

# e-HIGHWAY 2050

## Modular Development Plan of the Pan-European Transmission System 2050

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<b>WP 8</b>	<b>Enhanced Pan-European Transmission Planning Methodology</b>		
D 8.5.b	Prototype to assess robustness of a grid architecture		



		Date & Visa
Written by	Francisco Echavarren, Luis Rouco, Lukas Sigrist, COMILLAS	18/06/2015
Checked by	Patrick Panciatici, Jean Maeght, Camille Pache, RTE	24/06/2015
Validated by	Gérald Sanchis, Nathalie Grisey, RTE	14/09/2015

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# Document information

## General purpose

This document is the deliverable D8.5.b of the e-Highway2050 project. It contains the description of the prototype developed in the framework of Task 8.5, named “*Enhanced methodology to assess robustness of a grid architecture*”.

## Change status

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V1.0	15/07/2015	Modifications after exchanges within WP8	C. Pache
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## **EXECUTIVE SUMMARY**

Task 8.5 is aimed at investigating the robustness of the grid architectures proposed by previous tasks of Work Package 8 (WP8).

The robustness analysis involves the study of voltage-reactive power control and stability, transient stability and small-signal stability.

Voltage-reactive control and stability is concerned with the ability of the power system to supply its loads at admissible voltages. Voltage control analysis is aimed at determining reactive power resources to ensure that voltage profile is within admissible ranges. Voltage stability analysis computes the load margin to voltage collapse. Voltage-reactive power control and stability is addressed using steady-state models and AC load flow tools.

Transient stability is interested in the ability of synchronous generators to remain in synchronism in case of faults that may occur. Transient stability of a power system is measured by the critical clearing times of the faults. Critical clearing times below times of protections might either affect the design of the grid or require special protection schemes (defence plans).

Small-signal stability looks at the damping of the electromechanical oscillations of synchronous generators. Should the damping of electromechanical oscillations be below a safe value, power system stabilizer of generators must be redesigned. Damping controllers of FACTS devices and HVDC links can also contribute to the damping of generator oscillations.

Two families of tools to address robustness analysis of the proposed grid architectures have been developed. The tools are grouped into two categories:

- Tools for steady-state analysis
- Tools for transient stability analysis

The set of tools for steady-state analysis comprises a tool to transform a DC load flow into an AC load flow and a tool to assess voltage stability. A tool has been developed to transform a DC power flow into an AC power flow. Transmission expansion planning, that proposes the grid architectures to be analyzed, makes use of DC power flow, which is however not suitable for voltage-reactive power control and stability as well as transient and small signal stability analyses. A tool to assess voltage stability has also been developed. The risk of voltage instability of a power system can be measured by the distance of the steady-state power flow equations from the initial point of operation (base case) to its saddle node bifurcation point, known as the voltage collapse point. The tool is based on binary search techniques. Binary search consists of attempting gradual approaching movements towards an objective, and where the step size is dynamically corrected considering how far the point is from the objective.

The set of tools for transient stability analysis comprises a tool to build a dynamic model of the power system and a tool to assess transient stability. Prior to assessing transient stability, a dynamic model of the power system must be built. A tool has been developed for this purpose. It retrieves generator data from a solved AC load flow file and creates the dynamic data file, containing the parameters of the models of generators and other dynamic equipment. Since detailed model parameters of all generators are usually not known a priori, generators are grouped according to six typical generation technologies and each

technology is described by an existing reference plant with its standardized dynamic models and model parameters. A tool is also needed to assess transient stability, which is quantified by the critical clearing times (CCTs) of faults. This tool essentially determines the CCT for all possible solid three-phase transmission system faults in an iterative way. In every iteration, the power system response to the fault is simulated with PSS/E. CCT is attained when generators still remain in synchronism once the fault is cleared, i.e., relative generator angles do not continue diverging after the fault has been cleared.

# TABLE OF CONTENTS

- 1. Introduction .....7**
- 2. Tools for steady-state analysis .....8**
  - 2.1. MODEL DATA .....8
    - 2.1.1. Data records requirements .....8
    - 2.1.2. PSS®E .....8
    - 2.1.3. Eurostag .....9
    - 2.1.4. TEPES .....9
  - 2.2. TOOL TO DEVELOP AN AC LOAD FLOW MODEL FROM A DC ONE .....10
    - 2.2.1. DC model building .....11
    - 2.2.2. DC-to-AC module .....11
    - 2.2.3. QV adjustment .....12
  - 2.3. TOOL FOR VOLTAGE STABILITY ANALYSIS .....13
- 3. Tools for dynamic analysis .....16**
  - 3.1. MODEL DATA PSS/E .....16
  - 3.2. TOOL FOR CRITICAL CLEARING TIME CALCULATIONS .....20
- 4. References .....24**
- 5. Appendix .....25**

## Acronyms and definitions

<b>CCT</b>	Critical clearing time
<b>PSS/E</b>	Power System Simulator
<b>RES</b>	Renewable Energy Sources

## List of figures

Figure 2-1. Architecture of the developed tool.....	10
Figure 2-2. Flowchart of the full version of the DC-to-AC tool, including the AC vs. AC* performance test utility.....	11
Figure 2-3. Flowchart of the QV procedures to fix reactive power generation limits and bus voltages limits	13
Figure 2-4. Flowchart of the procedure to obtain the voltage collapse point and corresponding PV curves .	14
Figure 3-1 : Overview of the procedure to build the dynamic model of the system.....	17
Figure 3-2 : Dynamic model builder. ....	20
Figure 3-3 : Transient instability due to loss of synchronism.....	21
Figure 3-4 : Tool for critical clearing time calculations. ....	22
Figure 3-5 : Step-wise increments of the duration of the fault.....	23
Figure 5-1 : GENROU parameter sheet. ....	25
Figure 5-2 : GENSAL parameter sheet.....	26
Figure 5-3 : EXAC1 parameter sheet. ....	27
Figure 5-4 : EXAC3 parameter sheet. ....	28
Figure 5-5 : ESST4B parameter sheet.....	29
Figure 5-6 : STB6 parameter sheet.....	30
Figure 5-7 : TGOV3 parameter sheet. ....	31
Figure 5-8 : IEEEG1 parameter sheet. ....	32
Figure 5-9 : GGOV1 parameter sheet.....	33
Figure 5-10 : GAST2a parameter sheet. ....	34
Figure 5-11 : HYGOV1 parameter sheet.....	35

# 1. Introduction

Task 8.5 is aimed at investigating the robustness of the grid architectures proposed by previous tasks of Work Package 8 (tasks from 8.2 through 8.4).

The robustness analysis involves the study of voltage-reactive power control and stability, transient stability and small-signal stability.

This document describes the tools developed to address robustness analysis of the proposed grid architectures. The tools are grouped into two categories:

- Tools for steady-state analysis
- Tools for transient stability analysis

The set of tools for steady-state analysis comprises a tool to transform a DC load flow into an AC load flow and a tool to assess voltage stability. A tool has been developed to transform a DC power flow into an AC power flow. Transmission expansion planning, that proposes the grid architectures to be analyzed, makes use of DC power flow, which is however not suitable for voltage-reactive power control and stability as well as transient and small signal stability analyses. A tool to assess voltage stability has also been developed. The risk of voltage instability of a power system can be measured by the distance of the steady-state power flow equations from the initial point of operation (base case) to its saddle node bifurcation point, known as the voltage collapse point. The tool is based on binary search techniques. Binary search consists of attempting gradual approaching movements towards an objective, and where the step size is dynamically corrected considering how far the point is from the objective.

The set of tools for transient stability analysis comprises a tool to build a dynamic model of the power system and a tool to assess transient stability. Prior to assessing transient stability, a dynamic model of the power system must be built. A tool has been developed for this purpose. It retrieves generator data from a solved AC load flow file and creates the dynamic data file, containing the parameters of the models of generators and other dynamic equipment. Since detailed model parameters of all generators are usually not known a priori, generators are grouped according to six typical generation technologies and each technology is described by an existing reference plant with its standardized dynamic models and model parameters. A tool is also needed to assess transient stability, which is quantified by the critical clearing times (CCTs) of faults. This tool essentially determines the CCT for all possible solid three-phase transmission system faults in an iterative way. In every iteration, the power system response to the fault is simulated with PSS/E. CCT is attained when generators still remain in synchronism once the fault is cleared, i.e., relative generator angles do not continue diverging after the fault has been cleared.

## 2. Tools for steady-state analysis

### 2.1. Model data

This section comprises the description of the data sources used during the project. The principal data source is the TEPES output. This source provides essential information to describe the approximated DC model of the power system, thus the AC full model can be built.

Two other data sources have been considered. During the DC-to-AC tool development, actual power networks have been necessary to contrast and adjust the models. From an actual AC scenario, its approximated DC model is obtained, and using the DC-to-AC tool an approximation of the original AC scenario is obtained. This way, the performance of the DC-to-AC tool is tested by comparing the original AC scenario and its AC-to-DC-to-AC approximation. Those additional data sources correspond with standards 'Power Flow Raw Data File' of PSS<sup>®</sup>E and 'Load Flow Data File' of Eurostag.

