HYDROTUR

HYDROTUR – HydroStab Solution
Simulator for Hydraulic Turbines

Stability Studies
Preliminary settings of servocontrols for FRANCIS-KAPLAN-PELTON hydraulic turbines

User’s Guide – Version 2.3

by Pierre Perrichon

CONTENTS

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[12] Scilab Enterprises - Yvon Degré, Serge Steer, Scilab - De la théorie à la pratique - II-Modéliser et simuler avec XCOS, D-Booker, 2014.

Standard documents	References
Scilab Engineering	[1] [2] [3]
IEC normative references	[4] [5]
Scientific literature	[6] [7] [8] [9]
University documents	[10] [11]

TECHNICAL SUPPORT - CONTACTUPPORT TECHNIQUE - CONTACT

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Projet HYDROTUR

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Figure 1 : Technical support for the HYDROTUR - SEGPAL project

LIST OF SYMBOLS

ω, Ω	Unit rotation speed (rd.s^{-1})
a	Water wave velocity coefficient (m.s-1)
aut	Self-adjustment coefficient of the electrical network (s.u)
FTBF	Closed loop transfer function
FTBO	Open loop transfer function
g	Acceleration of gravity (m.s-2)
Head	Gross or net head (m)
I, MR2	Turbine+Alternator Inertia (T.m2)
Kd	Gain of the derivative action (s.u)
Kp	Governor gain (s.u)
L, Leq	Equivalent pipe length (m)
ma	Marge de module (s.u)
W, Power	Hydraulic unit power (MW)
Q	Unit flow rate (m3/s)
S, Seq	Equivalent pipe section (m2)
Speed	Unit rotation speed (rpm)
Ta	Mechanical group launch time (s)
Td	Time constant of the derivative action (s)
Ti	Integrator time constant (s)
Ts	Operating time of the adjustment organs (s)
Tw	Hydraulic unit launch time (s)
ty	Tachometric time constant (s)

ABSTRACT

HydroStab represents a functional box built in Scilab language, in the **HYDROTUR** software suite, and is dedicated to calculating the stability of a speed governor controlling a hydroelectric machine of the FRANCIS, KAPLAN, PELTON type.

HydroStab Solution provides the adjustment parameters of a series-parallel PID corrector allowing the operation of a hydroelectric unit, with a safety margin, and without divergence when commissioning the regulator on site.

Prior to the study, an Excel **CALTUR** sheet establishes a reduction of the hydraulic diagram, in accordance with the data from the plant (length of pipes per section, adjoining sections), and determines the equivalent length and section of a single group.

These results are then to be entered in HydroStab.

HydroStab then determines a convergence domain to be reached and provides a quadruplet (K p , T i , T d , K d), with graphical program proof.

The main method adopted is based on a mathematical technique based on the **Nyquist space**, and proposes to force the passage of the transfer function in open loop, by a point P, to guarantee a **gain margin of 6 dB**, with a fixed **module margin** ma=0.42.

This value is generally commonly accepted in the turbomachinery adjustment system, and is recommended by Electricité de France.

HydroStab complies with international standards IEC 60308 and 61362 in the calculated results.

Other methods (**Ziegler-Nichols, Takahashi**) are also integrated into HydroStab for comparative studies.

FOREWORD

The examples cited in this document are often based on characteristics of the Revin hydroelectric power station in France.

These informations are normally available on the NET, and are therefore not confidential (public documents of Electricité De France EDF)

The results calculated here are the sole responsibility of the author of this document, in Turbine mode.

They are only commented as a Tutorial in the presentation of HydroStab.

They do not in any way call into question the studies already carried out by project or project management, turbine manufacturers, design offices, commissioning engineering, within the limited framework of speed regulation for rotating machines.

This involves presenting a systematic method for approaching primary and relevant adjustment calculations to be carried out in the approach to speed stability studies of a hydroelectric unit.

Appendix G provides a brief description of the Revin power plant.

1 INTRODUCTION

1.1 Presentation

Hydroelectricity is an important and vital renewable energy source, which converts the energy of water into electricity. This energy source can be produced by hydroelectric production units (power plants), and must meet many functional demands (load taking, load shedding, network frequency adjustment, flow control, water level control, etc.).

Any change in operating conditions results in transient hydraulic operating regimes which it is preferable to anticipate by appropriate modeling of the control circuits, as environmental issues and hydraulic safety are key areas requiring the greatest attention and expertise.

Indeed, many accidents observed following ruptures of loading pipes, or linked to the turbine, often occur during discharges at full load, due to large hydraulic transients.

Therefore, it is necessary to develop controllers capable of controlling hydraulic transients.

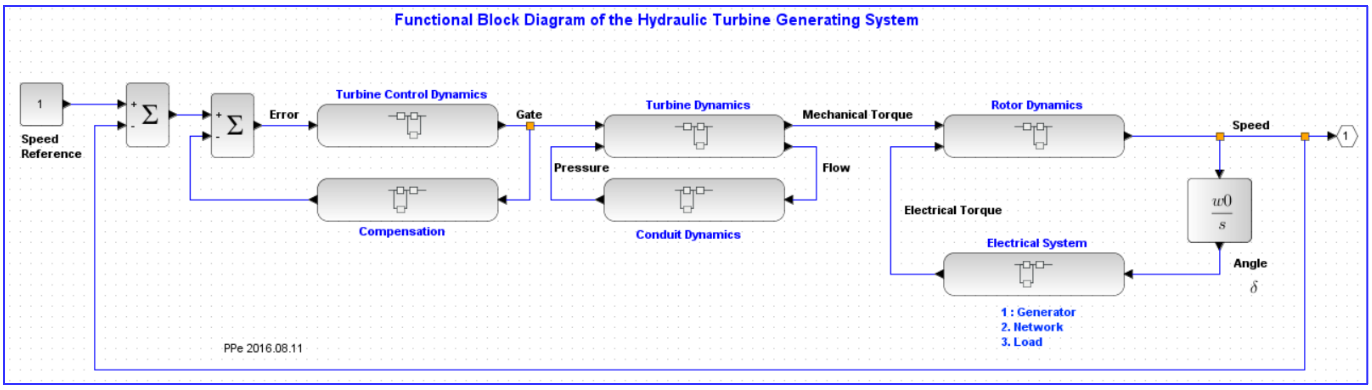

Figure 2 : General functional diagram of a hydroelectric control system

1.2 Linear approach to the stability adjustment of a hydroelectric group

The literature dealing with linear or nonlinear approaches to servo systems in Automation and Signal Processing is substantial. The presentations are numerous and all have their advantages and disadvantages.

It is however important to emphasize that the method adopted for the servo-control corrector must be of a complexity that can be understood by the operating and commissioning personnel of the plant; or, if the method is complex, add any calculation software allowing a relevant adjustment of the machine, while remaining compatible with the operational techniques in industrial engineering.

The purpose of this document is not to re-explain what is already easily found on the NET, but to describe the procedures adopted for adjusting a **PID type corrector**, within the framework of the **HYDROTUR** project.

The method selected and described is called the Open Loop Module Margin Method, in the NYQUIST geometric plane.

This method has already been tried and tested by some turbine manufacturers for over forty years, and has shown its effectiveness in the final adjustments of commissioning.

The classification table of synthesis methods indicated in [8] : *REGULATION INDUSTRIELLE chapitre 20 : METHODES DE COMMANDE : SYNTHESE, COMPARAISON ET CRITERES DE CHOIX page 518*.

The synthesis seems to confirm the relevance of using the PID regulator in an industrial environment, within the framework of single-input single-output SISO[1] systems.

Method	PID	Frequency other than PID	Polynomial	Predictive (linear) control	State approach	Fuzzy
Aptitude in Automatic	Low	Middle	Middle	Middle	High	Very low
Adapted to multivariable	Low	No	No	Yes	Yes	Yes but hard
Adapted to non-linear	Middle	No	No	No	No	Yes
On-site retouching	Yes	Yes, if the regulator is not very complex	No	No	No	Yes
Potential	Middle	Middle	High	High	High	Middle
Governor complexity	Low	Low to Middle	Middle	Middle	High	Low
Calculation volume (digital realization)	Low	Low	Depends on the order of the model	Depends on the order of the model	Raised if observant	Low
Others	Very present in the industrial environment	Graphic approach	Separation of setpoint / disturbance dynamics	Possibility of taking constraints into account	Separation of setpoint / disturbance dynamics	No model required
	Experimental setting possible	No need for an analytical model	Easy programming of automated synthesis		Very general modeling Systematic approach	

Figure 3 : Classification of synthesis methods

The HYDROTUR project proposes a systemic approach to speed regulation for hydraulic rotating machines and modeling of the functional elements presented in *Figure 2* .

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[1] SISO : **S**imple **I**nput-**S**imple **O**utput

These studies result in the provision of numerous documents and modeling software components, specially developed with the **Scilab/Xcos** software engineering platform, freely accessible and **available free of charge on the NET**.

An overview of the project is presented in the document "**HYDROTUR – Simulator for hydraulic turbines – Installation and user guide**". This document also indicates all the procedures to follow for the complete installation of HYDROTUR on a PC type computer under Windows, in the cited version of Scilab/Xcos.

The objective of this document is to provide a linear approach to the adjustment system of speed regulators in small movements from a **series-parallel PID corrector**; the nonlinear approach is widely presented in the different simulations for all types of FRANCIS, KAPLAN, or PELTON machines with horizontal or vertical axis: the list of proposed simulators is recalled in Appendix F. In particular, studies with **machine hills (n11, q11 c11) are available**.

HYdroStab Solution represents a calculation element in the HYDROTUR suite, allowing a relevant approach to the adjustment of the speed corrector involved in the speed regulation of a FRANCIS, KAPLAN, PELTON type hydraulic machine.

The objective is therefore to calculate and provide a quadruplet (K_p, T_i, T_d, Kd) of adjustment of a PID corrector, implemented in the speed regulation system of the group.

A stability study therefore aims to:

- to determine the parameters that best approximate the adjustment of a speed regulator of an electro-hydraulic group coupled to an isolated electrical network

- to characterize the frequency response of this group to load variations on the network, in order to provide a priori regulation parameters to the commissioning personnel and to avoid on-site optimization (which may not be feasible, or risky).

1.3 Terminology

Electro-hydraulic unit	Assembly consisting of a hydraulic turbine and an alternator coupled on the same shaft
Turbine	Device for converting hydraulic energy (kinetic energy of water under pressure) into mechanical energy (shaft rotation torque). May be Pelton, Francis, Kaplan or Bulb type
Alternator	Device for converting mechanical energy (shaft rotation torque) into electrical energy distributed on the network
Network	Set of electrical circuits (transformers, transmission lines, etc.) and electricity consumers to which the group is connected
Hydraulic circuit	Set of components (forced pipes, balance chimneys, tank, aspirator) ensuring the circulation of water from the upper basin to the turbine and from the turbine to the lower basin.
Gross head	Water level[2] difference between the upper basin and the lower basin
Net Head	Water pressure difference2 at the turbine "terminals", i.e. between the tank outlet and the vacuum inlet for Francis, Kaplan or bulb, between the injector(s) inlet and atmospheric pressure for Pelton
Adjustment organ	Organ used to control the flow of water sent to the turbine: valve for a Francis, injector(s) for a Pelton, valve-blade pair for a Kaplan turbine or a Bulb
Copying system	Assembly whose function is to transform an electrical position instruction into a position of the adjustment member. It consists of an actuator which transforms an electrical instruction into a flow of pressurized oil, a distributor (if necessary) which amplifies the flow of oil, a servomotor (controlled by the flow of oil

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[2] Rather than expressing this value in pascals or bars, the classic units of pressure, this value is generally given in meters, which is the height of the column of liquid required to create an identical pressure. With water, we speak of meters of water column (denoted mCE). where is the density of the fluid and the acceleration of gravity . For water 1,000 kg m-3 at 4 °C, and with the normal value of gravity g = 9.806 65 m s-2), the conversion is as follows: • 1 bar (105 pascals) corresponds to 10.1972 mCE; • Conversely, 1 mCE corresponds to 98.0664 mbar.

	from the actuator or distributor) which drives the adjustment member to the instruction position, a position measurement system which transforms the position of the servomotor or adjustment member into an electrical signal, and an electronic servocontrol responsible for developing the electrical instruction of the actuator according to the difference between the position instruction (from the speed regulator) and the position measured by the sensor (***see Appendix D.1***)

2 SUPPLY

2.1 Installing HydroStab

The HYDROTUR-HydroStab project is provided from a “HydroStab.zip” file, which must be unzipped.

HydroStab.zip

Le paquet peut être installé de différentes façons :

1. By the Scilab ATOMS module installer by pointing HYDROTUR-HydroStab in the “**Optimization**” module[3]
2. By entering the command **atomsInstall("HydroStab")** in the Scilab console
3. Manually, by dropping and unzipping the ZIP file into a user-defined directory, such as “HYDROTUR\HydroStab\” for example.

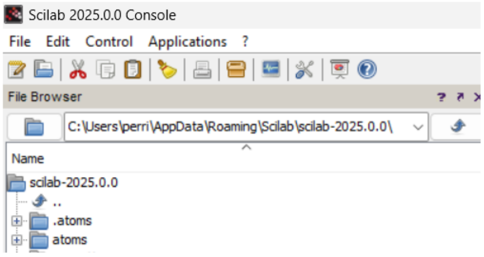
Figure 4 : Different Methods of Installing HydroStab

☞ **In automatic installation mode, the HydroStab package files are installed in the system Roaming**

The exact location can be known by typing the SCIHOME command in the Scilab console.

You can also enter the command chdir(SCIHOME) to access this directory directly.

Then access the atoms directory using the Scilab file browser by double-clicking



Scilab 2025.0.0 Console

File Edit Control Applications ?

File Browser

C:\Users\perri\AppData\Roaming\Scilab\scilab-2025.0.0\

Name

scilab-2025.0.0

..

.atoms

atoms

Figure 5 : HydroStab Auto-Install Directory

This software package includes the following:

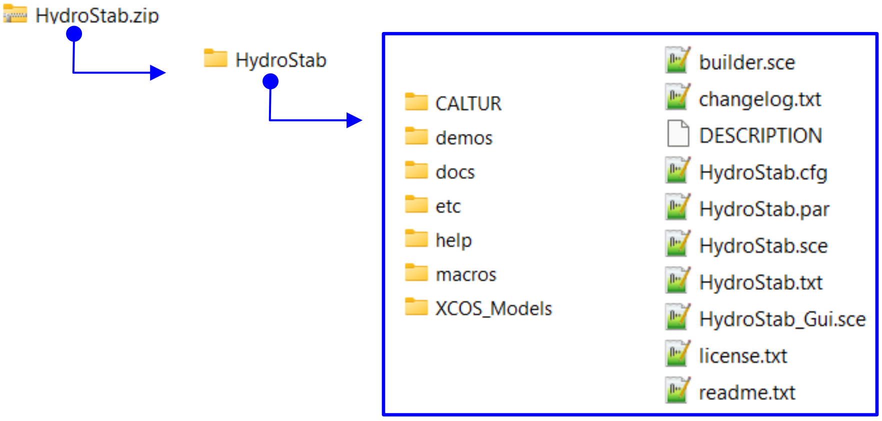


Figure 6 : Unzipping the HydroStab.zip file

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[3] In this case, enter “atomsGui” in the Scilab console and access the “Optimization” entity

Directory or File	Content
CALTUR	Spreadsheets (fr-en) in Excel xlsx format xlsx *(see §4.1, Appendix A)* • Calculation of the equivalent length and section of a hydraulic circuit
demos	Examples of achievements made under HydroStab – Saving these configurations to restart the simulations
docs	HydroStab documentation in French and English, in .pdf format
etc	Initialization (HydroStab.start file) and finalization (HydroStab.quit file). Scripts used in loading the HydroStab module loader.sce or unloading it unloader.sce
help	• Help files in XLM format divided into subdirectories in French (fr) and English (en) • Set of images used in the online help of the components (subdirectory "gui")
macros	Macros (.sci files) Set of source files written in Scilab language
XCOS_Models	Models of the transfer functions used in HydroStab, in XCOS graphic format “zcos” • FTBO.zcos : Open loop process transfer function • FTBF.zcos : Closed loop process transfer function • Test PID Parallèle - Mixte.zcos
builder.sce	Main manufacturer of the HydroStab module
changelog.txt	HydroStab version change history
DESCRIPTION	HydroStab Brief Description
HydroStab.cfg	Save the execution context of the last use of HydroStab
HydroStab.par	Default settings of the HydroStab toolbox
HydroStab.sce	Launch of HydroStab Direct launch also possible with the command to be entered in the Scilab console: **exec(HydroStab)**
HydroStab.txt	Set of texts used in the HydroStab software. French and English languages
HydroStab_Gui.sce	HydroStab GUI – User Guide Interface
licence.txt	Declaration of conformity to the CeCILL license Version 2.1
readme.txt	Recommendation for installing HydroStab on the computer

Figure 7 : HydroStab Directory Contents

2.2 Uninstalling HydroStab

- If HydroStab was installed as a Scilab ATOMS module, uninstallation is performed by running the following command in the Scilab console:

```
atomsRemove("HydroStab")
```

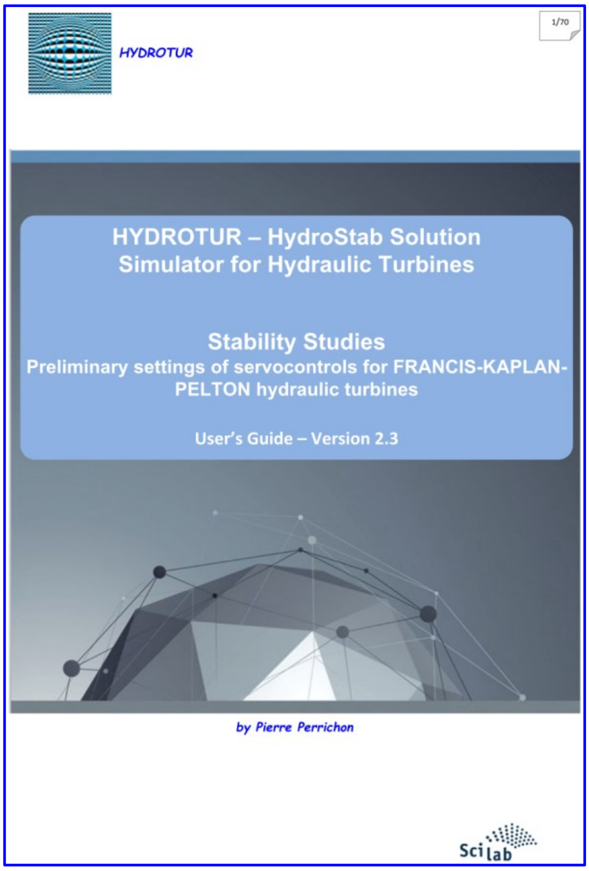
- If HydroStab was installed in a user directory, destroy that directory.

3 BUILDING AND LOADING THE HYDROSTAB TOOLBOX IN SCILAB

3.1 Foreword

Building the HydroStab toolbox requires a good understanding of the work [1][4] .

Its use only requires knowledge of this manual “**HYDROTUR - HydroStab - User Guide**” and the components it includes.



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HYDROTUR – HydroStab Solution
Simulator for Hydraulic Turbines

Stability Studies
Preliminary settings of servocontrols for FRANCIS-KAPLAN-PELTON hydraulic turbines

User's Guide – Version 2.3

by Pierre Perrichon

Scilab

D-BOOKER

I. LES FONDAMENTAUX

SCILAB
DE LA THÉORIE À LA PRATIQUE

Scilab

Pratique de Scilab validée par
scilab enterprises

Philippe Roux

Figure 8 : Scilab “Fundamentals” book

3.2 Prerequisites

The source codes of the executive are entirely written in Scilab language, and available in the **HydroStab\macros** directory

No prerequisites are therefore necessary for its use.

3.3 The builder.sce constructor

The script **builder.sce** file, located in the HydroStab directory, creates the HydroStab library and provides all the files needed to use it:

- Compilation of all the “.sci” macros, associated with the macros subdirectory of HydroStab\macros

Additionally, the builder.sce constructor provides and adds the following files to the HydroStab directory:

• clearner.sce	Cancels and deletes all files created by the builder.sce builder
• loader.sce	Loading the HydroStab library into Scilab.
• unloader.sce	Unloading the HydroStab library into Scilab

A listing, obtained by screen copy after launching the buider.sce constructor in Scilab, is provided in *Appendix H*

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[4] This book can be ordered online from D-Booker editions

3.4 The loader loader.sce

3.4.1 Loading

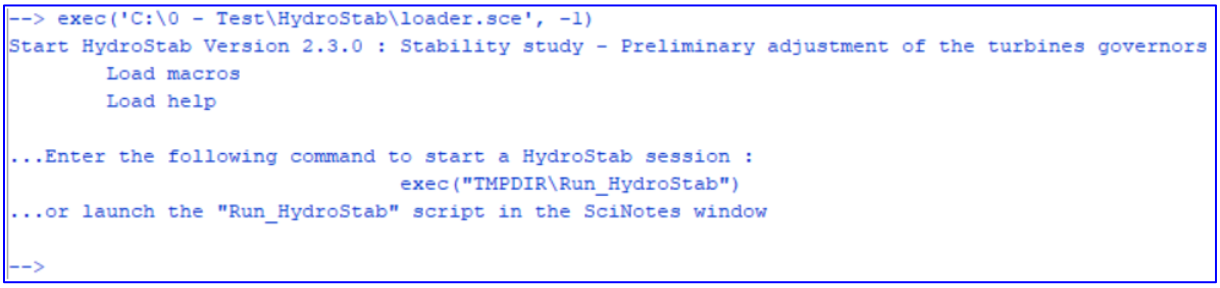
The **loader.sce** loader is created by the **builder.sce** interface, as shown in *§0*.

Running this script loads the library **HydroStab** into **Scilab**.

In the case of an automatic installation of HydroStab, the loader.sci file is launched automatically when Scibab is opened.

☞ **In case of manual installation (case n°3, see *Figure 4*), the loader must be launched by the operator before using HydroStab.**

We obtain the list of operations carried out in the Scilab console:



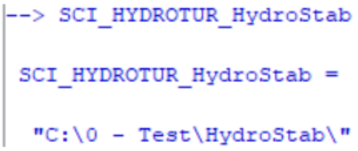
```
--> exec('C:\0 - Test\HydroStab\loader.sce', -1)
Start HydroStab Version 2.3.0 : Stability study - Preliminary adjustment of the turbines governors
        Load macros
        Load help

...Enter the following command to start a HydroStab session :
                                exec("TMPDIR\Run_HydroStab")
...or launch the "Run_HydroStab" script in the SciNotes window

-->
```

Figure 9 : Example of loading the HydroStab library in Scilab – Using the loader.sce file

As shown in the figure below, the operator launches a HydroStab session by entering the command **exec("TMPDIR\HydroStab")** in the Scilab console, or by executing the script « **Run_HydroStab**» in the SciNotes part of Scilab, indicated in *Figure 13*

3.4.2 Global variable due to HydroStab launch

Running the "loader.sce" file loads all compiled macros, and creates a global variable **SCI_HYDROTUR_HydroStab**, available during the entire HydroStab usage session



```
--> SCI_HYDROTUR_HydroStab

 SCI_HYDROTUR_HydroStab =

  "C:\0 - Test\HydroStab\"
```

Figure 10 : Environment variable **SCI_HYDROTUR_HydroStab**

This variable points to the HydroStab installation directory

3.4.3 Troubleshooting

☞ **The loader.sce file is not backward compatible across Scilab versions. For example, it is not possible to load HydroStab created with Scilab 2025.0.0 into Scilab 2024.1.0, or earlier versions.**

It is then necessary to restart the builder.sce constructor in the appropriate version of Scilab, especially when the installation of HydroStab is carried out in manual mode, as indicated in the *Figure 4*.

4 USER'S GUIDE

4.1 Reduction of hydraulic diagrams - EXCEL CALTUR Solution

4.1.1 Principle

CALTUR proposes a calculation method for reducing the hydraulic diagram of the power plant, in order to bring it back to the study of a simple circuit comprising only one turbine, supplied by a water supply through a single conduit of length ***Leq*** and section ***Seq***.

Ces deux données sont ensuite utilisées dans les circuits de calcul du logiciel HydroStab.

☞ **The CALTUR Excel spreadsheet is provided in the HydroStab\CALTUR directory, in English and French.**

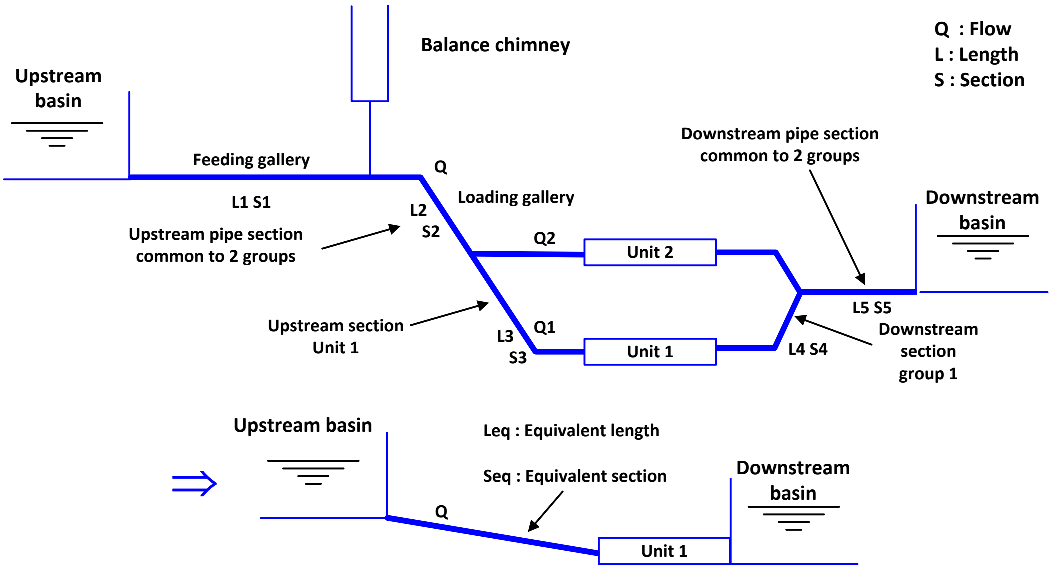


Figure 11 : Reduction of the hydraulic diagram - Preliminary calculations for the stability study of a hydraulic group

Appendix A presents the spreadsheets used in the calculator **CALTUR**.

Note that ***Leq*** and ***Seq*** can also be provided by the hydraulic expertise service [5].

In the following calculations, and as a first approximation, no account is taken of the pressure losses in the hydraulic circuit, unlike the non-linear approach of the simulation circuits proposed in HYDROTUR and which takes into account this data, calculated or imposed.

4.1.2 Calculation elements

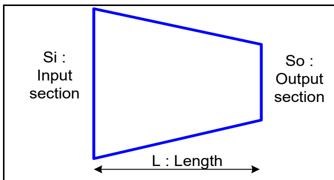
The **HydroStab** calculator uses a simplified model, deduced from a preliminary study of the hydraulic circuit.

This study determines the equivalent length and section Leq and Seq, allowing a complex hydraulic circuit to be reduced to a simple form using known methods, as shown in the figure above.

Non-exhaustive reminder of some formulas used in this study:

$L_{eq} = \sum_{i=1}^{n} L_i$	$\frac{L_{eq}}{S_{eq}} = \sum_{i=1}^{n} \frac{L_i}{S_i} \Rightarrow S_{eq} = \frac{L_{eq}}{\sum_{i=1}^{n} \frac{L_i}{S_i}}$

Of course, it is also necessary to take into account the section reductions in the circuit. For example, for a section of variable section:

	$S = \sqrt{Si * So}$

These parameters create the internal variables:

- **ag** : $\boxed{ag = \frac{ce}{g * Seq}}$ used in certain TURBADDUC blocks, for circuits not provided with machine hills.

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[5] Voit aussi *Figure 91*

- **Dh** : $\boxed{Dh = \sqrt{\frac{4*Seq}{\pi}}\ \text{(m)}}$ **Hydraulic diameter**

- The Reynolds number, for information purposes only, **Re :** $\boxed{\mathrm{Re} = \frac{2*rho*Qnom}{mu\sqrt{\pi}*Seq}}$ or $\boxed{\mathrm{Re} = \frac{V*rho*D_h}{mu}}$

, formula in which denotes **V___** the average speed of wate: $\boxed{V = \frac{Qnom}{Seq}}$

4.2 HydroStab Solution

4.2.1 HydroStab principle

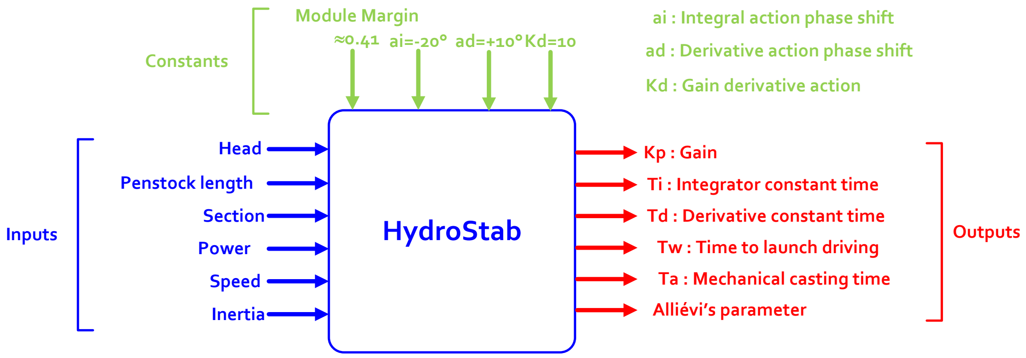


Figure 12 : Circuit for calculating the parameters of a Speed PID - Module Margin Method

HydroStab provides the adjustment parameters of a PID corrector allowing the operation of a hydroelectric group with a safety margin, and without divergence during commissioning.

The method adopted is based on a mathematical technique partially developed in this document.

