Coalesced Gas Turbine and Power System Modelling and Simulation using Modelica

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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
“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

- "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

Domain Independent Physical Systems Modeling

<table>
<thead>
<tr>
<th>Variable / Characteristic</th>
<th>Electricity</th>
<th>Mechanics Translation</th>
<th>Mechanics Rotation</th>
<th>Hydraulics</th>
<th>Heat System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effort (e)</td>
<td>Voltage</td>
<td>Force</td>
<td>Torque</td>
<td>Pressure</td>
<td>Temperature</td>
</tr>
<tr>
<td>Flow (f)</td>
<td>Current</td>
<td>Velocity</td>
<td>Angular Velocity</td>
<td>Volume Flow</td>
<td>Heat Flow</td>
</tr>
<tr>
<td>Power Flow (P=e·f)</td>
<td>Power</td>
<td>Power</td>
<td>Power</td>
<td>Power</td>
<td>Power · Temperature</td>
</tr>
</tbody>
</table>

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

\[ \dot{W}_c = m_a \cdot (h_2 - h_1) = \tau \cdot \omega \cdot \eta_{mech} \]
Heat Engine and Thermo-Dynamic Component Diagrams

Gas Turbine as a Carnot Heat Engine

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

\[ W = Q_1 - Q_2 \]
\[ \eta = \frac{W}{Q_1} = 1 - \frac{Q_2}{Q_1} \]
Gas Turbine Theory: The Brayton Cycle

Steady Flow energy equations:

\[ W_C = W_{12} = m \cdot c_p \cdot (T_2 - T_1) \]
\[ W_T = W_{34} = m \cdot c_p \cdot (T_4 - T_3) \]
\[ \dot{W}_C = m_a \cdot (h_2 - h_1) \]
\[ \dot{W}_T = (m_a + m_f) \cdot (h_3 - h_4) \]

Thermo – Mechanical conversion:

\[ \dot{W}_C = \tau \cdot \omega \cdot \eta_{mech} \]
\[ \dot{W}_T = \frac{\tau \cdot \omega}{\eta_{mech}} \]

\[ \eta_C = \frac{W_{\text{ideal}}}{W_{\text{actual}}} = \frac{(h'_2 - h_1)}{h_2 - h_1} \]
\[ \eta_T = \frac{W_{\text{actual}}}{W_{\text{ideal}}} = \frac{(h_3 - h'_4)}{h_3 - h'_4} \]
\[ \eta_C = \frac{T'_2 - T_1}{T_2 - T_1} \]
\[ \eta_T = \frac{\eta_C}{\eta_C + \eta_{th}} \]

\[ \eta_{th} = \frac{W_{tot}}{Q_{23}} \]

\[ W_{tot} = W_T - W_C \]
Coalesced Gas Turbine and Power System M&S using Modelica

Gas Turbine Theory: Component Operation Characteristics


Design Point Performance (rated values)

Off-Design Performance

\[
PR_c, \eta_c = f\left(\frac{m\sqrt{\theta}}{\delta}, \frac{N}{\sqrt{\theta}}\right) = f(m_c, N_c)
\]

\[
\theta = \frac{T_a}{T_{a0}} \quad \delta = \frac{P_a}{P_{a0}}
\]

\[
PR_c = f\left(\beta, \frac{N}{\sqrt{\theta}}\right)
\]

\[
\eta_c = f\left(\beta, \frac{N}{\sqrt{\theta}}\right)
\]

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

Look-up Tables
Gas Turbine Dynamics & Control

\[ T_x = \frac{T_a + A_3\delta + A_4W_f}{W_a} \]  \hspace{1cm} (1)

\[ CPR = \left( A_5W_a + A_6W_f \right) \frac{1}{\delta} + A_7 \]  \hspace{1cm} (2)

\[ P_m = \frac{1}{1 + T_{trb}s} \left( \frac{W_f - W_{f0}}{1 - W_{f0}} \right) \]  \hspace{1cm} (3)

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

\[ u(D\omega_C) = 1 + A_0D\omega_C + A_1D\omega_C^2 + A_2D\omega_C^3 \]

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

\[ \Delta\omega_C = \omega_C - 1 \]

\[ \omega_C = \omega \sqrt{\frac{T_{a0}}{T_a}} \]

Coalesced Gas Turbine and Power System M&S using Modelica

f₁, f₂ = f(ω)

Inlet Gate Vanes (IGVs) included
Impact on exhaust temperature

 Widely used before 2000’s (WECC). Shown to be deficient

Ctrl + Z

Simplifications

GGOV1

2001

Cigré

Frequency Dependent Model

2nd order model of turbine dynamics
Changes on controls

Model from previous slide

1983

Rowen

1992

Rowen

1994

IEEE

GAST

Simplifications

Power System Gas Turbine & Governor Models
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
**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 Rankine 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.

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**More info:**
- [https://casella.github.io/ThermoPower/](https://casella.github.io/ThermoPower/)
- [https://github.com/casella/ThermoPower](https://github.com/casella/ThermoPower)
Modelica Package Structure

- OpenCPS_D53B
  - TurboMachineryDomain
    - GTArrangements
    - GTModels
    - Tests
    - FreqAnalysis
  - PowerSystemDomain
    - Generation_Groups
    - Controls
    - NoiseInjections
    - Networks
    - Breakers
    - Loads
    - GTAnalysis
  - MultiDomain

- Physical Model - Gas Turbine
- Heat System + Hydraulic Rotational Mechanics
- ThermoPower (ThermoSysPro, Clarara, manufacturer specific)
- Electric Power Grid + Controls Models
- Electric Power Systems
- Multi-Domain
- OpenIPSL

Multi-Domain
Different scenarios for the generation group

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

System Data
- System Base: 10 MVA
- Frequency: 50 Hz
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“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

Coalesced Gas Turbine and Power System M&S using Modelica
Multi-domain Modelica Model: **ThermoPower**+OpenIPSL

Coalesced Gas Turbine and Power System M&S using Modelica
Model Identification
Parametrizing the GGOV Model w.r.t. the ThermoPower Turbine Model

\[ K_{\text{turb}} = 1.5 \]
\[ W_{\text{fml}} = 0.15 \]

\[ g_4(s) = \frac{1 + T_c}{1 + T_b} \]
\[ T_b = 0.14101 \]
\[ T_c = 0.11514 \]
\[ t_{\text{eng}} = 0 \text{ (no delay)} \]
\[ \dot{x} = Ax + Bu \]
\[ y = Cx + Du \]

**Eigenvalues and Contribution**

<table>
<thead>
<tr>
<th>Eigenvalue</th>
<th>( T(s) )</th>
<th>Contribution to states</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_1 = -7.092 )</td>
<td>0.141</td>
<td>( g_4(s), \dot{x} ) 100%</td>
</tr>
<tr>
<td>( p_2 = -0.25 )</td>
<td>4.0</td>
<td>( g_4(s), \dot{x} ) 61.9%</td>
</tr>
<tr>
<td>( \text{gasFlowActuator}, \dot{y} )</td>
<td>38.1%</td>
<td></td>
</tr>
</tbody>
</table>

Only a zero \( z_1 = -8.685 \) with \( T(s) = 0.115 \)
Time Response:
Response due to a Load Change Event - Multi-domain 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)
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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: