Experiences in Power System Multi-Domain Modeling and Simulation with Modelica & FMI

The Case of Gas Power Turbines and Power Systems

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Abstract—**The turbine-governor models that are currently used in studies of power systems include over-simplifications of turbomachinery elements. Due to the growing need to support intermittent energy resources with other energy sources like gas turbines, more detailed models including an explicit representation of the physical dynamics are attractive. In this paper, the advantages of the Modelica language and the FMI standard are considered to carry out modeling and multi-domain simulation of gas turbines with power grids, which can be used to evaluate scenarios of power variability. The work gathers preliminary results of the potential that FMUs offer to promote the exchange of turbine models by manufacturers and to conduct multi-domain simulations in several tools.**

Keywords—Power systems; Gas turbines; Multi-domain modeling and simulation; Modelica; Model Exchange, FMI

I. INTRODUCTION

A. Motivation

The integration of Variable Energy Resources (VER), such as wind and solar power, requires the presence of other power sources due to the intermittent nature impact on the power grid operation. The variability of wind and solar power is manifested in slow and fast fluctuations. The increase or reduction of power required to deal with fast power fluctuations can be achieved by means of fast response sources such as natural gas turbines [1].

A reliable operation of power systems with high penetration of VERs depends, among other factors, on more reliable models that can be tailored to the several kinds of power system simulations. In the early 1990s, computational limitations and the limited availability of both measurements and modeling data lead to the development of simple models, such as the GAST turbine-governor model [2] which was widely used in the United States, but has been demonstrated to be inaccurate and therefore has been replaced by slightly more detailed models such as the GGOV1 model. Existing gas turbine models, such as GGOV1 [3], IEEE [4] and the Rowen model [5], have different levels of complexity and accuracy and have been widely used. However, they implement an abstraction of the physical representation of the gas turbine dynamics, in the form of logic and transfer functions, which results in loss of information of non-linear physical dynamics. A recent study [6] shows that more detailed models are required to include the grid frequency dependency of gas turbines, with the aim of undertaking power system stability studies when the turbine is exposed to abnormal grid frequency variations. The correctness of the more complex physical models of gas turbines relies on the availability of data from the manufacturers who create and then share such models with turbine owners, but are not readily available for most grid analysts due to IP concerns.

B. Previous works

Another approach to improve modeling accuracy, for which specialized tools have been built [7][8], is to model the gas turbines using thermo-mechanical principles instead of transfer function approximations. While this approach is attractive, the domain specific tools available are not able to cope with the scale and complexity of power networks [9]. With the recent advances of Modelica in the area of large-scale modeling and simulation [10], its growing applicability for large power grids [11] and the purpose-built features of the Modelica language for multi-domain simulation, it is attractive to exploit the use of Modelica given the availability of suitable libraries for both domains: ThermoPower for the Gas Turbines [11], and OpenIPSL [12] for the power system.

Taking into consideration that either the turbine-controls, the turbine, or the power system model may not be available in Modelica or that the owner is not able to share the model due to intellectual property concerns, the FMI standard is a suitable approach exchange models. However, this will come at the price of unforeseen challenges with the simulation tools, which this paper reports on.

C. Paper Contributions

ITEA3 OpenCPS (Open Cyber-Physical System Model-Driven Certified Development) is a multidisciplinary European research project that involves partners such as Electricité de France (EDF), KTH, Linköping University, Saab and Siemens. The project started in December 15 and it is expected to finish at the end of 2018. The focus is placed on the creation of tools and environments for model-based development of cyber-physical systems which are becoming progressively complex and essential for the industry. There is also an implicit need to face challenges such as tool interoperability and vendor lock-ins. Within this context, the project aims to:

- Provide interoperability between the Systems Modeling Language (SysML), the Modelica language and the Functional Mock-up Interface (FMI) standards, together with improved (co-) simulation execution speed and verified code generation, to improve tool interoperability.
- Develop modeling and simulation toolchains that can be applied to cyber-physical and multi-domain systems [13].

