openCPS

Semantic and Physical Modeling and Simulation of Multi-Domain Energy Systems

Gas Turbines and Electrical Power Networks

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ice

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ITEA3

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Outline

- **Background**
  - Context, Motivation and Goals
  - Multi-Domain Dynamic System Modeling
  - The Gas Turbine in Power Systems
- **Equation Based Models**
  - OpenIPSL and ThermoPower
  - Modelica Models for Multi-Domain
  - Multi-Domain network models
- **Semantic Models**
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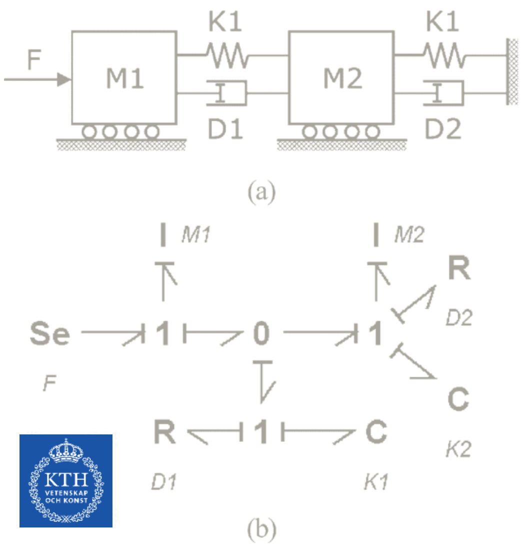
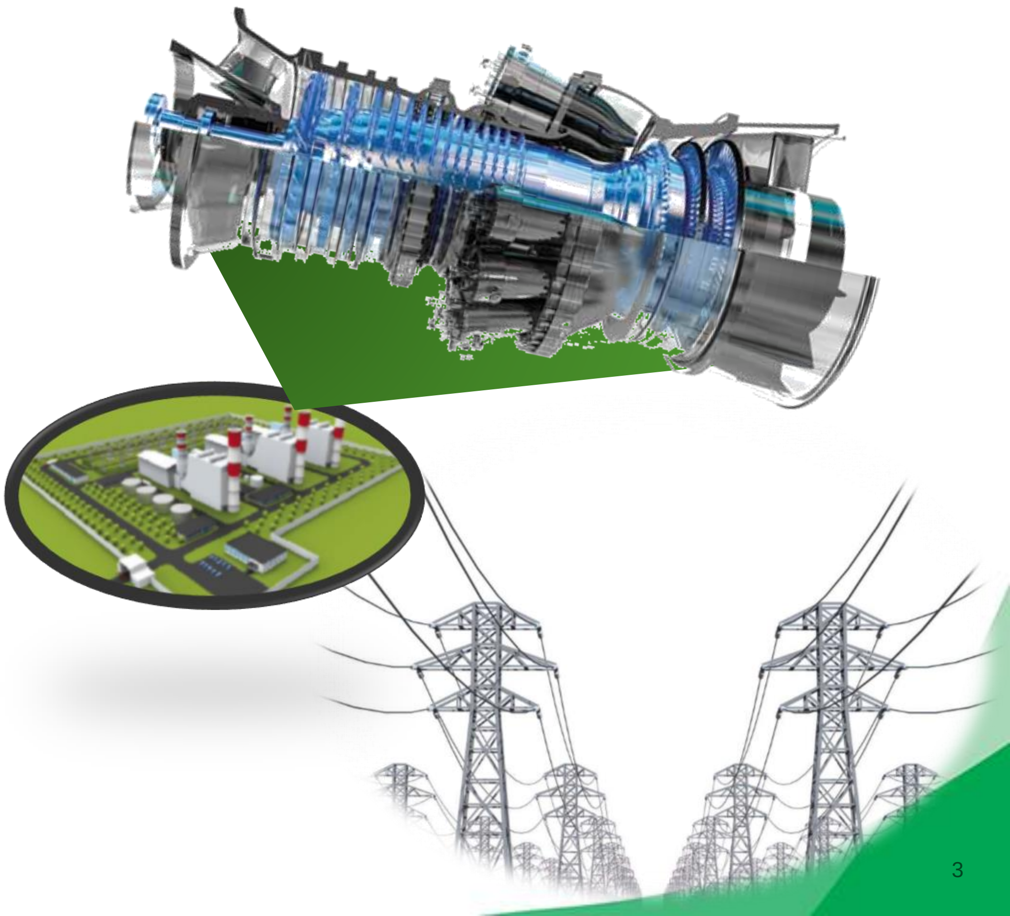
  - Modeling Methodology and Proposed Models
- **Simulation and Results**
  - Multi-domain model simulation
  - FMU generation and simulation in different environments
- **Conclusions and Further Work**

Part I: Background





Context, Motivation and Goals

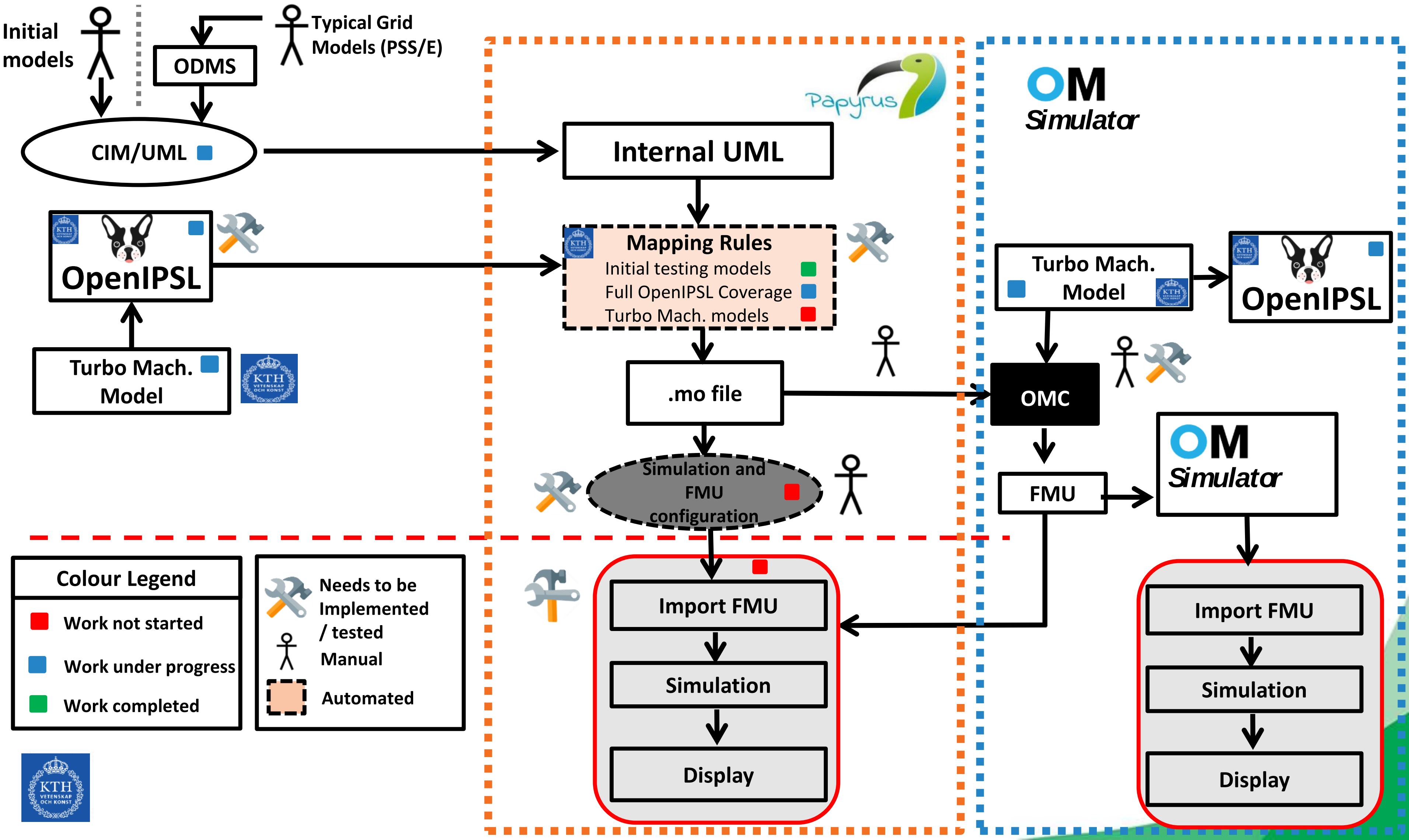
“KTH SmarTS Lab will develop ***benchmark network models*** *that will be used to test the functionalities of the OpenCPS toolchains for:*

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).

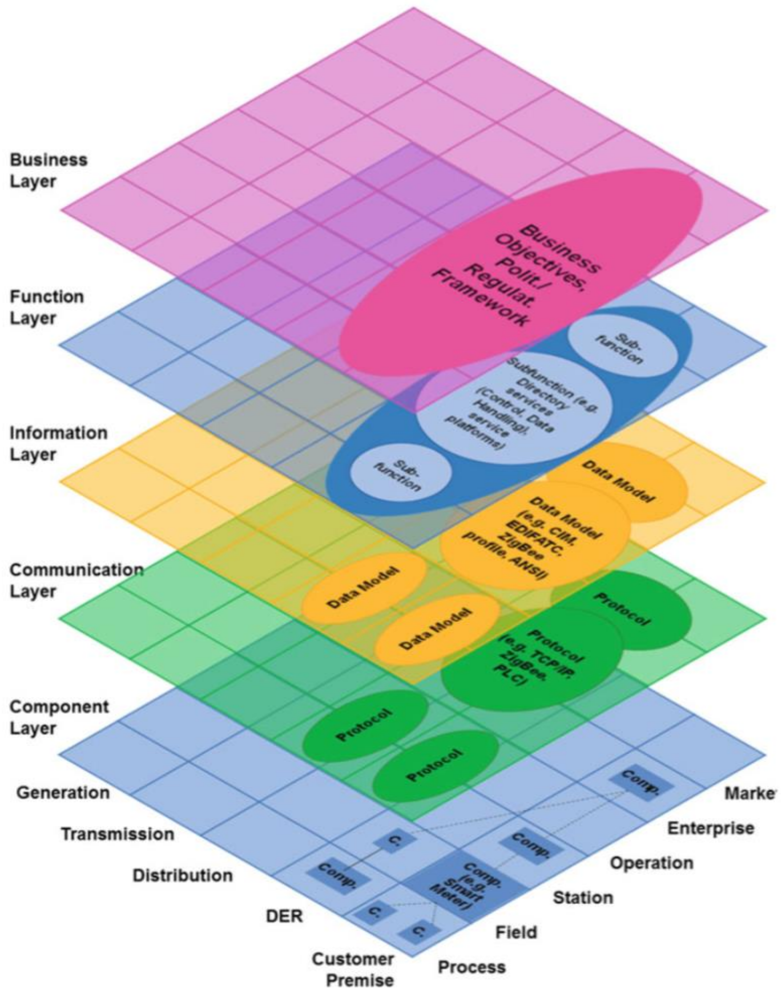
Context, Motivation and Goals

Graphical Description of Thesis Goals



Context, Motivation and Goals

Smart Grids (SGAM) Application Cases: Single Machine Infinite Bus

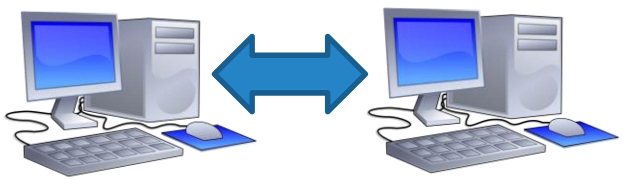


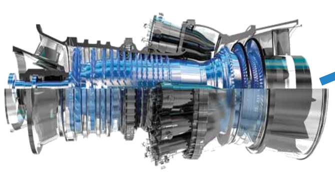
CIM / CGMES with UML / XML

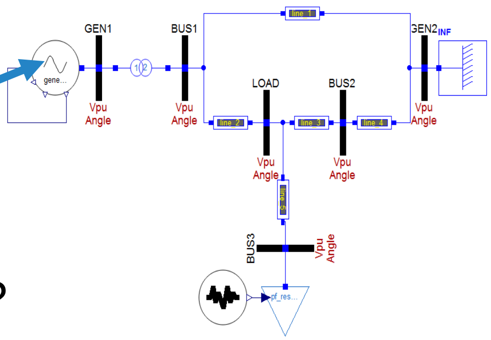
+

Modelica / FMI

TSO 1 **TSO 2**







Another Player !?

Context, Motivation and Goals

Why Gas Turbines?

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

CO2, SO2, NOX emission reduction → **Variable renewable resources** → **Enhanced grid flexibility & robustness**

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**.

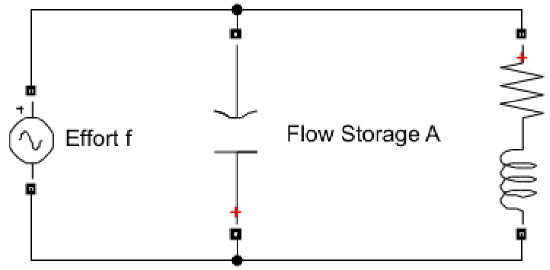
Heinen, S., Hewicker, C., Jenkins, N., McCalley, J., O'Malley, M., Pasini, S., & Simoncini, S. (2017). Unleashing the Flexibility of Gas: Innovating Gas Systems to Meet the Electricity System's Flexibility Requirements. IEEE Power and Energy Magazine, 15(1), 16-24.