#### 2.1.1. Data records requirements

The information needed to build a full AC power scenario cover a great number of data records for each device of the network, including topology, active power dispatch, and reactive power and voltage control resources operation. All this information is important to test the performance of the DC-to-AC tool, when an actual AC scenario is compared with its AC-to-DC-to-AC approximation (see section 2.2)

In the case of building an approximated DC model of a network, the information required is fewer and is mostly focused in both the topology and the active power dispatch, since reactive power is out from the approximated DC model formulation. To build the DC model from the data source, a set of characteristics of the different devices of the power network are required:

- Buses: Number, name, base voltage, area
- Lines: Initial and final buses, circuit identifier, series reactance, rate
- Transformers: Initial and final buses, circuit identifier, series reactance, phase shift, rate
- Generators: Bus, machine identifier, status, active power generation, active power generation limits
- Loads: Bus, load identifier, status, active power demand
- Areas: Number, name, desired interchange

#### 2.1.2. PSS<sup>®</sup>E

PSS<sup>®</sup>E is an integrated software for power system analysis calculations, such as power flow, fault analysis, contingency analysis and dynamic simulations, among others [1].

The bulk power flow data format of PSS<sup>®</sup>E consists of reading all the data required in power flow work from a Power Flow Raw Data File (RAW). RAW files consist of 19 groups of records, with each group containing a particular type of data required in power flow work, such as buses, loads, bus shunts, generators, non-transformer branches or transformers, among others.

The different groups of data are separated by a '0' character. Inside most of the groups every line represents a new device record, except some groups (such as the Transformers or the Two-Terminal DC



Transmission Lines), where two or more lines are needed for each device. The fields in every line are written using comma separated values (CSV) format. Table 3-2 shows an example:

Table 2-1: Bus data record example in a RAW file

```
1234, 'EUROSTAG', 380.0000, 1, 0.000, 50.000, 1, 10, 1.017841, 11.52514
```

According to the format definition for PSS®E, this bus is the number 1234 and its name is 'EUROSTAG', base voltage is 380 kV, bus type is 1 (PQ bus), shunt conductance and susceptance are 0.0 MW and 50.0 MVar, the bus belongs to area number 1 and zone 10, number base voltage is 380 kV, and finally bus voltage module and angle are 1.017841 and 11.52514°.

### 2.1.3. Eurostag

EUROSTAG® is a software developed for accurate and reliable simulations of power systems statics and dynamics, and used worldwide for studies, research, design and operational optimization by Transmission System Operators and Generation Companies, but also by consulting companies [2].

The power flow data format of EUROSTAG® are collected into an ECH file which contains different groups of records, with each group containing a particular type of data required in power flow work, such as buses, loads, bus shunts, generators, non-transformer branches or transformers, among others.

The different groups of data are distinguished by the first or two first characters of each line, which represents a code for the type of record, e.g. '1' represents node records or '41' represents power transformers. The rest of data included in the line record are organized using predetermined lengths for each record. Table 2-2 shows an example:

Table 2-2: Bus data record example in a ECH file

```

1FREUROSTAG          621.5000 25.40000
0.000000 50.00000 380.0000 1.017841 11.52514

```

First character '1' points out that this is a bus record. After that, the bus information is placed according to character positions. Therefore, bus name is 'EUROSTAG' (4 to 11), active and reactive power generation are 621.5 MW (31 to 38) and 25.4 MVar (40 to 47), shunt conductance and susceptance are 0.0 MW (67 to 74) and 50.0 MVar (76 to 83), base voltage is 380 kV (85 to 92), and finally bus voltage module and angle are 1.017841 (99 to 106) and 11.52514° (108 to 115).

### 2.1.4. TEPES

TEPES (Transmission Expansion Planning for an Electrical System) is the model developed by Comillas for grid expansion at nodal level. As Figure 2-1 shows, the robustness analysis will be applied to corresponds to the nodal development plan for the first horizons, carried out taking into account the optimal zonal modular development plan calculated in task 8.4 (see D8.4.b for the prototype description).

TEPES output collects the key information about the whole process, from the reduction of the initial network to the grid expansion at nodal level. TEPES output consists of an Excel spreadsheet, where each sheet represents different data records required for the model:

- Information about buses and zones are collected in sheets “Indices” and “Nodes”
- Branches data (lines and transformers) is located at sheet “Networks”
- Loads info and forecasted demand values for the different scenarios are in sheet “DemandDuration”
- Finally, generation units location and parameters can be found at sheet “Generation”, thus the forecasted generation values for the different scenarios

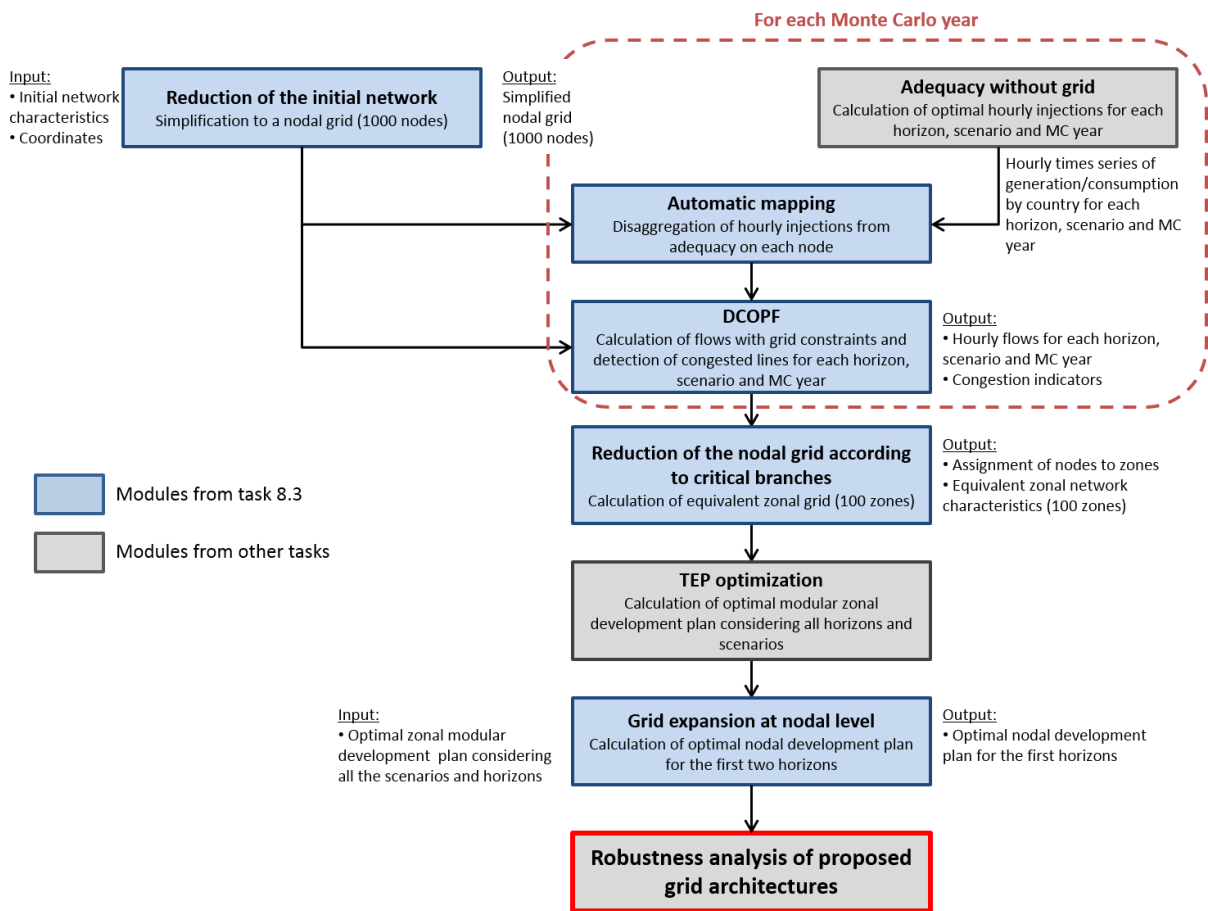


Figure 2-1. Architecture of the developed tool

## 2.2. Tool to develop an AC load flow model from a DC one

The main goal of the project is the development of a tool able to build an AC load flow model using a DC approximation. In addition, to test the performance of DC-to-AC tool, an alternatively entry for full AC models has been considered. AC formats considered, as section 2.1 shows, are PSS®E and Eurostag standards. The full AC model is convergent, and its DC approximation is obtained and used as entry for the DC-to-AC tool. Finally, the actual AC scenario and its AC-to-DC-to-AC approximation are compared. Figure 2-2 depicts a flowchart of the process.

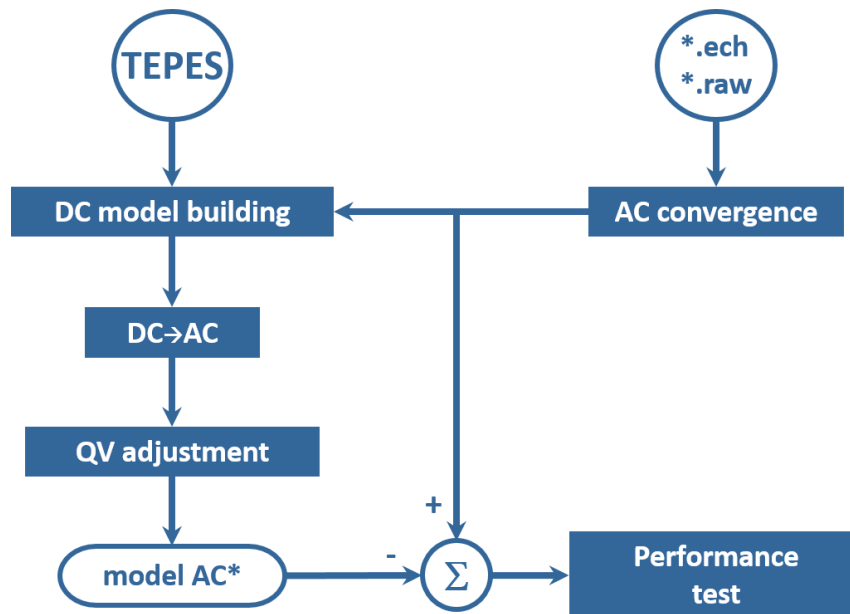


Figure 2-2. Flowchart of the full version of the DC-to-AC tool, including the AC vs. AC\* performance test utility

### 2.2.1. DC model building

The DC model building module is responsible for obtaining the initial DC model of the network. This module can build the DC model from either the TEPES format data or an actual AC model of the network.

