflow, water column separation models, transition from free surface to pressurized flow, pressure envelop representation and animation, IEEE excitation system and PSS models and transfer function computation. A major improvement of the SIMSEN software was the development of a fully new Graphical User Interface made available since December 2015 which considerably improved the use of the SIMSEN software. New simulation models and analysis tools are constantly developed to improve the SIMSEN software capabilities.

Results provided by SIMSEN have been validated by comparison with measurements in industrial projects, see the documents in Basic Theory/Examples of Validations folder. SIMSEN is already widely used by 48 industrial customers and by research centers.

SIMSEN Licenses:

- **Alstom Power Generation Ltd.:** Turbo generators
- **Alstom Power Generation Ltd.:** Electrical and Power Plant Control
- **ABB Industry:** Power Electronics and Adjustable Speed Drives: ***on site Swiss license***
- **ABB Industry AS Norway:** Power Electronics and Adjustable Speed Drives
- **ABB(China) Ltd, Shanghai Branch,** Shanghai, China
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- **HES-SO Valais-Wallis**, Sion, Switzerland
- **INPG-LEGI,** Grenoble, France
- **ENSE3,** Grenoble France

1.1 Overview of Program Capabilities

This software is an advanced numerical tool, widely used by the industry and academia for simulating the dynamics of power systems, with a strong capability to model entire hydropower plants, including complex hydraulic machinery, hydraulic waterways and systems, as well as electrical machines, power electronics and the control systems. This software allows multi-disciplinary approaches and a synergy between the different fields of engineering.

1.1.1 Overview of hydraulic modelling capabilities

The modeling principle of hydraulic systems is described in details in chapter 7. Briefly, waterways and systems models take into account distributed head losses, geometry, elasticity and wave speed. Hydraulic machines model takes into account the 4-quadrants performance hill chart to simulate their dynamic behavior. These models are formulated using an electrical analogy in order to facilitate the automatic equation generation of the whole system (using Kirchhoff voltage and current laws).

Available hydraulic systems elements cover following categories:

- turbines, storage pumps and reversible pump-turbines 4-quadrants transient operation;
- hydraulic and electrical machines interactions;
- cavitation / Water column separation;
- PID turbine governors;
- water hammer calculation, mass oscillations, surge tanks modeling;
- Etc.

1.1.2 Overview of electrical modelling capabilities

SIMSEN is a general electrical circuit transient simulator. Using elementary components like voltage sources, resistors, inductors, capacitors, etc., user can basically build its own circuit, without limitation. To facilitate modelling of industrial power systems, SIMSEN has a category of elements for three-phase elements (voltage source, loads, machines, etc.). The user can create any circuits from the three terminals, *a*, *b* and *c*, of a three-phase elements, included unsymmetrical circuits. Indeed, the state variables of the three phase elements are the physical line current, i_a, i_b and i_c for phases a, b and c. Hence, SIMSEN is a true three-phase simulator, by opposition to some other software that use a classical dqo (Park) reference frame for the state variables, combined to positive/negative sequences. SIMSEN is an electro-magnetic transient (EMT) simulator, which means that the models of the electrical machines and transformers consider the transient phenomenon of the magnetic flux coupling the different windings. This allows to finely model the electro-magnetic torque of machines as well as precisely evaluate their short-circuit transient responses. The models of the machines that are available are among the most detailed models listed in the IEEE Standards 1110. The models in SIMSEN are the model 2.1 and the model 3.3 for synchronous machines (see 8.1).

Available electrical systems elements cover following categories:

- electrical machines (synchronous, asynchronous, single or three phase, DC machines, Permanent magnet single phase);
- power electronics converters;
- electromagnetic transients in AC/DC networks;
- transient stability and general fault analysis;
- IEEE Standard excitation systems and PSS;
- control and regulation;
- Etc.

1.2 Overview of this Manual

The main objective of this *Quick User Guide* is to quickly present the possibilities offered by the SIMSEN software and allow for immediate ease of use with an intuitive software interface. **Chapter 2** describes the installation procedure and the hardware and software requirements for an optimal operation. **Chapter 3** presents the SIMSEN environment to facilitate the first steps with the SIMSEN software. **Chapter 4** describes the general procedure to create a SIMSEN model. **Chapter 5** presents the list of available electrical and hydraulic components modeled in the SIMSEN software. **Chapter 6** introduces hydraulic and electrical tutorials and examples. Finally, **Chapter 7** briefly presents the theory behind the SIMSEN software.

2 Installation

2.1 Hardware and software requirements

SIMSEN software is a Windows-compatible software and does not require any prerequisites for optimum operation.

2.2 Installation procedure

The only thing to do to install your SIMSEN package is to copy the package folder *SIMSEN_X_Y_Z* to any folder on your computer hard drive where you have write permission. Starting SIMSEN directly from the CD will not work, as it needs to write license information at start up.

In the root folder of the SIMSEN package, you will find the following sub folders:

- **Basic Theory** folder with PDF describing the theory behind the SIMSEN software
- **Examples:** folder with hydraulic and electrical SIMSEN examples
- **exe:** folder with executable applications (the software)
- **Help:** folder with all help information in PDF format
- **Tutorials:** folder with hydraulic and electrical tutorials with related PDF files

3 Starting and presentation of the SIMSEN environment

3.1 How to start SIMSEN

- open the folder "exe"
- double click on Simsen.exe
- insert the password. Password is only required the first time.
- SIMSEN is ready to be used.

3.2 Presentation of the SIMSEN environment

After launching the SIMSEN software, the main windows illustrated in Figure 1 appears in full screen. The white sheet at the center of the main window defines the space to create the SIMSEN model. In the left hand pane, the *Element library* contains all the hydraulic and electrical components modeled in the SIMSEN software. A short description of each of these components is given in Chapter 5. In the right hand pane, the *Element inspector* allows to quickly visualize and modify the component properties, see Section 4.3. Finally, the main menu bar at the top of the main window includes all actions that can be applied to the model created by SIMSEN software. Each menu is described in the following subsections.

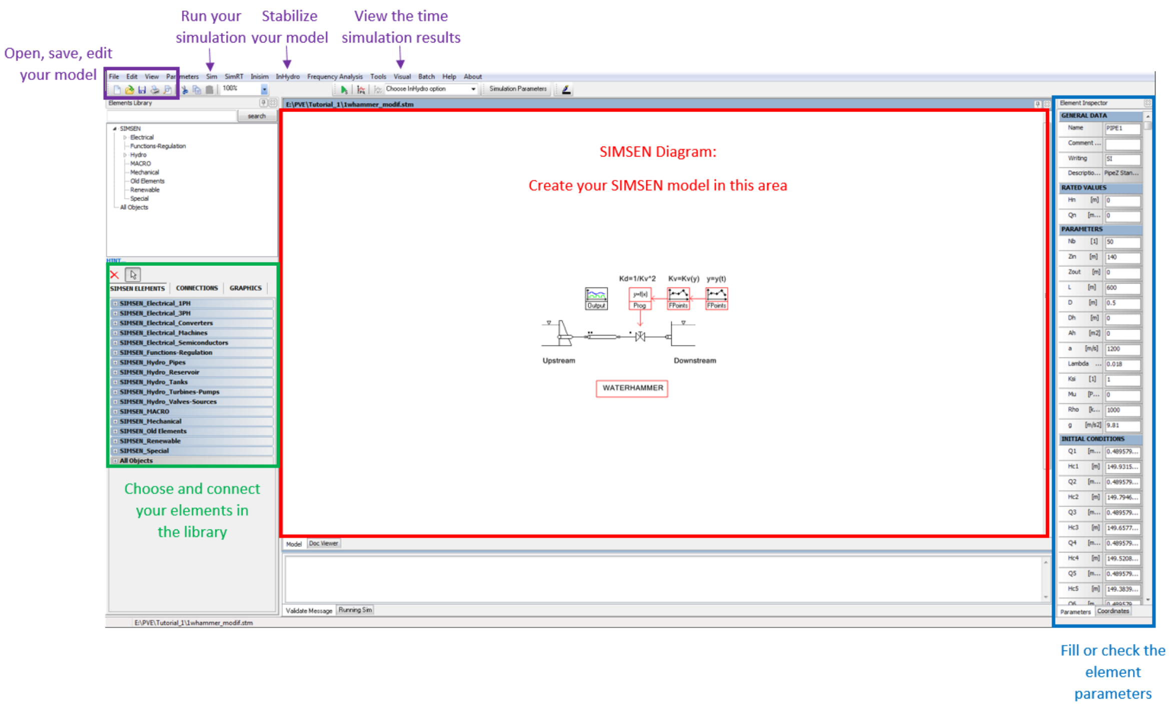


Figure 1: Graphical interface when you start SIMSEN software

3.2.1 File

New model (Ctrl+N)	Start a new circuit
Open model (Ctrl+F11)	Open a file with an existing circuit
Close model	Close the existing circuit
Close all models	Close all the open models
Save model (Ctrl+S)	Save the circuit and the simulation parameters
Save as	Same as **Save model**, but with the full name of the file (extension .stm)
Save macro as	Save the circuit of the macro as a .stm file
Import	Import a subcircuit in the edited circuit
Export	Export a subcircuit of the edited circuit
Examples	Access to examples and tutorials folders
Page Setup	Modify options dictating the way a document is formatted to print.
Print Preview	Preview the circuit drawing, before printing it
Print	Opens the printers dialog box of the operating system. Any installed printers can be used to print the model (e.g. paper printer, or pdf printer)
Quit Edisim	Exit the program *SIMSEN*

3.2.2 Edit

Undo (Ctrl+Z)	Undo the effects of one or more previous circuit editing commands
Redo (Shift+Ctrl+Z)	Redo any undo function again
Copy (Ctrl+C)	Copy an element or a pre-selected group of elements to the clipboard (operating system clipboard temporary memory)
Cut (Ctrl+X)	First performs a Copy action on the selected element or group before removing the selection from the model.
Paste (Ctrl+V)	Insert an element previously copied (Copy) or cut (Cut)
Rotate (Ctrl+R)	Rotate an element
Edit text (F2)	Change text by adding, deleting and rearranging letters
Delete (Ctrl+Del)	Remove an element or a pre-selected group of elements
Select all (Ctrl+A)	Select all text, elements or other objects of the SIMSEN model
Show Unconnected Wires	Show all unconnected wires of the SIMSEN model
Copy as image	Copy the SIMSEN model as an image into the clipboard (in a bitmap format, .bmp). This image can be then pasted into a picture tool (e.g. Paint of Windows). This action takes the zoom into account, i.e. the picture is also zoomed if current model is.

3.2.3 View

Grid	Display or hide the SIMSEN model grid
Show Linkpoints	Display or hide the linkpoints of each element
Zoom	Increase or decrease the SIMSEN model size
Elements names	Display the name of each element above its graphical symbol on the editing grid
Elements Library	Display the list of all available elements on the left panel of the screen. This library is to be used to select elements to be inserted into the model
Elements Inspector	On the right pane of the screen, display an interactive list of the selected element's parameters
Toolbars	Display or hide tool button at the top of SIMSEN window
Show References X/Y	Show the connection between the elements as function of the References X/Y defined in each element.

3.2.4 Parameters

Simulation Parameters	Display the simulation parameters dialog box
Element Parameters	Display the element parameters dialog box for the selected element
Apply	First, it evaluates the mathematical scripts defined in the CONSTANT DATA and the PARAMETERS section of the S*imulation Parameters* dialog box. Second, it applies the evaluated numerical values of parameters defined in the PARAMETERS section of the S*imulation Parameters* dialog box to the corresponding SIMSEN elements. NOTE: This is not mandatory to do. When a simulation is launched, these parameters assignment from the S*imulation Parameters* dialog box is automatically performed within the computation core. The Apply action is only a handy way of keeping the numerical values in the elements parameters dialog box up do date with the assignments done in the S*imulation Parameters* dialog box.

3.2.5 Sim

The click on the *Sim* button launches the Validation process and Ordinary Differential Equation (ODE) set generation process. The validation process validates the created circuit, ensures that the connections are feasible and that the key parameters of the elements are properly defined.
The ODE set generation process creates the equations systems from the circuit, using Kirchhoff’s voltage loop and current node laws. First step is to reduce the drawing of the circuit to a graph with nodes and branches. From this graph, the second step is to find the independent (linearly independent) loops of the graph. Possibly try to order those loops with a given logic that will help have a less sparse matrix of the system. Each loop is numbered and corresponds to a state variable of the system that will be numerically integrated. For each element, knowing to which loops it belongs, the dependency of its state variable to the others can be established. If element have internal state variables, those are inserted into the global state variable list.

If the circuit is valid and ODE set is generated, the GUI creates all the validated circuit files (.DAT) necessary for the further process of SIMSEN (Sim23.exe). In case where errors have been detected, an error message will be displayed.
Simulations are performed by a different program (executable) than the GUI, see Figure 2. The simulation core is Sim23.exe and is automatically launched by the GUI.

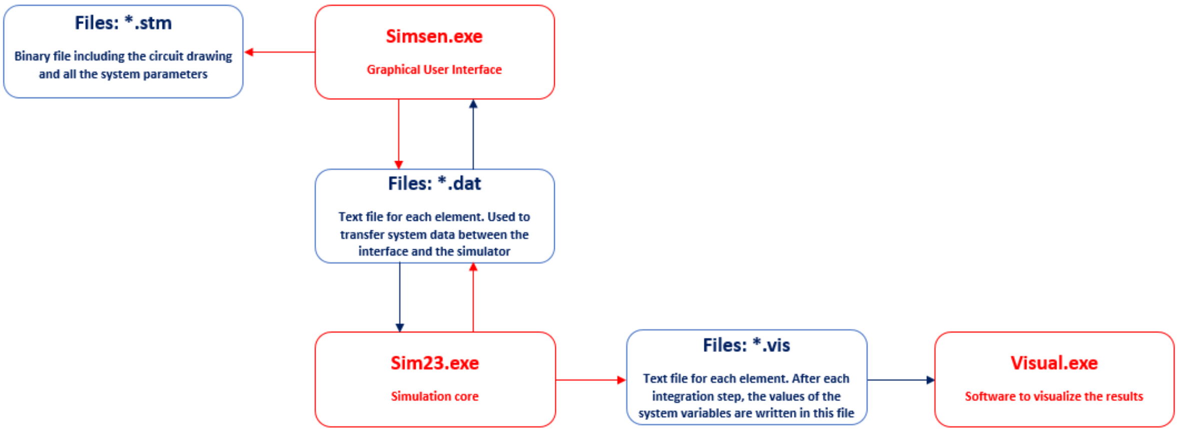


Figure 2 Load flow describing the global software architecture

During the simulation, the user can pause the simulation by pressing on any key in the window of the simulation core (Sim23.exe). Then he has the choice to either end the simulation by pressing on <e> or continue by pressing on <any other key>.
Before closing the simulation program, the user can choose if he wants to save the final state of the state variables to serve as new initial conditions of the model, for the next simulation. By pressing <s>, this will effectively update all initial conditions of the model (in the GUI) with the final value of the simulation just performed. Any other keys will leave the original initial conditions unaltered.

3.2.6 *Inisim*

Like *Sim*, a click on *Inisim*, launches the Validation and ODE set generation process. Then *Inisim* launches the SIMSEN Load Flow program (Inisim.exe), which will calculate the steady state load flow of the circuit, based on operating points specified by user, usually in terms of active and reactive power at different nodes of the power systems. Inisim is only to be used with power system elements, excluding any power semi-conductors. Inisim is based on a decoupled Newton-Raphson algorithm. Recommendations on usage of Inisim are given in section 4.8.
Inisim can be used similarly to *Sim*. At the end, the user also has the choice to effectively save the results of the load flow calculation into the model's initial conditions, in the GUI environment.

3.2.7 *InHydro*

A click on *InHydro* launches the Validation and Kirchhoff processes, described in Sections 3.2.5. There are 6 different possibilities to determine the initial conditions of a hydraulic system using *InHydro*:

1) to determine the initial conditions for **a system with different types of turbines and different procedure for each turbine;**
2) to determine the initial conditions for **a system with Francis turbines;**
3) to determine the initial conditions for **a system with Pelton turbines;**
4) to determine the initial conditions for **a system with Kaplan turbines;**
5) to determine the initial conditions for **a system with pumps**;
6) to determine the initial conditions for **a system without any turbine or pump**.

Each of these possibilities is fully described in Chapter 4.4.

3.2.8 Visual

This command launches the program Visual30.exe, which allows the user to visualize simulation results stored in .VIS files. The VISUAL program is a post-processing program that allows displaying curves on the screen, to apply Fourier analysis and other features. Please read the given documentation folder for more information about the Visual program.

3.2.9 Batch

Batch action refers to a special usage mode of SIMSEN. In batch mode, it is possible to launch several simulations automatically, optionally in parallel, for studies that requires a sensitivity analysis of a parameter, for example. SIMSEN offers a dedicated tool to manage simulations in batch mode, which is named SIMSENBatchTool.exe. It can be launched from this Batch menu item. SIMSENBatchToo.exe can be found in the /exe subfolder of the SIMSEN package. Please read the documentation related to the SIMSENBatchTool for more detail (help on SIMSENBatchTool).

3.2.10 Help

Give information about the simulation parameters and the Editor menu.

3.2.11 About

About defines additional information about SIMSEN software (Version number, Version name)

4 General procedure to create a SIMSEN model

In this chapter, the general procedure to create a SIMSEN model is described in details. Each step illustrated in Figure 3 is the subject of a separate section. For the practice of this procedure, many hydraulic and electrical tutorials are available in Chapter 6.

