Chapter 5

SYNCHRONOUS TURBINE GENERATORS

HYPERSIM

Digital Real-time Power System Simulator

Warning: we are working on updating this manual to correspond to the new Windows interface

5.1 INTRODUCTION

HYPERSIM® provides three different models of synchronous turbine generators: a hydraulic turbine generator, a tandem steam turbine generator and a cross-compound steam turbine generator.

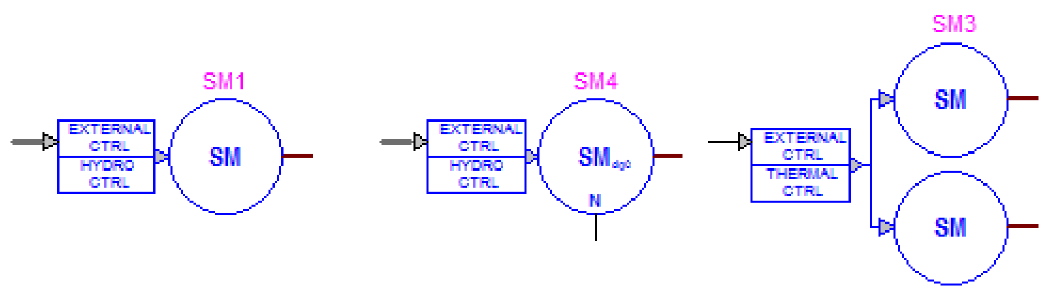
Each synchronous generator model is fully complete and functional by itself. Each model integrates various subsystems such as turbine, excitation system, stabilizer, shaft, etc. Any of those built-in subsystems can be bypassed and replaced by a custom, user-defined subsystem, giving a great flexibility on the modelling aspect.

The icons and diagrams of the hydraulic and thermal turbine generator models are illustrated respectively in Figure 5 - 1.

Only the modular model is provided for the thermal cross-compound turbine generator. However, this modularity is very limited because only the speed regulator can be modelled externally to the turbine generator block. The icon and diagram of the cross-compound turbine generator are shown in Figure 5 - 1.

Turbines / Generators Groups

Turbines / Generators Groups



Properties:	Main features:
7 Three models: – Hydraulic turbine/generator – Tandem steam turbine/generator – Cross-compound steam turbine/ generator	– The hydraulic and thermal models each have two versions
	Implementation: – Generic models – Modular model that can be mod-elled externally (except synchro-nous machine)

Figure 5 - 1 Icons and diagrams of turbine/generator groups

5.2 SYNCHRONOUS GENERATOR MODEL OVERVIEW

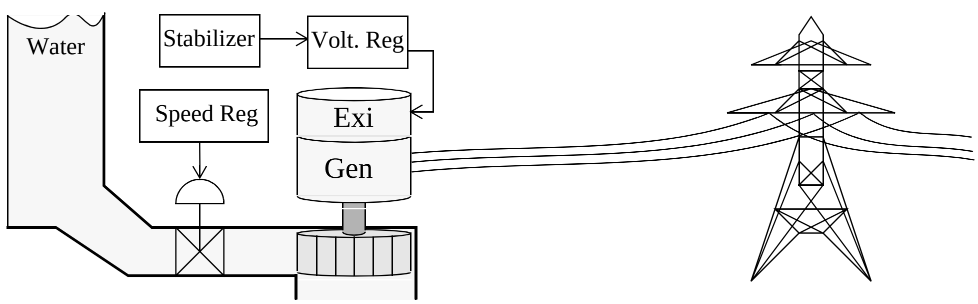


Figure 5 - 2 About hydraulic turbine generator

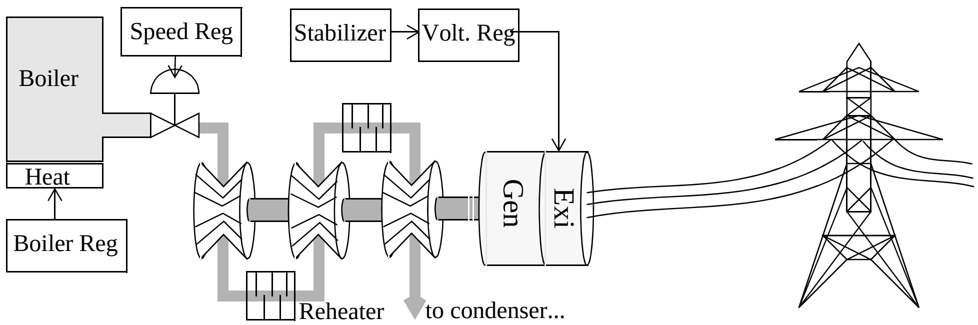


Figure 5 - 3 About tandem steam turbine generator

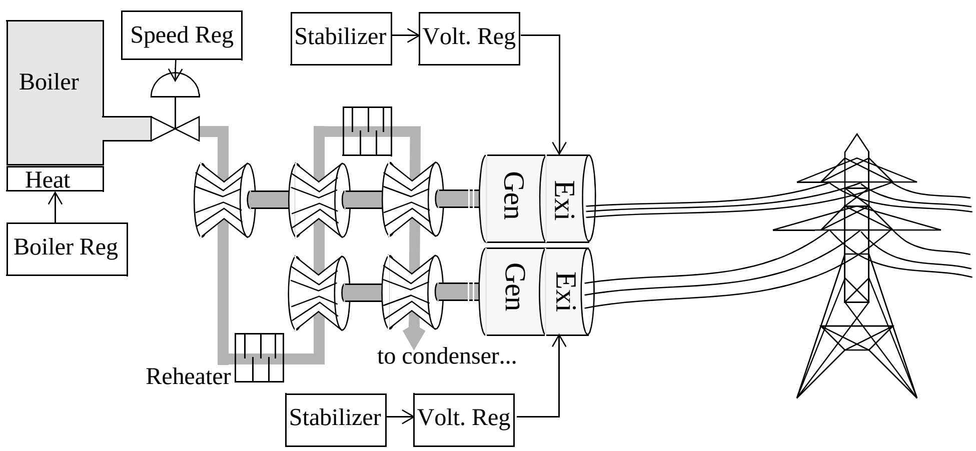


Figure 5 - 4 About cross-compound steam turbine generator

The following table describes the available subsystems and how they are integrated in machine models. Some subsystems are common to all types of machine models, so they are described here as generic models.

Subsystem	Hydraulic Turbine Generator	Tandem Steam Turbine Generator	Cross-compound Steam Turbine Generator
Synchronous Generator	1	1	2
Excitation system	1	1	2
Stabilizer	1	1	2
Boiler	-	1	1
Shaft	1 mass	10 masses	2x 5masses
Hydraulic Turbine	1	-	-
Tandem Steam Turbine	-	1	-
Cross-Compound Steam Turbine	-	-	1
Speed Regulator & Governor (Hydraulic turbine)	1	-	-
Speed Regulator & Governor (steam turbine)	-	1	-
Speed Regulator & Governor (cross-compound turbine)	-	1	-

As seen in the previous table, the synchronous alternator, the exciter and the stabilizer subsystem are the same for all three turbine generator models. These common generic subsystems are described first, followed by the features of each turbine generator group.

5.3 Common Generic Subsystems

5.4 Generic Synchronous Generator

5.4.1 Operation

The generic synchronous generator model implements the equations of the synchronous alternator in the Park axis (DQ), using Shutlz method’s. Since two sets of equations are necessary for D and Q axis, Figure 5 - 5 and 5 - 6 illustrate those sets of equations.

In addition, Figure 5 - 7 presents voltage, power and electromagnetic torque calculations to be used in the entire machine model.

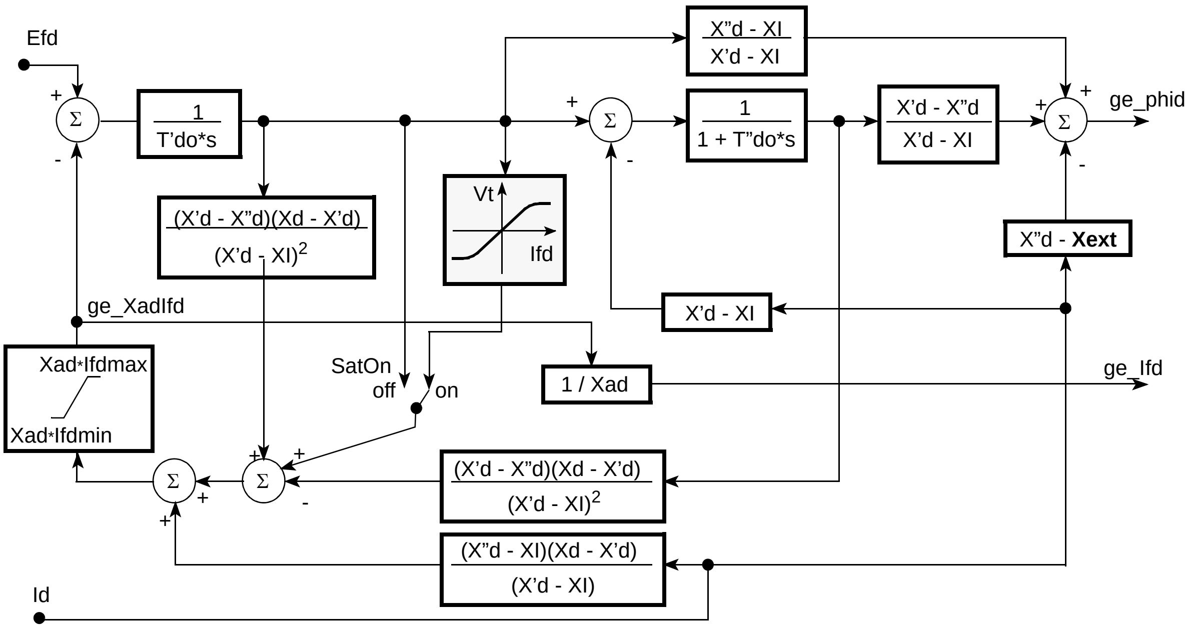


Figure 5 - 5 Generator block diagram, D axis

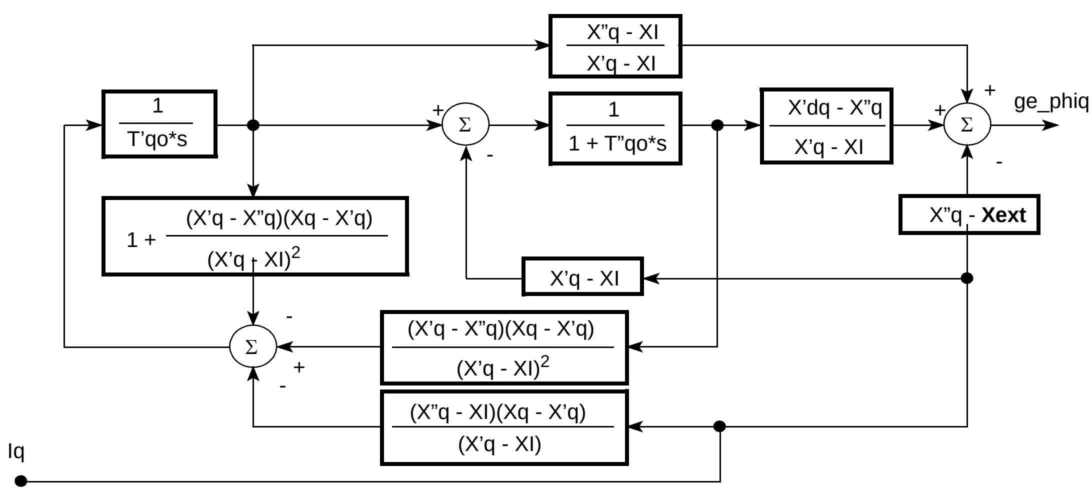


Figure 5 - 6 Generator block diagram, Q axis

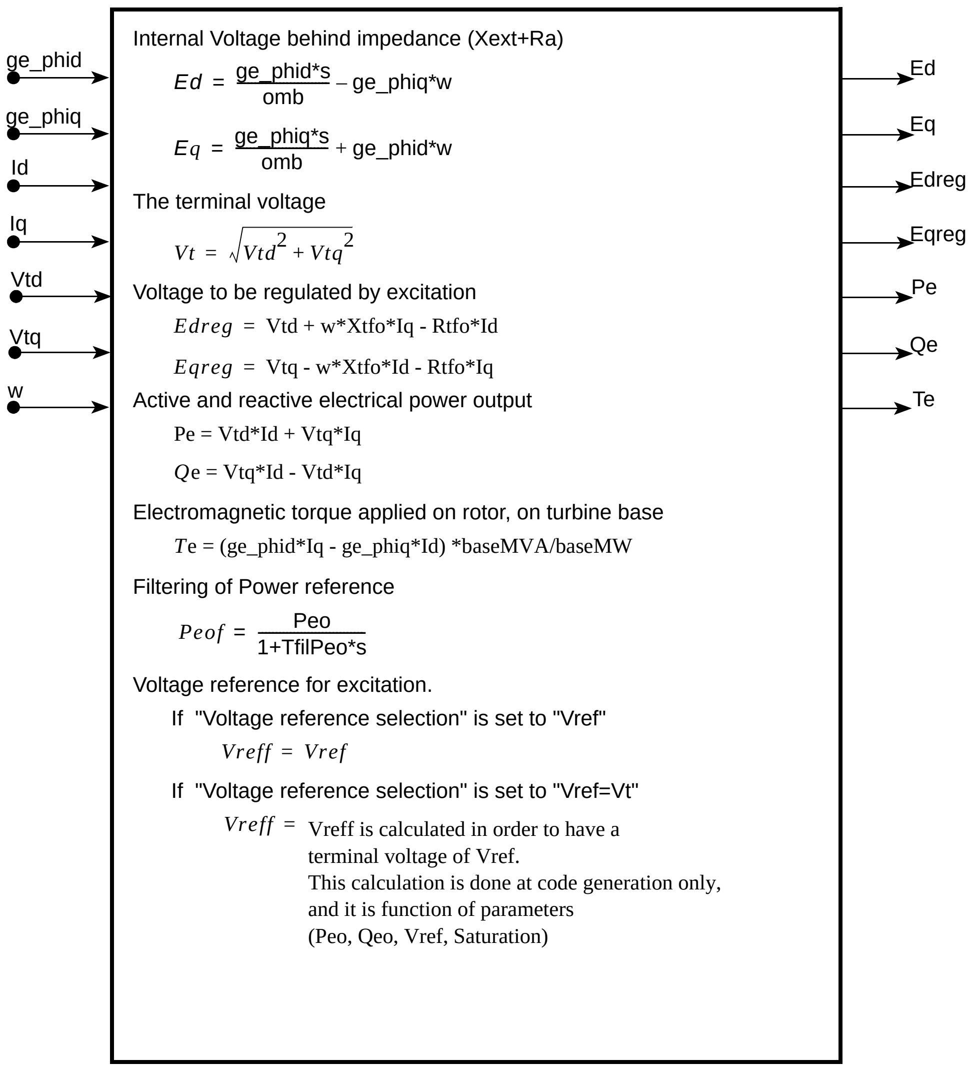


Figure 5 - 7 Generator block diagram, various machine calculations

5.4.2 Programmable General Parameters

- BaseMVA: Base nominal electrical power of generator (MVA)
- BaseMW: Base nominal mechanical power of turbine (MW)
- BaseVolt: Base nominal voltage (kV)
- Omb: Base nominal angular frequency (elec. rad/s)
- Vref: Voltage reference (pu)
- W0: Frequency reference (pu)
- Peo: Active power reference (MW)

- Qeo: Reactive power reference (Mvar).
  (Used only when “Voltage Reference Selection” is “Vref=Vt”).
- Voltage reference selection: Selection of reference signal for excitation.
  (HYPERSIM® can automatically calculate the value of Vref to supply to the excitation system in order to have a terminal voltage that corresponds to the Vref parameter. See Figure 5 - 8 for more details).
- TFilPeo: Power reference filter (s);
- *DYN key*: Key to access Dynedit database.

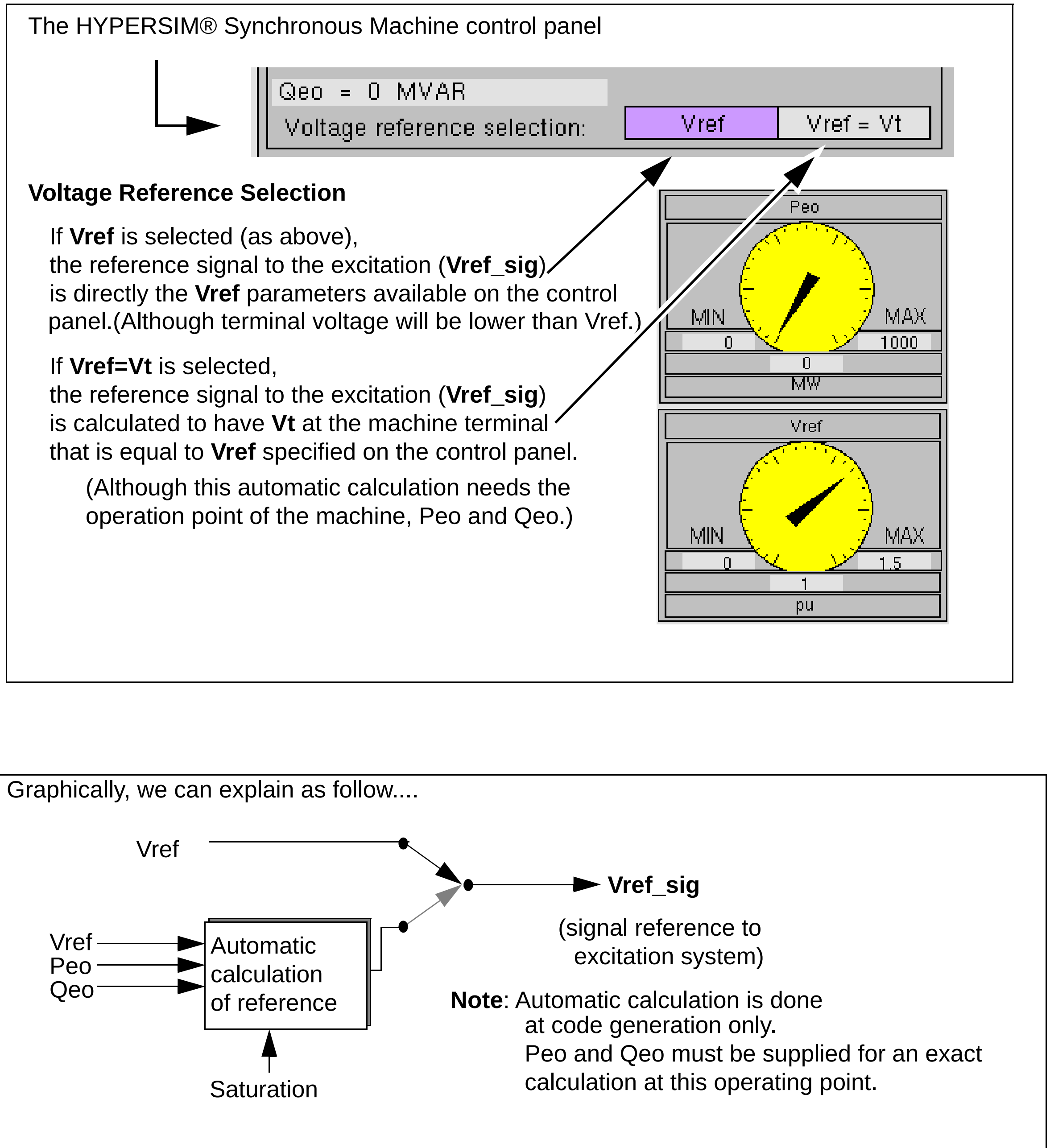


Figure 5 - 8 Voltage reference section of control panel

5.4.3 *Load Flow*

These parameters are provided by the steady-state solution of the network. They can be used to initialize the machines.

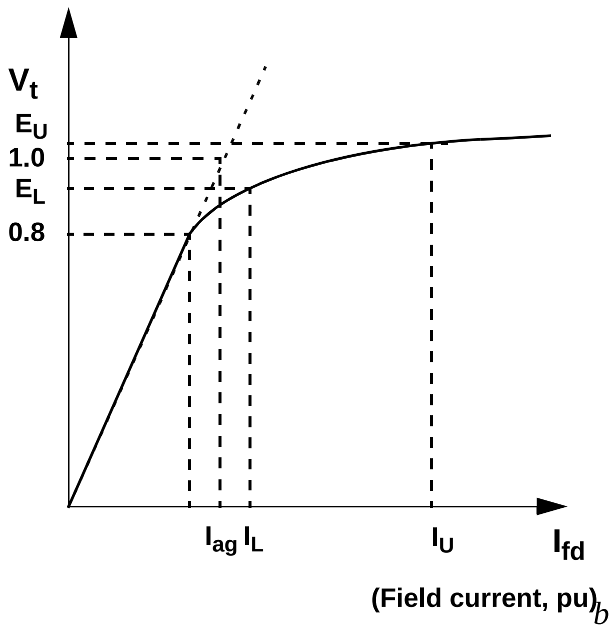
- *Type*: Type of bus (E = swing bus; G = generation bus)
- *Voltage*: Load flow voltage (pu)
- *Angle*: Load flow angle (Deg)

- *P*: Active power (MW)
- *Q Min:* Minimal reactive power (Mvar)
- *Q Max*: Maximum reactive power (Mvar).