The DC model building takes the topology and active power dispatch information of the network and builds the network considering only series reactance of lines and transformers, and assigns to each bus the active power balance between bus generation units and loads. The resulting model presents a linear relation between bus voltage angles and active power bus balance, defined by a matrix built from series reactance of lines and transformers:

### 2.2.2. DC-to-AC module

The DC-to-AC module uses the information of a DC approximation of a network, and uses it to build an equivalent full AC model.

In the case of power lines, the branch data in the DC load flow data set contains branch resistance and reactance. Standard overhead lines parameters are considered to obtain the lines susceptance: line length is determined from the actual line reactance and the pu/length reactance of a standard overhead line, then line susceptance is obtained multiplying it with the pu/length susceptance of a standard overhead line.

Considering the assignment of reactive power demand to the loads in the scenario, it is proportional to the active power demand, considering the same power factor for all the loads. This power factor can be set by the user.

Finally, in the case of reactive power capability (both maximum generation and consumption capability) of generators, the limits are established considering the same couple of power factors for all the generation

units, one for the minimum limit (leading power factor) and the other for the maximum limit (lagging power factor). Both power factors can be set by the user.

### **2.2.3. QV adjustment**

Once the equivalent full AC model has been built from the DC approximation network data, it is necessary to adjust its voltage profile. DC approximation data is enough to build a well-conditioned scenario from the active power point of view, i.e. voltage angles and active power flows through lines and transformers. However, DC approximation network data contain no information about reactive power dispatch: bus reactive power demand, generation units scheduled voltages, bus shunts location and magnitude, etc. As a consequence, to get a fully well-conditioned scenario, the reactive power dispatch and voltage profile have to be defined.

The QV adjustment implies two processes:

1. Assign the reactive power demand to the loads in the scenario. This assignment is proportional to the active power demand, considering the same power factor for all the loads. This power factor can be set by the user.
2. Decide the placement and magnitude of shunt reactors and capacitors. Since reactive power demand definition is based on uniformity criteria, some zones may present a reactive power imbalance considering their reactive power generation resources. To rebalance the system, shunt reactors and capacitors are optimally placed to fix reactive power limits violations of generation units.
3. Adjust the final voltages profile using voltage control actions. This final step consists of fixing violations of the generation reactive power limits and bus voltage limits. To achieve that, voltage control resources, such as generator voltages, are optimally adjusted.

The order shunts/generators may be changed or even alternated during the process. However, it is recommendable to start with shunts and then use generation units, since it is always advised to leave generation units with enough reactive power margins to ensure the security of the system. In addition, a network with no shunts and all the generation units using their reactive power margins to keep the reactive power balance of the system may be very close to the voltages collapse point. Thus the non-linearity will be appreciable and as a consequence first order sensitivities will be useless.

Modules 2 and 3 present an equivalent structure, depicted in Figure 2-3:

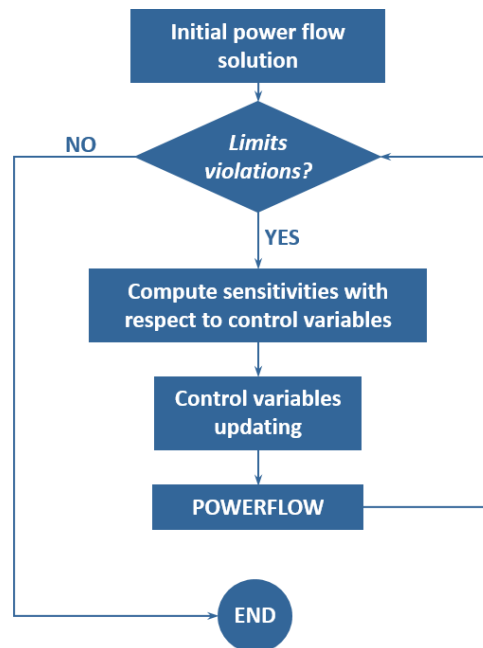


Figure 2-3. Flowchart of the QV procedures to fix reactive power generation limits and bus voltages limits

As Figure 2-3 shows, modules 2 and 3 start with the initial power flow solution and check if there are limits violations in the scenario (reactive power generation limits in step 2, bus voltage limits in step 3). If there exist violations, first order sensitivities of the out-of-limits magnitudes with respect to control variables (shunt reactors and capacitors in step 2, generator voltages in step 3) are computed, and used to optimize the control variables update.

### 2.3. Tool for voltage stability analysis

The tool developed to obtain state variables manifolds from starting point to voltage collapse is based on binary search techniques. Binary search consists of attempting gradual approaching movements towards an objective, and where the step size is dynamically corrected considering how far the point is from the objective.

As it is detailed in D8.5.a, the binary search implemented consists of considering an increment of the power dispatch control parameter and tries to find the corresponding solution. If solution exists, save the point and apply another power dispatch control parameter. If power flow is unfeasible for that power dispatch control parameter, the step is reduced. The process is considered finished when a minimum step is reached while the power dispatch control parameter is getting higher. Figure 2-4 depicts a flowchart of the process.

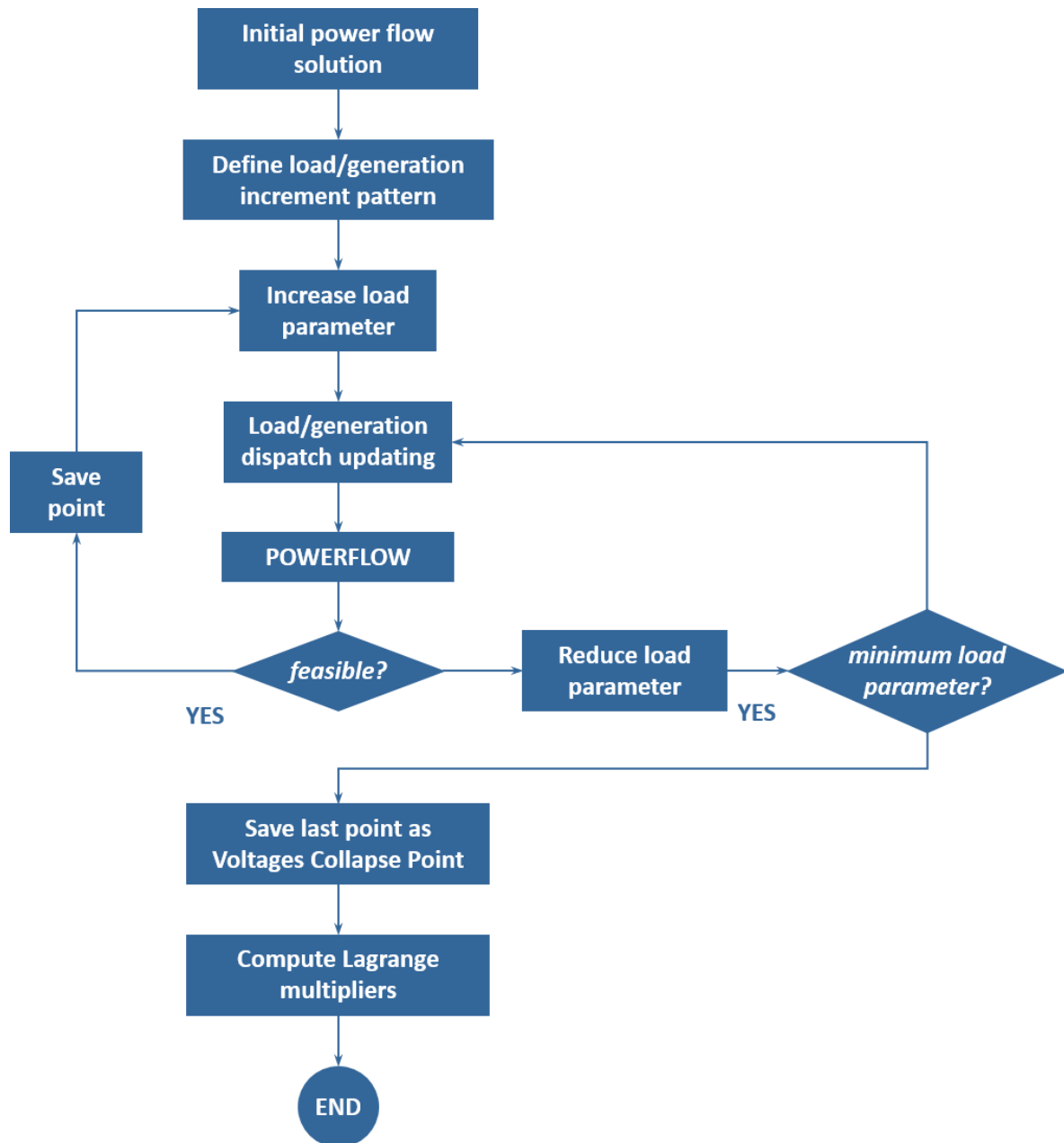


Figure 2-4. Flowchart of the procedure to obtain the voltage collapse point and corresponding PV curves

The procedure depicted in Figure 2-4 comprises the following modules:

- Power flow: Module that solves steady-state equations of the network. Output would be the power flow solution or a divergence warning.
- Load/generation pattern definition: This module establishes how the demand (active and reactive) and the generation dispatch (active) vary towards the voltage collapse point. Concerning active power, demand and generation total variations are set equal to each other to keep the system balanced. In the case of reactive power demand, it can be set to be constant, or to vary keeping constant the power factor of the loads.
- Load parameter control: It controls the evolution of the load parameter control. If power flow is feasible, the load parameter is increased to get closer to the voltage collapse point. On the

contrary, if power flow diverges, the load parameter is reduced until power flow converges or the minimum value for the load parameter variation is reached.