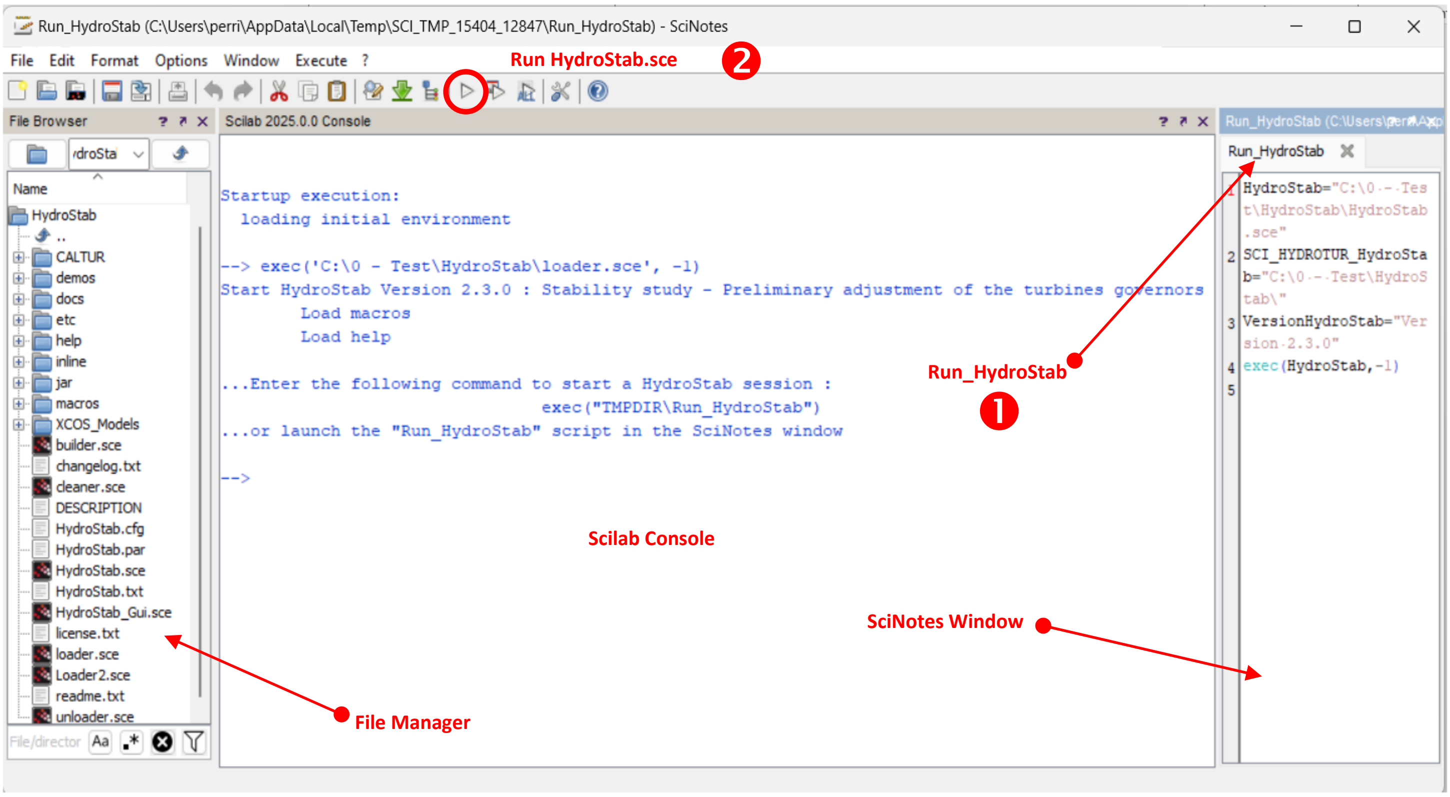
This method is called the **Module Margin Method.**

From the hydraulic data to be entered into the calculation software, and from a convergence domain to be reached and established in hypothesis by constant terms, a quadruplet (Kp, Ti, Td, Kd) is proposed, with graphical program proof.

4.2.2 Scilab Home Window

1. Start a Scilab session
2. If HydroStab was installed manually, first run the "loader.sce" loading file, in the installation directory chosen by the user
3. To launch HydroStab
    - Either by clicking on the **Run_HydroStab** file in the Scinotes window, then launching the script by pressing the arrow key indicated in *Figure 13*
    - Either by directly executing the **exec("TMPDIR\HydroStab")** command in the Scilab console
4. You can position yourself, after a first run, in the HydroStab installation directory, by typing the following command in the console:

chdir(SCI_HYDROTUR_HydroStab)



```
Startup execution:
  loading initial environment

--> exec('C:\0 - Test\HydroStab\loader.sce', -1)
Start HydroStab Version 2.3.0 : Stability study - Preliminary adjustment of the turbines governors
        Load macros
        Load help

...Enter the following command to start a HydroStab session :
                                exec("TMPDIR\Run_HydroStab")
...or launch the "Run_HydroStab" script in the SciNotes window

-->
```

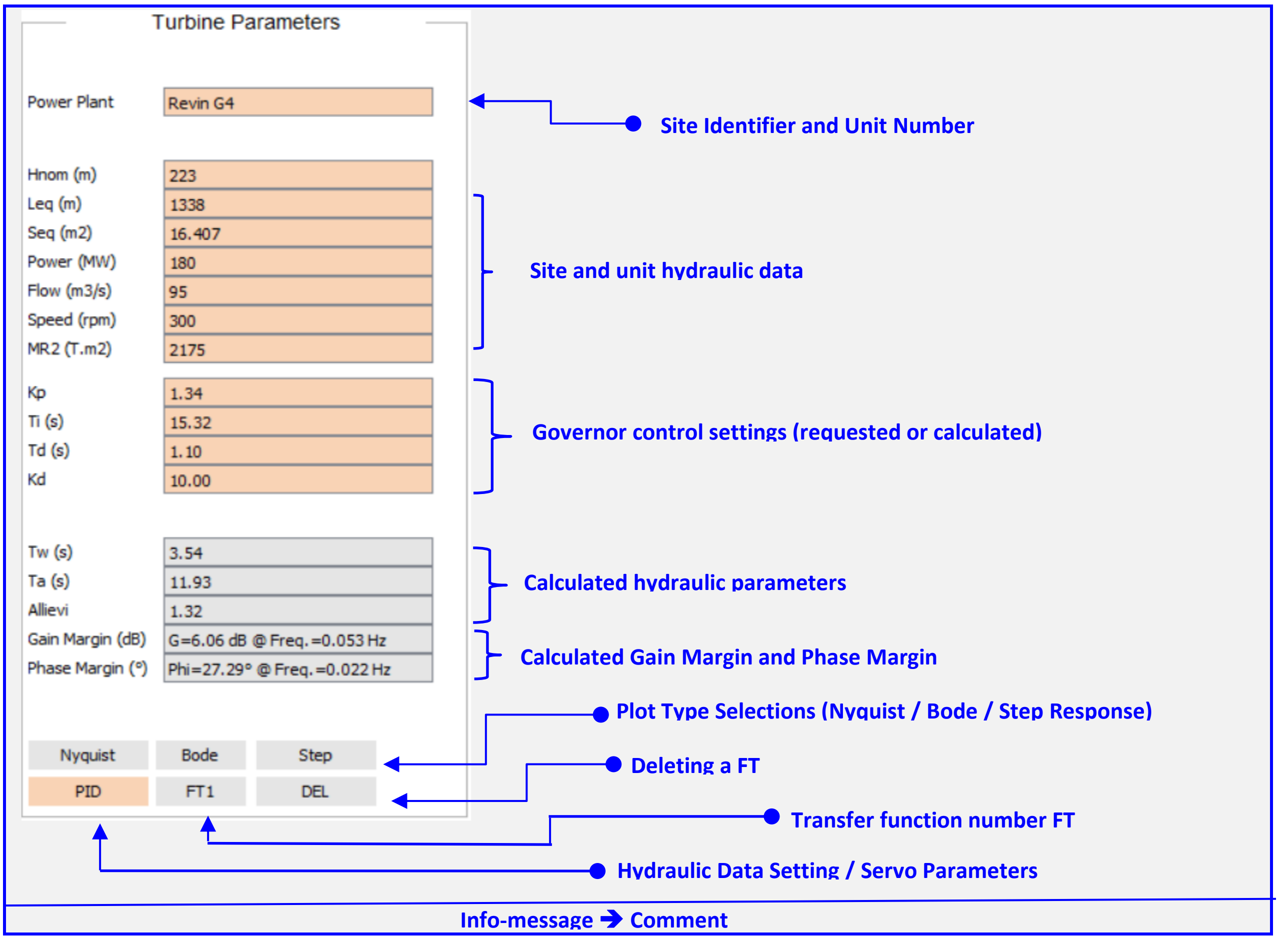
```
HydroStab="C:\0 - Test\HydroStab\HydroStab.sce"
SCI_HYDROTUR_HydroStab="C:\0 - Test\HydroStab\"
VersionHydroStab="Version 2.3.0"
exec(HydroStab,-1)
```

Figure 13 : Scilab home window and launch of the "**Run_HydroStab**" script

☞ Un aménagement et une organisation de l’espace Scilab est proposée en *Appendix F*

4.2.3 Reception Place

The calculation data must be entered in a single table, shown below.



Turbine Parameters

Power Plant	Revin G4
Hnom (m)	223
Leq (m)	1338
Seq (m2)	16.407
Power (MW)	180
Flow (m3/s)	95
Speed (rpm)	300
MR2 (T.m2)	2175
Kp	1.34
Ti (s)	15.32
Td (s)	1.10
Kd	10.00
Tw (s)	3.54
Ta (s)	11.93
Allievi	1.32
Gain Margin (dB)	G=6.06 dB @ Freq.=0.053 Hz
Phase Margin (°)	Phi=27.29° @ Freq.=0.022 Hz

Site Identifier and Unit Number

Site and unit hydraulic data

Governor control settings (requested or calculated)

Calculated hydraulic parameters

Calculated Gain Margin and Phase Margin

Plot Type Selections (Nyquist / Bode / Step Response)

Deleting a FT

Transfer function number FT

Hydraulic Data Setting / Servo Parameters

Info-message → Comment

Figure 14 : HYDROTUR Home Window - HydroStab Solution

4.2.3.1 Buttons Nyquist Bode Step

- Keys Nyquist and Bode are used to plot the Nyquist locus or Bode plane of the open-loop FTBO transfer function of the process, adjusted by a series-parallel PID type corrector.

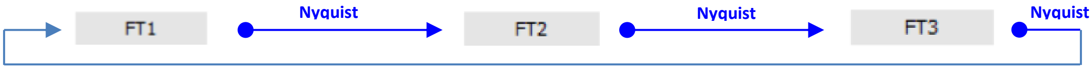
  The frequency sweeps, fmin_n=0.01Hz and fmax_n=100 Hz in the Nyquist plane, or fmin_b=0.01Hz and fmax_b=10 Hz in the Bode plane, can be adjusted, if necessary, by editing the file “HydroStab.par”.

- The closed-loop FTBF transfer function of the process looped back by the PID corrector is plotted with the key . Step . The numerical scope obtained represents the temporal response of the system to a double disturbance step, symmetrical at times t=0 and at time TSim/2, where TSim is the duration of the programmable simulation.

  TSim, simulation duration, and A_Ech; step amplitude can be in the file “HydroStab.par”, as well as the minimum ymin_Temp and maximum ymax_Temp values of the digital scope ordinate.

  ☞ The 3 buttons Nyquist Bode Step are used to validate the Hydraulic and/or Regulator data fields entered by the operator

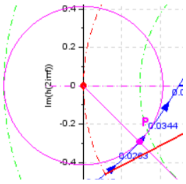
  A consecutive click on the same of these buttons causes the following transfer function to be displayed:



4.2.3.2 PID Button PID

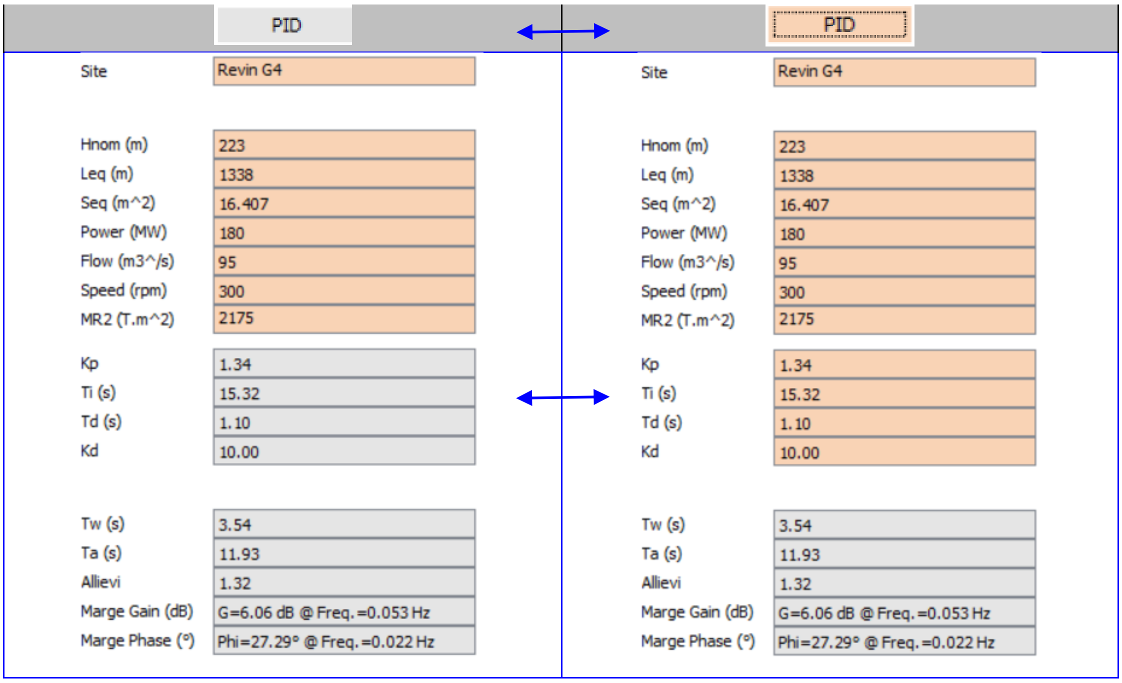
- The input boxes depend on the activity of the PID button, and are colored accordingly, in the editing windows.

If the PID key is released PID, the operator only enters the hydraulic data of the machine. In this case, the plot only refers to the single setting (Kp, Ti, Td, Kd), calculated by HydroStab.



☞ **In the Nyquist plane, this path necessarily passes through the optimal point P[6].**

The expected gain margin is then 6 dB for a Module Margin of 0.41 (+3dB)



Site	Revin G4	Site	Revin G4
Hnom (m)	223	Hnom (m)	223
Leq (m)	1338	Leq (m)	1338
Seq (m^2)	16.407	Seq (m^2)	16.407
Power (MW)	180	Power (MW)	180
Flow (m3^/s)	95	Flow (m3^/s)	95
Speed (rpm)	300	Speed (rpm)	300
MR2 (T.m^2)	2175	MR2 (T.m^2)	2175
Kp	1.34	Kp	1.34
Ti (s)	15.32	Ti (s)	15.32
Td (s)	1.10	Td (s)	1.10
Kd	10.00	Kd	10.00
Tw (s)	3.54	Tw (s)	3.54
Ta (s)	11.93	Ta (s)	11.93
Allievi	1.32	Allievi	1.32
Marge Gain (dB)	G=6.06 dB @ Freq.=0.053 Hz	Marge Gain (dB)	G=6.06 dB @ Freq.=0.053 Hz
Marge Phase (°)	Phi=27.29° @ Freq.=0.022 Hz	Marge Phase (°)	Phi=27.29° @ Freq.=0.022 Hz

Figure 15 : Menus for adjusting servos systems

If the PID key is pressed PID, the user can stack several adjustment quadruplets (Kp, Ti, Td, Kd) in order to simultaneously visualize their efficiencies or modify the hydraulic data.

This device thus facilitates optimal settings, taking into account significant variations in the tidal range (variation in the Head drop), or the operating point in power (Power) or flow (Flow).

☞ **Note: an optimal calculation triggered with the grayed out PID button PID, causes the calculation of the quadruplet (Kp, Ti, Td, Kd) following the Margin Module technique; then PID mode PID immediately becomes active again.**

4.2.3.3 FTx Button FT1

The button selects a transfer function from N calculated ones. It displays the number of the transfer function indicated mainly in the fields Kp, Ti, Td, Kd, Gain Margin and Phase Margin, as well as the hydraulic data of the recording.

---

[6] Voir § *7.1 Module Margin Method §7.1.1 Stability criterion in the Nyquist plane*

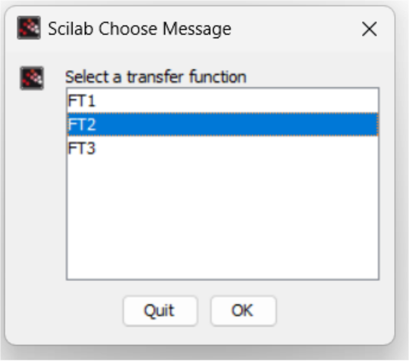
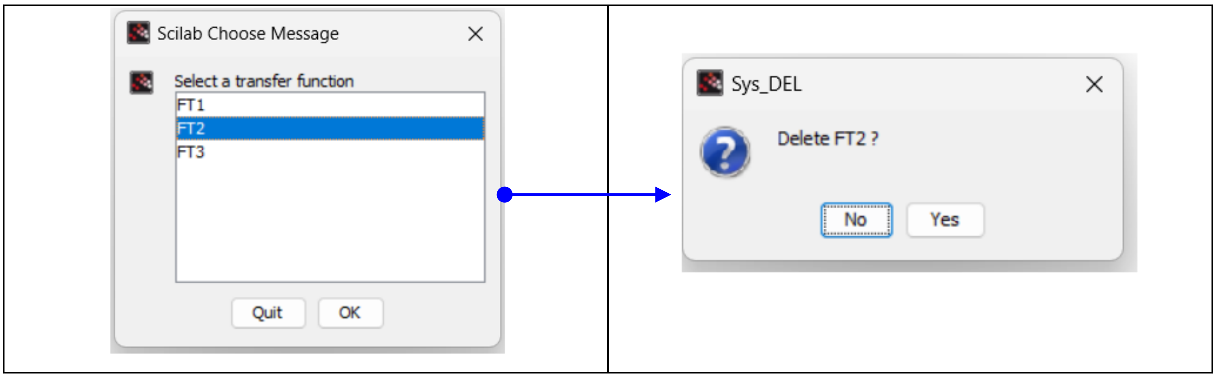


Figure 16 : Selecting one FT from N with the BP FT1

4.2.3.4 DEL Button DEL

The **DEL** button selects a transfer function from N to remove it from the law bundle. A confirmation request is proposed to avoid any handling errors.

☞ Permanent deletion only takes place if the configuration is saved again.



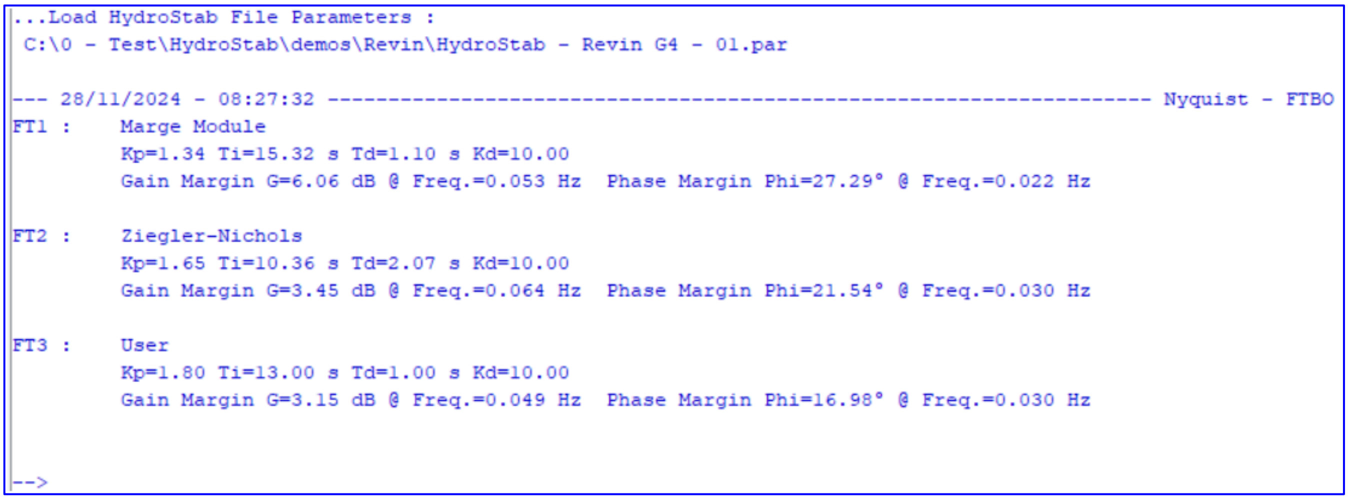
Delete FT2 ?

Figure 17 : Deleting one FT among N DEL

4.2.3.5 Printing legends in the Scilab console

In a HydroStab session, the graph legends are systematically ordered by their creation orders, following the settings used in the simulation (FT1, FT2, etc.)

The meaning of the legends is available on the Scilab console, after clicking on this element of the screen:



```
...Load HydroStab File Parameters :
 C:\0 - Test\HydroStab\demos\Revin\HydroStab - Revin G4 - 01.par

--- 28/11/2024 - 08:27:32 -------------------------------------------------------------------- Nyquist - FTBO
FT1 :     Marge Module
          Kp=1.34 Ti=15.32 s Td=1.10 s Kd=10.00
          Gain Margin G=6.06 dB @ Freq.=0.053 Hz  Phase Margin Phi=27.29° @ Freq.=0.022 Hz

FT2 :     Ziegler-Nichols
          Kp=1.65 Ti=10.36 s Td=2.07 s Kd=10.00
          Gain Margin G=3.45 dB @ Freq.=0.064 Hz  Phase Margin Phi=21.54° @ Freq.=0.030 Hz

FT3 :     User
          Kp=1.80 Ti=13.00 s Td=1.00 s Kd=10.00
          Gain Margin G=3.15 dB @ Freq.=0.049 Hz  Phase Margin Phi=16.98° @ Freq.=0.030 Hz


-->
```

Figure 18 : Printing legends and operations conducted in the Scilab console

4.2.3.6 *Graphics tools available*

The standard Scilab/Xcos graphics toolbar, in the graphics windows, is maintained in the GUI[7] HydroStab :

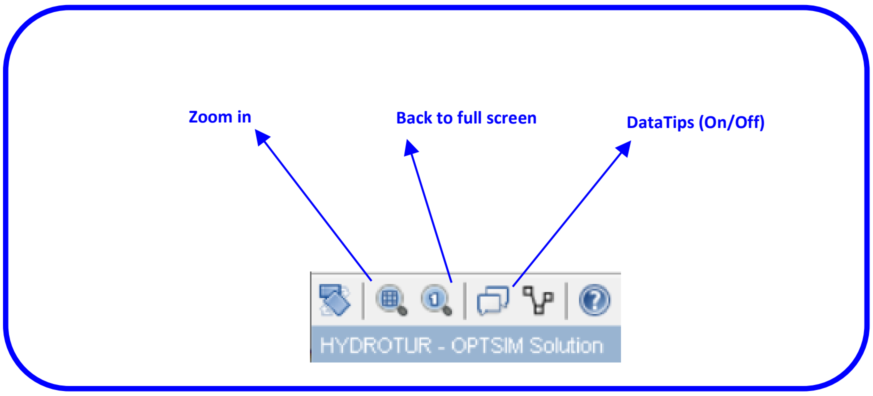


Figure 19 : Scilab Standard Graphics Toolbar

1. **Zoom in**

- Zooming in is available with the icon :

  Frame the area to be enlarged with the mouse using the right mouse button, then release the mouse

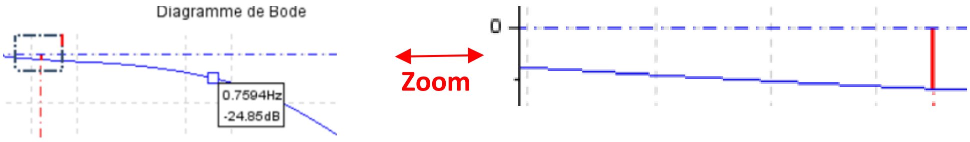


Figure 20 : Zooming in graphics windows

It is also possible to zoom in and out in the graphics window using the mouse wheel.

2. **Datatips**

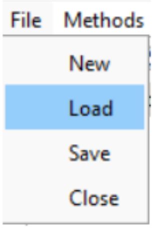
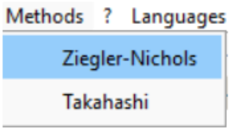
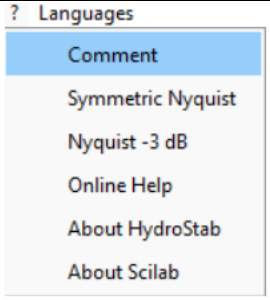
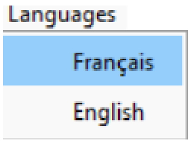
DataTips mode (marking data in a graph) is automatically implemented when HydroStab is launched. It can also be controlled with the tool

As a reminder:

```
Left click on the curve creates a datatip and right click on the datatip removes it.
```

4.3 Dedicated menus in HydroStab

4.3.1 Toolbar Menu

<table>
<tr>
<td>
</td>
<td>
</td>
<td>
</td>
<td>
</td>
</tr>
<tr>
<td>File Menu</td>
<td>Method Menu</td>
<td>Menu ?</td>
<td>Language Menu</td>
</tr>
</table>

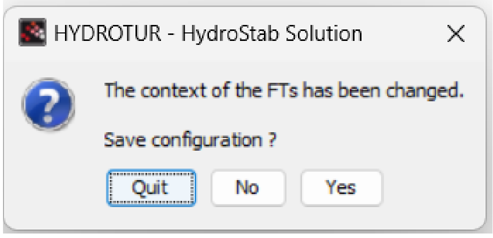
---

[7] GUI : **G**raphic **U**ser **I**nterface

4.3.2 File Menu

4.3.2.1 Create a new configuration

The function of creating a new configuration is preceded by a request for confirmation of the action, in order to avoid any unexpected loss of work in progress:



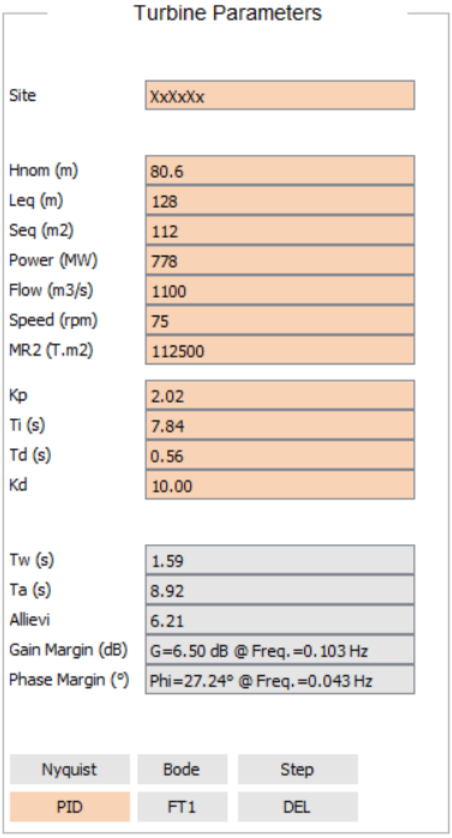
HYDROTUR - HydroStab Solution

The context of the FTs has been changed.

Save configuration ?

Figure 21 : Request for confirmation when creating a new configuration

If so, a new working page is displayed, showing the "default configuration" of HydroStab:



Turbine Parameters

Site	XxXxXx
Hnom (m)	80.6
Leq (m)	128
Seq (m2)	112
Power (MW)	778
Flow (m3/s)	1100
Speed (rpm)	75
MR2 (T.m2)	112500
Kp	2.02
Ti (s)	7.84
Td (s)	0.56
Kd	10.00
Tw (s)	1.59
Ta (s)	8.92
Allievi	6.21
Gain Margin (dB)	G=6.50 dB @ Freq.=0.103 Hz
Phase Margin (°)	Phi=27.24° @ Freq.=0.043 Hz

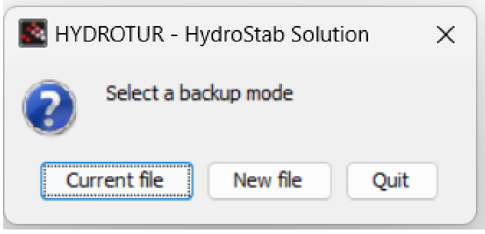
Figure 22 : HydroStab Default Configuration

It is therefore necessary to re-enter all the data communicated for the stability study, and save the data with a site name and possibly a group number.

4.3.2.2 Saving a configuration

Recording a HydroStab session is done with the "Save" function.

A choice of backup mode is offered as soon as the menu is activated:



Select a backup mode

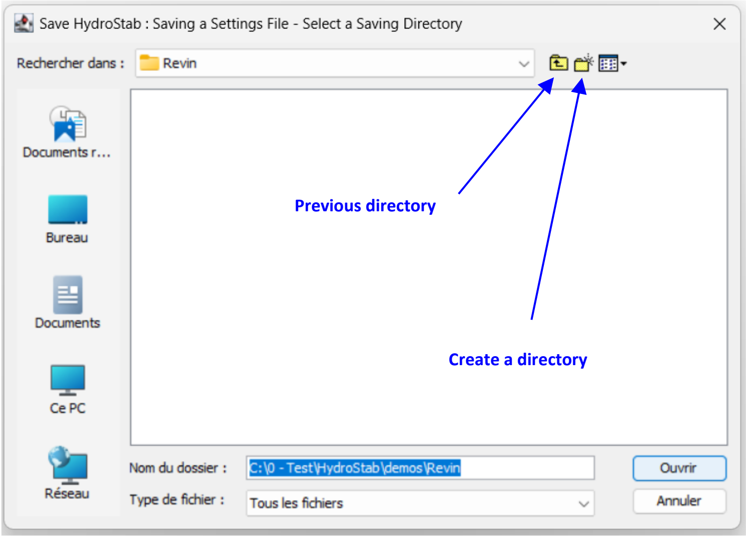
Figure 23 : Selecting the backup mode

The user can therefore:

- Modify the configuration of the existing file
- Save configuration with new automatic numbering of the recording file
- Simply return to the current HydroStab session, without any modifications

The record contains the unique set of the hydraulic configuration of the site, and all the tests carried out with different values of the hydraulic settings and the quadruplets (Kp, Ti, Td, Kd).