One of the project's work packages is focused in the development of use-cases and benchmark cyber-physical models that could be used to test the functionalities of the OpenCPS tools.

Within this context, this paper presents the development of a multi-domain gas turbine and power grid equation-based model, as a benchmark model for testing the functionalities of the OpenCPS toolchains. The Modelica multi-domain model is composed by the physical model of a gas turbine, the governor (a controller that regulates the turbine's speed) and a Single Machine Infinite Bus (SMIB) power network, modeled as independent FMUs and simulated as a single model.

The work presented in this paper is organized as follows. In section II, the developed Modelica package with its single-domain and multi-domain models is presented. Section III describes the simulations that were carried out on the models, and the tools that were used with that aim. In Section IV, the analysis of results is presented and the conclusions are stated in Section V.

II. MODELS

A. *Package Structure*

The equation based models were built or/and modified inside of a package structure in the Dymola F2016 Modelica IDE. The adopted package structure was conceived to classify the models in terms of the domain they belong to. The first two packages, namely *TurboMachineryDomain* and *PowerSystemDomain*, contain the physical gas turbine models and the electric power system models, respectively. A third package, called *MultiDomain*, comprises the results of merging components from the two former packages to obtain the multi-domain equation based models.

B. *Turbo-Machinery Domain Modelling*

The *TurboMachineryDomain* package contains models which employ ThermoPower components. Its contents are organized in 3 sub-packages, namely *GTArrangements*, *GTModels* and *Tests*. *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 steam, gas and combined cycle plants [11] [14].

The *GTArrangements* package was developed to include elementary gas turbine topologies. The *SingleShaftGT* model represents a single shaft gas turbine and it is based on the *Plant* model of the Brayton Cycle examples of *ThermoPower*. The model excludes the boundary conditions, sensors and actuators and only focuses on the internal components of the gas turbine. The parameters of the compressor, combustion chamber and turbine are propagated and therefore, the *SingleShaftGT* can be used as a generic block in the representation of gas power plants.

The second package has the models that result from combining the basic parametrized gas turbine arrangement with given boundary conditions, sensors and actuators. The only example included to date is the complete ThermoPower Single Shaft Gas Turbine *ThPowerSSGT* model, which is shown in Figure 1.

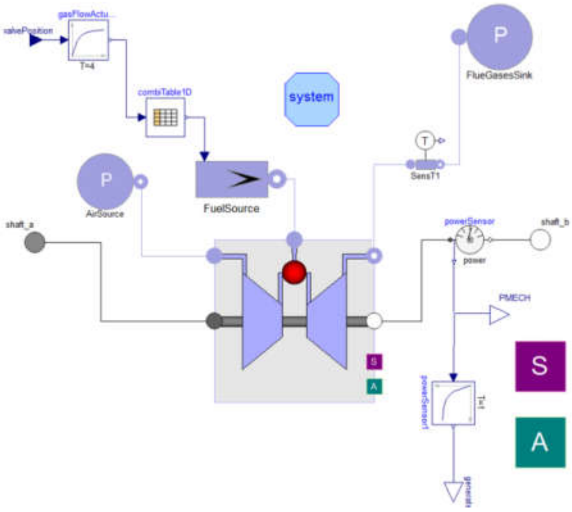


Fig. 1. The ThermoPower Single Shaft Gas Turbine model

C. *Power System Domain Modelling*

The use case 2 of the OpenCPS project work package which this paper reports on required different modeling of simulation scenarios. Two examples of these scenarios are a SMIB model without any controls and a SMIB model with only excitation system. The related generation group and control models were added within the sub-packages *Generation_Groups* and *Controls*, respectively.

The GGOV1 model implementation of the *OpenIPSL* library was modified so to fit the needs of the studies of this work. The re-design of the GGOV1 model consisted in explicitly showing its internal composite blocks. This means that a separate model was created for each of the three controls logics that are inside of the GGOV1 model, namely the load limiter, the acceleration limiter and the main governor. Another model was developed to represent only the turbine, thus obtaining a convenient way to re-use the models when a certain study requires only the turbine and the governor instead of all additional (simplified) turbine controls and protections.