5.4.4 Programmable Parameters

- ge_Xtfo, ge_Rtfo: These parameters are null when the output voltage of the generator is regulated; they represent the leakage reactance and the copper losses of the transformer when the voltage on the high-voltage side of the step-up transformer is regulated.
- ge_Xl: Armature leakage reactance (Xl) (pu)
- ge_Ra: Armature resistance (Ra) (pu)
- ge_Xd: Direct synchronous reactance (Xd) (pu)
- ge_Xd1: Direct transient reactance (Xd') (pu)
- ge_Xd2: Direct sub-transient reactance (Xd”) (pu)
- ge_Xq: Quadrature synchronous reactance (Xq) (pu)
- ge_Xq1: Quadrature transient reactance (Xq') (pu)
- ge_Xq2: Quadrature sub-transient reactance (Xq”) (pu)
- ge_Td01: Direct axis transient time constant (Tdo') (s)
- ge_Td02: Direct axis sub-transient time constant (Tdo”) (s)
- ge_Tq01: Quadrature axis transient time constant (Tqo') (s)
- ge_Tq02: Quadrature axis sub-transient time constant (Tqo”) (s)
- ge_Tdif: Differentiation time constant (default value = 0.0001s)
- ge_SatOn: Saturation (1 = yes / 0 = no)
- ge_Ifdmin: Lower limit of Ifd. To prevent Ifd from taking a negative value, set ge_Ifdmin= 0 (pu)
- ge_Ifdmax: Upper limit of Ifd (pu)
- ge_eu, ge_el, ge_sgu, ge_sgl: Parameters used to generate saturation curve as follows:

See Figure 5 - 9 (pu).



The saturation is considered linear from 0 to 0.8 pu of Vt (terminal voltage).

If Vt < 0.8

$$I_{fd} = V_t$$

If Vt > 0.8

$$I_{fd} = V_t + \Delta e_i$$

where:

$$\Delta e_i = a(e^{b(V_t - 0,8)} - 1)$$

$$a = \frac{E_L S_{GL}}{e^{b(E_L - 0,8)} - 1}$$

$$b = \frac{\ln[(E_U S_{GU} + a)/(E_L S_{GL} + a)]}{EU - EL}$$

***a* and *b* are found with some iteration, and are:**

$$S_{GU} = \frac{(I_U / I_{AG}) - E_U}{E_U}$$

$$S_{GL} = \frac{(I_L / I_{AG}) - E_L}{E_L}$$

Figure 5 - 9 Generator saturation curve

- ge_Two: Frequency setting time (in seconds, typically = 4s);
- ge_Ango: Initial angle of voltage behind ge_Xext;

5.5 GENERIC EXCITATION SYSTEM

5.5.1 Operation

The excitation system regulates the terminal voltage of the synchronous machine. It allows users to regulate the voltage at the terminals of the machine, or on the high-voltage side of the step-up transformer. This regulation is done by varying the field voltage Efd based on the difference between the desired user reference voltage Vref and the actual voltage ex_Vtreg. The signal Vstab from the stabilizer can be added to this regulation loop.

The excitation system is composed of two systems, a voltage regulator and the exciter.

The field voltage Efd is limited between ex_Vrmin and ex_Vrmax, based on the voltage to be regulated.

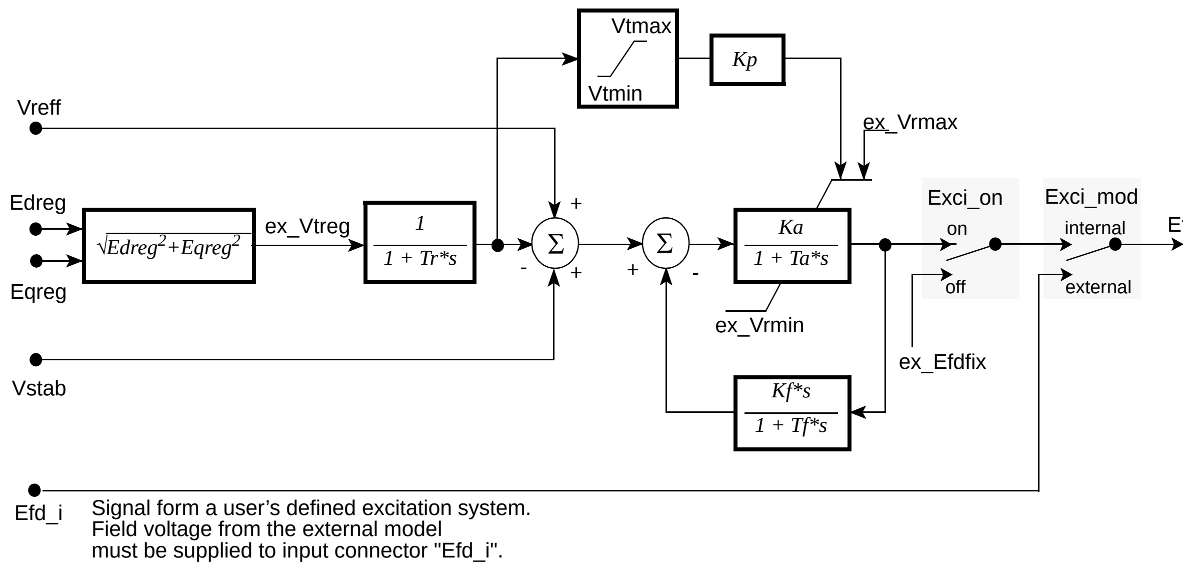


Figure 5 - 10 Generic exciter block diagram

5.5.2 Programmable Parameters

The parameters are shown in the block diagram of the excitation system (ex_Tr, ex_Ka, ex_Ta, ex_Kf, ex_Tf, ex_Vtmax, ex_Vtmin, ex_Vrmin, ex_Vrmax, ex_Efdfix, Exci_on). In addition, the excitation system can be off and set to a constant value. Moreover, the excitation system can be modelized externally by a user-defined model, depending on the state of exci_mod switch.

- exci_on: Selection of excitation system operation. (On=Normal regulation; Off=constant excitation)
- exci_mod: Selection of excitation system model. (Internal = actual model; External = model supply by user)
- ex_Tr: Voltage measurement time constant, (sec)
- ex_Ka: Voltage regulator gain
- ex_Ta: Voltage regulator time constant (sec)
- ex_Kf: Damping filter feedback gain
- ex_Tf: Damping filter feedback time constant (sec)
- ex_Kp: Proportional gain on voltage limit
- ex_Vtmin: Minimum static limit on voltage measurement (pu)
- ex_Vtmax: Maximum static limit on voltage measurement (pu)
- ex_Vrmin: Minimum static limit of excitation voltage (pu)

- ex_Vrmax: Maximum static limit of excitation voltage;
  The maximum limit applied to the regulator transfer function is always the minimal value between the output of the Kp gain and the ex_Vrmax value.
- ex_Efdfix: Constant excitation voltage. Used when Exci_on is off.

5.6 GENERIC STABILIZER

5.6.1 Operation

The stabilizer system is designed to damp most electromechanical oscillations. The stabilizer output is supplied to the excitation system, so it has an effect on the field voltage during transients. The block diagram of the stabilizer is shown in Figure 5 - 11**.** The stabilizer inputs are *Pe* or *Pef* (filtered electric power) and *x* (gate opening). For Hydraulic machine, the filtered electrical power *Pef* is used, calculated in the speed regulator. For steam turbine machine, the electrical power *Pe* is used with no filtering.

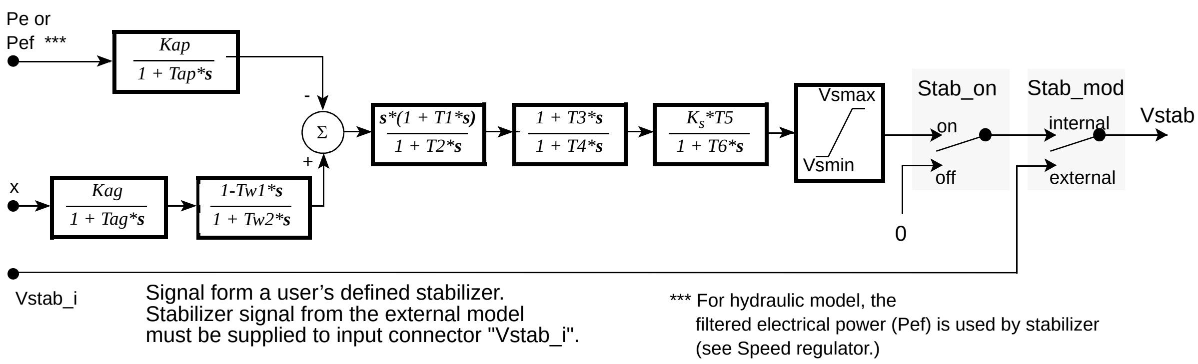


Figure 5 - 11 Generic stabilizer block diagram

5.6.2 Programmable Parameters

The parameters are shown in the block diagram of the stabilizer diagram (st_Kag, st_Kap, st_Tag, st_Tap, st_Ks, st_Tw1, st_Tw2, st_T1, st_T2, st_T3, st_T4, st_T5, st_T6, st_Vsmin, st_Vsmax). In addition, the stabilizer can be off via parameter *stab_on*. Moreover, the stabilizer can be modelized externally by a user-defined model, depending on the state of *stab_mod* switch.

- Stab_on: Selection of stabilizer operation. (On=Normal operation; Off=no stabilizer)
- Stab_mod: Selection of stabilizer model. (Internal: actual model; External: model supply by user)
- st_Kag: Gain on gate opening;
- st_Kap: Gain on electric power;
- st_Tag: Time constant on gate opening (s)
- st_Tap: Time constant on electric power (s)
- st_Ks: Stabilizer gain

- st_Tw1: Stabilizer time constant (s)
- st_Tw2: Stabilizer time constant (s)
- st_T1: Stabilizer time constant (s)
- st_T2: Stabilizer time constant (s)
- st_T3: Stabilizer time constant (s)
- st_T4: Stabilizer time constant (s)
- st_T5: Stabilizer time constant (s)
- st_T6: Stabilizer time constant (s)
- st_Vsmin: Minimum limit of stabilizer voltage (pu)
- st_Vsmax: Maximum limit of stabilizer voltage (pu).

5.7 Hydraulic Turbine Generators

Table 5–1 : HYPERSIM® QUICK REFERENCE

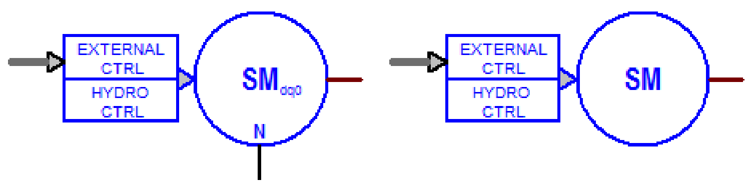
<table>
<tr><td rowspan="4">Hydraulic Turbine Generator</td><td colspan="2">Hydraulic Turbine Generator</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td rowspan="2">Properties:
The:
– Speed regulator;
– Turbine;
– Stabilizer;
– Excitation.
can be modified.</td><td>Main features:
This machine includes:
– A generic speed regulator for hydraulic generating plants;
– A generic hydraulic turbine and;
– A shaft model.</td></tr>
<tr><td>Implementation:
-</td></tr>
</table>

Figure 5 - 12 Icon and diagram hydraulic turbine generator

Figure 5 - 13 shows the schematic diagram of a hydraulic turbine generator. The shaded blocks in Figure 5 - 14 can be modelled externally to the turbine generator block using the CSI. A description of the speed regulator, the hydraulic turbine and a shaft model follows.

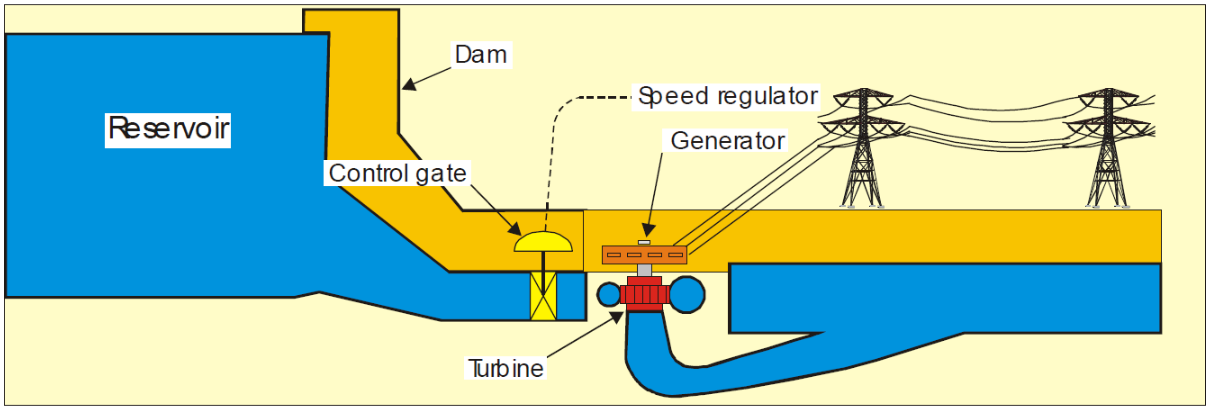


Figure 5 - 13 Schematic diagram of a hydraulic turbine generator

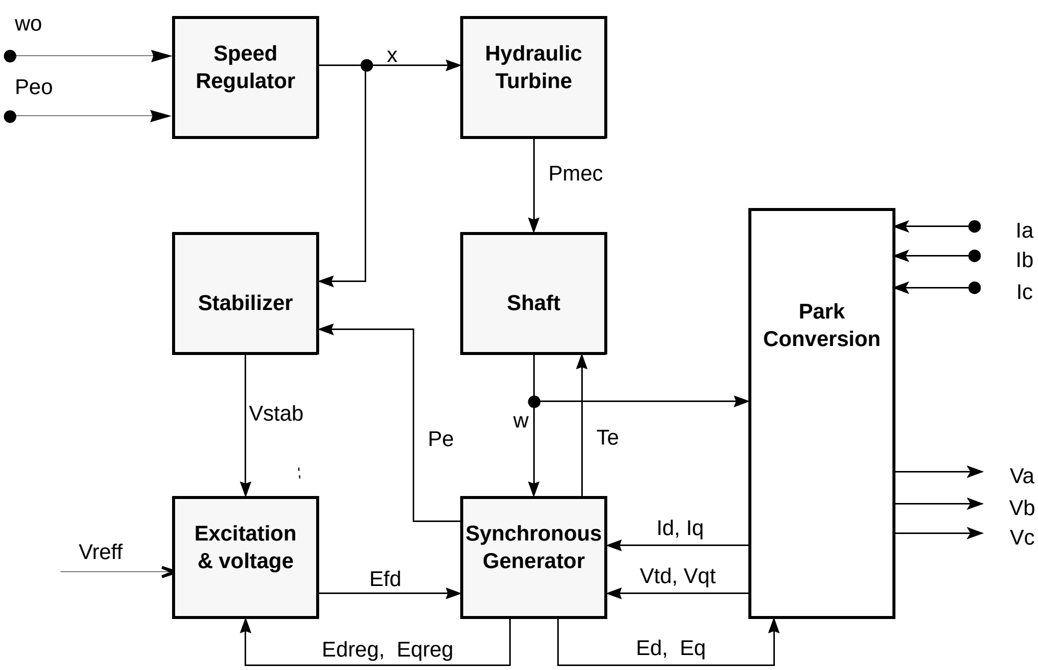


Figure 5 - 14 general diagram of a Hydraulic Turbine Generator

5.8 SPEED REGULATOR FOR HYDRAULIC TURBINE GENERATORS

5.8.1 Operation

The speed regulator is responsible for producing the gate opening signal *x* depending on actual electric power *Pe* and speed *w*. In fact, this type of regulator is a speed and power regulator, because it achieves a specific characteristic of regulation, called permanent droop between *Pe* and *w*. So, this regulator needs two different user references, *Peo* and *wo*.

The regulation characteristic is illustrated in Figure 5 - 15. It represents a line with a slope *-re_sigma* (permanent droop) on which the speed *w* is equal to the rated speed *wo* when the electric power required is equal to the reference power *Peof*. So, if the machine delivers more than its reference, the machine's speed will tend to decrease, depending on the permanent droop value.

The speed regulator has two different operating modes. The first operating mode, based on electrical power regulation, is achieved when *re_iop*=1. In that mode, the regulator will adjust x in order to have an electrical power output to be the same as the power reference (Peo).

The second speed regulator operating mode, based on gate opening regulation, will adjust the gate opening to have mechanical power output be the same as the electrical power reference. In that case, the friction losses (Tgo) are not considered in the regulation.

The block diagram of the power and speed regulator is illustrated in Figure 5 - 16.

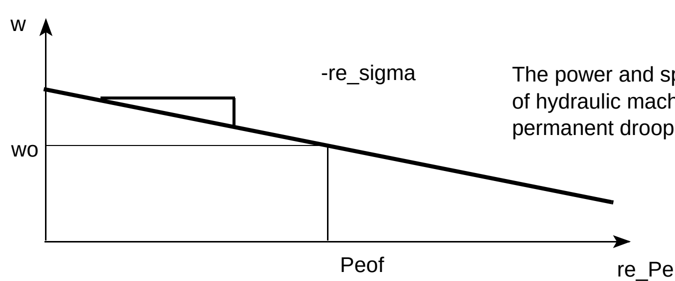


Figure 5 - 15 Speed and power regulation characteristic

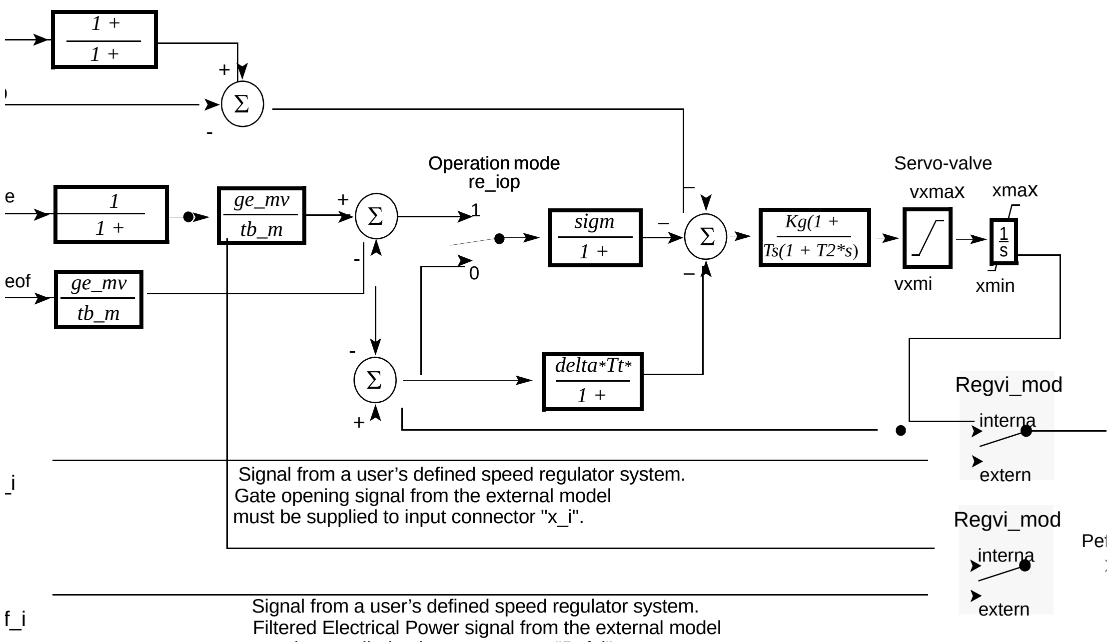


Figure 5 - 16 Speed and power regulator block diagram

5.8.2 Programmable Parameters

- Regvi_mod: Selection of speed regulator model. (Internal: actual model; External: model supply by user)
- re_Ta1: Time constant on speed measurements
- re_Ta2: Time constant on speed measurements
- re_Twatt: Time constant for power measurement;
- re_iop: Regulation mode (1 = Electrical power; 0 = Gate opening)
- re_sigma: Permanent droop
- re_delta: Transient droop
- re_Tp: Time constant for permanent droop
- re_Tt: Time constant for transient droop
- re_Kg: Regulator gain
- re_Ts: Time constant for servo-valve
- re_T1: Time constant for speed regulator
- re_T1: Time constant for speed regulator
- re_xmin: Lower limit of gate opening
- re_xmax: Upper limit of gate opening
- re_vxmin: Lower limit of gate speed at closing, (negative value)

- re_vxmax: Upper limit of gate speed at opening, (positive value).