1. Select the backup directory::



C:\0 - Test\HydroStab\demos\Revin

Figure 24 : Selecting a backup directory

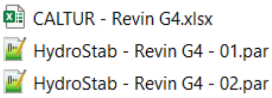
2. Validate or Cancel the operation

The name of the recording file is automatic, and consists of:

- of the prefix « HydroStab - »
- of the site ID indicated in the HydroStab window. For example


Revin G4

- this name is associated with an automatically calculated registration number: if this is the first record, the index is 01. Otherwise, the index is equal to that of the last record made, increased by 1 unit.
- the record suffix is « .par »

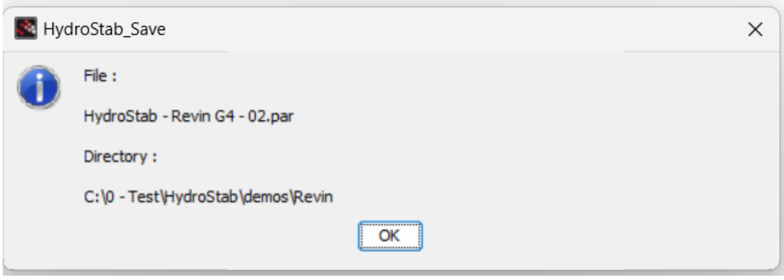


CALTUR - Revin G4.xlsx
HydroStab - Revin G4 - 01.par
HydroStab - Revin G4 - 02.par

Figure 25 : Naming recording files of a HydroStab session

☞The detailed structure of a backup file is shown in *Appendix C*

3. Once the recording has been validated and completed, a window displays the backup name.



HydroStab_Save

File :

HydroStab - Revin G4 - 02.par

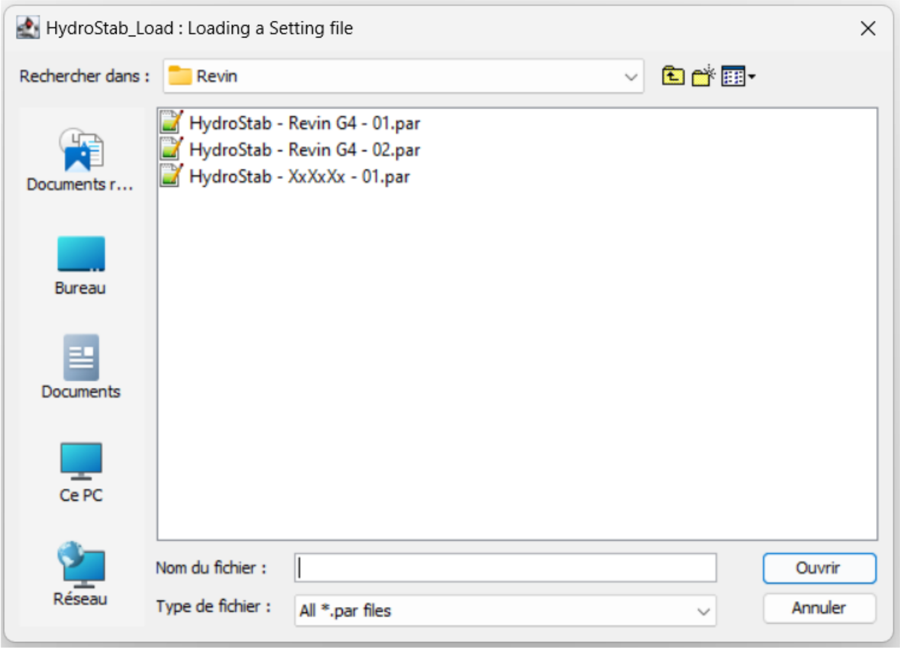
Directory :

C:\0 - Test\HydroStab\demos\Revin

Figure 26 : Confirmation of recording a HydroStab session

4.3.2.3 *Reloading a configuration*

1. To reload a working configuration, activate the “Load” function and bring up the file manager:



HydroStab_Load : Loading a Setting file

Rechercher dans : Revin

HydroStab - Revin G4 - 01.par
HydroStab - Revin G4 - 02.par
HydroStab - XxXxXx - 01.par

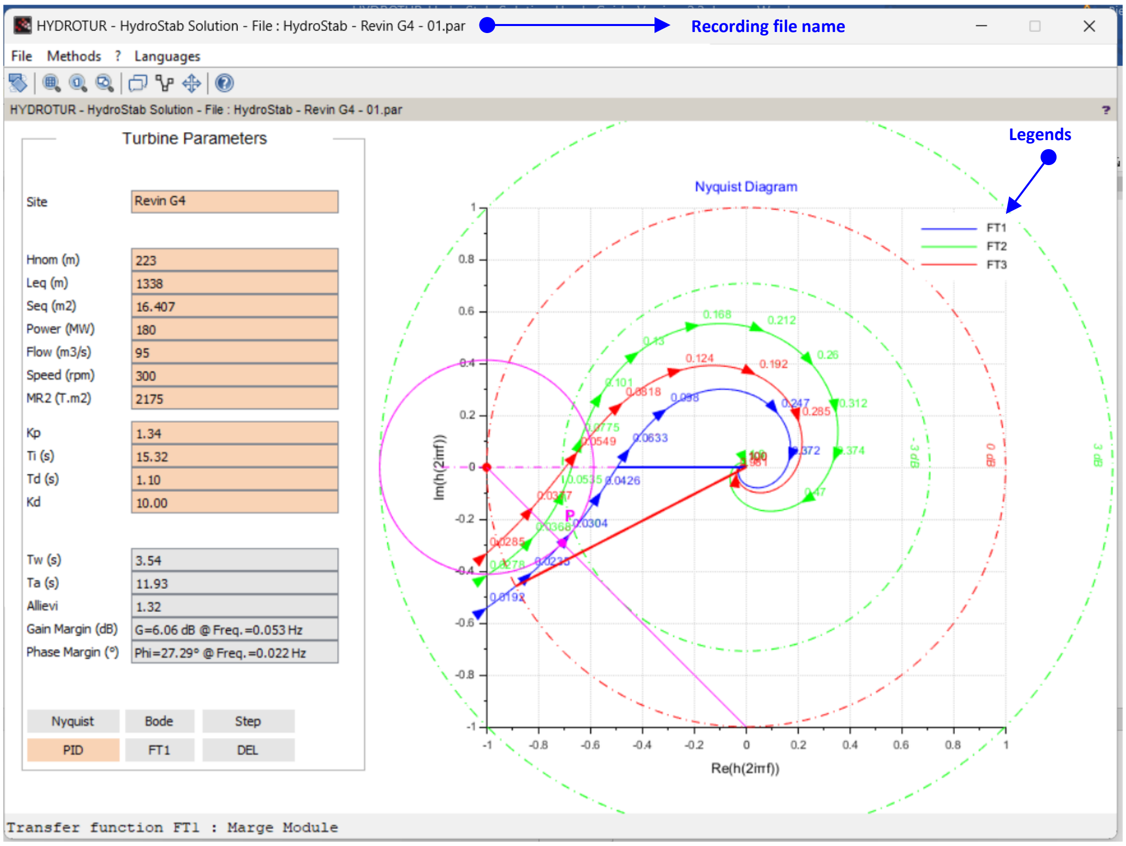
Nom du fichier :

Type de fichier : All *.par files

Figure 27 : Reloading a parameter file

The manager searches for files with the suffix ".par" in the selected tree.

2. After validation, the configuration, calculations, and plots are returned:



HYDROTUR - HydroStab Solution - File : HydroStab - Revin G4 - 01.par → **Recording file name**

Legends

HYDROTUR - HydroStab Solution - File : HydroStab - Revin G4 - 01.par

Turbine Parameters

Site: Revin G4
Hnom (m): 223
Leq (m): 1338
Seq (m2): 16.407
Power (MW): 180
Flow (m3/s): 95
Speed (rpm): 300
MR2 (T.m2): 2175
Kp: 1.34
Ti (s): 15.32
Td (s): 1.10
Kd: 10.00
Tw (s): 3.54
Ta (s): 11.93
Allievi: 1.32
Gain Margin (dB): G=6.06 dB @ Freq.=0.053 Hz
Phase Margin (°): Phi=27.29° @ Freq.=0.022 Hz

```
Transfer function FT1 : Marge Module
```

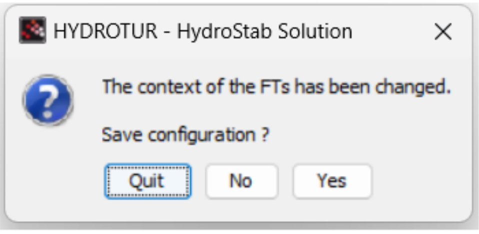
Figure 28 : Restoring a parameterization file

☞ *Note: The source file representing the figure above is indicated indiqué in Appendix C*

*4.3.2.4 Closing a HydroStab Solution session « **Close** » or* ☒

A HydroStab solution session is closed by activating the submenu, or more simply by clicking on the cross ☒ located at the top right of the execution window.

Before operation, HydroStab checks whether the initial configuration of the current job has changed. If so, a final confirmation request is requested to offer a recording of the session:



HYDROTUR - HydroStab Solution

The context of the FTs has been changed.

Save configuration ?

Figure 29 : Confirmation of closing a HydroStab session

4.3.3 « Methods » Menu

The "**Methods**" menu offers to juxtapose with the main Margin of Module method, well-known algorithms, for comparison:

- Ziegler-Nichols method
- Takahashi method
- Module Margin set to -3dB for gain margin comparison.

Leurs modes de fonctionnement sont indiqués dans la suite de ce document.

4.3.4 Menu ?

4.3.4.1 *Comment* Menu

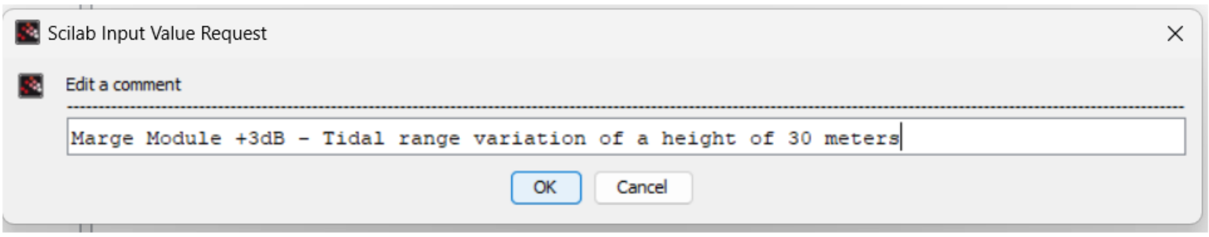
A comment corresponds to the text displayed in the “info_message” area of the main screen (*see Figure 14)*

This comment is initialized according to the method implemented by the user, with each new calculation introducing the plot of a new transfer function FT

Five attributes are possible, and automatically inserted by **HydroStab** :

- Marge Module +3dB
- Ziegler-Nichols
- Takahashi
- User
- Marge Module -3dB

The Comment menu allows you to enrich this content by adding additional information, such as a variation in the tidal range, flow rate, or any other particular condition of the test. (*see example in Appendix B)*.


Scilab Input Value Request

Edit a comment

Marge Module +3dB - Tidal range variation of a height of 30 meters

Figure 30 : Enriching a comment in the presentation

4.3.4.2 Menu *Symétrie Nyquist*

This function alternately adds or removes the symmetrical plot in the Nyquist diagram:

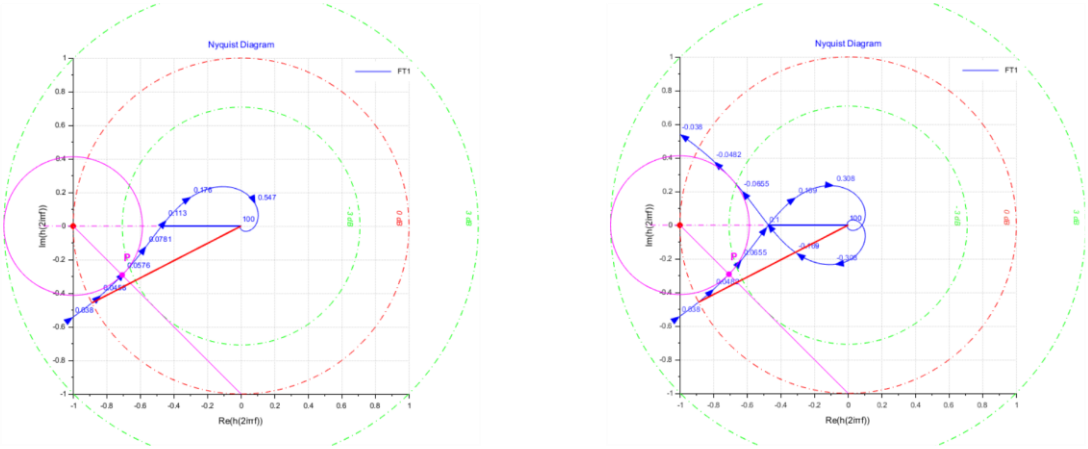


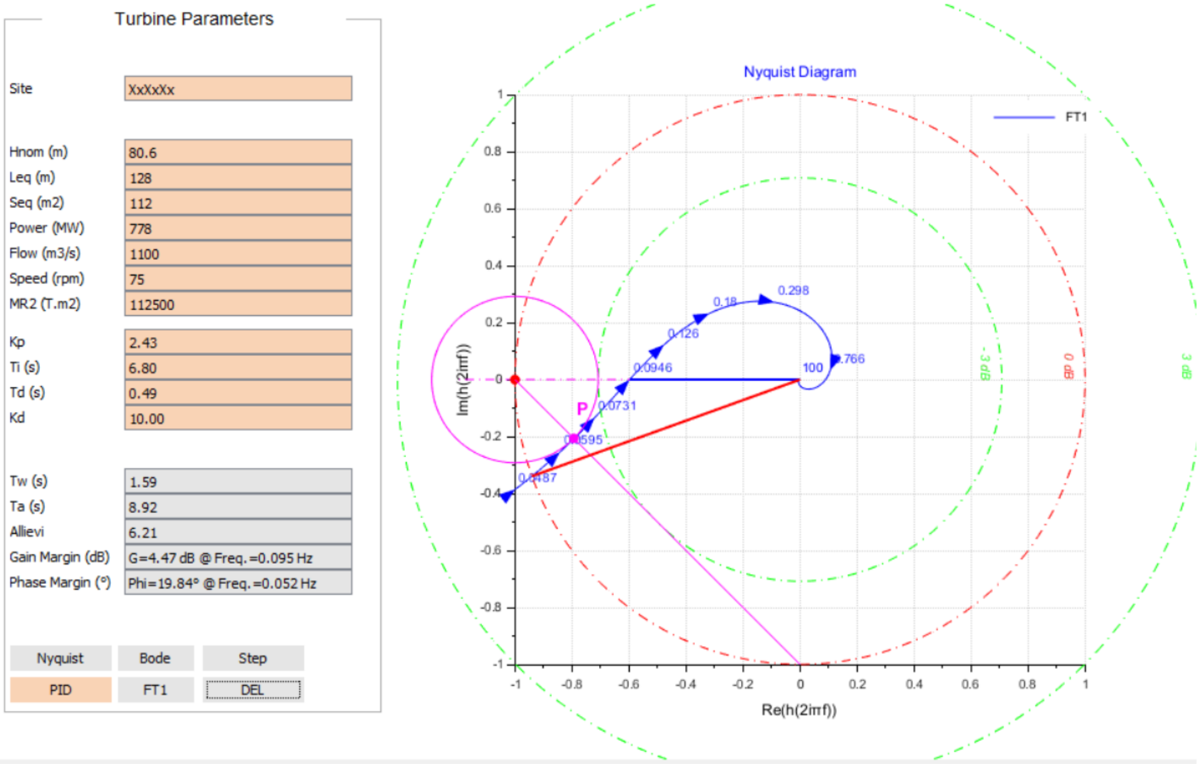
Figure 31 : Symmetry in the Nyquist plane

4.3.4.3 Nyquist -3dB Menu

In this case study, the module margin circle is tangent to the -3dB curve

The margin of gain is reduced.

This study, in this case, is to be compared with the methods of Ziegler-Nichols and Takahaschi proposed.



Turbine Parameters

Site	XxXxXx
Hnom (m)	80.6
Leq (m)	128
Seq (m2)	112
Power (MW)	778
Flow (m3/s)	1100
Speed (rpm)	75
MR2 (T.m2)	112500
Kp	2.43
Ti (s)	6.80
Td (s)	0.49
Kd	10.00
Tw (s)	1.59
Ta (s)	8.92
Allievi	6.21
Gain Margin (dB)	G=4.47 dB @ Freq.=0.095 Hz
Phase Margin (°)	Phi=19.84° @ Freq.=0.052 Hz

Figure 32 : Nyquist with Module Margin set to -3dB

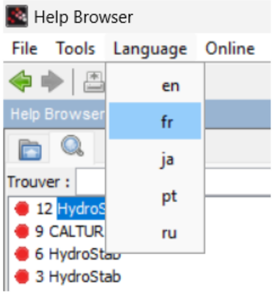
*4.3.4.4 « **Online Help** » Menu*

This menu opens the HydroStab online help. The online help can also be launched in the Scilab console by entering the command "**doc HydroStab**".

Online help is created in the HydroStab\help directory in files in "xlm" format.

Then, by recompiling the program, a ".JAR" file is available to create the English/French online help.

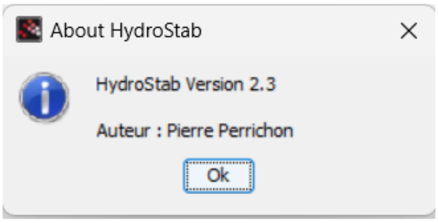
When a help page is open, it is possible to change the display language using the "Language" menu.



4.3.4.5 HydroStab Version

The version of HydroStab is displayed in the Scilab console when you launch a session of the program.

It can also be read using the menu in the HydroStab toolbar « **About HydroStab Solution** » :



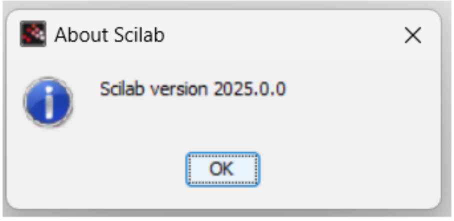
HydroStab Version 2.3

Auteur : Pierre Perrichon

Figure 33 : HydroStab Version

4.3.4.6 Scilab Version

The version of Scilab used is recalled here



Scilab version 2025.0.0

Figure 34 : Version de Scilab

This version can be downloaded from the site

https://www.scilab.org/

5 XCOS MODEL DIRECTORY

The calculations established in HydroStab are based on graphical representations of the elements to be considered, produced using the XCOS diagram editor.

In anticipation, these basic models are consistent with the general presentation made in *Figure 41*.

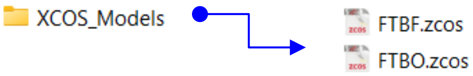


Figure 35 : XCOS Models – List of models

The transfer functions indicated below, cited as an example, refer to the parameters of the Revin Group 4 plant; i.e. with the calculated parameters Tw, Ta and aut=0 (*see next chapter*)

5.1 Scale model of the process to be adjusted

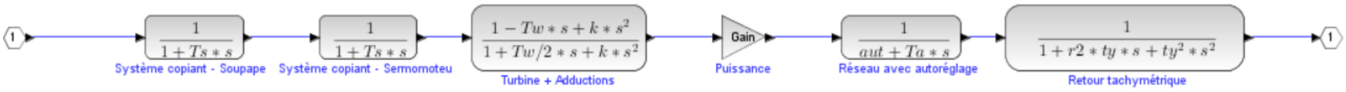
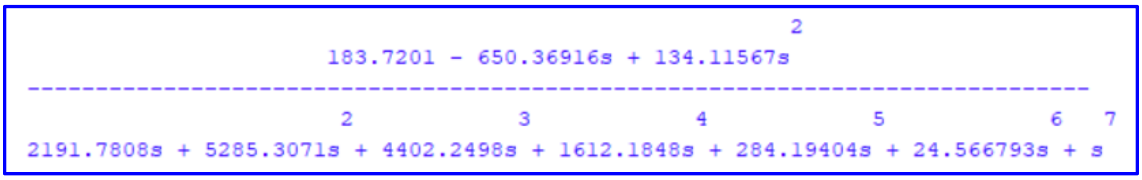


Figure 36 : Scale model of the process to be adjusted

- Process transfer function to be adjusted PROCESS – Polynomial representation [8]:



```
                                                        2
                      183.7201 - 650.36916s + 134.11567s
------------------------------------------------------------------------------
                       2            3            4            5            6   7
2191.7808s + 5285.3071s + 4402.2498s + 1612.1848s + 284.19404s + 24.566793s + s
```

5.2 Open loop process control model FTBO FTBO.zcos

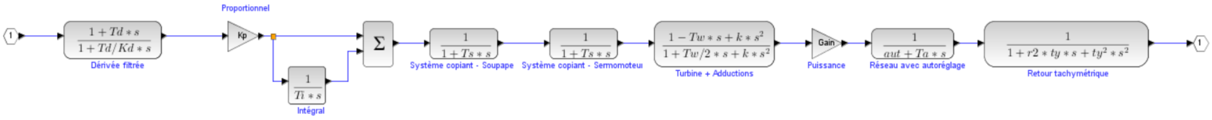
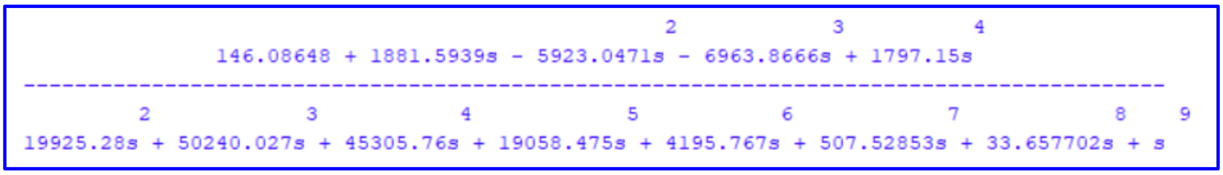


Figure 37 : FTBO model of closed loop process control

☞ Note: the process simulation is obtained directly from the FTBO by disengaging the speed PID, i.e.: Kp=1, Td=0 s, and Ti=1.e10 s

- Open Loop Transfer Function FTBO – Polynomial Representation s [8]:



```
                                                  2            3          4
               146.08648 + 1881.5939s - 5923.0471s - 6963.8666s + 1797.15s
-----------------------------------------------------------------------------------------
         2            3           4            5           6            7            8   9
19925.28s + 50240.027s + 45305.76s + 19058.475s + 4195.767s + 507.52853s + 33.657702s + s
```

---

[8] The transfer functions are given for information purposes, for a parameterization defined in the study of the Revin site by the transfer function FT1

5.3 Closed-loop process control model FTBF FTBF.zcos

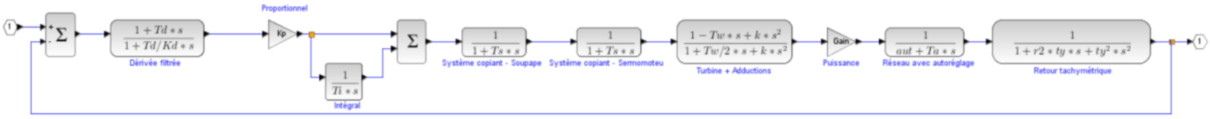
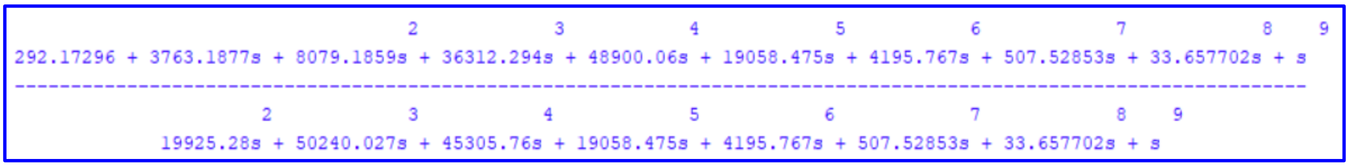


Figure 38 : Closed-loop process control model

- Closed Loop Transfer Function FTBF – Polynomial Representation [8] :



```
                                   2            3           4            5           6            7            8   9
292.17296 + 3763.1877s + 8079.1859s + 36312.294s + 48900.06s + 19058.475s + 4195.767s + 507.52853s + 33.657702s + s
-------------------------------------------------------------------------------------------------------------------
                      2            3           4            5           6            7            8   9
             19925.28s + 50240.027s + 45305.76s + 19058.475s + 4195.767s + 507.52853s + 33.657702s + s
```

5.4 Use in HydroStab program

Les The “FTBO” and “FTBF” data are global variables, and accessible at any time in the Scilab console:

- FTBO is represented in its polynomial form in s (*type FTBO*)
- FTBF is represented in its matrix state form (A, B, C, D) in state-space (*Type FTBF*)

6 CALCULATION ELEMENTS FOR DETERMINING THE STABILITY PARAMETERS OF THE SPEED REGULATOR

6.1 Introduction

Every project includes a phase of studying the stability of the hydraulic unit. It is therefore necessary here to recall the context of the speed regulator based on the essential elements characterizing a hydraulic power station.

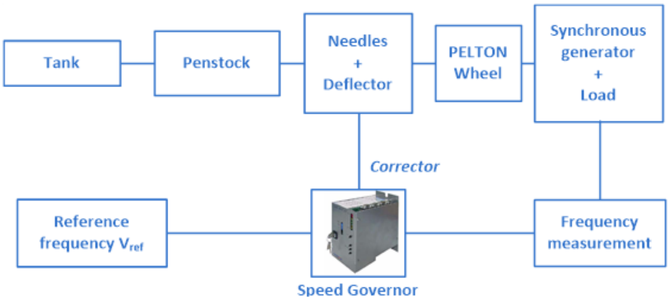


Figure 39 : Block diagram of a PELTON hydraulic unit

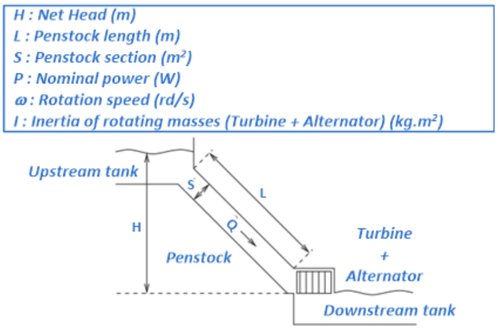


Figure 40 : Input data for a stability study

Two main phases of approach guarantee a priori the control of the work. These two phases are complementar

- ***Hydraulic***

Taking into account the water hammer and wave phenomena in the penstock, caused by the sudden closing of a valve (distributor of a FRANCIS or KAPLAN turbine, or injectors of a PELTON machine), a study of the hydraulic transients determines the opening and closing operating times of the adjustment devices, in order to minimize the overpressure generated in the pipe, following a load shedding, or an emergency shutdown of the group.

This study is conducted by hydraulic experts, specialists in Fluid Mechanics.

These operating times are controlled by flow reducers in the oil-hydraulic circuit, and thus condition the flow of oil admitted into the servomotor chambers. Unfortunately, this results in an increase in the overspeed measured on the machine.

- The expert study thus provides the best compromise between overpressure and overspeed by determining a double-slope oleohydraulic closing law, if necessary, and guarantees the safety conditions of the structure, without rupture of the conduit or runaway of the machine. **The Governor is therefore not a safety device.**
- ***Oleohydraulics***

Appendix D recalls the role of the speed governor in the oleohydraulic control chain.

The governor positioner in fact controls the water intake servomotor(s) on the hydraulic wheel via actuators.

- ***Électric***

The electrical stability study has the following objects:

- ✓ to determine the optimal quadruplet $\left[K_p, T_i, T_d, K_d\right]$ of the speed regulator of the group coupled to an isolated electrical network (aut=0)
- ✓ to characterize the group's response to load variations on the network.
- ✓ to provide the regulation parameters to the commissioning personnel and the operator, in order to minimize the optimization time on site, and therefore the volume of useful water to be used. This operation is, in fact, not always possible or easy to carry out.

6.1.1 Unit stability study

The “Conduit / Turbine / Alternator” assembly is considered to be similar to the “Conduit / Orifice / Rotating masses” assembly.

Two fundamental parameters are used to model the system shown in *Figure 39*, from the input data ( ) defined in *Figure 40*.

✓ he mechanical launch time (or specific inertia of the group), is the time necessary to make the rotating masses Turbine + Alternator pass from zero speed to rotation speed:

$$\boxed{T_a = \frac{I.\omega^2}{W}\ second(s)} \quad (3.1)$$

This time is justified from the fundamental equation of mechanics[9] $I.\frac{d\Omega}{dt} = C_m - C_r$

- The hydraulic launch time is the characteristic time of the pipe discharging at the speed $V = \frac{Q}{S}$ that the water takes from rest to reach this speed:[10] :

$$\boxed{T_w = \frac{L.Q}{g.H.S}\ second(s)}^{11} \quad (3.2)$$

, where g is the acceleration of gravity expressed in $m.s^{-2}$.

Noting the **hydraulic power** of the unit $\boxed{W = \rho.g.H.Q}$, either $\boxed{Q = \frac{W}{\rho.g.H}}$[12], and by reinjecting the value of the **hydraulic flow** Q into (3.2), we also obtain:

$$\boxed{T_w = \frac{L.W}{\rho.g^2.H^2.S}\ second(s)}^{13} \quad (3.3)$$

, where ρ denotes the density of water, in kg/m³

- On the other hand, and for information purposes, the significant Alliévi coefficient allows us to know the type of oscillations generated in the pipe. This coefficient is not involved in the calculations:

$$\boxed{Allievi = \frac{Q.a}{2.g.H.S}} \quad (3.4)$$

---

[9] [6] *Turbines hydrauliques et leur régulation - page 403*

[10] [6] *Turbines hydrauliques et leur régulation - page 450*

[11] This formula is used in the Excel worksheet « CALCUR »

[12] This formula is used in the Excel worksheet « CALCUR »

[13] This formula of Tw is used in the script « SolveurHydroStab.sci »

$\boxed{a}$ is the speed coefficient of the water wave (m/s)

If $Allievi > 1$, the water hammer caused by the sudden closing of a valve is called “mass”.

If $Allievi < 1$, The water hammer caused by the sudden closing of a valve is called a “wave”.

