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Multi-Domain Semantic Information and Physical Behavior Modeling of Power Systems and Gas Turbines Expanding the Common Information Model

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ABSTRACT Due to the rapid increase of intermittent energy resources (IERs), there is a need to have dispatchable production available to ensure secure operation and increase opportunity for energy system flexibility. Gas turbine-based power plants offer flexible operation that is being improved with new technology advancements. Those plants provide, in general, quick start together with significant ramping capability, which can be exploited to balance IERs. Consequently, to understand the potential source of flexibility, better models for gas turbines are required for power system studies and analysis. In this paper, both the required semantic information and physical behavior models of such multi-domain systems are considered. First, UML class diagrams and RDF schemas based on the common information model standards are used to describe the semantic information of the electrical power grid. An extension that exploits the ISO 15926 standard is proposed herein to derive the multi-domain semantics required by integrated electrical power grid with detailed gas turbine dynamic models. Second, the Modelica language is employed to create the equation-based models, which represent the behavior of a multi-domain physical system. A comparative simulation analysis between the power system domain model and the multi-domain model has been performed. Some differences between the turbine dynamics representation of the commonly used GGOV1 standard model and a more detailed gas turbine model are shown.

INDEX TERMS CIM, cyber-physical systems, dynamic simulation, equation-based modeling, IEC 61970, information modeling, ISO 15926, Modelica, power systems simulation, power systems modeling.

ACRONYMS

CEN	– European Committee for Standardization
CENELEC	– European Committee for Electrotechnical Standardization
CGMES	– Common Grid Model Exchange Specification
CIM	– Common Information Model
EC	– European Commission
ENTSO-E	– European National Transmission System Operators for Electricity
ERGEG	– European Regulators' Group for Electricity and Gas
ETSI	– European Telecommunications Standards Institute
GGOV1	– Gas Turbine Governor Model
GPML	– General Purpose Modeling Languages
IEC	– International Electrotechnical Commission
IEEE	– Institute of Electrical and Electronics Engineers
IER	– Intermittent Energy Resources
ISO	– International Organization for Standardization

OpenIPSL	– Open Instance Power System Library
OWL	– Web Ontology Language
PTI	– Power Technologies International
RDF	– Resource Description Framework
SySML	– Systems Modeling Language
TSO	– Transmission System Operator
UML	– Unified Modeling Language
W3C	– World Wide Web Consortium

I. INTRODUCTION

A. MOTIVATION

The efforts to achieve a more sustainable energy supply imply a transition to an overarching grid architecture that allows acceptable levels of reliability and security and affordable prices [1]. Due to the growing adoption of Intermittent Energy Resources (IER) for power generation, the challenges that their intermittent nature imposes on power grid operation requires special attention.

Reliable operation of power systems with high penetration of IERs depends, among other aspects, on more trustable forecasts and accurate models that can be used by various power system analysis tools; in particular, those that involve in power systems simulations.

On one hand, the variability of wind and solar power can be modeled as slow and fast fluctuations. On the other hand, the power increase/reduction required to deal with these power fluctuations can be achieved by means of ramping sources like gas natural turbines and their fast frequency regulation capabilities. The operational flexibility of gas power plants makes them a good backup for IERs.

Existing gas turbine models, such as GGOV1, IEEE [2] and Rowen, have different levels of complexity and accuracy. Gas turbine simple models were initially preferred, primarily due to computer power and data availability limitations of the time when they were proposed (i.e. early 1990s). However, the aforementioned widely-accepted models do not employ a detailed physical representation of the gas turbine dynamics. Instead, their representation is based on abstractions in the form of logic and transfer functions [3], which are approximations of the physics governing the thermo-mechanical process, not strictly the physical law's in mathematical form.

It has been recently shown [4] that more detailed models are required to incorporate the frequency dependency feature of gas turbines with the aim of performing power system stability studies during abnormal system frequency behavior; however, transfer functions approximations have shown to be insufficient for this purpose [5]. To ensure the correctness of the more complex physical models of gas turbines relies on the availability of data from the manufacturers, and thus it is reasonable to expect that they can provide such modeling data [4].