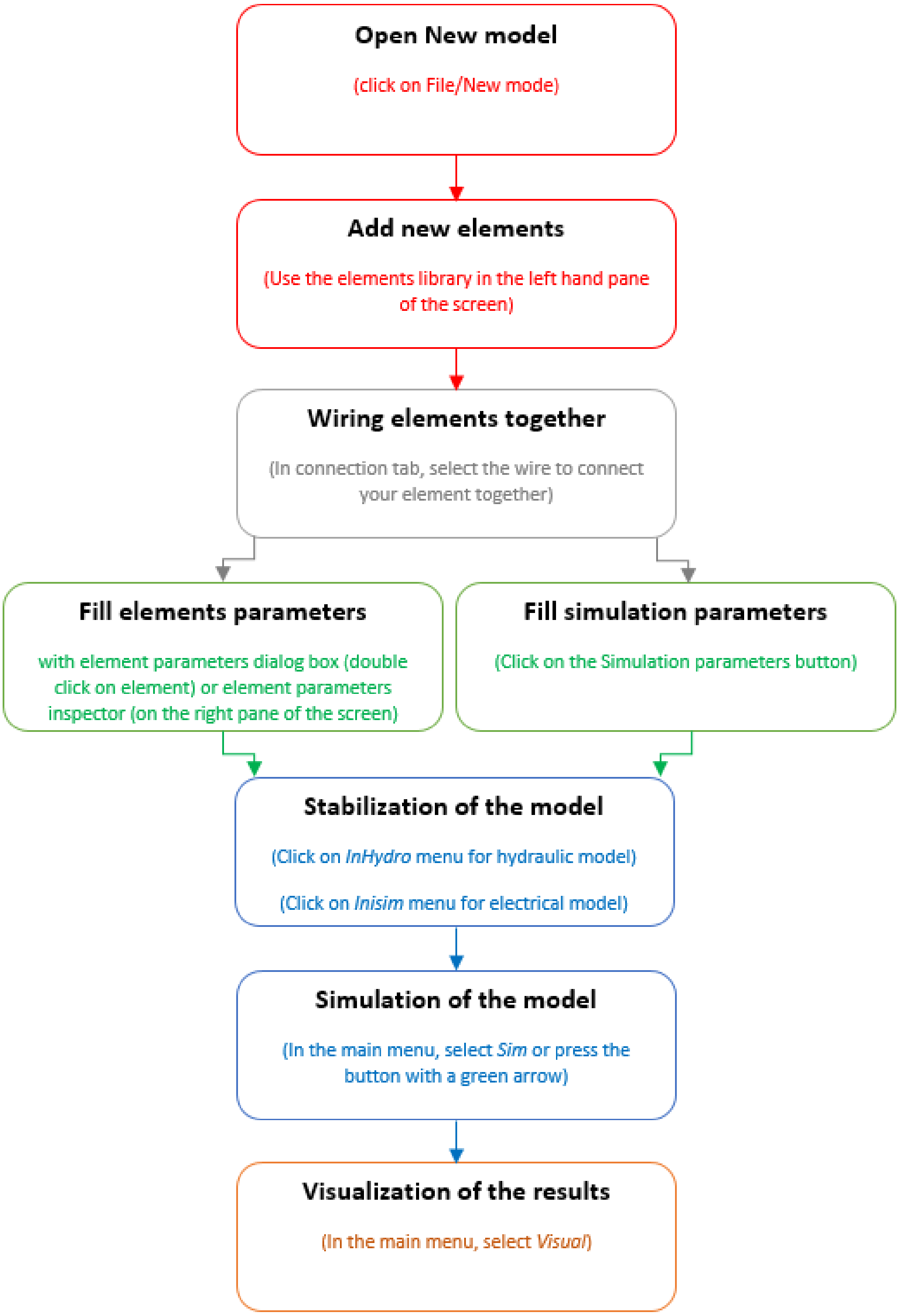


Figure 3 Load flow describing the procedure to create a new SIMSEN model

4.1 Add new elements

- in the left hand pane of the screen, you will find the elements library, which you can simply browse
- click on the element of your choice in the library browser
- insert this element by clicking in the simulation model window
- move your element by just dragging it
- rotate your element by right clicking and selecting "Rotate" in the contextual menu, or simply press "Ctrl-R" short cut on the keyboard
- element insertion is by default unique. You have to select again the element in the library to insert another one
- you can enter a multiple insertion mode for elements. For this, press the "Shift" key before selecting the element in the library.
- In this multiple insertion mode, each click in your model will insert a new element of the selected type.
- Quit this mode by pressing the button with a white arrow in the element library pane, or alternatively press "Esc" and then click in the model

4.2 Wiring elements together

- in the left hand pane of the screen, you will find elements library, which you can simply browse.
- switch the element browser to the CONNECTION tab
- select the wire or the crossing and place them in your simulation model
- wiring is performed in multiple steps, in each step you define a wire segment. Finish your wire by a left double-click. Alternatively, the wire is automatically finished when your last point is an element's terminal (e.g. a voltage source terminal)
- multiple insertion mode for the wire in unfortunately not yet available. However, you can quickly select the wire drawing mode from the context (popup) menu (right click to make the menu appear) or simply press "Ctrl-w".
- to connect two wires together, you need to select the crossing and place it at the intersection.

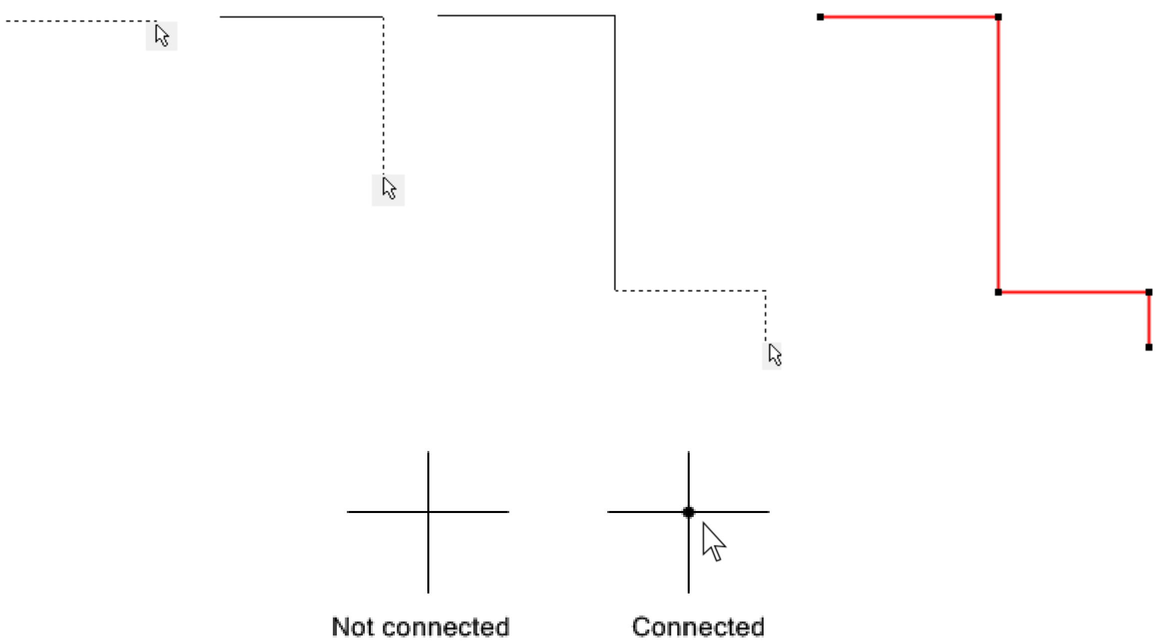


Figure 4 Illustration of the wiring and crossing methods

4.3 Fill elements parameter

To modify elements' parameters of the simulation model:

a) with element parameters dialog box
   - double click (left button) on any element to open the element parameters dialog box
   - modify the parameters and select "OK"
   - Click "Cancel" if you do not want your changes to be saved in the element

b) with element parameters inspector
   - select an element by clicking on it with left button
   - an inspector box, on the right pane of the screen, displays an interactive list of the selected element's parameters
   - directly modify the parameters' value in the element inspector editing fields
   - modified parameters are directly saved in the element
   - click Edit/Undo in the main menu bar if you want to revert your parameter change.

4.4 References X and Y

The sections REFERENCES X and REFERENCE Y in the Functions-Regulation elements allow respectively a read or write access for each parameter of your SIMSEN model. To simplify the values exchange, the reference format is defined as:

- REFERENCES X:

Element Quantity coeff1 coeff2 Legend Unit Comment

With:

- **Element** Name of the element where the quantity is read.
- **Quantity** Name of the quantity to be read.
- **Coeff1**, **Coeff2** Coefficients.

This means that the final value of the input x will be:

$$x = \text{Quantity(Element)} \cdot \text{coeff1} + \text{coeff2}$$

The **Legend** and the **Unit** are used as a label in the output file (if wished) to describe the input x. The **Comment** is just information for the user.

- REFERENCES Y:

Element Parameter=Quantity Coeff1 Coeff2 Legend Unit Comment

With:

- **Element** Name of the element where the parameter is changed.
- **Parameter** Name of the parameter that has to be changed.
- **Quantity** Name of the quantity in the present unit that is used to change the **Parameter** of the **Element**.
- **Coeff1**, **Coeff2** Coefficients.

This means that the final value of the parameter will be:

$$\text{Parameter(Element)} = \text{Quantity} \cdot \text{Coeff 1} + \text{Coeff 2}$$

The equal sign '**=Quantity**' after **Parameter** is not always required. If the present unit (in which you edit the REFERENCE Y) has only one single output channel (e.g. an FPOINT, its output is *y*), then there no need to specify which output channel must be affected to the target **Element.** HOWEVER, in case the present unit provides several output channels (e.g. a block PROG, which has 20 output channels y1 to y20), the **'=Quantity'** syntax is very important. It allows the selection of which output channel of the present unit must be affected to **Element Parameter**.

The **Legend**, **Unit** and **Comment** are just information for the user.

Finally, the coefficients **Coeff1** and **Coeff2** may also be entered as parameters from the main file (section CONSTANT DATA).

4.5 Stabilization with only hydraulic components

There are 6 different possibilities to determine the initial conditions of a hydraulic system using InHydro, see Figure 5:

1) to determine the initial conditions for **a system with different types of turbines and different procedure for each turbine;**
2) to determine the initial conditions for **a system with Francis turbines;**
3) to determine the initial conditions for **a system with Pelton turbines;**
4) to determine the initial conditions for **a system with Kaplan turbines;**
5) to determine the initial conditions for **a system with pumps**;
6) to determine the initial conditions for **a system without any turbine or pump**.

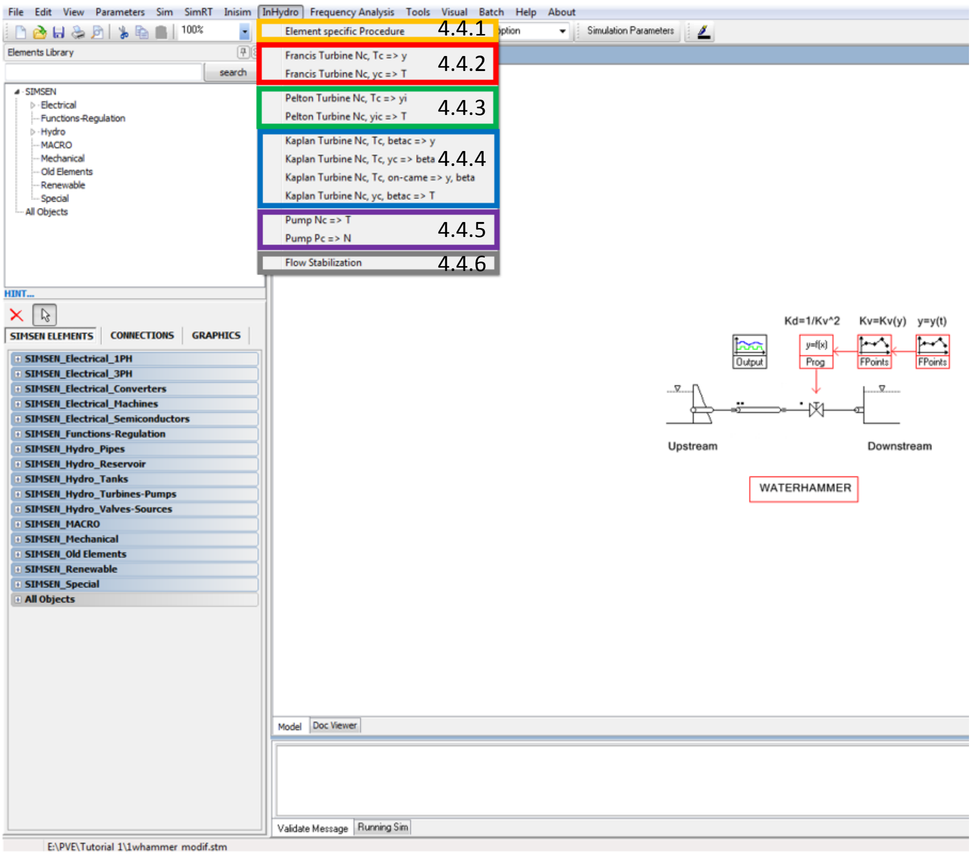


Figure 5 Illustration of the different possibilities to determine the initial conditions of a hydraulic system using InHydro

4.5.1 Element specific procedure

For systems featuring different types of turbines, it is possible to specify the initial condition procedure to be used for each hydraulic machine. In the parameter window, under the section “DATA”, one has to specify the procedure as it is illustrated in the examples below:

For Francis turbines:
<stabilization procedure>
Nc,yc -> T ; *first option*
; Nc,Tc -> y *; second option*
</stabilization procedure>

For Pelton turbines:
<stabilization procedure>
Nc,Tc,Ninj -> yi *; first option*
; Nc,yic -> T ; *second option*
</stabilization procedure>

For Kaplan turbines:
<stabilization procedure>
Nc,Tc,betac -> y ; *first option*
; Nc,Tc,yc -> beta ; *second option*
; Nc,Tc,on-cam -> y,beta ; *third option*
; Nc,yc,betac -> T *; fourth option*
</stabilization procedure>

For Pumps:
<stabilization procedure>
Nc -> T *; first option*
; Pc -> N *; second option*
</stabilization procedure>

Please note that “;” indicates that the line is a comment line and will not be considered.

4.5.2 Francis turbine

The determination of the initial conditions of a system with Francis turbine or pump-turbine is performed using the parameters given in “specified operating point” as follow:

```
- SPECIFIED OPERATING POINT:

Tc          [Nm] =  0.00000000000E+0000
Nc         [rpm] =  0.00000000000E+0000
yc           [1] =  0.00000000000E+0000
```

There are 2 possibilities to determine the initial conditions of a simulation with Francis turbine:

- the **specified rotational speed Nc and the torque Tc are known**, and the corresponding guide vane opening is determined using **“Turbine y determination**”; **Nc, Tc => y**
- the **specified rotational speed Nc and the guide vane opening yc are known**, and the corresponding torque is determined using **“Turbine Stabilization yc”; Nc, yc => T**

4.5.3 Pelton turbine

The determination of the initial conditions of a system with Pelton turbine is performed using the parameters given in “specified operating point” as follow:

```
- SPECIFIED OPERATING POINT:

Ninjc        [1] =  1
Tc          [Nm] =  0.00000000000E+0000
Nc         [rpm] =  0.00000000000E+0000
yc1          [1] =  0.00000000000E+0000
yc2          [1] =  0.00000000000E+0000
yc3          [1] =  0.00000000000E+0000
yc4          [1] =  0.00000000000E+0000
yc5          [1] =  0.00000000000E+0000
yc6          [1] =  0.00000000000E+0000
yc7          [1] =  0.00000000000E+0000
```

There are 2 possibilities to determine the initial conditions of a simulation with Pelton turbine:

- the **specified rotational speed Nc, the specified torque Tc and the nozzle combination Ninj are known**, and the corresponding nozzle positions are determined using **“Turbine y determination**”; **Nc, Tc, Ninj => yi**
- the **specified rotational speed Nc and the nozzle positions yic are known**, and the corresponding torque is determined using **“Turbine Stabilization yc”; Nc, yic => T**

4.5.4 Kaplan turbine

The determination of the initial conditions of a system with Kaplan turbine is performed using the parameters given in “specified operating point” as follow:

```
- SPECIFIED OPERATING POINT:

Tc          [Nm] =  0.00000000000E+0000
Nc         [rpm] =  0.00000000000E+0000
yc           [1] =  0.00000000000E+0000
betac        [1] =  0.00000000000E+0000
```

There are 4 possibilities to determine the initial conditions of a simulation with Kaplan turbine:

- the **specified rotational speed Nc, the specified torque Tc and the specified blade pitch angle are known**, and the corresponding guide vane opening is determined using **“Turbine y determination**”; **Nc, Tc, betac => y**
- the **specified rotational speed Nc, the specified torque Tc and the specified guide vane opening are known**, and the corresponding blade pitch angle is determined using **“Turbine beta determination**”; **Nc, Tc, yc => beta**
- the **specified rotational speed Nc and the specified torque Tc and are known and the on-cam surface is provided**, and the corresponding guide vane opening and blade pitch angle are determined using **“Turbine y determination on-cam**”; **Nc, Tc, on-cam => y, beta**
- the **specified rotational speed Nc, the specified guide vane opening yc and specified blade pitch angle betac are known**, and the corresponding torque is determined using **“Turbine Stabilization yc + betac”; Nc, yc, betac => T**

4.5.5 Pump stabilization

The determination of the initial conditions of a system with a pump is performed using the parameters given in "specified operating point" as follow:

```
- SPECIFIED OPERATING POINT:

Pc          [W] =   0.00000000000E+0000
Nc        [rpm] =   0.00000000000E+0000
```

There are 2 possibilities to determine the initial conditions of a simulation with pumps:

- the **specified rotational speed Nc, is known**, and the corresponding torque is determined using **"Pump Stabilization**"; **Nc => T**
- the **specified rotational torque Tc is known**, and the corresponding rotational speed is determined using **"Pump Stabilization Pc"; Pc=> N**

4.5.6 Flow stabilization

The determination of the initial conditions of a system without turbines or pump is performed using the procedure "Flow Stabilization".

4.5.7 Tuning of integration step for InHydro procedure

It may happen that the default integration step will not work properly for some stabilisations. For these cases, the user may specify in '*Main Parameters*' window under the section "CONSTANT" a tuning coefficient 'Kdt_InHydro'; the integration step will become: new_dt = dt * Kdt_InHydro. This option is only available during an InHydro procedure.

Example:

```
Kdt_InHydro = 0.1; rem: this will reduce the time step 10 times
```

4.6 Stabilization with hydraulic and electric components

For simulation example involving both hydraulic and electric components, it is possible to use independently *Inisim* or *InHydro* procedures on the same .stm. The interconnection between the two load flow procedures covers two standard simulation cases:

- Turbine mode: the rotational speed and active/reactive power of the generator are known, but the corresponding turbine guide vane opening is unknown; therefore, *Inisim* is used first to find initial conditions of the electrical installation, and then *InHydro* is used the find the guide vane opening producing the specified torque under the given hydraulic boundary conditions.

- Pumping mode: the pump guide vane opening and rotational speed are known, and the active power is unknown; therefore, *InHydro* is used first to find the required active power, then *Inisim* is used to find the corresponding initial conditions of the electrical installation.

For both cases, the condition to be satisfied being having the same torque and rotational speed at both end of the coupling shaft.

For hydroelectric applications, the model should comprise two mechanical masses to work properly: one for the moto/generator and one for the turbine. If only one mechanical mass is used, the update of specified torque of the turbine is not done.

At the end of the *InHydro* stabilization procedure, regarding the mechanical masses, the following task are done:

- update of the torsion angle between mechanical masses according to torque distribution (kpext);
- update of the external torque on the mechanical mass related to the synchronous machine (kpext = 0), but the external torque is set to zero if a synchronous machine is connected to this mass.

At the end of the *Inisim* procedure, regarding the mechanical masses, the following tasks are done:

- update of the torsion angle between mechanical masses according to torque distribution (kpext);
- update of the external torque on the mechanical mass related to the synchronous machine (kpext = 0):
- the external torque of the mass is updated if no turbine is connected;
- the external torque is set to zero if a hydraulic machine is connected to the mass, and the specified operating torque of the turbine is automatically updated.

