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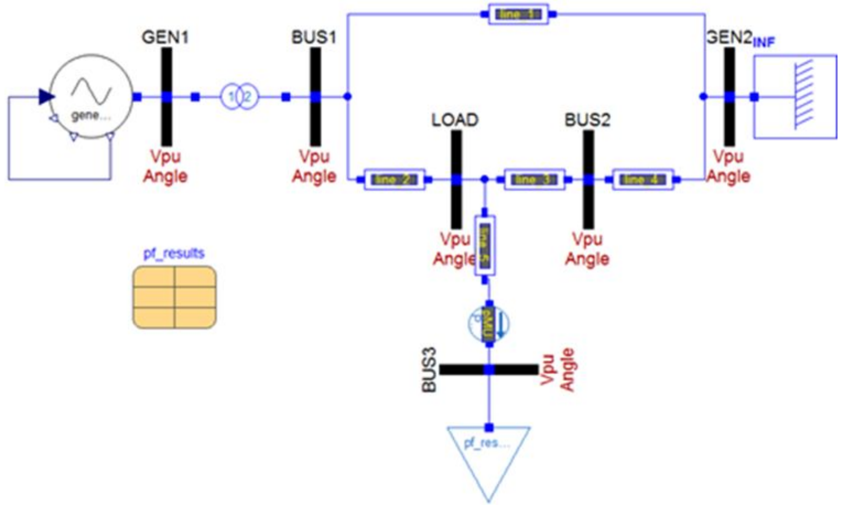

Coalesced *Gas Turbine and Power System* Modelling and Simulation using Modelica

Miguel Aguilera, Luigi Vanfretti, Tetiana Bogodorova & Francisco Gómez | 09/10/18

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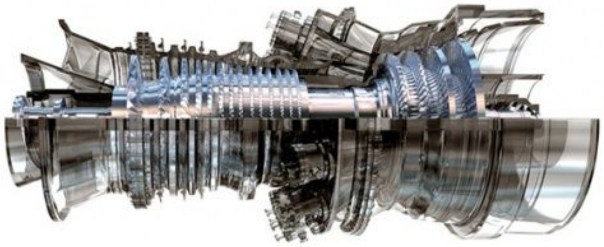
Overview

- Motivation:
  - OpenCPS project - Use Case 2: Multi-Domain Modeling
  - Need for more accurate power system models
  - Gas Turbines and their role in operational flexibility

- Multi-Domain Modeling
  - Thermo-Dynamic Modeling Principles
    - Thermo-Dynamic Component Diagrams
    - The Brayton Cycle
    - Component operation characteristics
  - Power System Modeling Principles and Models
    - Power System Domain-Specific Gas Turbine & Governor Models

- Multi-Domain Modeling using Modelica
  - OpenIPSL: Power System Domain Library
  - ThermoPower: Thermo-Dynamic Gas Turbine Domain Library
  - Coalesced Modelica Package



- Study Models & Results

- Conclusions

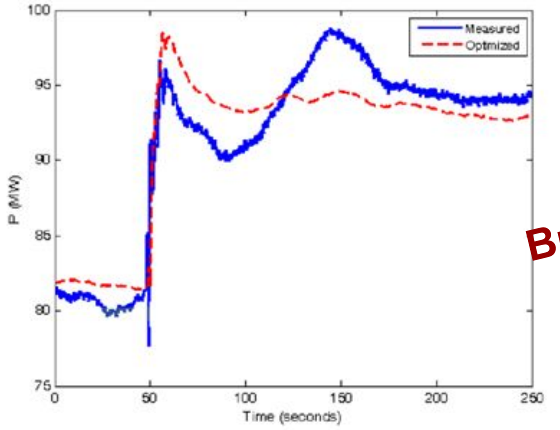
Motivation: Context within OpenCPS Project

- *"To develop **benchmark network models** that will be used to test the functionalities of the OpenCPS toolchains for:*
- ***Multi-domain** simulations of improved gas turbines and the power grid to meet European standardization requirements for grid connection that requires design space exploration and trade-off analysis and, information exchange requirements through the **IEC-CIM UML**-based Common Grid Modeling Exchange Standard (**CGMES**)"*

Use Case 2: Provide customers with advanced turbine models for grid analysis complying with EU standards (CGMES).

- Need of more detailed models for some power system stability studies.
  - **2001**: The widely used **GAST** model was replaced with **GGOV1**.
  - **Malaysia black out**: Example of abnormal frequency event, power imbalance after the formation of electrical power islands.

- **Frequency dependent models**: Power system & governor behaviour, equipment specific studies wt large frequency excursions.
- **Physical models**: The most complex and the most accurate ones. Obviously, suitable for dynamic behaviour analysis of gas turbines → **Manufacturers**



*** Yee, S. K., Milanovic, J. V., & Hughes, F. M. (2008)*

But also: Discrepancy with measurements

Motivation: Why Gas Turbines?

- Some targets to be reached in the road towards the Smart Grids

CO_2, SO_2, NOX emission reduction → **CO_2, SO_2, NOX emission reduction** → **CO_2, SO_2, NOX emission reduction**

Facts

- "The increased interdependence and rapid penetration of variable renewable energy sources (varRE) make the gas-electricity nexus a primary concern and opportunity for energy system flexibility".

- Several operational and system planning issues due to prolonged drought in hydro-energy dependent regions like Latin America -> **Need for dispatchable generation**!! There is an investment in liquefied natural gas (LNG) in South America resulting in a gas market growth.

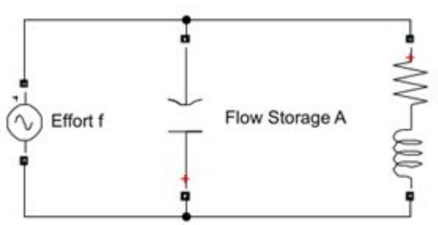
- Gas turbines plants offer **flexible operation** that is being improved with technology development. Gas turbine plants are in general more flexible that other forms of generation.. **They can start quickly and provide significant ramping capability**

Heinen, S., Hewicker, C., Jenkins, N., McCalley, J., O'Malley, M., Pasini, S., & Simoncini, S. (2017). Unleashing the Flexibility of Gas: Innovating Gas Systems to Meet the Electricity System's Flexibility Requirements. IEEE Power and Energy Magazine, 15(1), 16-24.

Domain Independent Physical Systems Modeling

In common

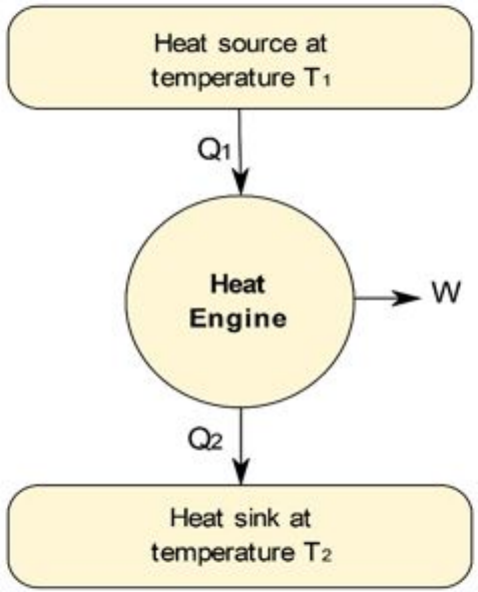
Variable / Characteristic	Electricity	Mechanics Translation	Mechanics Rotation	Hydraulics	Heat System
Effort (e)	**Voltage**	Force	**Torque**	**Pressure**	**Temperature**
Flow (f)	**Current**	Velocity	**Angular Velocity**	**Volume Flow**	**Heat Flow**
Power Flow (P=e·f)	**Power**	Power	**Power**	**Power**	**Power · Temperature**



- Dimensionless Variables (pu in Electric Power domain)
- Multi-Domain "Connectivity" based on Power

$$\dot{W}_C = \dot{m}_a \cdot (h_2 - h_1) = \tau \cdot \omega \cdot \eta_{mech}$$