6.2 Study in small movements

The small-movement simplifications of the analytical equations of the process lead to modeling the hydraulic group by the reduced system:

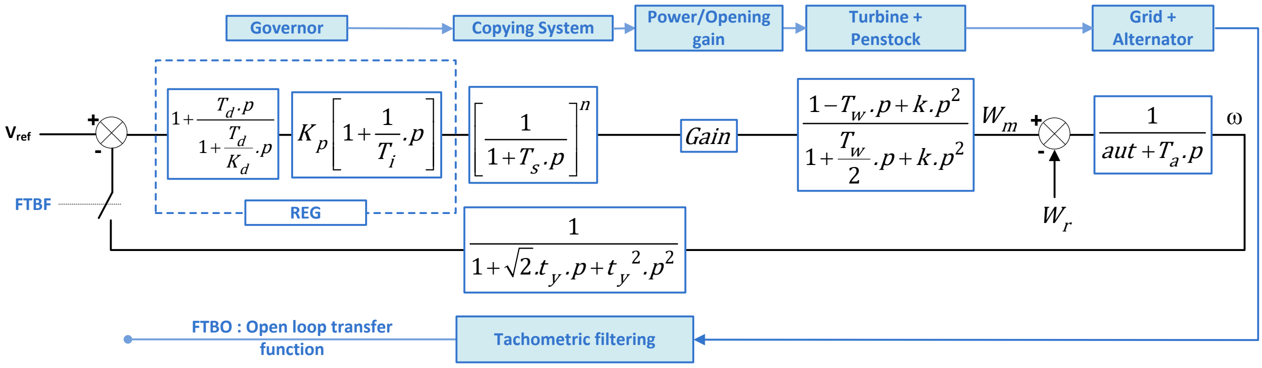


Figure 41 : Simplified calculation circuit for modeling a hydraulic group

The regulation parameters will therefore be calculated on this basis. We will therefore assume the calculation circuit presented in *Figure* 41, and we will initially focus on the system represented by the open-loop transfer function (FTBO).

Additional notations, hypotheses, and comments

Governor

- A detailed structure of the speed governor in the final circuit is also presented in *Appendix* ***E.2 : Speed governor for FRANCIS turbines***
- The modeled governor is astatic, i.e. $B_p = 0$, which is the worst case.

Copying System

Simplification :

- $n=1$ Single-stage position controller. The controller directly controls a proportional servovalve.
- $n=2$ Double-stage position regulator. The actuator (valve), controlled by the regulator, controls the main distributor (see schematic diagram in **Appendix D : HYDRAULIC STRUCTURE OF THE 2-STAGE SYSCOP COPYING SYSTEM**, *Figure 80*.

This simplification is only valid for small movements., i.e. for small load variations, and for servomotor movements not reaching the hydromechanical operating times.

In the calculations we adopt $\boxed{n=2}$ and $\boxed{T_s = 0.25\ s}$

Power/Opening gain

$\boxed{G=1}$. Here, the model does not take into account the Power/Opening linearization law

Turbine + Penstock

k is determined to take into account the water hammer wave in the pipe: $\boxed{k=\left(\frac{2.L}{\pi.a}\right)^2}$

$\boxed{a}$ est le coefficient de célérité. Il représente la vitesse de propagation des ondes de coup de bélier d'eau dans la conduite[14], exprimée en m/s,. Pour un orifice de 1 mètre de diamètre avec une conduite de 1 cm d'épaisseur $\boxed{a = 1000 \ \ m/s}$. Cette valeur est portée dans les calculs.

Grid + Alternator

$\boxed{aut}$ is the network self-adjustment coefficient, sometimes called "network droop".

When the turbine supplies a purely resistive network, the electric torque decreases when the speed of the unit increases ( ). When , the electric torque is independent of the frequency, the power increases with the speed of the unit.

In the calculations we adopt $\boxed{aut = 0}$, which is the worst case.

➔ *Note that the simulation with the fact that the process already includes a pure integrator.*

Tachometer

t_y is the tachometer module constant. In calculations, $\boxed{t_y = 0.1 \ s}$

7 OPTIMIZATION METHODS

7.1 Module Margin Method

7.1.1 Stability criterion in the Nyquist plane

The Nyquist plot consists of plotting the transfer function shown in *Figure 41* in the complex plane. Its disadvantage compared to the Bode plot is that explicit knowledge of the frequency is lost. Nevertheless, this plot allows to define a stability criterion known as the open-loop Nyquist criterion:

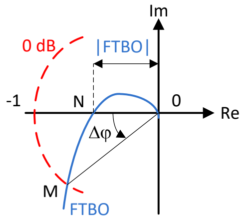


Figure 42 : Nyquist Plan

☞ **If the FTBO transfer function of a controlled system has no pole with a positive real part, then this system is closed-loop stable if, when describing the open-loop Nyquist locus FTBO in the direction of increasing frequencies, an observer sees the critical point (-1,0) to his left.**

Using this criterion, stability margins can be defined (***Figure 43***) :

- **Gain Margin** is defined as the reciprocal of the system gain at the pulse where the open loop system phase FTBO reaches -180°. It corresponds to *Figure 42* at point N, and is generally expressed in dB: $\boxed{Marge\ de\ Gain = -20 \log\left(\left|ON\right|\right) = (-20.\log\left(\left|FTBO\right|\right)}$. The **Critical Frequency** is the frequency where the phase falls below 180°.
- **Phase Margin** represents the difference between the phase of the FTBO system considered and -180° at the cut-off pulse ω_c , i.e. the pulsation for which the module is equal to 0 dB: $\boxed{Phase\ Margin = arg\left[FTBO\right] - (-180°)}$.

  It is also defined by the point M corresponding to the intersection of the Nyquist locus of FTBO with the unit circle centered at the origin and of unit radius (*Figure 42*).

The **HydroStab** software calculates the a priori adjustment values of the speed regulator control parameters in small movements, by imposing a minimum distance between the Nyquist locus and the critical point. This distance is also called **the Module Margin**.

This software is thus based on a frequency method, and is only applicable to a linear system.

---

[14] $\boxed{a}$ value is is calculated by $\frac{1}{a^2} = \rho\left[\frac{1}{\varepsilon} + \frac{D}{E.e}\right]$. See meaning and explanations in [6] page 434

The objective is to force the FTBO (regulator + process) to pass through an imposed point **P** in the Nyquist plane)

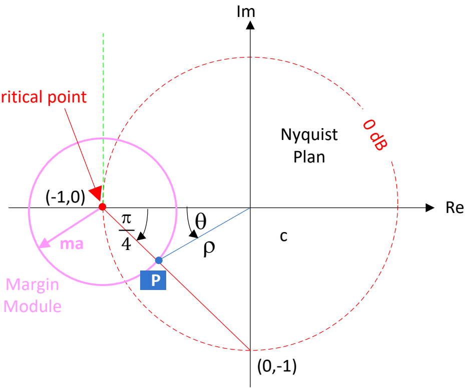
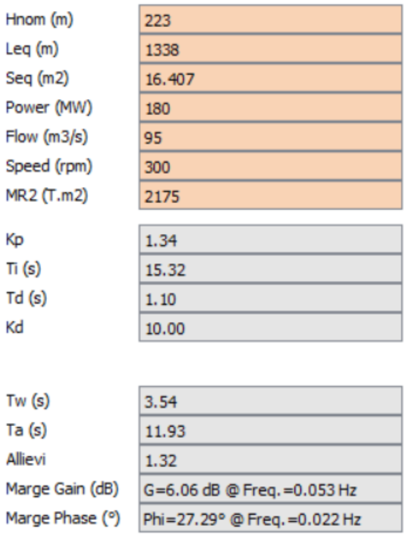


Figure 43 : Module Margin in the Nyquist Plane



Hnom (m)	223
Leq (m)	1338
Seq (m2)	16.407
Power (MW)	180
Flow (m3/s)	95
Speed (rpm)	300
MR2 (T.m2)	2175
Kp	1.34
Ti (s)	15.32
Td (s)	1.10
Kd	10.00
Tw (s)	3.54
Ta (s)	11.93
Allievi	1.32
Marge Gain (dB)	G=6.06 dB @ Freq.=0.053 Hz
Marge Phase (°)	Phi=27.29° @ Freq.=0.022 Hz

Figure 44 : Input data and results of the small motion stability study

ma denotes the margin module, and is represented by a circle of radius **ma** centered on the critical point (-1.0).

The point **P** targeted indicates the intersection between this circle and the line passing through the points (-1,0) and (0,-1).

The angle between this line and the axis Re is therefore equal to $\frac{\pi}{4}$.

7.1.2 Module Margin setting to +3 dB

7.1.2.1 Principle

The circle of radius ma is tangent to the circle of radius +3 dB:

$$20.\log(1+ma)=+3\text{ dB}$$

$$ma=10^{\frac{3}{20}}-1$$

i.e.

$$ma=0.4125375$$

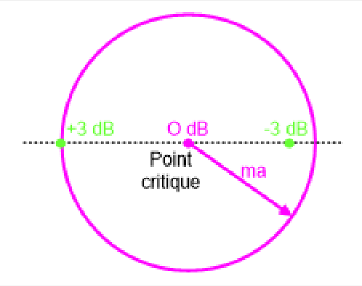


Figure 45 : Module Margin adjustment to +3 dB

7.1.2.2 Results at +3 dB

Module Margin **ma** ≈ 0.412	Integral action angle **ai**=-20°	Angle Action Derivative **ad**=+10°

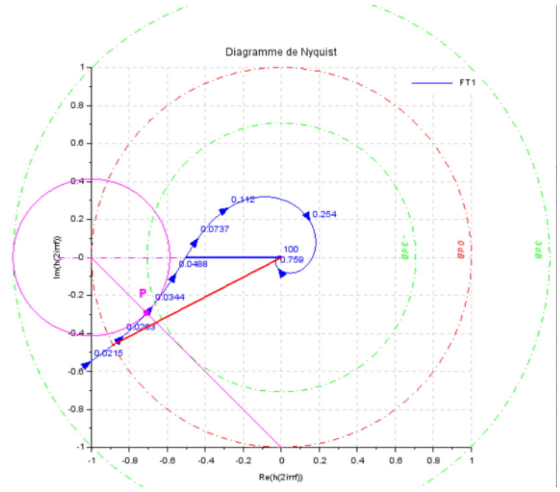


Figure 46 : Controller stability in the Nyquist plane (FTBO) – ma≈0.41

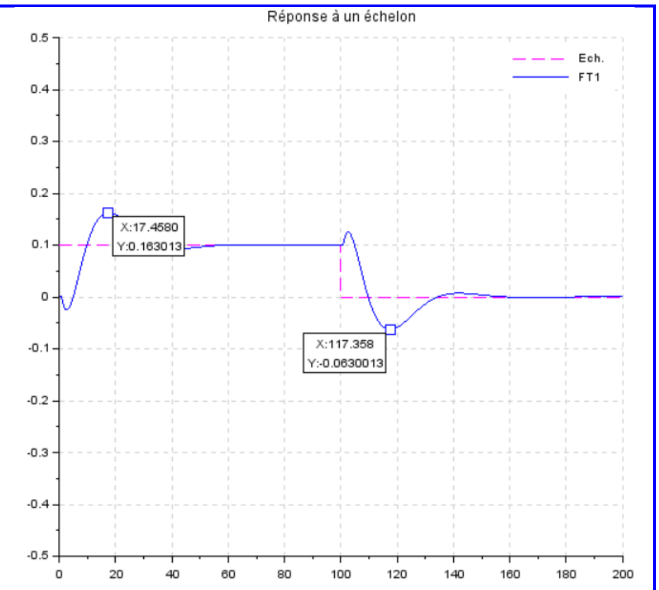
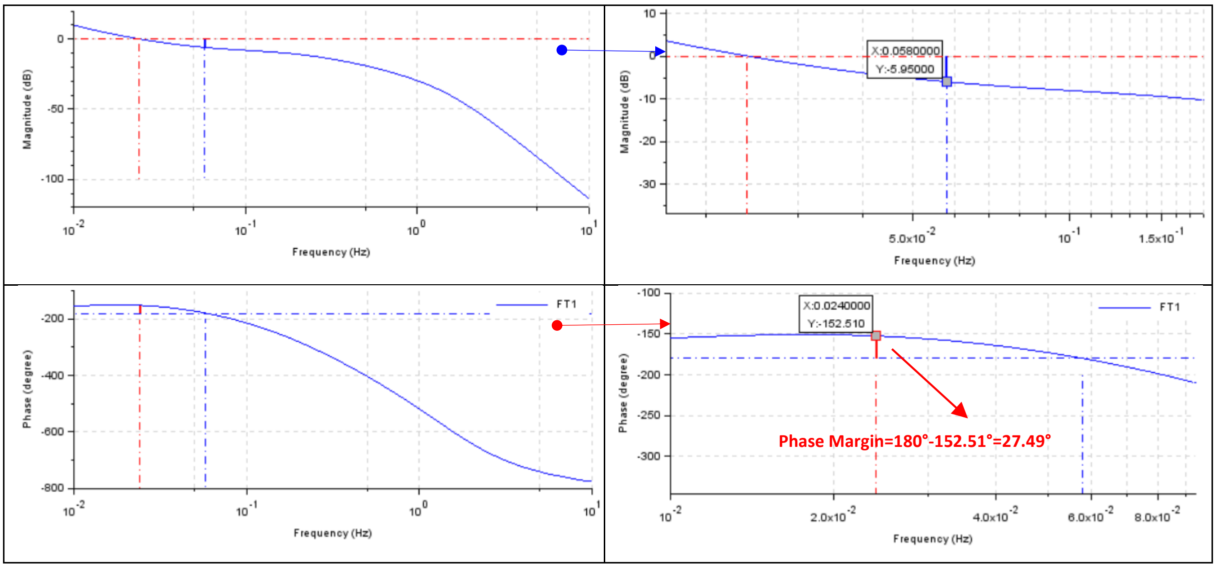


Figure 47 : Step responses of the small motion regulator (FTBF)

```
FT1 :     Kp=1.5100 Ti=13.6300 s Td=0.9800 s Kd=10.0000
          Marge de Gain G=5.95 dB @ Freq.=0.058 Hz          Marge de Phase Phi=27.49° @ Freq.=0.024 Hz
```

Figure 46 shows that the HydroStab software calculation circuit is well within its objective with a **ma** module margin set to +3dB. Thus, the Nyquist locus of the open-loop process is corrected by the PID to pass through point **P**.



Phase Margin=180°-152.51°=27.49°

Figure 48 : Open Loop Bode Plot - Gain and Phase Margins - Ma Setting at +3dB

As shown in *Figure 48*, the PID parameter tuning method establishes characteristics such as:

- The gain margin is approximately 6dB,, that is, at the frequency where the phase shift between input and output is -180°, the output/input gain is 6dB, i.e $10^{\frac{-6}{20}} \approx 0.5$

- The phase margin is approximately 27°, i.e. at the frequency where the output/input gain is 1 (0dB), the phase shift between the output and the input is -180°+27°≈-153°.

7.1.3 Adjusting the Module Margin to -3 dB

7.1.3.1 Principle

The circle of radius ma is tangent to the circle of radius -3 dB:

$$20.\log(1-ma)=-3\text{ dB}$$

$$ma=1-10^{\frac{-3}{20}}$$

Soit

$$ma=0.2920542$$

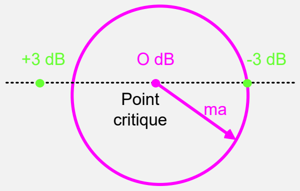


Figure 49 : Module Margin adjustment to -3 dB

7.1.3.2 Results at -3 dB

Module Margin **ma** ≈ 0.29	Integral action angle **ai**=-20°	Angle Action Derivative **ad**=+10°

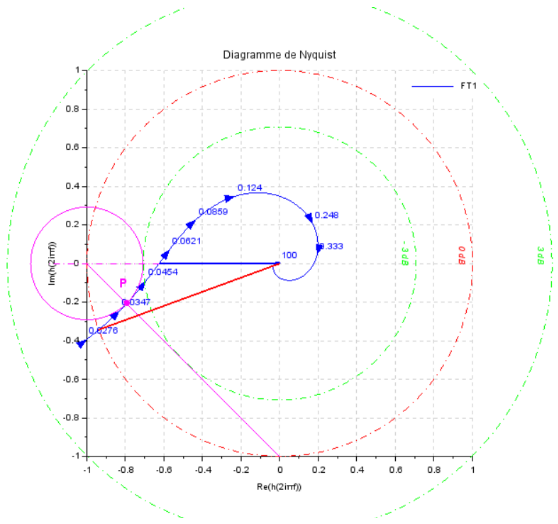


Figure 50 : Stabilité du régulateur dans le plan de Nyquist (FTBO) – ma=0.29

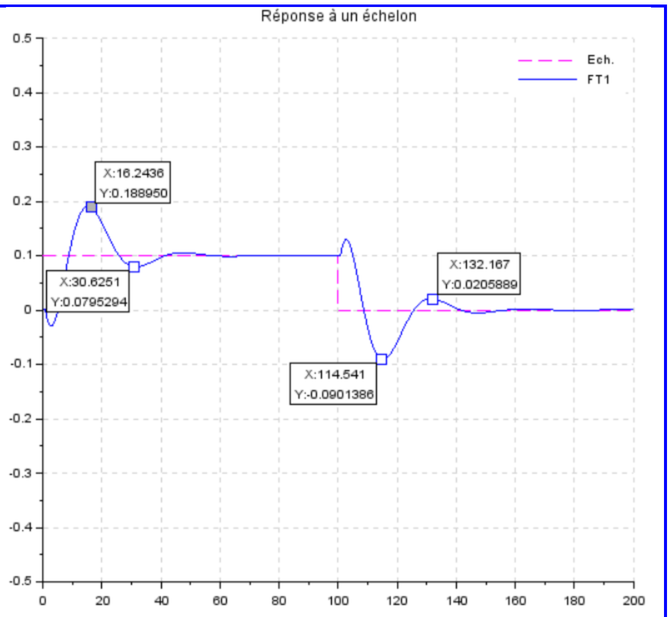
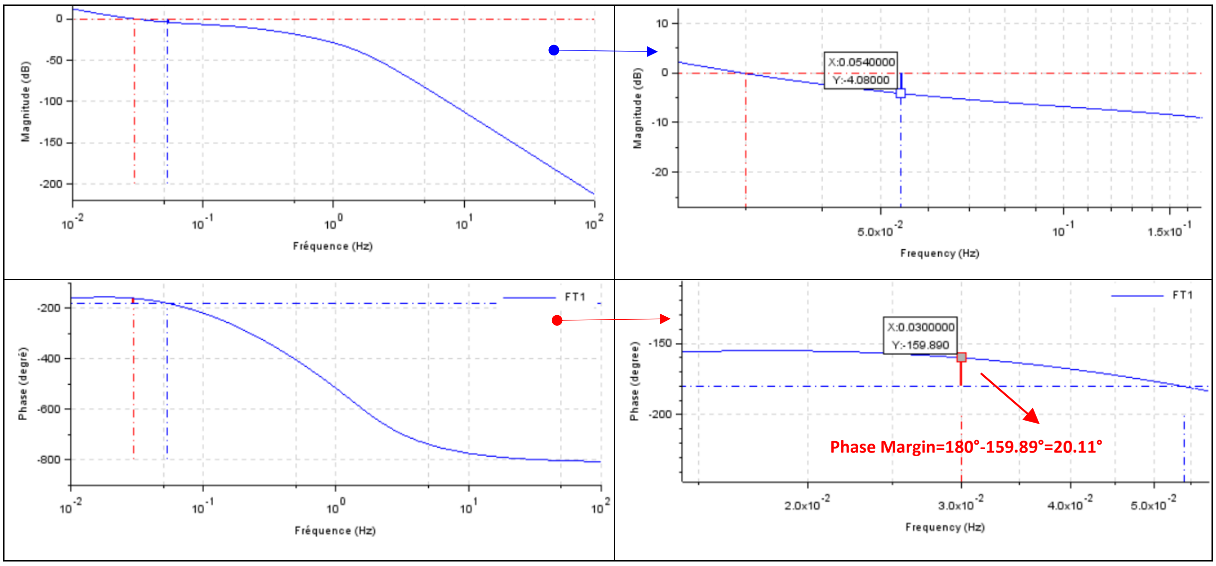


Figure 51 : Step responses of the small motion regulator (FTBF)

```
FT1 :    Kp=1.8000 Ti=11.8360 s Td=0.8470 s Kd=10.0000
         Marge de Gain G=4.08 dB @ Freq.=0.054 Hz        Marge de Phase Phi=20.11° @ Freq.=0.030 Hz
```

Figure 50 shows that the calculation circuit of the HydroStab software is well in line with its objective with a module margin **ma** set to -3dB. Thus, the Nyquist locus of the open-loop process is corrected by the PID to pass through point **P**.



Phase Margin=180°-159.89°=20.11°

Figure 52 : Open Loop Bode Plot - Gain and Phase Margins - ma Setting at -3dB

As shown in *Figure 52* , the PID parameter tuning method establishes characteristics such as:

- The gain margin is approximately 4dB, i.e. at the frequency where the phase shift between input and output is -180°, the output/input gain is 4dB, i.e. $10^{\frac{-4}{20}} \approx 0.63$
- The phase margin is approximately 20°, i.e. at the frequency where the output/input gain is 1 (0dB), the phase shift between the output and the input is -180°+20°≈-160°.

7.2 Ziegler-Nichol’s method

7.2.1 Principle of the method

The Ziegler-Nichols method allows the parameters of the regulator controlling the PROCESS[15] process to be adjusted.

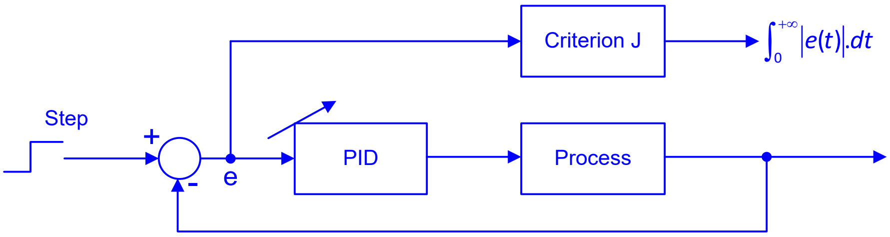


Figure 53 : Principle of the Ziegler-Nichols method

By simulating the loop of *Figure 53* for various models, Ziegler & Nichols (ZN) searched for the parameters of the PI, PD, PID controllers minimizing the J criterion:

$$J = \int_0^{+\infty} |e(t)|.dt \qquad (3.5)$$

, during an index variation of the setpoint, the system being in steady state at time t=0.

The method used is called « Pumping limit» :

- The process being looped by a proportional action regulator only, the critical gain K_{cr} is increased until sustained oscillations appear (pumping phenomenon).

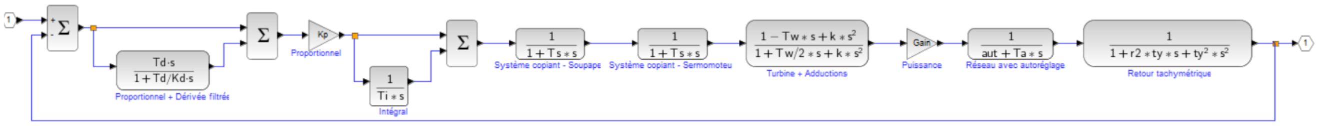


Figure 54 : Closed-loop PID “FTBF.zcos” for application of the Ziegler-Nichols method

7.2.2 Implementation of the method

7.2.2.1 *Selecting Manual or Automatic modes for implementation*

The file « **HydroStab.par** » contains the following parameters, allowing the adjustment of the Zieglers-Nichols, or Takahashi methods:

Setting	Meaning
Auto_ZN	Automatic or manual search for critical gain Kcr in Ziegler-Nichols or Takahashi methods (%t or %f)
Trace_ZN	Allows the display in the console of the iterations of the automatic search (%t or %f)
ZN_Datatip	Display (1) or not (0) of datatips of the Tosc oscillation period

Figure 55 : Choice of optimization parameters for the Zigler-Nichols or Takahashi methods

7.2.2.2 *Activation in manual mode*

The method is activated by selecting « **Ziegler-Nichols** » from the main menu bar of HydroStab:

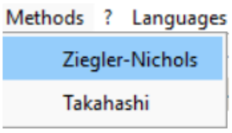


Figure 56 : Activation of the Ziegler-Nichols method

---

[15] Voir [9]

The research method is divided into a step 1 of manual adjustment of the critical gain Kcr, under the responsibility of the operator, and a step 2 of validation of the results of the calculated PID.

7.2.2.3 Initialization and configuration

The ZN model parameters are initialized, by default, with the values Ti=1.e+4 s, Td=0 s, and Kd=10. These values inhibit the Integral action and the derivative action.

The critical gain Kcr is initialized with the inverse of the optimization coefficient, applied to the current Kp value:

$$K_{cr} = K_p / 0.6 \qquad (3.6)$$

The other constants Ts, Tw, k, Gain, aut, Ta, r2, ty are identical to those corresponding to the simulation of the transfer function in progress in HydroStab. The number of this function is the one indicated on the FTx key FT1 .

7.2.2.4 Critical Gain Setting Kcr *- Validation of calculations* Validation

When the procedure is launched, an initial simulation is carried out with the input parameters specified above.

A digital oscilloscope is used to monitor the step response of the process, looped back by its PID corrector; a message box indicates the operations to follow.

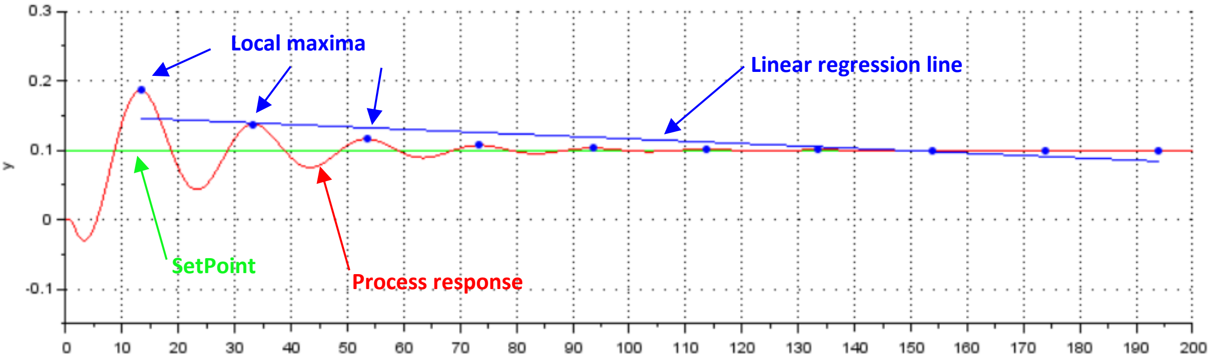
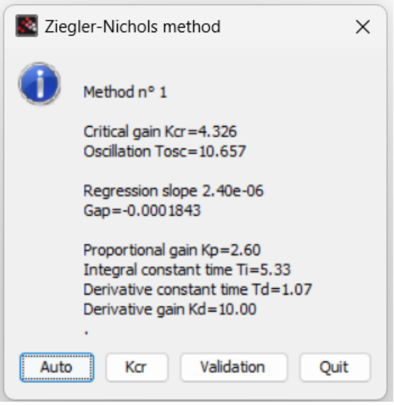


Figure 57 : Ziegler-Nichols scope with linear regression line and local maxima



Method n° 1

Critical gain Kcr=4.326
Oscillation Tosc=10.657

Regression slope 2.40e-06
Gap=-0.0001843

Proportional gain Kp=2.60
Integral constant time Ti=5.33
Derivative constant time Td=1.07
Derivative gain Kd=10.00

Figure 58 : Ziegler-Nichols Dialog Box

The scope visualizes:

- The setpoint step applied at time t=0
- The step response of the process
- The local maxima T_Max(i) of the response (●)
- The linear regression line in the least squares sense defined by the set of points Max(i)

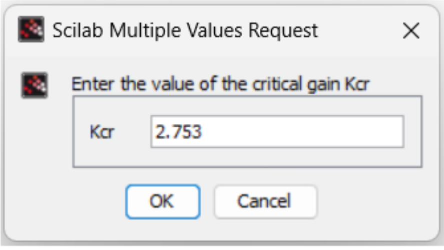
The period of the oscillations is automatically calculated by HydroStab, considering the average of the recorded time intervals:

$$T_{osc} = \left(\sum_{i=1}^{N-1} tMax(i+1) - tMax(i) \right) / (N-1) \qquad (3.7)$$

The “Ziegler-Nichols” dialog box provides the following information:

- The number of the method selected for calculating the parameters of the controlling PID
- The gain Kcr relative to the current estimate, i.e. that imposed by the operator during its test phase.
- The estimated period of the oscillations, in accordance with the formula *(3.7)*
- The slope of the linear regression line
- The calculated values of the adjustment triplet [Kp, Ti, Td], in accordance with the applied method *(*Figure 62 : Proposal for tuning a PID using the Ziegler-Nichols method – Method No. 1)

The various adjustment tests are carried out by clicking on the button Kcr ; in this case, an input box appears to enter the value of the Kcr gain:



Scilab Multiple Values Request

Enter the value of the critical gain Kcr

Kcr 2.753

Figure 59 : Kcr gain input box

One click on the button Quit immediately ends the ZN session to return to HydroStab.

One click on the button Validation causes the new FT, if it does not already exist, to be inserted into the list of current FTs.

In any case, HydroStab points to the FT resulting from this calculation (ex : FT4). Its representation in Nyquist or Bode planes, or its index representation are therefore available under HydroStab.

- Increase the value of the critical gain Kcr of the loop, by entering its value directly after pressing the button Kcr , until a sustained oscillation of the Corrector + Process is obtained.