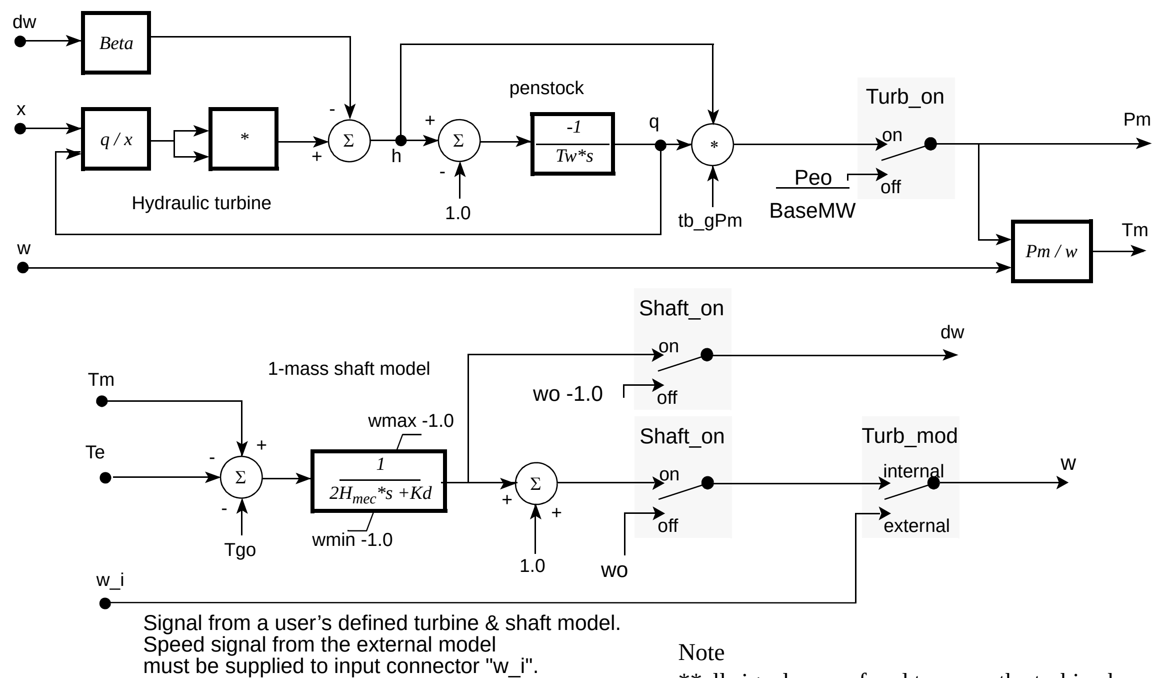
5.9 GENERIC HYDRAULIC TURBINE

5.9.1 Operation

The actual model of hydraulic turbine also includes the shaft system, that is represented as single mass.

The hydraulic turbine model is responsible for producing the mechanical power to be applied to the shaft system. The shaft system then applies the swing equations, in order to produce the speed of the machine.

The block diagram of the turbine model, including the shaft, is shown in Figure 5 - 17.



Note
**all signals are refered to pu on the turbine base (baseMW)

***The value Hmec is the inertia constant converted to turbine base.
Hmec = H * BaseMVA/BaseMW.

****tb_gpm is now obsolete, kept for compatibility.

Figure 5 - 17 Hydraulic turbine block diagram

5.9.2 Programmable Parameters

- Turb_mod: Selection of turbine and shaft model. (Internal: actual model; External: model supply by user)
- Turb_on: Selection of turbine operation. (On=Normal operation; Off=constant power equal to power reference Peo/baseMW)

- Shaft_on: Selection of shaft operation. (On=Normal operation; Off=constant speed equal to speed reference wo)
- tb_Beta: Effect of speed variation on the water height **h**
- tb_Tw: Water time response in penstock
- tb_H: Inertia constant (pu/MVA)
- tb_Kd: The damping coefficient
- tb_Kdstart: Damping coefficient of turbine at start-up time. This value helps to reach synchronism. (typically = 5)
- tb_TStart: Duration of turbine start-up (in seconds, typically 5 s)
- tb_wmax: Maximum limit of machine's speed (pu)
- tb_wmin: Minimum limit of machine's speed (pu)
- tb_Tg0: Torque representing total mechanical losses (pu/MW*s)
- tb_gPm: Operation mode of machine (1 = turbine generator; 0 = synchronous compensator). Obsolete, please use Turb_on.

5.9.3 List of Available Signals

At acquisition, the following signals are made available by the **sensors**:

- V_*label*_a, b, c: Three-phase voltage of power system (pu)
- I_*label*_a, b, c: Three-phase current of generator (pu)
- Id_*label*: Current of machine, D axis (pu)
- Iq_*label*: Current of machine, Q axis (pu)
- Ed_*label*: D axis voltage in front of Xext (pu)
- Eq_*label*: Q axis voltage in front of Xext (pu)
- Vt_*label*: Terminal voltage (pu)
- Efdgen_*label*: Field voltage (pu), now obsolete, replaced by Efd_*label*
- Efd_*label*: Field voltage (pu)
- Efd_i_*label*: Field voltage provided by an external module (pu)
- Ifd_*label:* Field current (pu)
- Vstab_*label*: Output voltage of stabilizer (pu)
- w_*label*: Angular speed (pu)
- w_i_*label*:Angular speed provided by an external module (pu)
- Te_*label*: Electrical torque (pu/MW*s)
- Te_i_*label*: Electrical torque (pu/MW*s) provided by an external module
- Tm_*label*: Mechanical torque (pu/MW*s)

- Pe_*label*: Active power (pu/MVA)
- Qe_*label*: Reactive power (pu/MVA)
- Pef_*label*: Filtered measured electrical power (pu/MVA)
- Pef_i_*label*: Filtered measured electrical power (pu/MVA) provided by an external module
- Pm_*label*: Turbine mechanical power (pu/MW)
- x_*label*: Gate opening (pu)
- x_i_*label*: Gate opening provided by an external module (pu).

5.9.4 Operating Mode

Using hydraulic synchronous machine, various operating modes are available. These modes are valid for both the hydraulic and thermal models, since they mainly concern the generic parts (generator-excitation):

1 Generating Mode – This is the most common mode. A positive mechanical torque is applied to the shaft of the machine, thereby inducing its rotation. This mechanical torque originates from a hydraulic or thermal turbine. The generator offers an equivalent electrical torque, but of opposite sign, thereby providing electric power to the network. Any imbalance between the electrical and mechanical couple translates into a speed variation of the turbine generator. The excitation circuit is used to regulate the output voltage of the machine and the speed regulator to control the water or steam input (thermal or hydraulic), thus ensuring a balance between the mechanical and the electrical couple.

2 Synchronous Compensator Mode – Any turbine generator can be used in the synchronous compensator mode by removing the turbine (hydraulic or thermal) and using the machine with no load. By adjusting the excitation circuit, it is possible to control the network voltage, and to provide or absorb the required reactive power.

3 Synchronous Motor Mode – The same machine can also be used as a motor, in other words with a reverse mechanical couple, allowing, for example, to pump water upstream to the dam.

4 Type 1 Machine Mode – In some cases, stability programs require a “Type 1" machine or a constant voltage source behind an impedance, but with a frequency varying as a true machine. Such a behaviour can also be emulated.

5.9.5 Hydraulic Turbine Generator Control Panel

Figure 5 - 18 shows the control panel of a hydraulic turbine generator.

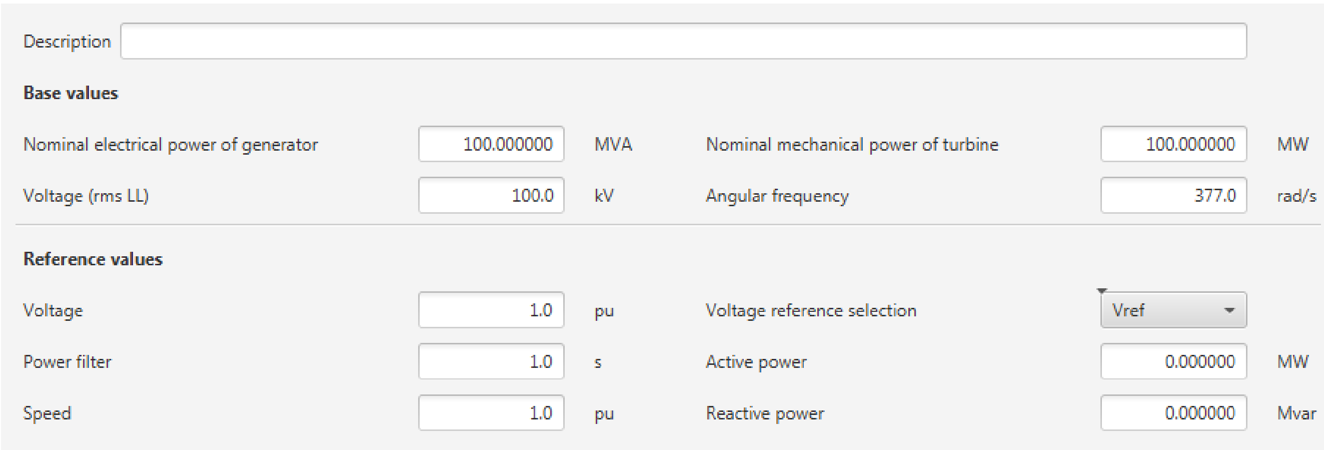


Figure 5 - 18 Hydraulic turbine generator control panel (general)

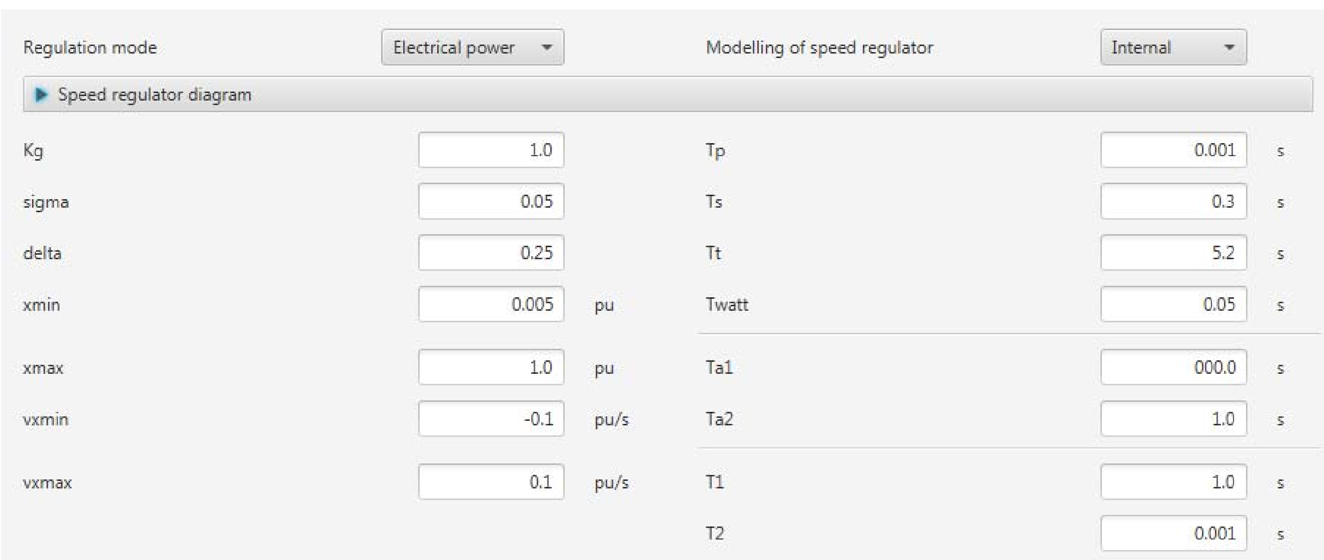
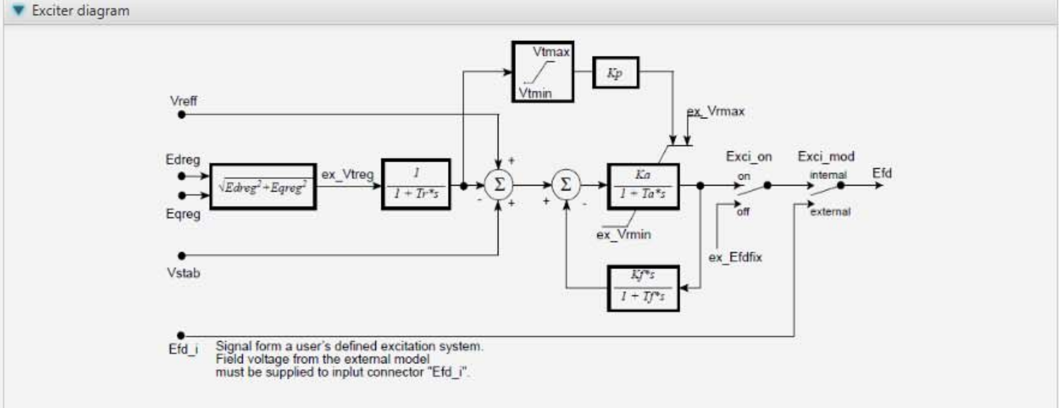


Figure 5 - 19 Hydraulic turbine generator control panel (speed/turbine)

Excitation circuit	On		Modelling of excitation circuit	Internal	

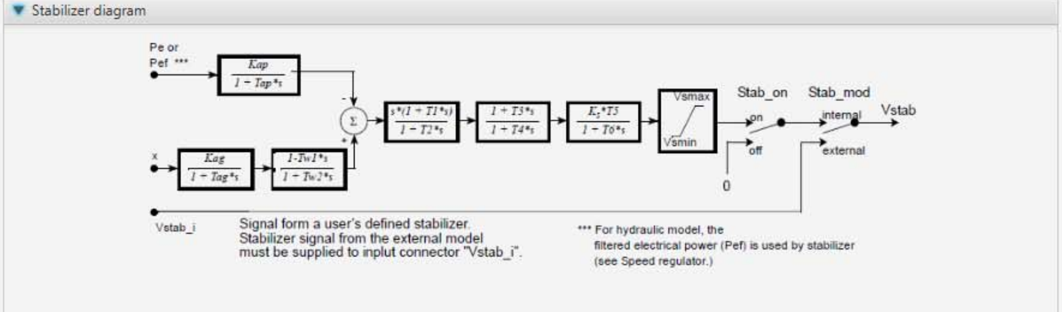
Exciter diagram



Kp	12.3		Tr	0.02	s
Ka	50.0		Ta	0.001	s
Kf	0.0		Tf	1.0	s
ex_Efdfix	0.0	pu			
ex_Vtmin	0.1	pu	ex_Vrmin	-12.7	pu
ex_Vtmax	100.0	pu	ex_Vrmax	12.3	pu

Stabilizer circuit	On		Modelling of stabilizer circuit	Internal	

Stabilizer diagram



Kap	1.0		Tap	0.015	s
Kag	1.0		Tag	0.015	s
Ks	5.289		Tw1	1.2	s
Vsmin	-0.15	pu	Tw2	0.072	s
Vsmax	0.15	pu	T1	0.01	s
			T2	0.66	s
			T3	0.001	s
			T4	2.0	s
			T5	1.0	s
			T6	0.001	s

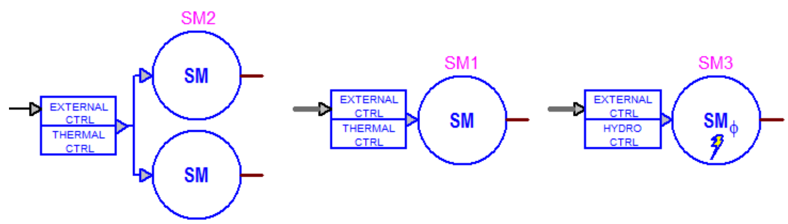
Figure 5 - 20 Hydraulic turbine generator control panel (excitation/stabilizer)

5.10 TANDEM THERMAL TURBINE GENERATORS

Table 5–2 : HYPERSIM® QUICK REFERENCE

Thermal Turbine Generator

Thermal Turbine Generator



Properties:	Main features:
The: – Speed regulator – Turbine – Stabilizer – Excitation – Boiler – 5-10 mass shaft. can be modified.	This machine includes: – A low-pass filter for the power reference Peo – A block that automatically calculates the voltage reference Vreff when the parameter Vref_select=1 – A generic models of a speed regulator for thermal plants – A multi-mass shaft – A boiler and – A steam turbine.
	Implementation: -

Figure 5 - 21 Icon and Diagram Thermal Turbine Generator

Figure 5 - 22 shows the schematic diagram of a thermal turbine generator (tandem-compound). The blocks are described in Section 5.4, on page 62.The shaded blocks can be modelled externally to the turbine generator block.

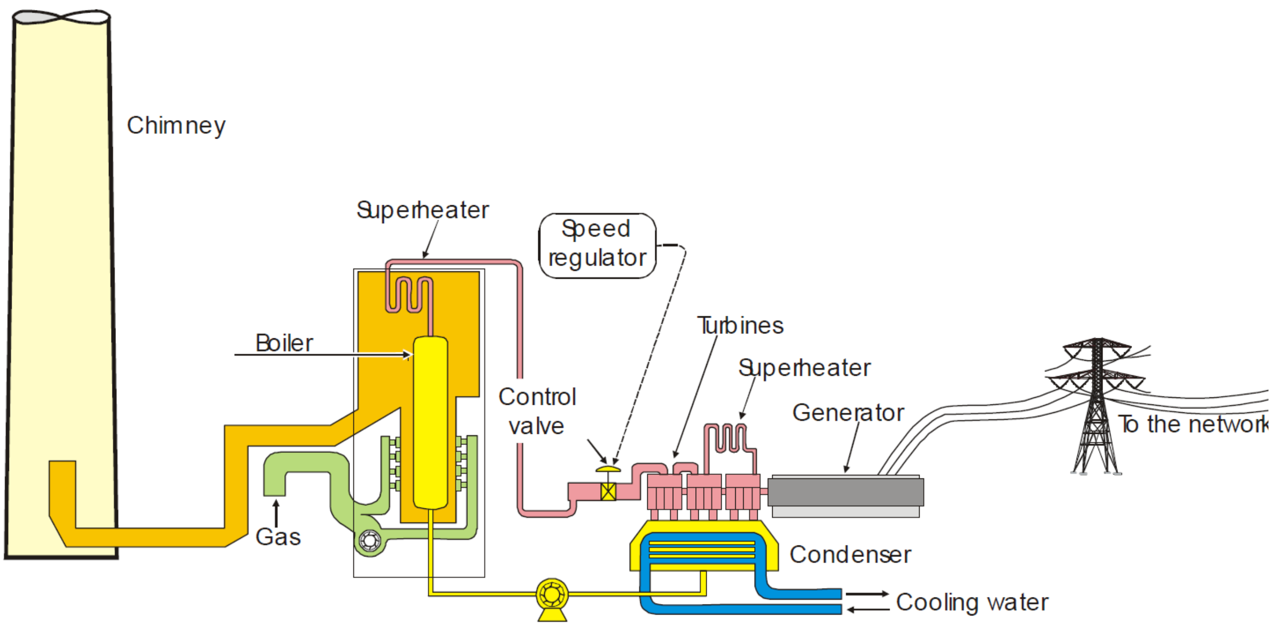


Figure 5 - 22 Schematic diagram of a thermal tandem turbine generator

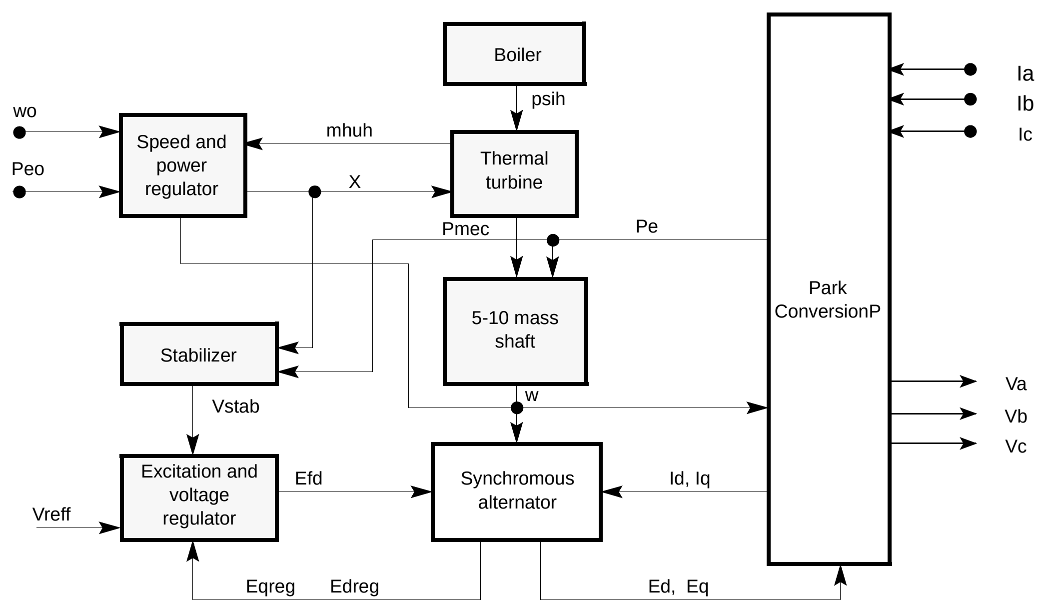


Figure 5 - 23 General diagram of a thermal turbine generator

5.11 Generic Boiler

5.11.1 Operation

The boiler subsystem is responsible for generating the steam pressure used in steam turbines. The actual boiler is used for both tandem and cross-compound machine.