- Lagrange multipliers computation: After the voltage collapse point has been reached, the corresponding Lagrange multipliers are computed to obtain first order sensitivities of the load margin

Therefore, the outputs of the tool for voltage stability analysis will be the load margin to the voltage collapse point and the corresponding PV curves. In addition, Lagrange multipliers may also be obtained.

## 3. Tools for dynamic analysis

This section presents the tools developed for the analysis of transient stability of electrical power systems. Transient stability is concerned with the ability of synchronous generators to remain in synchronism in case of a fault and it is quantified by the critical clearing times of faults.

Transient and small-signal stability analyses not only need the steady-state model of the network provided by an AC load flow, but also on the dynamic model of generators and other dynamic devices. At best, parameters of the dynamic models are fully known and the models are fully validated with respect to the real responses of generators and other dynamic devices. However, dynamic model data of electrical power systems is not always publicly available, typically due to confidentiality reasons. Additionally and even if data were available, the model does not necessarily reflect real responses in all circumstances.

First, the dynamic model builder is described. This tool retrieves generator data from a solved AC load flow file and creates the dynamic data file, containing the parameters of the standard model of each generator technology. Second, the tool for critical clearing time calculations is presented. This tool essentially determines the critical clearing time for all possible solid three-phase transmission system faults in an iterative way. In every iteration, the power system response to the fault is simulated with PSS/E.

### 3.1. Model data PSS/E

The dynamic model of the system is described by a dynamic data file. The dynamic data file is a text file (written according PSS/E rules in FORTRAN free format) that contains the model data of each generating unit. System model is built taking into account:

- Generator technology (i.e., nuclear, thermal, combined cycle, gas, hydro and RES units) and HVDC transmission technology (i.e., VSC or LCC)
- Model components of each generation technology (synchronous machine, excitation system, turbine-governor system and/or converter and supervisory controls)

Figure 3-1 provides an overview of the procedure to build the dynamic model of the system. The dynamic model builder essentially reads an AC load flow file and particularly the generator data and assigns to each generator a corresponding, standardized dynamic model based on its inherent technology (e.g., nuclear or hydro generation)<sup>1</sup>.

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<sup>1</sup> In the absence of further knowledge on dynamic load modelling issues, static constant current and constant admittance, active and reactive power loads are a priori used. However, if dynamic load model data is available, this data can be included in a similar fashion by assigning to each load a standardized dynamic model based on its inherent model characteristics.



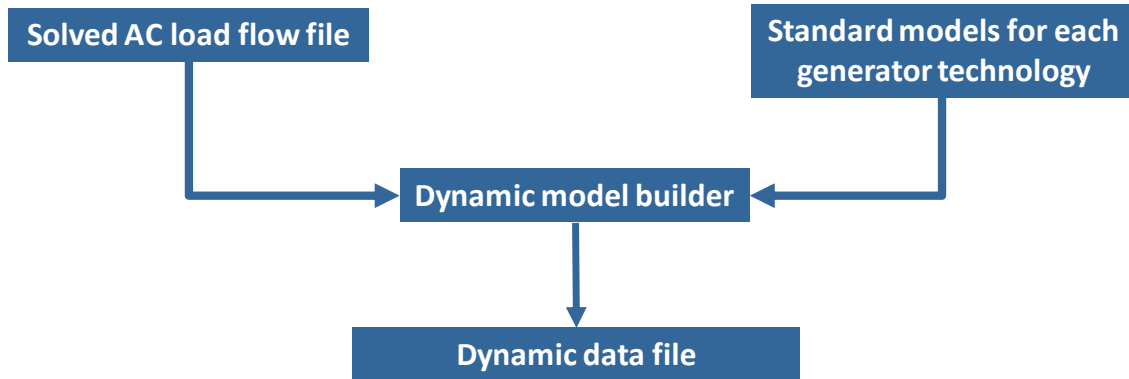


Figure 3-1 : Overview of the procedure to build the dynamic model of the system.

Since the parameters of the dynamic models of all generators within the ENTSO-e system are a priori not known, different generator technologies have been classified into six groups:

- Nuclear,
- Thermal,
- Combined cycle,
- Gas,
- Hydro, and
- RES

For each generator technology, the model components have been identified and an existing power plant with known model parameters has been used as a reference plant. The resulting models are referred to as *standard models*.

The standard models for each generator technology are available within a single Excel file, which is read by the dynamic model builder. Table 3-1 to Table 3-6 contain respectively the dynamic data of nuclear, thermal, combined cycle, gas, hydro and RES units. The data presented corresponds to reference plants located within the Iberian Peninsula. The approach can be easily extended to the pan-European context by using different standard models for different areas. The appendix in section 5 shows the PSS/E parameter sheets for each technology. Parameters of each generating unit technology are stored in a separate sheet within this Excel file. The dynamic model builder assigns the missing, necessary parameters such as bus number or bus ID and adapts other parameters such as maximum torque or turbine rating, depending on the machine rating.

Table 3-1: Dynamic data of a nuclear unit.

IBUS	'GENROU'	ID	6,42	4,40E-02	0,713	6,40E-02	2,81
			1	1,67	1,615	0,332	0,48
			0,265	0,213	7,50E-02	0,351 /	
IBUS	'EXAC1'	ID	0,00E+00	0,00E+00	0,00E+00	400	2,00E-02
			6,18	-5,56	0,84	3,00E-02	1
			0,36	0,45	1	3,9	1,30E-02
			5,21	0,176 /			
IBUS	'TGOV3'	ID	20	1,8	1	0,1	0,5
			-0,4	0,94	0,3	0,25	0,418
			6	0,00E+00	0,3	0,582	0,15
			0,26	60,26	1,1 /		

Table 3-2: Dynamic data of a thermal unit.

IBUS	'GENROU' ID	5	4,10E-02	0,62	7,40E-02	3,34
		1	2,32	2,2	0,26	0,5
		0,225	0,17	0,12	0,61 /	
IBUS	'EXAC3' ID	0	0	0	76,1	0,013
		7	-7	1,95	0,134	3,73
		0,143	1	0,05	2,05	0,144
		0,302	1	0,685	0,75	0,107
IBUS	'IEEEG1' ID	1	1,2 /			
		0	0	17	1	1
		0,49	8,65E-02	-8,65E-02	0,9	0
		0,25	0,00E+00	0,00E+00	0,00E+00	0,45
		0,00E+00	7	0,3	0,00E+00	0,4
		0,25	0,00E+00 /			

Table 3-3: Dynamic data of a combined cycle unit.

1 'GENROU'	1	6,315	0,044	0,664	0,087	6,122
		0	2,11	2,03	0,25	0,445
		0,2	0,15	0,045	0,262 /	
1 'ESST4B'	1	0	3,61	3,61	1	-0,87
		0,01	1	0	1	-0,87
		0	5,54	0	6,93	0,08
1 'GGOV1'	1	0	0 /			
		1	0	0,04	1	0,5
		-0,5	10	2	0	1
		1	0	0,5	1,5	0,15
		300	195	0	3	1
		0,2	1	0	0,1	-0,1
		0	0,01	10	0,1	1500
0	4	5	99	-99		
1 'PSS2A'	1	/				
		1	0	3	0	5
		2	2	0	2	0
		2	0,167	1	0,5	0,1
		15	0,2	0,03	0,15	0,03
0,1	-0,1 /					

Table 3-4: Dynamic data of a gas unit.

IBUS	'GENROU' ID	6,3	0,026	1,05	0,06	4,814
		0	2,14	1,974	0,262	0,276
		0,187	0,216	0,15	0,5 /	
IBUS	'EXAC1' ID	0	0,03	0,1	33	5
		17,3	-15	0,13	0,1	1
		0,36	0,45	1	4,8	0,452
		6,4	0,992 /			
IBUS	'GAST2A' ID	20	0	0,05	1	0,04
		0,2	75	0,03125	1,1	-0,1
		0,01	0,75	1	0,1	1
		0,1	0	0,2	0,8	15
		2,5	450	3,3	700	550
		-0,3604	1,36	1	1108,4	0,25
1202 /						

Table 3-5: Dynamic data of a hydro unit.

IBUS	'GENSAL'	ID	8,65	0,13	0,37	3,45	0	
			1,15	0,84	0,33	0,29	0,133	
			1,13	1,4 /				
IBUS	'ST6B'	ID	1	0,02	103	51,5	0	
			1	5,07	-4,46	0	1	
			1	5,15	6	5,07	-4,46	
			0	1 /				
IBUS	'HYGOV'	ID	0,048	1,875	12	0,1	0,2	
			0,061	1	0	1,95	1,2	
			0	0,2 /				
IBUS	'PSS2A'	ID	1	0	3	0	5	1
			3	3	0,01	3	3	
			3	0,05	1	0,4	0,1	
			4	0,13	0,03	0,13	0,03	
			0,05	-0,05 /				

Table 3-6: Dynamic data of a RES unit.