☞ **More generally, the gain Kcr must be adapted in opposition to the linear regression slope obtained**

- **If the slope of the regression line is positive, decrease the value of Kcr**
- **If the slope of the regression line is negative, increase the value of Kcr**

Figure 60 : General adjustment principle of the critical gain Kcr in the Ziegler-Nichols method

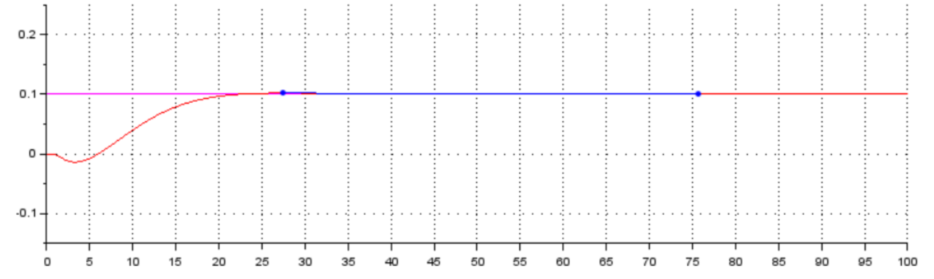
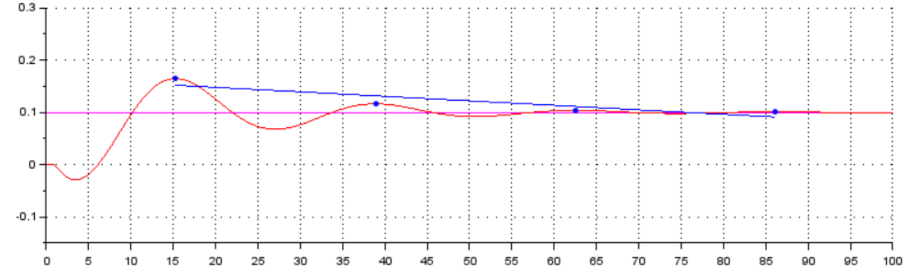
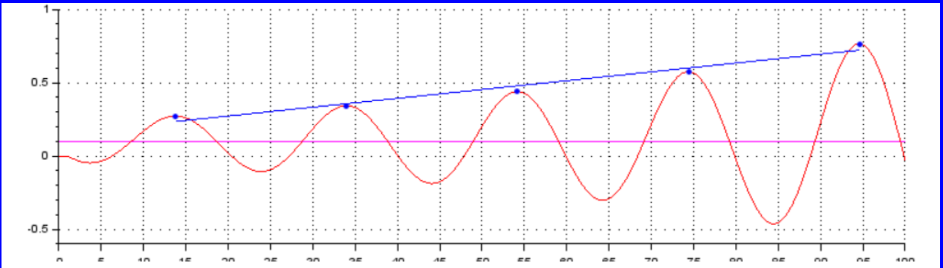
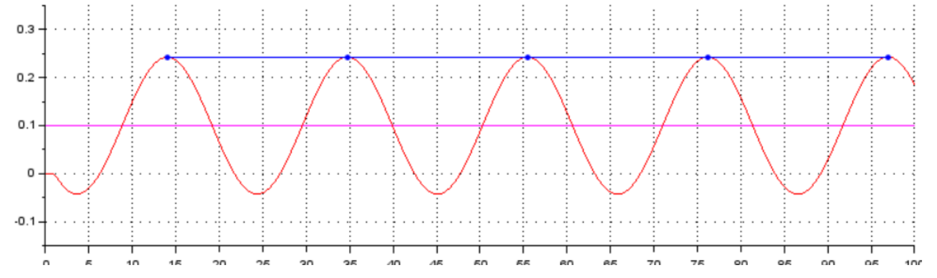
Setting values	Step responses of the closed-loop process
K_{cr}=1	
K_{cr}=2	
💣 **K_{cr}=3** ⛔	
K_{cr}=2.753	

Figure 61 : Example of Ziegler-Nichol's process adjustment

7.2.2.5 Calculations

Method 1, pre-selected in the "HydroStab.par" file (**ZN_Methode=1**), is then applied to calculate the speed regulator parameters.

Governor transmittance	Values of the controller parameters according to the Ziegler-Nichols method		
$PID = K_p.(1+\frac{1}{T_i.s}+T_d.s)$	$K_p = 0.6\ K_{cr}$	$T_i = 0.5\ T_{osc}$	$T_d = 0.1\ T_{osc}$ $K_d = 10$

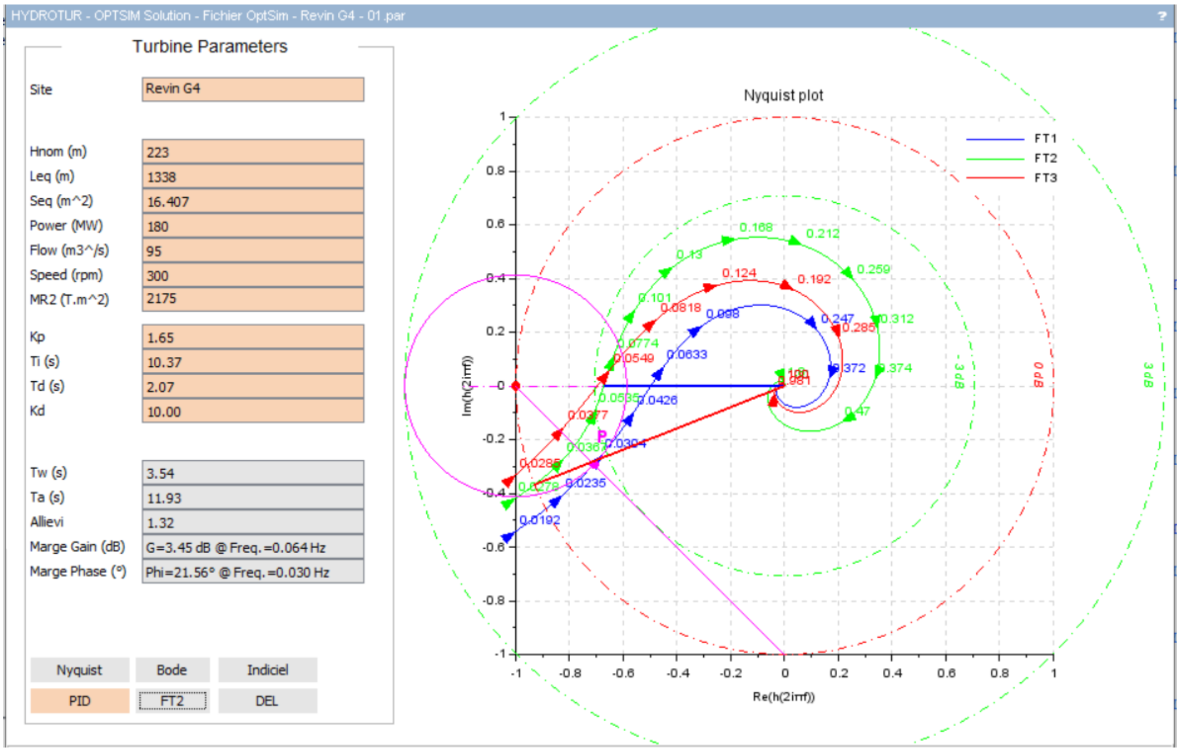
Figure 62 : Proposal for tuning a PID using the Ziegler-Nichols method – Method No. 1

We can verify that we have the well-known relationship at the stability limit:

$$T_i >> 4.T_d \tag{3.8}$$

7.2.2.6 *Verifications*

Referring to the examples given in the Revin case, and to the file “*HydroStab - Revin G4 - 01.par*”, we thus obtain the plot in the Nyquist plane of the transfer function FT2:



HYDROTUR - OPTSIM Solution - Fichier OptSim - Revin G4 - 01.par

Turbine Parameters

Site: Revin G4
Hnom (m): 223
Leq (m): 1338
Seq (m^2): 16.407
Power (MW): 180
Flow (m3^/s): 95
Speed (rpm): 300
MR2 (T.m^2): 2175
Kp: 1.65
Ti (s): 10.37
Td (s): 2.07
Kd: 10.00
Tw (s): 3.54
Ta (s): 11.93
Allievi: 1.32
Marge Gain (dB): G=3.45 dB @ Freq.=0.064 Hz
Marge Phase (°): Phi=21.56° @ Freq.=0.030 Hz

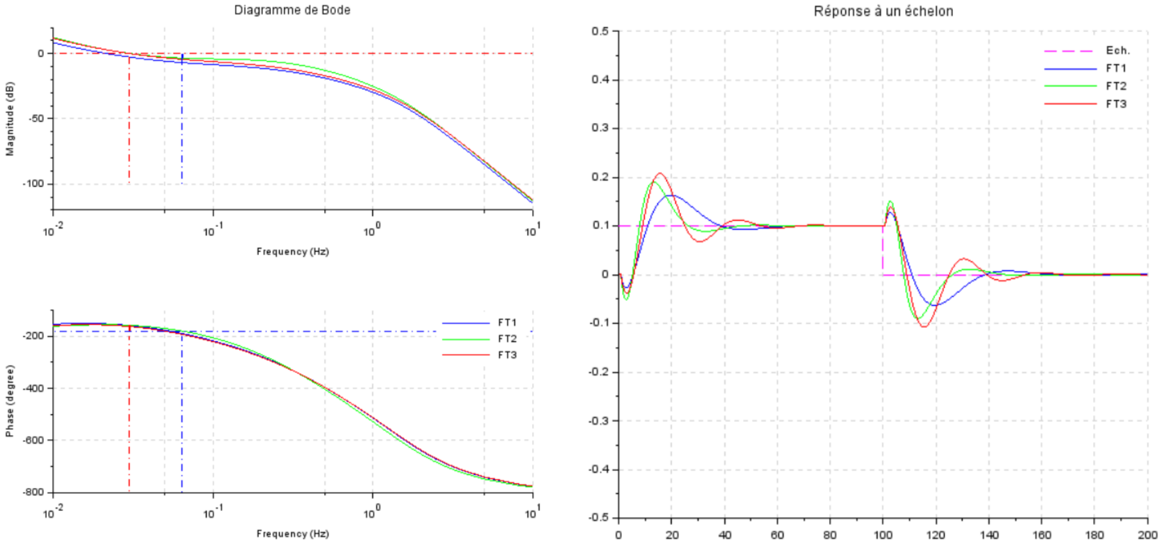
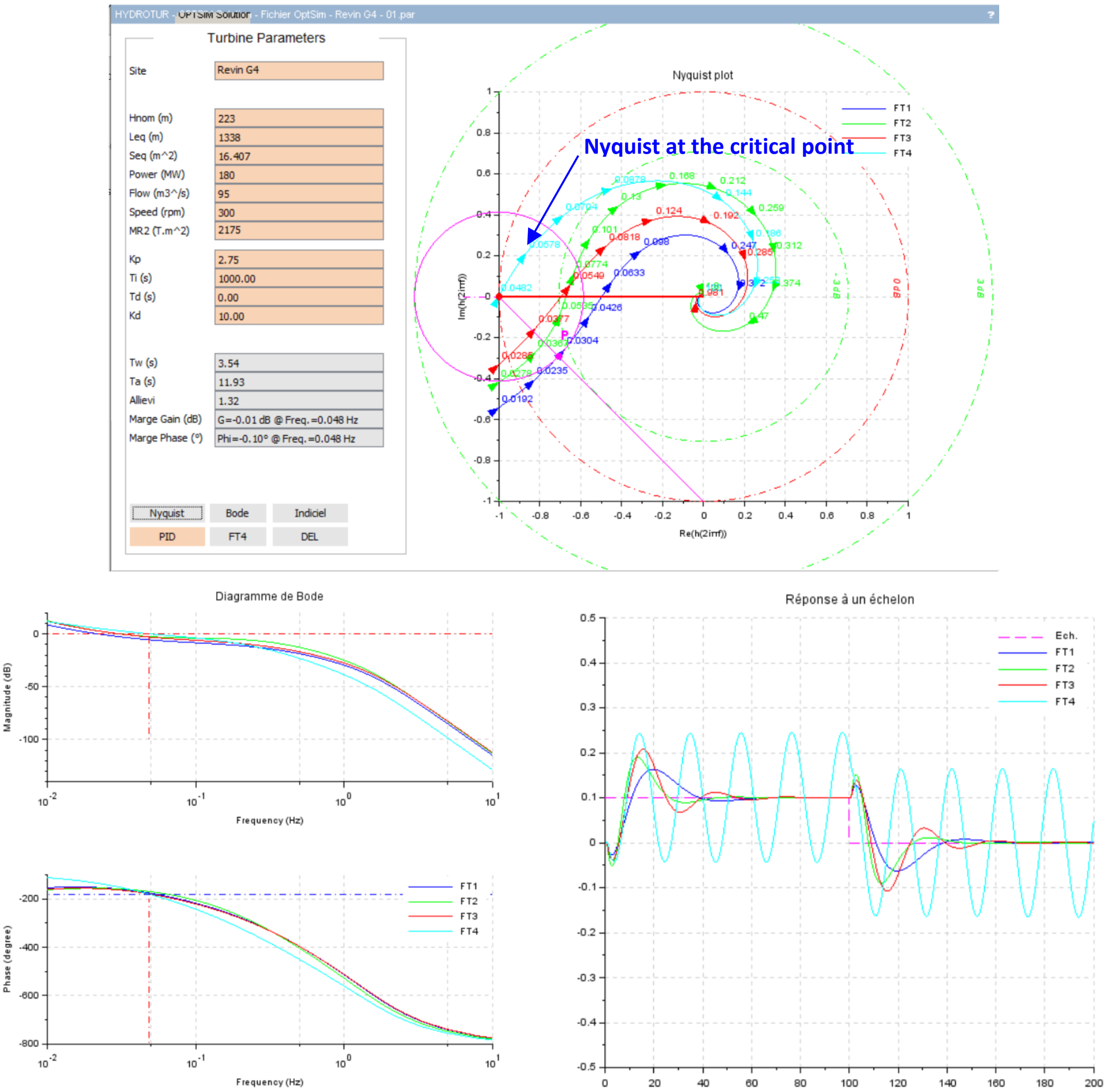


Figure 63 : Verifications of the Ziegler-Nichols method

It is also possible to check the critical gain Kcr obtained by the Ziegler-Nichols method.

To do this, enter a new program in HydroStab with the input data Kcr=2.75, Ti=1000, and Td=0:



HYDROTUR - OPTSIM Solution - Fichier OptSim - Revin G4 - 01.par

Turbine Parameters

Site: Revin G4
Hnom (m): 223
Leq (m): 1338
Seq (m^2): 16.407
Power (MW): 180
Flow (m3^/s): 95
Speed (rpm): 300
MR2 (T.m^2): 2175
Kp: 2.75
Ti (s): 1000.00
Td (s): 0.00
Kd: 10.00
Tw (s): 3.54
Ta (s): 11.93
Allievi: 1.32
Marge Gain (dB): G=-0.01 dB @ Freq.=0.048 Hz
Marge Phase (°): Phi=-0.10° @ Freq.=0.048 Hz

Figure 64 : Verification of the critical gain Kcr in the Nyquist plane

The critical gain Kcr obtained by the ZN method therefore corresponds exactly to the critical point (0, -1) ν indicated in the Nyquist plane.

Similarly, we obtain a non-divergent sustained oscillation of the step response.

- **T$_{osc}$** can be checked by programming the option **ZN_Datatip=1**. In this case, the datatips of the maximums Max(i) are automatically displayed, as shown below:

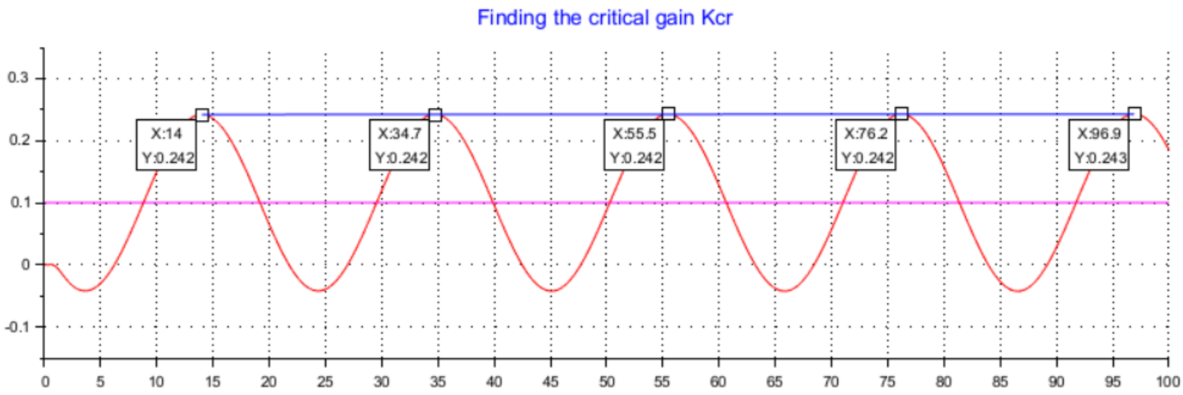


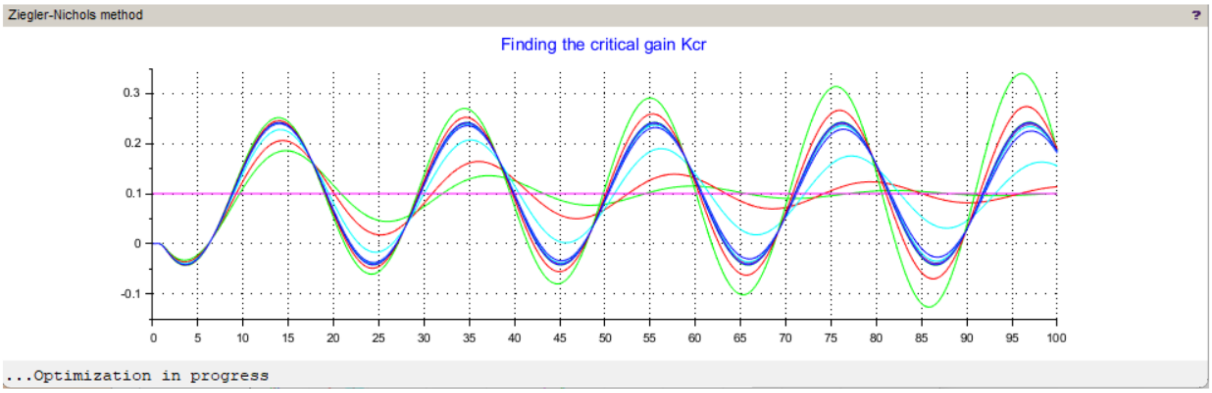
Figure 65 : Verification of the period of Tosc oscillations in the Ziegler-Nichols method

7.2.2.7 *Activation in Automatic mode*

The automatic search for the critical grain Kcr is carried out:

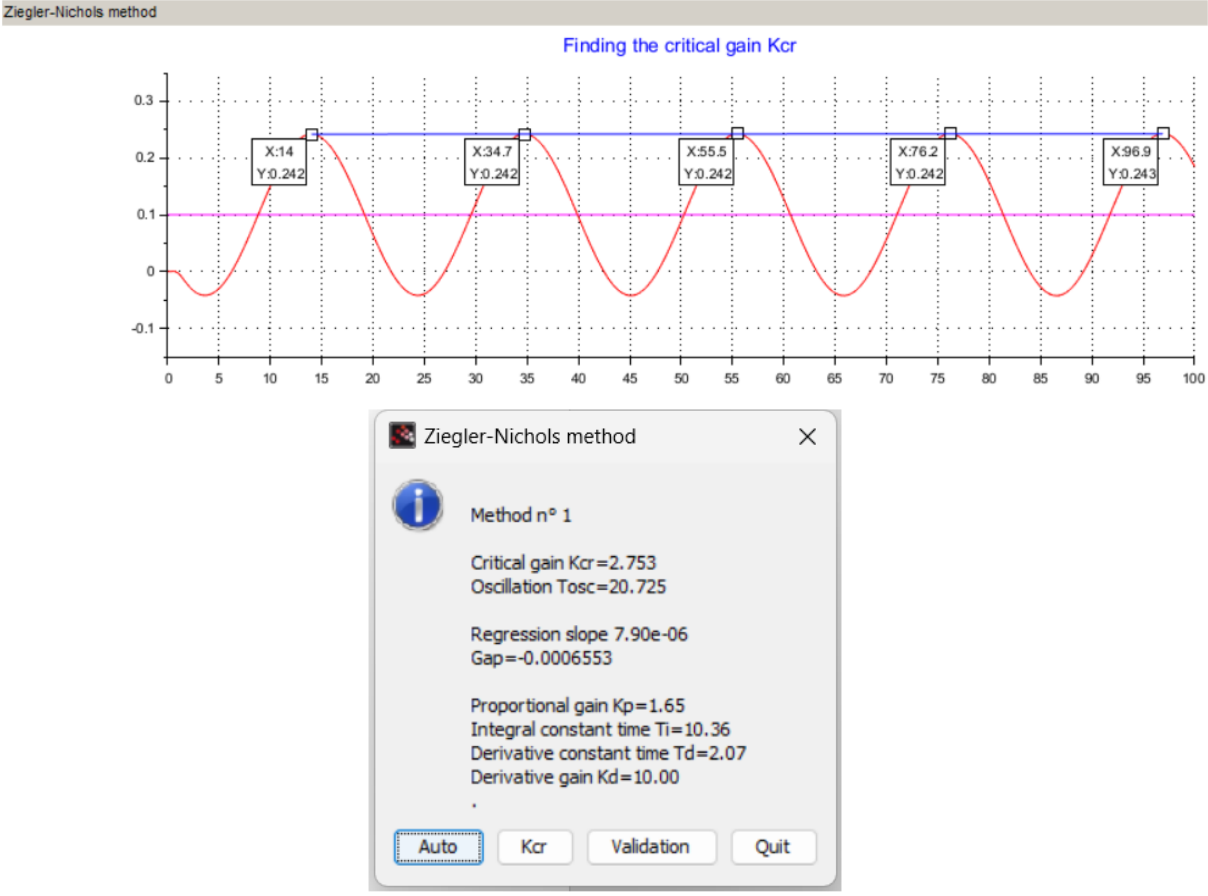
- either by programming the parameter Auto_ZN=%t in the file "**HydroStab.par**"
- either by activating the Auto button in the Kcr gain display window (see *Figure 58*)

Under these conditions, HydroStab automatically searches for the value of the gain Kcr by a series of iterations with variable steps, to determine a precise value of the gain to 1/1000 IIth.



```
...Optimization in progress
```

Figure 66 : Active phase of automatic search for critical gain Kcr



Method n° 1

Critical gain Kcr=2.753
Oscillation Tosc=20.725

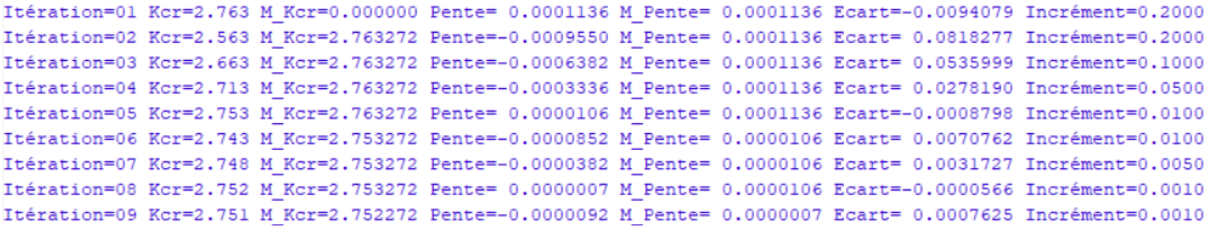
Regression slope 7.90e-06
Gap=-0.0006553

Proportional gain Kp=1.65
Integral constant time Ti=10.36
Derivative constant time Td=2.07
Derivative gain Kd=10.00

Figure 67 : Terminal phase of searching for critical gain Kcr

7.2.2.8 *“Trace_ZN” tracing option in automatic critical gain search Kcr*

L’option de traçage **Trace_ZN** de l’algorithme de recherche automatique permet l’affichage, dans la console Scilab, de l’ensemble des itérations réalisées :

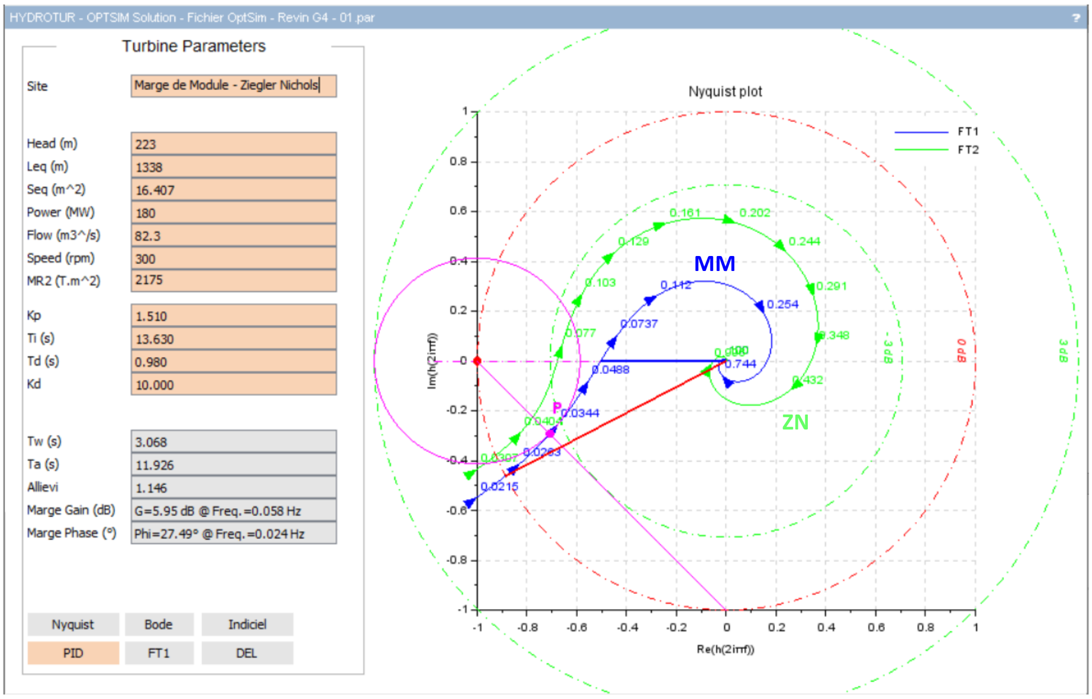


```
Itération=01 Kcr=2.763 M_Kcr=0.000000 Pente= 0.0001136 M_Pente= 0.0001136 Ecart=-0.0094079 Incrément=0.2000
Itération=02 Kcr=2.563 M_Kcr=2.763272 Pente=-0.0009550 M_Pente= 0.0001136 Ecart= 0.0818277 Incrément=0.2000
Itération=03 Kcr=2.663 M_Kcr=2.763272 Pente=-0.0006382 M_Pente= 0.0001136 Ecart= 0.0535999 Incrément=0.1000
Itération=04 Kcr=2.713 M_Kcr=2.763272 Pente=-0.0003336 M_Pente= 0.0001136 Ecart= 0.0278190 Incrément=0.0500
Itération=05 Kcr=2.753 M_Kcr=2.763272 Pente= 0.0000106 M_Pente= 0.0001136 Ecart=-0.0008798 Incrément=0.0100
Itération=06 Kcr=2.743 M_Kcr=2.753272 Pente=-0.0000852 M_Pente= 0.0000106 Ecart= 0.0070762 Incrément=0.0100
Itération=07 Kcr=2.748 M_Kcr=2.753272 Pente=-0.0000382 M_Pente= 0.0000106 Ecart= 0.0031727 Incrément=0.0050
Itération=08 Kcr=2.752 M_Kcr=2.753272 Pente= 0.0000007 M_Pente= 0.0000106 Ecart=-0.0000566 Incrément=0.0010
Itération=09 Kcr=2.751 M_Kcr=2.752272 Pente=-0.0000092 M_Pente= 0.0000007 Ecart= 0.0007625 Incrément=0.0010
```

Figure 68 : Trace_ZN tracing option

7.2.3 Comparison of the Margin Module and Ziegler-Nichol’s methods

7.2.3.1 *Comparison of methods in the Nyquist geometric plane*



HYDROTUR - OPTSIM Solution - Fichier OptSim - Revin G4 - 01.par

Turbine Parameters

Site: Marge de Module - Ziegler Nichols

Head (m): 223
Leq (m): 1338
Seq (m^2): 16.407
Power (MW): 180
Flow (m3^/s): 82.3
Speed (rpm): 300
MR2 (T.m^2): 2175

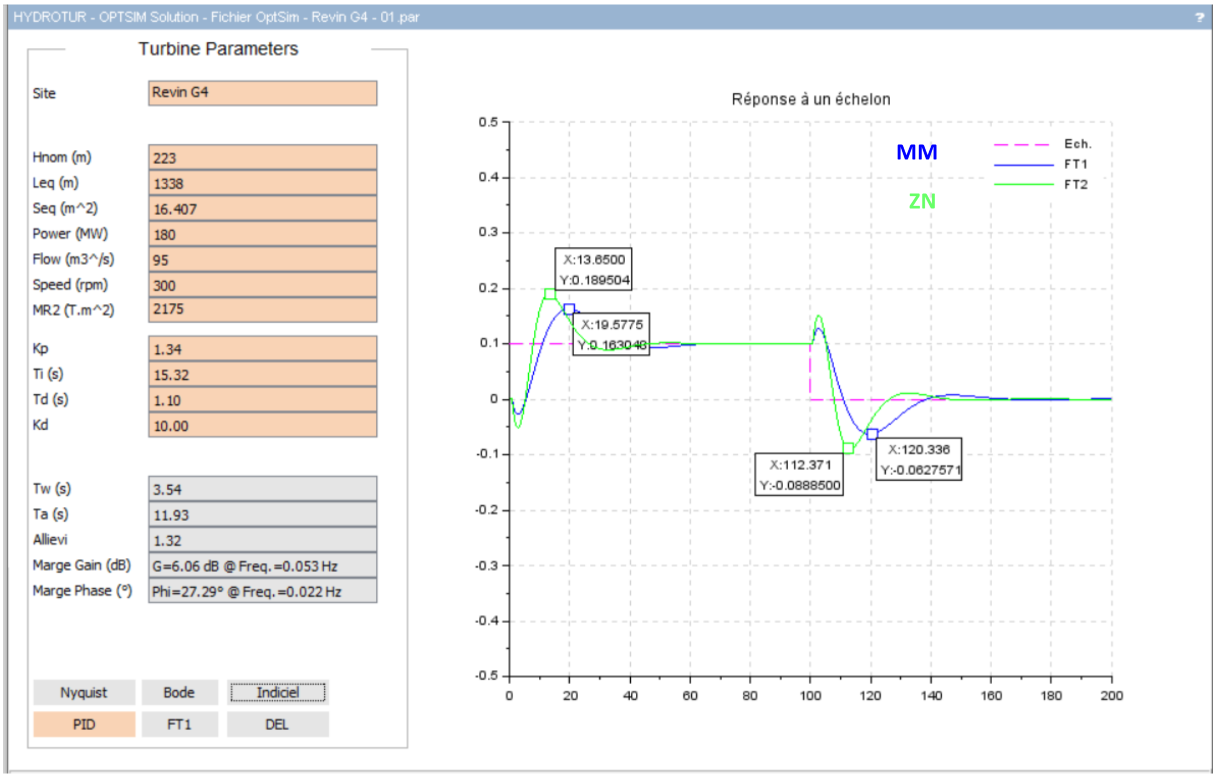
Kp: 1.510
Ti (s): 13.630
Td (s): 0.980
Kd: 10.000

Tw (s): 3.068
Ta (s): 11.926
Allievi: 1.146
Marge Gain (dB): G=5.95 dB @ Freq.=0.058 Hz
Marge Phase (°): Phi=27.49° @ Freq.=0.024 Hz

Figure 69 : Comparison of the Module Margin and Ziegler-Nichol’s methods in the Nyquist plane

☞ The margin gain goes from de 6 dB (**FT1 : Module Margin**) to 3.45 dB (**FT2 : Ziegler-Nichols**)

7.2.3.2 *Comparison of methods in the time domain*



HYDROTUR - OPTSIM Solution - Fichier OptSim - Revin G4 - 01.par

Turbine Parameters

Site	Revin G4
Hnom (m)	223
Leq (m)	1338
Seq (m^2)	16.407
Power (MW)	180
Flow (m3^/s)	95
Speed (rpm)	300
MR2 (T.m^2)	2175
Kp	1.34
Ti (s)	15.32
Td (s)	1.10
Kd	10.00
Tw (s)	3.54
Ta (s)	11.93
Allievi	1.32
Marge Gain (dB)	G=6.06 dB @ Freq.=0.053 Hz
Marge Phase (°)	Phi=27.29° @ Freq.=0.022 Hz

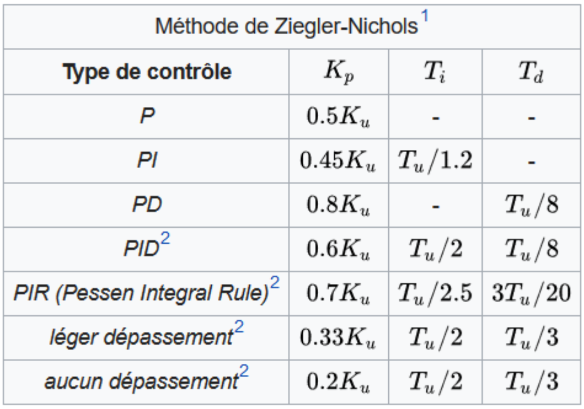
Figure 70 : Comparison of the Module Margin and Ziegler-Nichol's methods in the time domain

☞ The overshoot by the Module Margin method (*FT1: Module Margin*) is 2% lower than the overshoot obtained by the Ziegler-Nichols method (**FT2: Ziegler-Nichols**) for an equivalent velocity.