4.7 Recommendation for hydraulic model

4.7.1 CFL Condition

The Courant-Friedrichs-Lewy (CFL) condition applies to ensure stability of numerical resolution of propagation phenomena such as water hammer problems. If convective terms are neglected, this condition can be expressed as follows:

$$a \cdot dt \le dx$$

Where *dt* is the integration time step, *dx=L/Nb* is the length of the elements modeling the pipe, and *a* is the wave speed. The CFL condition defines the minimum integration time step to ensure that numerical integration is achieved with integration time step smaller than the time for hydraulic quantities (pressure or discharge) to propagate through an element of length *dx*. The minimum integration time step dt_{min} is calculated for each pipe prior the simulation and if the CFL condition is not fulfilled, a warning message is provided. **For piping system without hydraulic machine, the integration time *dt* could be set between 0.01 and 0.005s. For system with hydraulic machine, the integration time could be set between 0.005 and 0.002s. In case of numerical instabilities, first reduce the integration time step.**

4.7.2 Wave speed adaptation

To ensure integration stability, it has been identified, that for systems which are physically unstable (e. g. S-shape of pump-turbine characteristics), it is also important to exchange the hydraulic quantities between two pipes strictly at the end of the integration time step *dt*. To do so, it is necessary to use appropriate and uniform piping system discretization and adapted wave speed. The Figure 6 illustrates this problematic when two pipes are modeled only with one element, *Nb*=1.

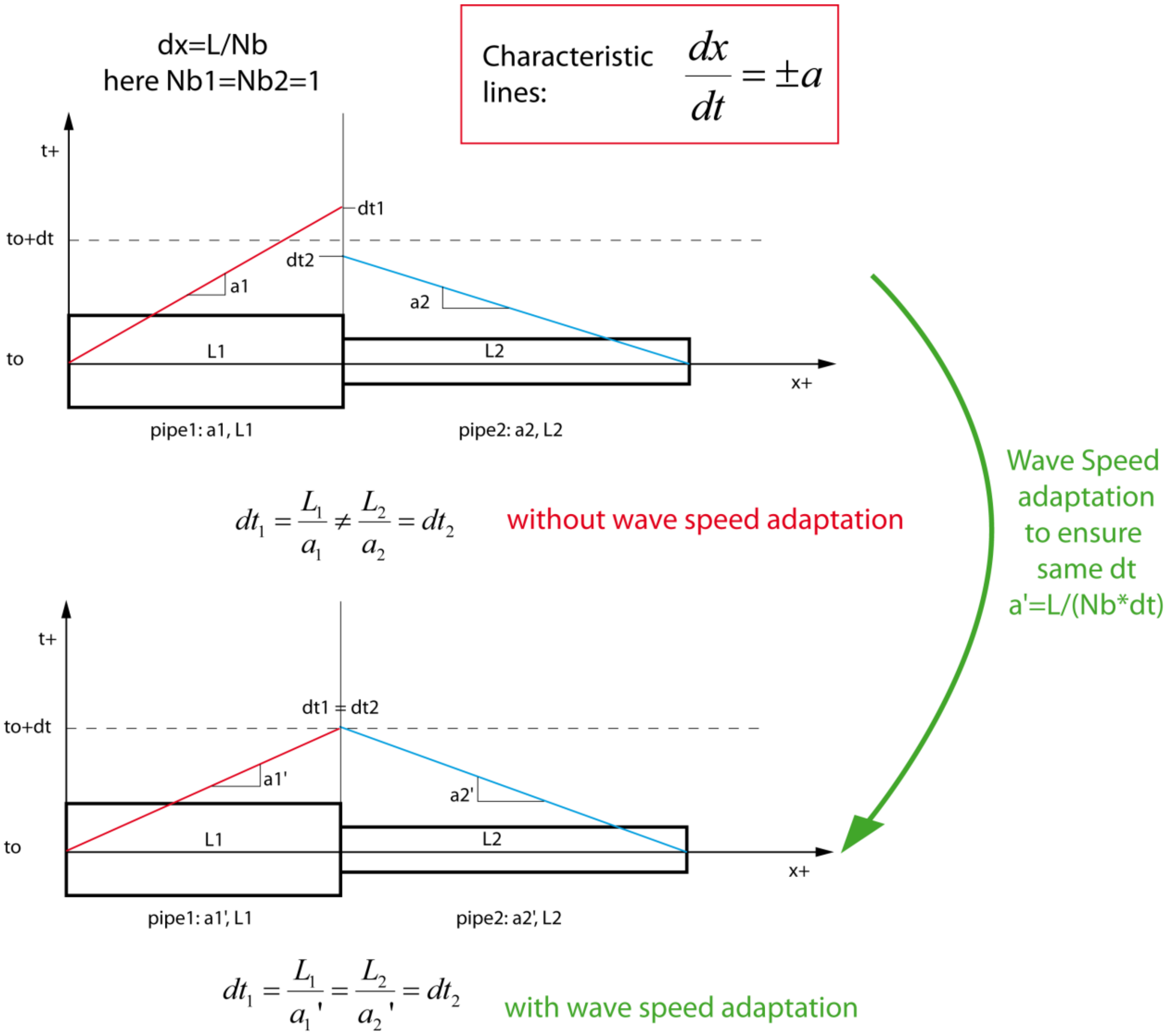


Figure 6 Illustration of the wave speed adaptation to ensure integration stability

To ensure stability and accuracy of the numerical integration process, it is required that the hydraulic quantities are transferred between pipes at the same time *dt1=dt2=dt*. As the ratio between pipe length and wave speed never gives the same propagation time *dt1* or *dt2*, the wave speed in the pipes must be adapted from *a* to *a'*. The wave speed is adapted with respect to a time basis *dT* so that the number of elements *Nb* modeling a pipe becomes a natural number:

$$Nb = \frac{L}{a' \cdot dT} \quad ; Nb \text{ is an integer}$$

Wave speed is preferred for adaptation as length of pipes are well defined while wave speed features uncertainties of about +/- 10% due to influence of piping surrounding, pipe fixing, air content, fluid temperature, etc. **For water hammer problem, *dT = 0.01s* is a standard value**.

4.7.3 Selection of number of elements Nb

To select appropriate and uniform discretization of the pipes of a system, one may use the following method:

- Compute the pipe wave speeds a_i ,
- Select a time basis, e.g.: $dT = 0.01$ s ,
- Calculate spatial discretization of the pipes: $dx_i = dT \cdot a_i$,
- Compute number of elements of each pipe: $Nb_i = L_i / dx_i$,
- Adapt the wave speeds a_i to a_i' to obtain an integer value of Nb_i : $Nb_i = L_i / (a_i' \cdot dT)$.

For headrace or tailrace tunnels located behind a surge tank, number of elements could be reduced to save computational time. *Nb = 30* could be recommended.

4.7.4 Hydraulic pipe modeling

It is strongly recommended to use the element *PIPEZ* instead of *PIPEN* to model a hydraulic pipe. In the *PIPEZ* model, it is possible to define the elevation of the pipe inlet and outlet and to analyze pressure lines along the piping system with the block named OUTPL, see the section 4.10. These pressure lines are the maxima and minima values reached during the transient as function of the position in the system.

4.7.5 Hydraulic turbine modeling

For hydraulic turbine, it is strongly recommended to consider turbine water inertia effect (spiral case, runner, draft tube) by setting appropriate value for the T*urbine equivalent length L_{equ}* and the *Turbine mean cross section A_{mean}*. The recommended values are the following:

- $L_{equ} = (5 \text{ to } 15) \cdot D_{ref}$
- $A_{mean} = \dfrac{\pi D_{ref}^2}{4}$

4.8 Recommendation for electrical model

The purpose of the electrical load flow *Inisim* and how to launch it is described in 3.2.6. Here are a few recommendations in order to use *Inisim* successfully. The first thing to do is to introduce the desired operating points in the different node elements composing you model. The node elements are of active type (synchronous machine, voltage source) or passive type (resistive-inductive-Capacitive loads). The operating points are generally to be introduced in the elements’ parameter, in the SPECIFIED OPERATING POINT section.

Active nodes:

The user can specify an active power (Pc), and a reactive power (Qc), or the voltage (Urms,c) and the phase (θc) of the of the node. In general, if Pc and Qc are specified, it is a PQ node and *Inisim* will calculate the voltage (Urms) and phase (θ) of the node. If Pc or Qc are not specified, i.e. leaving tem to 0, the specified node voltage (Urms,c) and phase (θc) will be imposed. In General, leaving the value of Pc or Qc to 0 means that user do not specify a PQ node and the resulting (calculated) active power and reactive will depend on the load flow results. If user wishes to specify a null value for Pc or Qc, a low value that can be considered as null (e.g. 1E-4 W) must be entered.

When Pc and Qc are specified, it is also important that the voltage (Urms,c) and phase (θc) of the node is set to a value that is close to the value that the load flow will find. Hence, for voltage (Urms,c), enter a value close to the rated voltage of the node. For the phase, you have to consider the possible phase shifting due to transformers (e.g. vector group Yd5) that are in between a node and the balance node (which has a phase reference). For example, let's say there is a balance node with phase set to 0, and there is a transformer of vector group Yd5 between it and a PQ node, and the balance node being on the primary side. In this case, the no-load phase shifting introduced by the transformer, which is -150°, is to be taken into account to introduce a "guess" value in the specified phase shift (θc) of the PQ node. That is, set θc to -150° (or 210°) in the SPECIFIED OPERATING POINT section of the PQ node. The load flow will then compute the real phase shift θ and node voltage Urms, due to power flows in the whole power network considered. See the electrical tutorials *Elec 3* (section 6.2.3) for an application of the transformer's phase shifting with *Inisim*.

The table below gives the phase shift introduced by the transformer for the vector groups available in SIMSEN. The phase shift is from primary to secondary, at no load:

Vector Group	Yy0	Yy6	Dd0	Dd6	Yd5	Yd11	Dy5	Dy11	Yd1	Yd7
Phase shift (°)	0	180	0	180	150	330	150	330	30	210

In order for the load flow algorithm to converge to a final solution, it is mandatory to introduce correct values in the RATED VALUES of each node elements. For active nodes, these are the normal rated values that come from data sheet of the node (e.g. data sheet of the synchronous machine).

Passive nodes:
For passive nodes, only Pc and Qc can be specified and *Inisim* will calculate the required value of R, L and C. In order for the load flow algorithm to converge to a final solution, it is mandatory to introduce correct value in the RATED VALUES of the passive elements. The rated apparent power (Sn) value must be close to the specified operating point ($(S_n)^2=(P_c)^2+(Q_c)^2$). The rated line voltage Un must be close to the nominal voltage of the bus to which the passive node is connected to. The rated frequency must be the node frequency, i.e. the nominal frequency of the power system considered. Rated values are important because they are used to compute the initial impedance to start the load flow. In case the initial impedance too far from the final value, the load flow will not converge.

4.9 Simulation of the model

- in the main menu, select *Sim*, or alternatively, press the button with a green arrow in the tool bar
- press Yes in the Message Box popping up. This will launch the simulator which performs the time simulation of the current model
- at the end of the simulation, press any Key to exit the simulator without updating initial conditions, or press "s" to save the initial conditions

4.10 Visualization of the simulation results

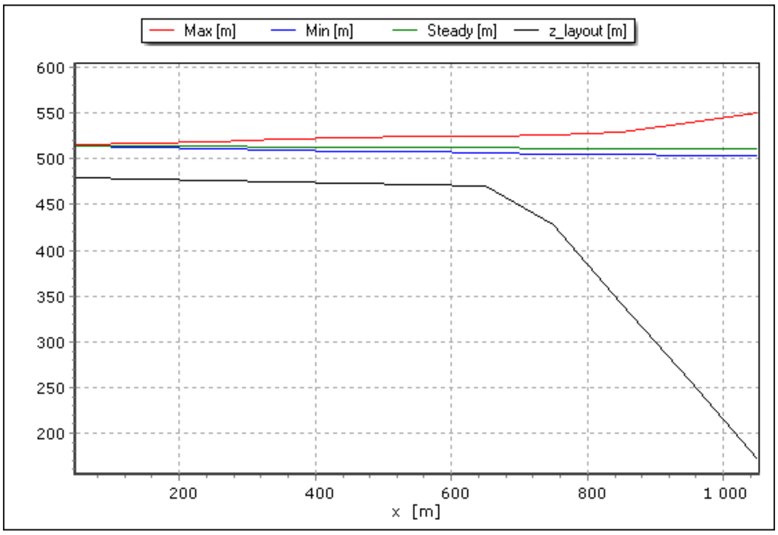
4.10.1 Generalities

This option allows plotting the results of the simulation. Each module generates a specific file of results, with the extension ***.VIS**. The **VISUAL** program is a post-processing program that allows displaying curves on the screen, to apply Fourier analysis and other features. Please read the given documentation folder for more information about the Visual program.

4.10.2 OUTPL element for spatial profiles

For transient analysis of hydroelectrical power plant, it is usual to represent pressure lines along the piping system. These pressure lines are the maxima and minima values reached during the transient as function of the position in the system. This block named OUTPL allows plotting spatial profiles of physical quantities along the piping system. With the OUTPL element, two types of representation can be performed with the visualization tool of SIMSEN: Visual.exe:

- A **static representation** as shown in the following figure;



  Four curves can be plotted:
  - The black curve is the profile of the system layout with the gallery and the penstock. This curve plots the coordinates of the pipes{x,z_layout} based on data in the pipe elements;
  - The blue curve is the minima values of the piezometric head Hcz reached during the transient as function of the position {x} in le layout;
  - The red curve is the maxima values of the piezometric head Hcz reached during the transient as function of the position {x} in le layout;
  - The green curve is the state of the system at the first time step of the simulation, representing the steady state of the piezometric head Hcz as function of the position {x} in le layout.

- A **dynamic representation** showing two curves:
  - One corresponding to the profile of the system layout by plotting the coordinates of the pipes {x,z_layout};
  - One corresponding to the instantaneous values of the piezometric head Hcz at a given time step as function of the position {x} in le layout.

These two representations can be extended to other quantities such as energy, flowrates, speed and so on. You can find more information in the OUTPL Help file and examples are illustrated in the OutPL folder.

4.10.3 Characteristic curves representation

The characteristic curves of a Francis, Pelton or Kaplan turbine can be directly represented with the Visual program. During a transient simulation, the evolution of the speed factor N_{11}, discharge factor Q_{11} and the torque factor T_{11}, defined in Chapter 7, can be illustrated on the characteristic curves of the machine, see the red curve on the Figure 7 and Figure 8.

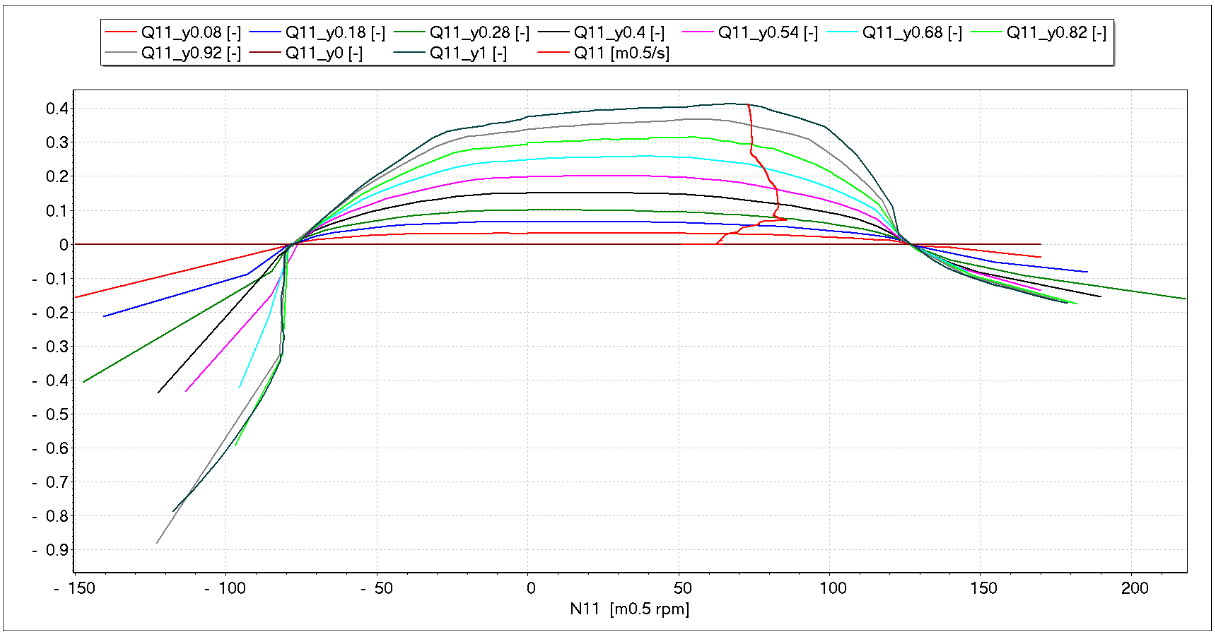


Figure 7 Illustration of the discharge factor as function of the speed factor for a pump-turbine.

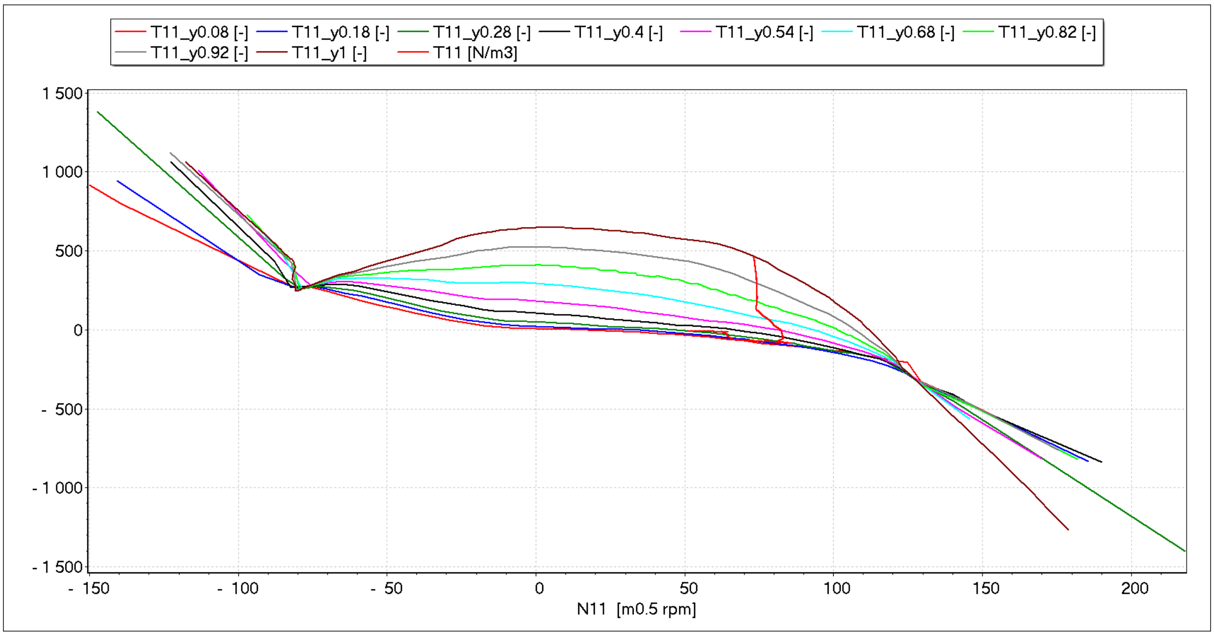


Figure 8 Illustration of the torque factor as function of the speed factor for a pump-turbine.