Heat Engine and Thermo-Dynamic Component Diagrams



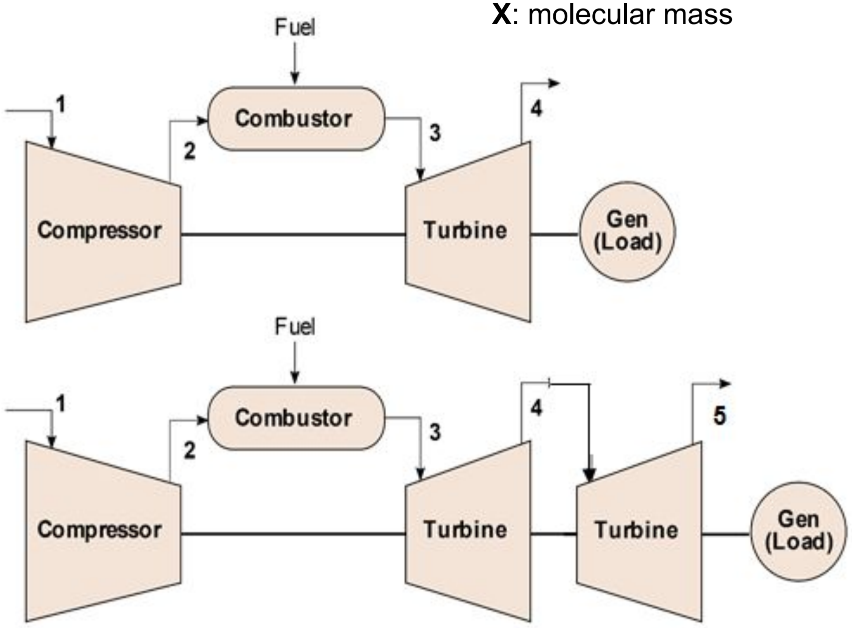
Gas Turbine as a Carnot Heat Engine

1st + 2nd Law of Thermodynamics
Concept of Entropy / Thermal Efficiency

$$W = Q_1 - Q_2$$

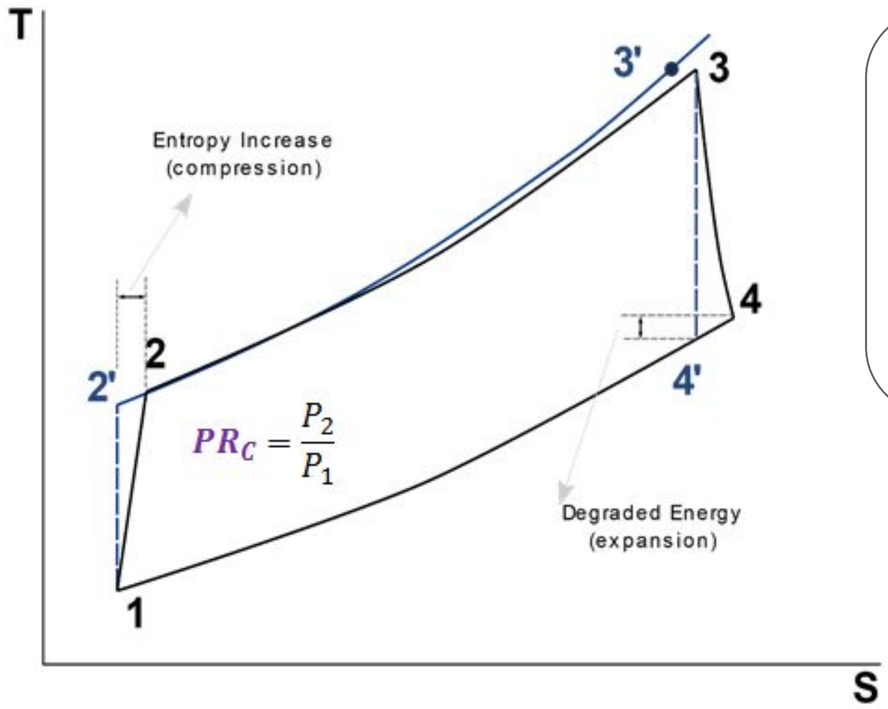
$$\eta = \frac{W}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

Thermodynamic State
P: pressure
T: temperature
X: molecular mass



Simple-Cycle Single-Shaft / Twin-Shaft Gas Turbines
(*plus modifications)

Gas Turbine Theory: The Brayton Cycle



Steady Flow energy equations: (1)

$$W_C = W_{12} = m \cdot c_p \cdot (T_2 - T_1)$$

$$W_T = W_{34} = m \cdot c_p \cdot (T_4 - T_3)$$

$$\dot{W}_C = \dot{m}_a \cdot (h_2 - h_1)$$

$$\dot{W}_T = (\dot{m}_a + \dot{m}_f) \cdot (h_3 - h_4)$$

Specific enthalpies

Thermo – Mechanical conversion: (2)

$$\dot{W}_C = \tau \cdot \omega \cdot \eta_{mech}$$

$$\dot{W}_T = \frac{\tau \cdot \omega}{\eta_{mech}}$$

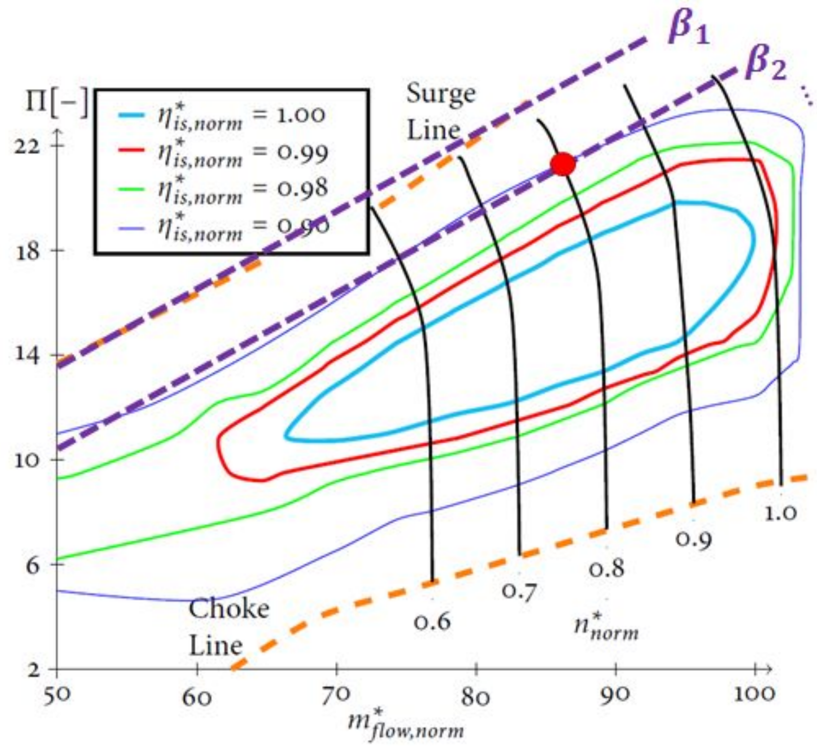
(3)

$$\eta_C = \frac{W_{ideal}}{W_{actual}} = \frac{(h_2' - h_1)}{h_2 - h_1} \qquad \eta_C = \frac{(T_2' - T_1)}{T_2 - T_1}$$

$$\eta_T = \frac{W_{actual}}{W_{ideal}} = \frac{(h_3 - h_4)}{h_3 - h_4'} \qquad \eta_T = \frac{(T_3 - T_4)}{T_3 - T_4'}$$

$$W_{tot} = W_T - W_C$$

$$\eta_{th} = \frac{W_{tot}}{Q_{23}}$$



E. Larsson, "Diagnosis and Supervision of Industrial Gas Turbines," Linköping University Electronic Press, 2012.

Design Point Performance (rated values)

↓

Off-Design Performance

$$PR_C, \eta_C = f\left(\frac{\dot{m}\sqrt{\theta}}{\delta}, \frac{N}{\sqrt{\theta}}\right) = f(\dot{m}_c, N_c)$$

$$\theta = T_a / T_{a0} \qquad \delta = P_a / P_{a0}$$

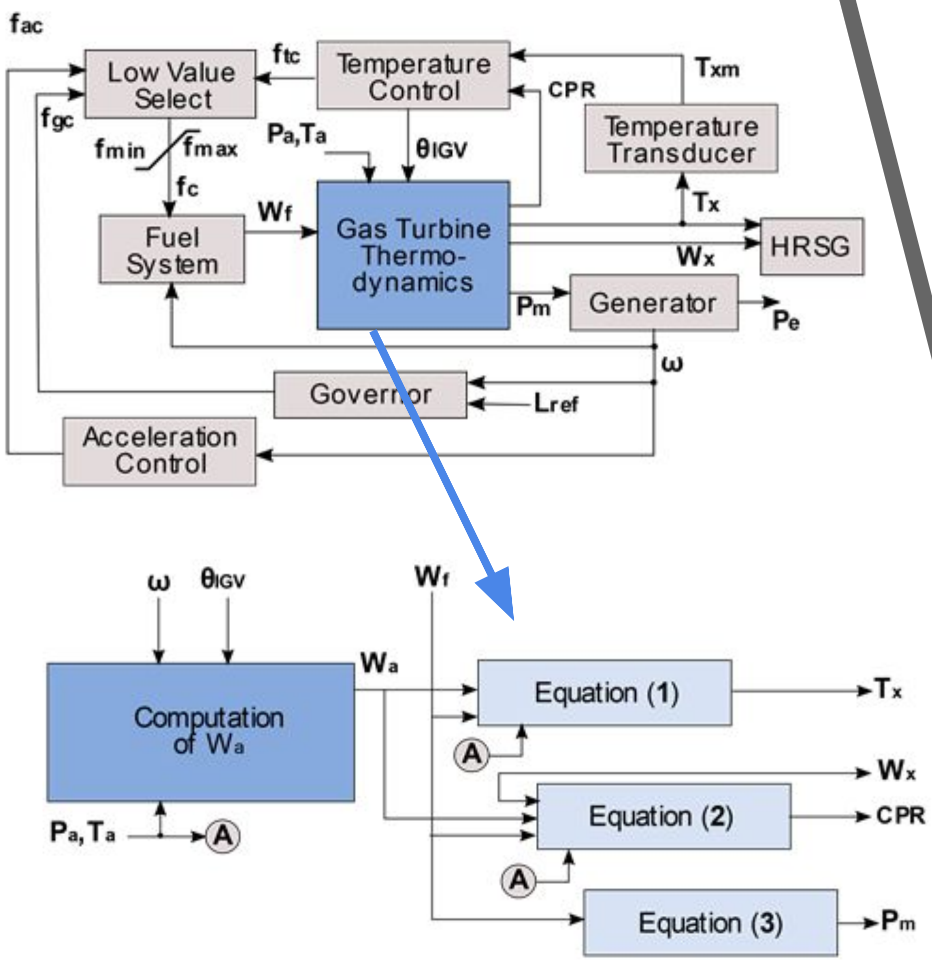
$$PR_C = f\left(\beta, \frac{N}{\sqrt{\theta}}\right)$$

$$\eta_C = f\left(\beta, \frac{N}{\sqrt{\theta}}\right)$$

$$\frac{\dot{m}\sqrt{\theta}}{\delta} = f\left(\beta, \frac{N}{\sqrt{\theta}}\right)$$