Multi-Domain Dynamic System Modelling

Domain Independent Physical Systems Modeling

- Dimensionless Variables (p.u. in Electric Power domain)
- Multi-Domain Connection

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 $(P = e \cdot f)$	Power	Power	Power	Power	Power · Temperature



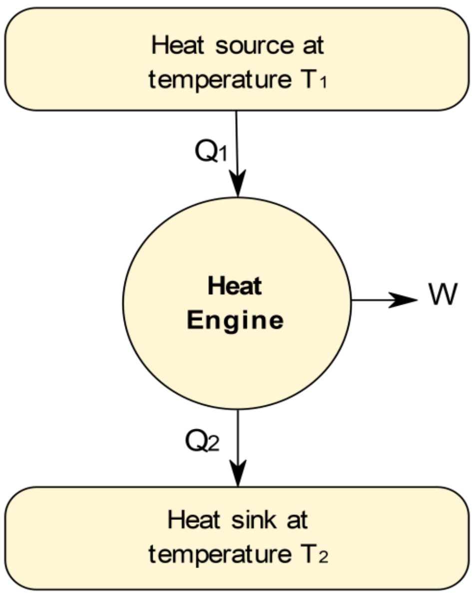
Kirchoff's Law

Mechanics & Thermo-Fluid

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

Multi-Domain Dynamic System Modelling

Heat Engine and Thermo-Dynamic Component Diagrams

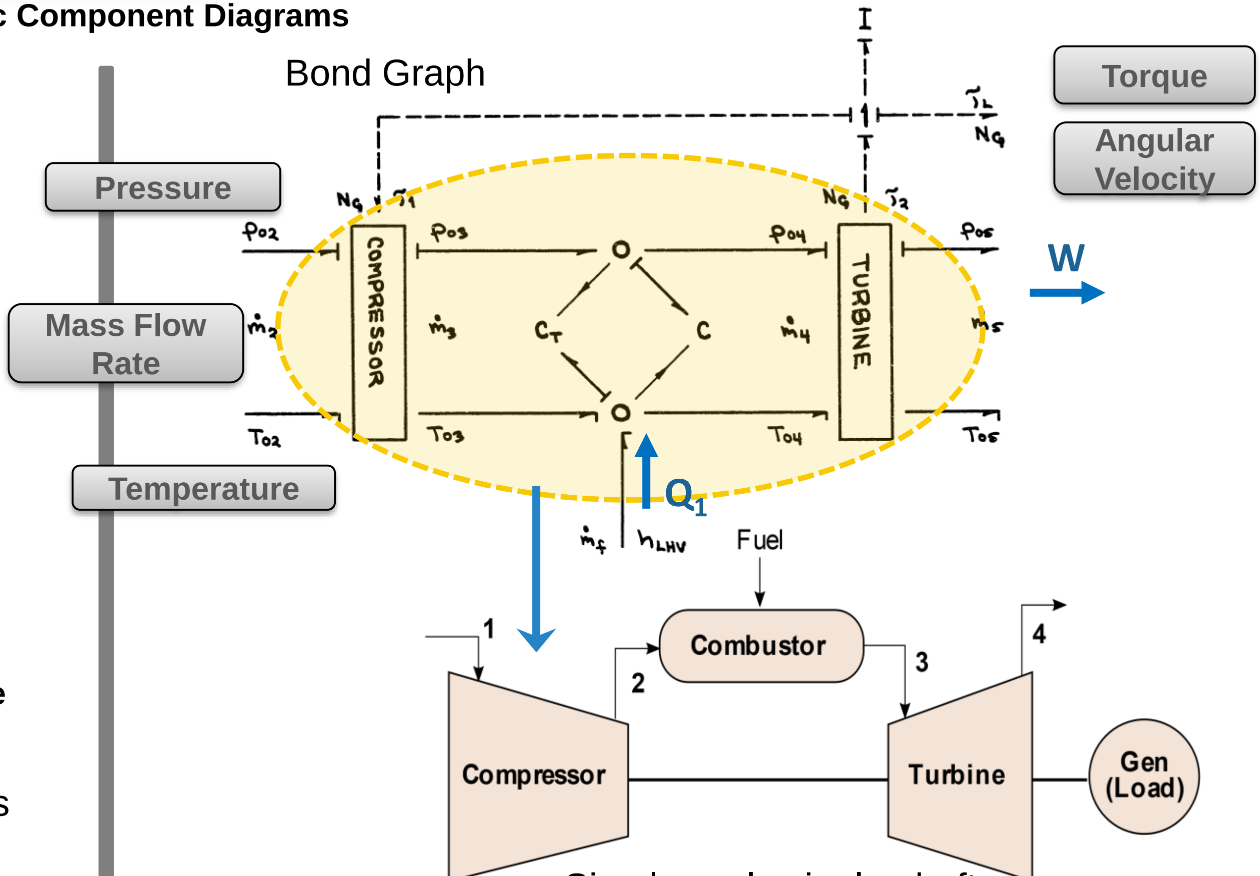


Gas Turbine as a Carnot Heat Engine

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

$$W = Q_1 - Q_2$$

Bond Graph



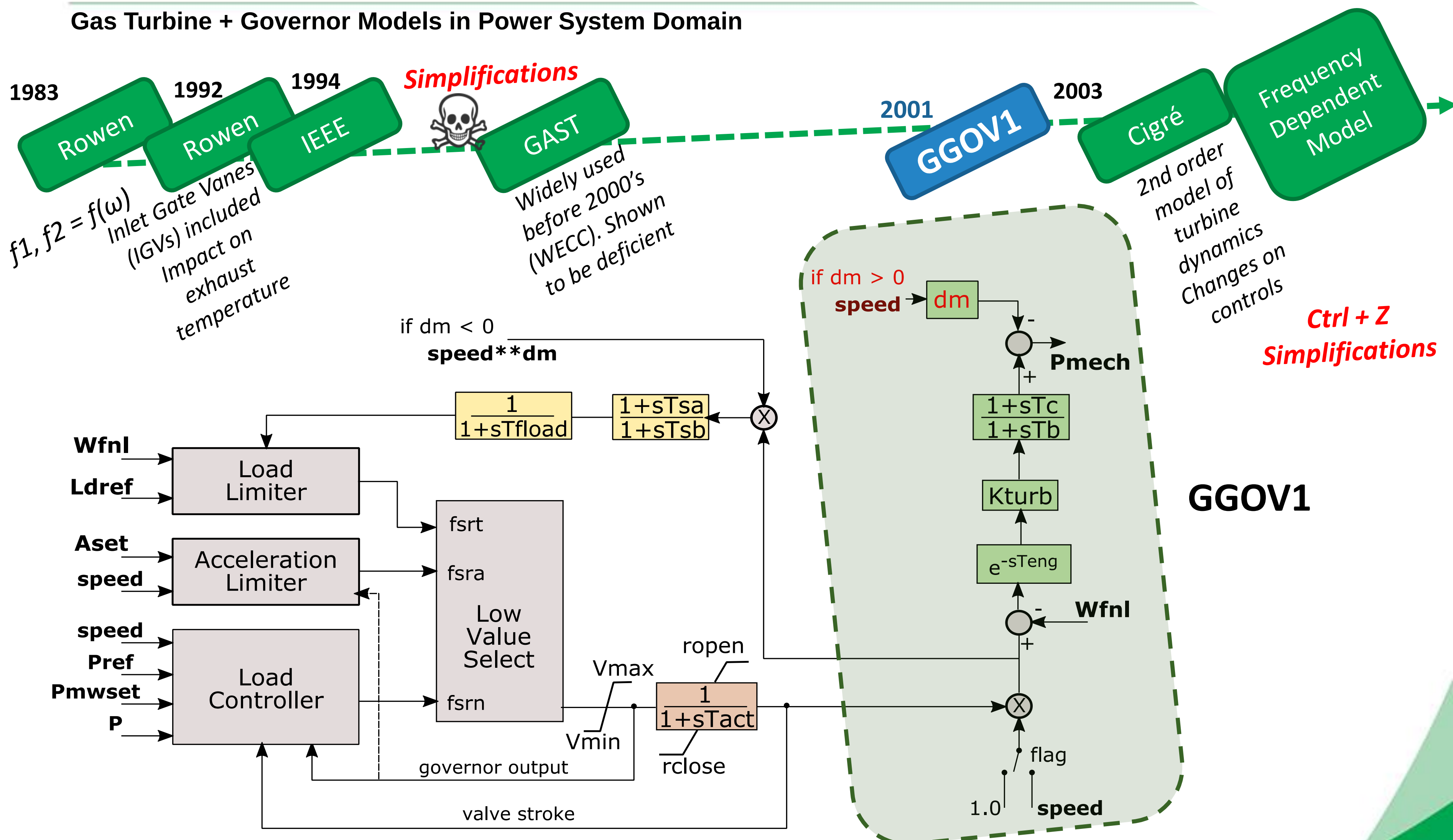
Simple-cycle single-shaft

Markunas, A. L. (1972). Modeling, simulation, and control of gas turbines (Doctoral dissertation, Massachusetts Institute of Technology).

Zimmer, D., & Cellier, F. E. (2006, September). The Modelica multi-bond graph library. In Proceedings of the 5th International Modelica Conference (pp. 559-568).
Broenink, J. F. (1999). Object-oriented modeling with bond graphs and Modelica. SIMULATION SERIES, 31, 163-168.

The Gas Turbine in Power Systems

Gas Turbine + Governor Models in Power System Domain

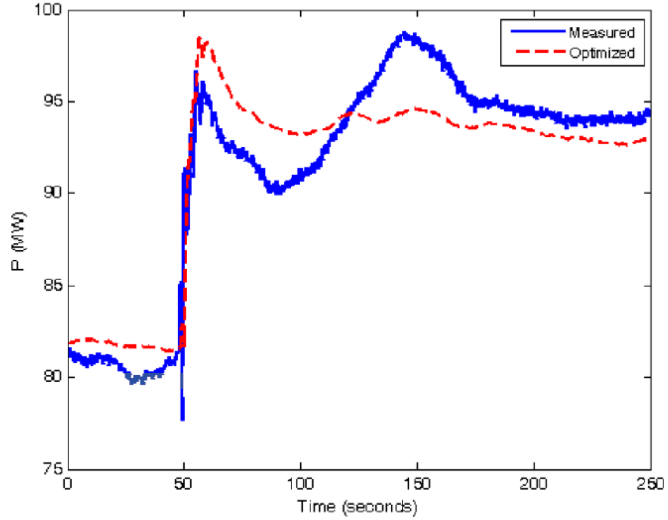


Yee, S. K., Milanovic, J. V., & Hughes, F. M. (2008). Overview and comparative analysis of gas turbine models for system stability studies. IEEE Transactions on power systems, 23(1), 108-118.

The Gas Turbine in Power Systems

Gas Turbine + Governor Model Limitation

- **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.



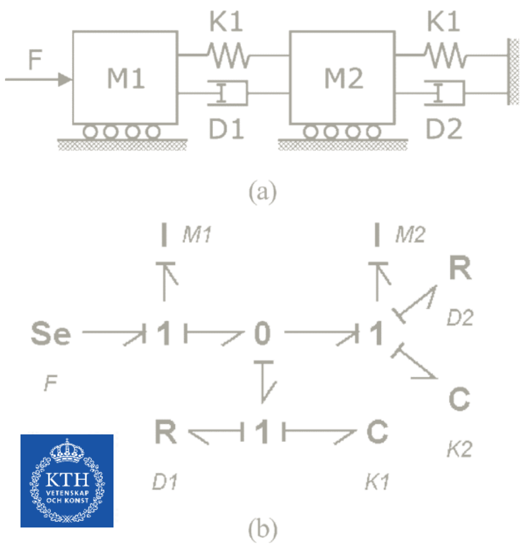
Also: Discrepancy with measurements

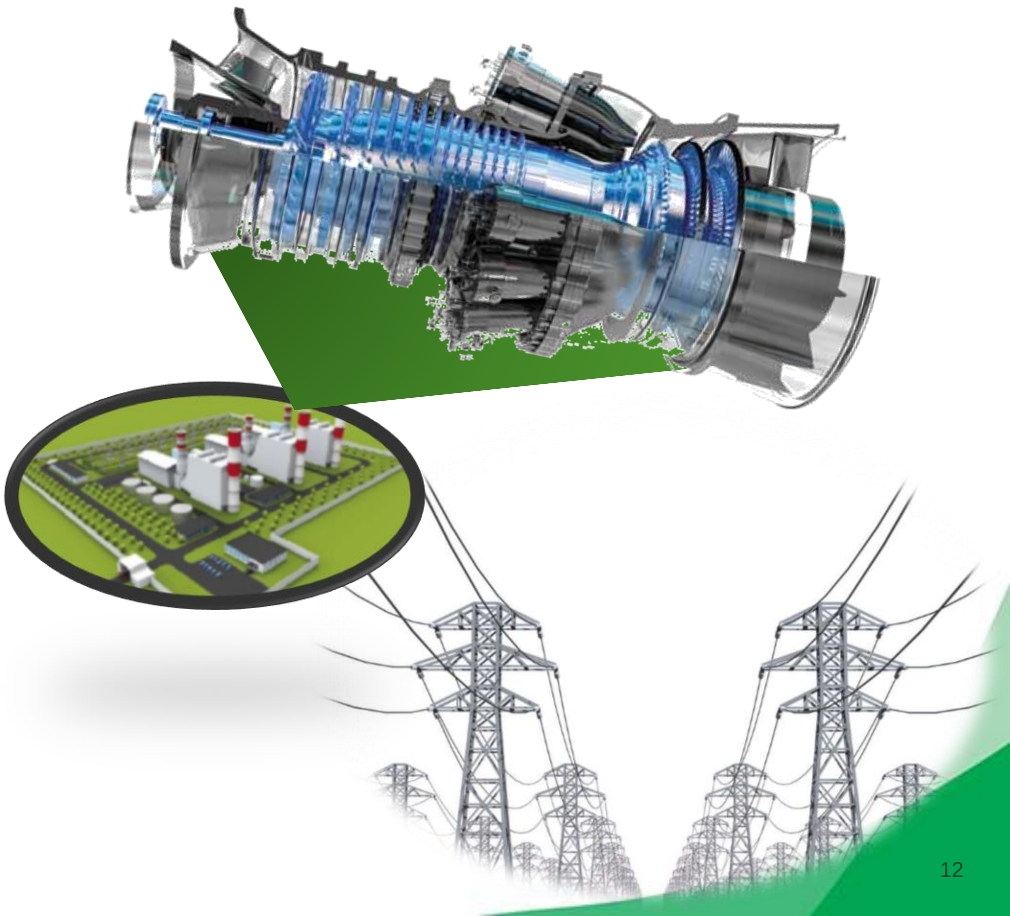
*** Yee, S. K., Milanovic, J. V., & Hughes, F. M. (2008)*

Frequency dependent models: Power system & governor behavior, 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**