The boiler block diagram is shown in Figure 5 - 24. The upper part of this figure presents the boiler pressure regulator, and the lower part presents the boiler itself. The boiler input is the high pressure steam flow mhuh and the output is the boiler pressure psih. As mentioned earlier, the boiler subsystem includes a PI type pressure regulator that controls the steam pressure output. Since the boiler has slow dynamics with respect to the other model, this subsystem is often neglected and set as a constant pressure source.

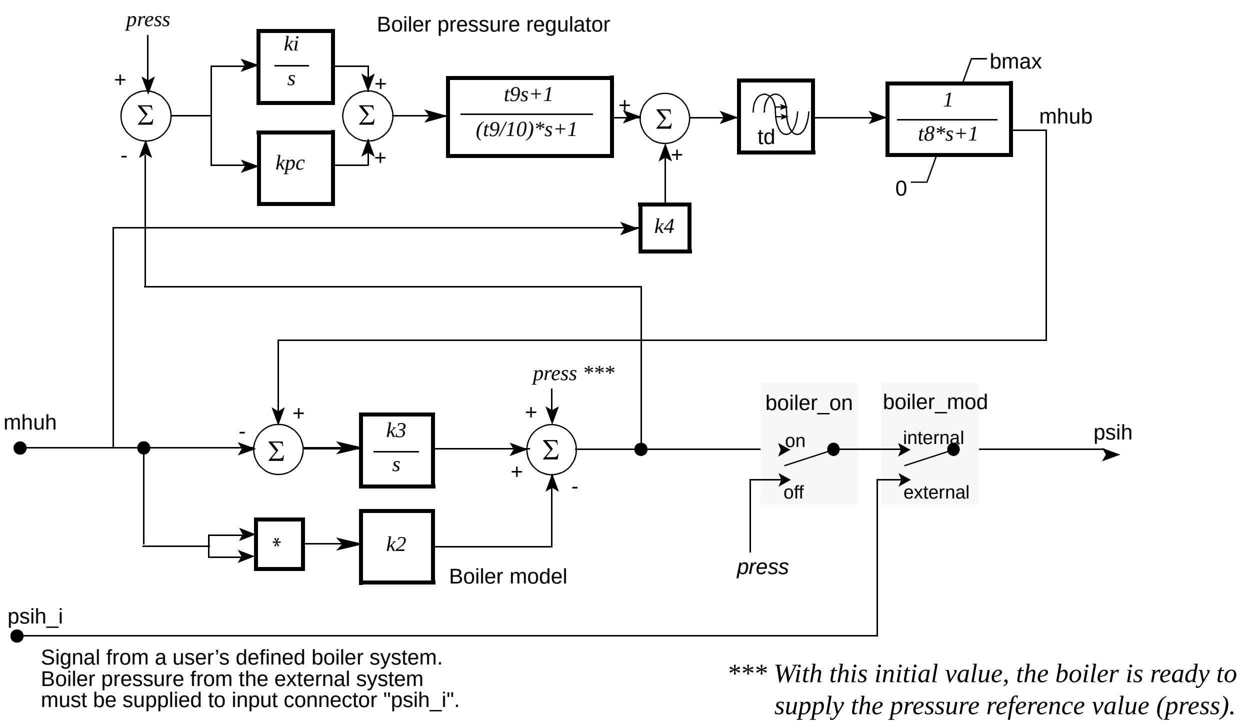


Figure 5 - 24 Boiler block diagram

5.11.2 Programmable Parameters

- boiler_on: Selection of boiler operation. (On=Normal operation; Off=no boiler, constant pressure)
- boiler_mod: Selection of boiler model. (Internal: actual model; External: model supply by user)
- *ch_press*: Boiler pressure output reference (pu)
- *ch_bmax*: Upper limit of boiler pressure (pu)
- *ch_kpc*: Proportional gain of boiler regulator (pu)

- *ch_ki*: Integral gain of boiler regulator (pu)
- *ch_k2*: Load loss coefficient (pu)
- *ch_k3*: Heat capacity coefficient (pu)
- *ch_k4*: High pressure effect (pu)
- *ch_t8*: Boiler constant (s)
- *ch_t9*: Boiler setting constant (s)
- *ch_td*: Boiler delay setting (s).

5.12 Speed Regulator for Tandem Thermal Turbine Generators

5.12.1 Operation

The speed regulator is responsible for producing the gate opening signal x, based on the measurement of speed w signal. The regulation characteristic is slightly different from the hydraulic model, since it does not depends on electric power Pe.

The block diagram of the speed regulator, including the servo-valve, is illustrated in Figure 5 - 25.

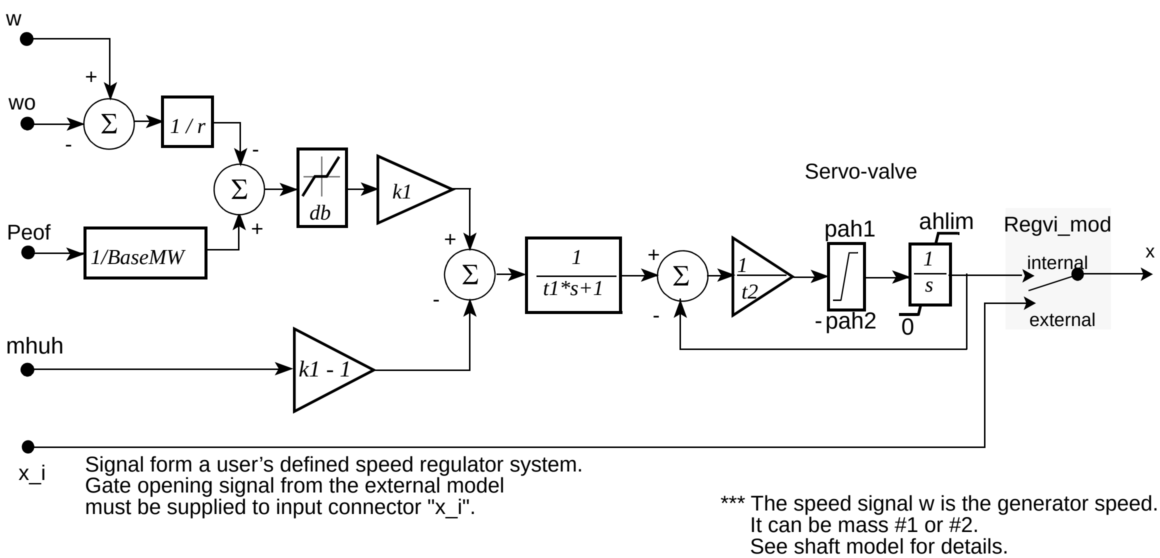


Figure 5 - 25 Speed regulator block diagram

5.12.2 Programmable Parameters

- Regvi_mod: Selection of speed regulator model. (Internal: actual model; External: model supply by user)
- *tb_r*: Permanent droop (pu)
- *tb_db*: Dead band of speed regulator (pu)
- tb_k1: Regulator gain (pu)
- tb_t1: Time constant of speed relay (s)
- tb_t2: Time constant os servo-valve (s).
- *tb_pah1*: Upper limit of valve speed at opening, (absolute value) (pu)
- *tb_pah2*: Lower limit of valve speed at closing, (absolute value) (pu)
- *tb_ahlim*: Upper limit of valve opening (pu).

5.13 Tandem Steam Turbine

5.13.1 Operation

The steam turbine subsystem is responsible for producing the required mechanical torque. In this typical configuration of turbines, 3 pressure stages are implemented. The name "Tandem turbine" comes form this installation, where the steam flow has to pass through different turbine stages, all mounted on the same shaft. Between each turbine stage, various equipment, like reheater or crossover, can be modelized via their response time constants.

As inputs, this subsystem receive the steam pressure psih and the gate opening x. As a result, three mechanical torque th, ti, tl, are produced.

The physical modelling of the tandem steam turbine is presented in Figure 5 - 27. It describes most common configuration of tandem steam turbine, with single reheat, double reheat, and steam crossover.

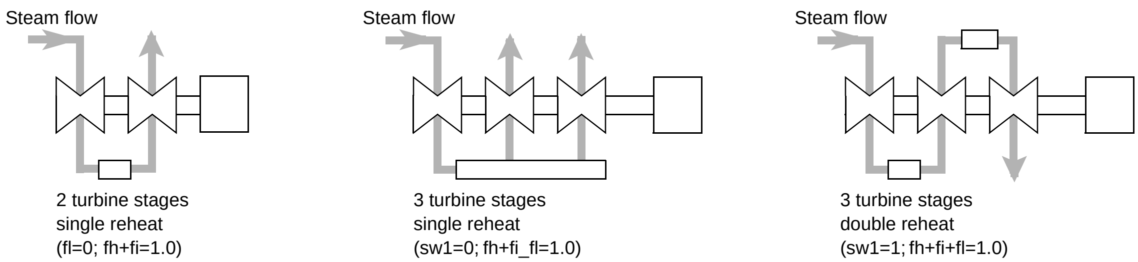


Figure 5 - 26 Typical configuration of tandem steam turbine

On the modelling aspect, the block diagram of the steam turbine is shown in Figure 5 - 27, describing the steam chest, the three turbine stages and the available reheaters. About parameter settings, it is important that the sum of power fraction factor, fh, fi, fl, must always be equal to 1.0. Also, the parameter Tr1 and Tr2 can represents reheaters or crossover, depending on turbine configuration. Third, the parameter sw1 allow users to by-pass the second reheater.

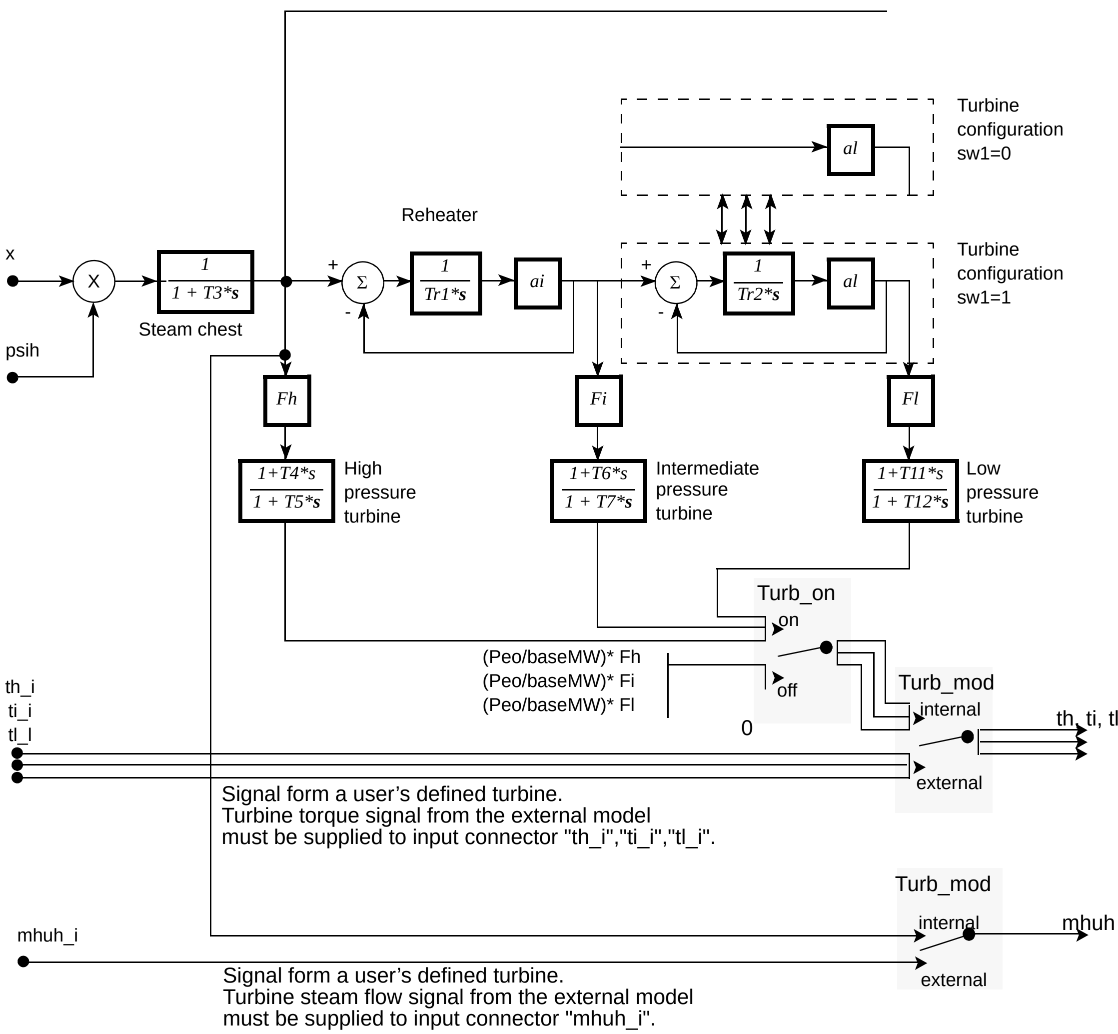


Figure 5 - 27 Steam turbine block diagrams

5.13.2 Programmable Parameters

- tb_t3: Time constant of steam chest (s)
- tb_Tr1: Time constant of reheater 1 (s)

- tb_Tr2: Time constant of reheater 2 (s)
- tb_fh: Fraction of mechanical power provided by HP turbine (pu)
- tb_fi: Fraction of mechanical power provided by IP turbine (pu)
- tb_fl: Fraction of mechanical power provided by LP turbine (pu)
- *tb_t4*: High pressure turbine time constant (s)
- tb_t5: High pressure turbine time constant (s)
- tb_t6: Intermediate pressure turbine time constant (s)
- tb_t7: Intermediate pressure turbine time constant (s)
- tb_t11: Low pressure turbine time constant (pu)
- tb_t12: Low pressure turbine time constant (pu)
- *tb_ai*: IP valve opening (pu)
- *tb_al*: LP valve opening (pu)
- tb_swl: By-pass of second reheater
- turb_on: Selection of turbine operation. (On=Normal operation; Off=no turbine, constant mechanical power equal to Peo)
- turb_mod: Selection of turbine model. (Internal: actual model; External: model supplied by user).

5.14 GENERIC SHAFT

5.14.1 Operation

The shaft model offers a multi-mass implementation. Thus, it can be used to study sub-synchronous resonance phenomena. The objective of this model is to modelize the mechanical distortion and oscillation occurring in the shaft. First, a shaft model receives as inputs the three mechanical torque signals (th,ti,tl) coming from each steam turbine stage. As a results, the shaft model produces speed signal for each individual masses in the system.

Such a shaft model is represented physically in Figure 5 - 28. It can be observed that the different stages of the turbines are located on the same shaft, thus explaining possible torsional oscillations between different stages. The actual shaft model allows users to represent the behaviour using 1, 5 or 10 masses.

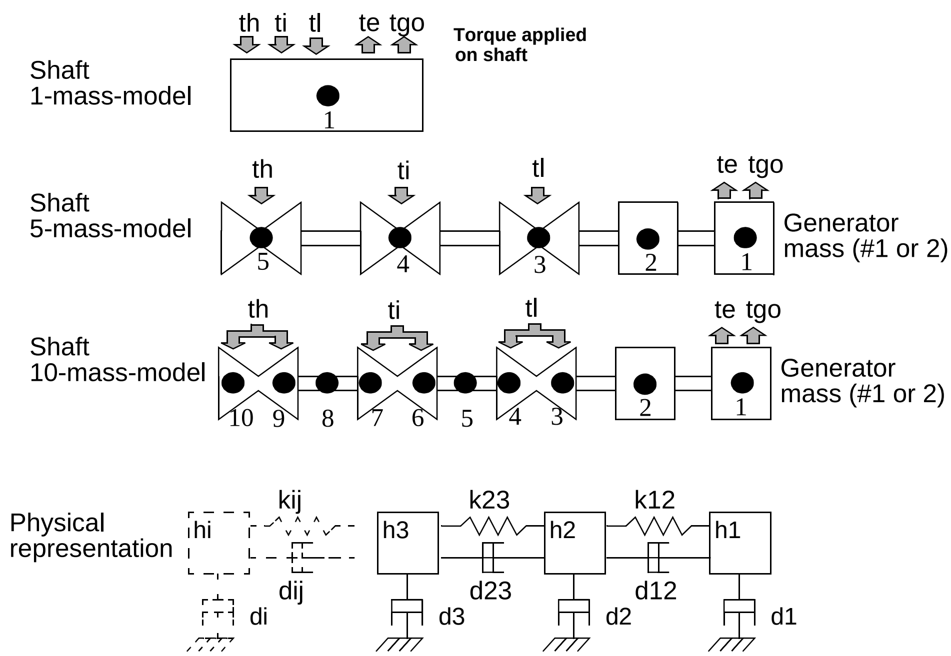


Figure 5 - 28 Representation of shaft model

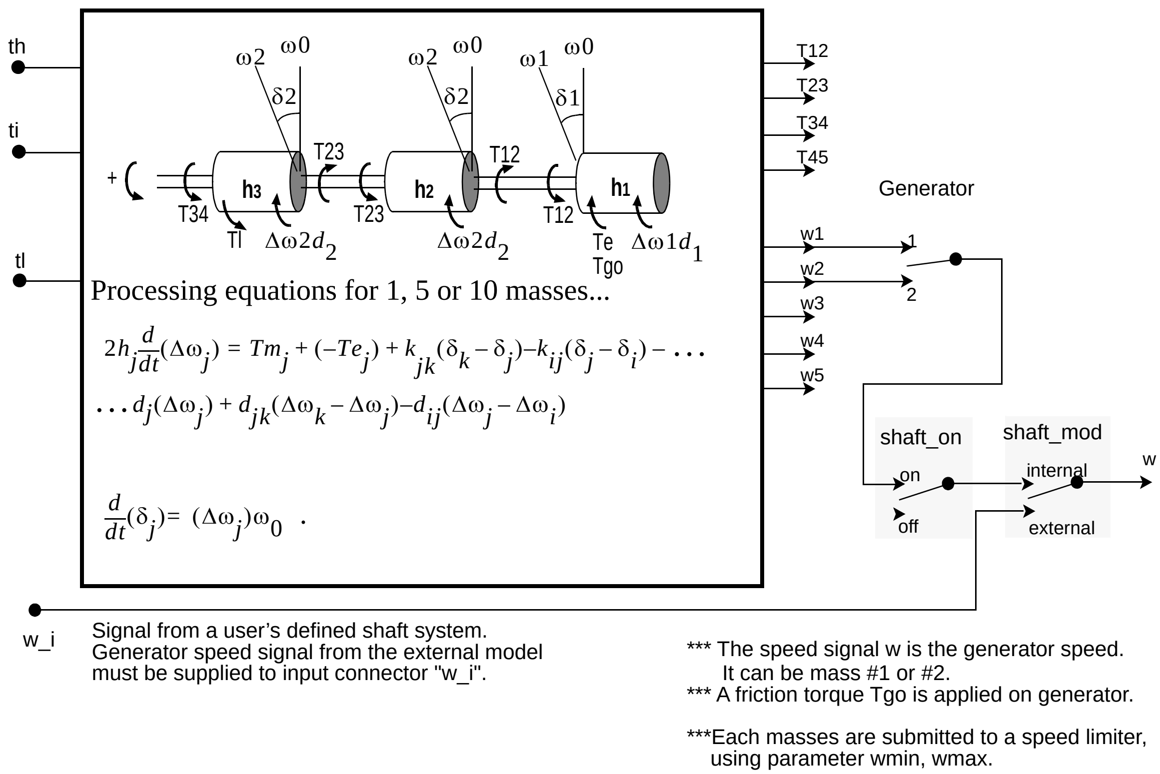


Figure 5 - 29 Implementation of shaft model

5.14.2 Programmable Parameters

- Shaft_on: Selection of shaft operation. (On=Normal operation; Off=constant speed equal to reference speed wo)
- Shaft_mod: Selection of shaft model. (Internal: actual model; External: model supply by user)

Number of masses: Number of masses in shaft model, 1, 5 or 10 masses.
This value must be 1 if there is no need for detailed shaft modelling. In this case, all the parameters (hi, di) must be concentrated in mass no 1.