Look-up Tables

Gas Turbine Dynamics & Control



$$T_X = \frac{T_a + A_3\delta + A_4 W_f}{W_a} \qquad (1)$$

$$CPR = \left(A_5 W_a + A_6 W_f\right)\frac{1}{\delta} + A_7 \qquad (2)$$

$$P_m = \frac{1}{1 + T_{trb}s}\left(\frac{W_f - W_{f0}}{1 - W_{f0}}\right) \qquad (3)$$

(*)

$$W_a = q(T_a, P_a)\,u(\Delta\omega_C)\,\frac{\sin(\theta_{IGV} - \theta_0)}{\sin(\theta_{max} - \theta_0)}$$

$$u(\Delta\omega_C) = 1 + A_0\Delta\omega_C + A_1\Delta\omega_C^2 + A_2\Delta\omega_C^3$$

$$q(T_a, P_a) = \frac{P_a}{P_{a0}}\sqrt{\frac{T_{a0}}{T_a}}$$

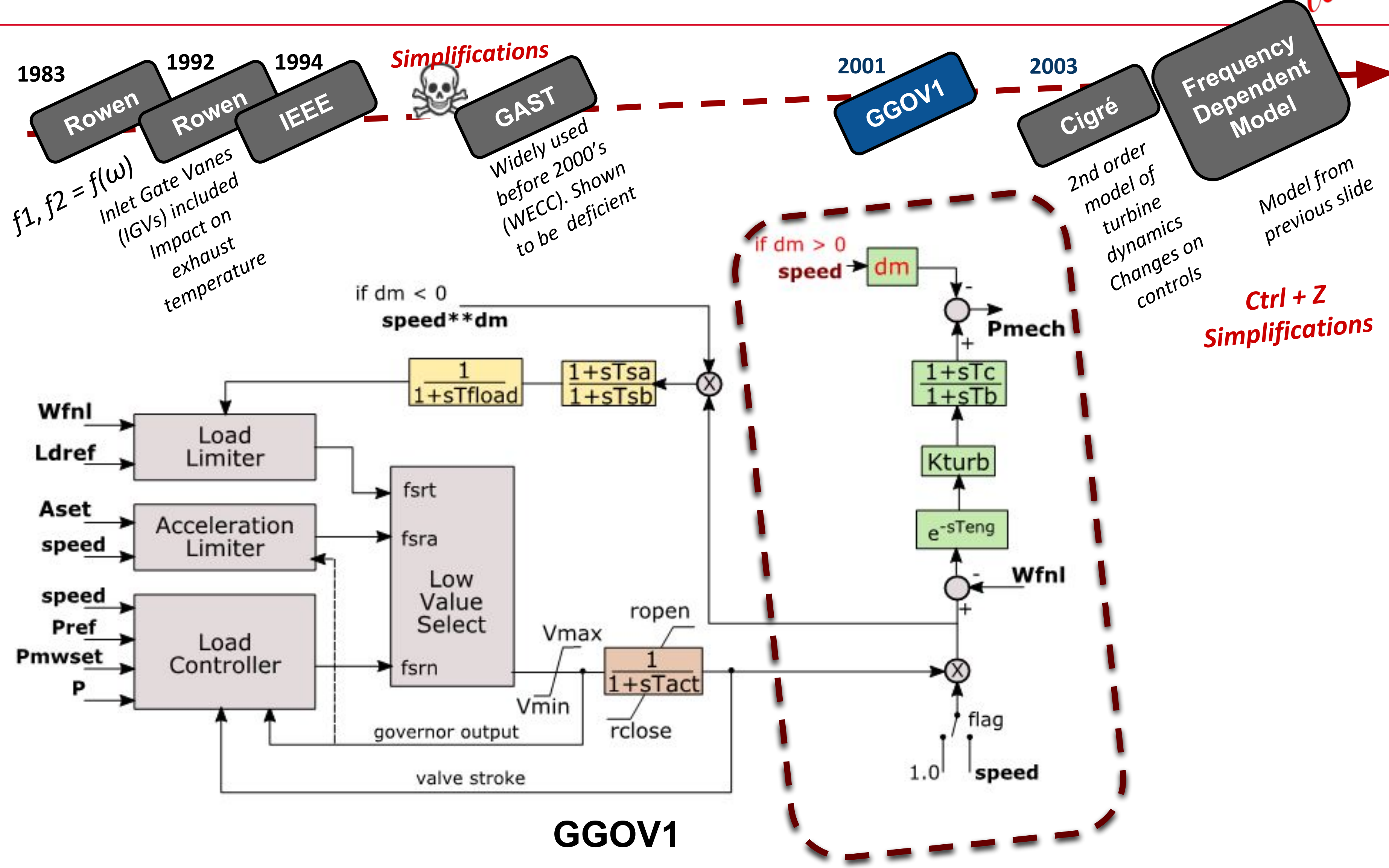
$$\Delta\omega_C = \omega_C - 1$$

$$\omega_C = \omega\sqrt{\frac{T_{a0}}{T_a}}$$

Frequency Dependent Model

"Dynamic models for turbine-governors in power system studies," IEEE Power Energy Soc. Tech. Rep. PES-TR1, 2013

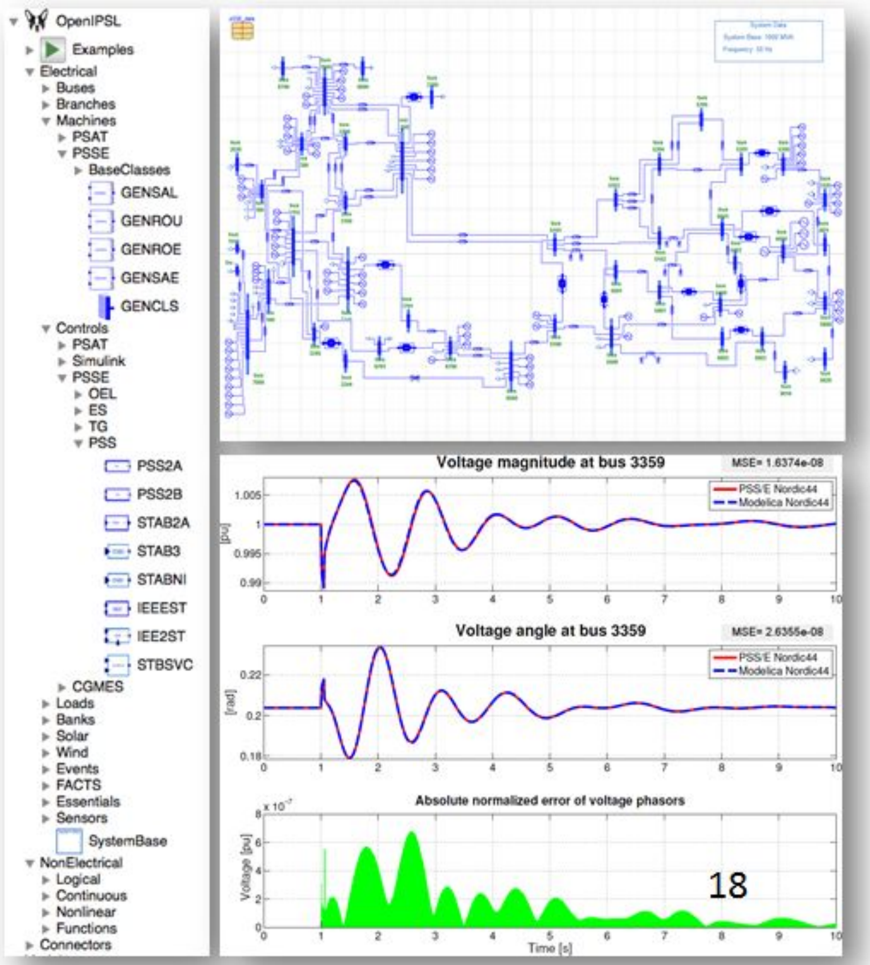
Power System Gas Turbine & Governor Models