A SMIB network model was developed for each of the generation groups. These models follow the inheritance feature of the Modelica language to extend one of two basic partial models, where common network elements and parameters are specified. Figure 2 shows the SMIB network case where the load model is stochastic and the generation group has no controls.

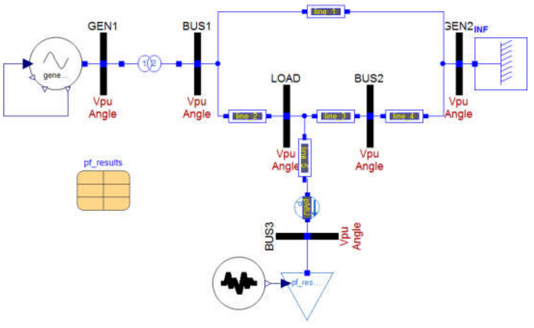


Fig. 2. SMIB network model with no turbine and governor models

As it can also be seen from Figure 2, the SMIB network model also entails the definition of a variable load component, which can behave deterministically or stochastically. The latter requires a noise signal as an input.

The Modelica code of this variable load model is as follows:

```
model VariableLoad "PSS/E Load with variation"
  extends OpenIPSL.Electrical.Loads.PSSE.BaseClasses.baseLo
ad;
  parameter Real d_P "Active Load Variation (pu)";
  parameter Modelica.SIunits.Time t1 "Time of Load Variatio
n";
  parameter Modelica.SIunits.Time d_t "Time duration of loa
d variation";
protected
  parameter Real PF=if q0 == 0 then 1 else p0/q0;
  parameter Real d_Q=(p0 + d_P)/PF - q0;
public
  Modelica.Blocks.Interfaces.RealInput u annotation (Placem
ent(transformation(extent={{48,16},{88,56}}), iconTransform
ation(extent={{-100,36},{-62,74}})));
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;
```

The code of this model is essentially the same as the original variable load model from the OpenIPSL library, with the difference that it has a real input for modulation **u**. Consequently, the new model has a component representing the physical load variability plus a component that allows for active power modulation. The second component is adjusted by the parameters `d_P`, `d_t` and `t1`, while the former relies on the definition of the modulation, namely noise injection source that is connected to this model.

This model allows to consider the stochastic behavior of the load, which in this case represents an "aggregate" of an entire area of the system. As such, this allows to also consider VER variability at the lower voltage levels aggregated by this load.

D. Multi-Domain Modelling

A SMIB network model and a governor block model from the *PowerSystemDomain* package can be combined with the physical model of a gas turbine from the *TurboMachineryDomain* package. The result of this procedure gives the so-called multi-domain model that can be appraised in Figure 3.

A template called group set has been created to allow the connection between the electro-mechanical generator model and the detailed gas turbine model. Even though they still rely on the previously defined groups of the *PowerSystemDomain* package, they also include an **interface block**. The function of this new element is to relate the rotational mechanics (flange internal variables) of the gas turbine model with the generator mechanical power and speed, as shown below:

```
model TM2EPConverter
  "Interface between OpenIPSL generators and ThermoPower ga
s turbine models"
  import Modelica.Constants.pi;
  outer OpenIPSL.Electrical.SystemBase SysData
  parameter Integer Np=2;
  parameter OpenIPSL.Types.ApparentPowerMega S_b=SysData.S_
b
    "System base power"

  Modelica.Mechanics.Rotational.Interfaces.Flange_a shaft
  Modelica.Blocks.Interfaces.RealOutput PMECH
  Modelica.Blocks.Interfaces.RealInput SPEED
  Real omega_e;
equation
  omega_e = der(shaft.phi)*Np;
  SPEED = omega_e/(100*pi) - 1;
  PMECH = der(shaft.phi)*shaft.tau/(S_b*1e6);
end TM2EPConverter;
```