B. INFORMATION MODELING STANDARDS AND RELATED WORKS

After the adoption of the "Third Energy Package" [6] of legislative proposals, the European Commission (EC) issued the mandate M/490 to the European standardization bodies CEN/CENELEC and ETSI. A resulting report [7] considered that the Common Information Model (CIM) (IEC 61970, 61968 and 62325) [8] together with IEC 61850 [9] were the most relevant data models that are required for establishing a "common information model that is to be used throughout many applications and systems".

CIM supports both detailed connectivity model, also called *node-breaker*, and electrical topology model, also called *bus-branch* model. The detailed connectivity model is the input to a topology processor. Traditionally the long-term planning tools have been operating on bus-branch model where the output of a topological process is designed rather than computed. Modifications of this *bus-branch* model have been proposed in [10], which address limitations for on-line network operations that require topology connectivity information and equipment parameter information.

Although the CIM is currently addressing the requirement of dynamic information exchange through IEC-61970-302 [11], the underlying modeling approach represent dynamics models by a name, parameter list and block diagram description based on logic and transfer functions. Consequently, it is expected that software vendors have implemented those block diagrams interpretation in the same or similar way. As part of the CIM for dynamic conformity, the behavior for a given event might be compared against the expected behavior and might not incorporate all necessary information to accurately represent power plants, whose characteristics can provide relevant impact on power systems studies. To address these issues, standards such as the ISO 15926 [12], which is driven by the oil and gas industry, can be exploited and its data model can be integrated into the CIM. The work in [13] enumerates different characteristics of this ISO standard, which can elucidate the exchange of more detailed power systems information models.

Furthermore, information exchange of CIM for dynamic models can be complemented with equation-based modeling to provide a strict mathematical representation of the models. The work in [14] provides a proof of concept in this direction, which can be easily extended provided that (1) the equation-based models for both detailed turbine and power grid are available, (2) the CIM is expanded with the ISO's semantics and associated data, and (3) that mapping rules between the information and equation rules are defined, seen in [12].

C. CONTRIBUTIONS

In this paper, the semantic information provided by the ISO 15926 standard for power plant operation was studied. From the ontological information provided by this standard, implementation designs are proposed herein.

The first proposal covers a basic UML design for a more detailed description of gas turbines, which can be integrated to the UML-based semantics proposed by the CIM standard. The second design proposal involves a full adoption of RDF semantics. It requires that the semantics subsets from the concepts of the CIM IEC 61970 and the ISO 15926 to be expressed in terms of the RDF language, by the definition's extension given by the standards IEC 61970-501. The CIM standard should be harmonized with the ISO 15926 to make it possible to make studies that utilize both information sets.

Multi-domain studies are getting more and more relevant and there is a need for modeling languages that can support and represent different static and dynamic behavior of multi-domain physical systems. To comply with possible industry interoperability requirements, regarding the simulation of power system dynamic models, this work considers modeling and simulation, and comparison, of power system domain (GGOV1-based) models vs. multi-domain models of gas turbines and grid, using the Modelica equation-based modeling language. This work proposes and gives a proof-of-concept on the use of Modelica libraries to include turbo-machinery features in multi-domain power systems for both the multi-domain semantic information modeling and dynamic simulation of these models.

The value of this work is that, while the first part results in making available all necessary semantic modeling information of multi-domain representation in CIM; the second part provides all necessary equation-based models in Modelica. Thus, the approach in [14] can be rapidly applied for multi-domain model transformation from an extended CIM model to a Modelica-based simulation model.

D. PAPER ORGANIZATION

The organization of this paper is divided in the following sections. In Section II a basic description of the available modeling languages for information and equation-based modeling is given. In Section III the authors present a proposal for extending the CIM standard with information from other information standards. Section IV shows how the equation-based modeling language is used for the development of multi-domain models that can be applied to power system simulation studies. Finally, in Section V the authors summarize the conclusions and discussion of this work.