The *OpenIPSL* Library

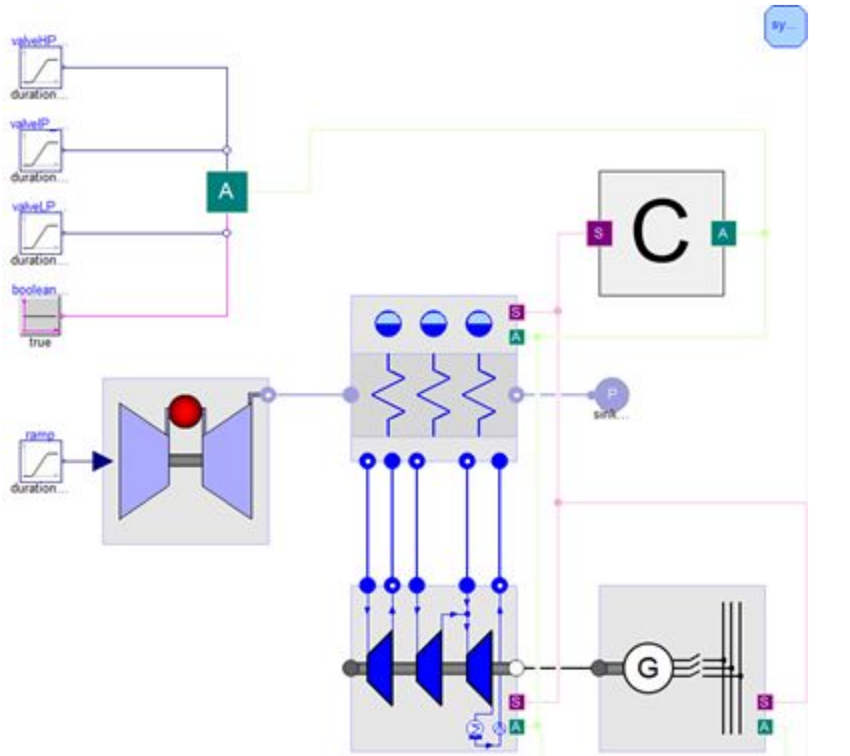
- **OpenIPSL** is an open-source Modelica library for power systems
  - -It contains a set of **power system components** for **phasor time domain** modeling and simulation
  - Models have been **validated** against a number of reference tools

- **OpenIPSL** enables:
  - -**Unambiguous** model exchange
  - -Formal **mathematical description** of models
  - -**Separation** of **models** from IDEs and **solvers**
  - Use of **object-oriented** paradigms



The *ThermoPower* Library

- **ThermoPower** is an open-source Modelica library that provides components that can be used to model thermal power plants.
  - -Some examples of the types of power plants that can be modeled are: fossil-fired Ranking cycle, **gas turbine** and combined cycle.
  - **Water** and **Gas** packages provide models of components where the working fluid is water/steam or gas mixtures, respectively.
  - --Default **models of fluids** can be replaced by those compliant with the Modelica.Media interface.
  - **ThermoPower** was developed by **Francesco Casella**, Alberto Leva and their research group in Politecnico di Milano.

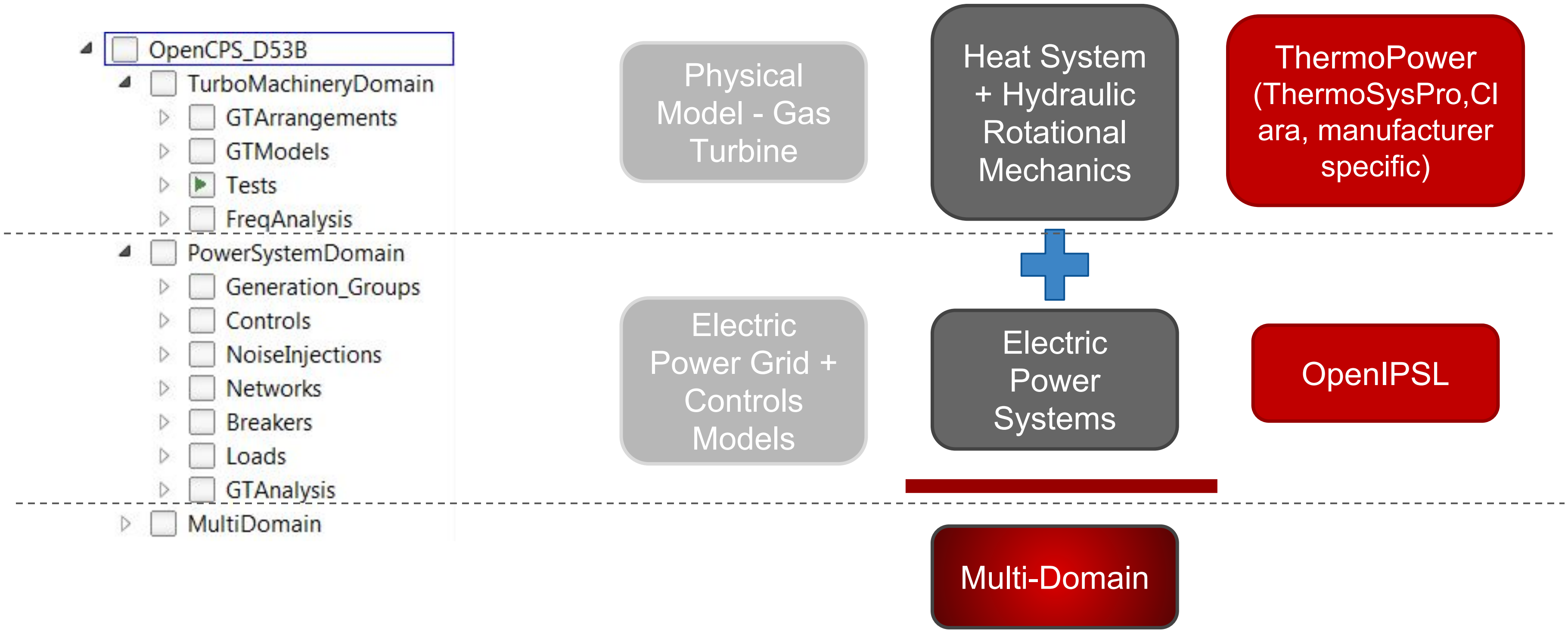


- Casella, F. (2009). Object-oriented modelling of power plants: a structured approach. *IFAC Proceedings Volumes*, *42*(9), 249-254.

More info:

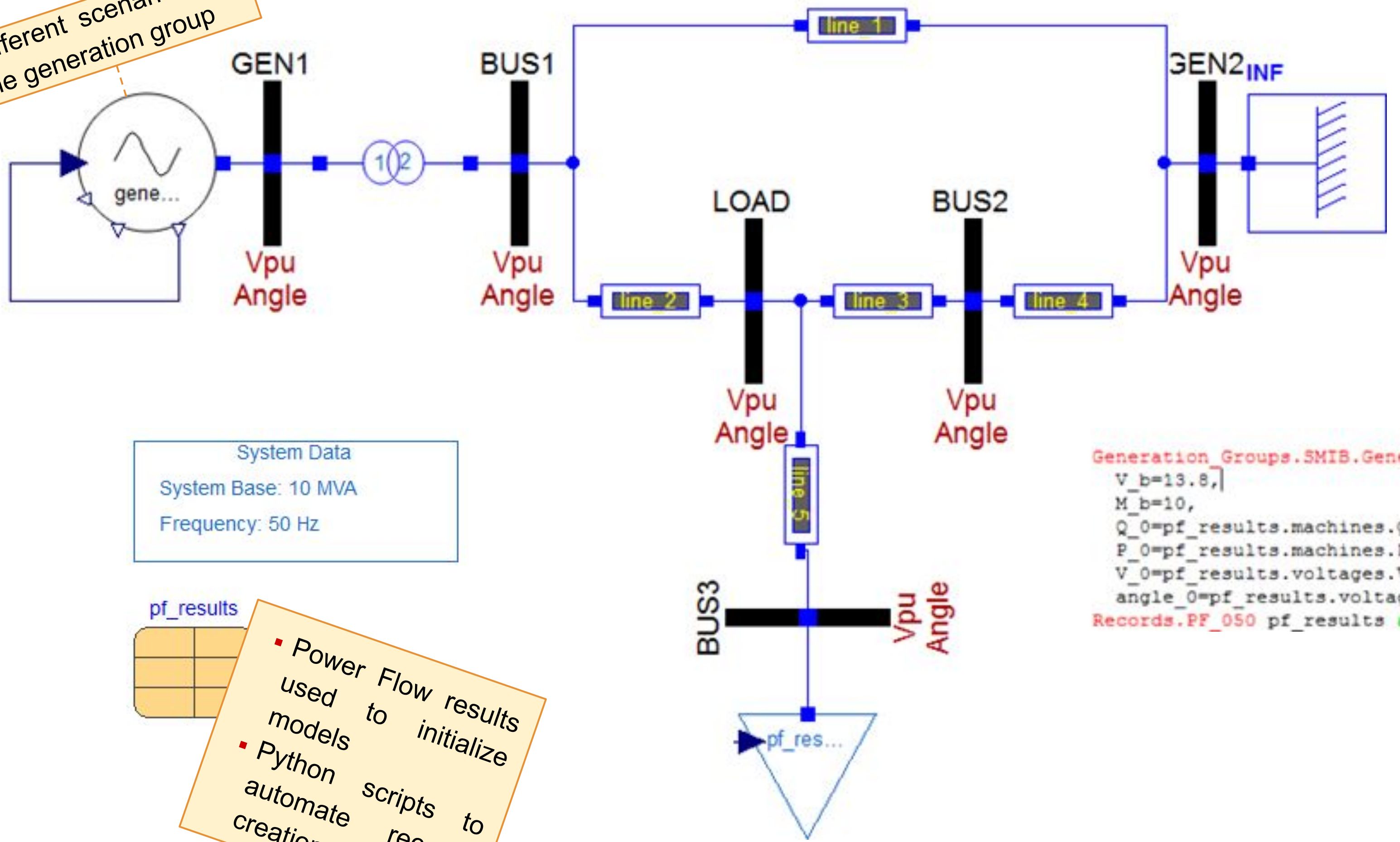
- https://casella.github.io/ThermoPower/
- https://github.com/casella/ThermoPower