4.10.4 RMS – MEAN – Max – Min – Max dy/dx

When you click on the *RMS/Mean/… analysis* button 

in the **VISUAL** program, you can compute the following expression for each simulation results displayed in the **VISUAL** window:

- the mean value,
- the Root Mean Square (RMS) value,
- the minimal value with its corresponding time value,
- the maximal value with its corresponding time value,
- the maximum dy/dx value and between which x values,
- the y values at calculation start and stop times.

The definitions of the mean value and the RMS value are described in the Help of the VISUAL program.

For instance, this tool is applied for the hydraulic tutorial 5, simulating the emergency shut down (ESD) of a Francis turbine. The dynamic behavior of the Francis turbine is illustrated in Figure 9. The ESD is initiated from the full guide vane opening and at t=10s the electromagnetic torque is set to 0 and bilinear closing law is undertaken.

With the *RMS/Mean/… analysis* button 

, the window illustrated in Figure 10 appears and the expression listed above are computed. These results can be copied and pasted in an Excel file with the *Copy all to clipboard* button and can also be exported to cvs file with *Export to cvs file* button.

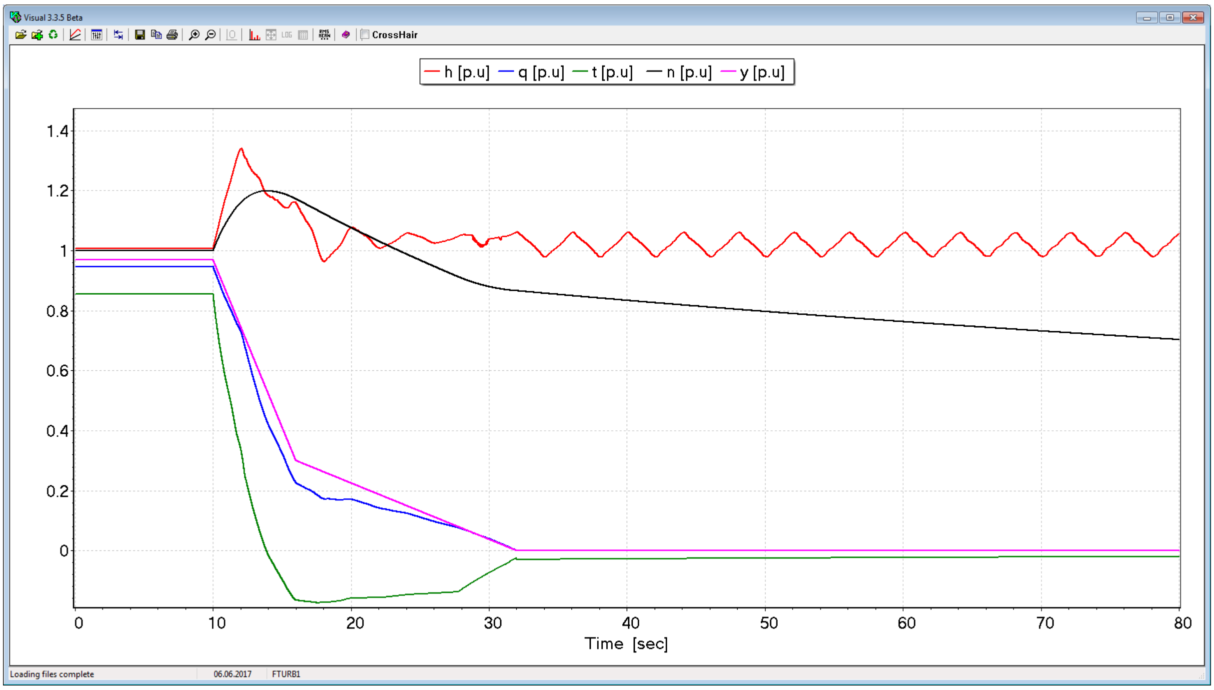
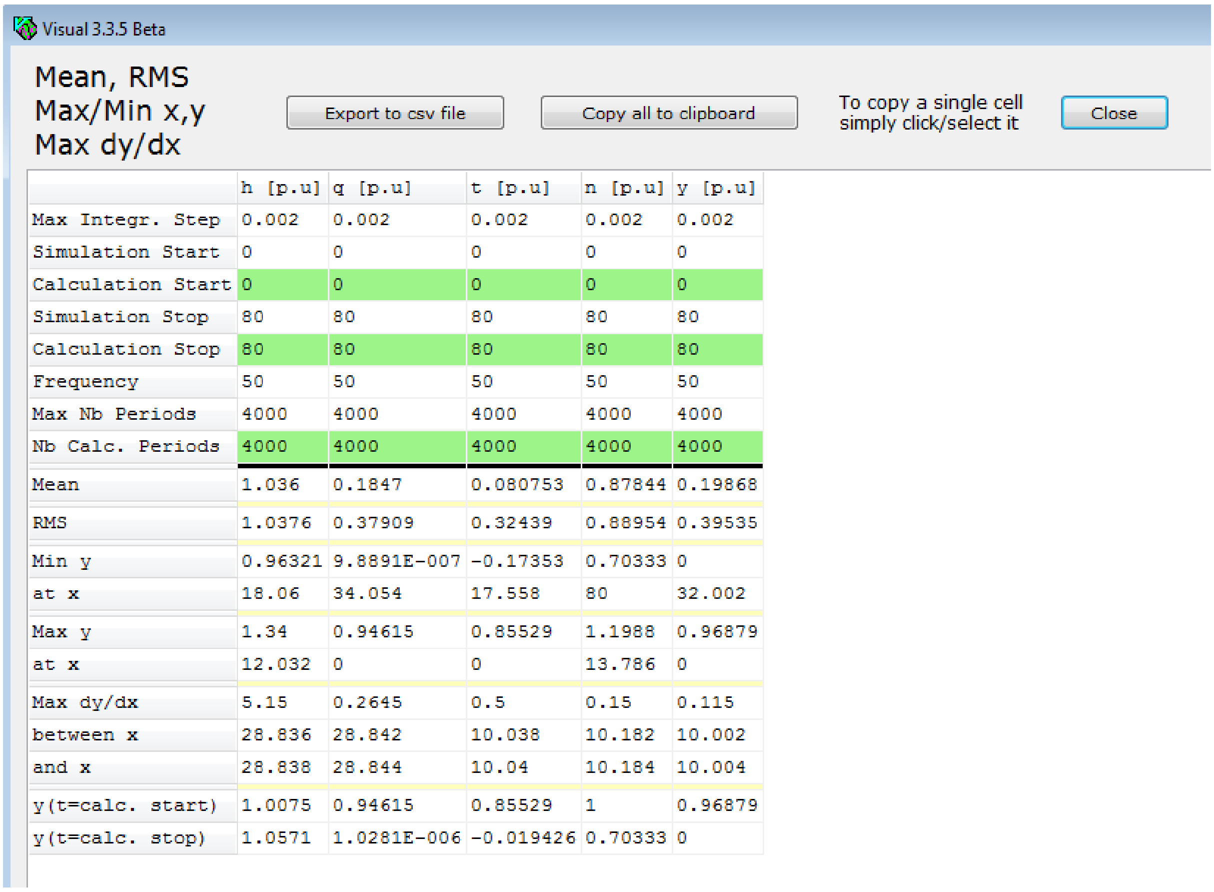


Figure 9 Dynamic behavior of a Francis turbine in Hydraulic tutorial 5.



	h [p.u]	q [p.u]	t [p.u]	n [p.u]	y [p.u]
Max Integr. Step	0.002	0.002	0.002	0.002	0.002
Simulation Start	0	0	0	0	0
Calculation Start	0	0	0	0	0
Simulation Stop	80	80	80	80	80
Calculation Stop	80	80	80	80	80
Frequency	50	50	50	50	50
Max Nb Periods	4000	4000	4000	4000	4000
Nb Calc. Periods	4000	4000	4000	4000	4000
Mean	1.036	0.1847	0.080753	0.87844	0.19868
RMS	1.0376	0.37909	0.32439	0.88954	0.39535
Min y	0.96321	9.8891E-007	-0.17353	0.70333	0
at x	18.06	34.054	17.558	80	32.002
Max y	1.34	0.94615	0.85529	1.1988	0.96879
at x	12.032	0	0	13.786	0
Max dy/dx	5.15	0.2645	0.5	0.15	0.115
between x	28.836	28.842	10.038	10.182	10.002
and x	28.838	28.844	10.04	10.184	10.004
y(t=calc. start)	1.0075	0.94615	0.85529	1	0.96879
y(t=calc. stop)	1.0571	1.0281E-006	-0.019426	0.70333	0

Figure 10 Analysis of mean, maximal and minimal values for each dynamic parameter of the Francis turbine.

4.10.5 Fourier analysis

When you click on the *Fourier analysis* button  in the **VISUAL** program, the window illustrated in Figure 11 appears and the user can define:

- The starting time,
- The based frequency,
- The number of periods used for the analysis,
- Up to which harmonic the analysis should be performed.

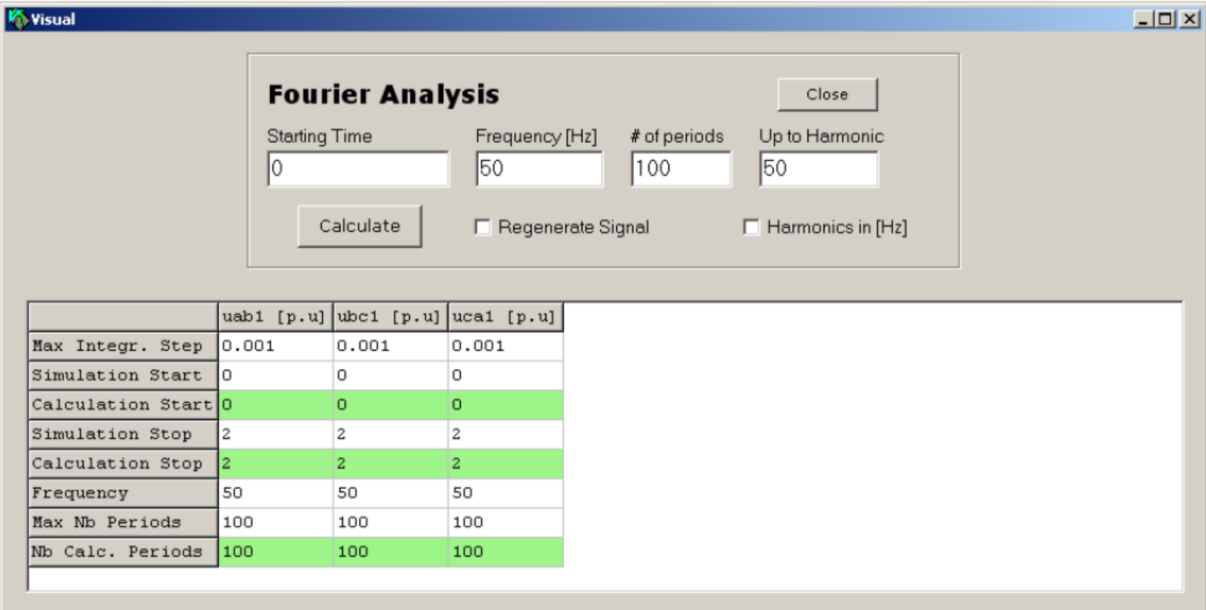


Figure 11 Fourier analysis window in the **VISUAL** program.

The user can also choose to display the harmonics in harmonic count or in Hertz, see Figure 12.

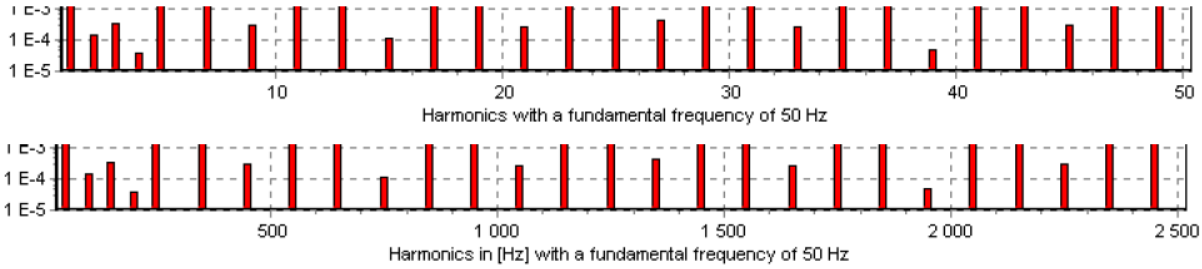


Figure 12 Illustration of the harmonics in harmonic count (top) and in Hertz (bottom).

To visually validate the Fourier analysis, it is possible to rebuild the analyzed signal based on the harmonic analysis with the *regenerate check box*, see Figure 13

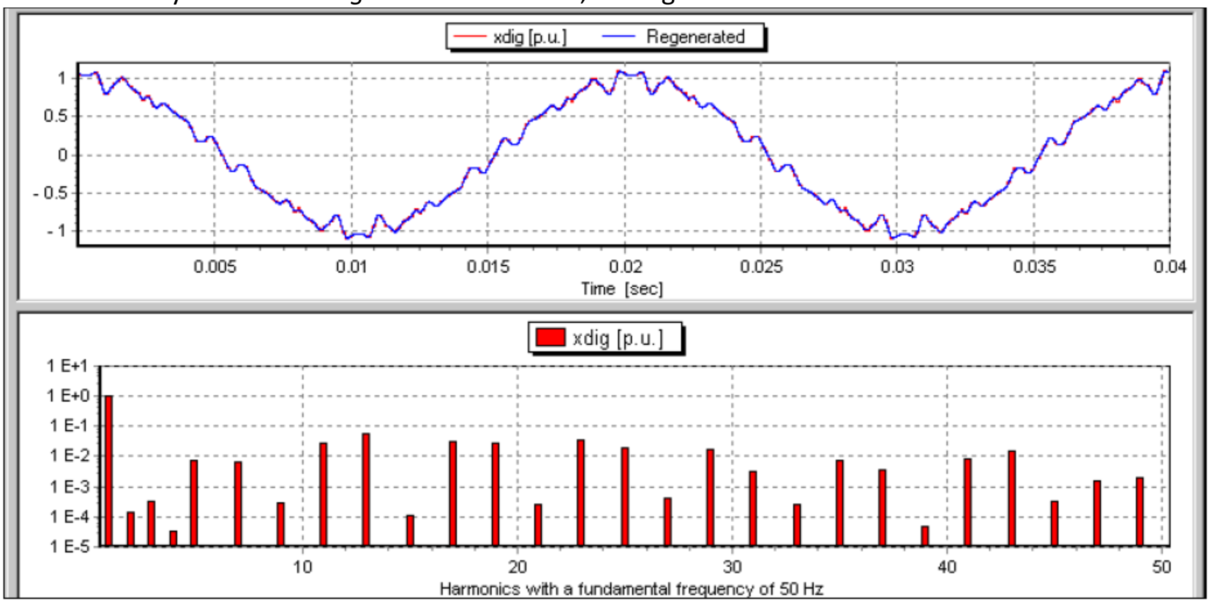
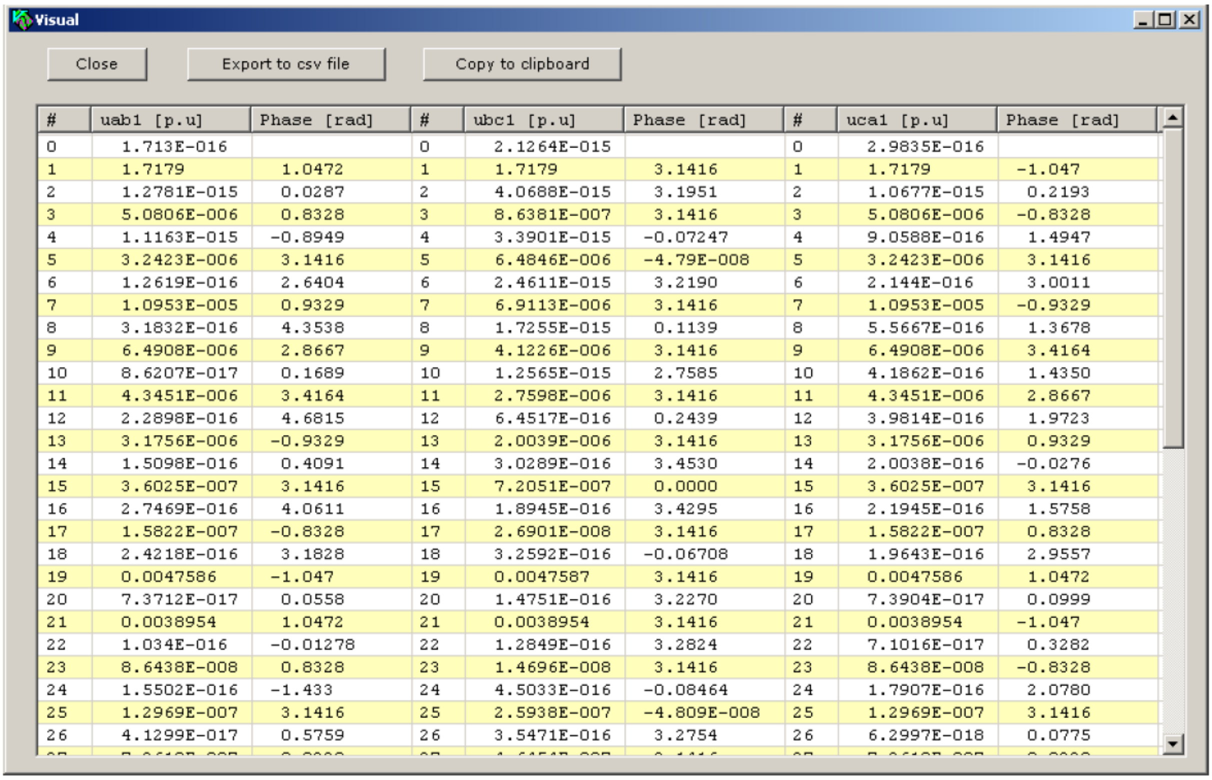


Figure 13 Validation of the Fourier analysis with the regenerate function.