7.2.3.3 *Other possible settings regarding the Ziegler-Nichols method*

The site https://fr.wikipedia.org/wiki/M%C3%A9thode_de_Ziegler-Nichols also indicates other values for this adjustment mode.

These calculations were attempted in this study, but gave disappointing results: they do not seem suitable for hydraulic studies.



Méthode de Ziegler-Nichols[1]

Type de contrôle	K_p	T_i	T_d
P	$0.5K_u$	-	-
PI	$0.45K_u$	$T_u/1.2$	-
PD	$0.8K_u$	-	$T_u/8$
PID[2]	$0.6K_u$	$T_u/2$	$T_u/8$
PIR (Pessen Integral Rule)[2]	$0.7K_u$	$T_u/2.5$	$3T_u/20$
léger dépassement[2]	$0.33K_u$	$T_u/2$	$T_u/3$
aucun dépassement[2]	$0.2K_u$	$T_u/2$	$T_u/3$

Figure 71 : Ziegler-Nichol's method setting values available on the NET

7.3 TAKAHASHI Method

7.3.1 Principle of the method

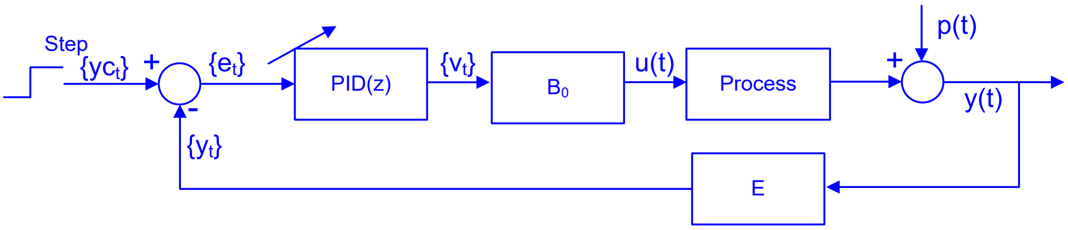


Figure 72 : General principle of Takahashi's method

B_0	Blocker 0 order
E	Sampler – sampling period dt_Ech=0.1 s
PID (z)	PID Speed in z (discrete transfer function)
P(t)	Disturbance

The procedure for obtaining the parameters Kp, Ti and Td is analogous to that set out in the Ziegler-Nichols method

- The simulations are digital
- The criterion to be minimized is $J = \sum_{t=0}^{\infty} e_t^2$

HydroStab only performs an approximation of the TAKAHASHI method.

7.3.2 Calculations

En fonction du gain Kcr trouvé, HydroStab assoie les calculs

Governor transmittance	Values of the regulator parameters according to the TAKAHASHI method		
$PID = K_p.(1+\frac{1}{T_i.s}+T_d.s)$	Kp=0.6*(1-dt/Tosc)*Kcr	Ti=0.5*(Tosc-dt)	$Td = Tosc^2 \,/\, (8 * Tosc - dt)$ $Kd = 4$

Figure 73 : PID tuning by TAKAHASHI method

7.3.3 Comparison of Module Margin methods (FT1), ZN (FT2), Takahashi (FT3)

7.3.3.1 Nyquist

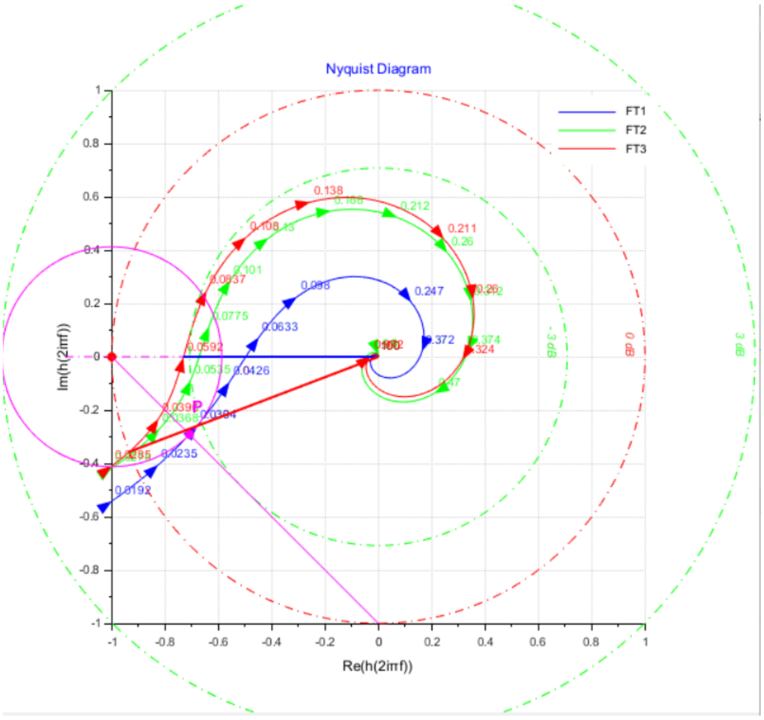


Figure 74 : Comparison of Module Margin (FT1), ZN (FT2), Takahashi (FT3) - Nyquist methods

7.3.3.2 Step responses

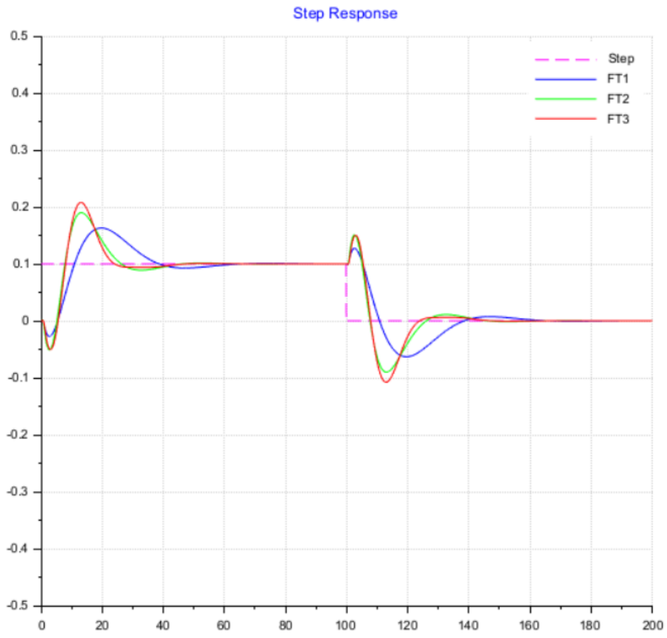
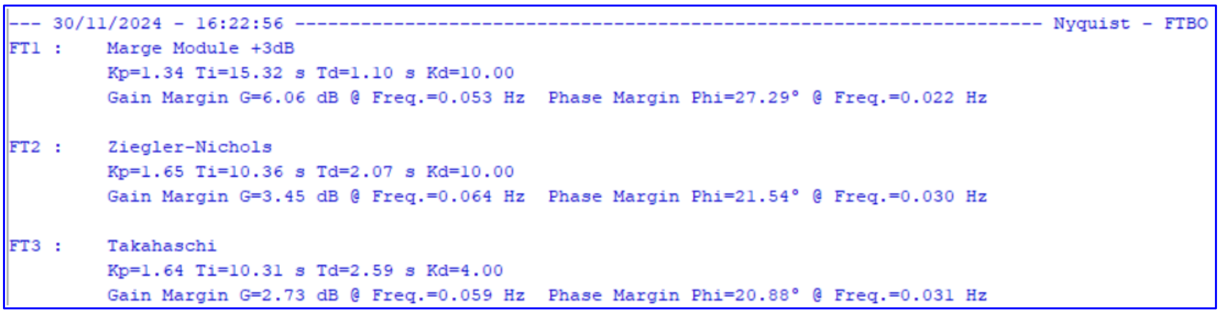


Figure 75 : Comparison of Module Margin methods (FT1), ZN (FT2), Takahashi (FT3) – Step responses

7.3.3.3 *Gain and phase margins*



```
--- 30/11/2024 - 16:22:56 --------------------------------------------------------------------- Nyquist - FTBO
FT1  :      Marge Module +3dB
            Kp=1.34 Ti=15.32 s Td=1.10 s Kd=10.00
            Gain Margin G=6.06 dB @ Freq.=0.053 Hz  Phase Margin Phi=27.29° @ Freq.=0.022 Hz

FT2  :      Ziegler-Nichols
            Kp=1.65 Ti=10.36 s Td=2.07 s Kd=10.00
            Gain Margin G=3.45 dB @ Freq.=0.064 Hz  Phase Margin Phi=21.54° @ Freq.=0.030 Hz

FT3  :      Takahaschi
            Kp=1.64 Ti=10.31 s Td=2.59 s Kd=4.00
            Gain Margin G=2.73 dB @ Freq.=0.059 Hz  Phase Margin Phi=20.88° @ Freq.=0.031 Hz
```

Figure 76 : Comparison of Module Margin methods (FT1), ZN (FT2), Takahashi (FT3) – Gain and phase margins – Scilab console

8 NON-LINEAR SIMULATION OF THE REVIN POWER PLANT

The previous study showed approximate methods, providing the elementary tuning of the quadruplet K_p,T_i,T_d,Kd of the speed PID corrector.

This last chapter covers the simulation of nonlinear systems, as described in the models of the HYDROTUR component library, developed under XCOS, and the list of which is recalled in Appendix **E** .

8.1 Study method

1 Carry out a linear simulation under **HydroStab** with the hydraulic data of the structure
2 Transfer the hydraulic data and the quadruplet (K_p,T_i,T_d,Kd) into the turbine simulator programming files.
3 Use the pertubograph on the network load to optimize the Kp gain, following different sequences
4 Record each sequence

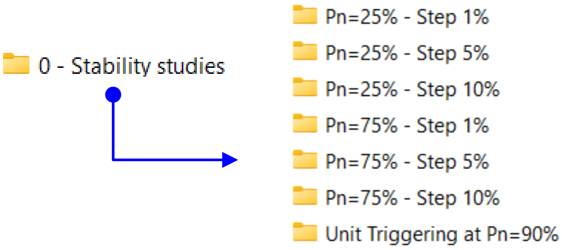
The perturbograph, used in Appendix ***E.6***, is one of the elements provided in the ATOMS HYDROTUR-SegPal module, an extension of the XCOS standard library, which can be downloaded from the site:

http://atoms.scilab.org/toolboxes/SegPal/2.2.2

8.2 Characteristics of simulations

In this document, we simply add the results of the simulations carried out, and available in the directory:

HydroStab\Revin



☞ **These studies are part of the third HYDROTUR – HydroSim component, available in the ATOMS module of Scilab**

To view these “scg” files, open Scilab, navigate to these directories using the Scilab browser, then double-click on the files.

☞ **In general, it is a question of finding the best compromise between the driving overspeeds/overpressures.**

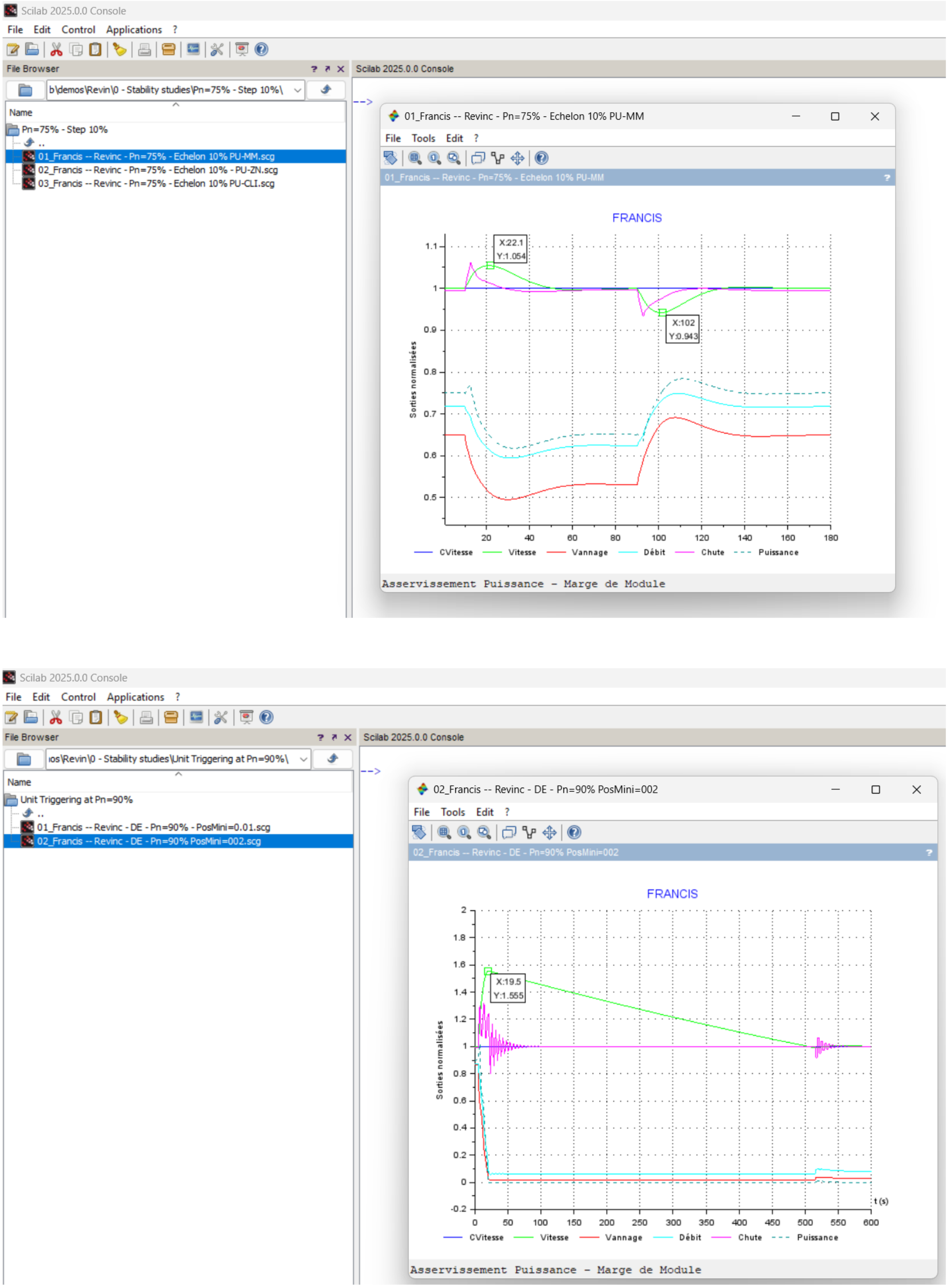
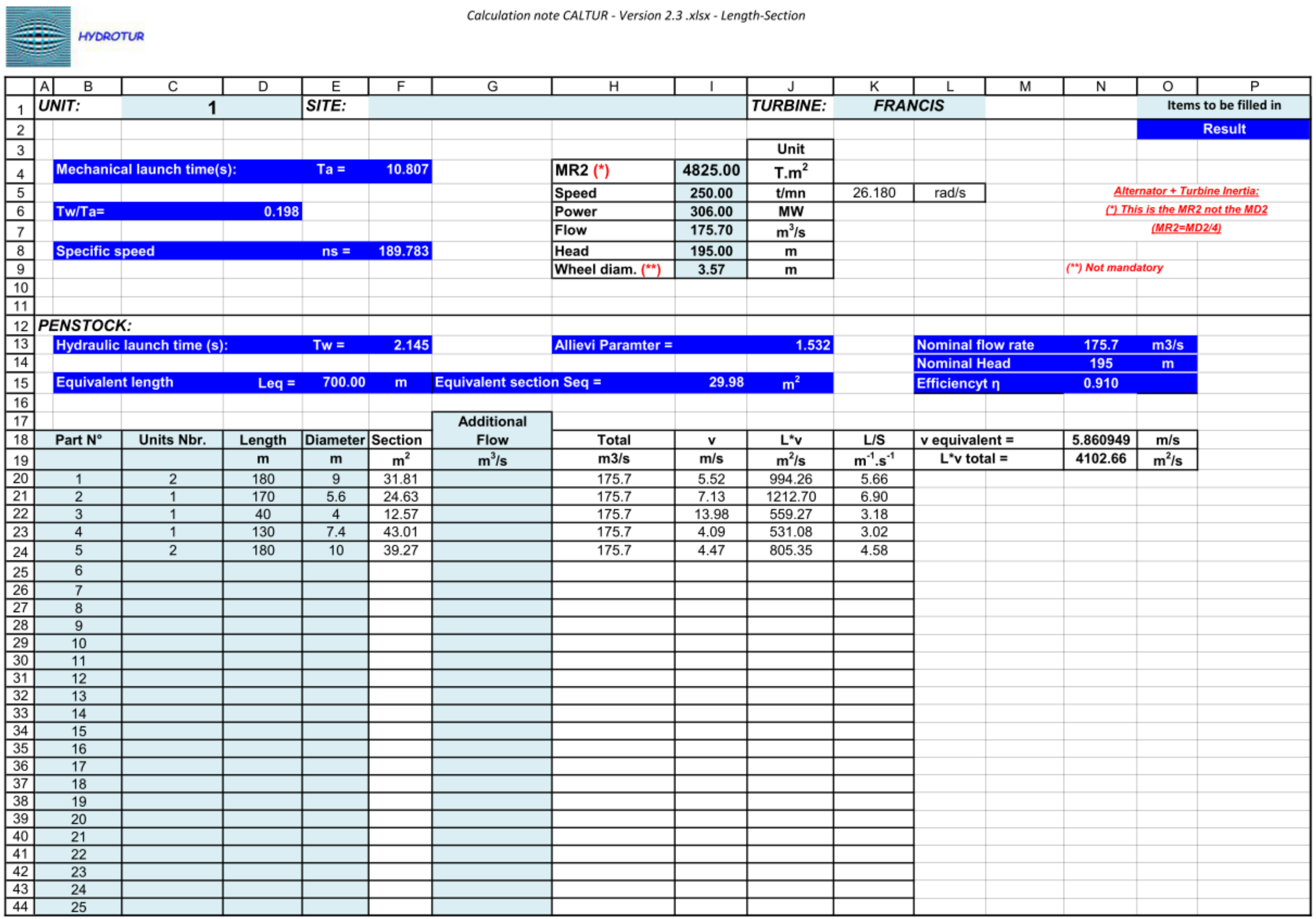


Figure 77 : Example of non-linear simulations on the Revin plant

APPENDIX

A. HYDROSTAB-CALTUR: EXCEL SPREADSHEET

A.1 Main sheet "Length-Section"

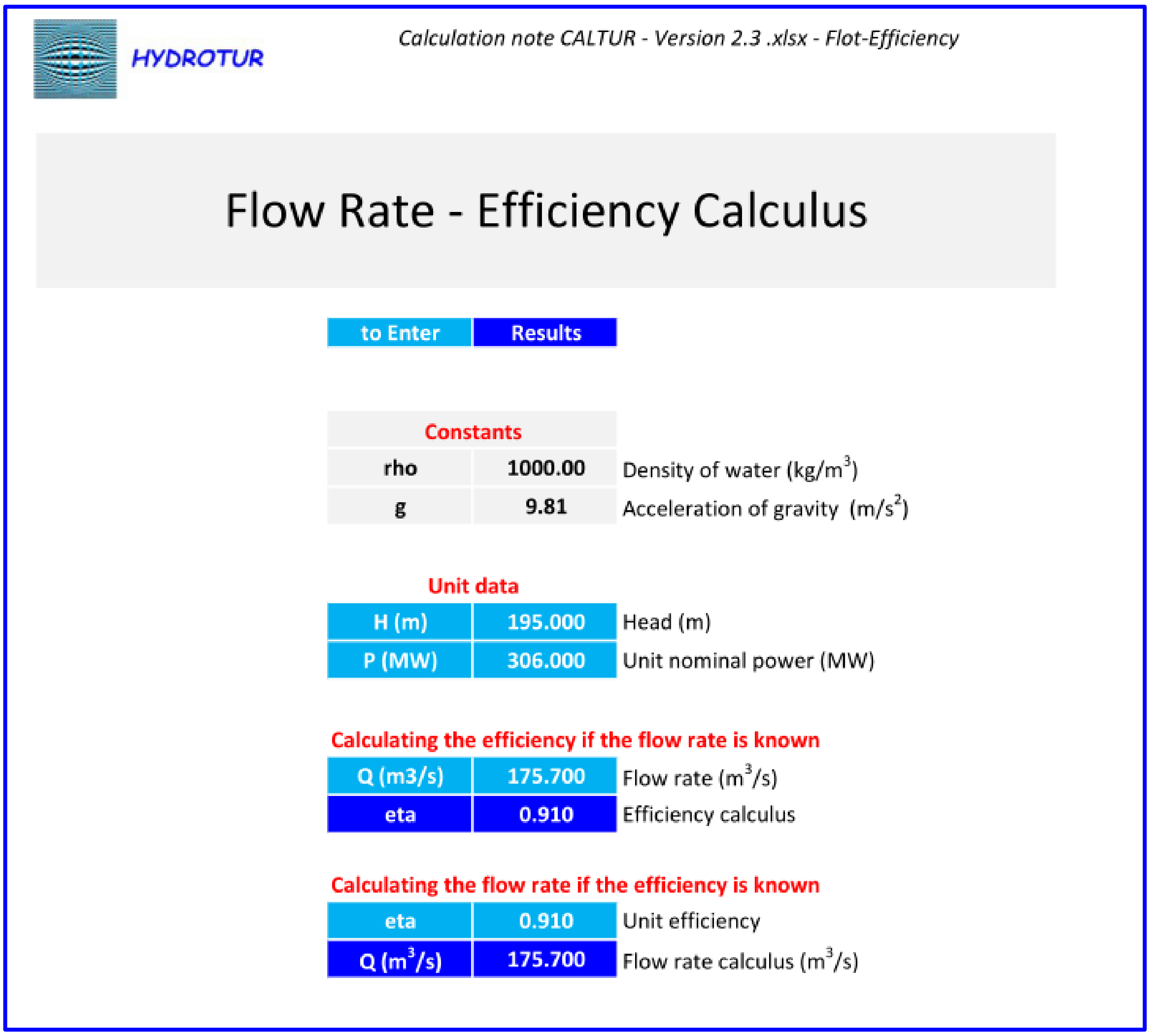


Calculation note CALTUR - Version 2.3 .xlsx - Length-Section

HYDROTUR

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	UNIT:		1		SITE:					TURBINE:	FRANCIS				Items to be filled in	
2															Result	
3										Unit						
4		Mechanical launch time(s):			Ta =	10.807		MR2 (*)	4825.00	T.m^2						
5								Speed	250.00	t/mn	26.180	rad/s			Alternator + Turbine Inertia:	
6		Tw/Ta=		0.198				Power	306.00	MW					(*) This is the MR2 not the MD2	
7								Flow	175.70	m^3/s					(MR2=MD2/4)	
8		Specific speed			ns =	189.783		Head	195.00	m						
9								Wheel diam. (**)	3.57	m				(**) Not mandatory		
10																
11																
12	PENSTOCK:															
13		Hydraulic launch time (s):			Tw =	2.145		Allievi Paramter =		1.532		Nominal flow rate		175.7	m3/s	
14												Nominal Head		195	m	
15		Equivalent length		Leq =	700.00	m	Equivalent section Seq =		29.98	m^2		Efficiencyt η		0.910		
16																
17							Additional									
18		Part N°	Units Nbr.	Length	Diameter	Section	Flow	Total	v	L*v	L/S	v equivalent =		5.860949	m/s	
19				m	m	m^2	m^3/s	m3/s	m/s	m^2/s	m^{-1}.s^{-1}	L*v total =		4102.66	m^2/s	
20		1	2	180	9	31.81		175.7	5.52	994.26	5.66					
21		2	1	170	5.6	24.63		175.7	7.13	1212.70	6.90					
22		3	1	40	4	12.57		175.7	13.98	559.27	3.18					
23		4	1	130	7.4	43.01		175.7	4.09	531.08	3.02					
24		5	2	180	10	39.27		175.7	4.47	805.35	4.58					
25		6														
26		7														
27		8														
28		9														
29		10														
30		11														
31		12														
32		13														
33		14														
34		15														
35		16														
36		17														
37		18														
38		19														
39		20														
40		21														
41		22														
42		23														
43		24														
44		25														

A.2 - “Flow- efficiency” secondary sheet



HYDROTUR

Calculation note CALTUR - Version 2.3 .xlsx - Flot-Efficiency

Flow Rate - Efficiency Calculus

to Enter	Results

Constants

rho	1000.00	Density of water (kg/m^3)
g	9.81	Acceleration of gravity (m/s^2)

Unit data

H (m)	195.000	Head (m)
P (MW)	306.000	Unit nominal power (MW)

Calculating the efficiency if the flow rate is known

Q (m3/s)	175.700	Flow rate (m^3/s)
eta	0.910	Efficiency calculus

Calculating the flow rate if the efficiency is known

eta	0.910	Unit efficiency
Q (m^3/s)	175.700	Flow rate calculus (m^3/s)

Formula

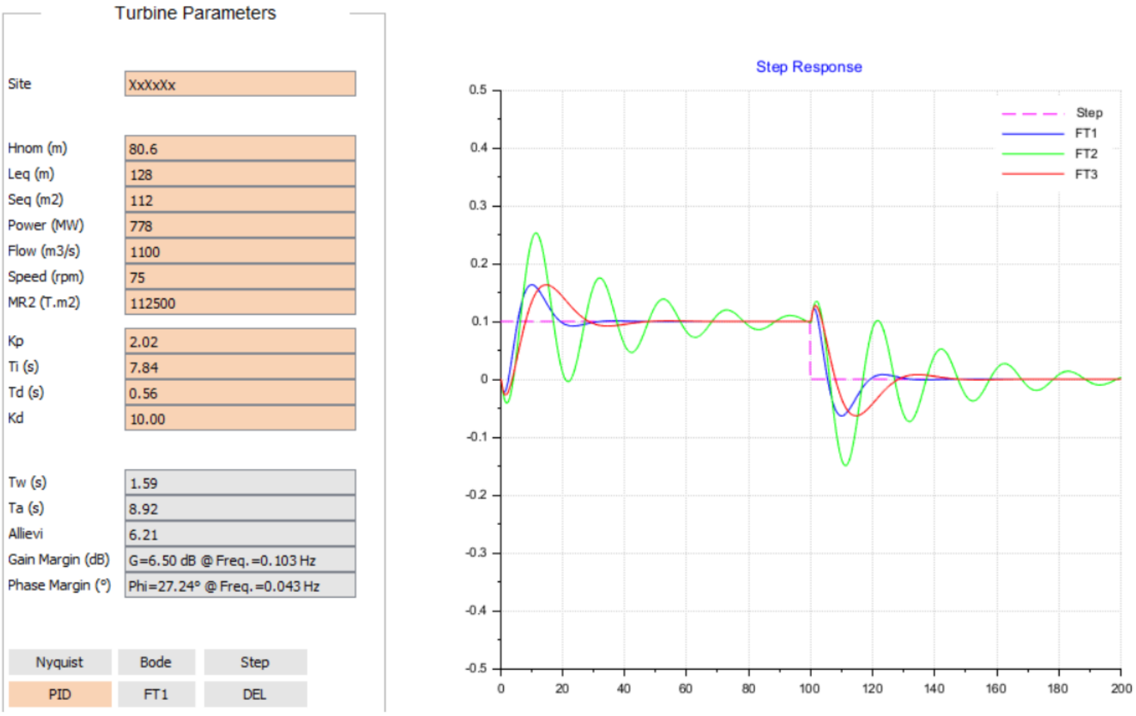
$$P = \eta.\rho.g.H.Q$$

B. SEASONAL VARIATIONS – TIDAL RANGE – ADAPTATION OF PID

In the example below, we assume a site subject to a strong tidal range

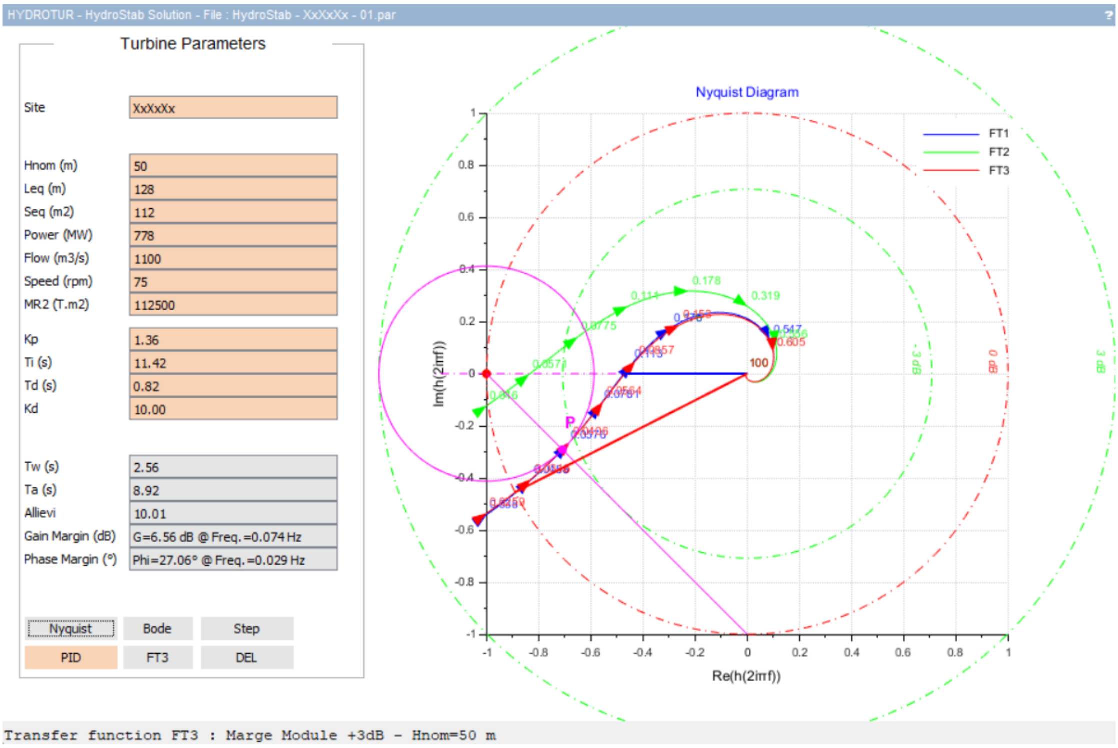
The PID, calculated with a head of 80 m, becomes unstable for a head passing to 50 m