Modelica Package Structure



Single Machine Infinite Bus Network Model

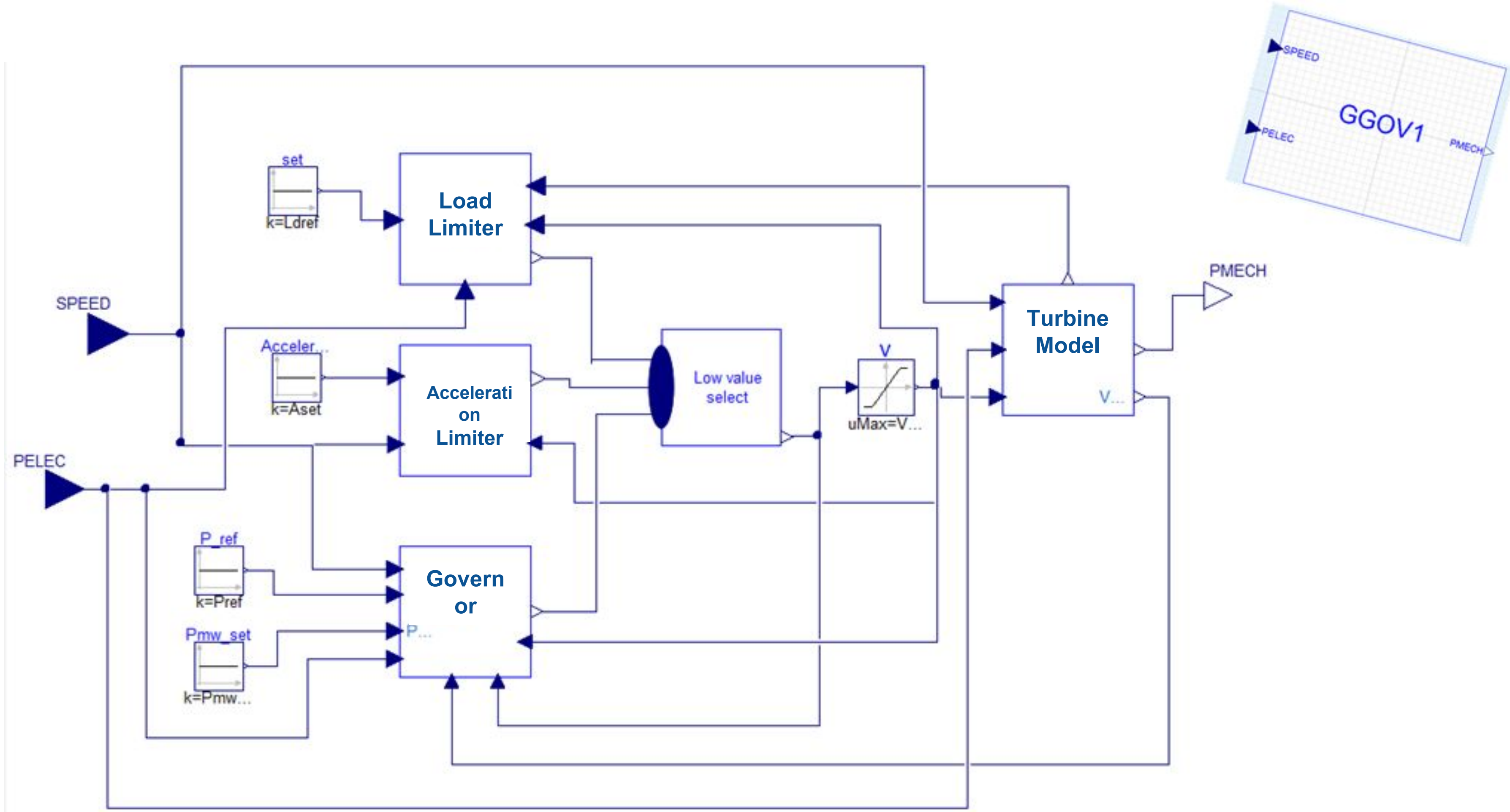
Different scenarios for the generation group



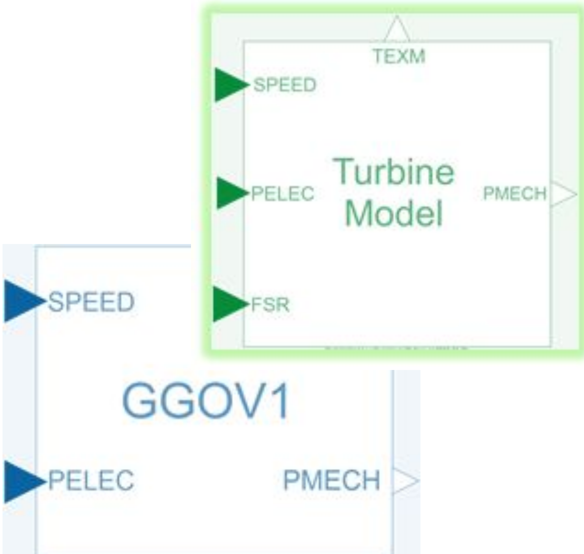

```
Generation_Groups.SMIB.Generator generator(
  V_b=13.8,
  M_b=10,
  Q_0=pf_results.machines.Q1_1,
  P_0=pf_results.machines.P1_1,
  V_0=pf_results.voltages.V1,
  angle_0=pf_results.voltages.A1) a;
Records.PF_050 pf_results a;
```

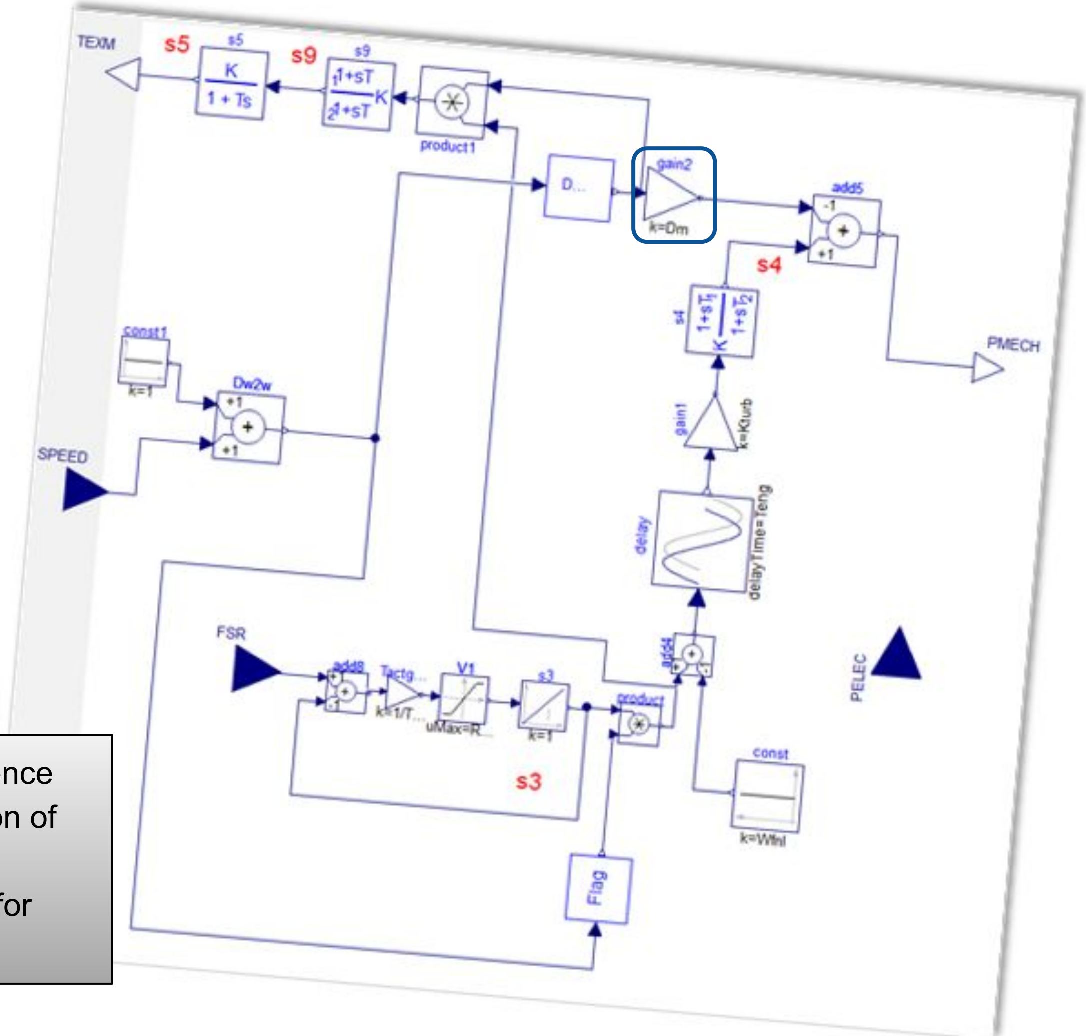
- Power Flow results used to initialize models
- Python scripts to automate records creation