IBUS	'USRLOD'	ID	'GNWTBL'	12	1	0	22	4	19	0
				1,5	0,2	0,15	0,8	5		
				0,9	10	0	0,5	0		
				0,1	0,8	0,4	0	0,9		
				0,85	0,5	0,1	0,1	900		
		1	1,2 /							

Figure 3-2 shows a detailed flow chart of the dynamic model builder. Once the solved AC load flow file in raw format has been read, a dynamic data file is created automatically. The dynamic model builder retrieves from the AC load flow file data related to generators; particularly, the bus number, the bus ID, generated active power  $P_{gen}$ , maximum active power  $P_{max}$ , and the source reactance  $X_{Source}$ . According to the bus ID, where one letter indicates the technology (e.g., N: nuclear, S: steam, X: combined cycle, G: gas, H: hydro and W: RES), the parameters of the standard model of the corresponding technology is read from the Excel file and written to the dynamic data file. TRATE and SNOM parameters of GGOV1 and GAST2A models and of GNWTBL model, respectively, need to be adapted according to the machine rating  $M_{base}$ , where

$$M_{base} = \frac{P_{max}}{\cos\varphi}$$

Further, the dynamic model builder checks whether the generated active power is below the maximum active power, and the source reactance is set according to the subtransient reactance of the d-axis of the  $dq$ -model of the synchronous machine:

$$X_{Source} = X''_d$$

Finally, RES generation is converted into a corresponding negative load, since the GNWTBL model is implemented as a load model. Adapted generator data needs to be written to the solved AC load flow file, overwriting the previous data entries. The process is repeated until all generators have a dynamic data model assigned.

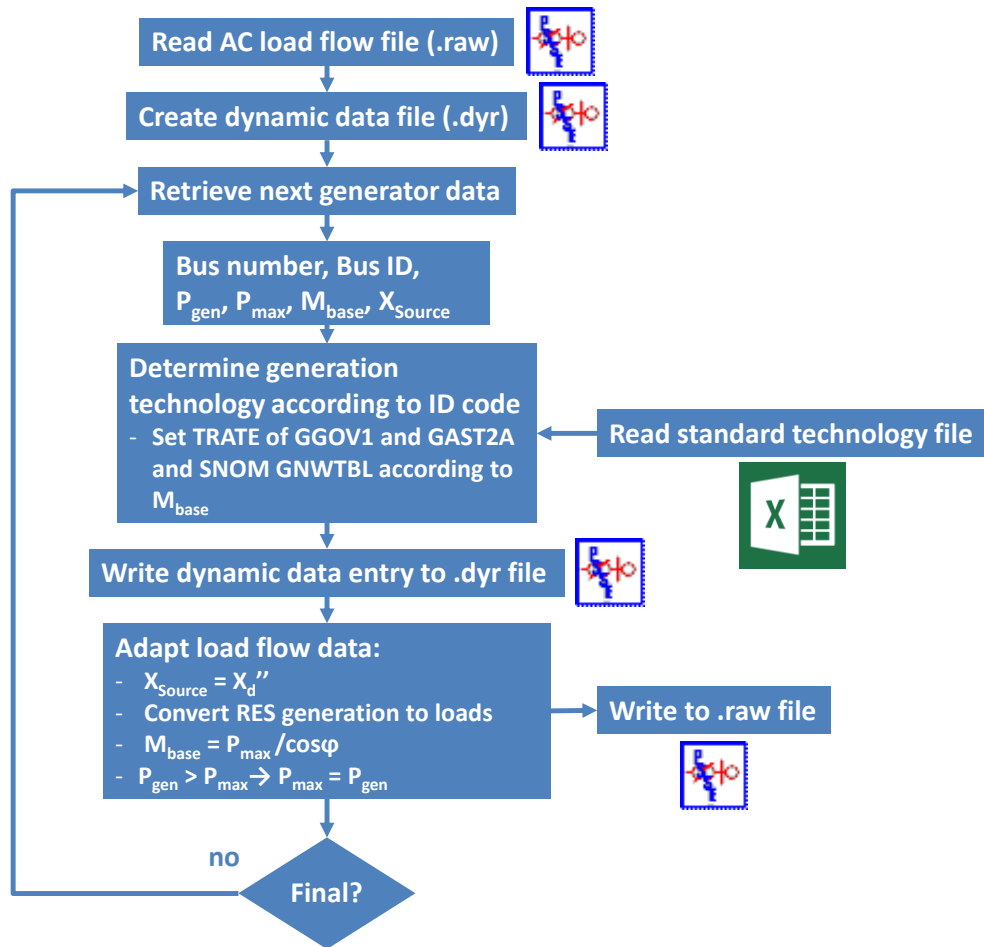


Figure 3-2 : Dynamic model builder.

### 3.2. Tool for critical clearing time calculations

The determination of the critical clearing time (CCT) is a complex task and it is usually not possible to accurately predict CCTs in a deterministic way due to high complexity and non-linearity of the dynamic power system model, reflecting the system behavior during electromechanical transients. By contrast, the behavior of the power system and in particular the response to a solid three-phase fault is iteratively simulated by increasing the faults endurance until one or several generators lose synchronism, instant when the power system is said to turn unstable. The longest length of the solid three-phase fault before the system turns unstable is then the CCT.

The tool makes use of PSS/E in order to simulate the dynamic behavior of a power system to a fault. The tool determines the CCT for all possible three-phase transmission system faults. Bus faults and line faults can be simulated. CCT is attained when generators still remain in synchronism once the fault is cleared, i.e., relative generator angles do not continue diverging after the fault has been cleared. Figure 3-3 illustrates transient instability due to the loss of synchronism. In a stable case, relative angles return after a transient to their initial values once the fault has been cleared and when the system has not been subject to changes (e.g., disconnection of a line). However, if the relative angles do not return to their initial values but instead continue diverging, the system is unstable. According to the instant when relative angles start diverging, the system is either 1<sup>st</sup> swing unstable typically due to the lack of synchronizing torque or subsequent swing unstable, which might occur in large power system due to the superposition of several modes of

oscillations causing large generator angle excursions<sup>2</sup>. Note that instability is typically reflected in a continuous, non-oscillatory increase of relative angles.

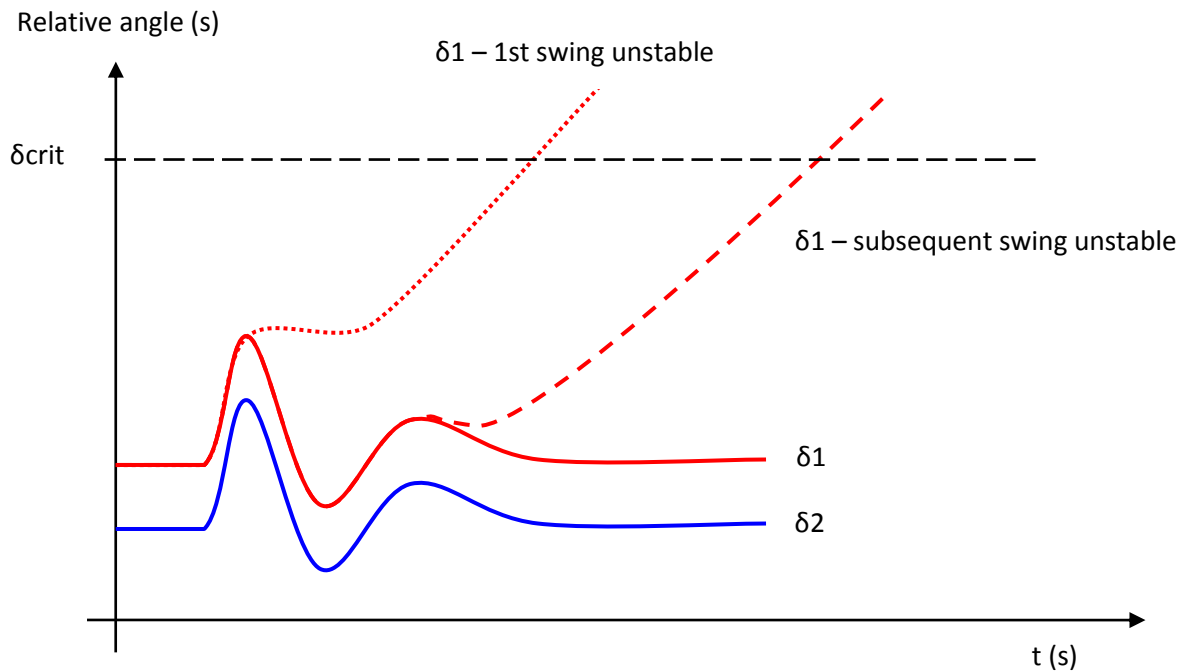


Figure 3-3 : Transient instability due to loss of synchronism.

In order to determine by simulations whether the system has turned unstable, the evaluation of the relative angles is observed. Since instability is tantamount to a continuous, non-oscillatory increase of relative angles, a critical angle is imposed. If one relative angle exceeds this critical angle, the system is deemed unstable. Clearly, the critical angle needs to be above the maximum of the first swing (see Figure 3-3), but it should be neither too large in order to avoid increasing simulation time unnecessarily.