II. BACKGROUND

A. SEMANTIC WEB MODELING AND GENERAL PURPOSE MODELING LANGUAGES

The World Wide Web Consortium (W3C) provides standard Semantic Web languages to create semantic models of the real world. The Resource Description Framework (RDF) [15] is a semantic modeling language, utilized in Semantic Web for managing distributed data, which organizes the data providing an integrated description of objects in the world and their relationships. The Semantic Web refers objects from the real world as resources and thus, this definition is extended to apparatuses from engineering domain.

Because RDF manages the data in table cells of three values (see Table 1), the basic data construct for RDF is called a *triple*. A triple has a subject as the identifier of a row; the predicate as the identifier of a column and the object as the identifier of the value of a cell [16]. RDF is used by the CIM to implement an ontology with semantics from the power systems domain. The Web Ontology Language (OWL) [17] is another language from the Semantic Web that provides properties and data values for distributed data modeling.

TABLE 1. **Sample of gas turbine components triples.**

Subject	*Predicate*	*Object*
GasTurbine	consist_of	Compressor
Compressor	has_property	InletDesign Temperature
InletDesign Temperature	has_magnitude	Temperature

The concept of classes and attributes plays an important role in the development of information models but also in Model-Driven Software Engineering. Information models that are described by classes and attributes are often applied in software development [18]. The Unified Modeling Language (UML) is an Object Management Group (OMG) ISO Standard that provides specifications for system modeling [19] based on these concepts.

The UML offers a set of modeling elements representing the properties, structure and behavior of the system using attributes, classes and objects and their relations. The OMG defines also an extension of UML for the modeling of system engineering applications that considers hardware, software, information, and processes, called System Modeling Language (SysML) [20].

UML includes static information, such as the properties and structure of the system, and dynamic information, such as the methods that define the behavior of the system. UML semantics are classified in structural and behavioral categories. The former defines the meaning of the model's elements of an engineering domain at a specific point in time, e.g. through a class diagram representation. The latter category, on the other hand, defines model elements that change over time, e.g. by means of a sequence diagram representation.

In this work, an OWL representation for power plant modeling is studied, from where a proposal to extend the CIM is defined so to enhance the current existing UML and RDF representation of power system information.

B. INFORMATION MODELING FOR POWER SYSTEMS

The European Regulators' Group for Electricity and Gas (ERGEG) defined a set of recommendations stating the need for compliance and consistency with mandate M/490 and highlighting the importance of the interdependencies and information exchange of the national implementations of grid models, which refers to both static and dynamic information upon which these models are implemented [1].

Within this context, the CIM and the Common Grid Model Exchange Specification (CGMES) [21] adopted by the ENTSO-E provide the means for information exchange between Transmission System Operators (TSOs), to comply with the regulation and mandates. The CIM and CGMES reflect current TSO requirements for modeling of the ENTSO-E area for steady-state power flow and dynamic simulations (for relevant region) within the following standard packages:

1) IEC 61970-301 CIM Base defines a static information UML package containing semantics for the physical features of the power network and electrical and non-electrical characteristics of equipment static models.

2) IEC 61970-302 CIM for Dynamics Specification defines an information profile, containing the UML semantics for the dynamic characteristics of regulating equipment models, such as Turbine Governors or Excitation Systems.

The power system semantics that are specified by these two packages can be expressed in terms of the IEC 61970-552 CIM XML Model Exchange Format. CIM/XML is a subset of the RDF/XML standard format for serializing RDF with the CIM semantics. Thus, once a CIM model follows the RDF/XML format, its information can be processed with graph-based algorithms for power flow computation applications [22] or combined with equation-based models for dynamic simulations [14].

C. ISO 15926 FOR POWER PLANTS MODELING

The system dynamic information that the CIM IEC 61970-457 standard aims to cover, plays an important role for the coordination of Electricity Generation Companies and TSOs in planning and operation procedures. Some typical examples of such coordination include system reliability or plant operation, which are essential to avoid and correct large system disturbances. The CIM standard uses ontology languages like RDF so that we can easily harmonize with other ontologies that provide other information details, e.g. to model non-electrical energy equipment.