Full GGOV1 Model with OpenIPSL



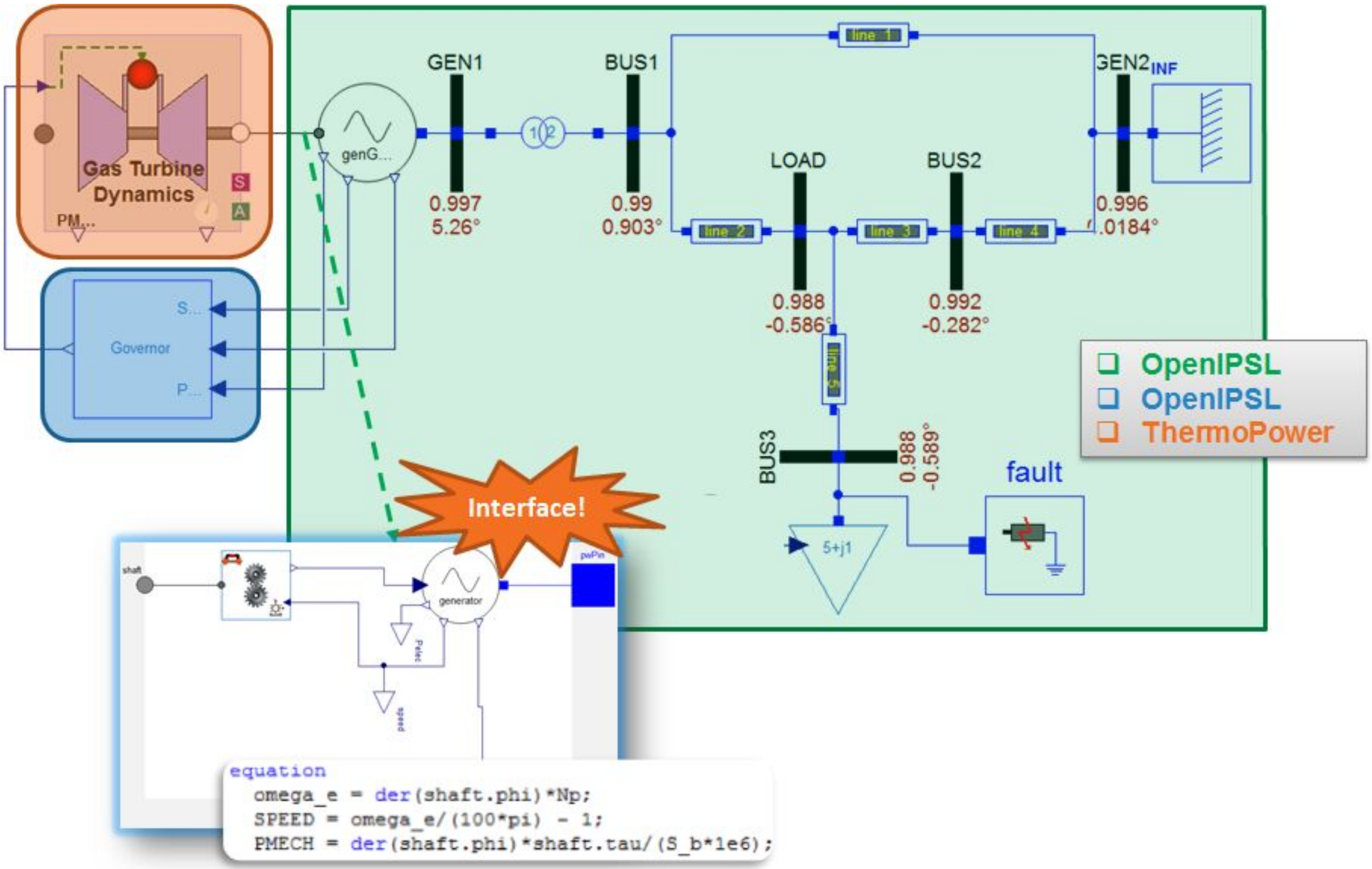
GGOV1 Turbine and Governor Blocks





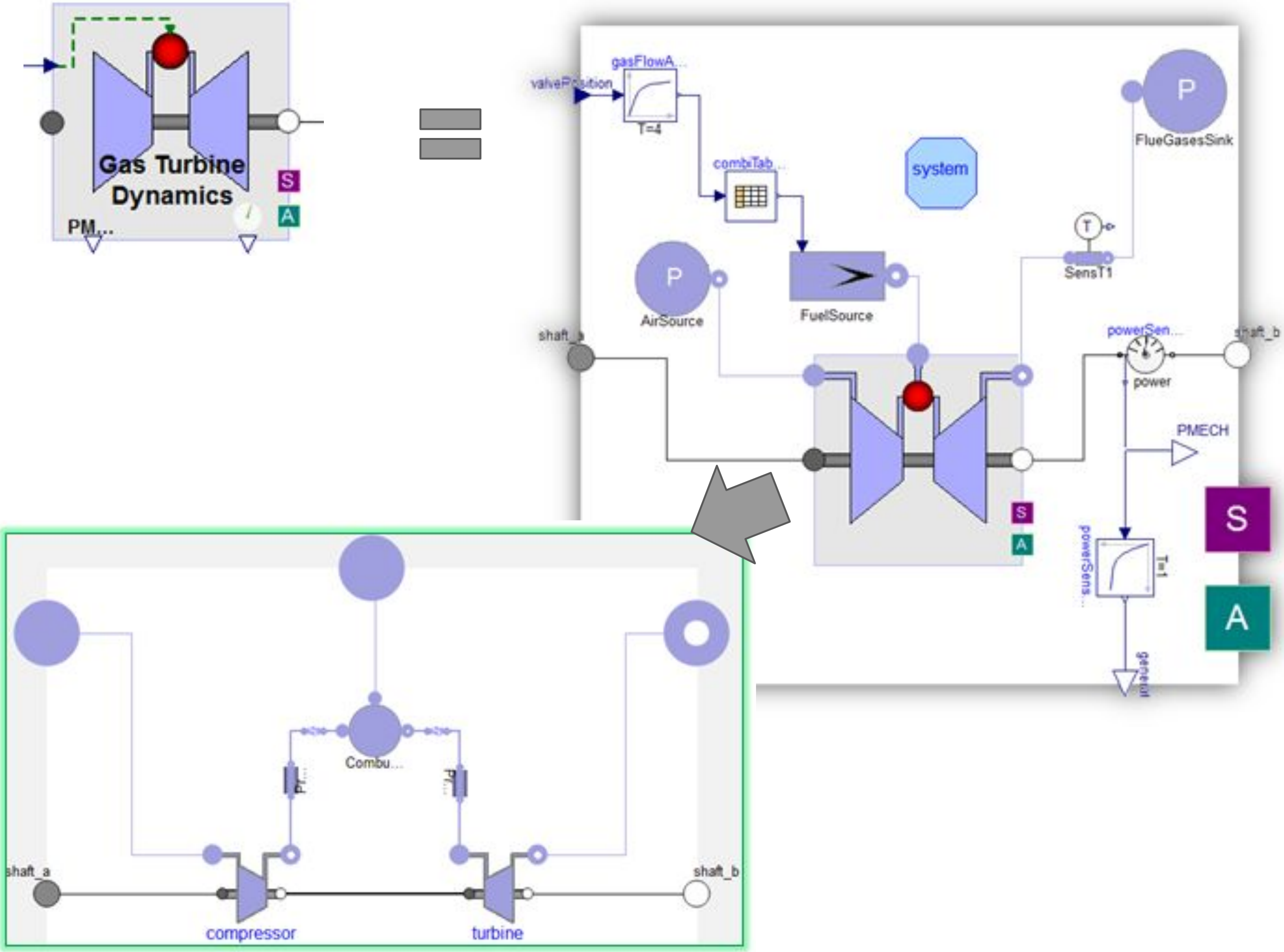
"A ***speed damping factor*** can be modeled to influence the temperature limit as a rather gross approximation of the speed dependence of the turbine rating. This is, however, not very accurate". Recommended value for parameter dm is **zero**.