If detailed shaft modelling is necessary, you may select 5 or 10 masses. By selecting appropriate data for inertia and stiffness, it is possible to modelize any number of masses between 1 and 10. Using an infinite value for stiffness will result in grouping 2 masses together.

If a 5 masses model is selected, all parameter related to the 5 first masses must be established.

- ar_d1Start: Value of ar_d1 during start-up time; This value helps to reach synchronism. (typically = 10)
- ar_tStart: Duration of startup time. (typically = 10s) (s)
- *ar_tg0*: Mechanical friction losses, applied on generator mass (pu)

- *ar_h1, ar_h2,...*: Mass inertia in second, based on generator *BaseMVA* (pu)
- *ar_k12, ar_k23,...*: Shaft stiffness coefficients in (pu/rad) based on turbine *BaseMW* (pu)
- *ar_d1, ar_d2,...*: Mass self-damping factors in (pu torque/pu speed) based on turbine *BaseMW*; This parameter is also called steam damping, will help to damp torsional oscillation. Typical value is 25% of inertia (pu).
- *ar_d12, ar_d23,...*: Shaft mutual-damping factors in (pu torque/pu speed) based on turbine *BaseMW*; This parameter is also called steam damping, will help to damp torsional oscillation. Typical value is 25% of inertia.
- Generator mass: Selection of mass number that represents the generator. This mass will receive the electrical torque signal.(Mass #1 or #2). Since the signal w is generator speed, w is then speed of mass #1 or #2 depending on this parameter. (Typically, 2 configurations are possible; First: Mass #1 is generator, and mass #2 is a gearbox. Second: Mass #1 is exciter, mass #2 is generator.
- Low pressure turbine: Selection of mass number that represents the low pressure turbine. Those masses will receive the mechanical torque tl, spitted in 50-50% on two masses.(Mass #3-4 or #4-5). Valid for 10-masses only.
- Intermediate pressure turbine: Selection of mass number that represents the intermediate pressure turbine. Those masses will receive the mechanical torque ti, spitted in 50-50% on two masses.(Mass #6-7 or #7-8). Valid for 10-masses only.

5.14.3 List of Available Signals

At acquisition, the following signals are made available by the **sensors**:

- V_*label*_a,b,c: Voltages at the breaker terminals (V)
- I_*label*_a,b,c: Currents from the generator (A)
- Id_*label*: Machine current, D axis (pu)
- Iq_*label*: Machine current, Q axis (pu)
- Ed_*label*: Voltage behind inductance (pu)
- Eq_*label*: External, direct axis and quadrature (pu)
- Vt_*label*: Output voltage (pu)
- Efdgen_*label*: Field voltage (pu)
- Efd_i_label: Field voltage (pu) provided by an external module
- Ifd_*label*: Field current (pu)
- Vstab_*label*: Stabilizer output signal (pu)
- Vstab_i_*label:*Stabilizer output signal provided by an external module
- w_*label*: Angular speed (pu)
- w_i_*label*: Angular speed (pu) provided by an external module
- Te_*label*: Electrical torque based on generator rating (pu / MW*s)

- Pe_*label*: Active power (pu / MVA)
- Qe_*label*: Reactive power (pu / MVA)
- Pef_*label*: Filtered electric power (pu / MVA)
- psih_*label*: Steam pressure at high pressure stage (pu)
- psih_i_*label*: Steam pressure at high pressure stage (pu) provided by an external module
- mhuh_*label*: Flow of high pressure steam (pu)
- mhuh_i_*label*: Flow of high pressure steam (pu) provided by an external module
- Th_*label*: Mechanical torque of high pressure turbine (pu / MW*s)
- Th_i_*label*: Mechanical torque of high pressure turbine (pu / MW*s) provided by an external module
- Ti_*label*: Mechanical torque of intermediate pressure turbine (pu / MW*s)
- Ti_i_*label*: Mechanical torque of intermediate pressure turbine (pu / MW*s) provided by an external module
- Tl_*label*: Mechanical torque of low pressure turbine (pu / MW*s)
- Tl_i_*label*: Mechanical torque of low pressure turbine (pu / MW*s) provided by an external module
- x_*label*: valve opening (pu)
- wxxx1.n_*label*: Angular speed of mass n (pu)
- T12.nm_*label*: Mechanical torque applied by mass n to mass m (pu).

5.14.4 Thermal Turbine Generator Control Panel

Figure 5 - 30 shows the control panel of a thermal turbine generator.

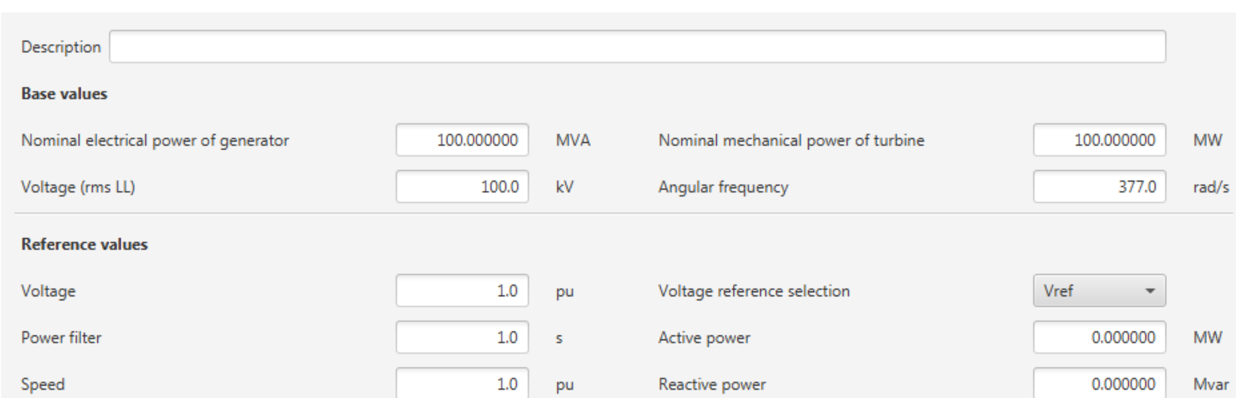


Figure 5 - 30 Thermal turbine generator control panel (general)

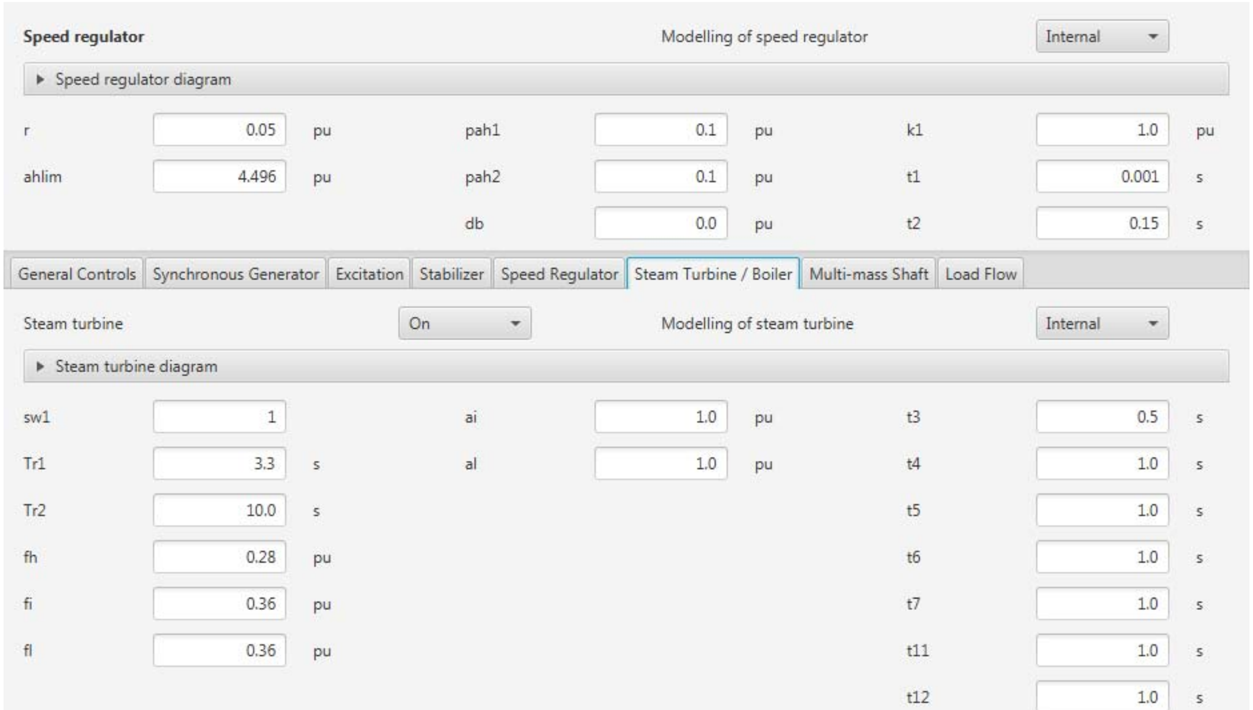


Figure 5 - 31 Thermal turbine generator control panel (speed/turbine)

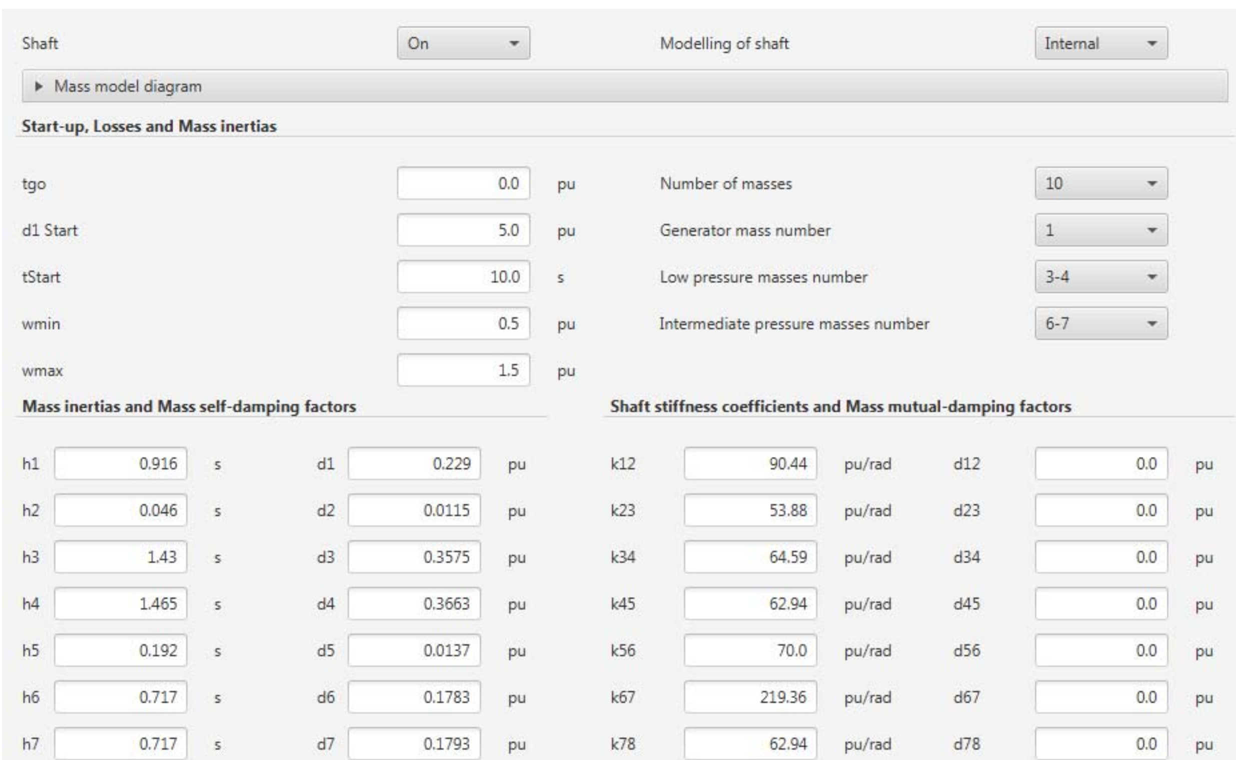


Figure 5 - 32 Thermal turbine generator control panel (shaft/boiler)

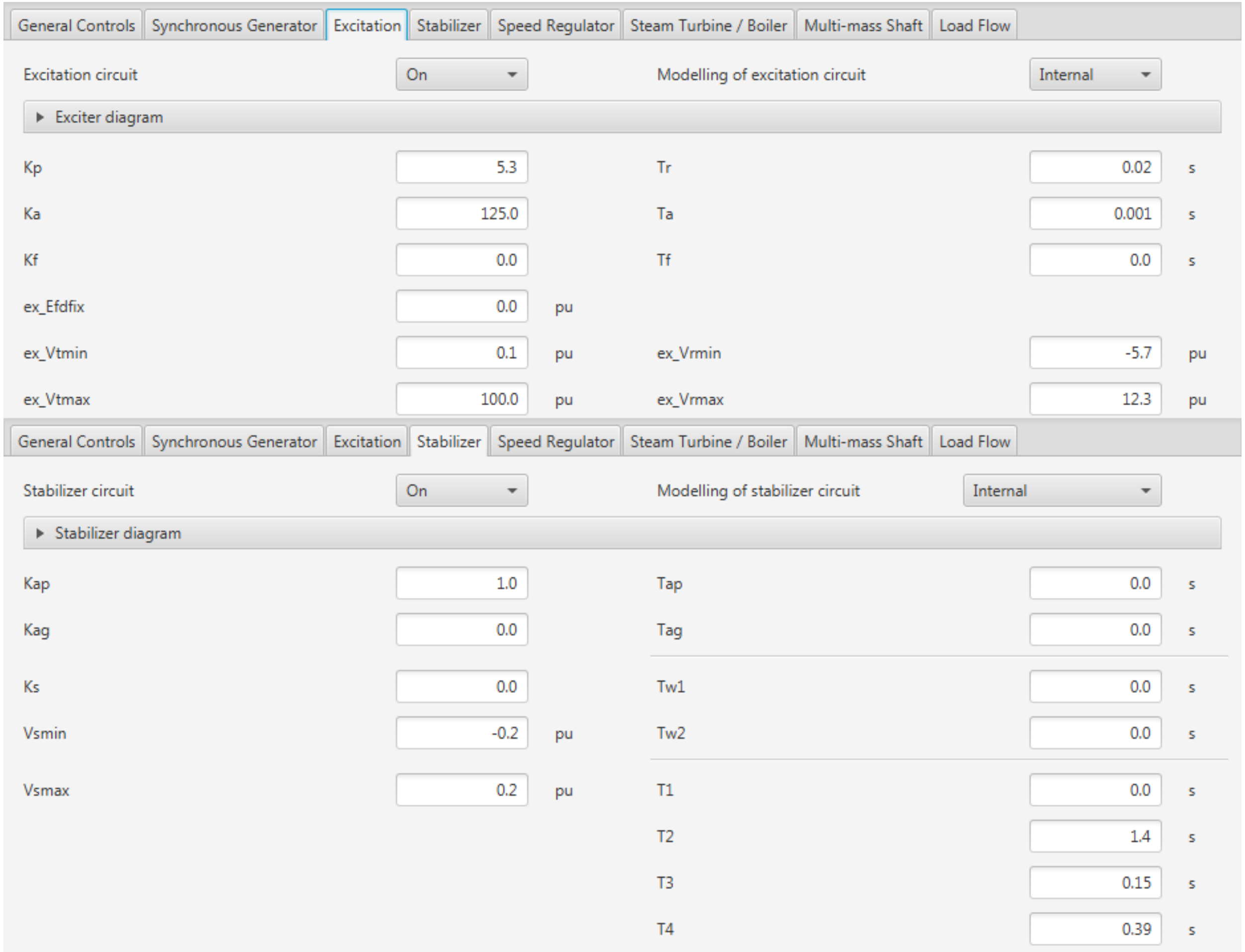


Figure 5 - 33 Thermal turbine generator control panel (excitation/stabilizer)

5.15 CROSS-COMPOUND THERMAL TURBINE-GENERATOR

5.15.1 Introduction

The cross-compound thermal turbine generator has two generating units (primary and secondary) and only one boiler. Many components of this model are similar to those of the ordinary thermal turbine generator. Only the turbines, the speed regulator and the shaft are different. The list of parameters and available signals is the same for both generating units of the cross-compound thermal plant. An “_s” suffix is added to the names of parameters and available signals of the second generator.

5.15.2 Cross-Compound Thermal Turbine Generator Model

Figure 5 - 35 shows the general diagram of a cross-compound thermal turbine generator. In this model, only the speed regulator can be modelled externally with the control system interface (CSI).

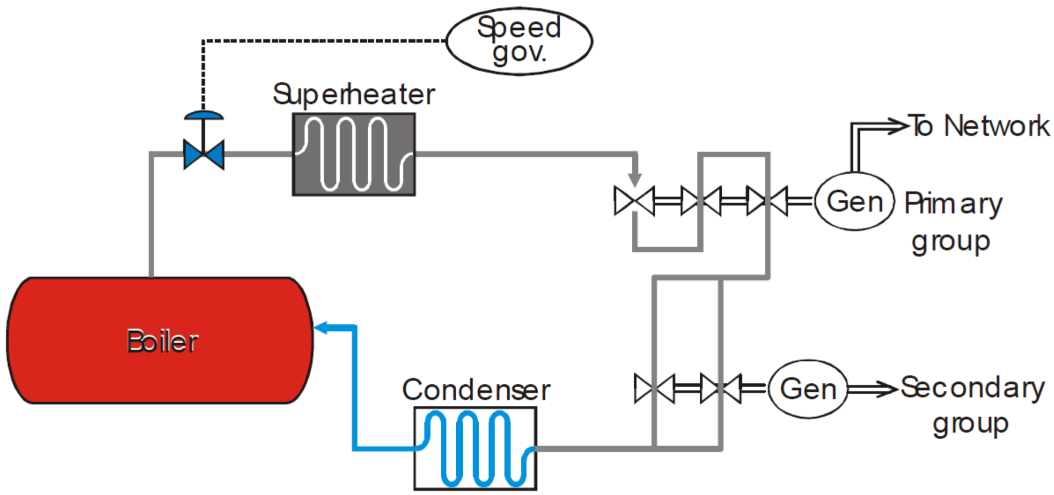


Figure 5 - 34 Schematic diagram of a cross-compound turbine generator

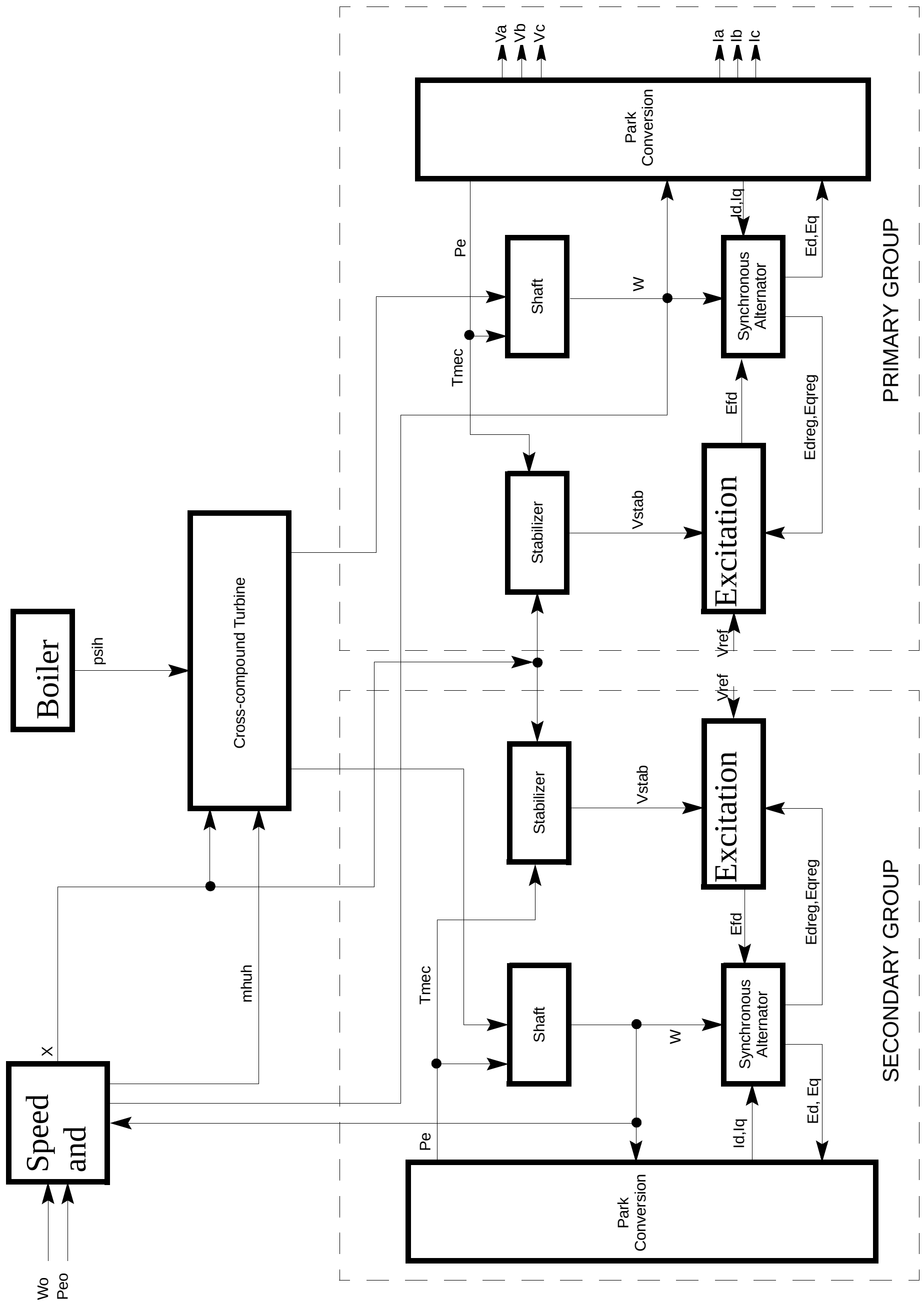


Figure 5 - 35 General diagram of a cross-compound thermal turbine generator

5.16 SPEED REGULATOR

5.16.1 Operation

The block diagram of the speed regulator is shown in Figure 5 - 36. It is similar to the tandem turbine generator, except that the latter regulates a signal originating from one of both generators.