The details of each harmonic value (amplitude and phase) for each analyzed curve can be displayed in a table with the *Details of Fourier Analysis* button . These values can be exported to standard csv file or copied and pasted in Excel file with the *Copy to clipboard* button, see Figure 14



#	uab1 [p.u]	Phase [rad]	#	ubc1 [p.u]	Phase [rad]	#	uca1 [p.u]	Phase [rad]
0	1.713E-016		0	2.1264E-015		0	2.9835E-016	
1	1.7179	1.0472	1	1.7179	3.1416	1	1.7179	-1.047
2	1.2781E-015	0.0287	2	4.0688E-015	3.1951	2	1.0677E-015	0.2193
3	5.0806E-006	0.8328	3	8.6381E-007	3.1416	3	5.0806E-006	-0.8328
4	1.1163E-015	-0.8949	4	3.3901E-015	-0.07247	4	9.0588E-016	1.4947
5	3.2423E-006	3.1416	5	6.4846E-006	-4.79E-008	5	3.2423E-006	3.1416
6	1.2619E-016	2.6404	6	2.4611E-015	3.2190	6	2.144E-016	3.0011
7	1.0953E-005	0.9329	7	6.9113E-006	3.1416	7	1.0953E-005	-0.9329
8	3.1832E-016	4.3538	8	1.7255E-015	0.1139	8	5.5667E-016	1.3678
9	6.4908E-006	2.8667	9	4.1226E-006	3.1416	9	6.4908E-006	3.4164
10	8.6207E-017	0.1689	10	1.2565E-015	2.7585	10	4.1862E-016	1.4350
11	4.3451E-006	3.4164	11	2.7598E-006	3.1416	11	4.3451E-006	2.8667
12	2.2898E-016	4.6815	12	6.4517E-016	0.2439	12	3.9814E-016	1.9723
13	3.1756E-006	-0.9329	13	2.0039E-006	3.1416	13	3.1756E-006	0.9329
14	1.5098E-016	0.4091	14	3.0289E-016	3.4530	14	2.0038E-016	-0.0276
15	3.6025E-007	3.1416	15	7.2051E-007	0.0000	15	3.6025E-007	3.1416
16	2.7469E-016	4.0611	16	1.8945E-016	3.4295	16	2.1945E-016	1.5758
17	1.5822E-007	-0.8328	17	2.6901E-008	3.1416	17	1.5822E-007	0.8328
18	2.4218E-016	3.1828	18	3.2592E-016	-0.06708	18	1.9643E-016	2.9557
19	0.0047586	-1.047	19	0.0047587	3.1416	19	0.0047586	1.0472
20	7.3712E-017	0.0558	20	1.4751E-016	3.2270	20	7.3904E-017	0.0999
21	0.0038954	1.0472	21	0.0038954	3.1416	21	0.0038954	-1.047
22	1.034E-016	-0.01278	22	1.2849E-016	3.2824	22	7.1016E-017	0.3282
23	8.6438E-008	0.8328	23	1.4696E-008	3.1416	23	8.6438E-008	-0.8328
24	1.5502E-016	-1.433	24	4.5033E-016	-0.08464	24	1.7907E-016	2.0780
25	1.2969E-007	3.1416	25	2.5938E-007	-4.809E-008	25	1.2969E-007	3.1416
26	4.1299E-017	0.5759	26	3.5471E-016	3.2754	26	6.2997E-018	0.0775

Figure 14 Fourier analysis window in the **VISUAL** program.

4.11 Getting and using Help

4.11.1 Element help file

- select an element by clicking on it with left button
- right click to pop up the contextual menu
- in the contextual menu, select Help on "Element class" to open corresponding Help file of your selected element
- alternatively, select Help/Help on "Element class" in the main menu bar
- alternatively, press F1.

4.11.2 General Help files

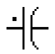
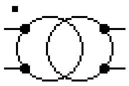
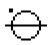
- select Help/Editor or Help/Simulator_Parameter in the main menu bar

4.11.3 Mouse functions

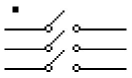
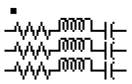
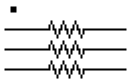
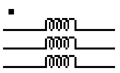
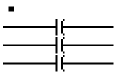
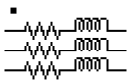
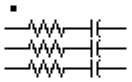
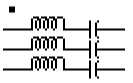
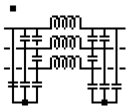
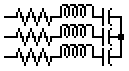
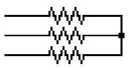
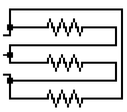
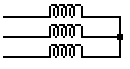
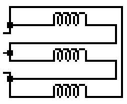
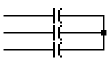
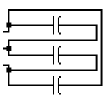
- left button click: selection click
- left double click: open element's parameter dialog box
- right button click: contextual pop up menu

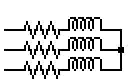
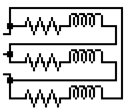
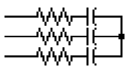
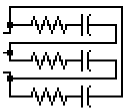
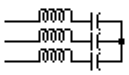
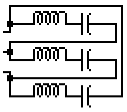
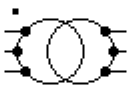
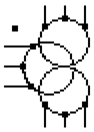
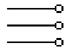
5 List of available elements

5.1 Electrical Elements 1ph

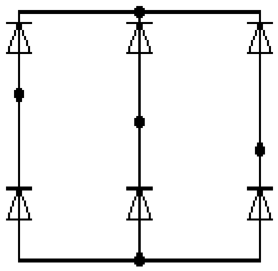
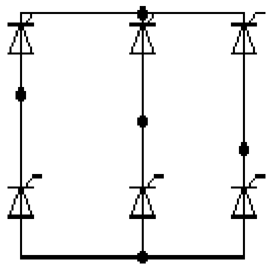
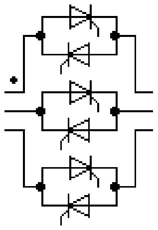
Symbols	Name	Description
	Circuit Breaker 1ph	ON/OFF switching with or without currents zero crossing detection. Lumped R-L elements.
	Linked Inductor 1ph	The single-phase linked inductor may be linked with n other inductors. it is possible to design every magnetic linked circuit. Thus, for example, the user can design special transformers or magnetic linked parts of an electrical circuit.
	RLC Impedance 1ph	Single phase (two poles) passive elements, with resistive (R), inductive (L) and capacitive (C) terms. This element is declined in four different pictures but the underlying model is the same. User can select the desired picture depending on the dominant term R, L or C that he wants to represents.
		
		
		
	Transformer 2x1ph	Phase-shifting taken into account. Automatic inductance calculation depending on rated values and short-circuit impedance.
	Voltage Supply 1ph	Voltage supply with infinite power. AC (sinus, triangle, rectangle) or DC.

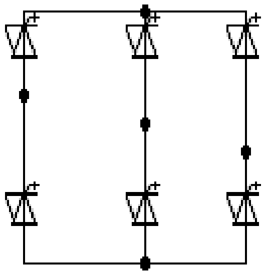
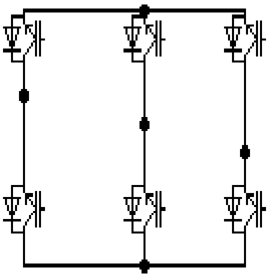
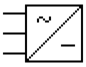
5.2 Electrical Elements 3ph

Symbols	Name	Description
	Circuit Breaker 3ph	ON/OFF switching with or without currents zero crossing detection. Lumped R-L elements.
	Transmission Line 3ph (lumped)	This three-phase transmission line (connection) is a lumped R-L-C model. It contains resistive (R), inductive (L) and capacitive (C) terms. This element is declined into several pictures but the underlying model is the same. The user can select the picture that best represents the dominant terms of its transmission line (pure R, L or C, mixed R-L, R-C, L-C, or all R-L-C)
		
		
		
		
		
		
	Transmission Line 3ph: (PI)	3ph connection. Lumped R-L-C elements.
	Electrical Load 3ph, star or delta connection	This is a general three-phase load element, with a star or delta connection. It contains resistive (R), inductive (L) and capacitive (C) terms. This element is declined into several pictures but the underlying model is the same. The user can select the picture that best represent the dominant terms of the load (pure R, L or C, mixed R-L, R-C or L-C or all terms (R-L-C). The values for the R, C and L terms are the values per phases. Values seen from terminals depend on the type of connection (star or delta).
		
		
		
		

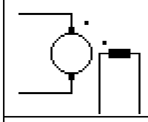
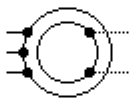
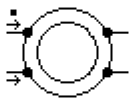
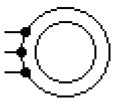
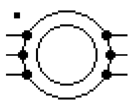
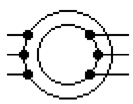
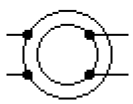
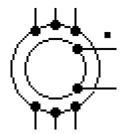
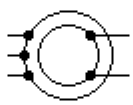
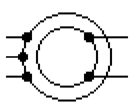
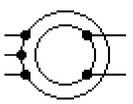
		
		
		
	Transformer 2x3ph	Phase-shifting taken into account. Automatic inductance calculation depending on rated values and short-circuit impedance.
	Transformer 3x3ph	Phase-shifting taken into account. Automatic inductance calculation depending on rated values and short-circuit impedance. Special transformer for 12 pulse supply.
	Voltage Supply 3ph	AC voltage system with infinite power.

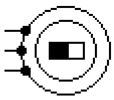
5.3 Electrical Converters

Symbols	Name	Description
	Diode Rectifier 3ph	Current rectifier. 6 diodes in one unit.
	Current Converter 3ph	Current converter with integrated command. 6 Thyristors in one unit.
	Current Variator 3ph	Current variator with integrated command. 6 Thyristors in one unit.

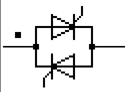
	Voltage Inverter 3ph with GTO's	Voltage Source Inverter with integrated command. 6 GTO Thyristors with antiparallel diode in one unit.
	Voltage Inverter 3ph with IGBT's	Voltage Source Inverter with integrated command. 6 IGBT Transistors with antiparallel diode in one unit.
	Average Model of Converter	This models the three-phase terminals of a three-phase inverter. The DC side is « ideal » or modelled within the control. This model can be used when details of commutations of converters are not required, but only the fundamental wave of the output. Can be used with Inisim. The control of the output (magnitude, phase and frequency) is to be provided by user, using any control blocks.

5.4 Electrical Machines

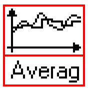
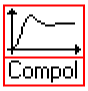
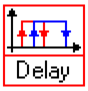
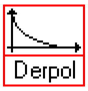
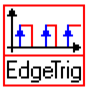
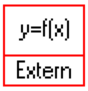
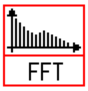
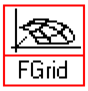
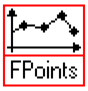
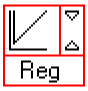
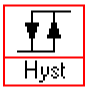
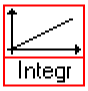
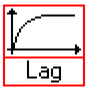
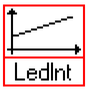
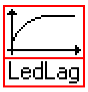
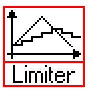
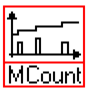
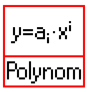
Symbols	Name	Description
	DC Machine	DC applications. Rotor and stator terminals are both accessible.
	Generalized Machine 3ph	3ph generalized machine with several rotor-circuits. Star or delta connections. D-Q equivalent circuit-diagram.
	Induction Machine CR 2ph	2ph induction machine with squirrel Cage Rotor (CR). Parameters of equivalent circuit-diagram.
	Induction Machine CR 3ph	3ph induction machine with squirrel Cage Rotor (CR). Star or delta connections. Parameters of equivalent circuit-diagram.
	Induction Machine CR with Open Terminals 3ph	3ph induction machine with squirrel Cage Rotor (CR). Parameters of equivalent circuit-diagram.
	Induction Machine WR 3ph	3ph induction machine with Wound Rotor (WR) and rotor terminals. Star or delta connections. Parameters of equivalent circuit-diagram. For doubly fed induction/generators application.
	Synchronous Machine 1ph	1ph synchronous machine. Special machine for 1ph network supply. D-Q equivalent circuit-diagram.
	Synchronous Machine 2x3ph	2x3ph synchronous machine with Solid Iron Rotor. Special machine for LCI drive. Parameters of the D-Q equivalent circuit-diagram.
	Synchronous Machine SIR 3ph	3ph synchronous machine with Solid Iron Rotor (SIR) (turbo-alternator). Star or delta connections. Parameters of the D-Q equivalent circuit-diagrams. Model level 3.3 according to IEEE Std 1110 (see 8.1)
	Synchronous Machine LR 3ph	3ph synchronous machine with Laminated Rotor (LR). Star or delta connections. Parameters of the D-Q equivalent circuit-diagrams. Model level 2.1 according to IEEE Std 1110 (see 8.1)
	Synchronous Machine SIR 3ph 2	3ph synchronous machine with Solid Iron Rotor (SIR) (turbo-alternator). Has one additional damper circuit in the d axis compared to Synchronous Machine SIR 3ph. Parameters of the D-Q equivalent circuit-diagrams. No corresponding model level according to IEEE Std 1110

	Synchronous Machine Permanent Magnet 3ph	3ph with permanent magnet rotor. Star or delta connections. Parameters of the equivalent circuit-diagram.

5.5 Electrical Semiconductors

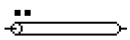
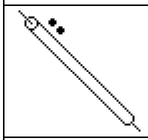
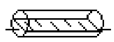
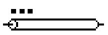
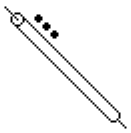
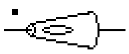
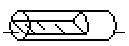
Symbols	Name	Description
	Diode	The anode and cathode of the diode can be wired to any other elements. OFF to ON state transition is controlled by voltage across the diode. ON state PN junction polarization voltage given as parameters. ON to OFF state transition is controlled by current through the diode. Reverse recovery current given as parameter. ON state conduction losses driven by the ON state resistance, given in parameters. OFF state is a high resistance, given in parameters
	Thyristor	Similar to the Diode but with a controlled (delayed) OFF to ON transition by the firing gate. The firing gate signal is a logical signal (0 = gate not fired, 1 = gate is fired). ON to OFF transition is same as Diode, as well as ON state conduction losses and OFF state high impedance.
	Triac	2 Thyristors in anti-parallel in one unit.
	GTO Thyristor	Similar to the Thyristor but with a controlled (delayed) OFF to ON transition and controlled (forced) ON to OFF transition, by the firing gate. The firing gate signal is a logical signal. ON to OFF transition is same as Diode (when no gate control is applied before), as well as ON state conduction losses and OFF state high impedance.
	GTO Thyristor with Diode	Similar to GTO Thyristor but with a diode in anti-parallel, used to build bidirectional switches.
	IGBT Transistor	Fully controlled switch. OFF to ON and ON to OFF transition controlled by the gate signal (logical signal). Voltage, current and gate control. Lumped R-L elements with voltage supply.
	IGBT Transistor with Diode	Same as IGBT Transistor but with an anti-parallel diode included (to protect IGBT from negative voltage and provide good negative current conduction path).
	Varistor	Voltage protection. Lumped R-L elements with voltage supply.

5.6 Functions-Regulation

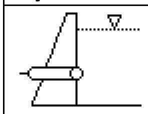
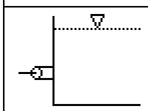
Symbols	Name	Description
	Averager	Average value calculation (digital filter).
	Low-Pass Filter 2nd Order	Low-pass filter 2nd order.
	Delay	Delay function with mono-stable output.
	High-Pass Filter	High-pass filter.
	Edge Trigger	Variations detection
	Link to DLL	Link to a DLL file.
	Fast Fourier Transform	Online Fast Fourier Transform.
	Grid Function	Using this function, it is possible to introduce a data surface. The Grid Function provides one output signal y. y=f(x1,x2)
	Points Function	Using this function, it's possible to introduce a special curve, which could be difficult to introduce with the Prog unit.
	Regulator	P, I, PI, PD or PID control with integrated limitations and anti-reset windup.
	Hysteresis	Hysteresis comparator with threshold function.
	Integrator	Integrator.
	Low-Pass Filter 1st Order	Low-pass filter 1st order.
	Derivate/Integrator	High-pass filter and integrator.
	Derivate/Low-Pass Filter	Derivate and low-pass filter.
	Limiter	Digital limitation with ramp.
	Modifications Counter	Variations counter.
	Polynom	Polynom function

y=f(x) Prog	Program	The user may calculate with only one block diverse logical and mathematical functions.
PulsGen	Pulse Generator	Pulses generation with command.
PSS2B	Power System Stabilizer IEEE PSS2B	It corresponds to the power system stabilizer type PSS2B proposed in IEEE Std 421.5™-2005: IEEE Recommended Practice for Excitation System Models for Power System Stability Studies
ST1A	IEEE Excitation System Model ST1A	It corresponds to the system model proposed in IEEE Std 421.5™-2005: IEEE Recommended Practice for Excitation System Models for Power System Stability Studies.
R S y RSflipflop	Reset/Set Flip-Flop	Set/Reset functions and memory.
Sample	Sample	Sample function with sample & hold command.
G(s) STrans	S-Transfer Function	Generalized G(s) transfer function in the S-domain.
x y Table	Logic Table	Multiplexor. Logical conditions. Truth table.
TCount	Time Counter	Time calculation between modifications of command.
UDLimit	Up Down Limiter	Ramp Limiter unit, with independent configurable limit for both up and down slopes.
V Reg	Voltage Regulator	PID control. ABB Unitrol® model.
G(z) ZTrans	Z-Transfer Function	Generalized G(z) transfer function in the Z-domain.
PSS4B	Power System Stabilizer IEEE PSS4B	It corresponds to the power system stabilizer type PSS4B proposed in IEEE Std 421.5™-2005: IEEE Recommended Practice for Excitation System Models for Power System Stability Studies
ST4B	IEEE Excitation System Model ST4B	It corresponds to the system model proposed in IEEE Std 421.5™-2005: IEEE Recommended Practice for Excitation System Models for Power System Stability Studies.
ST8C	IEEE Excitation System Model ST8C	It corresponds to the system model proposed in IEEE Std 421.5-2005/Cor AC9C and ST8C: IEEE Recommended Practice for Excitation System Models for Power System Stability Studies.

5.7 Hydraulic Pipes

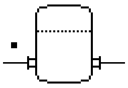
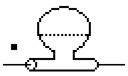
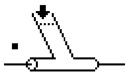
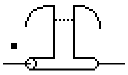
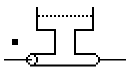
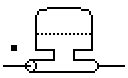
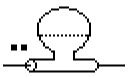
Symbols	Name	Description
	Pipe Z	A circular cross-section pipe taking into account distributed head losses, inertia and compressibility of the of water and elastic pipe
	Pipe Z	A circular cross-section pipe. This element models the same physics than the previous one. Only the bitmap is different.
	Open Channel (*)	An open channel with trapezoidal cross-section.
	Open Channel (*)	An open channel with circular cross-section which can be non-prismatic (fluvial flow only (subcritical)).
	Pipe A (*)	A circular cross-section pipe. The wave speed is computed with Henry law or a gas free model
	Pipe A (*)	A circular cross-section pipe. The wave speed is computed with Henry law or a gas free model
	Draft Tube Model (*)	The DTube module is an advanced pipe model with: - non-prismatic sections, i.e. expanding or contracting cross sections; - convective terms which are not neglected like in a standard pipe model; - cavitation volume dynamics induced by inlet swirling flow. This model can be used to model cavitation surge phenomena in a draft tube of hydraulic machine such as Francis or Kaplan turbines.
	Open Channel with Pressurized Transition (*)	The OpenChT module corresponds to a prismatic open channel with circular cross-section which can simulate transition between free-surface and pressurized flow.

5.8 Hydraulic Reservoir

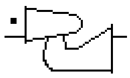
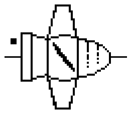
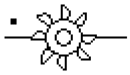
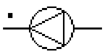
Symbols	Name	Description
	Dam	Reservoir with infinite volume
	Reservoir	Reservoir with infinite volume

(*) Only available in a specific library

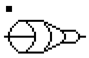
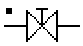
5.9 Hydraulic Tanks

Symbols	Name	Description
	Air Vessel	Air vessel where the gas capacitance term can be expressed using perfect gas behavior considering polytropic transformation of the gas.
	Cavity Compliance	The volume of a cavitation volume being function of the head and discharge, its model is based on the volume variation due to piezometric head and discharge changes.
	Generalized Surge Shaft	The GShaft module is an advanced SShaft module allowing to model: • inclined water column through modifiable parameters such as inertia and cross-sections; • inflow conditions; • overflow above a weir. For instance, with the generalized Surge Tank, the inertia of the water column is directly modifiable by the user which allows to model inclined water columns (not the case with the SShaft).
	Surge shaft	With the standard SShaft module, inertia is computed from water level elevation and cross-section area which limits the modeling to vertical water columns.
	Surge tank	The surge tank element models the head losses at the inlet diaphragm and the discharge storage
	Surge vessel	With the surge vessel element, the gas capacitance term can be expressed using perfect gas behavior considering polytropic transformation of the gas
	Viscoelastic Cavity	This model is used to model a pipe element with cavitation development which dynamics is described by cavitation compliance parameter and mass flow gain factor.
	Differential Surge Tank	The differential surge tank differs from the simple surge tank by adding a riser pipe. The riser is usually central, but may be arranged on one side of the throttled surge tank.