- FT1 – PID “Summer” Module Margin, 80 m head
- FT2 – Winter conditions: the head goes from 80 m to 50 m. The PID is unstable
- FT3 : The “Winter” PID is recalculated using the Module Margin method



Turbine Parameters

Site	XxXxXx
Hnom (m)	80.6
Leq (m)	128
Seq (m2)	112
Power (MW)	778
Flow (m3/s)	1100
Speed (rpm)	75
MR2 (T.m2)	112500
Kp	2.02
Ti (s)	7.84
Td (s)	0.56
Kd	10.00
Tw (s)	1.59
Ta (s)	8.92
Allievi	6.21
Gain Margin (dB)	G=6.50 dB @ Freq.=0.103 Hz
Phase Margin (°)	Phi=27.24° @ Freq.=0.043 Hz



Turbine Parameters

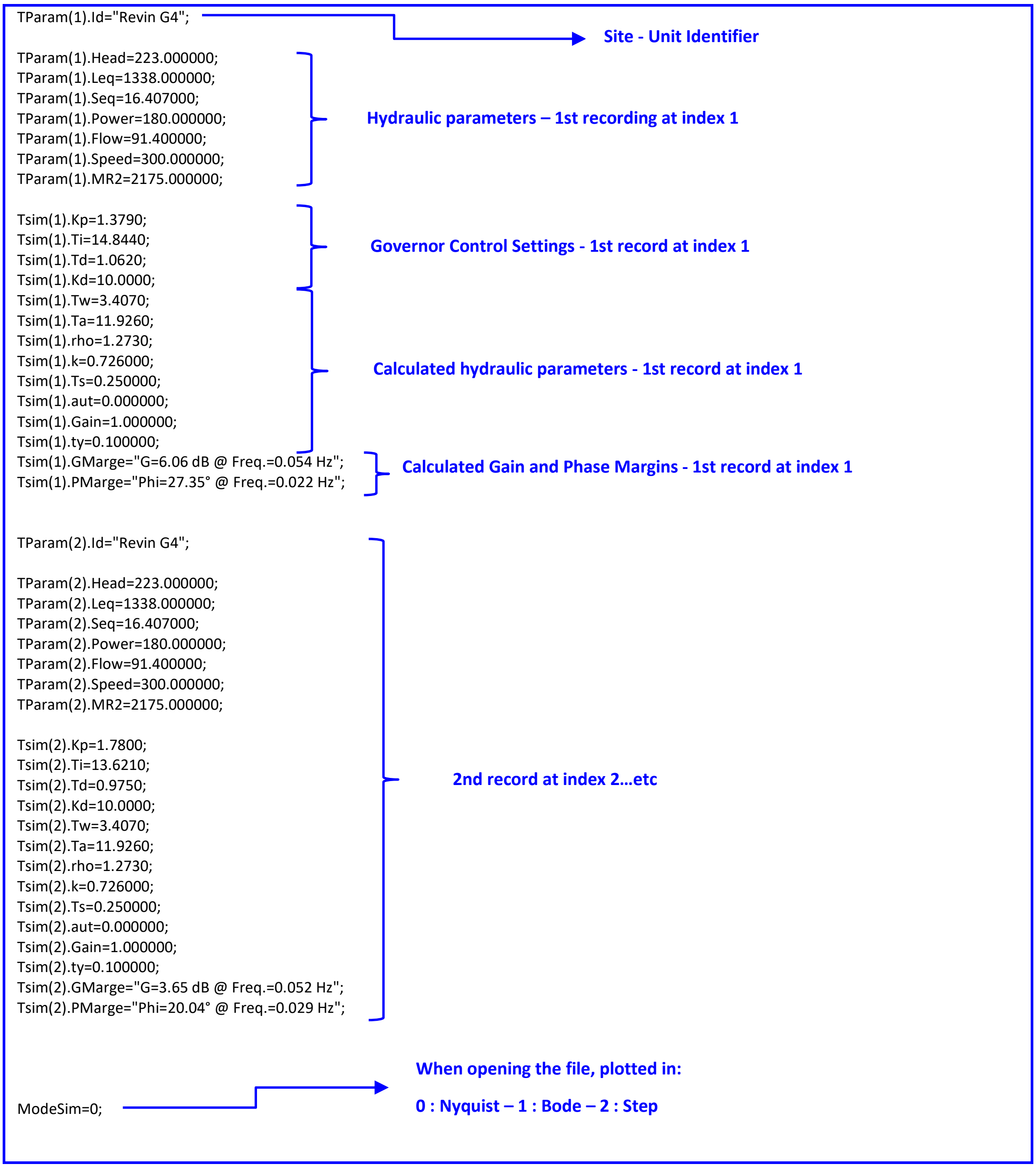
Site	XxXxXx
Hnom (m)	50
Leq (m)	128
Seq (m2)	112
Power (MW)	778
Flow (m3/s)	1100
Speed (rpm)	75
MR2 (T.m2)	112500
Kp	1.36
Ti (s)	11.42
Td (s)	0.82
Kd	10.00
Tw (s)	2.56
Ta (s)	8.92
Allievi	10.01
Gain Margin (dB)	G=6.56 dB @ Freq.=0.074 Hz
Phase Margin (°)	Phi=27.06° @ Freq.=0.029 Hz

Transfer function FT3 : Marge Module +3dB - Hnom=50 m

Figure 78 : Tidal variation - "summer" and "winter" PID– File : HydroStab\demos\Test\ HydroStab - XxXxXx - 01.par

☞ **Conclusion: the plant operator will therefore have to switch the PID parameter sets mid-season**

C. EXAMPLE OF A HYDROSTAB SESSION RECORDING FILE



```
TParam(1).Id="Revin G4";

TParam(1).Head=223.000000;
TParam(1).Leq=1338.000000;
TParam(1).Seq=16.407000;
TParam(1).Power=180.000000;
TParam(1).Flow=91.400000;
TParam(1).Speed=300.000000;
TParam(1).MR2=2175.000000;

Tsim(1).Kp=1.3790;
Tsim(1).Ti=14.8440;
Tsim(1).Td=1.0620;
Tsim(1).Kd=10.0000;
Tsim(1).Tw=3.4070;
Tsim(1).Ta=11.9260;
Tsim(1).rho=1.2730;
Tsim(1).k=0.726000;
Tsim(1).Ts=0.250000;
Tsim(1).aut=0.000000;
Tsim(1).Gain=1.000000;
Tsim(1).ty=0.100000;
Tsim(1).GMarge="G=6.06 dB @ Freq.=0.054 Hz";
Tsim(1).PMarge="Phi=27.35° @ Freq.=0.022 Hz";


TParam(2).Id="Revin G4";

TParam(2).Head=223.000000;
TParam(2).Leq=1338.000000;
TParam(2).Seq=16.407000;
TParam(2).Power=180.000000;
TParam(2).Flow=91.400000;
TParam(2).Speed=300.000000;
TParam(2).MR2=2175.000000;

Tsim(2).Kp=1.7800;
Tsim(2).Ti=13.6210;
Tsim(2).Td=0.9750;
Tsim(2).Kd=10.0000;
Tsim(2).Tw=3.4070;
Tsim(2).Ta=11.9260;
Tsim(2).rho=1.2730;
Tsim(2).k=0.726000;
Tsim(2).Ts=0.250000;
Tsim(2).aut=0.000000;
Tsim(2).Gain=1.000000;
Tsim(2).ty=0.100000;
Tsim(2).GMarge="G=3.65 dB @ Freq.=0.052 Hz";
Tsim(2).PMarge="Phi=20.04° @ Freq.=0.029 Hz";


ModeSim=0;
```

Site - Unit Identifier

Hydraulic parameters – 1st recording at index 1

Governor Control Settings - 1st record at index 1

Calculated hydraulic parameters - 1st record at index 1

Calculated Gain and Phase Margins - 1st record at index 1

2nd record at index 2…etc

When opening the file, plotted in:

0 : Nyquist – 1 : Bode – 2 : Step

Figure 79 : Structure of a ".PAR" record in a HydroStab session

D. HYDRAULIC STRUCTURE OF THE 2-STAGE SYSCOP COPYING SYSTEM

D.1 Working principle of double-stage copying system

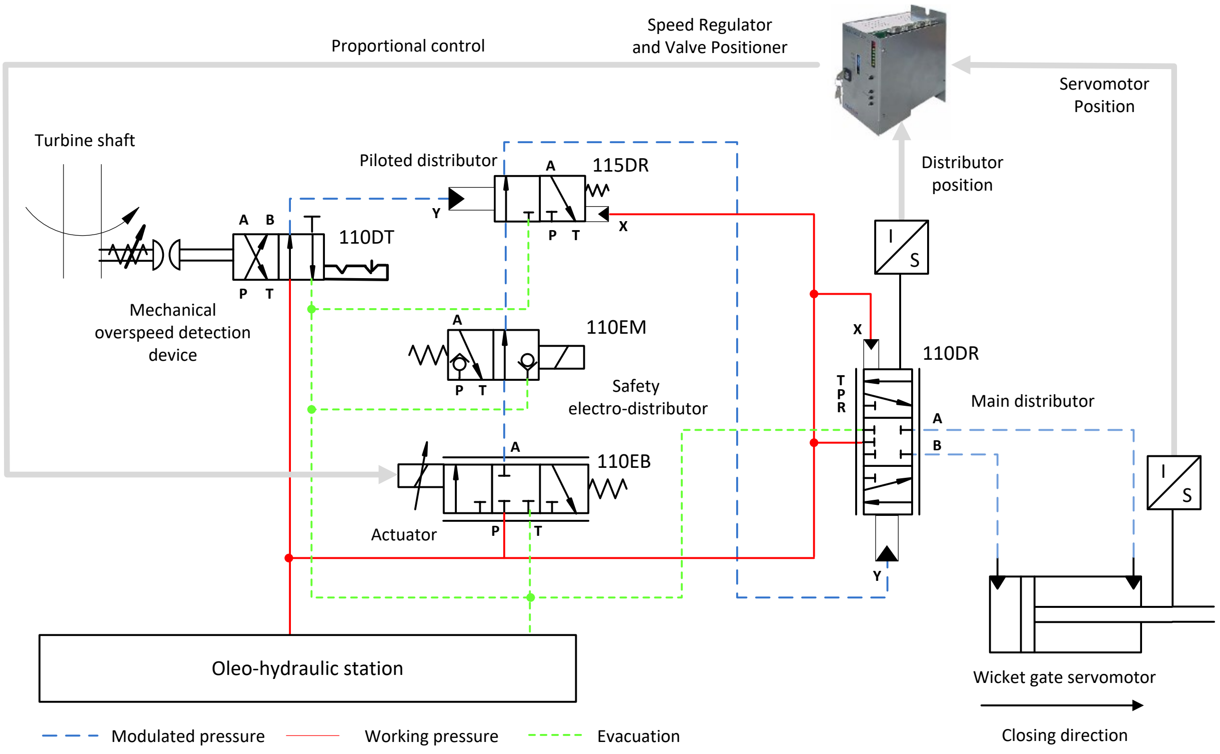


Figure 80 : Simplified control diagram of the control unit – SYSCOP copying system with 2 control units

E. ELEMENTS OF HYDROTUR-HYDROSIM DIAGRAMS

E.1 List of HYDROTUR-HydroSim schematic libraries

■ Available ☐ Forecast

Turbine type	Name/Directory	Features
FRANCIS	FR2	Turbine and pipes modeled according to analytical formulas – Wave hammer
	FR4	Turbine and adductions modeled using machine hills Interpolation and extrapolation on torque and flow (q11,c11)=F(N,O)
	FR5	Turbine and adductions modeled using machine hills Interpolation and extrapolation on torque and flow **(q11,c11)=F(Arctg(φ),O)**
PELTON **(HYDROTUR Scilab 6 :** **1 single PELTON diagram now covers all PELTON models)**	PELT1	PELTON turbine horizontal axis, 1 needle and 1 deflector Deflector following the pilot injector Turbine and pipe modeled according to analytical formulas
	PELT2	PELTON turbine horizontal axis, 2 needles and 1 deflector Deflector following the pilot injector Turbine and pipe modeled according to analytical formulas
	PELT3	Pelton vertical axis 3 needles with or without jet dispatcher. Deflectors following the pilot injector Turbine and pipe modeled according to analytical formulas
	PELT4	Pelton vertical axis 4 needles with or without jet dispatcher. Deflectors following the pilot injector Turbine and pipe modeled according to analytical formulas
	PELT5	Pelton vertical axis 5 needles with or without jet dispatcher. Deflectors following the pilot injector Turbine and pipe modeled according to analytical formulas
	PELT6	Pelton vertical axis 6 needles with or without jet dispatcher. Deflectors following the pilot injector Turbine and pipe modeled according to analytical formulas
KAPLAN	KB1	Turbine and adductions modeled using an analytical hill Interpolation and extrapolation on the geometric average Blades/Wicket gates and Speed. **(Reduced torque** $= \mathbf{F}\left(\mathbf{N}, \sqrt{\mathbf{P} * \mathbf{V}}\right)$**)**
	KB2	Turbine and pipe modeled by a transfer function. Combination between guides and blades

Figure 81 : List of available nonlinear models and algorithms

E.2 Speed governor for FRANCIS turbines

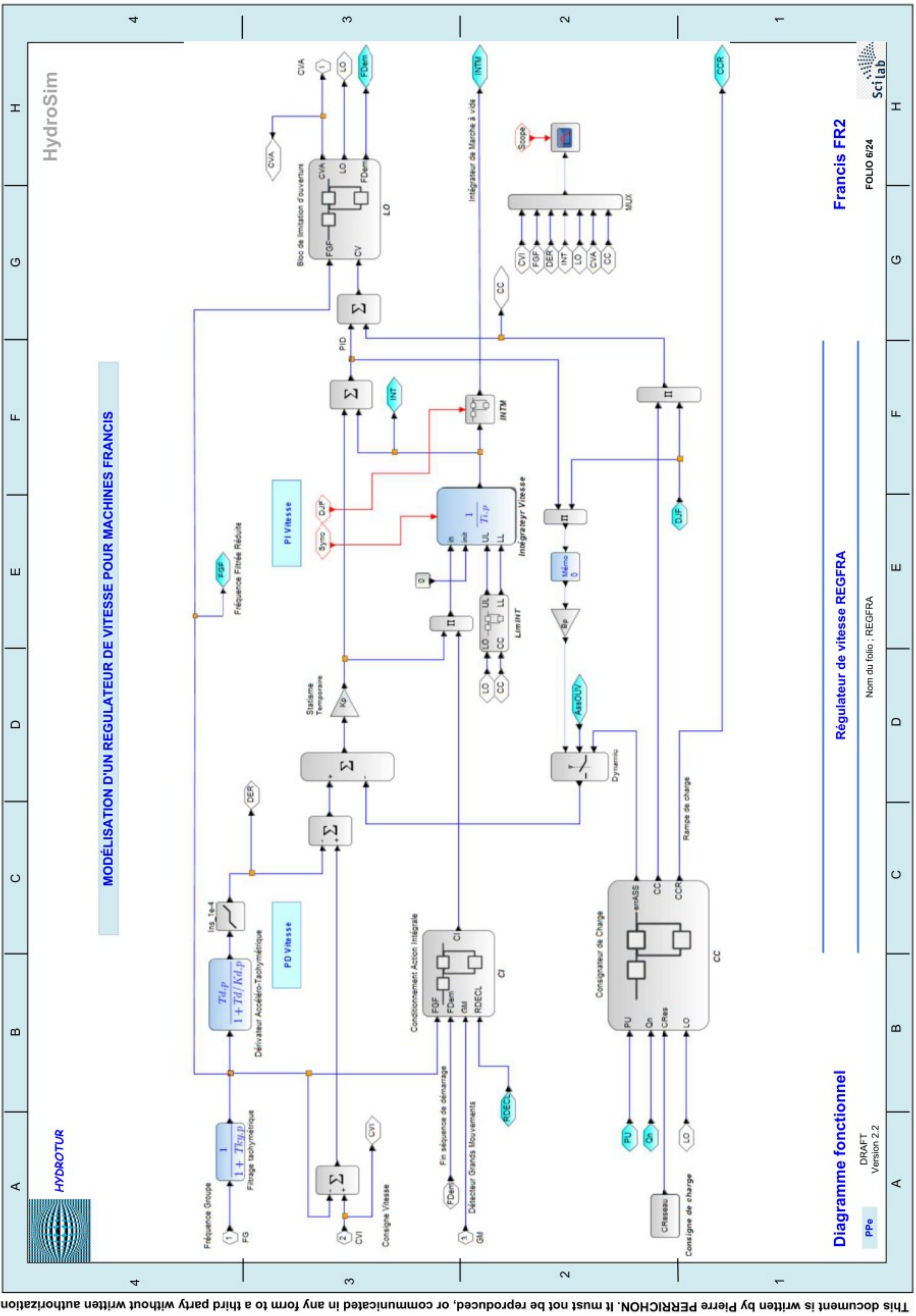
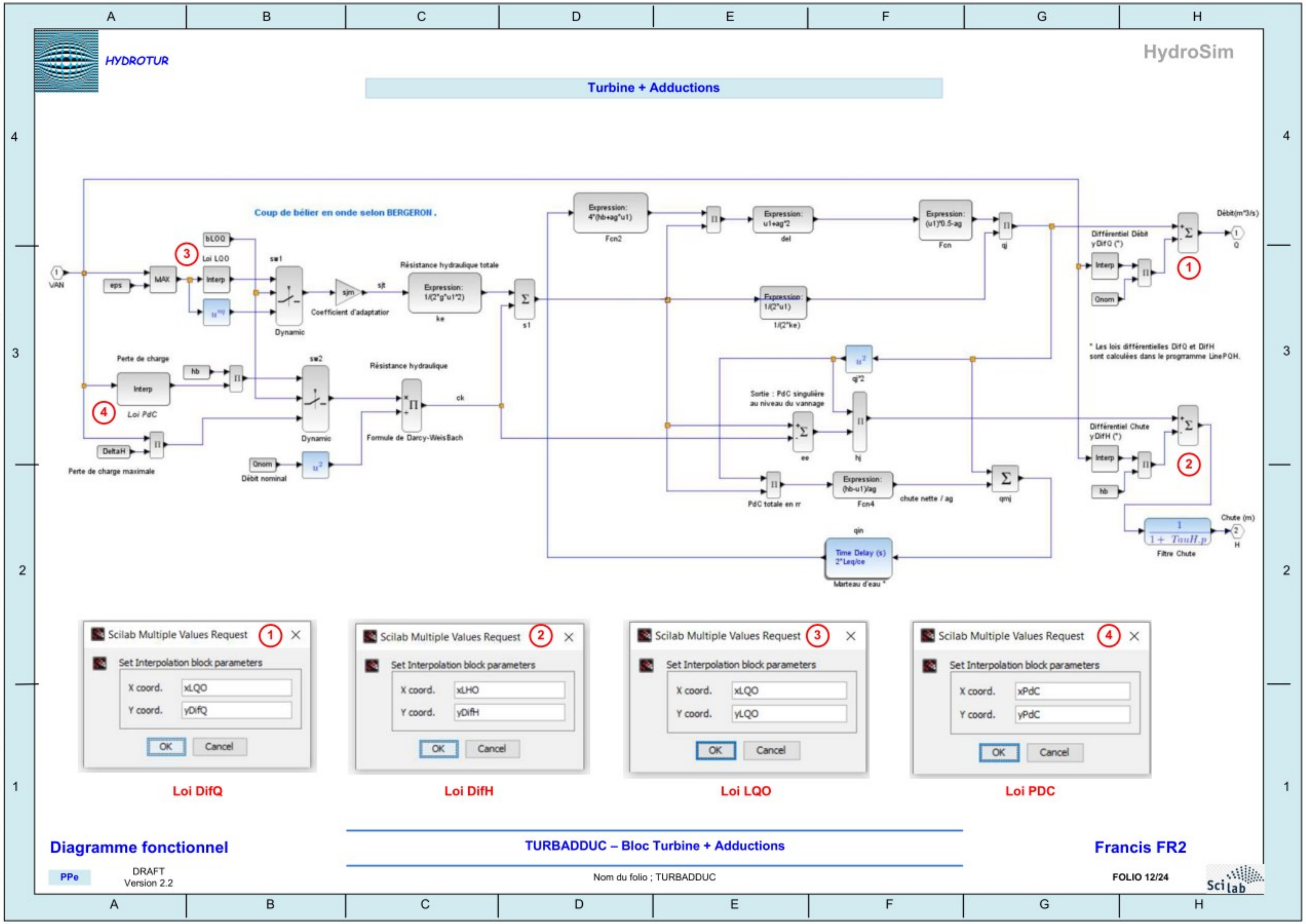


Figure 82 : Speed governor for FRANCIS turbines

E.3 Modeling of the Turbine + Adduction circuit by analytical equations



① Loi DifQ
X coord. xLQO
Y coord. yDifQ

② Loi DifH
X coord. xLHO
Y coord. yDifH

③ Loi LQO
X coord. xLQO
Y coord. yLQO

④ Loi PDC
X coord. xPdC
Y coord. yPdC

Figure 83 : Modeling of the Turbine + Adduction circuit by analytical equations

E.4 Modeling of the Turbine + Adduction circuit with machine hills [n11-c11-q11]

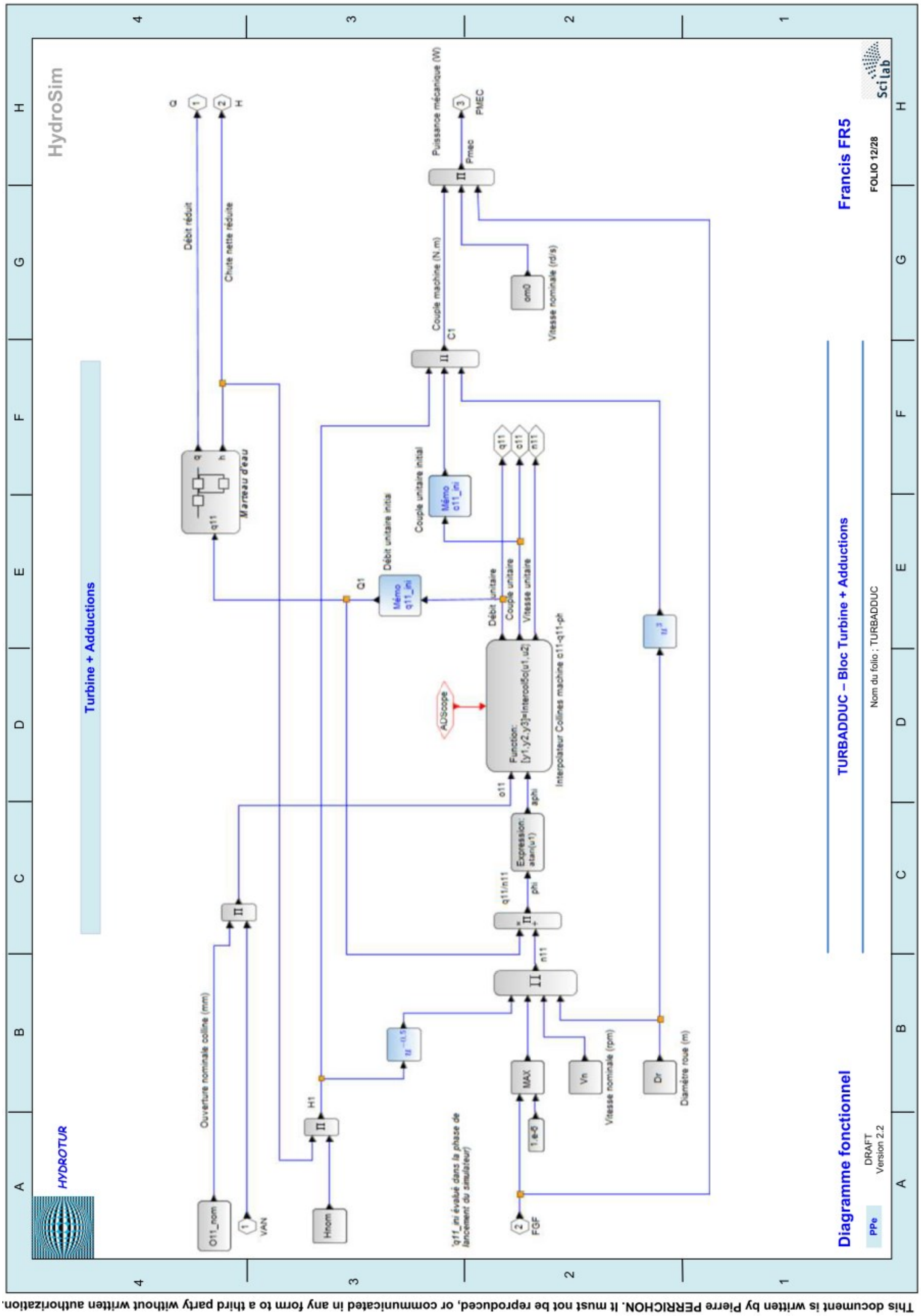
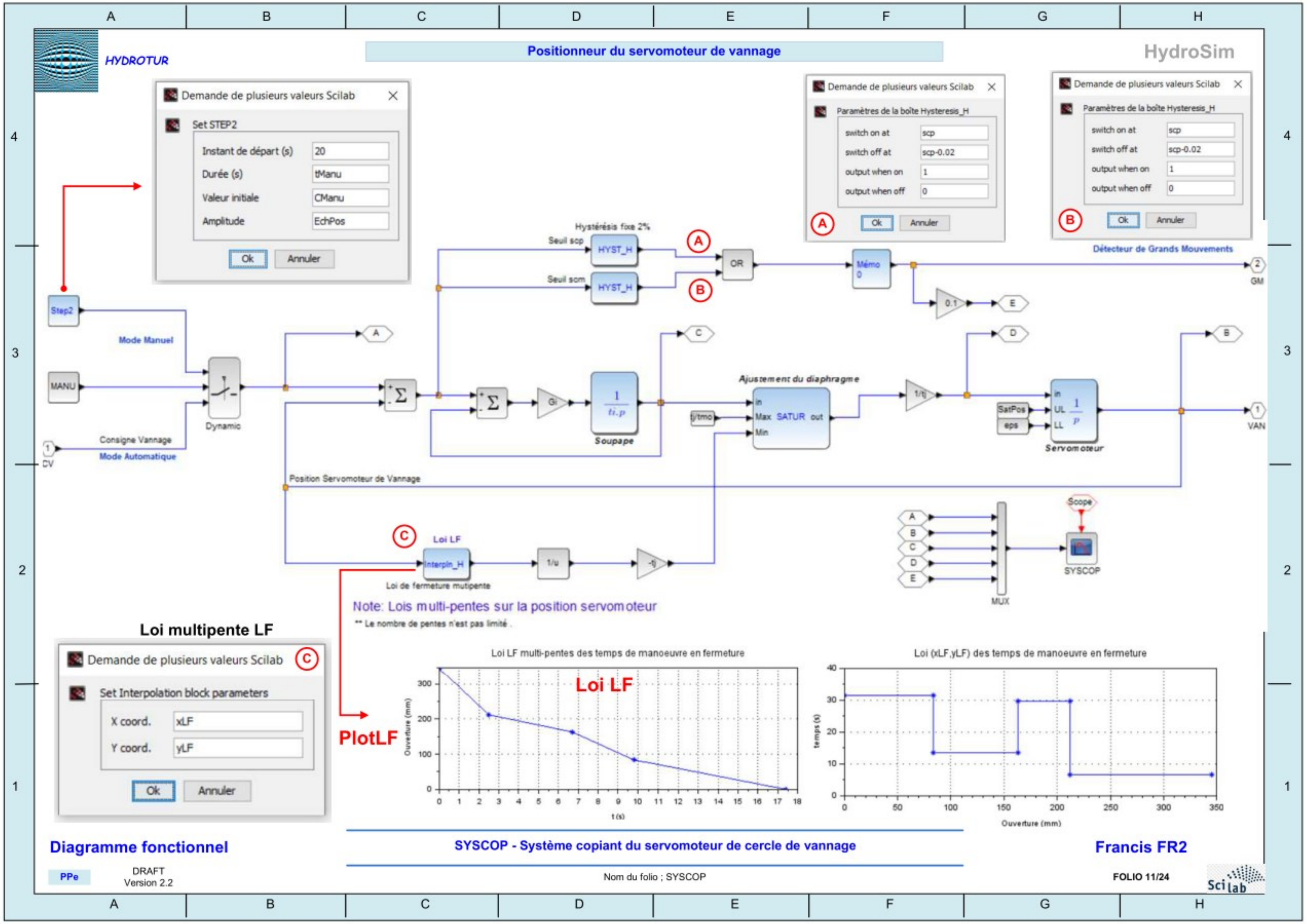


Figure 84 : Modeling of the Turbine + Adduction circuit with machine hill [n11-c11-q11]

E.5 Modeling the copying system



Demande de plusieurs valeurs Scilab
Set STEP2
Instant de départ (s) 20
Durée (s) tManu
Valeur initiale CManu
Amplitude EchPos