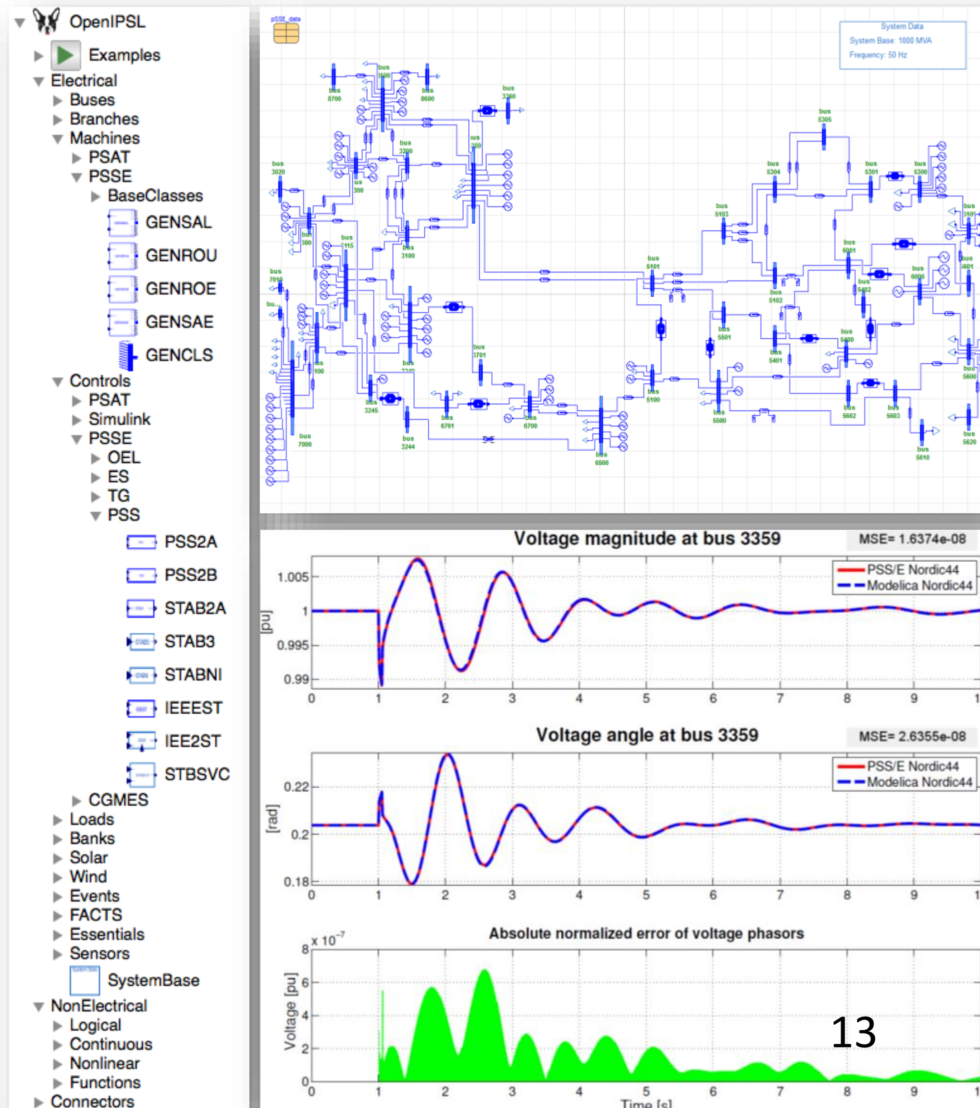
Part II: Equation Based Model





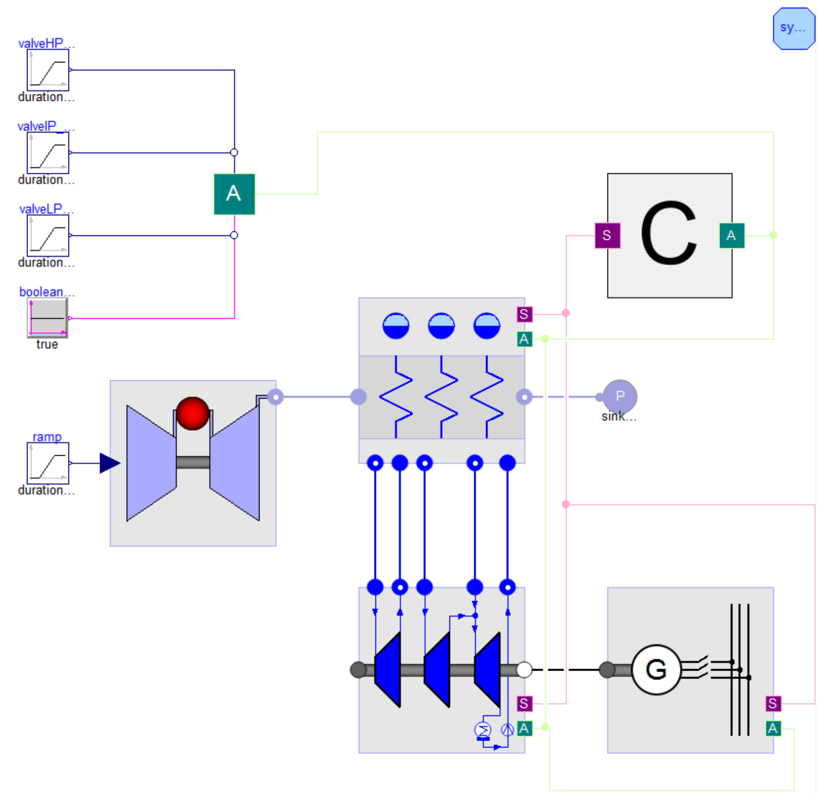
The *OpenIPSL* Library

- **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.

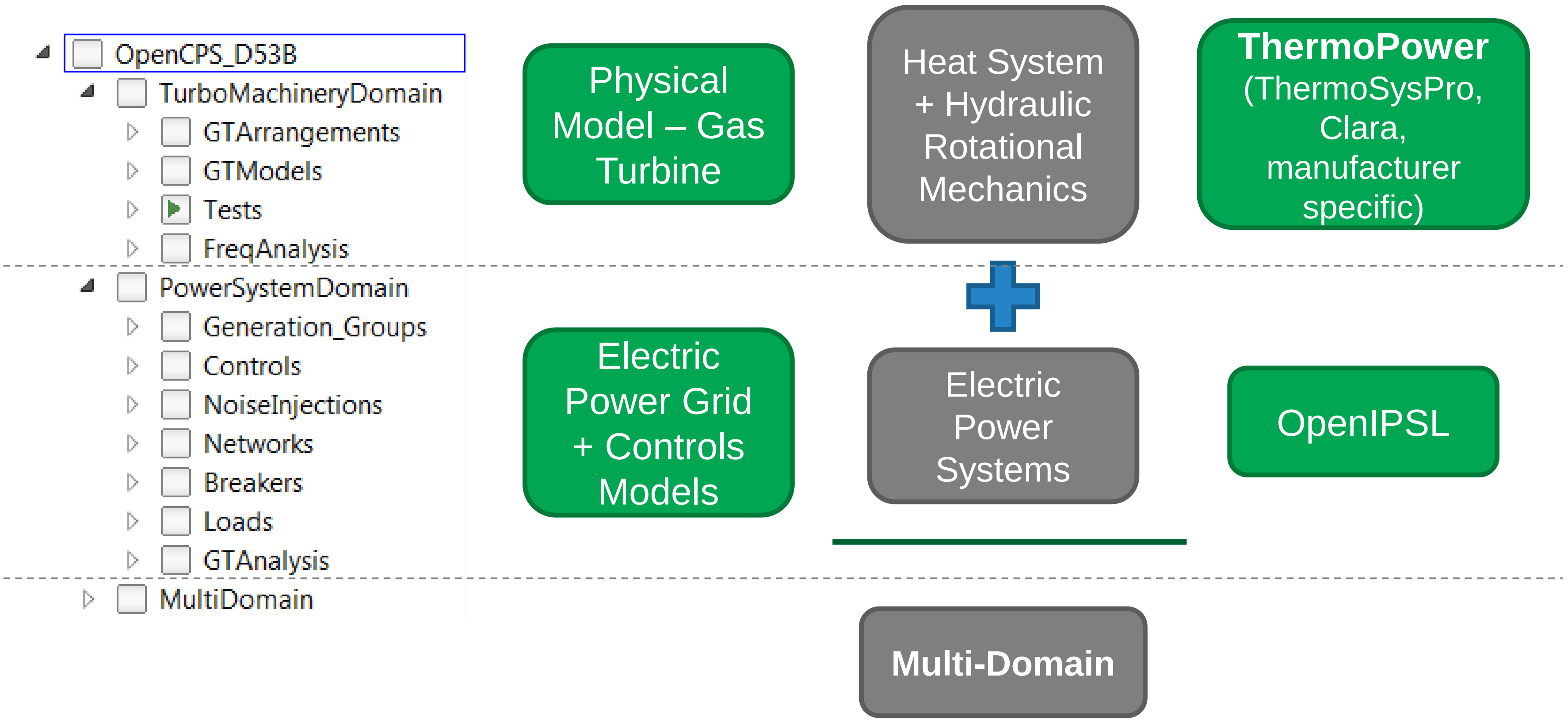


- Casella, F. (2009). Object-oriented modelling of power plants: a structured approach. *IFAC Proceedings Volumes*, *42*(9), 249-254.