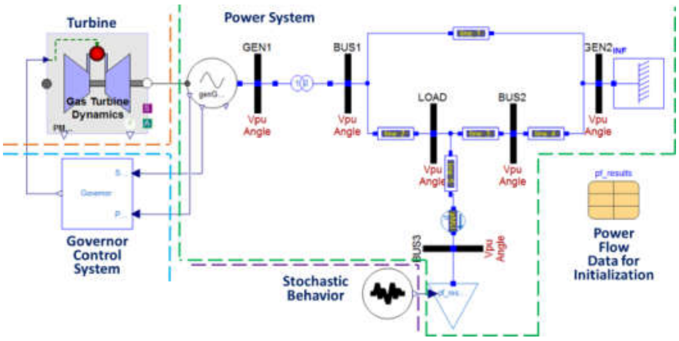


Fig. 3. Multi-domain SMIB model with GGOV1-based governor model

III. STUDIES USING THE MODELS

A. Load Change Event Simulations

A comparative study was carried out to verify the time-domain response of the models under a load change event. A simulation of 100 seconds was performed on both the multi-domain and power-system models with the same governor model. The active power of the load was increased by 0.2 pu after 30 seconds of simulation, and was set back again to the original value after 20 seconds.

In the second simulation scenario, the load model contained a sinusoidal variation of 0.02 Hz and 0.05 pu of amplitude to model slow variability in the aggregate load model's response. Noise has also been injected to represent rapid stochastic variability. The sample period of the noise has been set to 0.02 seconds, while the expectation value and the standard deviation were set to 0 and 0.0005, respectively.

B. Simulations using FMUs

The multi-domain models above are those developed for Use Case 2 of the work package D5.3B in the ITEA3 OpenCPS project (mentioned in section I.C). Hence, the models need to be compatible and follow the different toolchains of OpenCPS. Two work streams were adopted in the form of Master Simulation Tools (MST) which are depicted on Figure 4, together with the long-term scope of testing for this use case.

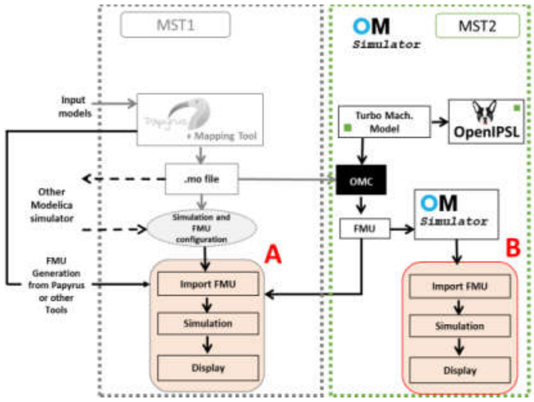
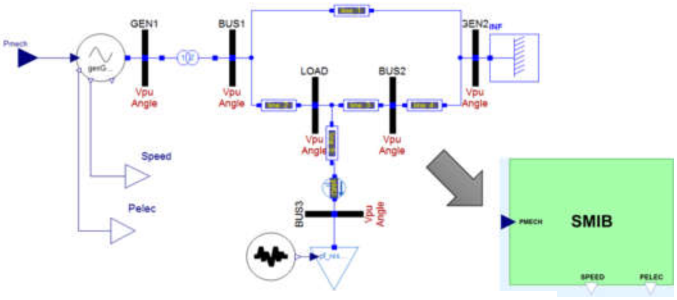


Fig. 4. MST Workflows for OpenCPS D5.3B Use Case 2

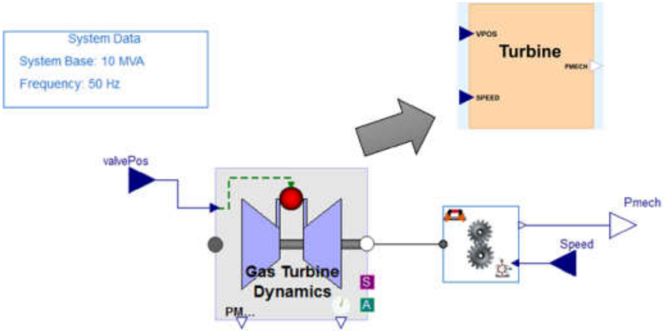
Blocks A and B of the MST workflows diagram in Figure 4, refers to a stage that involved the import of FMUs, their simulation and the results display. The simulation of such FMUs will be carried out using OpenModelica and Papyrus when all the functionalities required are developed in the OpenCPS project. In order to determine potential challenges that both Papyrus and OpenModelica will face with the models described in the previous section, a test was conducted in three other FMI-compliant tools.