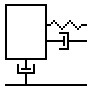
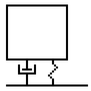
5.10 Hydraulic Turbines – Pumps

Symbols	Name	Description
	Francis Turbine	Francis turbine model (4 quadrants characteristic curves)
	Kaplan Turbine	Kaplan turbine model (double regulated turbine model)
	Pelton Turbine	Pelton turbine model with multiple injectors and deflectors modeling
	Pump	Pump model

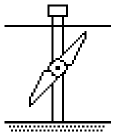
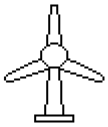
5.11 Hydraulic Valves – Sources

Symbols	Name	Description
	Discrete loss	Discrete loss model where the head losses depend on the losses coefficient and the reference cross section area.
	Pressure source	The pressure source corresponds to a head difference H between its inlet and outlet. The pressure source can be positive or negative.
	Valve	The valve is open when the valve stroke *s* is equal to one and closed when *s* is equal to zero.

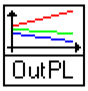
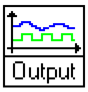
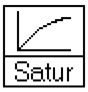
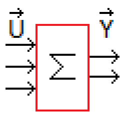
5.12 Mechanical

Symbols	Name	Description
	Mechanical Mass	Mechanical mass model where a reduction gear and the total inertia of the mass can be defined.
	Stator	This unit represents the mechanical stator of a rotating machine. It takes into account the mechanical reaction of the stator frame to the building in order to estimate the stress.

5.13 Renewable model

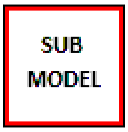
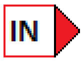
Symbols	Name	Description
	Tidal turbine	The model of the tidal turbine is based on the momentum and continuity equation applied to the stream tube of the turbine. However, the pressure ratio related to energy transfer is unknown. Here an empirical formulation of the power coefficient derived from measurements is used.
	Wind turbine	The model of the wind turbine is based on the momentum and continuity equation applied to the stream tube of the turbine. However, the pressure ratio related to energy transfer is unknown. Here an empirical formulation of the power coefficient derived from measurements is used.

5.14 Special elements

Symbols	Name	Description
	Neutral	For electrical elements only. This element allows to access neutral point of star connected three-phase loads or windings. Thus, a circuit with connected neutrals point can be created.
	OUTPL	This block named OUTPL allows plotting spatial profiles of physical quantities along the piping system. For transient analysis of hydroelectrical power plant, it is usual to represent pressure lines along the piping system. These pressure lines are the maxima and minima values reached during the transient as function of the position in the system. An animation of the transient piezometric lines are also available, see 3.2.8.
	Output	This block permits to store in the same file different quantities belonging to different units. Thus, the user can reduce considerably the size of the file of results.
	Saturation	This unit permits to take into account the Saturation Effect of three reactances x1, x2 and x3 of electrical machines.
	Inputs / Outputs of the System for Frequency Analysis (*)	This block allows defining the inputs U and the outputs Y of the system according to the state space formulation

(*) Only available in a specific library

5.15 Sub models

Symbols	Name	Description
	SUBMODEL	This block allows users to create a model that is nested into another, with the particularity that all elements inside are completely isolated from the parent model. This allows implementing a given functionality in a submodel and reuse it by simply copying the block and only adapting the input/output connections.
	SUBMODEL INPUT	This block allows users to define the set of inputs that a submodel needs. The defined inputs can be used internally and must be connected from the parent model of the submodel. This block must only be used inside a Submodel block.
	SUBMODEL OUTPUT	This block allows users to define the set of outputs that a submodel provides to the parent model. This block must only be used inside a Submodel block.

6 Tutorials and Examples

The SIMSEN hydraulic tutorials and the associated PDF files are available in the folder '*Tutorials/Hydraulic*'. The SIMSEN electrical tutorials and the associated PDF files are available in the folder '*Tutorials/Electrical*'. Alternatively, you can directly access the examples and tutorials folders using the menu *File/Examples...* of the main menu bar. It is highly recommended to perform all the tutorials before studying the different hydraulic and electrical examples.

6.1 Hydraulic Tutorials

6.1.1 Tutorial Hydro 1: Waterhammer in pipe

This tutorial shows how to simulate the transient response of a piping system due to valve closure. The Figure 15 shows the layout of the system of interest. The system is made of an upstream and downstream reservoir, a pipe and a downstream valve. The simulation will proceed in two phases. First, the initial conditions are determined using a stabilization procedure. In the second phase, the transient behavior of the piping system resulting from downstream valve closure is simulated.

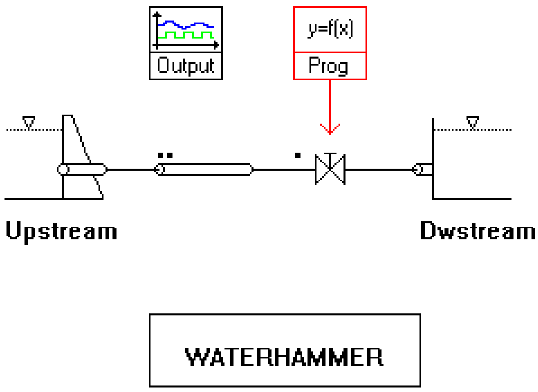


Figure 15 : Layout of the system of interest

6.1.2 Tutorial Hydro 2: Mass oscillation

This tutorial shows how to simulate the transient response of a piping system due to valve closure. The Figure 16 shows the layout of the example of interest that is made of an upstream and downstream tank, a gallery, a surge tank, a penstock and two valves. The simulation will proceed in two phases. First, the initial conditions are determined using a stabilization procedure. In the second phase, the transient behavior of system resulting from the downstream valve closure is simulated.

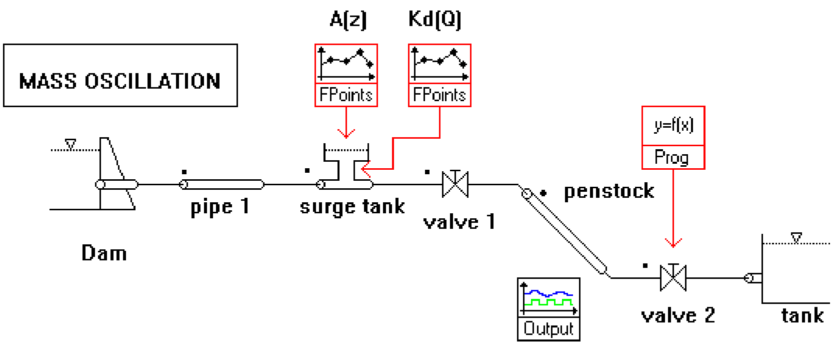


Figure 16 : Layout of the example of interest

6.1.3 Tutorial Hydro 3: Mass oscillation with surge shaft

This tutorial shows how to simulate the transient response of a piping system due to valve closure. The
Figure 17 shows the layout of the example of interest that is made of an upstream and downstream tank, a surge shaft, a gallery, a surge tank, a penstock and three valves. The simulation will proceed in two phases. First, the initial conditions are determined using a stabilization procedure. In the second phase, the transient behavior of system resulting from the downstream valve closure is simulated.

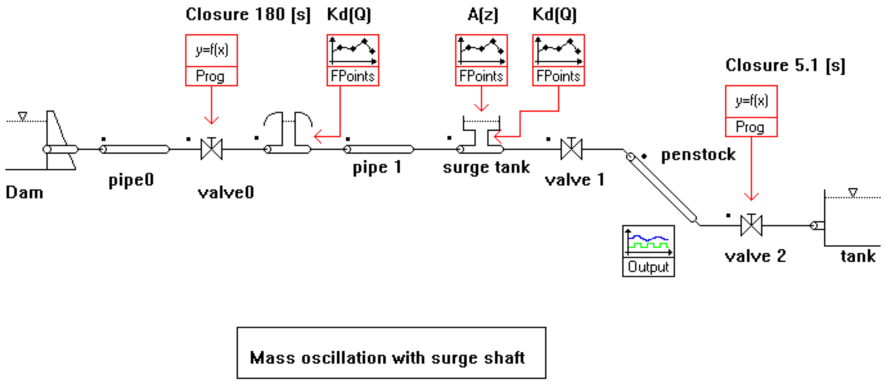


Figure 17 : Layout of the example of interest

6.1.4 Tutorial Hydro 4: Load rejection

This tutorial shows how to simulate the transient response due to load rejection in a hydroelectric power plant. The Figure 18 shows the layout of the system of interest that is made of an upstream reservoir, a penstock, 2 mechanical masses, a Francis turbine and its speed regulator and a downstream tank. The simulation will proceed in two steps. First, the initial conditions are calculated by using a stabilization procedure. In a second step, the transient behavior of the installation resulting from a 40% load rejection is simulated.

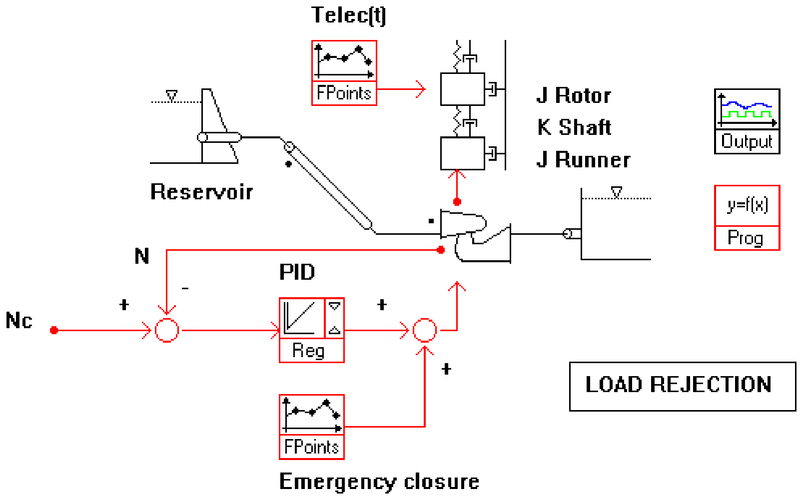


Figure 18 : Layout of the system of interest

6.1.5 Tutorial Hydro 5: Emergency shut down

This tutorial shows how to simulate the transient resulting from emergency shut down. The Figure 19 shows the example we are going to study comprising a tank, a penstock, 2 mechanical masses and a pump turbine. The emergency shutdown is initiated from the full guide vane opening, at t=10s the electromagnetic torque is set to 0 and bilinear closing law is undertaken.

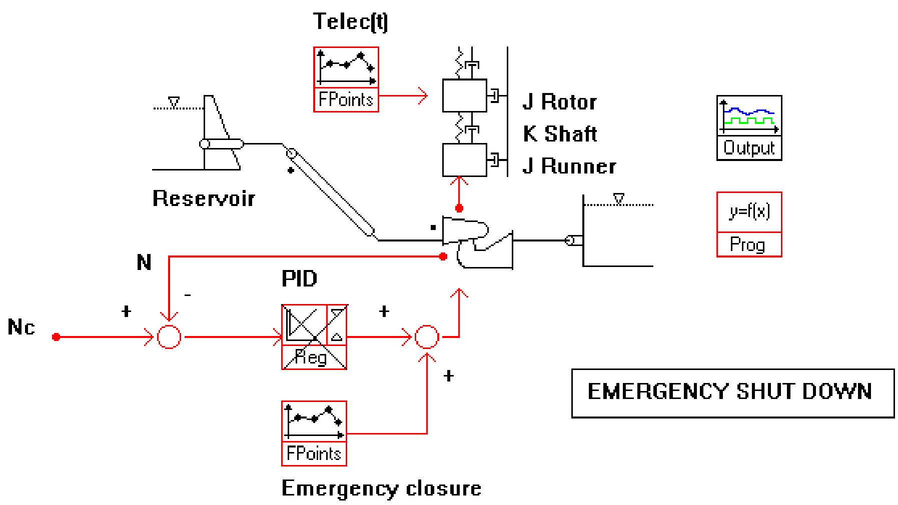


Figure 19 : Layout of the system of interest

6.1.6 Tutorial Hydro 6: Pump start up with linear speed up

This tutorial shows how to simulate a pump start up with linear speed up. The Figure 20 shows the example we are going to study comprising an upstream reservoir, a penstock, a pump turbine and a downstream tank. The simulation will proceed in two steps. First, the initial conditions are calculated by using a stabilization procedure. In a second step, the transient behavior of the installation resulting from the pump start up is simulated. The pump starts from zero rotational speed and goes to nominal operating rotational speed in 9 seconds. Once the nominal rotational speed is reached, the valve is opened linearly in 18 seconds.

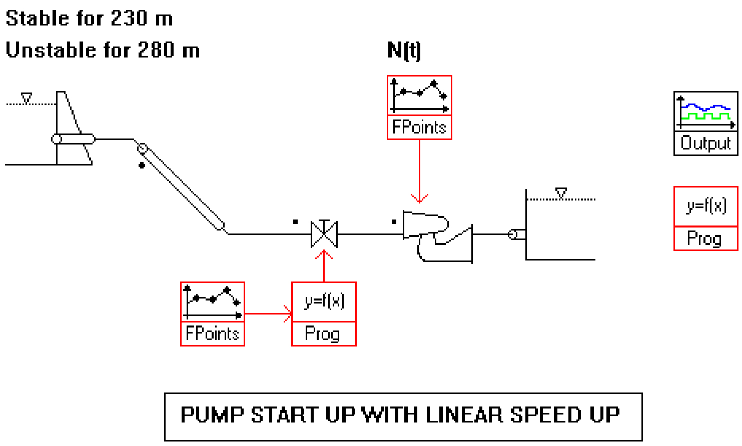


Figure 20 : Studied example

6.1.7 Tutorial Hydro 7: Pump start up

This tutorial shows how to simulate a pump start up with linear speed up. The Figure 21 shows the example we are going to study comprising an upstream reservoir, a penstock, a valve, 2 mechanical masses, a pump turbine and a downstream tank. This example being based on the previous tutorial, “6pstartl.stm”, the simulation will proceed in three steps as the initial conditions are identical. First step, the transient behavior of the installation resulting from the pump start up is simulated. To speed up the pump, external torque is applied on the rotor inertia. Once the nominal rotational speed is reached, the valve is opened linearly in 18 seconds. Second step, the initial conditions of the system are recalculated for another head. Third step, the transient behavior is recalculated with the new head.

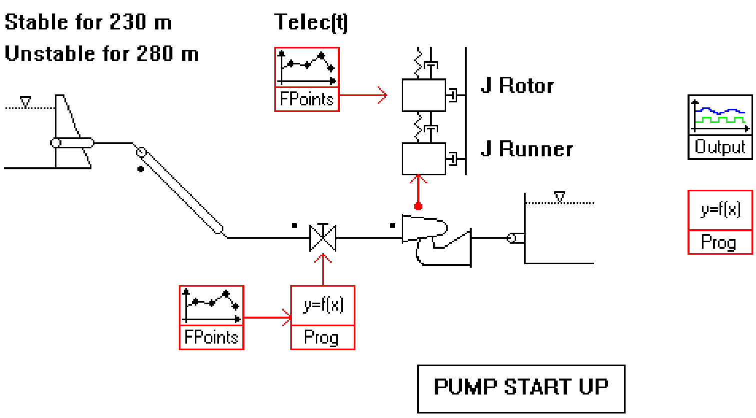


Figure 21 : Studied example

6.1.8 Tutorial Hydro 8: Hydroelectric transient

This tutorial shows how to simulate the transient behavior of a whole hydroelectric power plant resulting from a power acceptance followed by an emergency shutdown. The Figure 22 shows the example we are going to study comprising an upstream reservoir, a penstock, 2 mechanical masses a pump turbine, a downstream tank, a generator with its voltage regulator, a transformer and the infinite electrical grid. This example being based on 2 previous tutorials, “5tstop.stm”, and “1hydro.stm”, the simulation will proceed in three steps. First step, the initial conditions of the electrical part are determined. Second step, the initial conditions of the hydraulic installations are determined according to the generator specified operating point. Third and last step, the transient behavior of the installation is simulated. The transient event of concerns is the successive power acceptance and emergency shutdown.