The ISO 15926 is an international standard created to model information that is produced during all the stages of a plant life-cycle process, i.e. from its design and construction to its operation. ISO 15926 provides the representation and the exchange of life-cycle data, based on the generic data model introduced by its ISO 15926-2 specification [23]. Furthermore, its ISO 15926-4 specification [24] introduces a reference data dictionary, which provides detailed information of plant objects, such as pipes and valves, which are required for the development of individual plant models. It offers a user-oriented language with basic terminology for representing integrated plant operations [25]. However, it requires to be mapped to a General-Purpose Modeling Languages (GPML), such as the UML. This paper aims to facilitate the creation and edition of models for this domain while ensuring interoperability with the CIM.

The ISO 15926 standard is denoted using OWL modeling semantics. Its modeling capabilities are studied herein, to gather the relevant features that can be integrated within the CIM. This ISO standard considers an object *Thing* as the most general entity type, which can be identified as an equivalent to the CIM *IdentifiedObject* class, and can be specialized into the two subtypes that are illustrated by FIGURE 1.

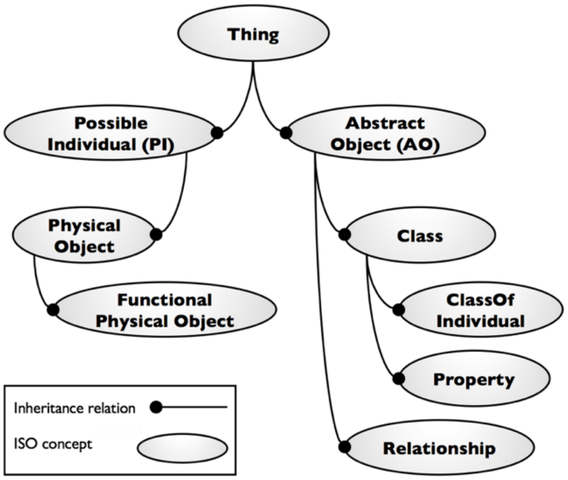

FIGURE 1. Subset of entity types from the ISO generic data model.

The entity type *Possible Individual (PI)* is required for the representation of industrial plant data, because it is a thing that exists in space and time. A *PhysicalObject* defines a PI that is a distribution of matter, energy or both, and its subclass *FunctionalPhysicalObject* determines the physical objects by their function.

The entity type *AbstractObject (AO)* is defined as a thing that does not exist in space-time. Therefore, AO models the classification and relationships between PIs. At this, ISO 15926-2 implements a comprehensive classification schema. In this paper, the main focus is put on subtypes *Class and ClassOfIndividual*,which are used to classify PI instances. Additionally, the *Property* subtype can be employed to quantify a number on a scale, and the *Relationships* subtype is aimed to be used to extend the structural modeling with the description of relationships between two or more *things*,e.g. specialization or temporal sequence [26].

In this work, relevant information from the ISO 15926 is modeled in UML, to provide a modeling proposal for integration of power plant information into the CIM.

D. EQUATION-BASED MODELING FOR MULTI-DOMAIN SYSTEM SIMULATION

The CIM for Dynamics profile includes the definition of block diagrams of the correspondent network components and their attributes. However, a computer-readable description would require a unique mathematical specification to guarantee consistency for modeling [27]. The mathematical representation of these models must be developed to ensure unambiguous modeling, consistent exchange of the information to represent dynamic behavior, and most importantly, to perform consistent simulations in different tools. The Modelica language satisfies these requirements [28] and it allows the implementation of an unambiguous equation-based description of mathematical models defining a power network.

Modelica is an object-oriented equation-based programming and modeling language, which allows the modeling of cyber-physical systems using a strict and openly standardized mathematical representation for dynamic modeling and simulation. It describes connections with bidirectional instead of unidirectional signal flows, such as connections used within Simulink [28].