A simulation of the multi-domain model with stochastic load behavior was made in Dymola, and the Modelon FMI Toolbox and FMI Kit for MATLAB/Simulink. The multi-domain model was implemented from three FMUs. For this purpose, the original model was split into three blocks, from which FMUs were generated for Model Exchange in Dymola. These blocks corresponded to the governor, the detailed turbine model and the SMIB network model.

Figure 5 show how the SMIB network and the turbine blocks have been created from their respective Modelica models. The ThermoPower gas turbine model makes use of flanges but FMU blocks require *RealInput* / *RealOutput* interfaces. Thus, the *TM2EPConverter* (presented in section II) has to be moved from the generator group model to the turbine block, shown in the bottom of the figure.



(a) Power System FMU Model



(b) Gas Turbine FMU Model

Fig. 5. FMU blocks creation from the source Modelica models

It can be seen in Figures 6 and 7 how the FMU blocks were combined to re-create the complete Multi-Domain model in Dymola and Simulink, respectively. The blocks were exported and imported as FMUs for Model Exchange according to the FMI 2.0 standard.

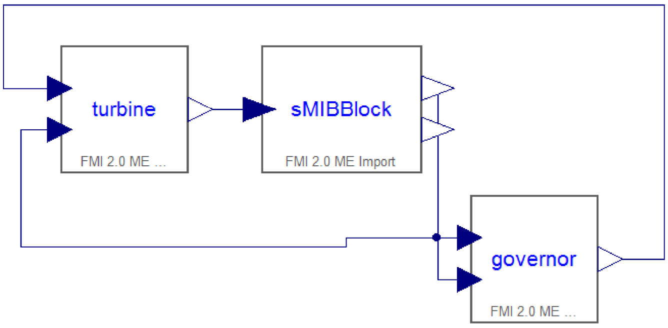


Fig. 6. FMU-based multi-domain model in Dymola

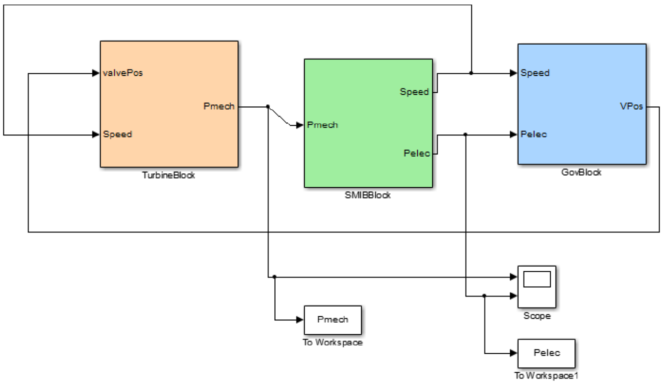


Fig. 7. FMU-based multi-domain model in Simulink

IV. RESULTS

The results of the studies and simulations performed on the models are presented in this section.

A. Simulations using the Entire Modelica Models in Dymola and OpenModelica

The governor was added to the Multi-Domain and Power System-only models to evaluate their time response to a load change. It is worth to mention that the limiters were not included as part of the control logic.

Figure 8 shows a plot of the electrical power delivered by the generator. The simulation was performed with the variable step DASSL solver and a tolerance of $1x10^{-4}$.