Figure 3-4 shows a detailed flow chart of the tool for CCT calculations in case of three-phase bus faults. The tool is implemented in Python and calls PSS/E load flow and dynamic simulation routines. The tool reads an AC load flow file and solves the load flow before converting loads and generators. Constant power loads (as typically modeled for load flow analysis) are converted into loads with user defined fractions of constant power, constant current and constant admittance loads. The Thevenin equivalents of generators (as modeled for load flow analysis) are converted into Norton equivalents by making use of source impedance  $Z_{Source}$ . The user needs also to specify the critical angle  $\delta_{crit}$ , the simulation time  $t_{fin}$ , the instant of fault  $t_0$ , and the initial value of the duration of the fault  $t_{fit}$  (e.g, 0 ms). Finally, the dynamic data must be read.

The tool computes for every possible solid three-phase bus fault the CCT by incrementing  $t_{fit}$  iteratively and by adjusting these increments iteratively. For each value of  $t_{fit}$ , the relative angles are read and compared to  $\delta_{crit}$ . If one relative angle exceeds the critical angle, the system is deemed unstable and the preceding value of  $t_{fit}$  is saved as CCT. This process is repeated until at every bus a solid three-phase short circuit has been applied. Analogously, line faults are simulated and their CCT determined.

<sup>2</sup> With badly tuned excitation system controllers, the system might turn unstable far beyond the first swing. However, this is due to small signal instability, causing in this case an oscillatory instability.

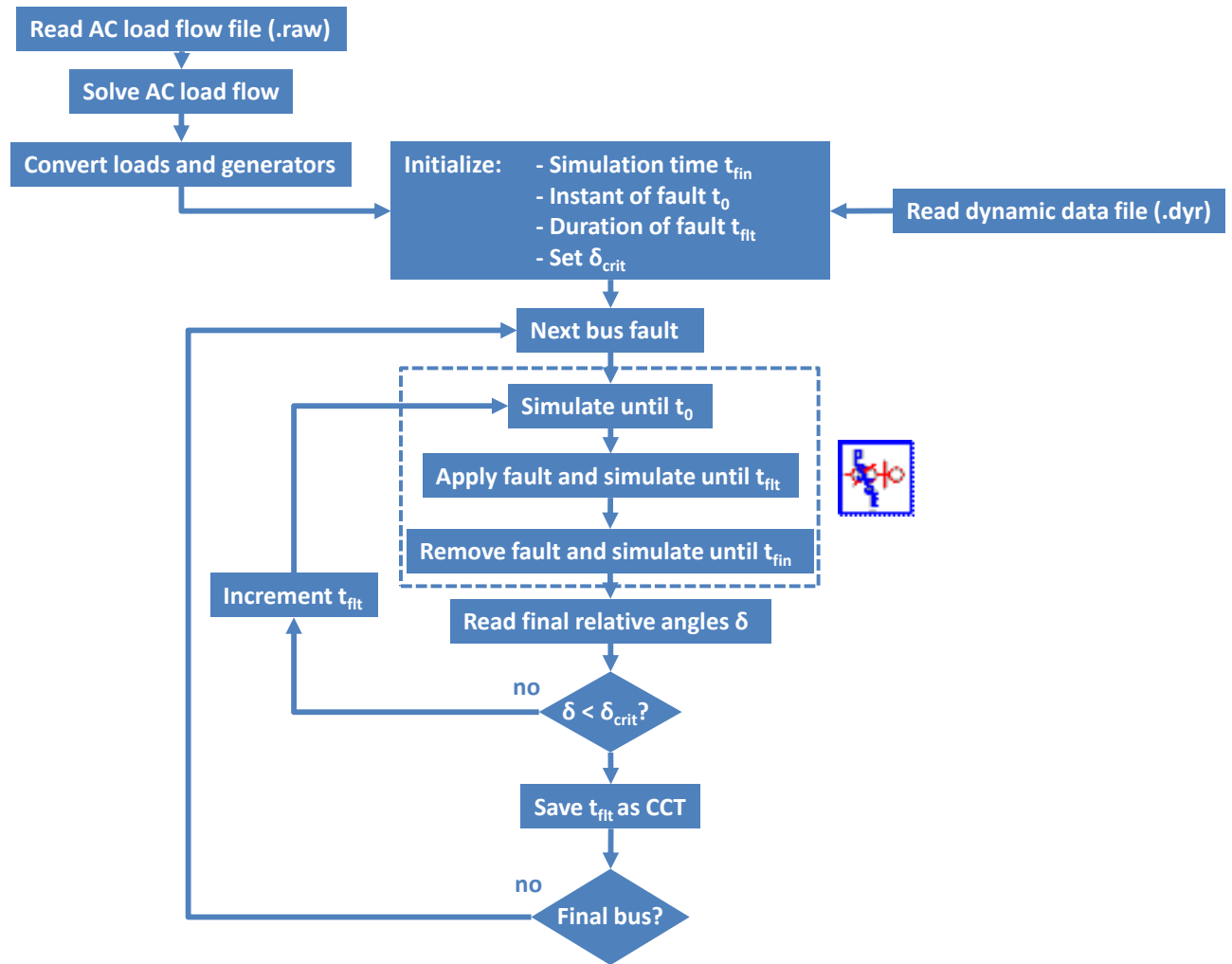


Figure 3-4 : Tool for critical clearing time calculations.

In order to improve the efficiency of the CCT calculations, the variation of  $t_{fit}$  is also carried out iteratively. In other words and instead of incrementing  $t_{fit}$  starting from 0 by steps of 1 ms, the initial value of  $t_{fit}$  is firstly incremented by larger increments (e.g., 100 ms) and whenever an unstable system arises for a given  $t_{fit}$ , the increment is reduced (e.g., 20 ms) and the CCT calculation is resumed at the precedent value of  $t_{fit}$ . This increment reduction is repeated until a resolution of  $t_{fit}$  of 1 ms is reached. Figure 3-5 details this process.

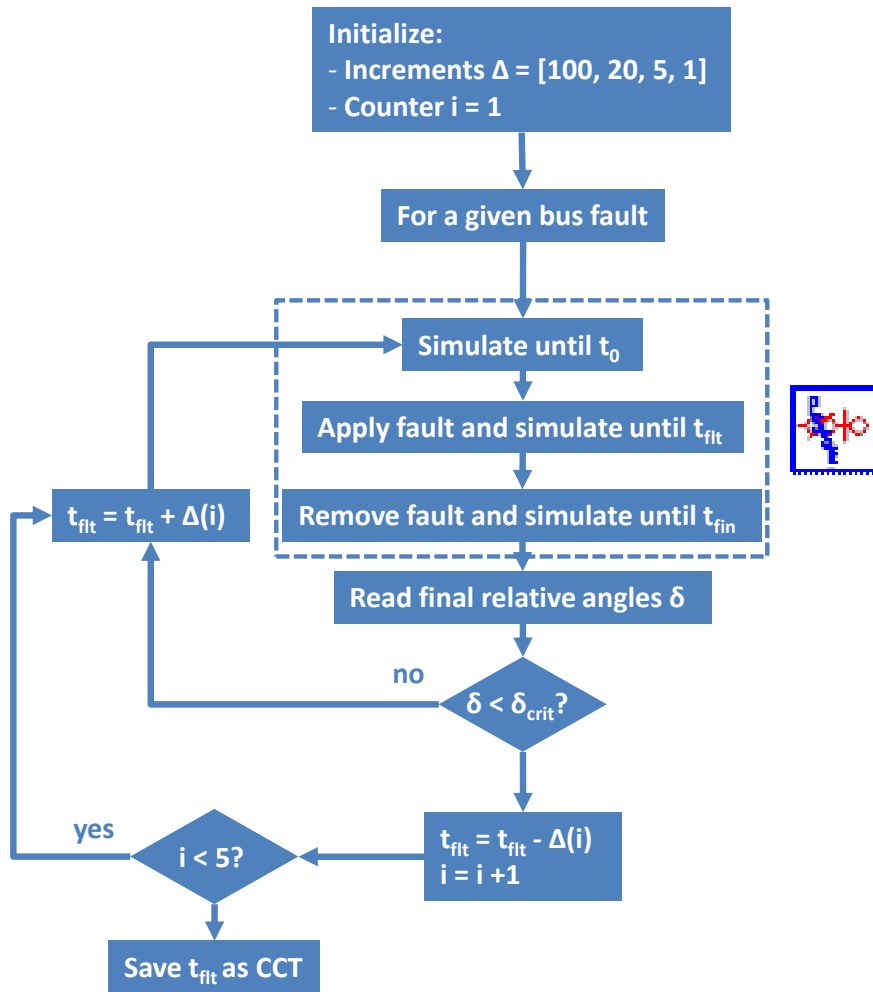


Figure 3-5 : Step-wise increments of the duration of the fault.

Finally, it is noteworthy that the accuracy of the CCT determination largely depends on the accuracy of the data of the dynamic power system model. The data of the standard models described in section 3.1 corresponds to the reference plants located within the Iberian Peninsula and it gives rise to reasonable CCTs for the Spanish-French power system as reported in [3]. The underlying dynamic data needs to be checked and probably updated in order to extend the CCT computation to the ENTSO-e system.

## **4. References**

- [1] Siemens Power Technologies International (Siemens PTI), *PSS®E 32.0.5 Online Documentation*, Oct 2010.
- [2] Tractebel – RTE, *Load Flow Data File* from *EUROSTAG PACKAGE 4.5 Documentation*, Dec 2010.
- [3] E-HIGHWAY 2050 consortium, “Deliverable D8.5a – Enhanced methodology to assess robustness of a grid architecture”, September 2015.