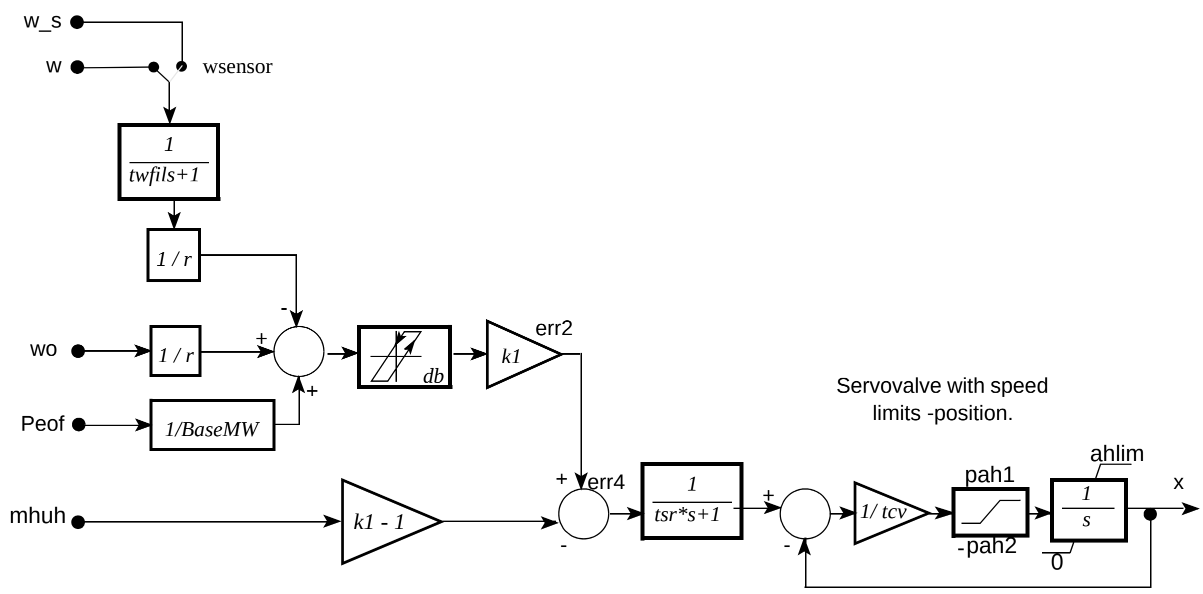


Figure 5 - 36 Speed regulator block diagram

5.16.2 Programmable Parameters

- *Speed regulator*: Selector for internal or external speed regulator;
- *tb_wsensor*: Selection of the generator whose speed is to be regulated
- *tb_wfil*: Time constant of the speed sensor (s)
- *tb_r*: Permanent droop (pu)
- *tb_db*: Dead-band of regulator (pu)
- *tb_pah1*: Valve speed (absolute) upper limit when opening (pu)
- *tb_pah2*: Valve speed (absolute) upper limit when closing (pu)
- *tb_ahlim*: Valve opening upper limit (pu)
- *tb_k1*: Regulator gain (pu)
- *tb_tsr*: Time constant of speed valve relay (s)
- *tb_tcv*: Inverse of valve speed (speed = 1 / tb_tcv) (s).

5.17 STEAM TURBINE

5.17.1 Operation

Figure 5 - 37 shows the block diagram of the steam turbine model.This diagram represents the steam tank, the three stages of the turbine and the heaters.

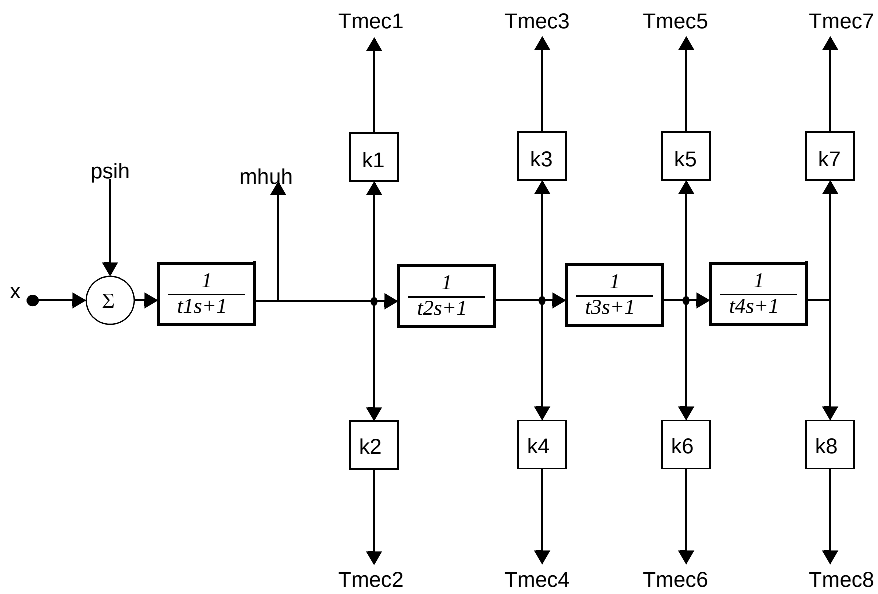


Figure 5 - 37 Steam turbine block diagram

5.17.2 Programmable Parameters

- *tb_t1*: Turbine time constant (separator, superheater, steam chest, re-heater or cross over) (s). Typical values are 0.2s for steam chest, 8s for re-heater and 0.4s for cross over
- *tb_t2*: Turbine time constant (separator, superheater, steam chest, re-heater or cross over)) (s)
- *tb_t3*: Turbine time constant (separator, superheater, steam chest, re-heater or cross over)) (s)
- *tb_t4*: Turbine time constant (separator, superheater, steam chest, re-heater or cross over)) (s)
- *tb_k1,...,8*: Mechanical power part provided by the turbine (fractions of generation in high (FHP), intermediate (FIP) or low turbines (FLP)). Typical values for FHP, FIP and FLP are 0.25, 0.3 and 0.45 respectively.

5.17.3 List of Available Signals

At acquisition, the following signals are made available by the **sensors**. Only signals from sub-systems common to both turbine generators and signals from the primary turbine generator are listed. The names of signals from the secondary turbine generator are obtained by adding a suffix "_s" to the names of signals from the primary turbine generator.

- V_*label*_a,b,c: Voltages at the breaker terminals (V)
- I_*label*_a,b,c: Currents from the generator (A)
- Id_*label*: D axis generator current (pu)
- Iq_*label*: Q axis generator current (pu)
- Ed_*label*: Voltage behind inductance (pu)
- Eq_*label*: External, D and Q axes (pu)
- Vt_*label*: Output voltage (pu)
- Efd_*label*: Field voltage, general (pu)
- Vstab_*label*: Stabilizer output voltage (pu)
- w_*label*: Angular speed (pu)
- Te_*label*: Electrical torque based on generator rating (pu / MW*s)
- Pe_*label*: Active power (pu / MVA)
- Qe_*label*: Reactive power (pu / MVA)
- Pef_*label*: Filtered electric power (pu / MVA)
- psih_*label*: Vapor pressure at high pressure level (pu)
- mhuh_*label*: Flow of high pressure vapor (pu)
- Tmec*1,...,8_label:* Mechanical couple flow of high pressure steam (pu)
- x_*label*: Valve opening (pu)
- x_i_*label*: Valve opening when the speed regulator is modeled externally (pu)
- Ifd_*label*: Field current (pu)
- w2,...,n_*label*: Angular velocity of mass n (pu)
- T12,...,nm_*label*: Mechanical torque applied by mass n to mass m (pu)
- Edreg_*label*: Mechanical torque applied by mass n to mass m (pu). Voltage to be regulated by excitation for D-axis (Ed)
- Eqreg_*label*: Mechanical torque applied by mass n to mass m (pu) Voltage to be regulated by excitation for Q-axis (Eq).

5.18 MULTI-MASS SHAFTS

5.18.1 Operation

Figure 5 - 38 illustrates the physical layout of the two shafts. It can be observed that different stages of the turbines are supported by the same shaft. This layout can potentially induce torsional oscillations between different masses on the same shaft.

The model of the thermal turbine generator has two shafts, each with either one or five masses. In addition, the cross-compound turbine generator model allows the application of a mechanical torque to each turbine mass. Since the masses are hard-coded, shaft models with a mass number other than 1 or 5 will be simulated by setting the inertia of non-existent masses to very small values and the rigidity factors adjacent to the shafts to a very high value.

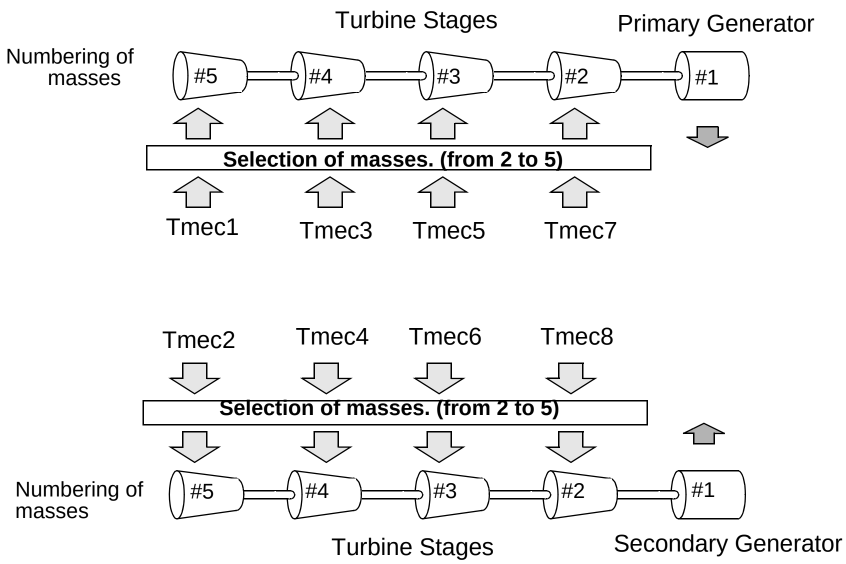


Figure 5 - 38 Shaft model with spring-masses

5.18.2 Programmable Parameters

- *ar_tg0*: Torque representing mechanical losses
- *ar_nbmasse*: Number of masses on a shaft, 1 to 5
- *ar_h1, ar_h2,...*: Inertia (in seconds) of masses based on the generator *BaseMVA*
- *ar_d1, ar_d2,...*: Damping factors of masses based on the turbine *BaseMW* (in pu torque/pu speed)
- *ar_k12, ar_k23,...*: Rigidity factors between masses based on the turbine *BaseMW* for a 3600 rpm machine (in pu/rad)
- *ar_d1Start*: Value of *ar_d1* at starting
- *ar_tStart*: Time (in seconds) during which *ar_d1* = *ar_d1Start*
- *Mass_Tmec1*: Mass to which torque Tmec1 is applied
- *Mass_Tmec2*: Mass to which torque Tmec2 is applied (Secondary shaft)
- *Mass_Tmec3*: Mass to which torque Tmec3 is applied
- *Mass_Tmec4*: Mass to which torque Tmec4 is applied (Secondary shaft)

- *Mass_Tmec5*: Mass to which torque Tmec5 is applied
- *Mass_Tmec6*: Mass to which torque Tmec6 is applied (Secondary shaft)
- *Mass_Tmec7*: Mass to which torque Tmec7 is applied
- *Mass_Tmec8*: Mass to which torque Tmec8 is applied (Secondary shaft).

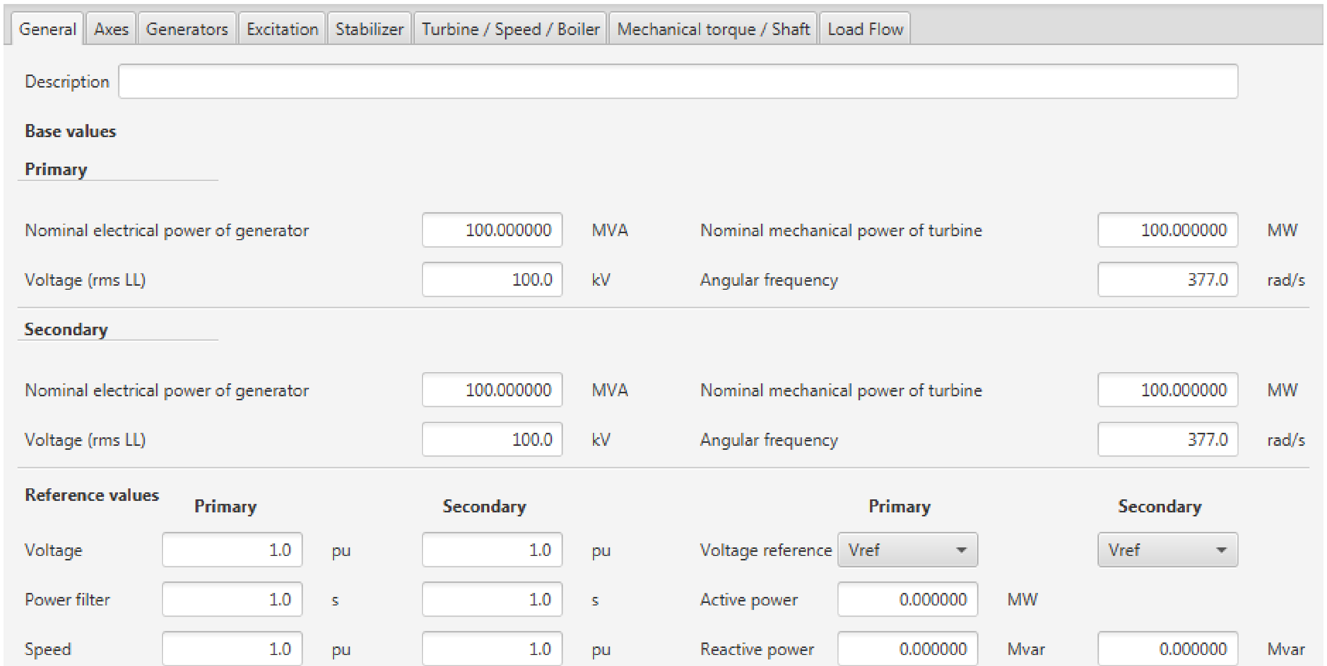


Figure 5 - 39 Cross-compound thermal turbine generator control panel (general)

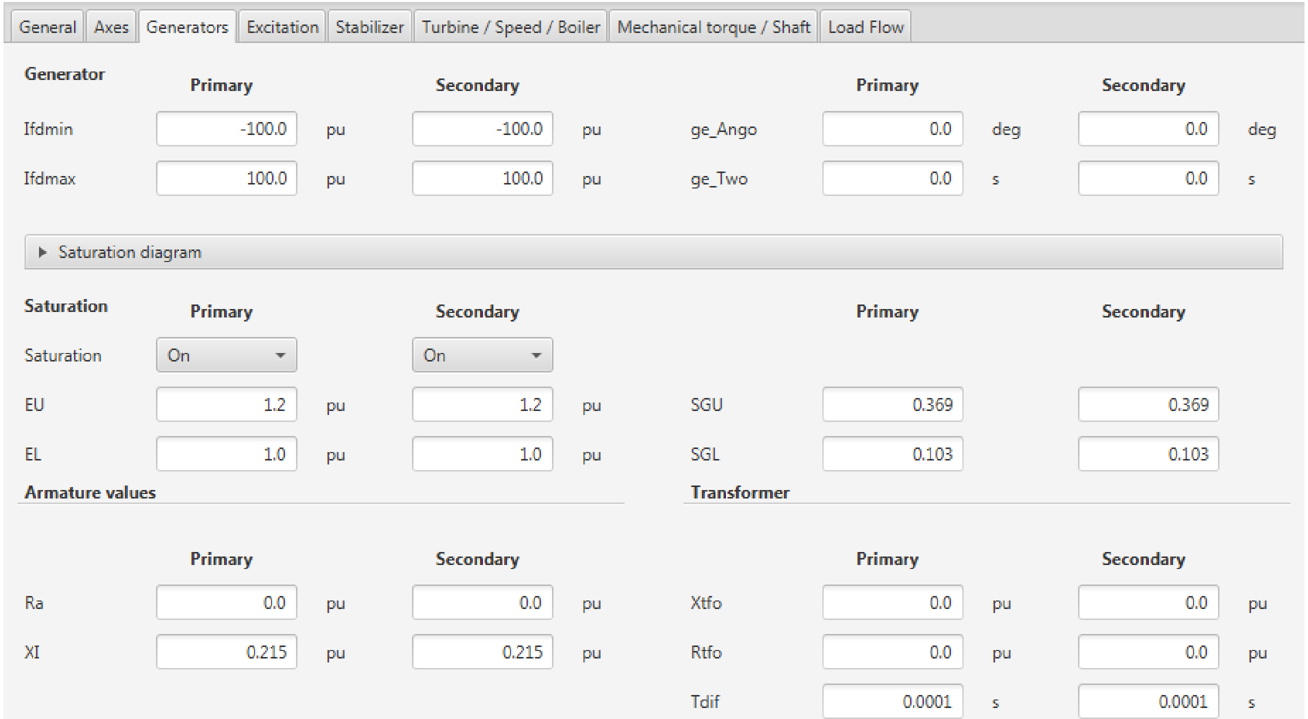


Figure 5 - 40 Cross-compound thermal turbine generator control panel (generators)

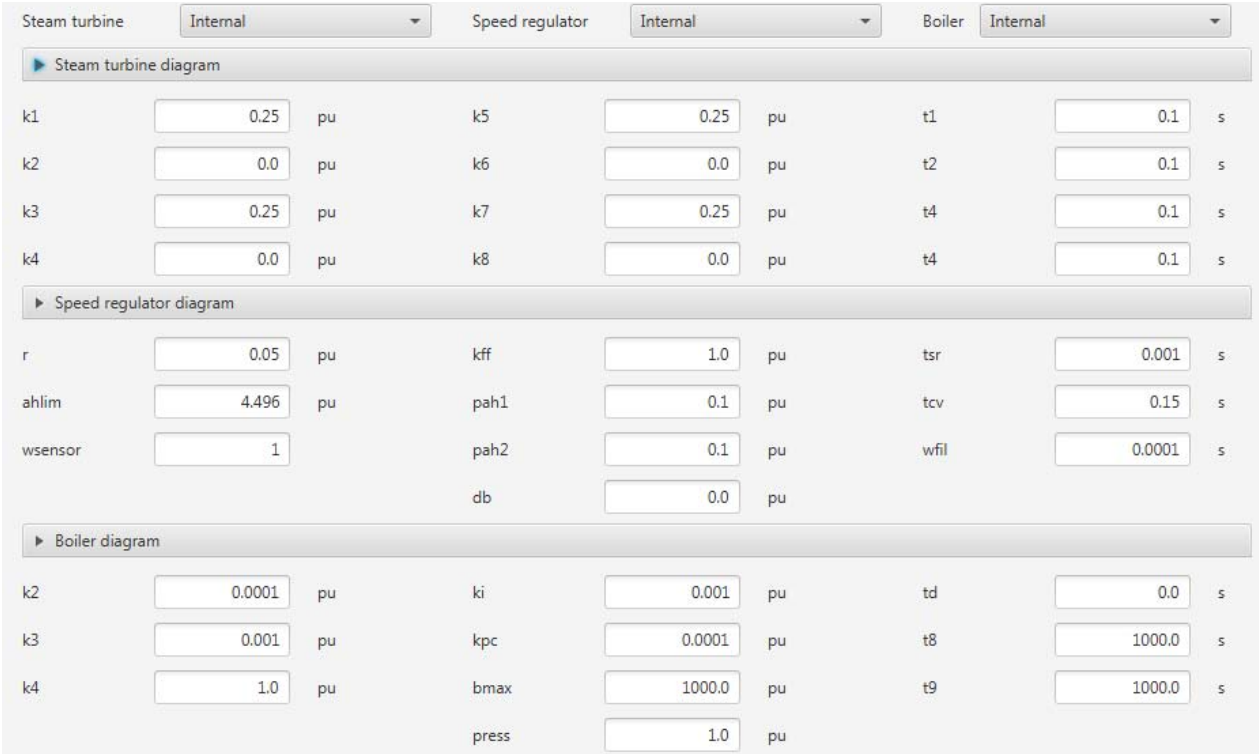


Figure 5 - 41 Cross-compound thermal turbine generator control panel (turbine/speed/boiler)