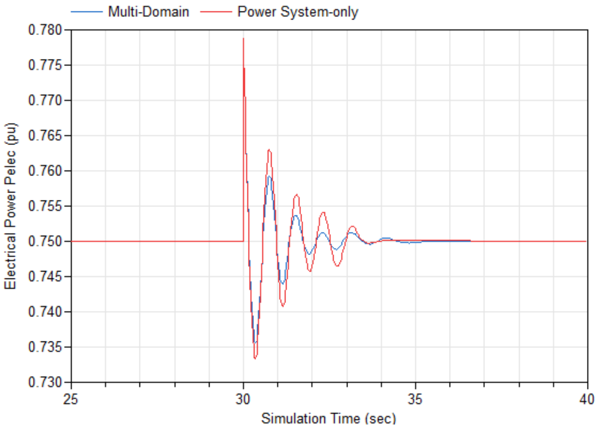


Fig. 8. Electrical Power Response Comparison

The load change test was then applied to the models with the stochastic model of the load. Figure 9 shows once again the time response of the generator electrical power.

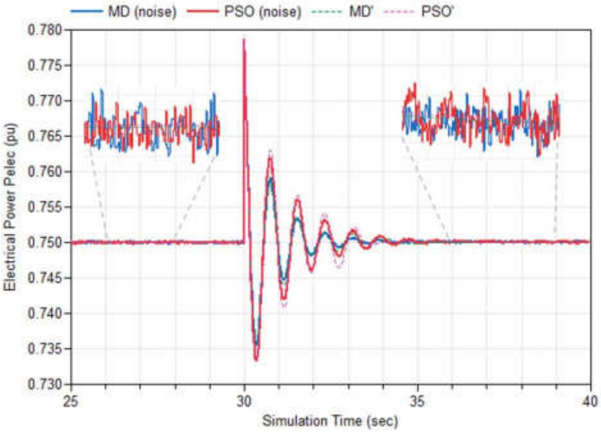


Fig. 9. Electrical Power Response Comparison when the models have stochastic load. MD stands for multi-domain and PSO stands for Power System-only.

Fixed step solvers with the same sample period of the noise and the appropriate tolerance adjustment were required to perform simulations. However, none of the available fixed step solvers in Dymola worked. The DASSL solver was used instead with the interval length set to the sample period of the noise.

A successful simulation of the original multi-domain model with noise was performed to verify that OpenModelica was compliant with both OpenIPSL and ThermoPower components. In other words, once the same simulations of this section were performed in OpenModelica, the same results were obtained.

B. Simulation Results from FMU Models

The SMIB network model with stochastic load, the governor and the physical gas turbine model were exported from Dymola as FMUs. Then they were imported and simulated in Dymola, and Simulink as described in Section III. Figures 10 and 11 show the electric power response difference for a simulation without any perturbations and for the load change event, respectively. The used solvers are displayed in the legend of the plots.