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

Modelica Models for Multi-Domain

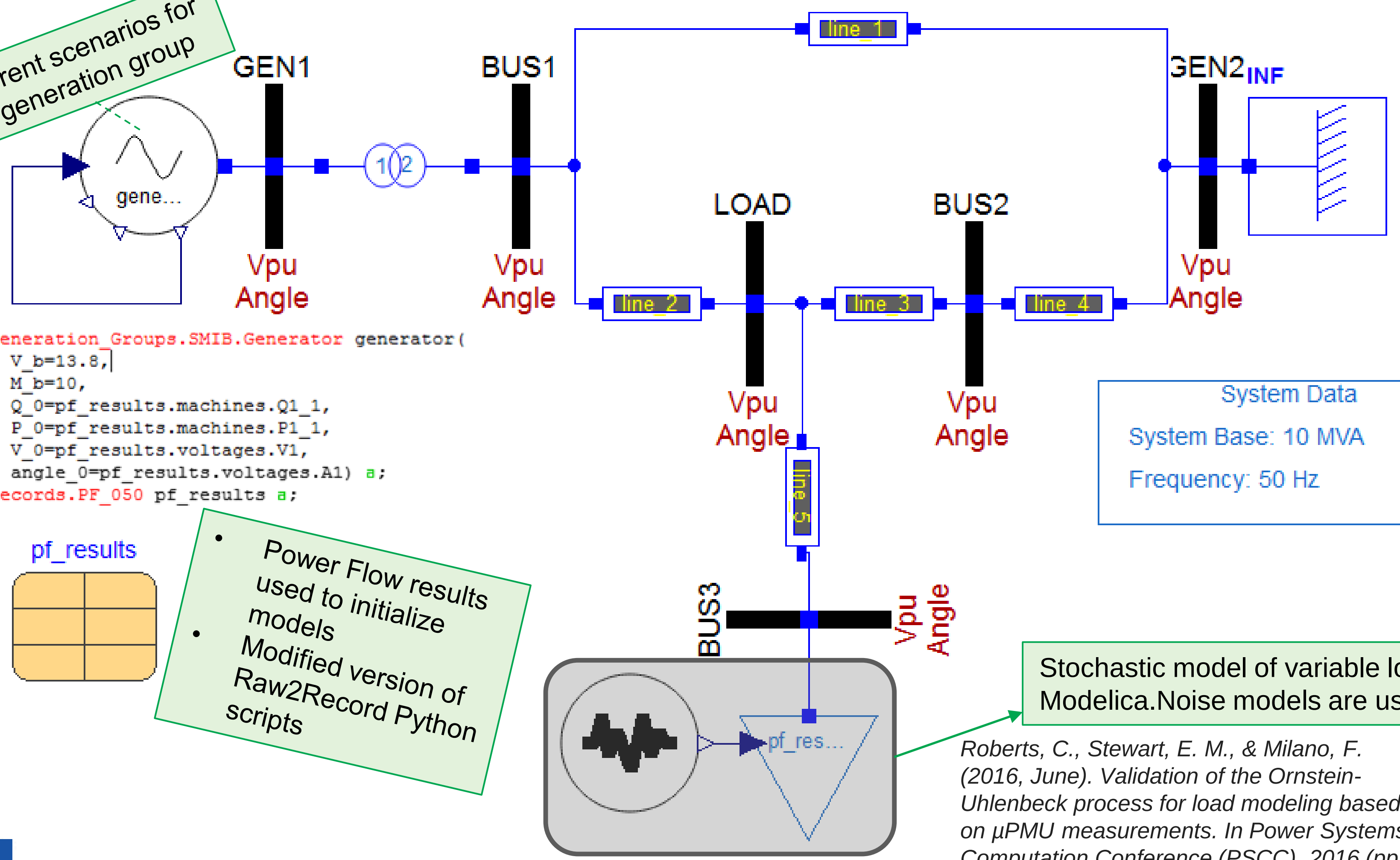
Package Structure



Modelica Models for Multi-Domain

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;
```

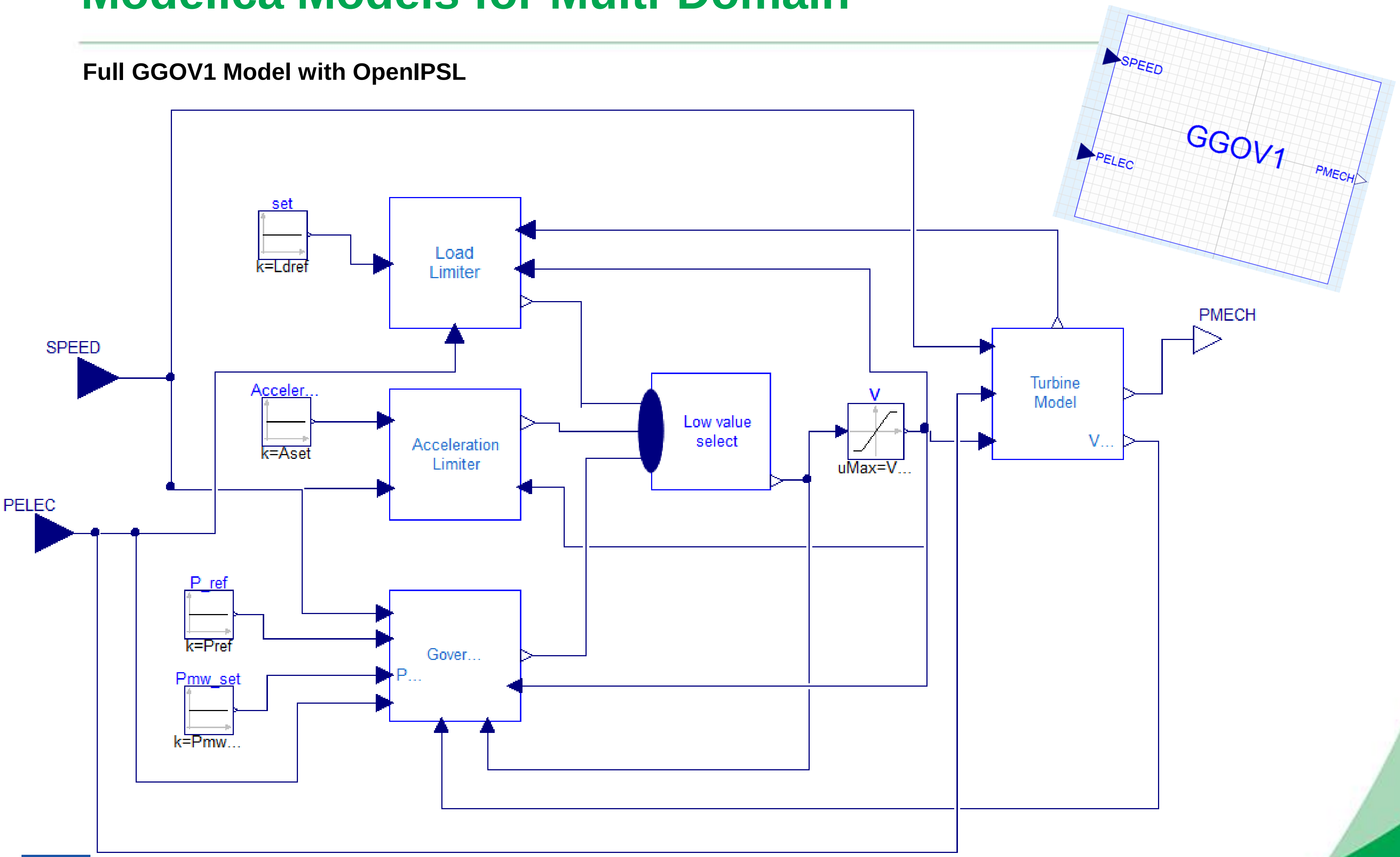
- Power Flow results used to initialize models
- Modified version of Raw2Record Python scripts

Stochastic model of variable load Modelica.Noise models are used.

Roberts, C., Stewart, E. M., & Milano, F. (2016, June). Validation of the Ornstein-Uhlenbeck process for load modeling based on µPMU measurements. In Power Systems Computation Conference (PSCC), 2016 (pp. 1-7). IEEE.

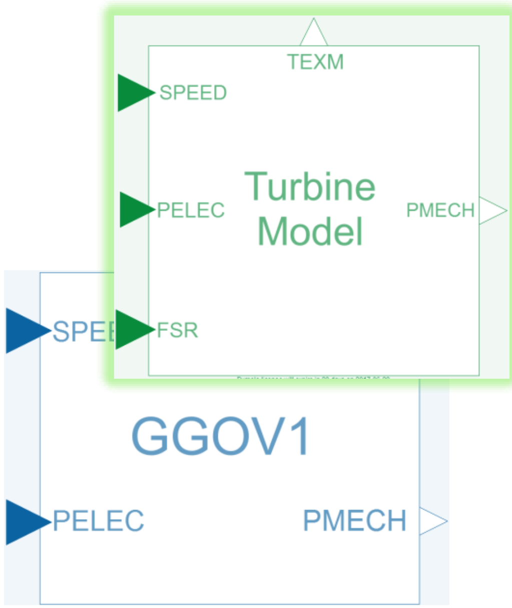
Modelica Models for Multi-Domain

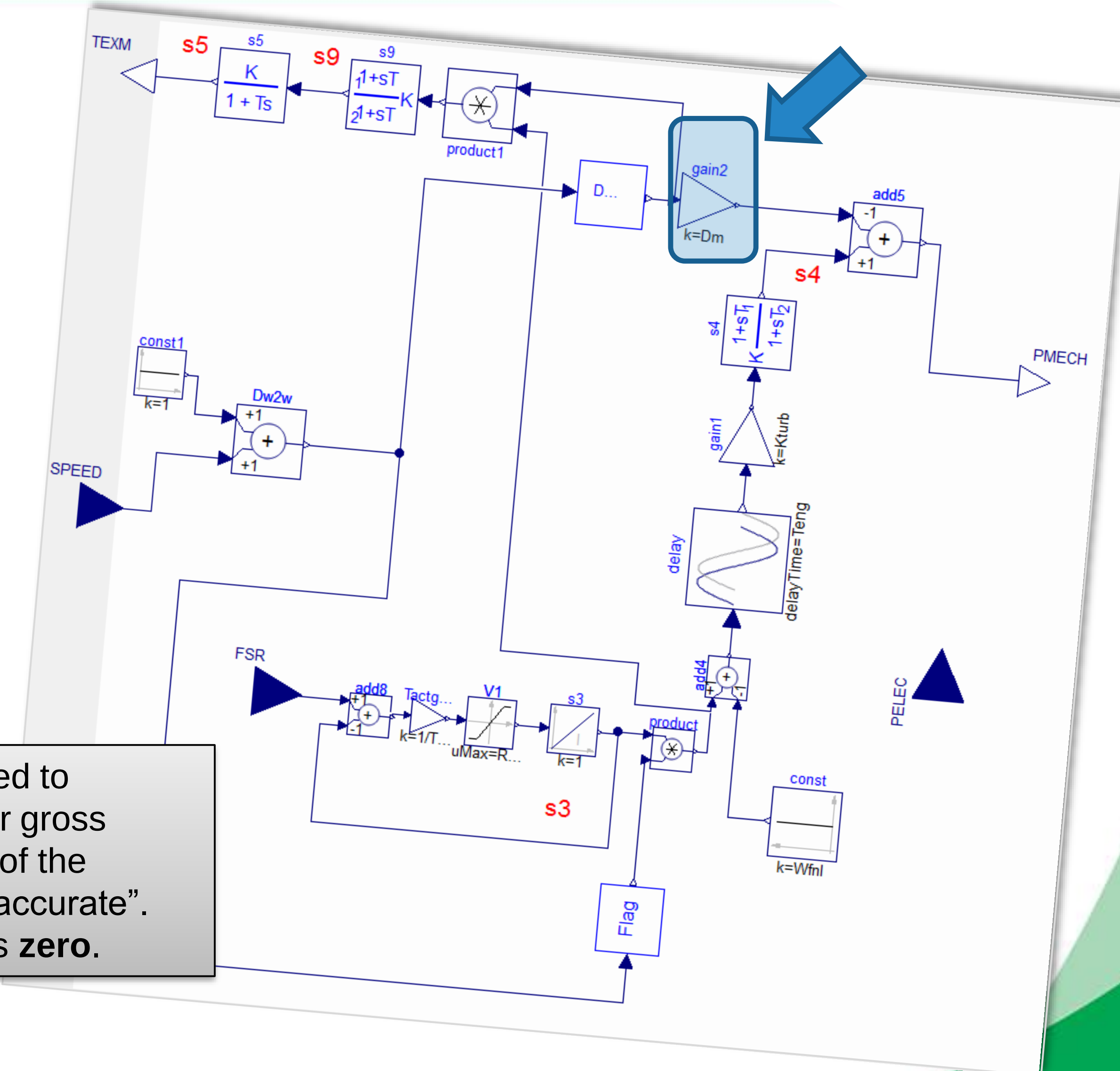