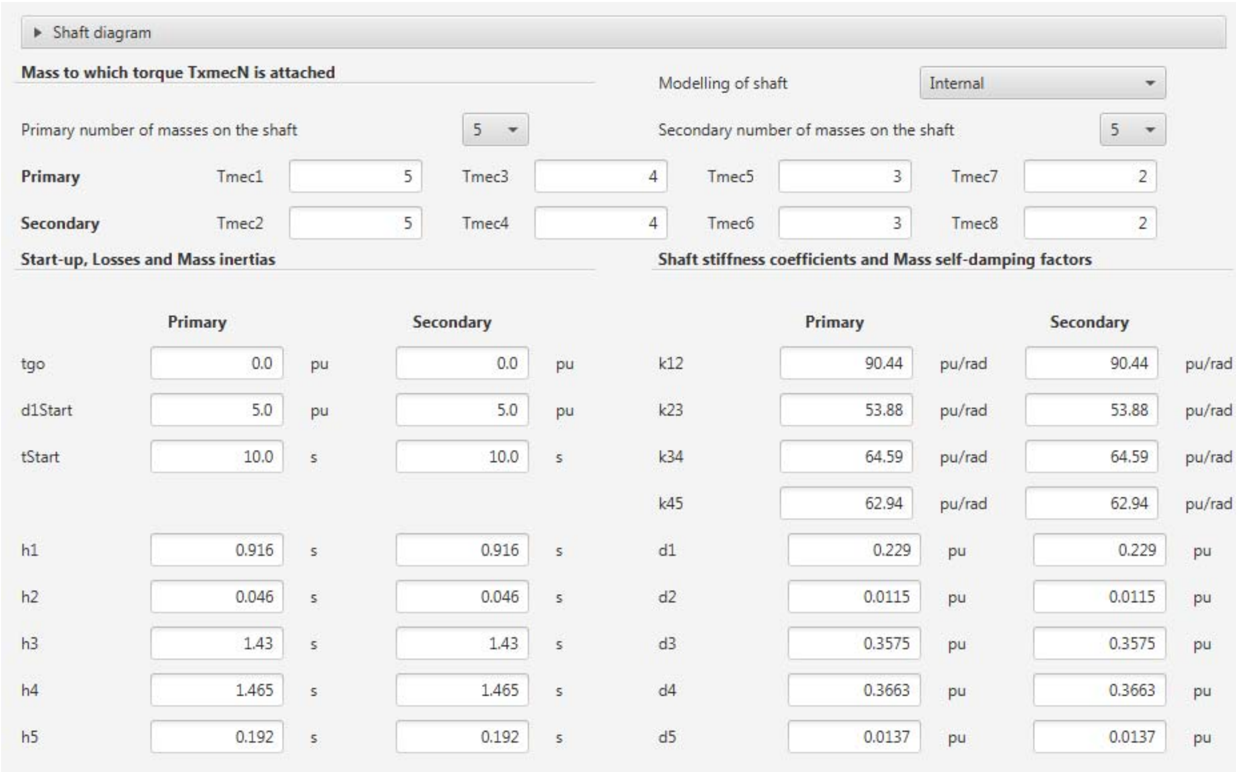


Figure 5 - 42 Cross-compound thermal turbine generator control panel (mechanical torque/shaft)

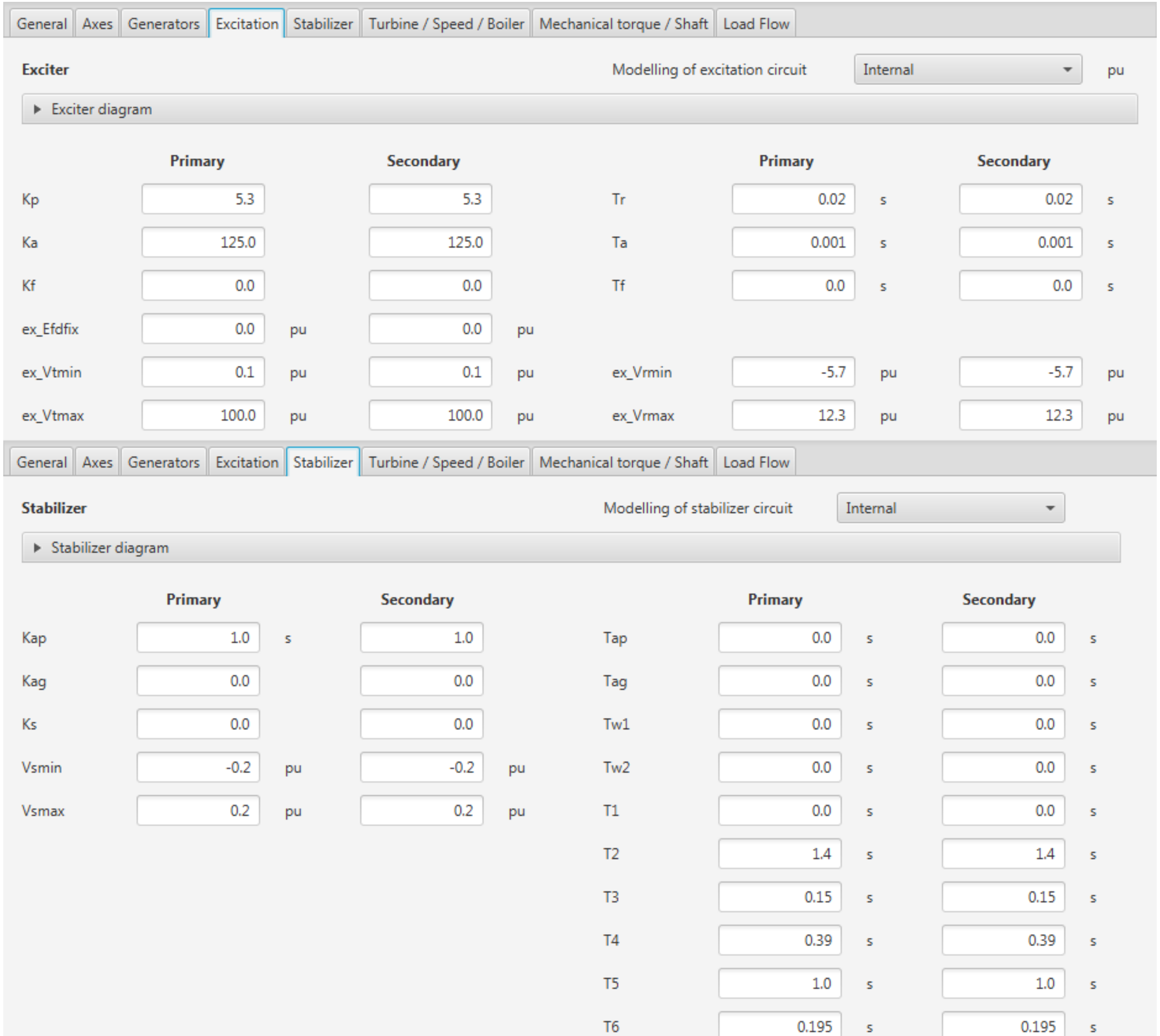


Figure 5 - 43 Cross-compound thermal turbine generator control panel (excitation/stabilizer)

5.19 Phase domain synchronous machine

5.19.1 Introduction

This synchronous machine can represent round or salient pole machines operating as motors or generators without using Park's transformation. Exploiting the winding functions theory, the effect of non-sinusoidal windings are included in the simulation. Furthermore, several different stator internal faults can be simulated and their impact on multiple parallel windings can be observed. The neutral impedance is user-specified.

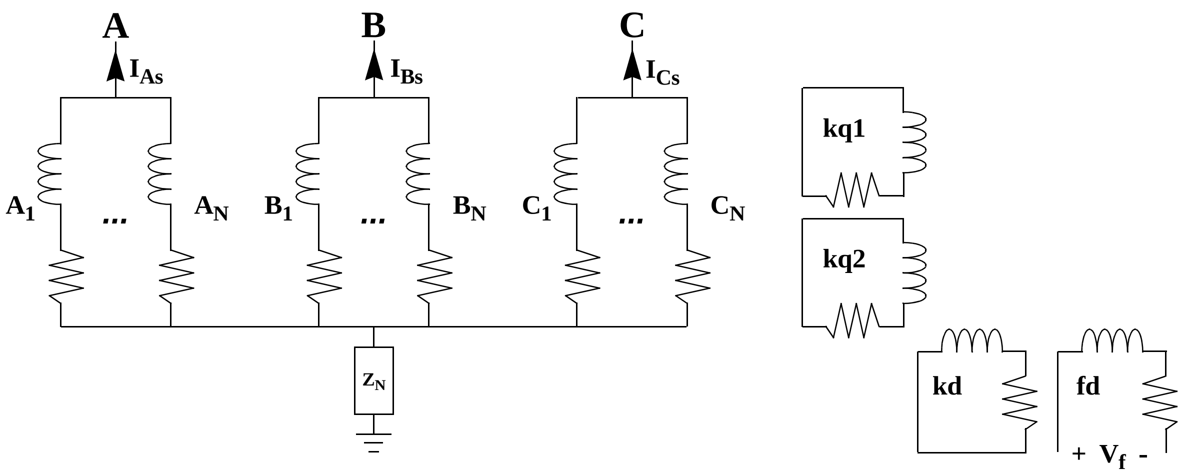


Figure 5 - 44 Multiple parallel windings synchronous machine with neutral impedance (round rotor)

This block includes the electrical model and a 1-mass mechanical model. Other systems such as turbine, excitation system, stabilizer, etc. are not integrated in this model and have to be externally implemented.

Implemented stator internal faults are

1- Single winding to ground

2- Phase-phase shorted windings

3- Phase-phase windings to ground

4- Three phase shorted windings

5- Three phase windings to ground

6- Single phase shorted windings

7- Single phase windings to ground

8- Single winding shorted turns

5.19.2 Model Overview

The stator is composed of N parallel windings per phase, all connected to ground with a Z_N impedance. The N parallel windings of one phase are spatially distributed around the stator. Their positions is used to compute the winding functions necessary for the self and mutual inductance parameters.

The rotoric circuit is composed of the field winding and one damper winding in the direct axis while the quadrature axis contains one or two damper windings for saliant or round rotors respectively. All damper windings are shorted.

The block diagram of the phase-domain machine is shown in Figure 5 - 5.

The stator reactance matrix for a single winding per phase machine is given as

$$X_s = \begin{bmatrix} X_{ls} + X_{Axx} - X_{Bxx}\cos 2\theta & X_{Axy} - X_{Bxy}\cos\left(2\theta - \frac{2\pi}{3}\right) & X_{Axy} - X_{Bxy}\cos\left(2\theta + \frac{2\pi}{3}\right) \\ X_{Axy} - X_{Bxy}\cos\left(2\theta - \frac{2\pi}{3}\right) & X_{ls} + X_{Axx} - X_{Bxx}\cos\left(2\theta + \frac{2\pi}{3}\right) & X_{Axy} - X_{Bxy}\cos 2\theta \\ X_{Axy} - X_{Bxy}\cos\left(2\theta + \frac{2\pi}{3}\right) & X_{Axy} - X_{Bxy}\cos 2\theta & L_{ls} + X_{Axx} - X_{Bxx}\cos\left(2\theta - \frac{2\pi}{3}\right) \end{bmatrix}$$

where X_{ls} is the leakage reactance, X_{Axx} and X_{Bxx} are the constant and time-variant part of the self reactance while X_{Axy} and X_{Bxy} are for the mutual reactances. Finally, θ is the rotor electrical angle. The X_A and X_B parameters are calculated from the winding functions. The mutual reactance matrix between the stator and the rotor, refered to the stator for a salient-pole machine, is

$$X'_{sr} = \begin{bmatrix} X_{mq}\cos\theta & X_{md}\cos\theta & X_{md}\cos\theta \\ X_{mq}\cos\left(\theta - \frac{2\pi}{3}\right) & X_{md}\cos\left(\theta - \frac{2\pi}{3}\right) & X_{md}\cos\left(\theta - \frac{2\pi}{3}\right) \\ X_{mq}\cos\left(\theta + \frac{2\pi}{3}\right) & X_{md}\cos\left(\theta + \frac{2\pi}{3}\right) & X_{md}\cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}$$

where X_{md} and X_{mq} are the magnetizing reactance for the direct and quadrature axis respectively. Finally, the rotor reactance matrix, refered to the stator takes the following form.

$$X'_r = \begin{bmatrix} X_{lkq} + X_{mq} & 0 & 0 \\ 0 & X_{lfd} + X_{md} & X_{md} \\ 0 & X_{md} & X_{lkd} + X_{md} \end{bmatrix}$$

X_{lkq}, X_{lfd} and X_{lkd} are the leakage reactance for the q-axis damper, the field winding and the d-axis damper.

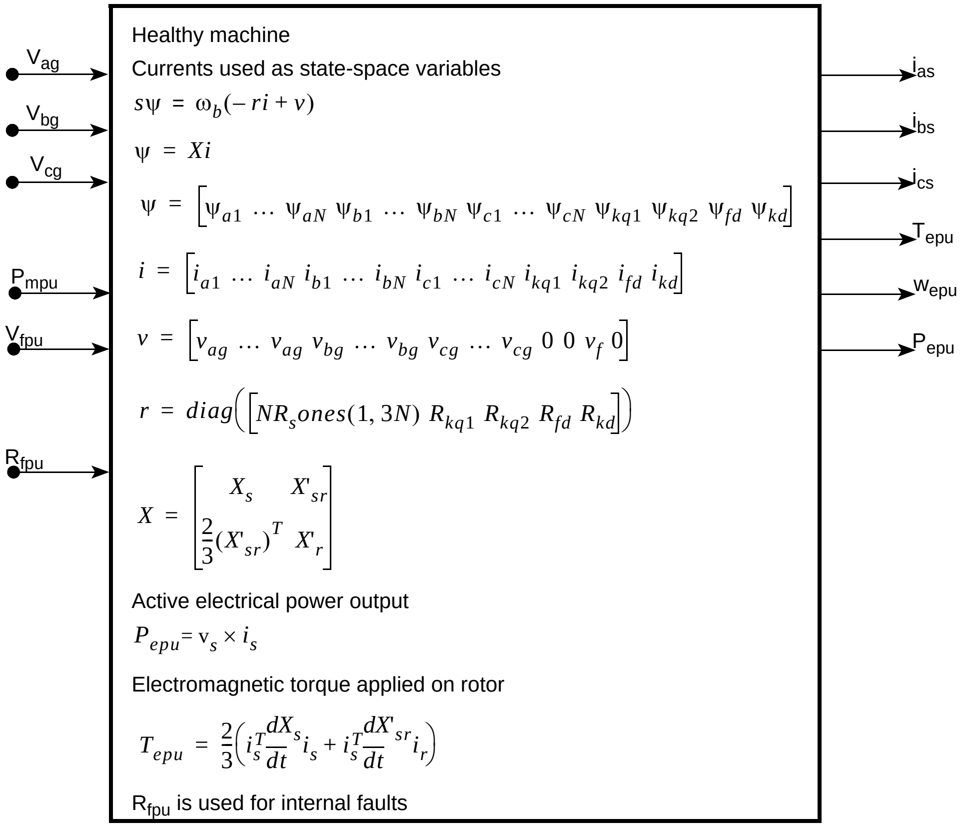


Figure 5 - 45 Phase-Domain Synchronous Machine Block Diagram (healthy machine)

5.19.2.1 Programmable General Parameters

- S_{base}: Base nominal electrical power of generator (MVA);
- V_{baseLL}: Base nominal voltage (kV);
- w_b: Base nominal angular frequency (elec. rad/s);

5.19.2.2 Programmable Parameters

- Xls: Armature leakage reactance (pu);
- Xmd: Direct magnetizing reactance (pu);
- Xmq: Quadrature magnetizing reactance (pu);
- Xlkq1: Quadrature damper winding 1 leakage reactance (stator side) (pu);
- Xlkq2: Quadrature damper winding 2 leakage reactance (stator side) (pu);
- Xlfd: Field winding leakage reactance (stator side) (pu);

- Xlkd: Direct damper winding leakage reactance (stator side) (pu);
- Rs: Armature resistance (pu);
- Rkq1: Quadrature damper winding 1 resistance (stator side) (pu);
- Rkq2: Quadrature damper winding 2 resistance (stator side) (pu);
- Rfd: Field winding resistance (stator side) (pu);
- Rkd: Direct damper winding resistance (stator side) (pu);
- Rg: Neutral connection resistance (pu);
- H: Inertia constant (pu.s);
- F: Friction constant (pu);
- P: Number of poles;
- N_slot: Number of stator slots;
- N_cs: Number of conductors per slot;
- N: Number of parallel windings per phase;
- Winding functions for complete phase and each individual windings.

5.19.2.3 List of Available Signals

At acquisition, the following signals are made available by the **sensors**:

- ias, ibs, ics: Three-phase current of the machine (A);
- ias_pu, ibs_pu, ics_pu: Three-phase current of the machine (pu);
- iax_pu, ibx_pu, icx_pu: Parallel winding x current (pu);
- iafx_pu, ibfx_pu: Faulted winding current (x odd: top part; x even: bottom part) (pu);
- ig_pu: Neutral current (pu);
- idef_Tx: Fault current of type x (pu);
- ifd, ikd, ikq1, ikq2: Rotor windings current (pu);
- we_pu: Angular speed (pu);
- Te_pu: Electrical torque (pu);
- Pe_pu: Active power (pu);
- Theta_e_deg: Rotor electrical angle (degres).

5.19.3 Winding functions

5.19.3.1 Introduction

Typically, machine models assume that windings' spatial distribution around the stator is sinusoidal. This is very practical since inductance calculations and the overall model are drastically simplified. On the other hand, since this hypothesis neglects spatial harmonics and asymmetries in the windings, those models cannot directly take into account phenomena, such as internal faults, that introduce asymmetries.

The present model does not make this assumption but additional informations about the stator windings are necessary to establish the winding functions. a simple mathematical tool that enables the treatment of non sinusoidal stator windings.

5.19.3.2 Necessary Parameters

To establish the winding functions of a particular machine, one needs to know the following parameters and informations:

- The number of poles;
- The number of slot in the stator armature;
- The number of conductors per slot;
- The number of parallel windings per phase;
- The slot sequence for each individual winding.

With those informations, the winding function for each winding and for each whole phase can be calculated.

5.19.3.3 Method

First of all, all slot sequence numbers have to be shifted to align slot 1 and the middle of a pole winding of phase A. Then, a «positive» direction must be established. Typically, the winding current flows up or down a bar in the stator's slot, so one of those direction is labeled positive. Finally, one goes through all the stator's slots, adding z for each positive bars and subtracting the same value for each opposite bars. The value of z depends if the winding function calculated is for a whole phase or a single parallel winding. In the first case z equals 1/a while in the other it's worth 1.

In summary, the winding function for a whole phase is:

$$n_x(k) = n_x(k-1) + z \text{ for k = 1 to N\_slot and } z = \begin{cases} 1/a \text{ for positive bars} \\ -1/a \text{ for negative bars} \\ 0 \text{ otherwise} \end{cases}$$

and for a single windings:

$$n_x(k) = n_x(k-1) + z \text{ for k = 1 to N\_slot and } z = \begin{cases} 1 \text{ for positive bars} \\ -1 \text{ for negative bars} \\ 0 \text{ otherwise} \end{cases} .$$

Example of winding functions are given below for the precompiled models.

5.19.3.4 Inductance calculations

Once all winding functions *n* for a specific machine are available, the various inductances can be computed according to the following formula

$$L_{yx} = L_{xy} = k_0[\langle n_x n_y\rangle - \langle n_x\rangle\langle n_y\rangle] - k_2[\langle n_x n_y \cos(2p\theta)\rangle - \langle n_x\rangle\langle n_y \cos(2p\theta)\rangle - \langle n_y\rangle\langle n_x \cos(2p\theta)\rangle]$$

where k_0 and k_2 are geometrical coefficient obtained from electrical parameters and intermediary inductance calculations; $\langle X\rangle$ is the expected value of X; p the number of pole pairs and θ the rotor electrical angle.