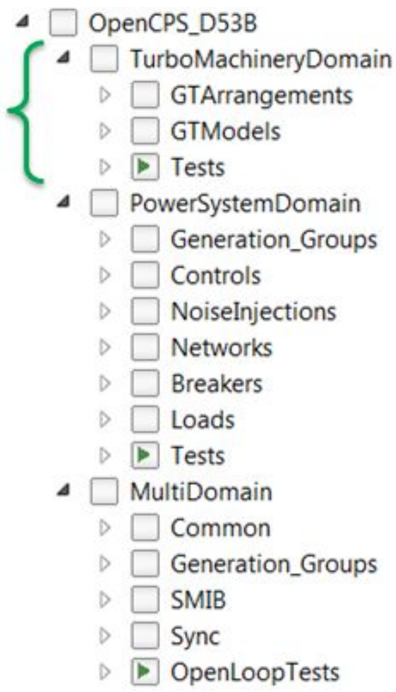
Multi-domain Modelica Model: ThermoPower+OpenIPSL

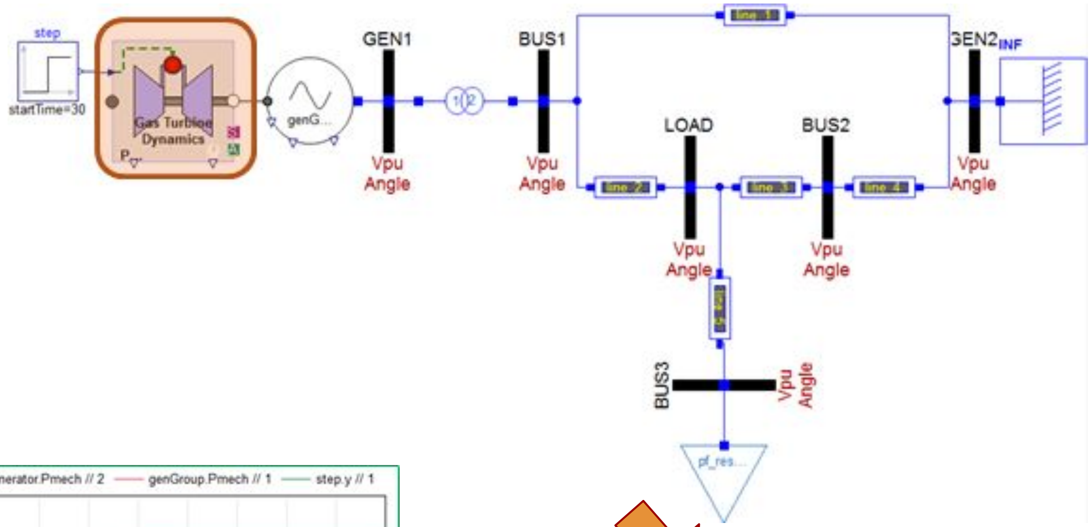


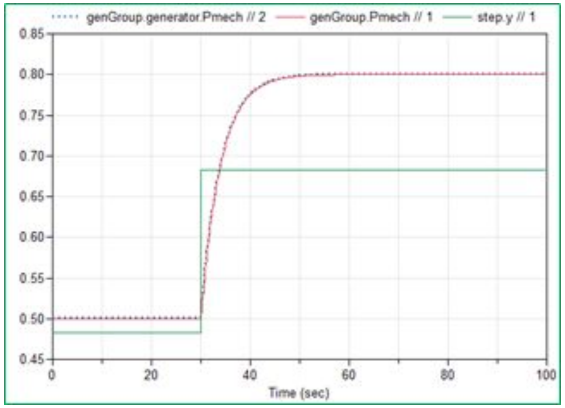

```
equation
  omega_e = der(shaft.phi)*Np;
  SPEED = omega_e/(100*pi) - 1;
  PMECH = der(shaft.phi)*shaft.tau/(S_b*1e6);
```

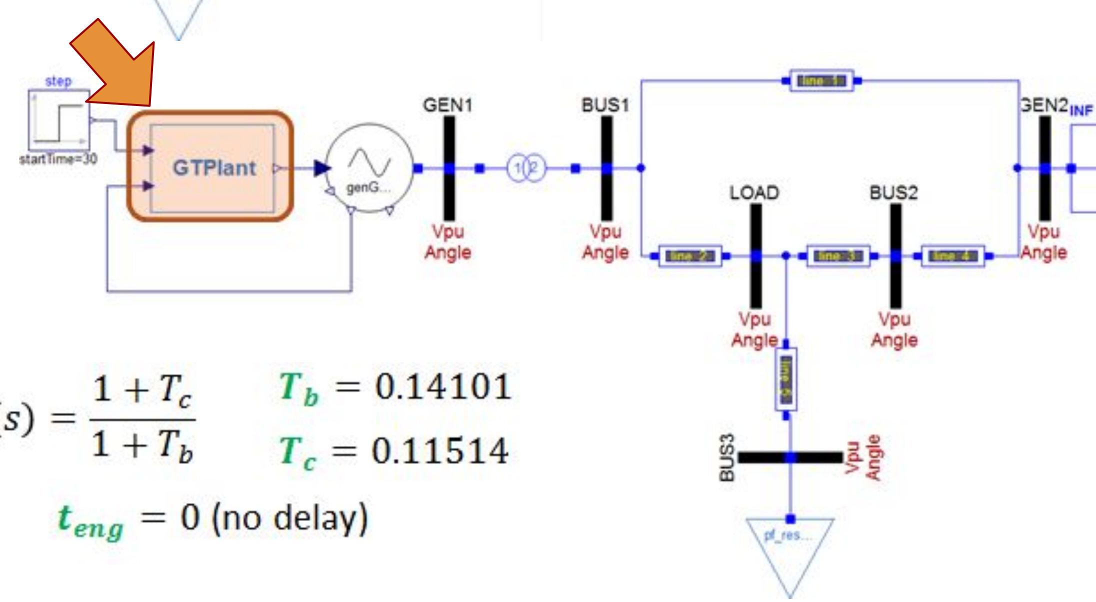
Multi-domain Modelica Model: **ThermoPower**+OpenIPSL











$K_{turb} = 1.5$

$W_{fnl} = 0.15$

$$g_4(s) = \frac{1 + T_c}{1 + T_b}$$

$T_b = 0.14101$

$T_c = 0.11514$

$t_{eng} = 0$ (no delay)

Eigenanalysis

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

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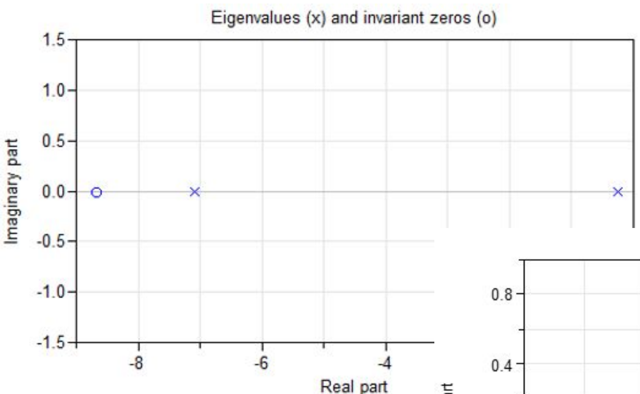
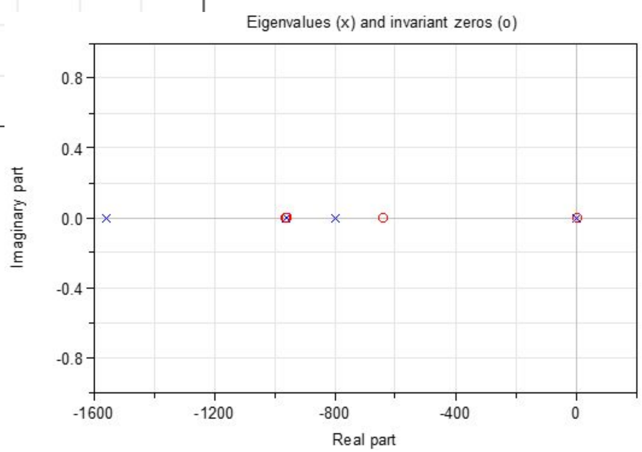
Eigenvalue	T(s)	Contribution to states	
		State	Contribution (%)
$p_1 = -7.092$	0.141	$g_4(s).x$	100
$p_2 = -0.25$	4.0	$g_4(s).x$	61.9
		$gasFlowActuator.y$	38.1