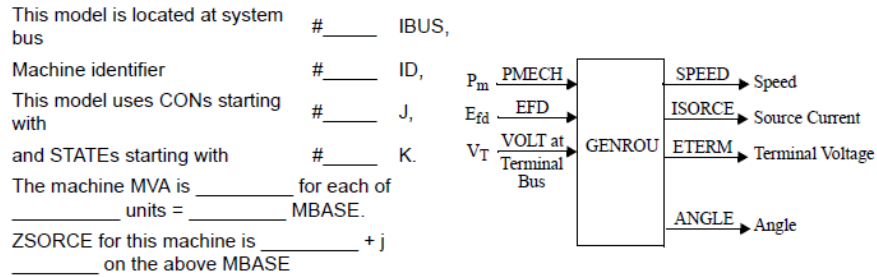


## 5. Appendix

Figure 5-1 to Figure 5-11 show the parameter sheets of different synchronous machines, excitation system and turbine-governor system technologies. The dynamic data is written in a text file according PSS/E rules using FORTRAN free format. The order of parameters as shown in the parameter sheets must be strictly maintained.

### 1.19 GENROU

#### Round Rotor Generator Model (Quadratic Saturation)



CONs	#	Value	Description
J			$T'_{do} (>0)$ (sec)
J+1			$T''_{do} (>0)$ (sec)
J+2			$T'_{qo} (>0)$ (sec)
J+3			$T''_{qo} (>0)$ (sec)
J+4			H, Inertia
J+5			D, Speed damping
J+6			$X_d$
J+7			$X_q$
J+8			$X'_d$
J+9			$X'_q$
J+10			$X''_d = X''_q$
J+11			$X_l$
J+12			S(1.0)
J+13			S(1.2)

**Note:**  $X_d, X_q, X'_d, X'_q, X''_d, X''_q, X_l, H,$  and  $D$  are in pu, machine MVA base.

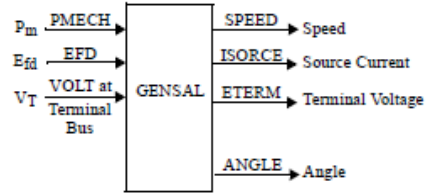
$X''_q$  must be equal to  $X''_d$ .

Figure 5-1 : GENROU parameter sheet.

### 1.21 GENSAL

#### Salient Pole Generator Model (Quadratic Saturation on d-Axis)

This model is located at system bus # \_\_\_\_\_ IBUS,  
 Machine identifier # \_\_\_\_\_ ID,  
 This model uses CONs starting with # \_\_\_\_\_ J,  
 and STATES starting with # \_\_\_\_\_ K.  
 The machine MVA is \_\_\_\_\_ for each of units = \_\_\_\_\_ MBASE.  
 ZSORCE for this machine is \_\_\_\_\_ + j \_\_\_\_\_ on the above MBASE.



CONs	#	Value	Description
J			$T'_{do}$ (>0) (sec)
J+1			$T''_{do}$ (>0) (sec)
J+2			$T''_{qo}$ (>0) (sec)
J+3			H, Inertia
J+4			D, Speed damping
J+5			$X_d$
J+6			$X_q$
J+7			$X'_d$
J+8			$X''_d = X''_q$
J+9			$X_i$
J+10			S(1.0)
J+11			S(1.2)

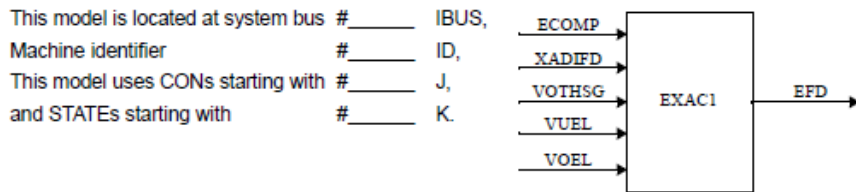
Note:  $X_d$ ,  $X_q$ ,  $X'_d$ ,  $X''_d$ ,  $X''_q$ ,  $X_i$ , H, and D are in pu, machine MVA base.

$X''_q$  must be equal to  $X''_d$ .

Figure 5-2 : GENSAL parameter sheet.

## 6.24 EXAC1

### IEEE Type AC1 Excitation System

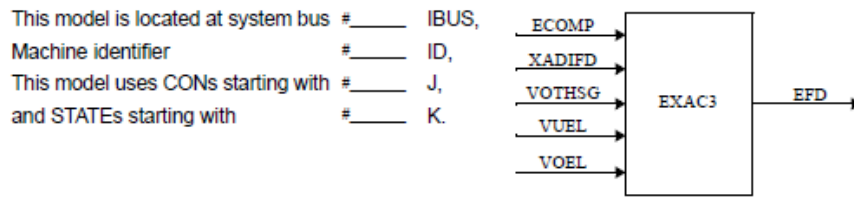


CONs	#	Value	Description
J			$T_R$ (sec)
J+1			$T_B$ (sec)
J+2			$T_C$ (sec)
J+3			$K_A$
J+4			$T_A$ (sec)
J+5			$V_{RMAX}$
J+6			$V_{RMIN}$
J+7			$T_E > 0$ (sec)
J+8			$K_F$
J+9			$T_F > 0$ (sec)
J+10			$K_C$
J+11			$K_D$
J+12			$K_E$
J+13			$E_1$
J+14			$S_E(E_1)$
J+15			$E_2$
J+16			$S_E(E_2)$

Figure 5-3 : EXAC1 parameter sheet.

### 6.27 EXAC3

#### IEEE Type AC3 Excitation System

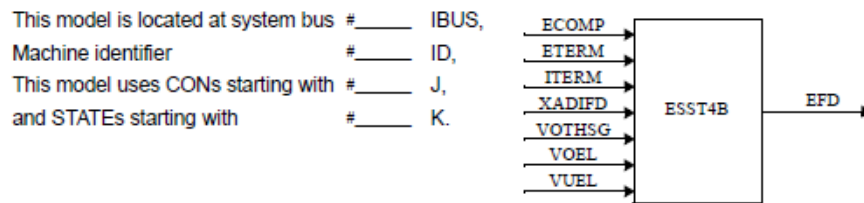


CONs	#	Value	Description
J			$T_R$ (sec)
J+1			$T_B$ (sec)
J+2			$T_C$ (sec)
J+3			$K_A$
J+4			$T_A$ (sec)
J+5			$V_{AMAX}$
J+6			$V_{AMIN}$
J+7			$T_E > 0$ (sec)
J+8			$K_{LV}$
J+9			$K_R (>0)$
J+10			$K_F$
J+11			$T_F > 0$ (sec)
J+12			$K_N$
J+13			$EFD_N$
J+14			$K_C$
J+15			$K_D$
J+16			$K_E$
J+17			$V_{LV}$
J+18			$E_1$
J+19			$S_E(E_1)$
J+20			$E_2$
J+21			$S_E(E_2)$

Figure 5-4 : EXAC3 parameter sheet.

## 6.21 ESST4B

IEEE Type ST4B Potential or Compounded Source-Controlled Rectifier Exciter



CONs	#	Value	Description
J			$T_R$ (sec)
J+1			$K_{PR}$
J+2			$K_{IR}$
J+3			$V_{RMAX}$
J+4			$V_{RMIN}$
J+5			$T_A$ (sec)
J+6			$K_{PM}$
J+7			$K_{IM}$
J+8			$V_{MMAX}$
J+9			$V_{MMIN}$
J+10			$K_G$
J+11			$K_P$
J+12			$K_I$
J+13			$V_{BMAX}$
J+14			$K_C$
J+15			$X_L$
J+16			THETAP

Figure 5-5 : ESST4B parameter sheet.

## 6.60 ST6B

### IEEE 421.5 2005 ST6B Excitation System

This model is located at system bus #\_\_\_\_\_ IBUS,  
 Machine identifier #\_\_\_\_\_ ID,  
 This model uses CONs starting with #\_\_\_\_\_ J,  
 STATEs starting with #\_\_\_\_\_ K,  
 VARs starting with #\_\_\_\_\_ L,  
 and ICON #\_\_\_\_\_ M.

CONs	#	Value	Description
J			$T_R$ regulator input filter time constant (sec)
J+1			$K_{PA}$ (pu) (> 0) voltage regulator proportional gain
J+2			$K_{IA}$ (pu) voltage regulator integral gain
J+3			$K_{DA}$ (pu) voltage regulator derivative gain
J+4			$T_{DA}$ voltage regulator derivative channel time constant (sec)
J+5			$V_{AMAX}$ (pu) regulator output maximum limit
J+6			$V_{AMIN}$ (pu) regulator output minimum limit
J+7			$K_{FF}$ (pu) pre-control gain of the inner loop field regulator
J+8			$K_M$ (pu) forward gain of the inner loop field regulator
J+9			$K_{CI}$ (pu) exciter output current limit adjustment gain
J+10			$K_{LR}$ (pu) exciter output current limiter gain
J+11			$I_{LR}$ (pu) exciter current limit reference
J+12			$V_{RMAX}$ (pu) voltage regulator output maximum limit
J+13			$V_{RMIN}$ (pu) voltage regulator output minimum limit
J+14			$K_G$ (pu) feedback gain of the inner loop field voltage regulator
J+15			$T_G$ (> 0) feedback time constant of the inner loop field voltage regulator (sec)

Figure 5-6 : STB6 parameter sheet.