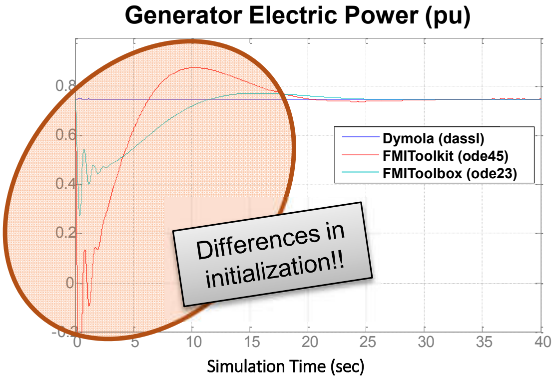


Fig. 10. FMU simulation initialization differences

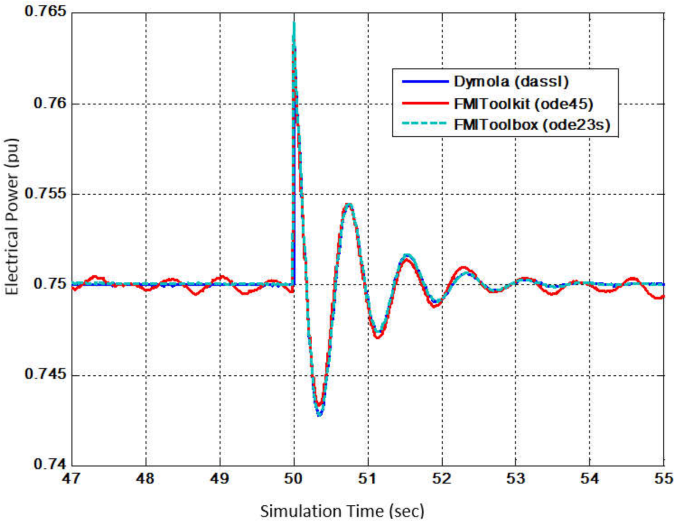


Fig. 11. Electrical Power response from FMU simulation in several tools

Several issues were faced during the FMU simulation and will be reported in the discussion section.

OpenModelica was also tested in the procedure that involved the import and simulation of FMUs but, it was not possible to compile the FMUs once they were imported.

V. DISCUSSION

The explicit model of the ThermoPower gas turbine is colloquially described as "academic" and lacks the expected complexity of a model that a manufacturer could provide. However, it is still possible to appreciate certain differences in the responses of typical variables of interest when compared to those of a commonly used model in power system analysis. For instance, the GGOV1-based turbine model is not dependent on the shaft speed and therefore, the changes on the mechanical power are due to the governor response. This is however not the case of the ThermoPower turbine model. This is one of the reasons why a different oscillatory behavior is obtained in the response of the electric power of the Multi-domain model and the Power system-only model (see Figure 8).

As can be appreciated in Figure 9, the inclusion of the stochastic behavior of the load yields to more realistic results. This is especially convenient in positive-sequence phasor time simulations performed in the context of cyber physical systems. It is important to keep in mind the need to produce simulation results that better resemble the measurements of the system.

The simulation with FMUs seems to be still a challenge. Several difficulties were found in the different tools that were used. Although it is always possible to generate, import and simulate FMUs from Dymola, this is not the case of the remaining tools. In OpenModelica, for instance, it has not been possible to compile the models with the FMUs. The log shows a compilation error when the default `gcc` compiler is used. The authors speculate that the minimalistic GNU sub-system used by Open Modelica cannot see the environment variables required by the compiler. An attempt to change the compiler to the Microsoft VS 2013 was not successful. MATLAB/Simulink often crashed when the FMU toolboxes were used to simulate the multi-domain system. In many cases the simulation was stopped due to an error that was always by-passed by the solvers in Dymola. This initialization problem relies on the ThermoPower model and is reported as a "*logarithm of a negative number*" error.

Finally, to obtain equivalent results it is necessary to ensure the availability of the corresponding solvers in the different tools. The variance that, for instance, the different solvers produce in the initialization stage is evident in the response of Figure 10. These issues are expected to be solved once the tools fully implement the co-simulation with solver features of the FMI standard, or that the tools make additional efforts in their initialization methods they apply when using the model exchange standard as in this paper.

VI. CONCLUSIONS AND FUTURE WORK

The following conclusions and recommendations can be drawn from the present work:

- A multi-domain model has been derived to allow detailed representations of gas turbines and in power grid simulations. Although the models are simple due to the lack of publically available information, the turbine modeling methodology provides a framework for future studies with multi-domain models in power systems.
- It is possible to exchange the models in the form of FMUs. This opens an opportunity of getting detailed models of the gas turbines from the manufacturers while protecting their intellectual property. The right choice of the *solver*, its availability throughout the different tools and the *process noise modeling* (load and/or generation uncertainties) is still a challenge.
- The two Simulink-based tools used the FMI for ME feature which requires them to initialize and simulate ALL of the FMUs using their own solvers. Our results show that both tools will need to enhance their initialization methods to provide consistent response among tools.

A better model that includes among other things the *valves dynamics* is desired and would allow better modeling of the fuel mass flow rate. The present model can be extended to cover *Combined-cycle power plants*, using *ThermoPower* and other libraries such as *ThermoSysPro* [15] which contain a complete model of combined cycle plants that can be used as a starting point.

ACKNOWLEDGMENT

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