Full GGOV1 Model with OpenIPSL



Modelica Models for Multi-Domain

GGOV1 Turbine Block

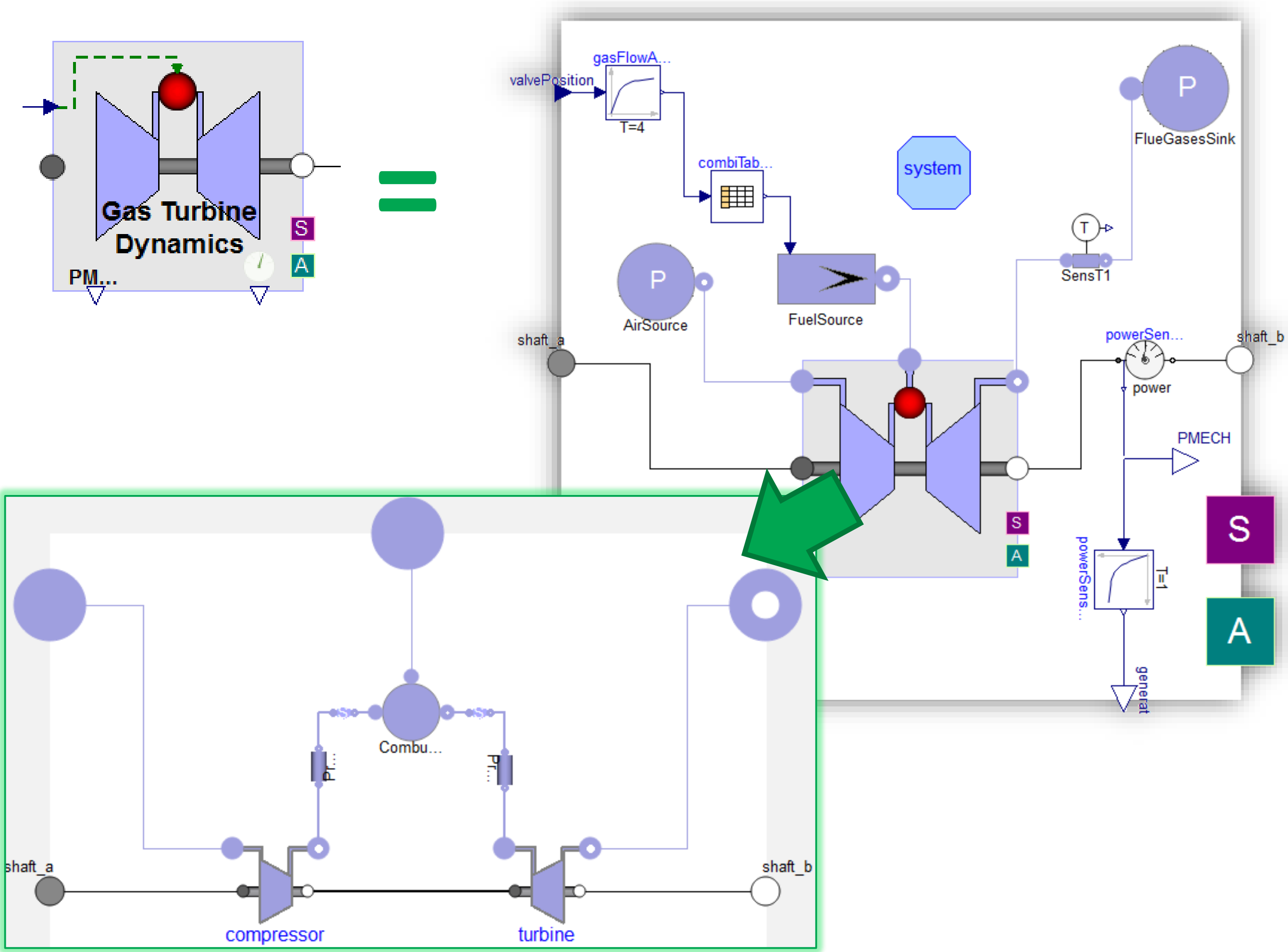


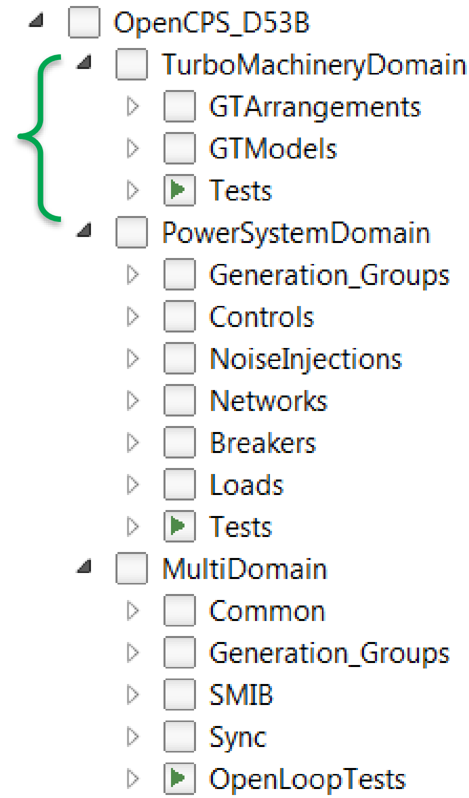


"A ***speed damping factor*** can be modeled to influence the temperature limit as a rather gross approximation of the speed dependence of the turbine rating. This is, however, not very accurate". Recommended value for parameter dm is **zero**.

Multi-Domain network models

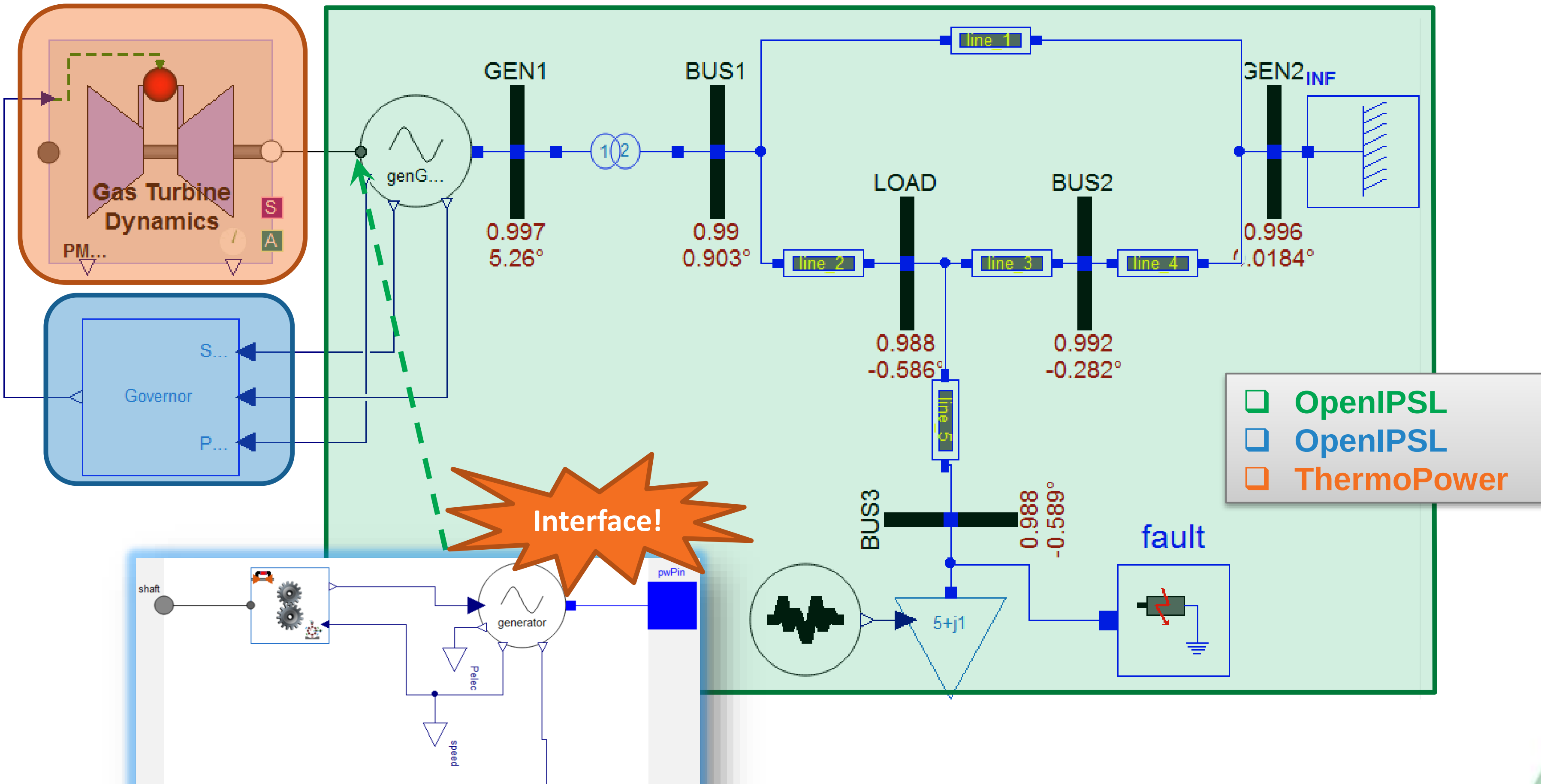
Multi-domain Modelica Model: ThermoPower + OpenIPSL





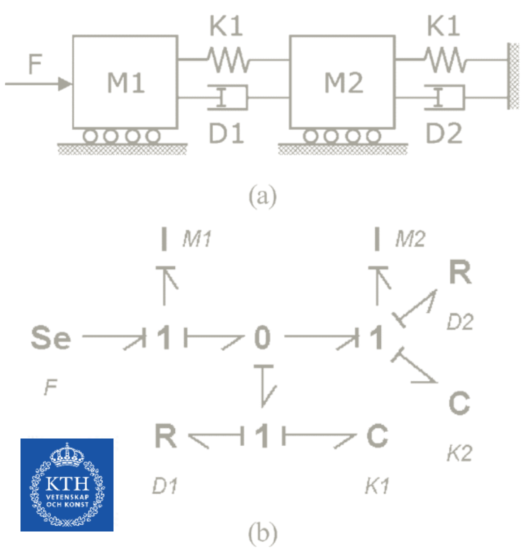
Multi-Domain network models

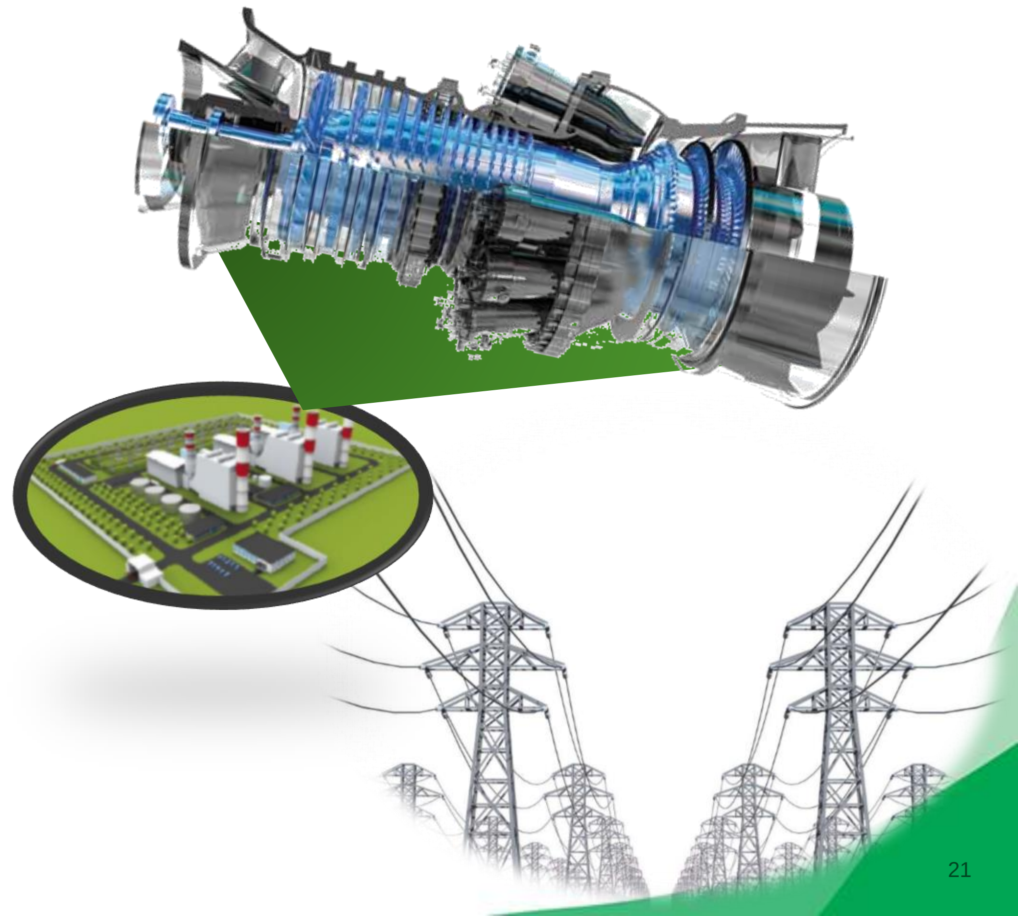
Multi-domain Modelica Model: ThermoPower + OpenIPSL



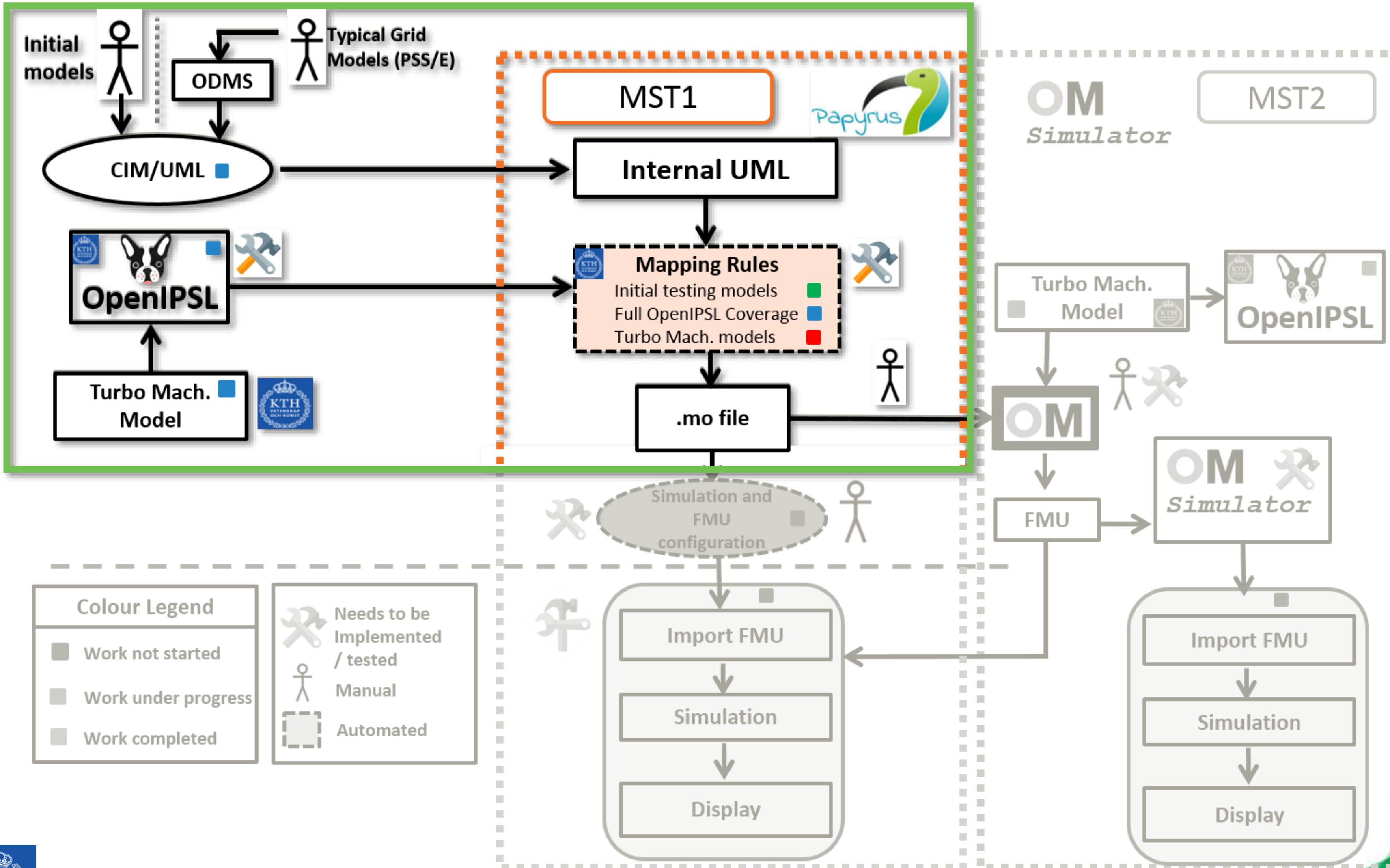

```
equation
  omega_e = der(shaft.phi)*Np;
  SPEED = omega_e/(100*pi) - 1;
  PMECH = der(shaft.phi)*shaft.tau/(S_b*1e6);
```

Part III: Semantic Model



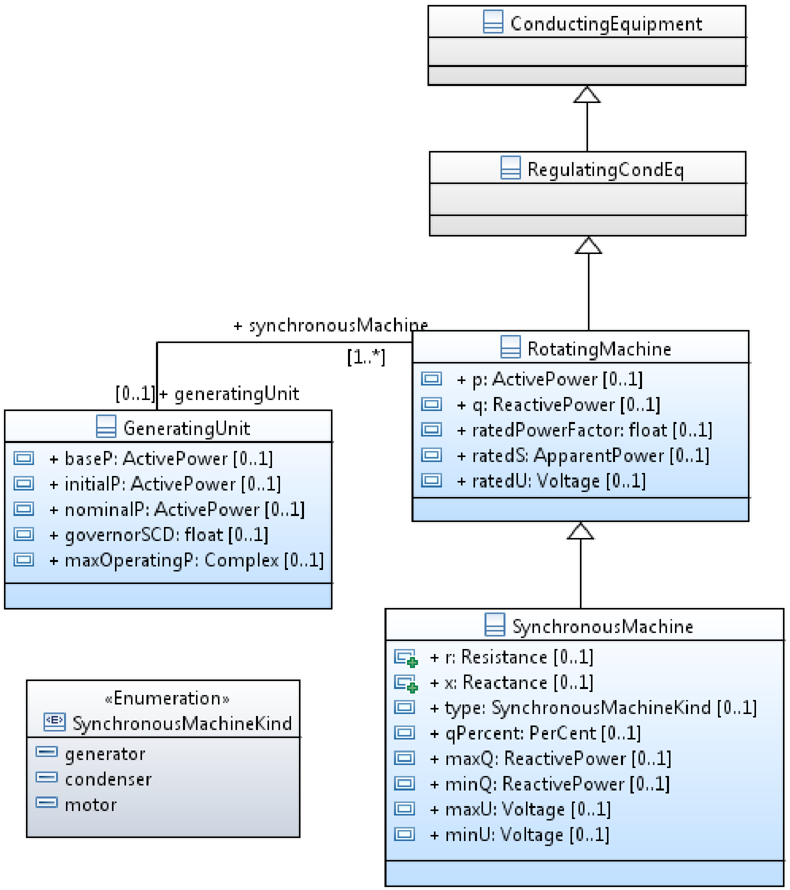


Common Information Model in Papyrus



Common Information Model in Papyrus

The CIM semantics for Power Systems



CIM/CGMES UML → **Semantics + Information each component in system**

SysML → **Define interactions between components**

Modelica + OpenIPSL → **Provide the mathematical computer language to define equations**

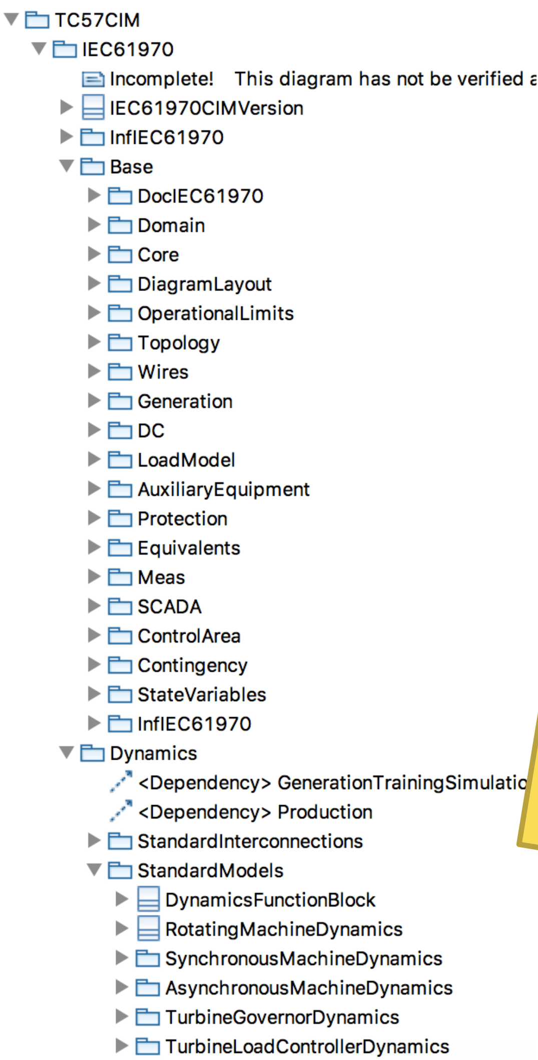
YOU COMPLETE ME!

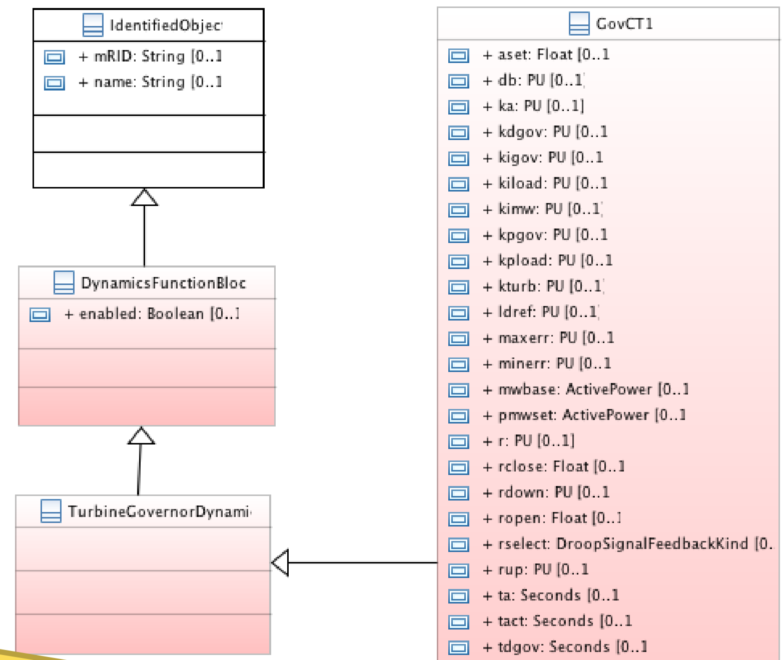
F. Gómez, L. Vanfretti and S. H. Olsen, "CIM-Compliant Power System Dynamic Model-to-Model Transformation and Modelica Simulation," in IEEE Transactions on Industrial Informatics, vol. PP, no. 99, pp. 1-1. doi: 10.1109/TII.2017.2785439

Common Information Model in Papyrus

The CIM / UML Modeling for Power Systems

UML



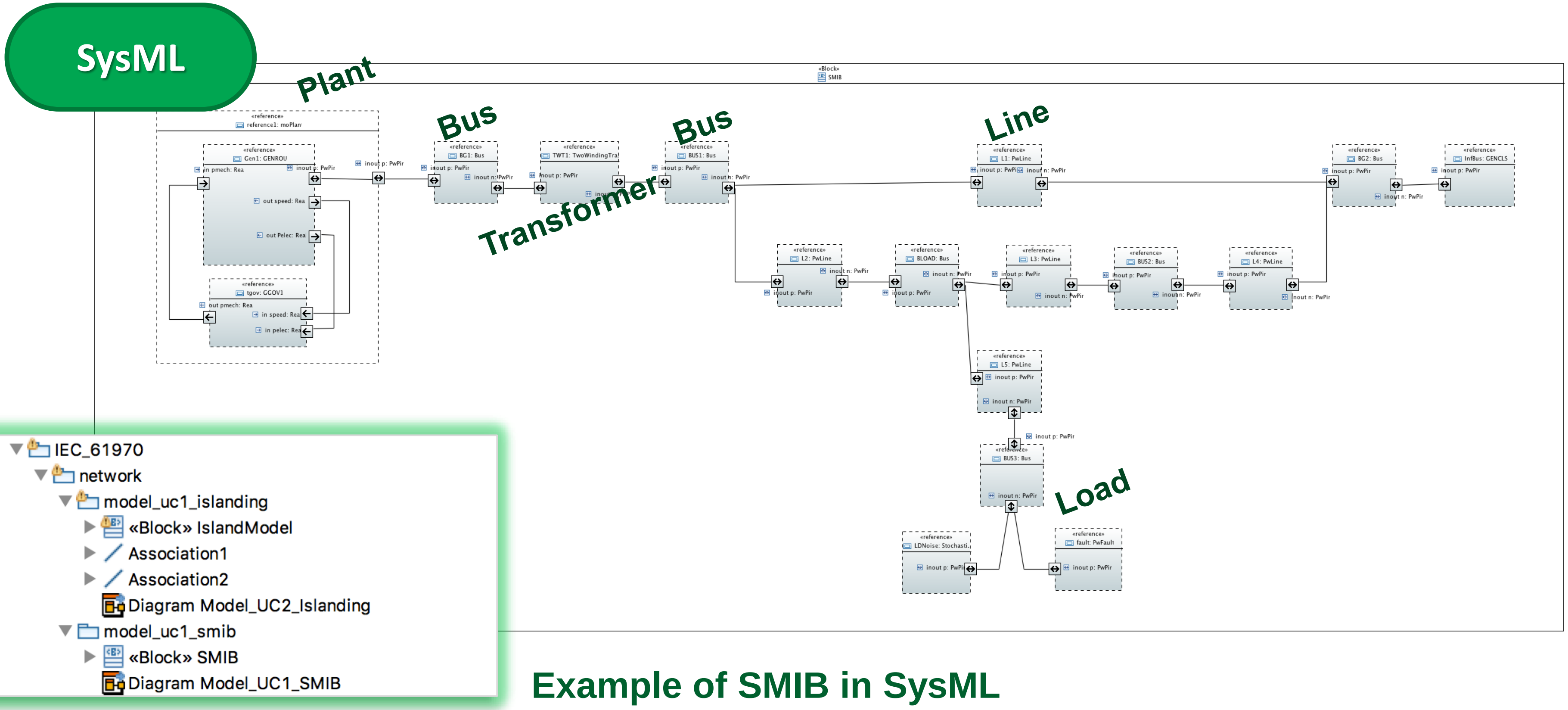


Only parameters for Governor Class diagram to be completed with Turbine parameters (ISO 15926)

Example: Class diagram for GovCT1

Modeling Methodology and Proposed Models

SysML extension for the CIM / UML



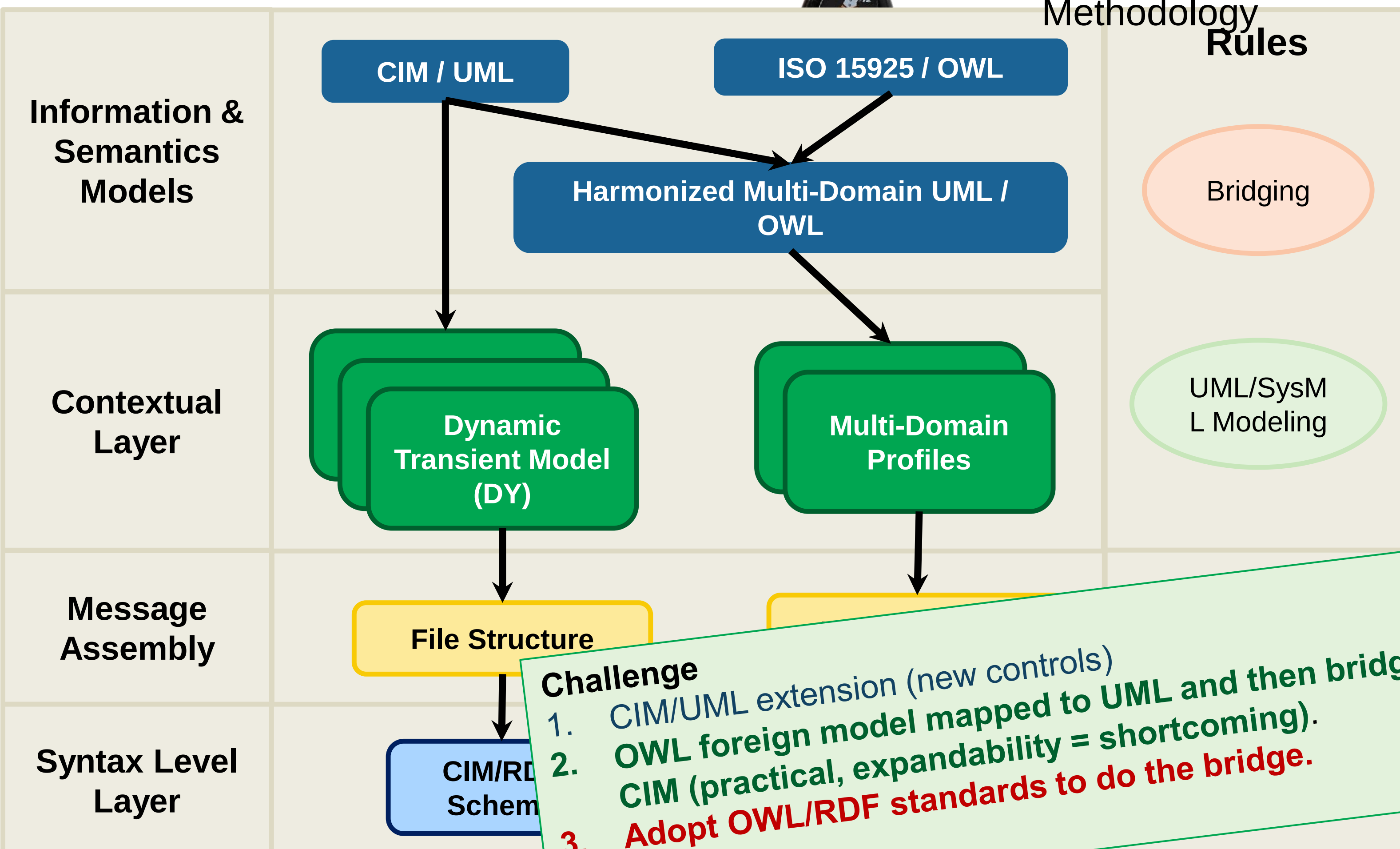
Example of SMIB in SysML

- Plant contains *Generator block* and *Turbine block*
- Turbine defined as:
  - *Standard* model used by Power System Simulation Tools.
  - Detailed *explicit* model of Turbine dynamics (Multi-Domain).

Modeling Methodology and Proposed Models

ISO Standard Proposal for Multi-Domain Modeling

UN/CEFACTS
CCTS Modeling
Methodology



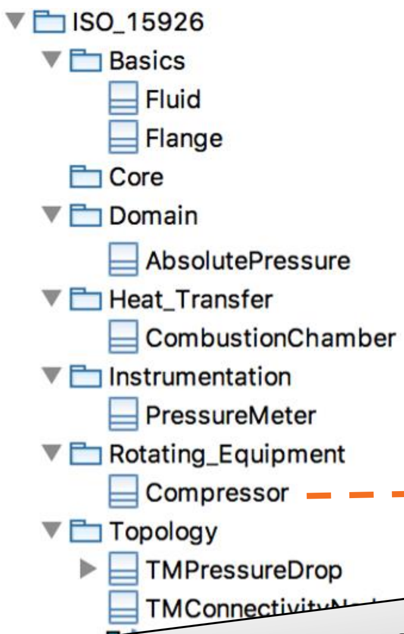
Challenge

1. CIM/UML extension (new controls)
2. **OWL foreign model mapped to UML and then bridged to CIM (practical, expandability = shortcoming).**
3. **Adopt OWL/RDF standards to do the bridge.**

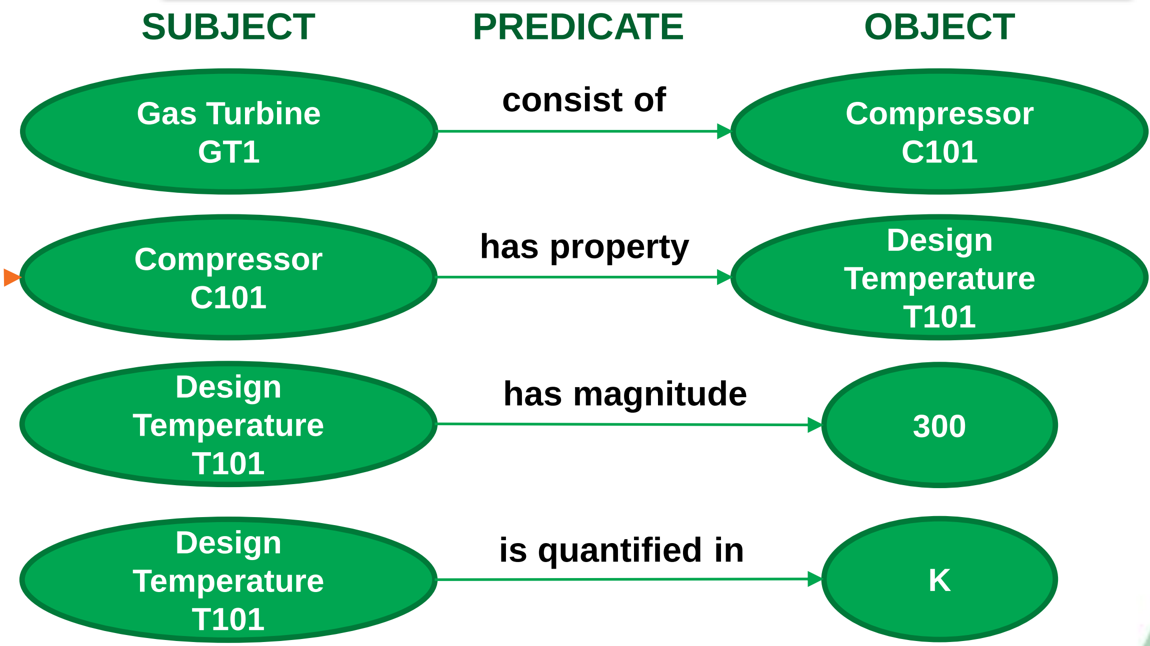
Modeling Methodology and Proposed Models

ISO 15926 Standard Proposal for Multi-Domain Modeling

Challenge 1: ISO standard is distributed in OWL notation -> transformation to UML **(MSc Thesis results!)**
Challenge 2: Creation of namespaces* and profiles, compatible with CIM, to include ISO models



Similar Structure to organize or classify **Classes / Components**
Source: ISO definitions
https://www.posccaesar.org/wiki/ISO15926