The inductances can be expressed in a more convenient form:

$$L_{yx}(\theta) = L_{xy}(\theta) = L_{yx0} + L_{yx1}\cos(2p\theta) + L_{yx2}\sin(2p\theta) .$$

L_{yx0}, L_{yx1} and L_{yx2} are computed before the simulation. This expression could be further reduced to a single trigonometric function with a phase term but its computational cost is quite high for faulty machines with numerous parallel windings.

5.19.4 Parameter set example

Two full parameter sets are shown in the following table as well as the original standard parameters. The conversion was done using Canay's work.

Table 5–3 : Generic 4-pole turbo-alternator and 48-pole hydraulic generator models parameters

Parameters	Turbo-alternator	Hydraulic generator
Type	Round	Salient
S_{base} (MVA)	675	370
V_{baseLL} (kV)	24	13.8
w_b (rad/sec)	120π	120π
Xls (pu)	1.3372e-1	1.5723e-2
Xmd (pu)	1.9633	9.6928e-1
Xmq (pu)	1.8363	5.9328e-1
Xlkq1 (pu)	2.0543e-1	4.5117e-1
Xlkq2 (pu)	1.0138	N/A
Xlfd (pu)	3.0335e-1	4.8771e-1

Table 5–3 : Generic 4-pole turbo-alternator and 48-pole hydraulic generator models parameters

Parameters	Turbo-alternator	Hydraulic generator
Xlkd (pu)	3.8567e-1	8.3011e-1
Rs (pu)	1.8300e-3	2.6360e-3
Rkq1 (pu)	2.4457e-2	1.9789e-1
Rkq2 (pu)	3.0294e-2	N/A
Rfd (pu)	5.6863e-4	5.2903e-4
Rkd (pu)	5.1693e-2	4.0598e-2
Rg (Ω)	500	500
H (pu.s)	2.5	4.1
F (pu)	0	0
P	4	48
N_slot	60	540
N_cs	2	2
N	2	6
Standard parameters		
Rs (pu)	0.00183	0.002636
Xls (pu)	0.215	0.015
Xd (pu)	2.097	0.985
Xd’ (pu)	0.395	0.340
Xd" (pu)	0.29	0.249
Xq (pu)	1.97	0.609
Xq’ (pu)	0.643	0.60
Xq" (pu)	0.29	0.272
Tdo’ (s)	10.661	7.348
Tdo" (s)	0.033	0.075
Tqo’ (s)	0.415	N/A
Tqo" (s)	0.056	0.14

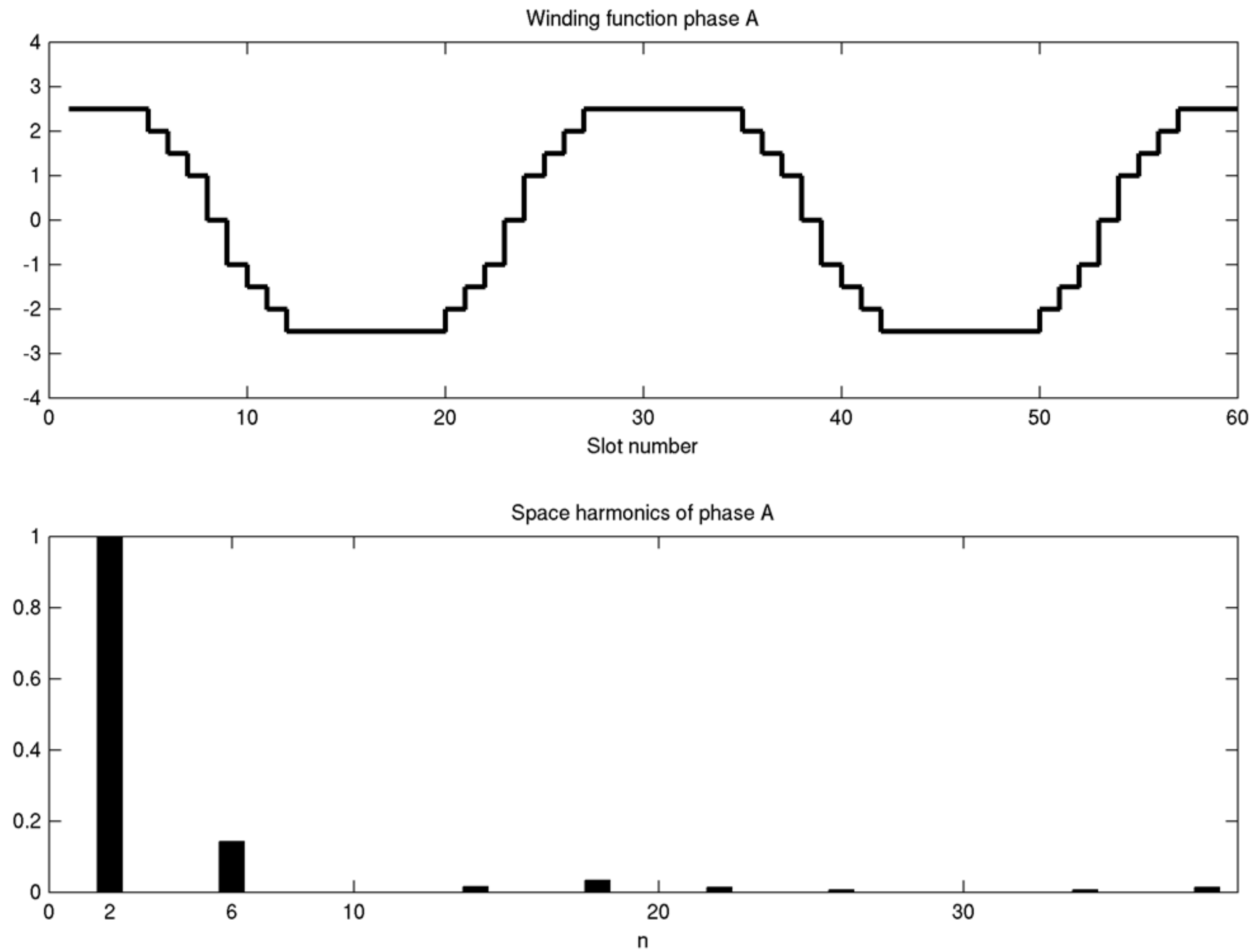


Figure 5 - 46   Winding function for phase A (A1 and A2 winding) of generic turbo-alternator

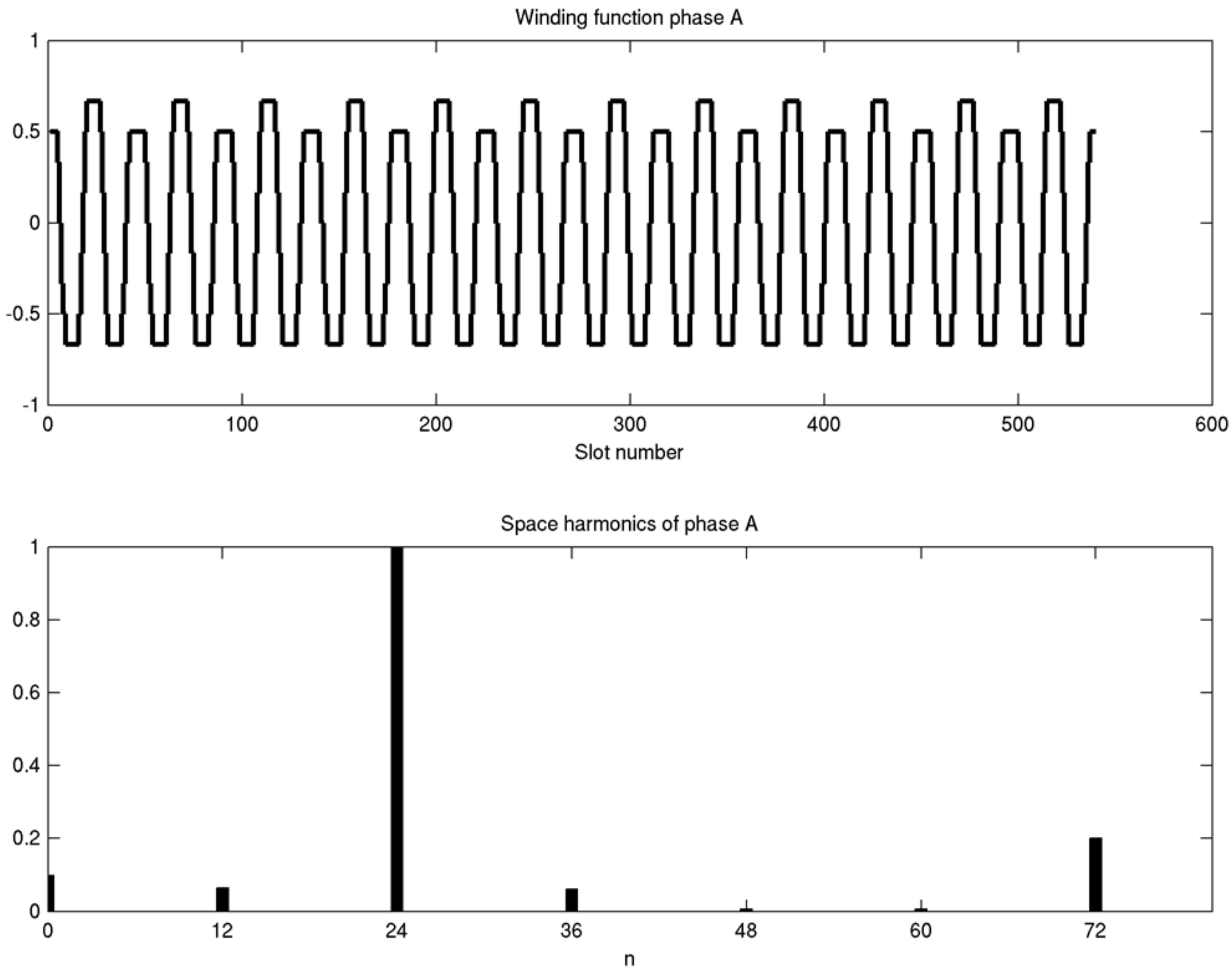


Figure 5 - 47 Winding function and its spectral analysis for phase A (A1 to A6 winding) of generic hydraulic generator

5.19.5 Internal faults

As mentioned earlier, this model supports eight types of stator internal faults. Each one will be detailed in the following sections.

The location of the fault is specified in percents, where 0% is the neutral point and 100% is the terminal of the particular phase.

5.19.5.1 Type 1: Single Winding to ground

In this type of fault, one winding is shorted to the ground through a resistor Rfg as shown in the following schematic (rotoric circuit and windings' resistance not illustrated). The faulted winding is separated in two parts, A_{f1} and A_{f2}. The same is also true for the related winding function. The two resulting winding functions are then used to calculate A_{f1} and A_{f2} self and mutual inductances.

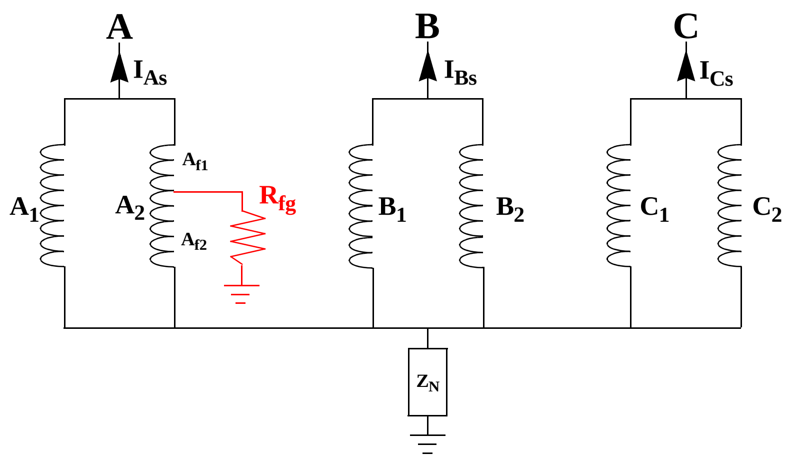


Figure 5 - 48 Type 1 fault in a synchronous machine with two parallel windings and neutral impedance

During healthy behavior, R_{fg} must be very large (> 1e6 pu) and to trip the faulty behavior, it has to be stepped down to a very small value. This mechanism is valid for all types of fault.

$$i_{faultT1} = i_{af1} - i_{af2}$$

$$i_{ain} = i_{a1} + i_{af1} \qquad i_{aout} = i_{a1} + i_{af2}$$

$$i_g = i_{aout} + i_{b1} + i_{b2} + i_{c1} + i_{c2}$$

5.19.5.2 Type 2 & 3: Phase-Phase Shorted Windings (to ground)

Two windings from different phases are shorted together through two resistors, R_{fa} and R_{fb} and the mid point is grounded through R_{fg}. A type 2 fault is when the mid point remains ungrounded, i.e. R_{fg} stays very large during the fault, while a type 3 implies very small values for all three resistors for the duration of the fault. These two types of stator internal faults are treated together since they affect the winding functions the same way. As illustrated by Figure 5 - 49, both faulty windings are treated as an upper and lower part separated by the fault point.

$$i_{faultT2} = i_{af1} - i_{af2}$$

$$i_{faultT3} = i_{af1} + i_{bf1} - i_{af2} - i_{bf2}$$

$$i_{ain} = i_{a1} + i_{af1} \qquad i_{aout} = i_{a1} + i_{af2}$$

$$i_{bin} = i_{b1} + i_{bf1} \qquad i_{bout} = i_{b1} + i_{bf2}$$

$$i_g = i_{aout} + i_{bout} + i_{c1} + i_{c2}$$

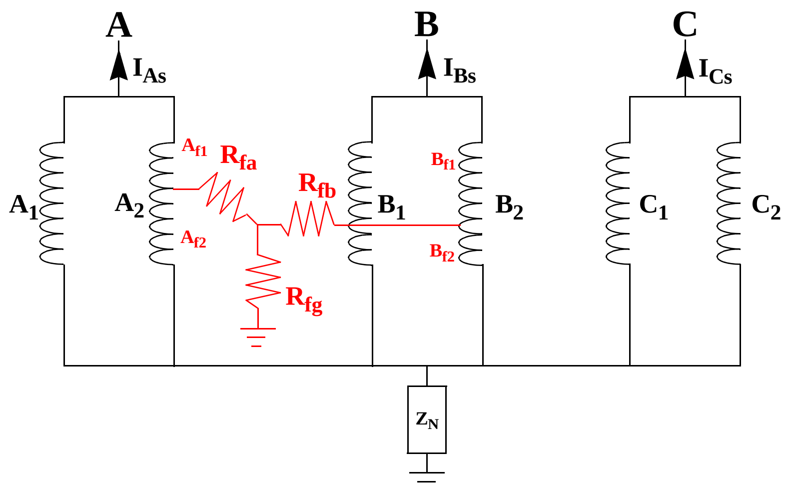


Figure 5 - 49 Type 2 and 3 fault in a synchronous machine with two parallel windings and neutral impedance

5.19.5.3 Type 4 & 5: Three-Phase Shorted Windings (to ground)

Very similar to type 2 and 3, this fault type also involves a winding from the remaining phase. A type 5 fault involves a small R_{fg} while type 4 does not. Type 4 fault current is arbitrary set as the current flowing through Rfa.

$$i_{faultT4} = i_{af1} - i_{af2}$$

$$i_{faultT5} = i_{af1} + i_{bf1} + i_{cf1} - i_{af2} - i_{bf2} - i_{cf2}$$

$$i_{ain} = i_{a1} + i_{af1} \qquad i_{aout} = i_{a1} + i_{af2}$$

$$i_{bin} = i_{b1} + i_{bf1} \qquad i_{bout} = i_{b1} + i_{bf2}$$

$$i_{cin} = i_{c1} + i_{cf1} \qquad i_{cout} = i_{c1} + i_{cf2}$$

$$i_g = i_{aout} + i_{bout} + i_{cout}$$

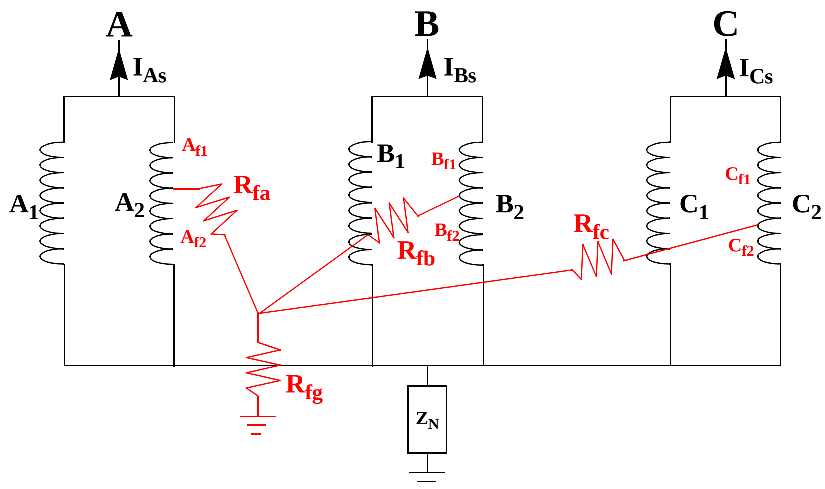


Figure 5 - 50 Type 4 and 5 fault in a synchronous machine with two parallel windings and neutral impedance

5.19.5.4 Type 6 & 7: Single Phase Shorted Windings (to ground)

Similar to type 2 and 3, this internal fault is between two windings of the same phase. To realize a type 6 fault (winding-winding), R_{fg} must be kept very large during the fault while a type 7 fault, winding-winding-ground, the grounding resistor must be stepped down to a small value.

$$i_{faultT6} = i_{af1} - i_{af2}$$

$$i_{faultT7} = i_{af1} + i_{af3} - i_{af2} - i_{af4}$$

$$i_{ain} = i_{af1} + i_{af3} \qquad i_{aout} = i_{af2} + i_{af4}$$

$$i_g = i_{aout} + i_{b1} + i_{b2} + i_{c1} + i_{c2}$$

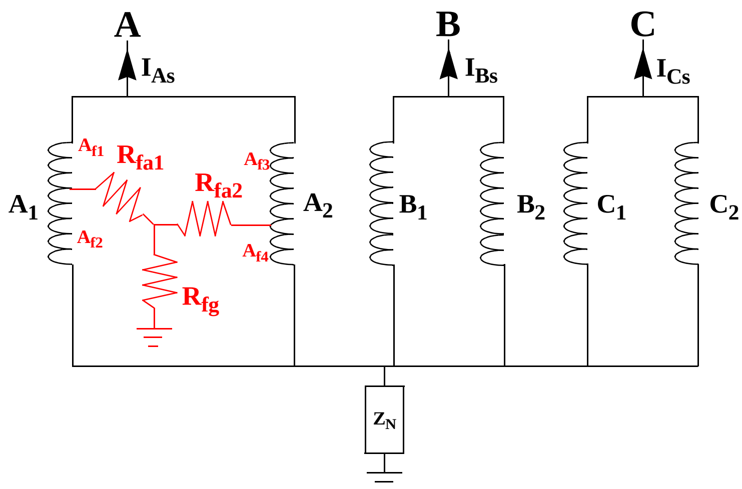


Figure 5 - 51 Type 6 and 7 fault in a synchronous machine with two parallel windings and neutral impedance

5.19.5.5 Type 8: Single Winding Shorted turns

This type of fault involves only one winding where a number of turns are shorted. That particular winding is split into three sub-windings, as shown in Figure 5 - 52, but, mathematically, it's treated as two since the same current, i_{af1}, flows through A_{f1} and A_{f3}.

$$i_{faultT8} = i_{af1} - i_{af2}$$

$$i_{ain} = i_{aout} = i_{a1} + i_{af1}$$

$$i_g = i_{aout} + i_{b1} + i_{b2} + i_{c1} + i_{c2}$$

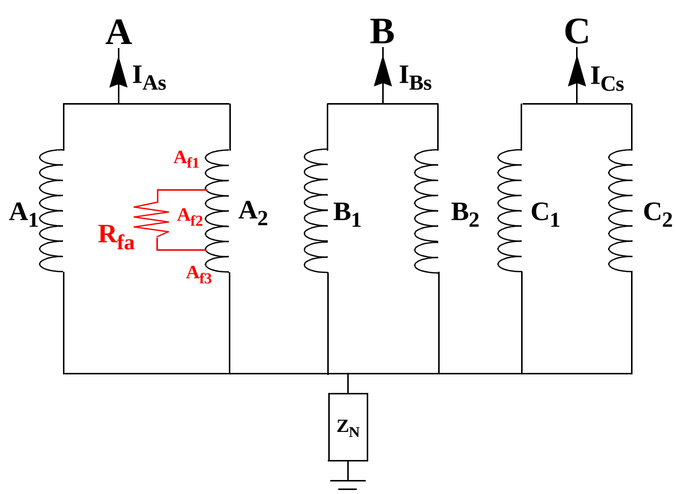


Figure 5 - 52 Type 8 fault in a synchronous machine with two parallel windings and neutral impedance