## 7.22 TGOV3

### Modified IEEE Type 1 Speed-Governing Model With Fast Valving

This model is located at system bus # \_\_\_\_\_ IBUS,  
 Machine identifier # \_\_\_\_\_ ID,  
 This model uses CONs starting with # \_\_\_\_\_ J,  
 and STATES starting with # \_\_\_\_\_ K,  
 and VARs starting with # \_\_\_\_\_ L.

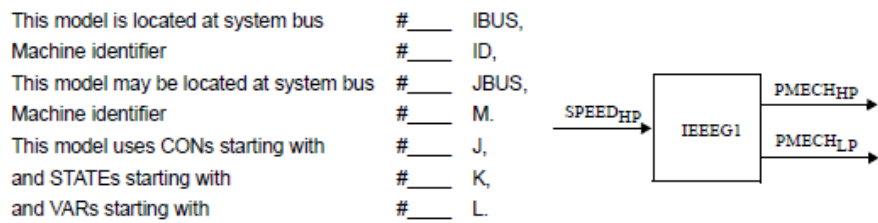


CONs	#	Value	Description
J			K
J+1			T <sub>1</sub> (sec)
J+2			T <sub>2</sub> (sec)
J+3			T <sub>3</sub> (>0) (sec)
J+4			U <sub>0</sub>
J+5			U <sub>c</sub> (< 0)
J+6			P <sub>MAX</sub>
J+7			P <sub>MIN</sub>
J+8			T <sub>4</sub> (sec)
J+9			K <sub>1</sub>
J+10			T <sub>5</sub> (> 0) (sec)
J+11			K <sub>2</sub>
J+12			T <sub>6</sub> (sec)
J+13			K <sub>3</sub>
J+14			T <sub>A</sub> (sec)
J+15			T <sub>B</sub> (sec)
J+16			T <sub>C</sub> (sec)
J+17			P <sub>RMAX</sub> (pu)

Figure 5-7 : TGOV3 parameter sheet.

### 7.13 IEEEG1

#### IEEE Type 1 Speed-Governing Model



CONs	#	Value	Description
J			K
J+1			T <sub>1</sub> (sec)
J+2			T <sub>2</sub> (sec)
J+3			T <sub>3</sub> (> 0) (sec)
J+4			U <sub>o</sub> (pu/sec)
J+5			U <sub>c</sub> (< 0) (pu/sec)
J+6			P <sub>MAX</sub> (pu on machine MVA rating)
J+7			P <sub>MIN</sub> (pu on machine MVA rating)
J+8			T <sub>4</sub> (sec)
J+9			K <sub>1</sub>
J+10			K <sub>2</sub>
J+11			T <sub>5</sub> (sec)
J+12			K <sub>3</sub>
J+13			K <sub>4</sub>
J+14			T <sub>8</sub> (sec)
J+15			K <sub>5</sub>
J+16			K <sub>6</sub>
J+17			T <sub>7</sub> (sec)
J+18			K <sub>7</sub>
J+19			K <sub>8</sub>

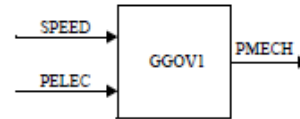
Figure 5-8 : IEEEG1 parameter sheet.



## 7.8 GGOV1

### GE General Governor/Turbine Model

This model is located at system bus #\_\_\_\_ IBUS,  
 Machine identifier #\_\_\_\_ ID,  
 This model uses CONs starting with #\_\_\_\_ J,  
 and STATES starting with #\_\_\_\_ K,  
 and VARs starting with #\_\_\_\_ L,  
 and ICONs starting with #\_\_\_\_ M.



CONs	#	Value	Description
J			R, Permanent droop, pu
J+1			T <sub>pelec</sub> , Electrical power transducer time constant, sec
J+2			maxerr, Maximum value for speed error signal
J+3			minerr, Minimum value for speed error signal
J+4			K <sub>pgov</sub> , Governor proportional gain
J+5			K <sub>igov</sub> , Governor integral gain
J+6			K <sub>dgov</sub> , Governor derivative gain
J+7			T <sub>dgov</sub> , Governor derivative controller time constant, sec
J+8			v <sub>max</sub> , Maximum valve position limit
J+9			v <sub>min</sub> , Minimum valve position limit
J+10			T <sub>act</sub> , Actuator time constant, sec
J+11			K <sub>turb</sub> , Turbine gain
J+12			W <sub>fni</sub> , No load fuel flow, pu
J+13			T <sub>b</sub> , Turbine lag time constant, sec
J+14			T <sub>c</sub> , Turbine lead time constant, sec
J+15			T <sub>eng</sub> , Transport lag time constant for diesel engine, sec
J+16			T <sub>load</sub> , Load Limiter time constant, sec
J+17			K <sub>pload</sub> , Load limiter proportional gain for PI controller
J+18			K <sub>iload</sub> , Load limiter integral gain for PI controller
J+19			L <sub>dref</sub> , Load limiter reference value pu
J+20			D <sub>m</sub> , Mechanical damping coefficient, pu
J+21			R <sub>open</sub> , Maximum valve opening rate, pu/sec
J+22			R <sub>close</sub> , Maximum valve closing rate, pu/sec
J+23			K <sub>imw</sub> , Power controller (reset) gain
J+24			A <sub>set</sub> , Acceleration limiter setpoint, pu/sec
J+25			K <sub>a</sub> , Acceleration limiter gain

CONs	#	Value	Description
J+26			T <sub>a</sub> , Acceleration limiter time constant, sec (> 0)
J+27			T <sub>rate</sub> , Turbine rating (MW) <sup>1</sup>
J+28			db, Speed governor deadband
J+29			T <sub>sa</sub> , Temperature detection lead time constant, sec
J+30			T <sub>sb</sub> , Temperature detection lag time constant, sec
J+31			R <sub>up</sub> , Maximum rate of load limit increase
J+32			R <sub>down</sub> , Maximum rate of load limit decrease

<sup>1</sup> If the turbine rating [CON(J+27)] is greater than zero, the input PELEC is converted in the model to per unit on turbine rating base, else PELEC is converted to per unit on machine base.

Figure 5-9 : GGOV1 parameter sheet.

## 7.6 GAST2A

### Gas Turbine Model

This model is located at system bus #\_\_\_\_ IBUS,  
 Machine identifier #\_\_\_\_ ID,  
 This model uses CONs starting with #\_\_\_\_ J,  
 and STATES starting with #\_\_\_\_ K,  
 and VARs starting with #\_\_\_\_ L.



CONs	#	Value	Description
J			W, governor gain (1/droop) (on turbine rating)
J+1			X (sec) governor lead time constant
J+2			Y (sec) (> 0) governor lag time constant
J+3			Z, governor mode: 1 Droop 0 ISO
J+4			E <sub>TD</sub> (sec)
J+5			T <sub>CD</sub> (sec)
J+6			T <sub>RATE</sub> turbine rating (MW)
J+7			T (sec)
J+8			MAX (pu) limit (on turbine rating)
J+9			MIN (pu) limit (on turbine rating)
J+10			E <sub>CR</sub> (sec)
J+11			K <sub>3</sub>
J+12			a (> 0) valve positioner
J+13			b (sec) (> 0) valve positioner
J+14			c valve positioner
J+15			τ <sub>f</sub> (sec) (> 0)
J+16			K <sub>f</sub>
J+17			K <sub>5</sub>
J+18			K <sub>4</sub>
J+19			T <sub>3</sub> (sec) (> 0)
J+20			T <sub>4</sub> (sec) (> 0)
J+21			τ <sub>t</sub> (> 0)
J+22			T <sub>5</sub> (sec) (> 0)
J+23			a <sub>f1</sub>

CONs	#	Value	Description
J+24			b <sub>f1</sub>
J+25			a <sub>f2</sub>
J+26			b <sub>f2</sub>
J+27			c <sub>f2</sub>
J+28			T <sub>R</sub> (degree), Rated temperature <sup>1</sup>
J+29			K <sub>8</sub> (pu), Minimum fuel flow
J+30			T <sub>C</sub> (degree), Temperature control <sup>1</sup>

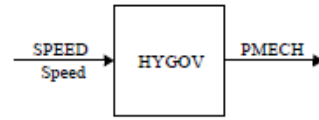
<sup>1</sup> Units can be °F or °C depending on constants a<sub>f1</sub> and b<sub>f1</sub>.

Figure 5-10 : GAST2a parameter sheet.

## 7.9 HYG0V

### Hydro Turbine-Governor

This model is located at system bus #\_\_\_\_\_ IBUS,  
 Machine identifier #\_\_\_\_\_ ID,  
 This model uses CONs starting with #\_\_\_\_\_ J,  
 and STATES starting with #\_\_\_\_\_ K,  
 and VARs starting with #\_\_\_\_\_ L.



CONs	#	Value	Description
J			R, permanent droop
J+1			r, temporary droop
J+2			$T_r$ (>0) governor time constant
J+3			$T_f$ (>0) filter time constant
J+4			$T_g$ (>0) servo time constant
J+5			$\pm$ VELM, gate velocity limit
J+6			$G_{MAX}$ , maximum gate limit
J+7			$G_{MIN}$ , minimum gate limit
J+8			$T_w$ (>0) water time constant
J+9			$A_t$ , turbine gain
J+10			$D_{turb}$ , turbine damping
J+11			$q_{NL}$ , no power flow

Figure 5-11 : HYG0V1 parameter sheet.