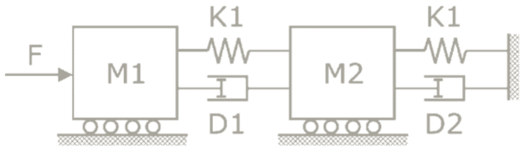


(RDF Named Graph / Triples)

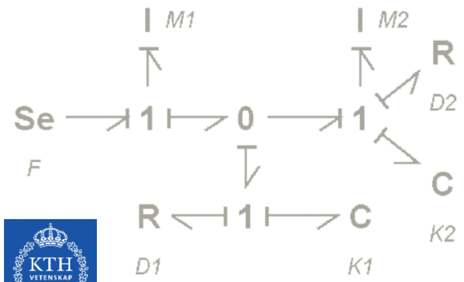
*
- xmlns:cim="http://iec.ch/TC57/2013/CIM-schema-cim16#"
- xmlns:pti="http://www.pti-us.com/PTI_CIM-schema-cim16#"
- xmlns:entsoe="http://entsoe.eu/CIM/SchemaExtension/3/1#"

Kim, B., Teijgeler, H., Mun, D., Sun, D., Hwang, J., & Han, S. (2008). A Representation and Implementation of Process Plant Models using OWL and ISO 15926. In PLM08 Conference.

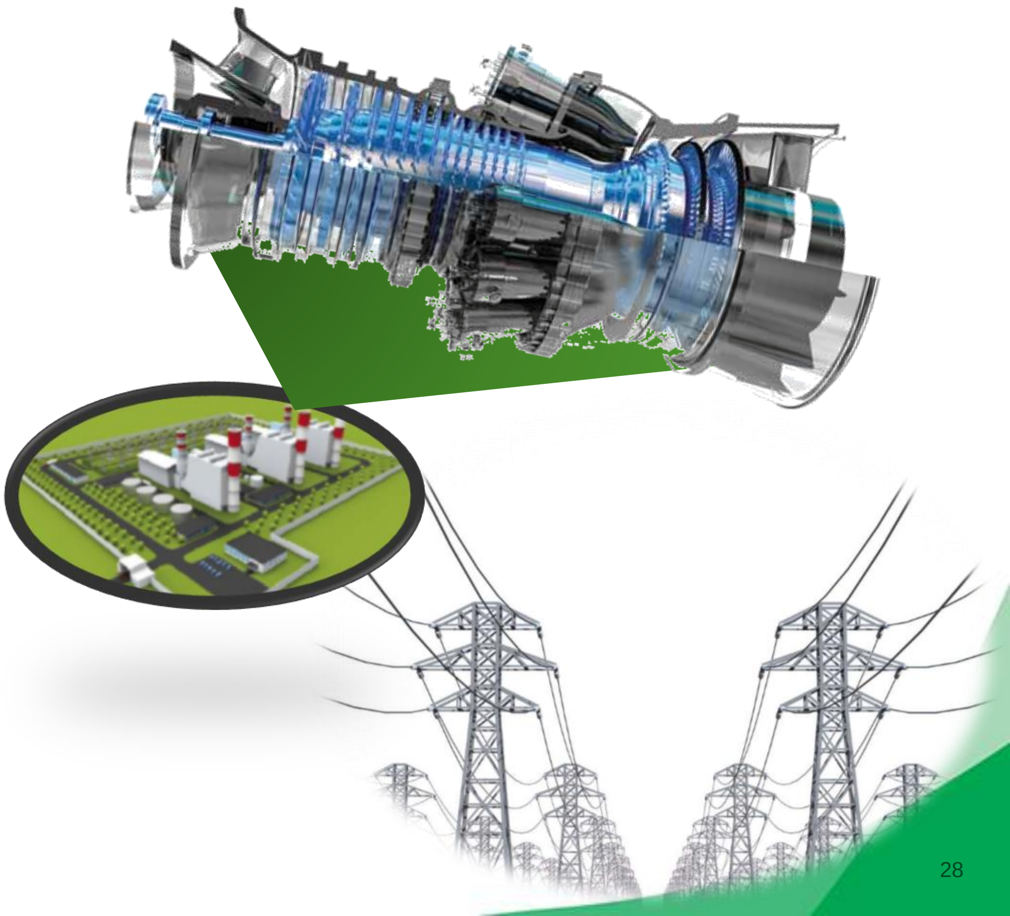
Part IV: Simulation and Results



(a)

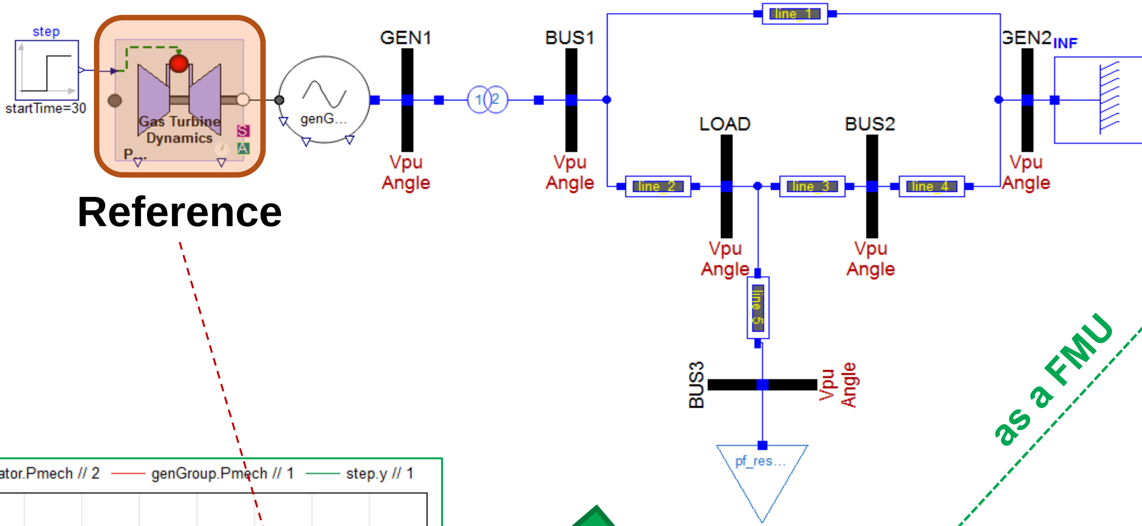


(b)



Multi-domain model simulation

Model Identification

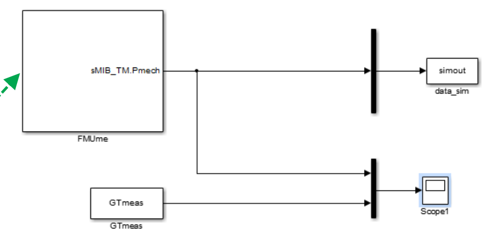


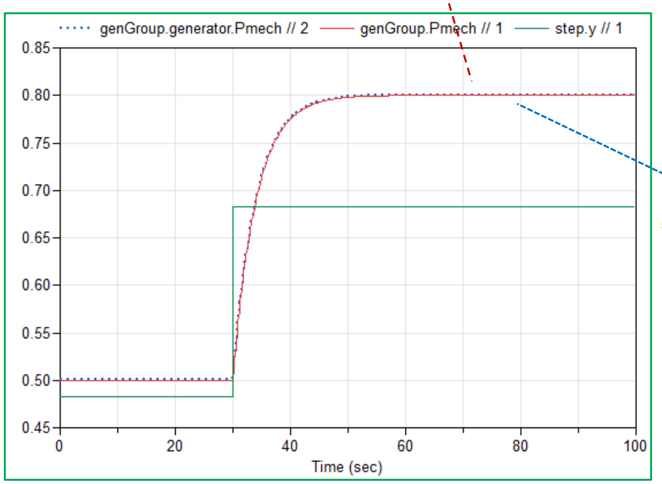
Reference

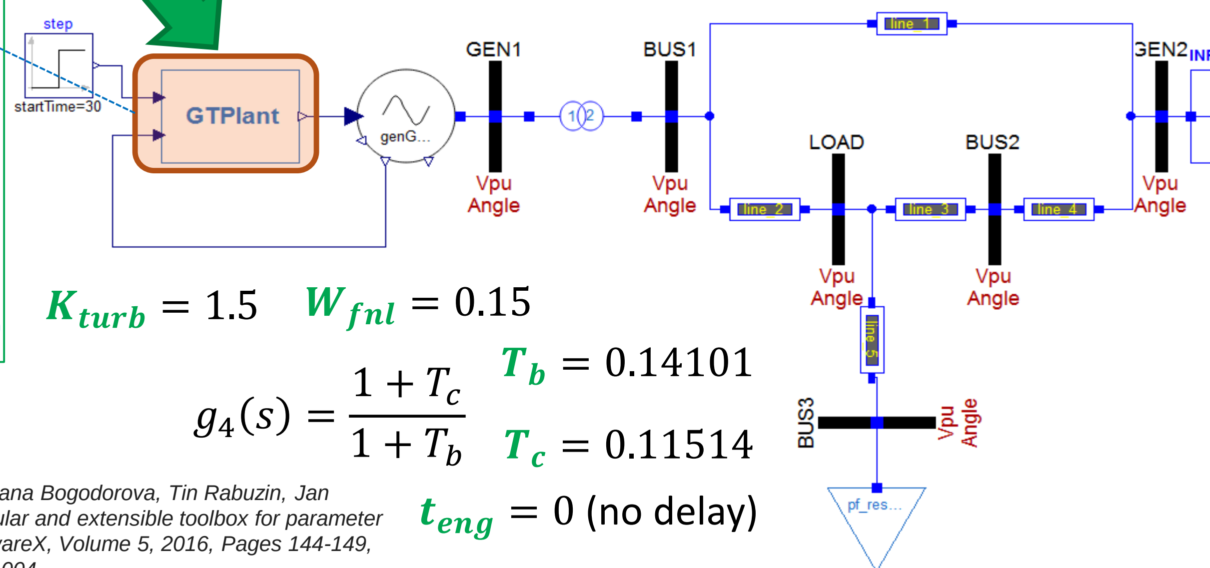
Tools:

- RaPId
- MATLAB `ident`

as a FMU







$K_{turb} = 1.5 \quad W_{fnl} = 0.15$

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

$T_b = 0.14101$

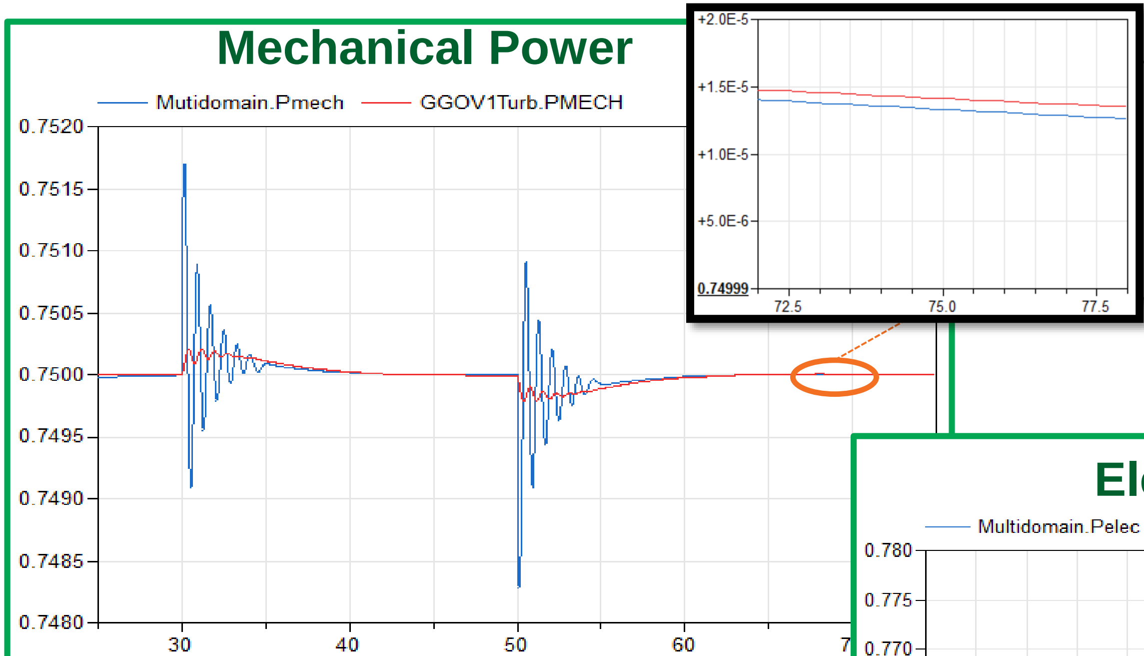
$T_c = 0.11514$

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

Luigi Vanfretti, Maxime Baudette, Achour Amazouz, Tetiana Bogodorova, Tin Rabuzin, Jan Lavenius, Francisco José Goméz-López, RaPId: A modular and extensible toolbox for parameter estimation of Modelica and FMI compliant models, SoftwareX, Volume 5, 2016, Pages 144-149, ISSN 2352-7110, https://doi.org/10.1016/j.softx.2016.07.004.

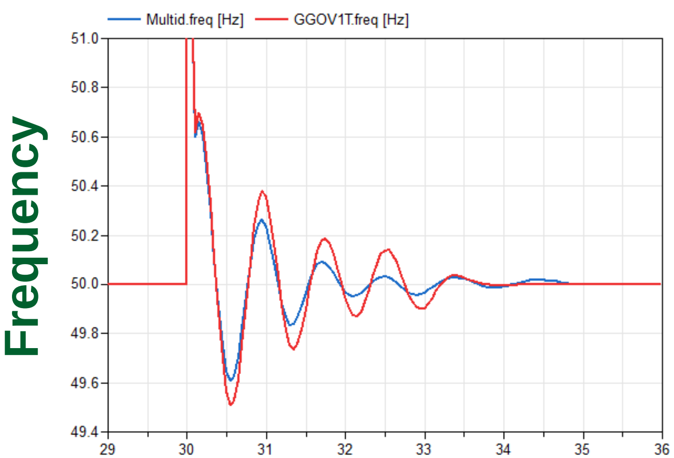
Multi-domain model simulation

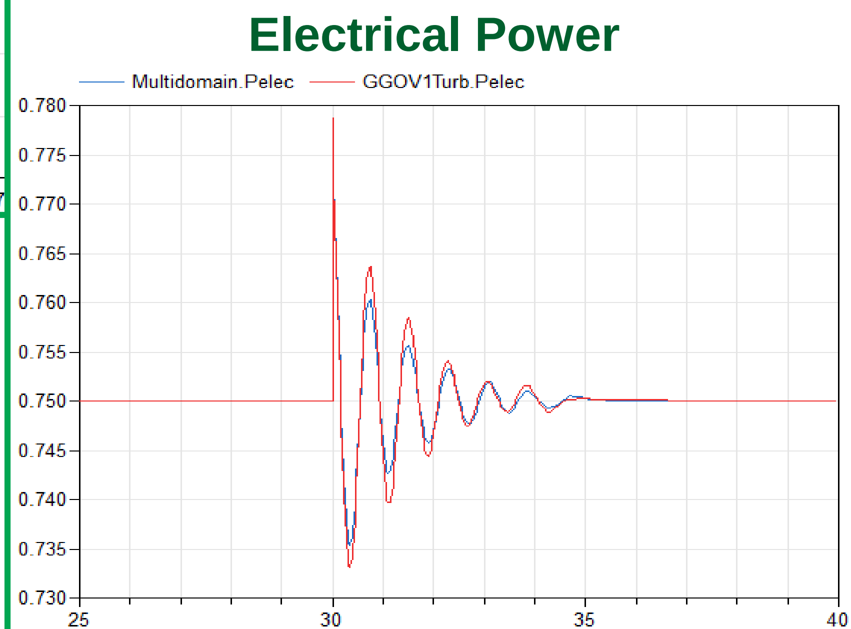
Time Response with Load Change Event Multidomain vs GGOV1 Turbine Models



Load Change Event

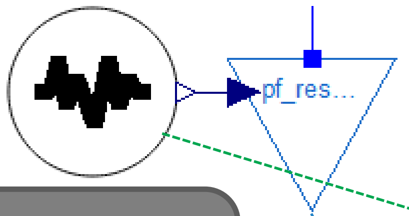
Increase of 0.2 pu in active power at ***t=30 sec*** of simulation. After 20 sec, the active power is set back again to the original value (0.75 pu)





Multi-domain model simulation

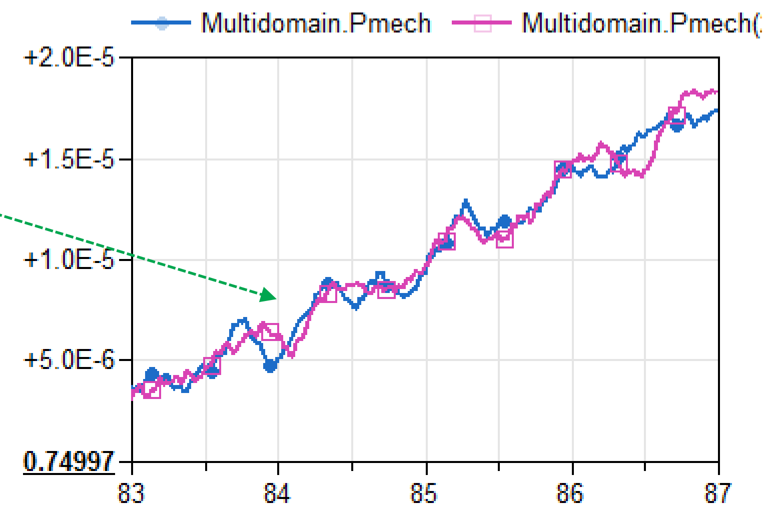
Stochastic Load Model



Noise Model

- Expectation value
- Standard deviation
- Sample Period

Sine wave or **ramp** containing the noise can be used to model the “normal” load variation



Seed generator →**Different result**

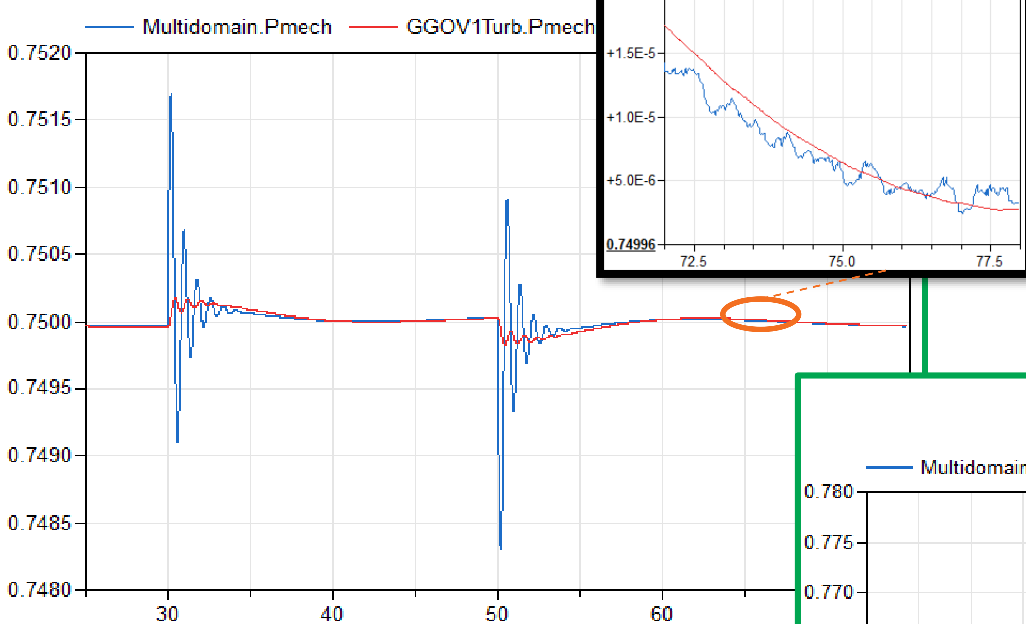
```
model VariableLoad "PSS/E Load with variation"
…
  parameter Real d_P "Active Load Variation (pu)";
…
public
  Modelica.Blocks.Interfaces.RealInput u;
equation