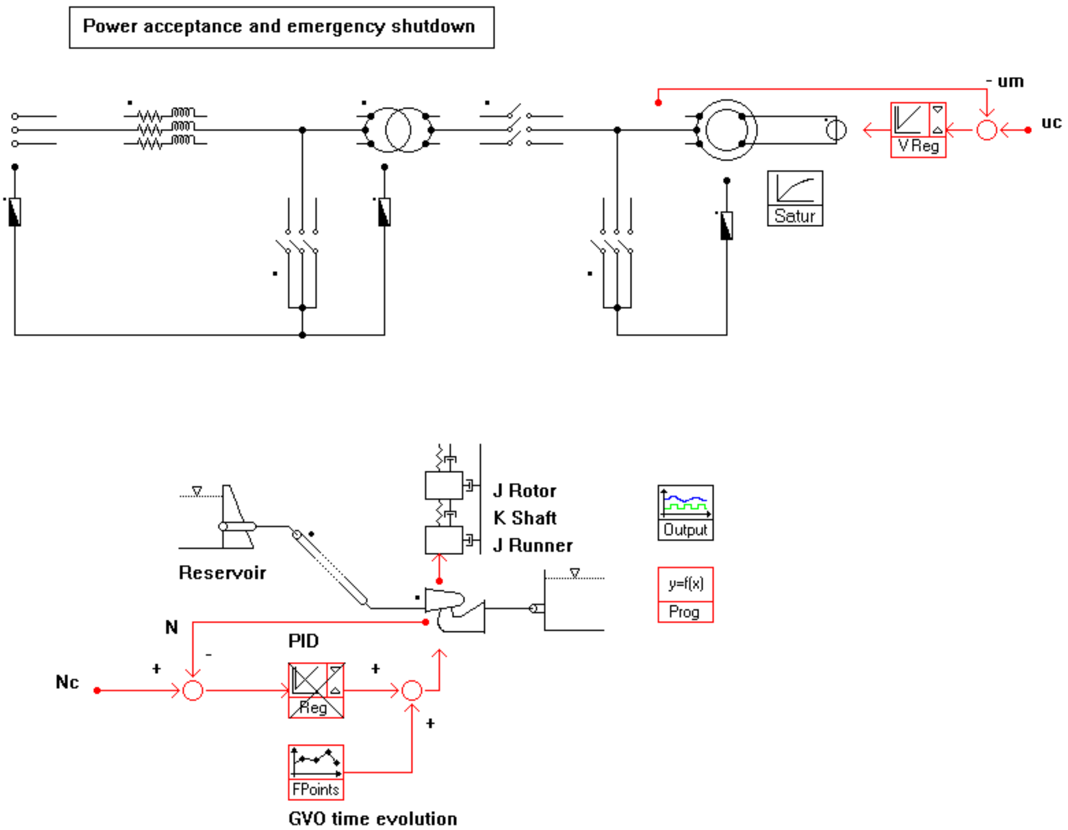


Figure 22 : Studied example

6.1.9 Tutorial Hydro 9: Pelton

This tutorial shows how to simulate the transient behavior of a Pelton turbine. The Figure 23 shows the Pelton turbine example comprising an upstream reservoir, a penstock, feeding a Pelton turbine with 4 injectors, a mechanical mass and a downstream reservoir. The following cases are simulated:

- Emergency shutdown
- Emergency shutdown without deflector activation
- Emergency shutdown without deflector activation nor injector closure
- Emergency shutdown without deflector activation with 3 injectors instead of 4 injectors

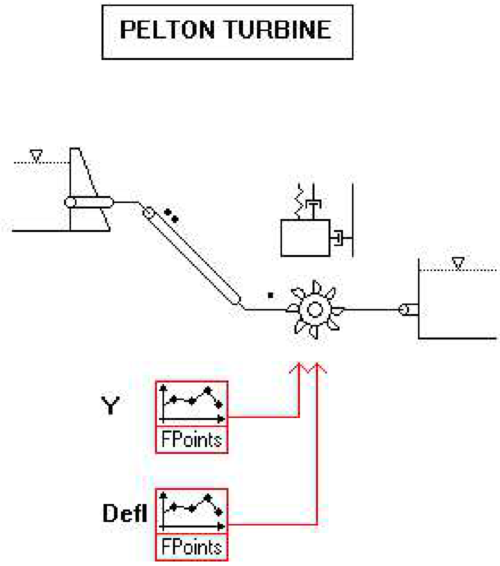


Figure 23 : Studied example

6.1.10 Tutorial Hydro 10: Kaplan

This tutorial shows how to simulate the transient behavior of a Kaplan turbine. The Figure 24 shows the example we are going to study comprising an upstream reservoir, a penstock, feeding a Kaplan turbine, two mechanical masses and a downstream reservoir. The simulation follows a five steps procedure. First step, the emergency shutdown of the Kaplan turbine is simulated with the tutorial example ready to be simulated. Second step, the initial conditions of a new operating point is calculated acting on the guide vane opening. Then a load rejection is simulated. Third step, new initial conditions are determined acting on the blade pitch angle and then a load rejection is simulated again. Fourth step, new operating point is determined for given guide vane opening and blade pitch angle and a load acceptance is simulated. Finally, the fifth step consists of determining new operating conditions using on-cam relation between guide vane opening and blade pitch angle, and a load acceptance is simulated again, using the on-cam relation.

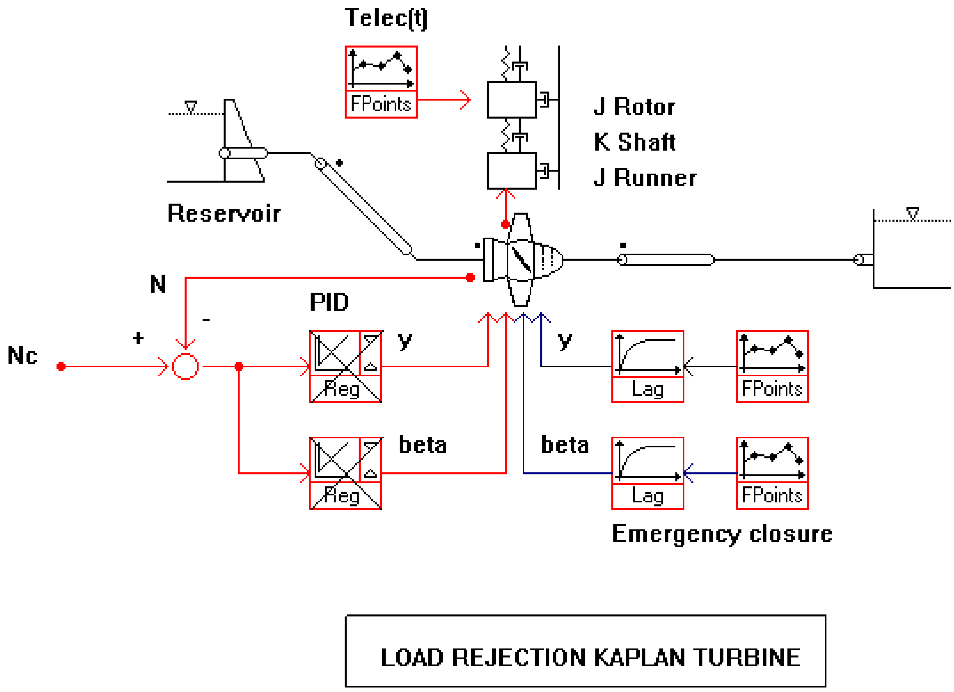


Figure 24 : Studied example

6.2 Electrical Tutorials

6.2.1 Tutorial Elect 1: Transient response of an R-L-C Circuit

This tutorial shows you how to simulate the transient response of an R-L-C circuit after the switching-off of a circuit breaker. The Figure 25 shows the example we are going to study. The simulation will proceed in two phases. First, from initial conditions set to zero and the circuit breaker switched-on, the circuit will reach a steady state with zero voltage over the inductor and zero current through the capacitor. In a second stage, from the steady state reached in stage one, the circuit breaker is switched-off and we study the transient behavior.

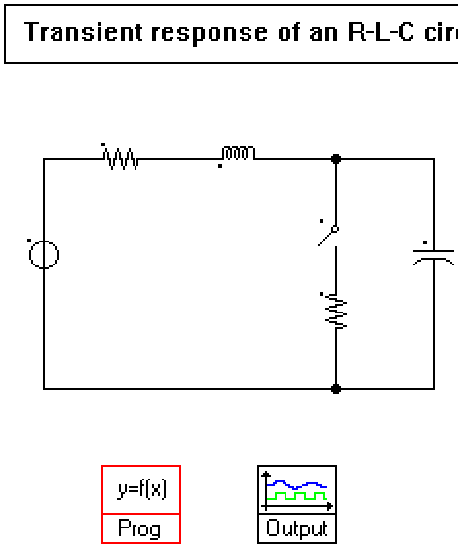


Figure 25 : Studied example

6.2.2 Tutorial Elect 2: Startup of an induction motor

This tutorial shows you how to simulate the no-load start up as well as the rated motor operating point of an induction motor. The Figure 26 shows the example we are going to study. The initial condition is a machine at standstill, the currents nil, the circuit breaker is then switched on to start the motor.

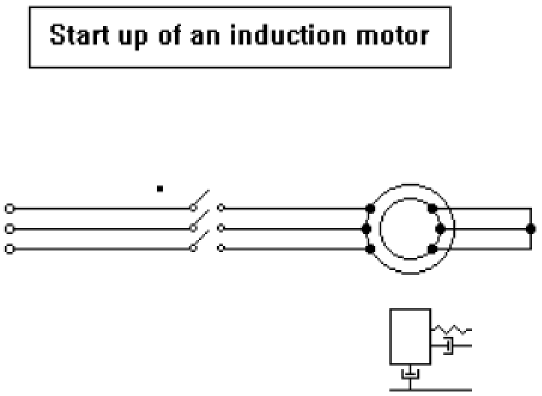


Figure 26 : Studied example

6.2.3 Tutorial Elect 3: Hydro-generator in transient operating modes

This tutorial shows you how to simulate the behavior of a hydro-generator during transient operating modes like: short circuits, earth fault and wrong synchronization. The Figure 27 shows the example we want to study.

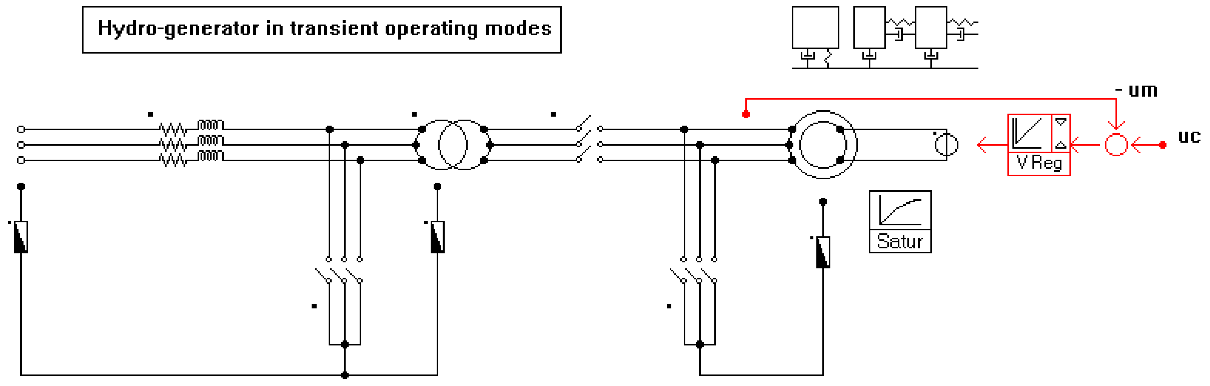


Figure 27 : Studied example

6.2.4 Tutorial Elect 4: Induction motor fed by voltage source inverter tuned with vector control

This tutorial shows you how to simulate an adjustable speed drive dealing with an induction motor fed by voltage inverter tuned with vector control. It also will explain you how to implement the regulation part of the drive. The Figure 28 shows the example we are going to study. The vector control allows splitting the flux and the torque regulation of the induction motor. The main advantage is to act separately on each corresponding component of the stator current to adjust the required flux and torque. Therefore, it is possible to improve the dynamic behavior of an induction motor fed by voltage source inverter. The simulation will proceed in two phases. During the first phase, the induction machine is magnetized at standstill. During the second phase, the machine is accelerated (change of speed set value in the regulation) and loaded (change of the mechanical torque acted on the mechanical mass).

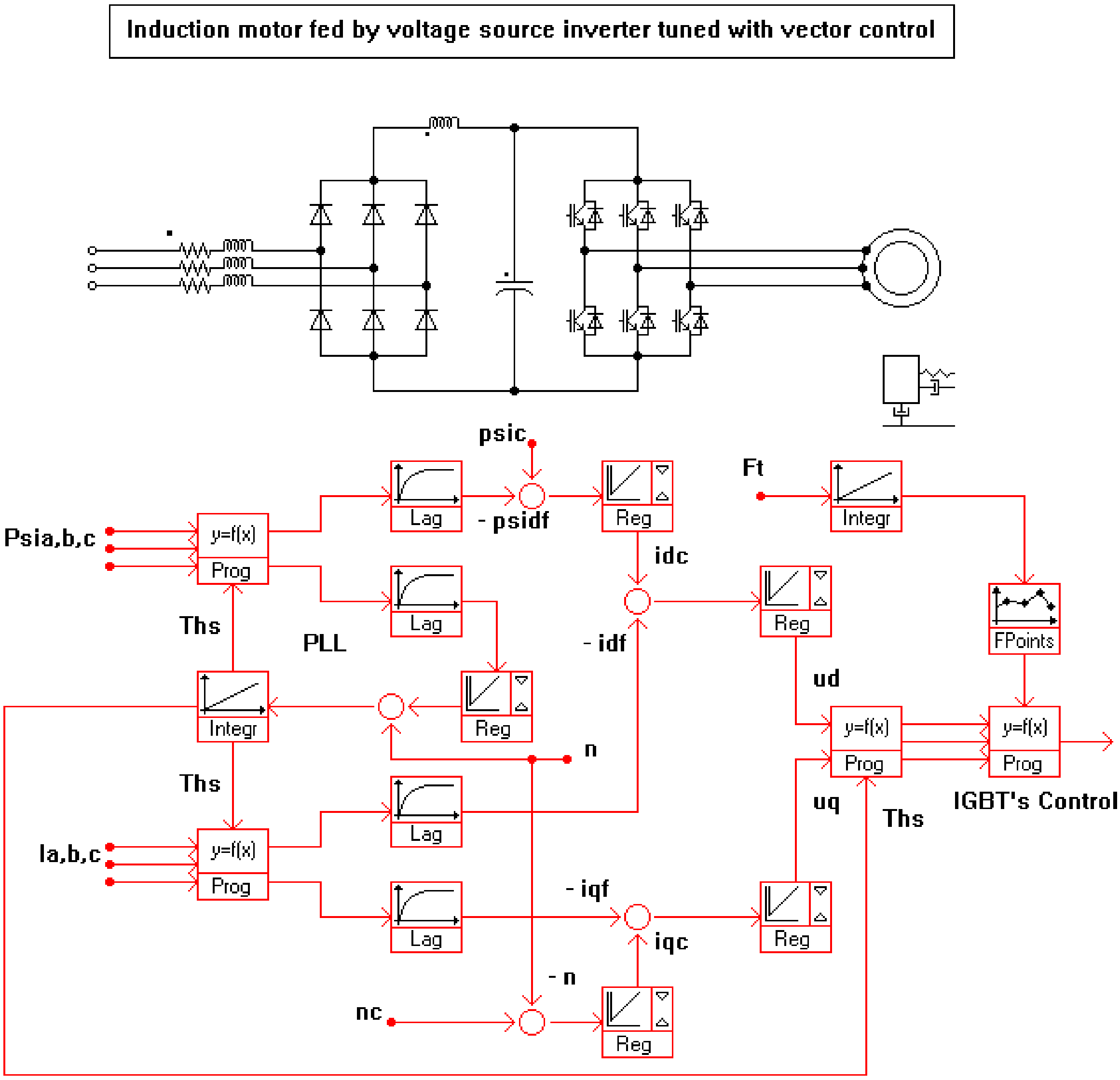


Figure 28 : Studied example

6.2.5 Tutorial Elect 5: Synchronous machine fed by a frequency converter (Load commutated inverter – LCI)

This tutorial shows you how to simulate an adjustable speed drive dealing with a synchronous machine fed by a frequency converter of type LCI (Load Commutated Inverter). It also explains you how to implement the digital regulation of the drive. The Figure 29 shows the example we are going to study. The simulation starts with specified initial conditions from the main file: the machine is excited and the mechanical speed is set to 80%. This way, it is possible to reach pretty quickly a steady-state operating point of the synchronous motor.

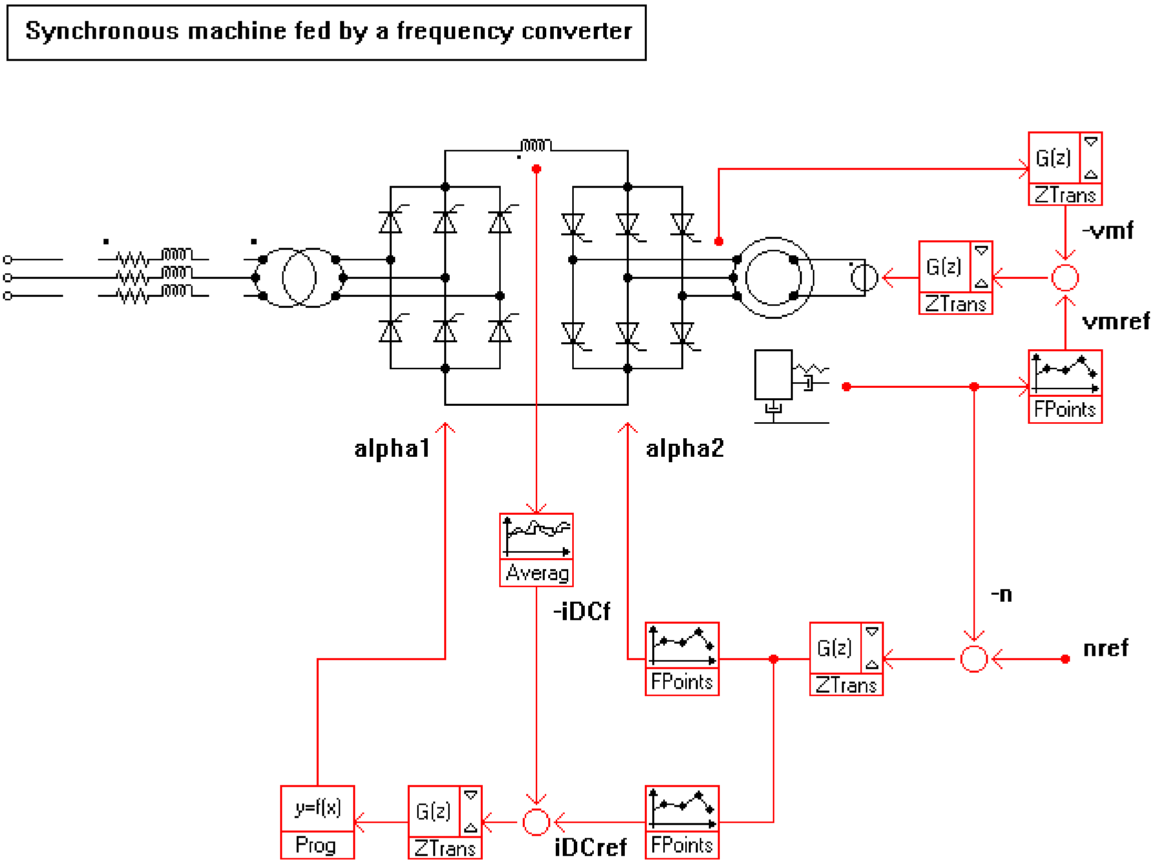


Figure 29 : Studied example

6.3 Hydraulic examples

In the folder '*Examples/Hydraulic*', many examples of hydraulic modeling can be viewed. A brief description of each of these examples is presented below.
Simulation of fast pump-to-turbine and turbine-to-pump transition of pump-turbine unit with imposed speed ramps.

- **5A_TStop_VarSpeed_TransN:** Simulation of fast pump-to-turbine and turbine-to-pump transition of pump-turbine unit with imposed speed ramps;
- **5B_TStop_VarSpeed_P:** Simulation of fast pump-to-turbine and turbine-to-pump transition of pump-turbine unit with imposed power ramps;
- **air:** Pump start-up with damping of BPF excitation by the air vessel.
- **butterfly:** Water hammer in a pipe with blocked injector and butterfly valve closure.
- **delayed_load_rejection:** Emergency shut down of two Francis turbines with time delay.
- **directcp:** Pump start-up with direct coupling of induction motor.
- **draft_tube_pressure:** Calculation of the kinetic head, piezometric head and static pressure in the draft tube.
- **gshaft:** Gshaft modeling example in a piping system due to valve closure.
- **GvoTransition:** Use of GVO transition dealing with small opening modelling;
- **Hydraulic_short_circuit_PumpPelton:** Modeling of hydraulic short-circuit between pump and Pelton;
- **inflow:** Mass oscillation with surge tank overflow and surge tank inflow.
- **inject:** Injector of Pelton turbine.
- **loading:** Pelton turbine modeled with valve; loading and load rejection at worst moment.
- **LoadingEsdPump:** Pump loading and emergency shutdown at the worst surge tank downsurge.
- **LoadingEsdTurbine:** Turbine loading and emergency shutdown at the worst surge tank downsurge.
- **loadramp:** Francis turbine with power control and load ramp.
- **local:** isolated network operation with 25% load rejection (hydroelectric model in folder '*he*' and only hydraulic model in folder '*hy*').
- **OutPL:** Two examples to illustrate the OutPL block element:
  - *WHammer_2pipes*: simulation of a water hammer with two different pipes diameters;
  - *MassOsc*: mass oscillation simulation.
- **overflow:** Mass oscillation with surge tank overflow.
- **para_units:** 2 Francis turbines in parallel with synchronous generator:
  - *hydroel2.stm*: load rejection and acceptance;
  - *hydroel3.stm*: short-circuit + emergency shutdown;
  - *hydroel4.stm*: wrong synchronization Unit 1 at t = 2s.
- **PID_NP_ARW_Rate_limiter:** Simulation of start and synchronization of Francis turbine with complex speed and power regulator;
- **Pturb_Resynchronization:** Simulation of Pelton full load rejection and resynchronization with speed regulator;
- **Pump_direct_start_induction_motor:** Simulation of pump start with torque characteristic of induction machine as function of speed;
- **pumpckv:** Pump starts against check valve and power failure.