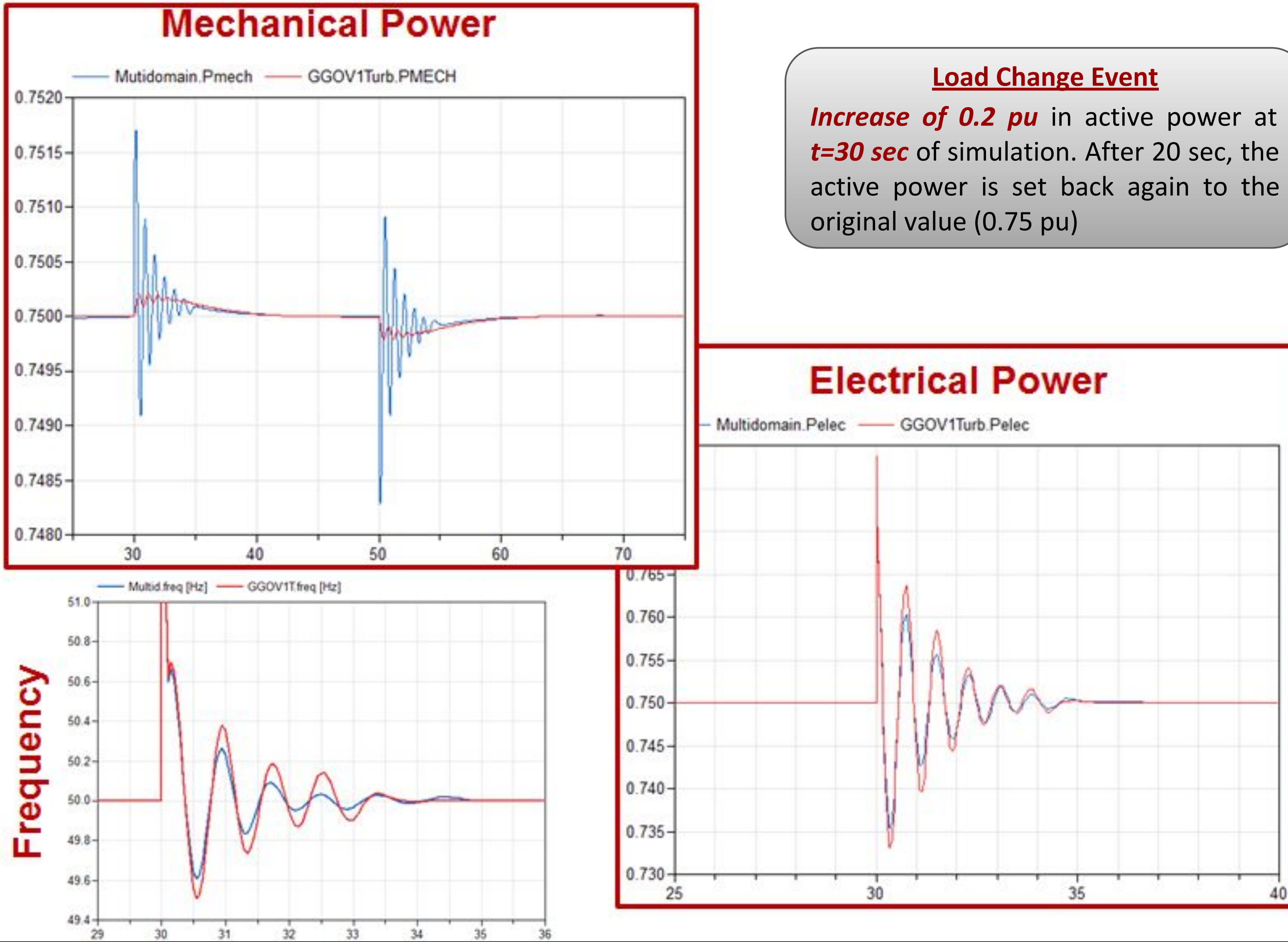
only a zero *z1* = -8.685 with *T*(*s*) = 0.115





Eigenvalue	T(s)	Relevant contribution to states	
		State	Contribution (%)
$p_1 = -1.56 \times 10^3$	6×10^{-4}	$CC.fluegas.p$	99.9
$p_2 = -9.63 \times 10^2$	0.001	$CC.fluegas.T$	97.2
$p_3 = -9.63 \times 10^2$	0.001	$CC.fluegas.T$	75
		$CC.fluegas.X_i$	12.2
$p_4 = -9.63 \times 10^2$	0.001	$CC.fluegas.T$	94.8
$p_5 = -9.63 \times 10^2$	0.001	$CC.fluegas.T$	86.4
		$CC.fluegas.X_i$	5.5
$p_6 = -9.63 \times 10^2$	0.001	$CC.fluegas.T$	99.4
$p_7 = -7.98 \times 10^2$	1.3×10^{-3}	$CC.fluegas.p$	99.9
$p_8 = -0.25$	4.000	$CC.fluegas.p$	99.6
$p_9 = -0.05$	20.00	$CC.T_m$	100
$p_{10} = 0$	---	$speedSource.q$	100

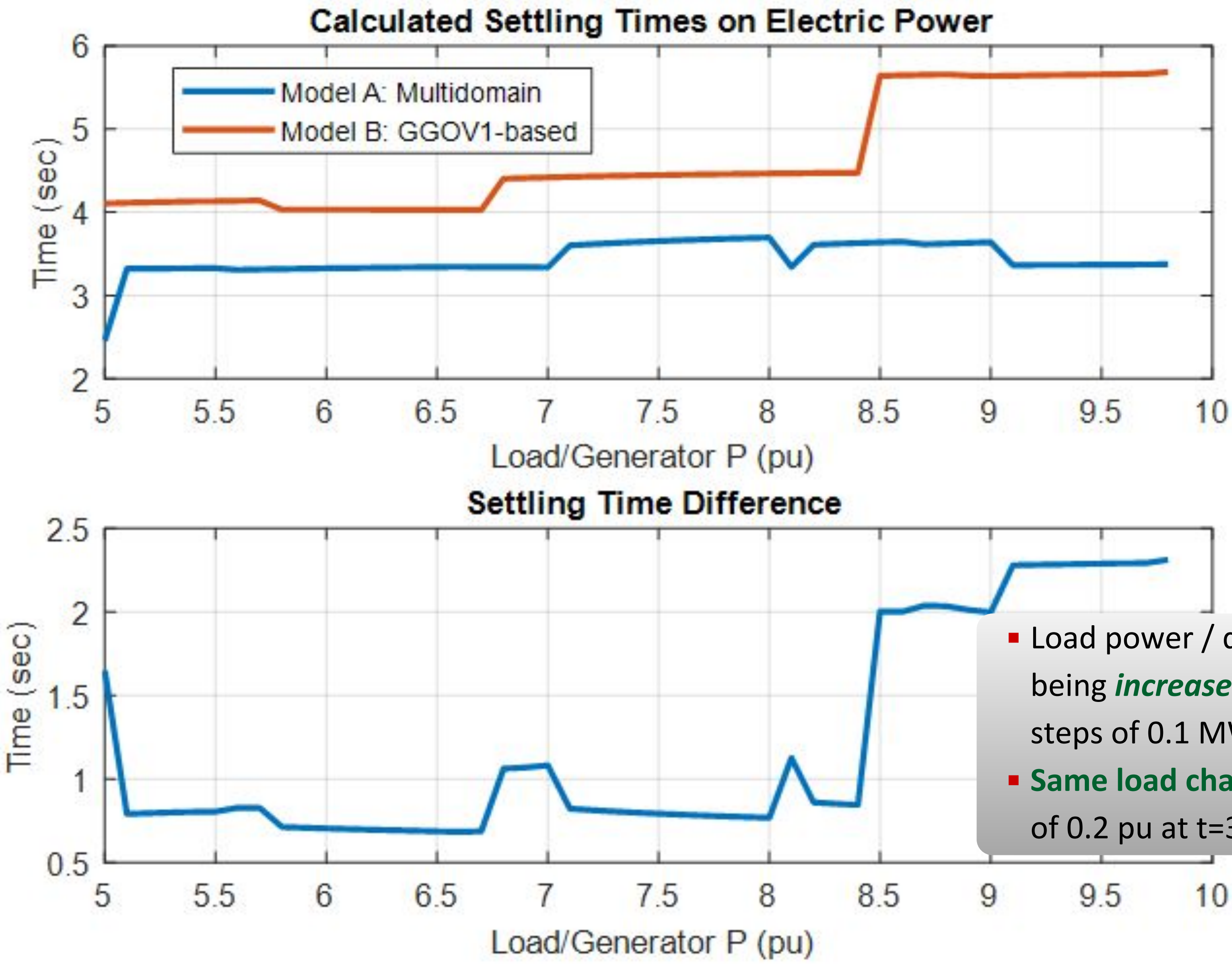
Zero	Amount	T(s)
$z_1 = -9.644 \times 10^2$	1	0.001
$z_i = -9.632 \times 10^2$	4	0.001
$z_6 = -6.441 \times 10^2$	1	1.6×10^{-3}
$z_7 = -0.050$	1	20.000
$z_8 = -6.651 \times 10^{-14}$	1	1.503×10^{13}



Load Change Event

Increase of 0.2 pu in active power at ***t=30 sec*** of simulation. After 20 sec, the active power is set back again to the original value (0.75 pu)

Time Response:
Performance Comparison



- Load power / dispatched generator power are being ***increased from 5 MW to 9.8 MW*** in steps of 0.1 MW.
- **Same load change event** is applied (increase of 0.2 pu at t=30 sec)

Conclusions

- A **multi-domain model** has been derived to allow simulations of *detailed representations of gas turbines and the electric power grid*.
  - Models are simple (due to the lack of available modeling information) **(-)**
  - Methodology provides a ***framework for future studies with multi-domain models in power systems*** **(+)**
- A relevant source of differences between the simple turbine model (GGOV1) and the multi-domain explicit turbine is the *representation of the speed influence* on the *gas turbine dynamics*.
  - Study was limited by the ***lack of measurements*** that could have served as a reference for the model's tuning and validation
  - It would be of value to analyze the differences between the models in *other power network variables* (not only in the generator response).
- Work gives a **proof-of-concept** on the use of Modelica for joint modeling of complex energy sources ***without the loss of information*** that traditional power system approaches incur in.
  - Multi-domain approach is thus valuable for power system analysts (e.g. controller designers, dynamic performance analysts).
- Reproducibility of Research:
  - Models and results from this paper are available on Github on: https://github.com/ALSETLab/2018_AmericanModelicaConf_PowerGrid_plus_PowerSystems

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