  if time >= t1 and time <= t1 + d_t then
    kI*S_I.re*v + S_Y.re*v^2 + kP*(S_P.re + d_P) + u = p.vr*p.ir + p.vi*p.ii;
    kI*S_I.im*v + S_Y.im*v^2 + kP*(S_P.im + d_Q) = (-p.vr*p.ii) + p.vi*p.ir;
  else
    kI*S_I.re*v + S_Y.re*v^2 + kP*S_P.re + u = p.vr*p.ir + p.vi*p.ii;
    kI*S_I.im*v + S_Y.im*v^2 + kP*S_P.im = (-p.vr*p.ii) + p.vi*p.ir;
  end if;
end VariableLoad;
```

Load varies `d_P` in the time interval between `t1` and `t1+d_t`.
Noise model can be added as real input **u**.

Multi-domain model simulation

Time Response with Load Change Event Multidomain vs GGOV1 Turbine Models

Mechanical Power

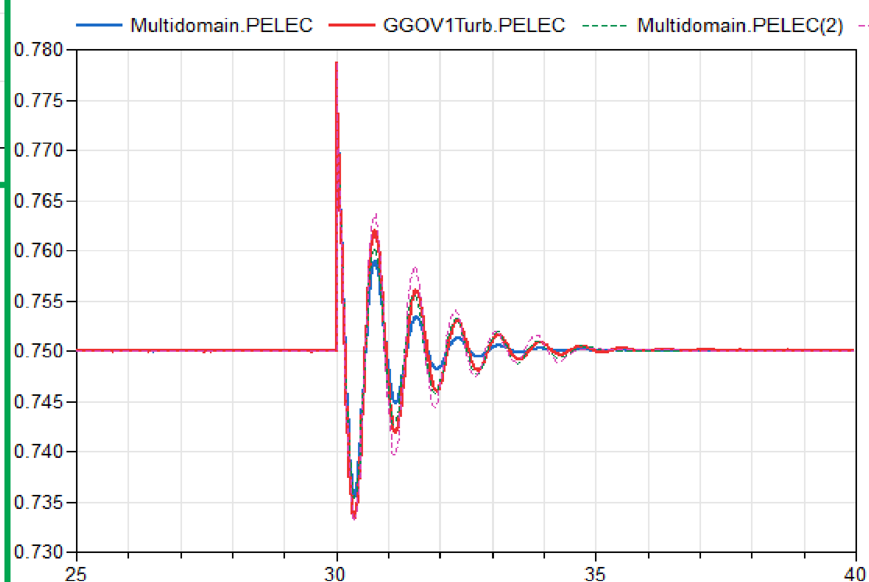


+ NOISE!!

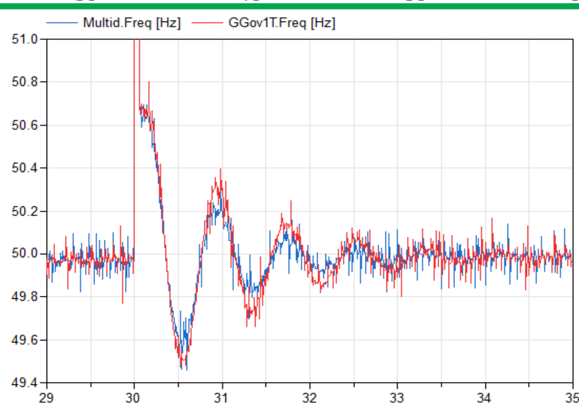
Load Change Event

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)

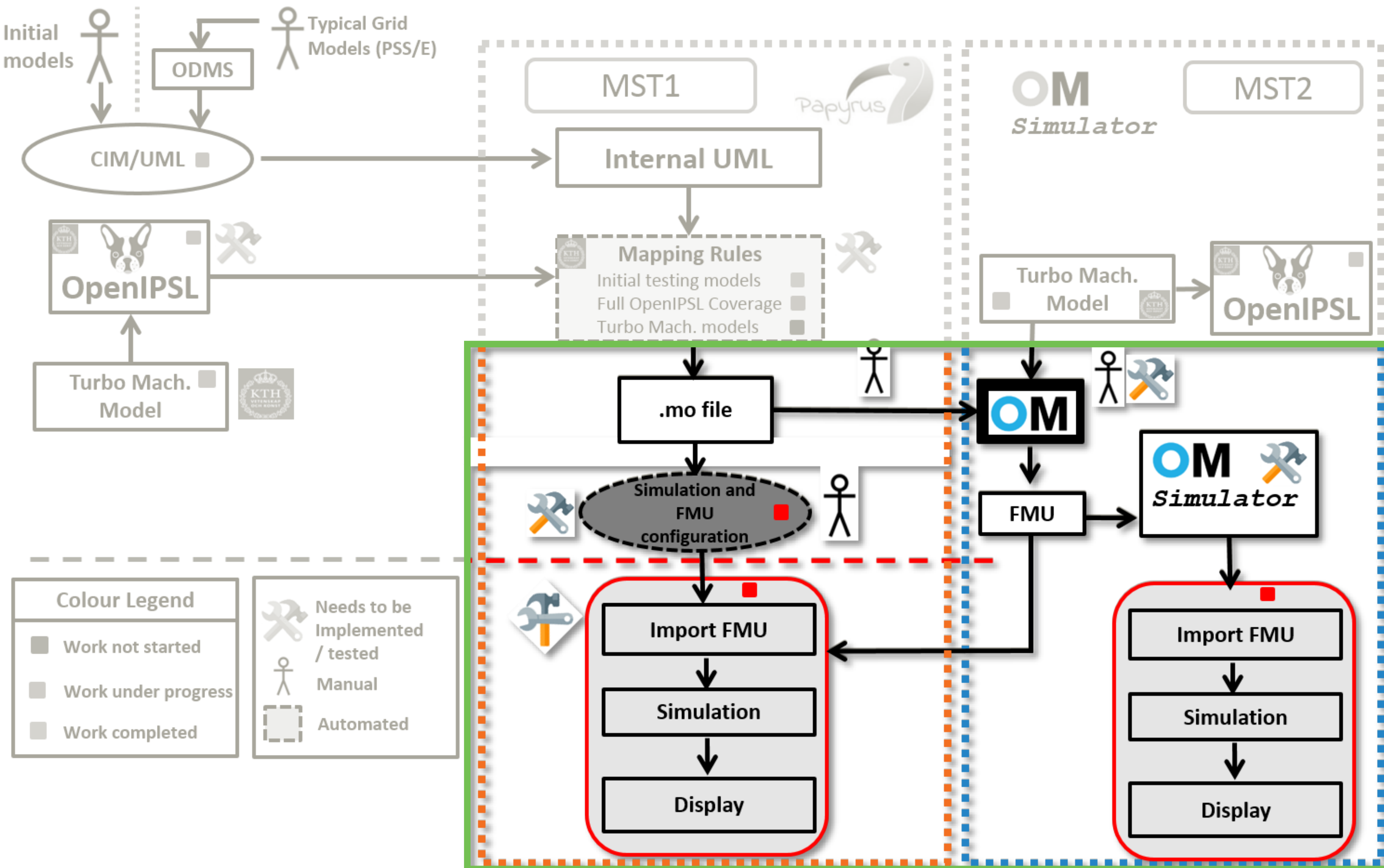
Electrical Power



Frequency

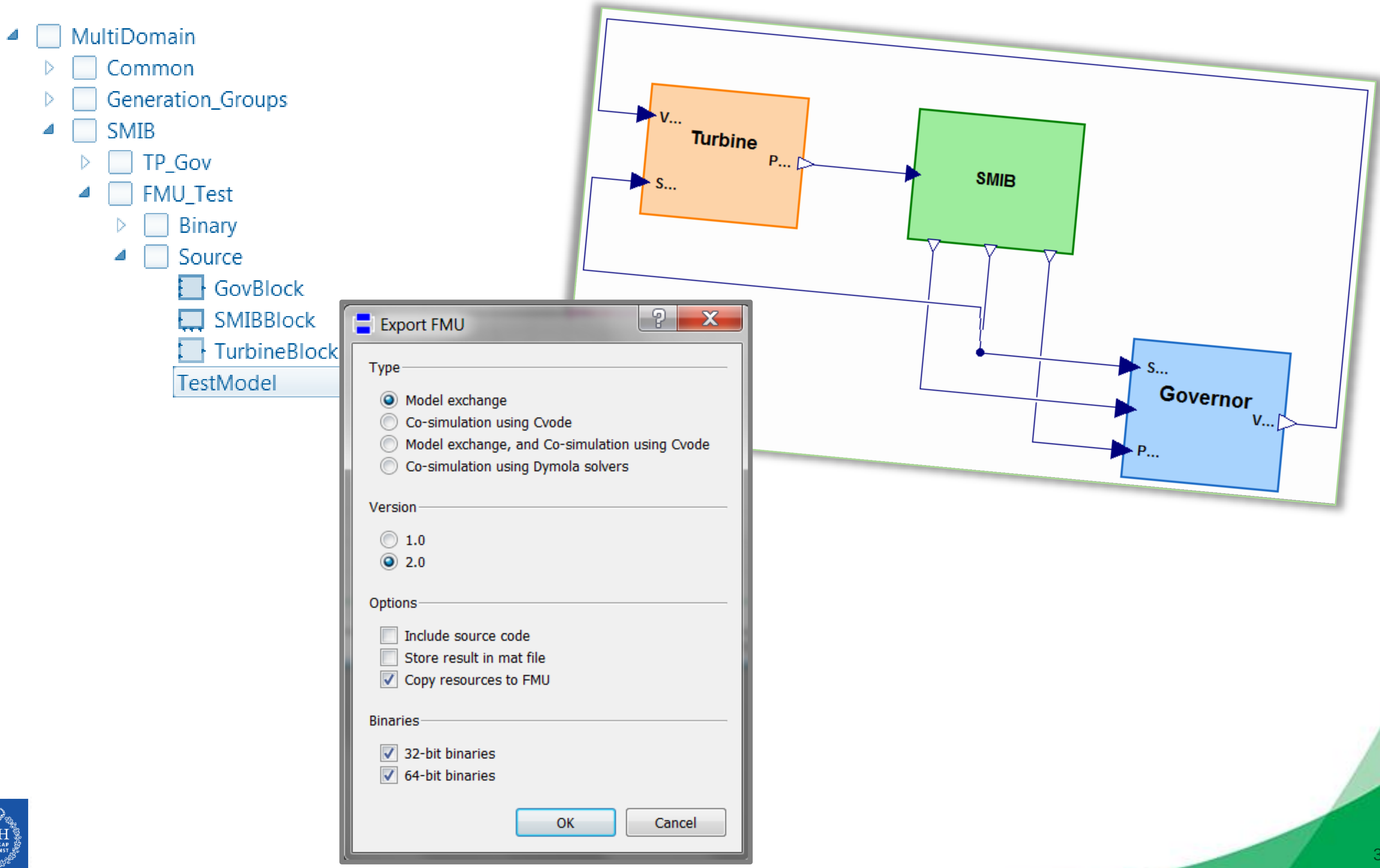


FMU Generation and Simulation



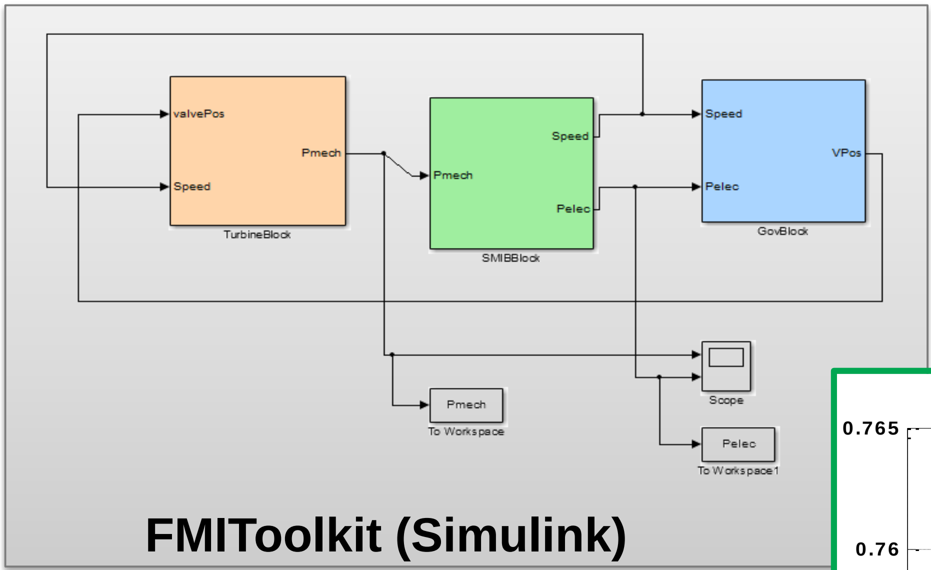
FMU Generation and Simulation

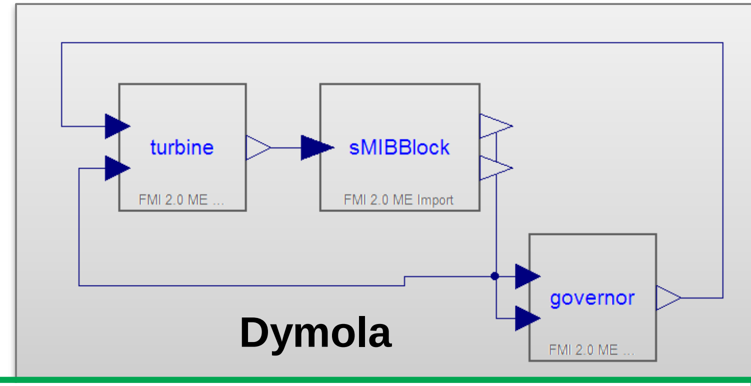
Preparation and Compilation of FMUs

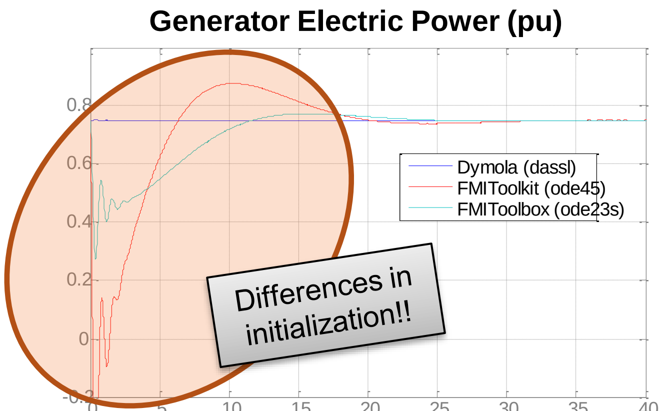


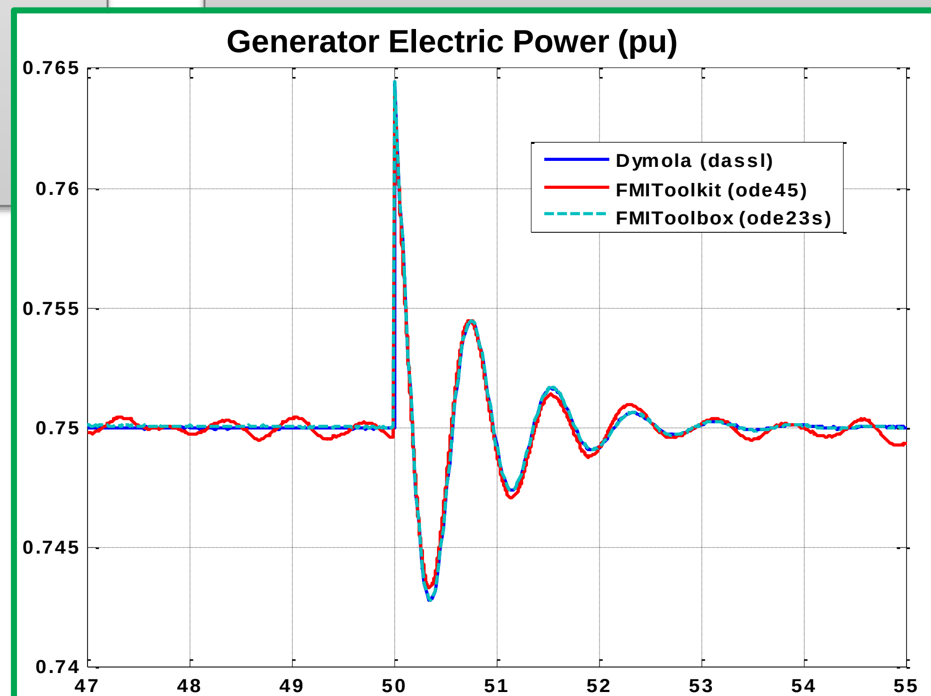
FMU Generation and Simulation

FMUs Simulation in different environments









Conclusions and Future Work

- A multi-domain semantic and equation-based model has been derived to allow simulations of detail representations of gas turbines and the electric power grid.
- Differences in the simple turbine model (GGOV1) and the multi-domain explicit turbine model have been shown. A relevant source of that difference is the *representation of the speed influence* on the *gas turbine dynamics*.
- It is possible to exchange the models in the form of FMUs. This leads to the opportunity of getting detailed models of the gas turbines from the manufacturers while protecting their IP. The right choice of the *solver* and the *noise modeling* are still a challenge.
- A better model that includes among other things the *valves dynamics* is desired. This will be useful in the study of *forced oscillations phenomena* in power systems coming from gas power plants. This model can be extended to cover *Combined-cycle power plants*.
- It is recommended to follow the ISO 15926 standard more strictly.

Thank you!

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