- **pumppf:** Pump power failure with spherical valve.
- **pumptr:** External torque disturbance on pump operation.
- **resona:** Valve closure at first pipe resonance.
- **resynchr:** Francis turbine disconnection, resynchronisation and loading.
- **resynchrst_rp_bt:** Francis turbine with surge tank adduction with speed control with permanent and transient droop.
- **shaft:** Mass oscillation with surge shaft example.
- **spheric:** Water hammer in a pipe with blocked injector and spherical valve closure.
- **TurbLoadRejWylieStreeter:** Simulation of Francis turbine load rejection, example from Wylie and Streeter;
- **valve:** Example of valve parameterization.
- **vessel:** Mass oscillation with surge vessel.
- **ViscoC:** Nonlinear compliance and mass source modeling of cavitation draft tube vortex rope
- **wind:** Wind turbine example.

6.4 Electrical examples

In the folder '*Examples/Electrical*', many examples of electrical modeling can be viewed. A brief description of each of these examples is presented below.

- **1hydro:** Hydro-generator in transient operating modes.
- **1turbo:** Short-circuit of a large turbo generator.
- **acnet:** AC medium voltage network.
- **cascade:** Slip-energy recovery drive.
- **dcdrive:** DC drive.
- **dtc2l:** Induction motor fed by voltage inverter tuned with Direct Torque Control.
- **hvdcsvc:** HVDC transmission with SVC.
- **ieee:** Examples using IEEE standard regulators (Voltage, Power stabilizer)
- **lci6:** Synchronous machine fed by a frequency converter (load commutated inverter).
- **rlc:** Transient response of an RLC circuit.
- **smex:** Synchronous machine with excitation converter.
- **smfc:** Synchronous machine fed by a frequency converter.
- **startim:** Start-up of an induction motor.
- **transfo:** 18 pulse transformer.
- **vector2l:** Induction motor fed by voltage source inverter tuned with vector control.
- **vector3l:** Induction motor fed by three-level voltage inverter tuned with vector control.
- **vsi:** Multi level Voltage Source Inverter (VSI) feeding an induction motor.

7 Presentation of electrical analogy for hydraulic component

This software, developed by the EPFL (Ecole Polytechnique Fédérale de Lausanne), allows modeling of a complete hydroelectric power plant including both hydraulic and electrical components. To get the same set of equations between electrical and hydraulic systems, modeling of the hydraulic components is based on an electrical analogy.

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, yield to the well-known Allievi hyperbolic equations:

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

With:

- *a*: wave speed [m/s];
- *A*: cross section area [m^2];
- *D*: pipe diameter [m];
- *h*: piezometric head [m];
- *Q* flow rate [m^3/s];
- *x*: abscissa [m];
- *t*: time [s].

Using the finite difference method with a 1st order centered scheme discretization in space and a scheme of Lax for the flow rate state variable, this approach leads to a set of nonlinear ordinary differential equations which can be represented as a T-shaped equivalent electrical scheme as shown in Figure 30. The RLC parameters of this equivalent scheme are given by:

$$R = \frac{\lambda \cdot |\overline{Q}| \cdot dx}{2 \cdot g \cdot D \cdot A^2} \qquad L = \frac{dx}{g \cdot A} \qquad C = \frac{g \cdot A \cdot dx}{a^2} \tag{2}$$

The hydraulic resistance *R*, the hydraulic inductance *L* and the hydraulic capacitance *C* correspond respectively to energy losses, inertia and storage effects due to wall deflection and fluid compressibility. To model a pipe of length L, Nb elementary pipes of length dx are concatenated. Finally, a set of 1st order ordinary differential equations is made up by developing Kirchoff laws of the equivalent electrical scheme and is solved in time by the 4th order Runge-Kutta method.

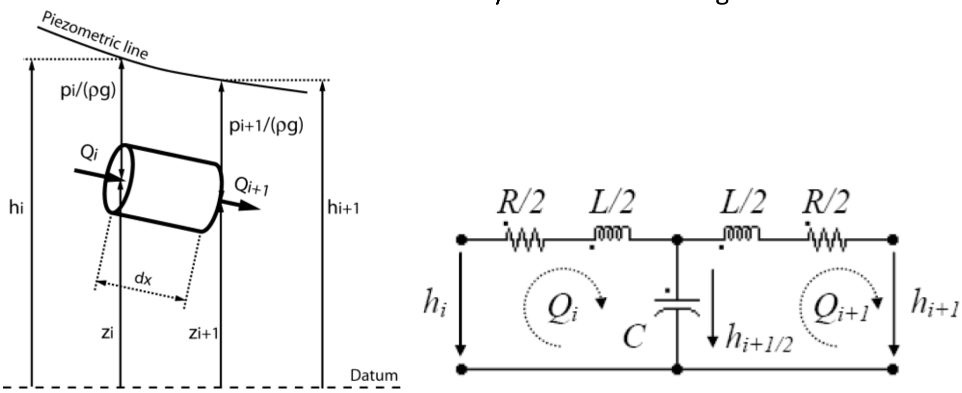


Figure 30 Pipe of length dx (left) and equivalent electrical scheme (right).

This modeling approach is extended to the most common hydraulic components such as surge tanks, surge shafts, air vessels, valves, reservoirs, Pelton turbines, Francis and Kaplan turbines, pumps, etc. Turbine modeling is based on the 4 quadrants static characteristic curves defined from discharge factor Q_{11}, speed factor N_{11} and torque factor T_{11} as follow:

$$Q_{11} = \frac{Q}{D_{ref}^{\ 2}\sqrt{H}} \qquad N_{11} = \frac{N \cdot D_{ref}}{\sqrt{H}} \qquad T_{11} = \frac{T}{D_{ref}^{\ 3} H} \tag{3}$$

With:

- H: turbine net head [m];
- T: turbine mechanical torque [N.m];
- N: runner rotation speed [rpm];
- D_{ref}: reference diameter [m].

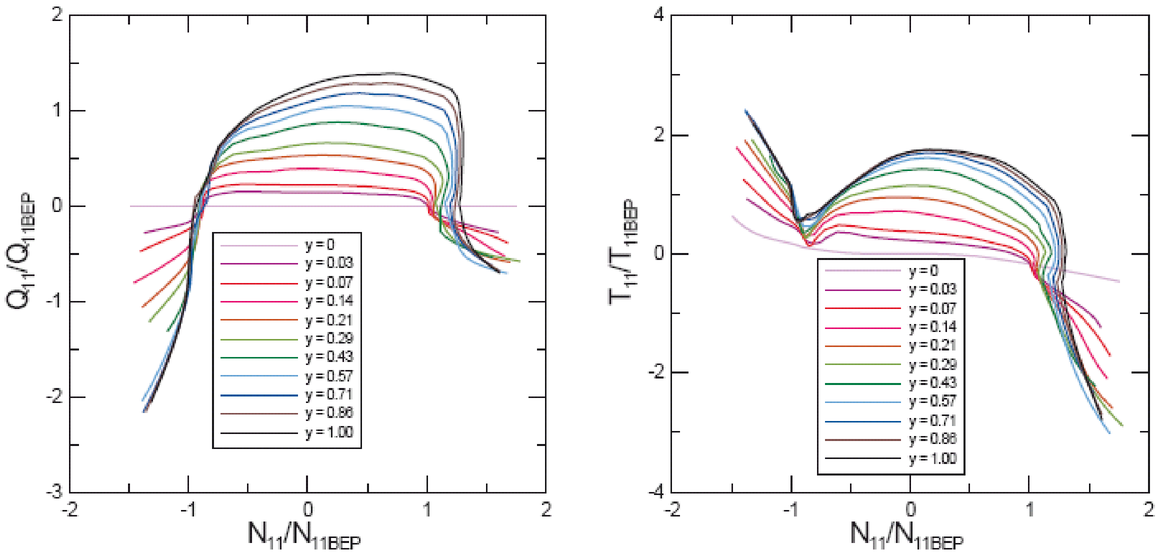


Figure 31 Illustration of the 4-quadrant characteristic curves

Some pump-turbine characteristics exhibit a typical pump-turbine S-shape between the 1st and the 4th quadrants leading to numerical troubles for the interpolation of the Q_{11} values in the surface characteristics. This problem has been successfully solved by using the Suter polar representation.

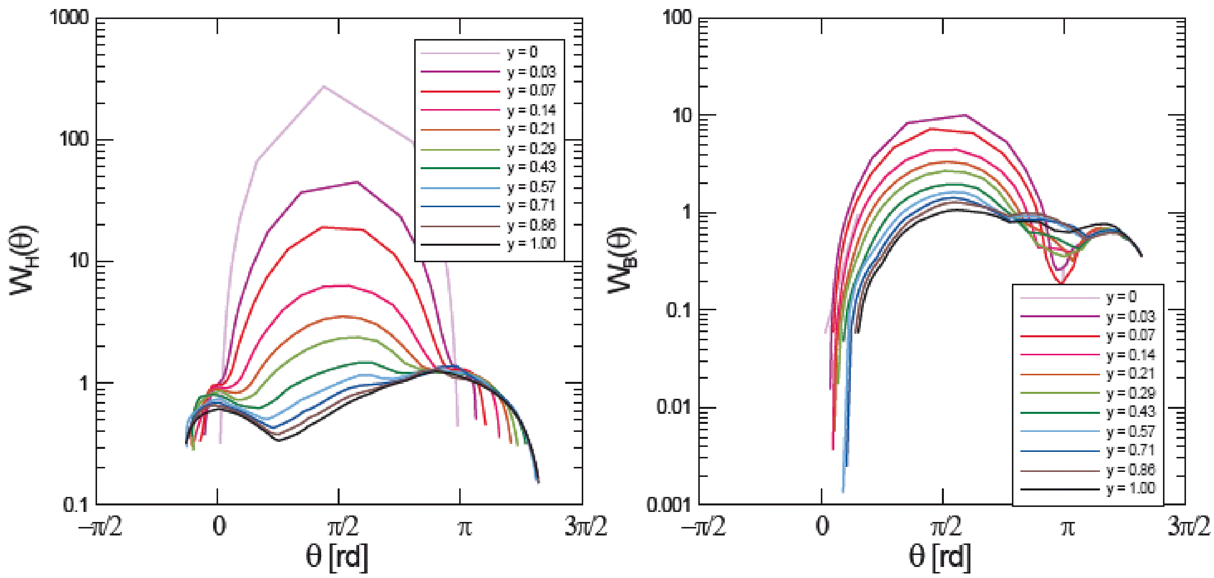


Figure 32 Illustration of the 4-quadrant characteristic curves with Suter polar representation

7.1 Definitions

Pressure head is defined as:

$$h_p = \frac{p}{\rho g} \qquad \text{[mWC]} \tag{4}$$

the piezometric head as:

$$h_z = Z + \frac{p}{\rho g} \qquad \text{[masl]} \tag{5}$$

and head as:

$$H = h_z + \frac{C^2}{2g} = Z + \frac{p}{\rho g} + \frac{C^2}{2g} \qquad \text{[masl]} \tag{6}$$

with:

- C: mean flow velocity [m/s];
- Z: elevation [masl];
- p: pressure [Pa];
- ρ: water density [kg/m^3];
- g: acceleration gravity [m/s^2].

Flow rate is defined as:

$$Q = C \cdot A \; \text{[m}^3\text{/s]} \tag{7}$$

with:

- A: cross section area [m^2].

Regular head losses in pipes are defined as:

$$\Delta H_r = \lambda \frac{L}{D} \frac{Q \cdot |Q|}{2gA_{ref}{}^2} \; \text{[mWC]} \tag{8}$$

with:

- D: pipe diameter [m];
- λ: Darcy-Weisbach friction loss coefficient [-].

Finally, singular head losses of a component can be expressed as:

$$\Delta H_r = \frac{K_d}{2gA_{ref}{}^2} Q \cdot |Q| \; \text{[mWC]} \tag{9}$$

with:

- K_d: singular head loss coefficient [-];
- A_{ref}: reference cross section [m^2].

8 Presentation of electrical components modelling

8.1 Synchronous machines

The IEEE standards 1110 (2002), entitled "IEEE Guide for Synchronous Generator Modelling Practices and Applications in Power System Stabilities Analyses" presents different levels of modelling of synchronous machines (see Figure 33). In SIMSEN, the models level 2.1 and 3.3 are available, which are among the most detailed. Besides, machines models in SIMSEN are true three phase, i.e. state variable are line currents (i_a, i_b and i_c). Hence, these models can also be used to model any non-symmetrical load case.

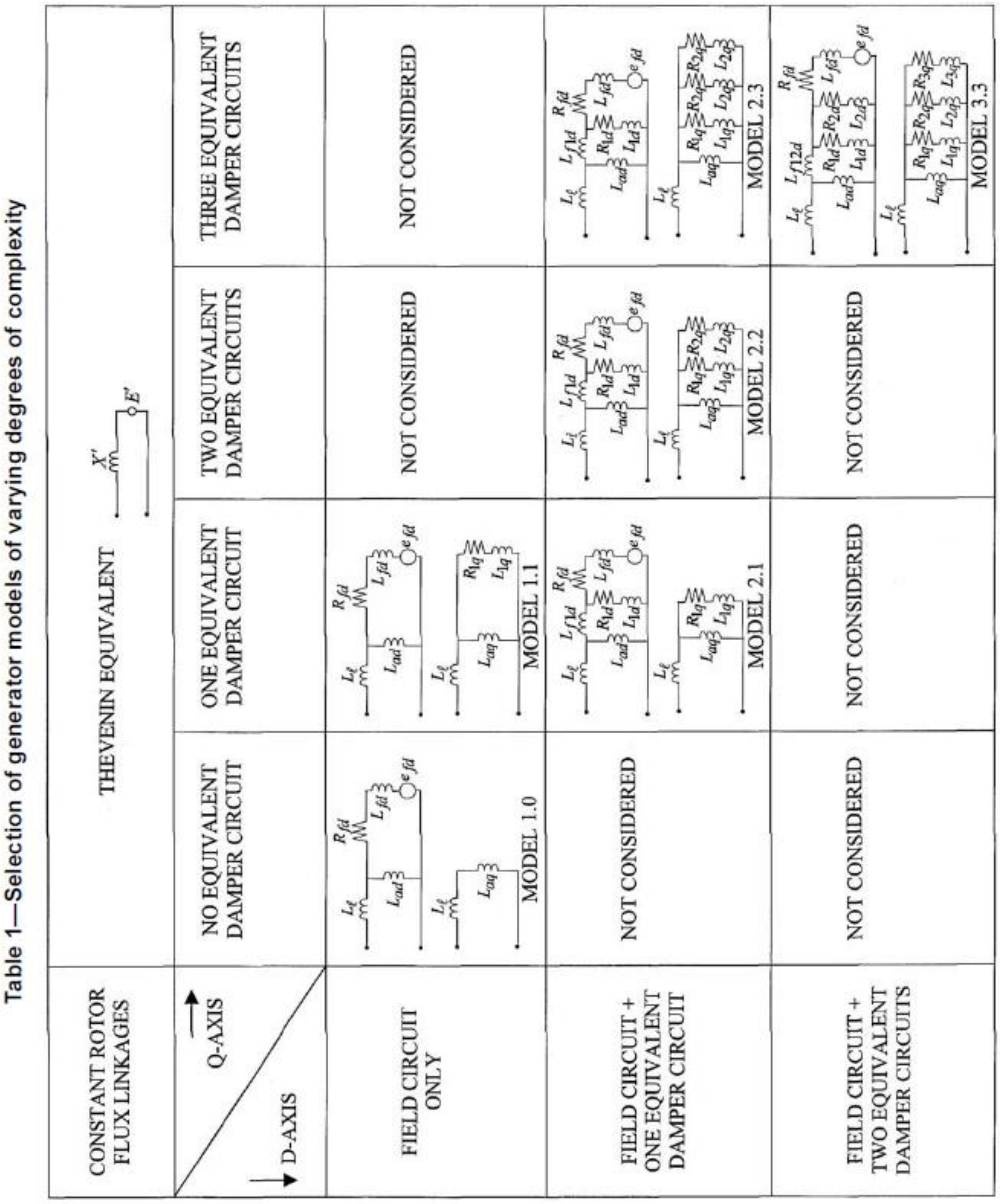


Figure 33 – source : IEEE Std 1110 (2002)

8.2 Semiconductors

As shown in 5.5, SIMSEN provides a library of semi-conductors. They all have parameters that represents the silicon devices' ON and OFF states characteristics (conductions losses, forward voltage) as well as parameters that define proper conditions for conduction state changes (OFF to ON and vices versa transitions). The ON and OFF states are modelled with a low resp. high impedance. In numerical simulations, this change in conduction state change represents a discontinuity in state variables that cannot be supported by the discretization scheme and numerical integration procedure. A discontinuity would lead to failure of the simulations. Besides, in reality, semi-conductors do not switch their conduction states instantaneously. The switching mechanism is also a transient phenomenon, at the scale of power electronics time constants, in the range of microseconds. Therefore, all models of semiconductors in SIMSEN allow the user to enter a parameter named *dT*, which is the switching time constant. It guaranties that the switching of the semi-conductor will be at least a first order response of the given time constant. Of course, depending on the elements surrounding the semi-conductor, this switching time can differ and might be larger. Some other simulation software that also offer semi-conductors models use a different technic, which consists in generating as many different ODE sets as there are combinations of switch states in the model. Hence, when a semi-conductor changes its state, the integration procedure switches to a different ODE set that represents the new circuit with the modified switch state. This allows to model instantaneous switching.

SIMSEN

Simulation Software for the Analysis of Electrical Power Networks, Adjustable Speed Drives and Hydraulic Systems

SIMSEN Research, Development, and ownership:

Ecole polytechnique fédérale de Lausanne
CH-1015 Lausanne
Switzerland
http://simsen.epfl.ch
simsen@epfl.ch

SIMSEN Development, Distribution, Support and Training ensured by:

Power Vision Engineering Sàrl
Chemin des Champs-Courbes 1
CH – 1024 Ecublens
Switzerland
info@powervision-eng.ch
Phone: +41 21 691 45 13
Fax: +41 21 691 45 13
www.powervision-eng.ch

Demo version available on: http://simsen.epfl.ch