Demande de plusieurs valeurs Scilab
Paramètres de la boîte Hysteresis_H
switch on at scp
switch off at scp-0.02
output when on 1
output when off 0

Demande de plusieurs valeurs Scilab
Paramètres de la boîte Hysteresis_H
switch on at scp
switch off at scp-0.02
output when on 1
output when off 0

Demande de plusieurs valeurs Scilab
Set Interpolation block parameters
X coord. xLF
Y coord. yLF

Figure 85 : Modeling of the double-stage copying system

E.6 Network Circuit Modeling

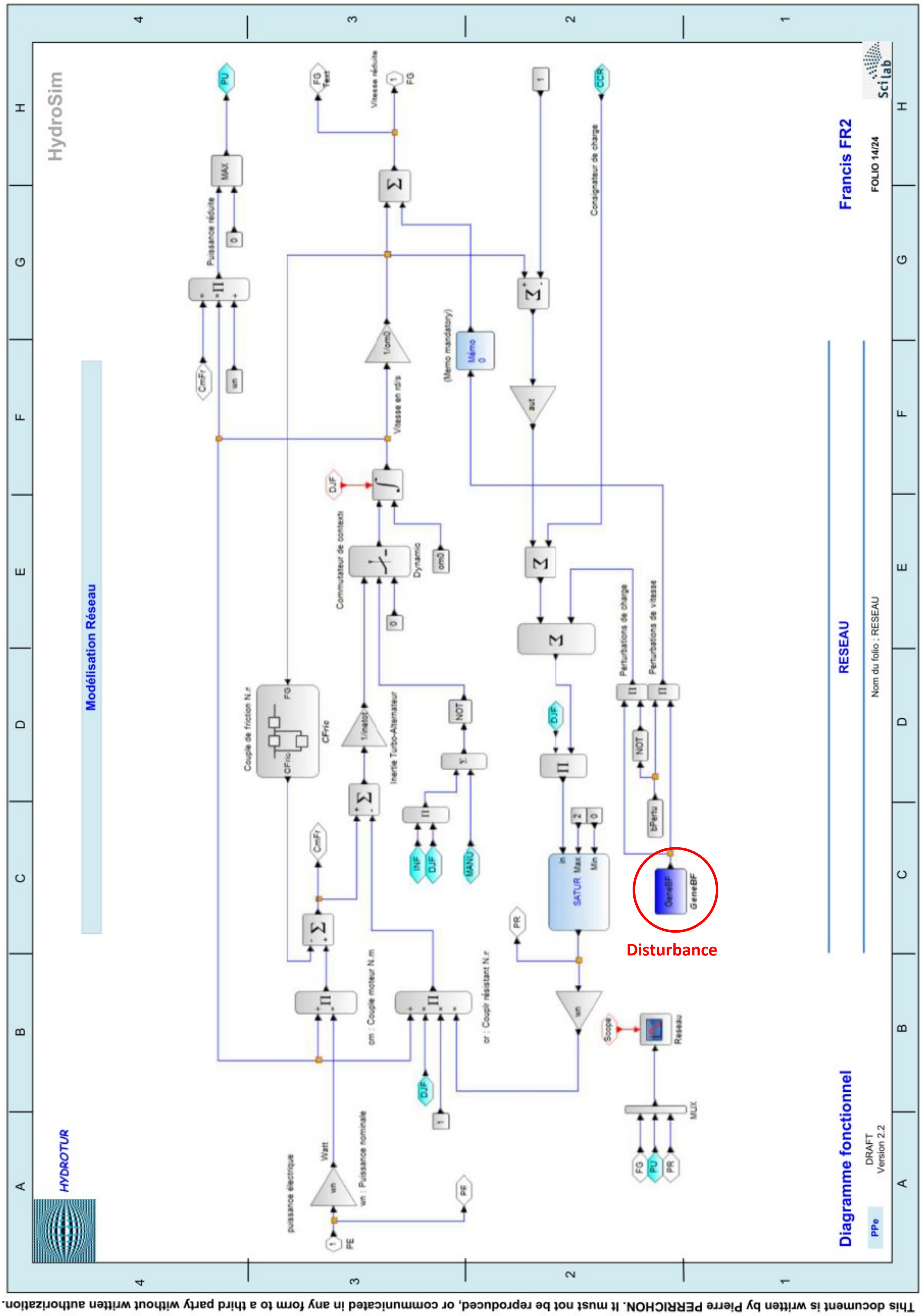


Figure 86 : Network Circuit Modeling

F. LAYOUT AND ORGANIZATION OF THE SCILAB SPACE

1. After installation and first launch of Scilab, we obtain the screen below:

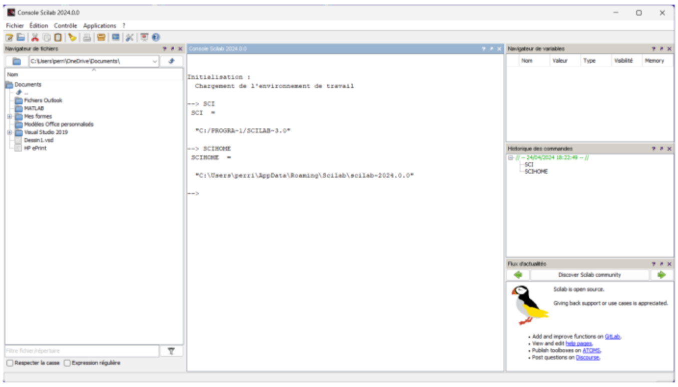
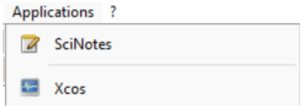


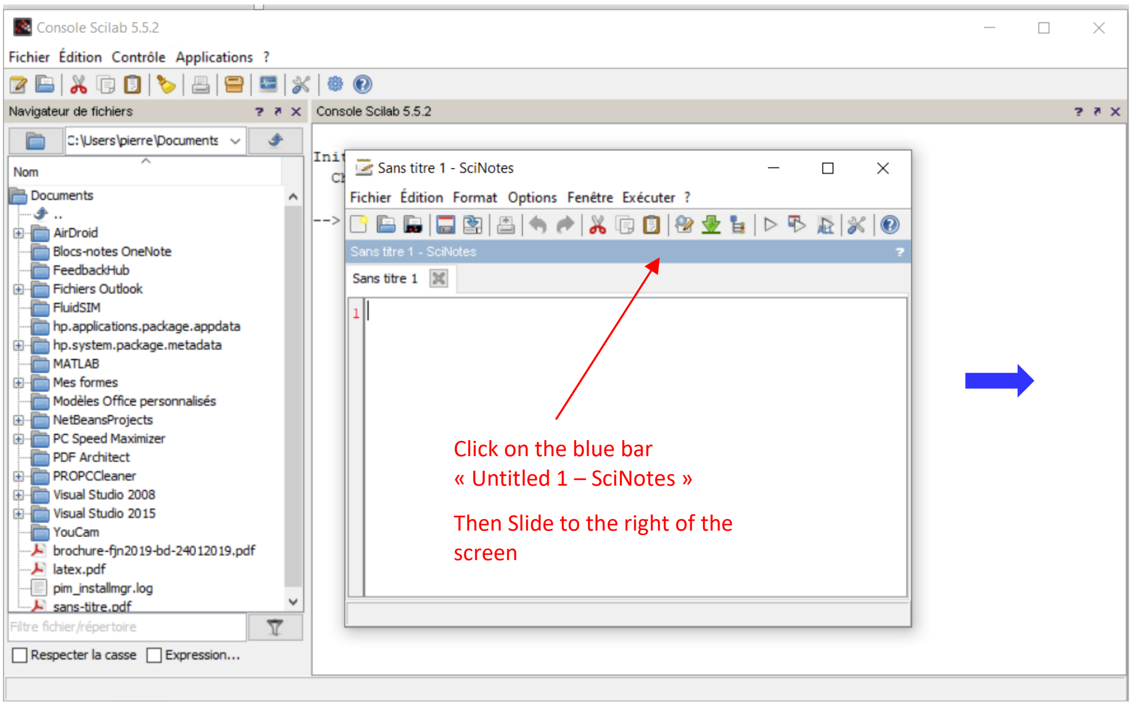
Figure 87 : First Scilab home screen after installation

, and close the three panes on the right of the screen



2. Open SciNotes in tApplications➔Scinotes

3. After Click on the blue bar “Untitled 1 – SciNotes” and, while holding down the left mouse button, drag the window to the right below the center of the console screen, which allows it to be anchored to the right.



Click on the blue bar
« Untitled 1 – SciNotes »

Then Slide to the right of the screen

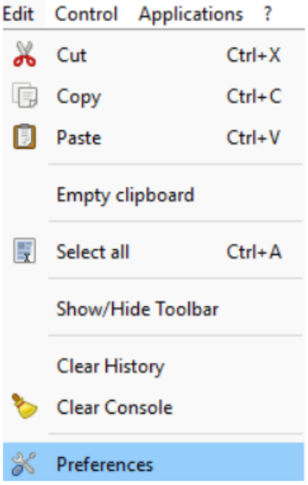
Figure 88 : Anchoring the SciNotes window in the Scilab space

.

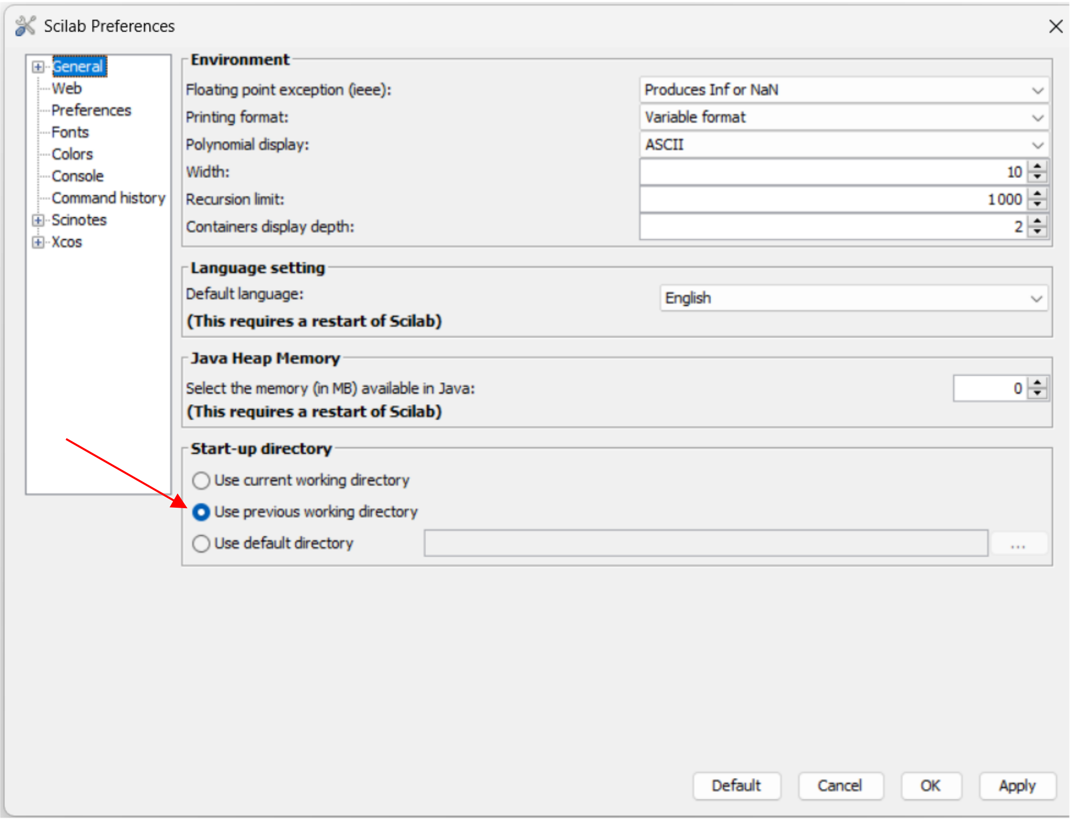
We thus obtain the operational device presented in *Figure 13*

4. Save the working environment and customizations

Click on « Edit➔Preferences »



In the “General” menu, click on “Use previous working directory” to avoid re-navigating in the file manager



Environment

Floating point exception (ieee): Produces Inf or NaN

Printing format: Variable format

Polynomial display: ASCII

Width: 10

Recursion limit: 1 000

Containers display depth: 2

Language setting

Default language: English

(This requires a restart of Scilab)

Java Heap Memory

Select the memory (in MB) available in Java: 0

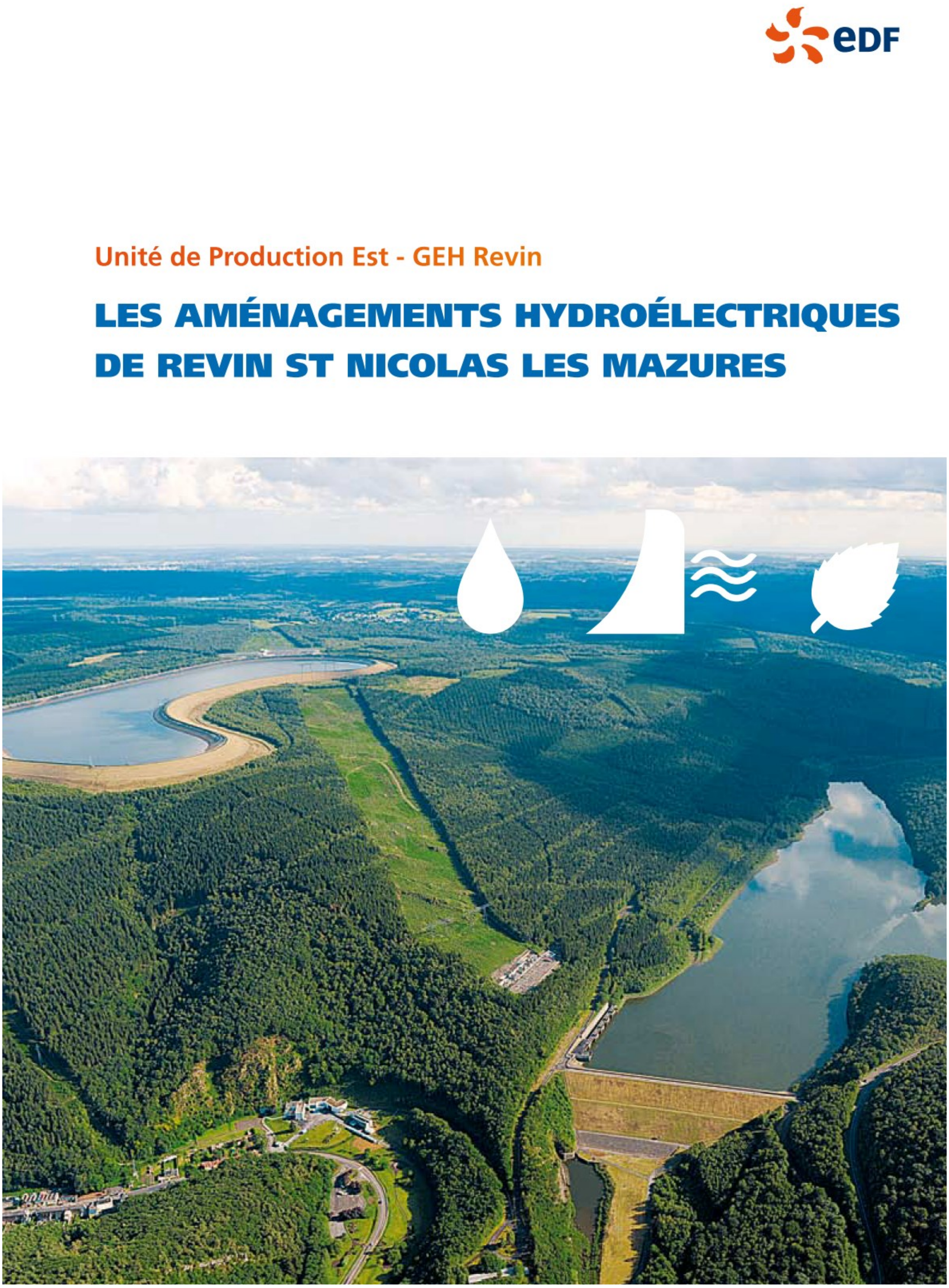
(This requires a restart of Scilab)

Start-up directory

○ Use current working directory
● Use previous working directory
○ Use default directory

Figure 89 : Saving the Scilab working environment

G. REVIN HYDROELECTRIC POWER PLANT



Unité de Production Est - GEH Revin

LES AMÉNAGEMENTS HYDROÉLECTRIQUES
DE REVIN ST NICOLAS LES MAZURES

Une énergie renouvelable, stockable, et disponible rapidement

L'aménagement de Revin St Nicolas les Mazures, a été la 1ère usine EDF équipée de **4 groupes réversibles** «turbine/pompe» de **200 MW** de puissance chacun. C'est actuellement la 3^e STEP en France par la puissance totale installée.

2 minutes seulement suffisent pour qu'elle atteigne sa puissance maximale de **800 MW** (soit 1/3 de la puissance totale de la centrale nucléaire de Chooz qui nécessite plusieurs heures pour monter en puissance).

Mais son originalité principale réside dans son mode de fonctionnement.

Pendant les périodes de forte consommation d'électricité, l'eau du bassin supérieur est turbinée puis stockée dans le bassin inférieur. Pendant les heures de faible consommation, l'eau du bassin inférieur est pompée, grâce aux groupes réversibles pour être stockée à nouveau dans le bassin supérieur. Et ainsi de suite.

Par sa rapidité d'intervention et sa réserve de puissance, la STEP joue un rôle essentiel dans la sécurité et la régulation de l'alimentation électrique des clients d'EDF. Elle pourrait également soutenir le redémarrage de la production d'électricité dans l'hypothèse d'une panne générale.

Compte tenu de son rôle spécifique, la mise en service de l'usine est commandée à distance depuis le **Centre de Conduite Hydraulique** de Lyon.

Une trentaine de salariés assurent au quotidien l'exploitation des ouvrages ainsi que leur maintenance.

La STEP de Revin en quelques chiffres

Mise en service : 1976
Puissance totale : 800 MW
disponibles en 2 mn

Usine souterraine

Caverne principale : 115 m de longueur, 17 m de largeur, 16 m de hauteur
Tunnel d'accès : 170 m de longueur
4 groupes réversibles de 200 MVA, turbine de type Francis

Poste de transformation

4 transformateurs de 200 MVA
13 000/400 000 Volts

Bassin supérieur

Superficie : 66 ha
Digue : 4 200 m de longueur, 9 à 18 m de hauteur
Volume total : 8,5 millions de m^3
Volume utile : 6,9 millions de m^3

Bassin inférieur

Barrage : 300 m de longueur en crête, 35 m de hauteur
Volume total : 9 millions de m^3
Volume utile : 6,9 millions de m^3
Noyau central en argile

Lac des Vieilles Forges

5 millions de m^3

Figure 90 : Revin hydroelectric power plant

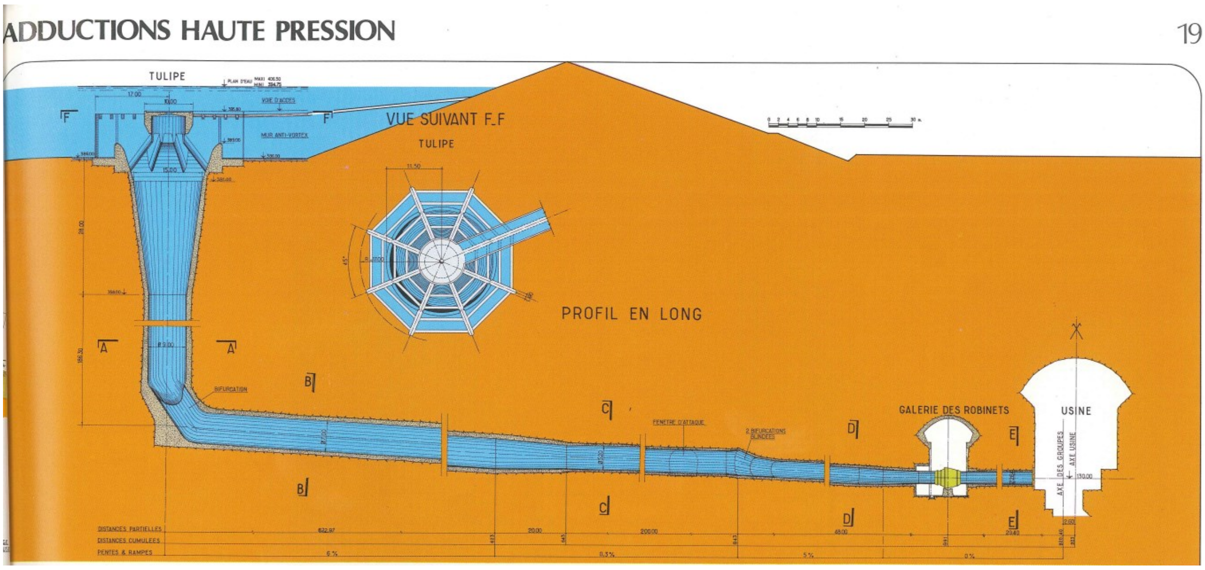
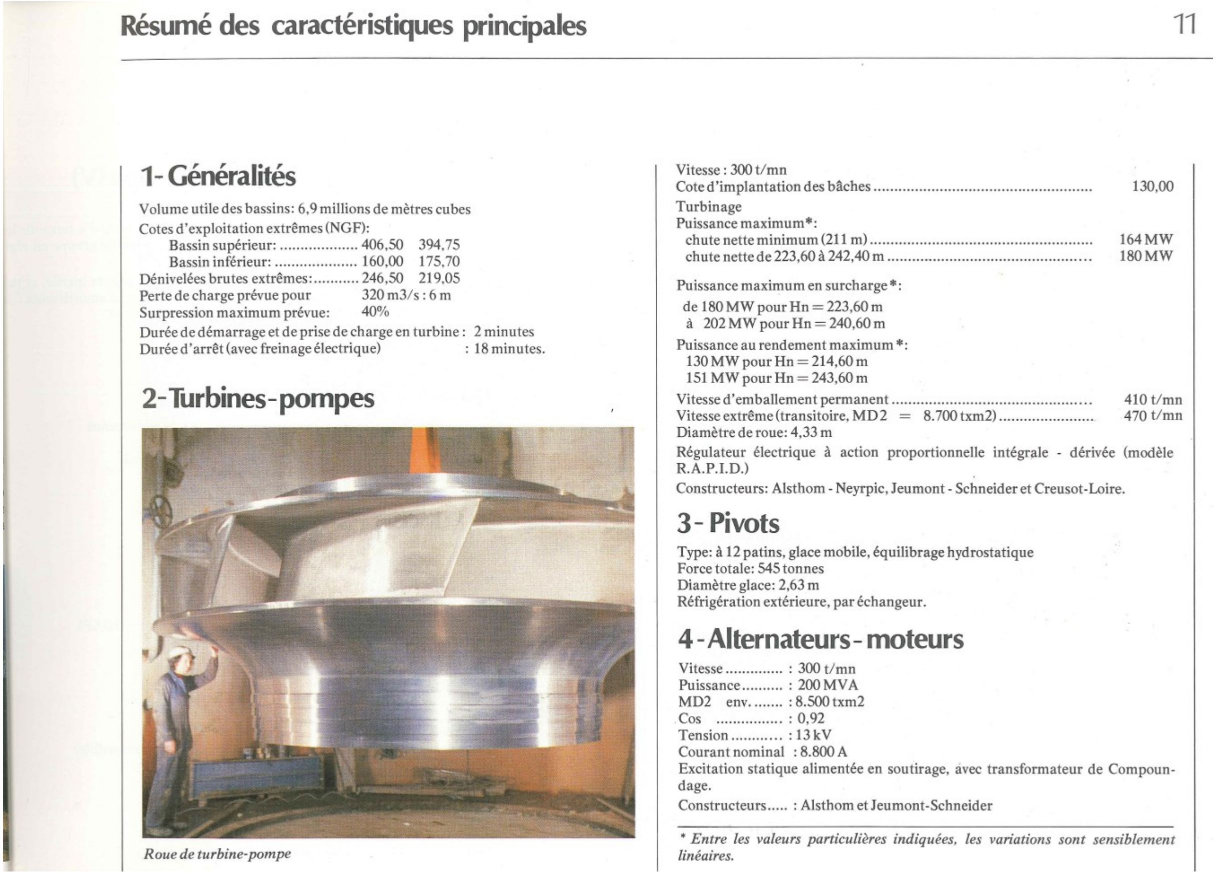


Figure 91 : Revin - Length/Equivalent section – Studies



Résumé des caractéristiques principales

11

1- Généralités

Volume utile des bassins: 6,9 millions de mètres cubes

Cotes d'exploitation extrêmes (NGF):
Bassin supérieur: 406,50 394,75
Bassin inférieur: 160,00 175,70
Dénivelées brutes extrêmes:.......... 246,50 219,05
Perte de charge prévue pour 320 m3/s : 6 m
Surpression maximum prévue: 40%

Durée de démarrage et de prise de charge en turbine : 2 minutes
Durée d'arrêt (avec freinage électrique) : 18 minutes.

2-Turbines-pompes

Roue de turbine-pompe

Vitesse : 300 t/mn
Cote d'implantation des bâches 130,00

Turbinage
Puissance maximum*:
chute nette minimum (211 m) .... 164 MW
chute nette de 223,60 à 242,40 m .... 180 MW

Puissance maximum en surcharge*:
de 180 MW pour Hn = 223,60 m
à 202 MW pour Hn = 240,60 m

Puissance au rendement maximum*:
130 MW pour Hn = 214,60 m
151 MW pour Hn = 243,60 m

Vitesse d'emballement permanent .... 410 t/mn
Vitesse extrême (transitoire, MD2 = 8.700 txm2) .... 470 t/mn
Diamètre de roue: 4,33 m

Régulateur électrique à action proportionnelle intégrale - dérivée (modèle R.A.P.I.D.)

Constructeurs: Alsthom - Neyrpic, Jeumont - Schneider et Creusot-Loire.

3- Pivots

Type: à 12 patins, glace mobile, équilibrage hydrostatique
Force totale: 545 tonnes
Diamètre glace: 2,63 m
Réfrigération extérieure, par échangeur.

4-Alternateurs-moteurs

Vitesse .... : 300 t/mn
Puissance.......... : 200 MVA
MD2 env. .... : 8.500 txm2
Cos .... : 0,92
Tension .... : 13 kV
Courant nominal : 8.800 A
Excitation statique alimentée en soutirage, avec transformateur de Compoundage.
Constructeurs..... : Alsthom et Jeumont-Schneider

---

* *Entre les valeurs particulières indiquées, les variations sont sensiblement linéaires.*

Figure 92 : Revin - Characteristics of Revin turbine pumps

H. LISTING TYPE APRES EXECUTION DU CONSTRUCTEUR BUILDER.SCE

```
--> exec('C:\PPe\0 - Scilab\0 - Xcos8\10 - TURBINES\0 - HydroStab ATOMS\HydroStab\builder.sce', -1)

Construction du fichier Toolbox_names.sce dans le répertoire \etc\...

Building macros...
-- Creation of [HydroStablib] (Macros) --
genlib: Processing file: AddLegend.sci
genlib: Processing file: Bode.sci
genlib: Processing file: Calcul_FTB0_FTBF.sci
genlib: Processing file: ChangeLanguage.sci
genlib: Processing file: ChargeurXcos.sci
genlib: Processing file: CheckValues.sci
genlib: Processing file: ClearCurves.sci
genlib: Processing file: Colorize_PID__Button.sci
genlib: Processing file: DelHydroStabFigure.sci
genlib: Processing file: Display_Info_Message.sci
genlib: Processing file: Display_Results.sci
genlib: Processing file: FT_Select_GUI.sci
genlib: Processing file: FindObj_PPe.sci
genlib: Processing file: Get_FT_Button.sci
genlib: Processing file: Gradient.sci
genlib: Processing file: HydroStab_About.sci
genlib: Processing file: HydroStab_Files.sci
genlib: Processing file: HydroStab_Load.sci
genlib: Processing file: HydroStab_Load_cfg.sci
genlib: Processing file: HydroStab_Param_Def.sci
genlib: Processing file: HydroStab_Save.sci
genlib: Processing file: HydroStab_Save_cfg.sci
genlib: Processing file: HydroStab_Takahashi.sci
genlib: Processing file: HydroStab_XcrossClosure.sci
genlib: Processing file: HydroStab_Ziegler_Nichols.sci
genlib: Processing file: Init_FormatPID.sci
genlib: Processing file: K_FT.sci
genlib: Processing file: Load_IHM_PID.sci
genlib: Processing file: Load_IHM_Param.sci
genlib: Processing file: Load_PID_IHM.sci
genlib: Processing file: Load_Param_IHM.sci
genlib: Processing file: Nyquist.sci
genlib: Processing file: NyquistSymetrique.sci
genlib: Processing file: Nyquist_PPe.sci
genlib: Processing file: Nyquist_Switch.sci
genlib: Processing file: PPe_show_margins.sci
genlib: Processing file: PlotDB.sci
genlib: Processing file: Plot_Max_Reglin.sci
genlib: Processing file: PlotterErase.sci
genlib: Processing file: PrintScilabConsole.sci
genlib: Processing file: Print_sim_G_P_Marge.sci
genlib: Processing file: Read_Marge.sci
genlib: Processing file: Recherche_sim.sci
genlib: Processing file: ResetStructureSim.sci
genlib: Processing file: Saturation_FT.sci
genlib: Processing file: Scilab_About.sci
genlib: Processing file: Select_Save.sci
genlib: Processing file: Set_FT_Button.sci
genlib: Processing file: SolveurHydroStab.sci
genlib: Processing file: Sys_Bode.sci
genlib: Processing file: Sys_Compute.sci
genlib: Processing file: Sys_DEL.sci
genlib: Processing file: Sys_FT_GUI.sci
genlib: Processing file: Sys_Indiciel.sci
genlib: Processing file: Sys_Nyquist.sci
genlib: Processing file: Temporel.sci
genlib: Processing file: Titre_Echelon.sci
genlib: Processing file: ZN.sci
genlib: Processing file: ZN_GUI_1.sci
genlib: Processing file: ZN_GUI_2.sci
genlib: Processing file: ZN_Grille.sci
genlib: Processing file: ZN_Optimize.sci
genlib: Processing file: isSite.sci
```

```
genlib: Processing file: post_xcos_simulate.sci
genlib: Processing file: sysPID.sci
Generating loader.sce...
Generating unloader.sce...
Generating cleaner.sce...
```

Figure 93 : Listing after execution of the builder.sce constructor

LIST OF FIGURES

Personal Notes