Another language that allows for mathematical representations is the Wolfram Language, that is used in the Mathematica tool [39]. Mathematica is a proprietary computer-aided mathematics tool, which provides symbolic manipulation of equations and solvers. It also supports object-oriented paradigm with strong focus on solving pure mathematical operations, such as algorithm development. With Mathematica as a modeling language is also possible to describe the equations of the physical system, but it requires much more manual labor to develop the models than in Modelica. Mathematica models cannot run as standalone applications, unless the target system have the same configuration as the system used to generate the executable files of the model. In fact, to address these limitations, Mathematica now provides means to interface Modelica models using the SystemModeler[1] Modelica-compliant software.

A model in Modelica is entirely decoupled from the mathematical solver that is used to provide a numerical solution of the equations [28]. This characteristic guarantees an unambiguous way of modeling by providing a standard language to prescribe dynamic behavior. Modelica models need to be provided with adequate starting guess values to perform simulations. The OpenIPSL library [27] uses as starting guess from power flow solution values, and Modelica tools solvers compute the initial conditions of the entire dynamic model (for all algebraic and dynamic equations) to perform dynamic simulations.

The authors' previous works in the FP7 iTESLA project have used Modelica for power system modeling and Modelica-compliant tools have been used for simulations. The results from these simulations have been compared with those of proprietary simulation tools [29], [30].

III. MULTI-DOMAIN INFORMATION MODELING

This work proposes an extension for the current three-layer architecture that is used for CIM project implementation so to include more detailed information of non-electric power and energy systems. The aim is to develop better representations of the dynamic models of primary energy sources within the power system domain, illustrated herein for the case of Gas Turbines

A. EXTENDING THE CIM MODELING CONTEXT FOR MULTI-DOMAIN SUPPORT

The development of power system models using the CIM is based on message construction and a profiling methodology, which includes contextual modeling rules and a modeling framework. This framework is comprised by three main layers, as illustrated in FIGURE 2.

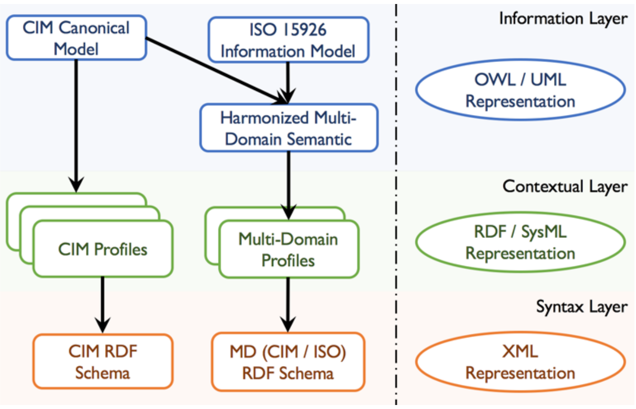

FIGURE 2. **Layered Architecture for the generation of CIM-based models with multi-domain information.**

The Information Model layer contains the entire CIM information canonical model represented in UML. The Contextual Model layer encapsulates the profile definition, and the Syntactical Model applies message assembly rules and implementation for information exchange [31].

FIGURE 2 shows a picture of the CIM modeling framework that includes the proposal for the extensions for the CIM profiling process. In the Information Layer, the multi-domain information from the ISO 15926 is added. The OWL representation of ISO 15926 can be parsed into UML, to complement the CIM canonical model with additional classes and attributes. The OWL representation is still considered in the Information Layer due to its natural integration with RDF artifacts in the Contextual Layer. Moreover, the current CIM Profiles can be extended, in parallel, with new profiles that can be used to describe multi-domain information.

With the inclusion of ISO information and the CIM Dynamics profile, the standard power system information models can be extended including more detailed information from another engineering domain. Thus, equivalent parameters related to transfer functions and gains that are commonly used to model the mechanical parts in the simulation model, could be substituted by parameters and equations from the thermo-mechanical domain that better describe the dynamic behavior of such components. FIGURE 3 shows the CIM GovCT1 turbine-governor model without the equivalent parameter. This model is selected in this work as example, because it suits the representation of gas turbines and shaft-combined cycle turbines.

Moreover, the standard power system can be designed by using SysML in such a way that it can be possible to express complete information about components, their constraints as well as inputs/output ports. The SysML representation can enhance the information models with additional physical information. In the Syntax Layer, the same

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[1] http://wolfram.com/system-modeler/

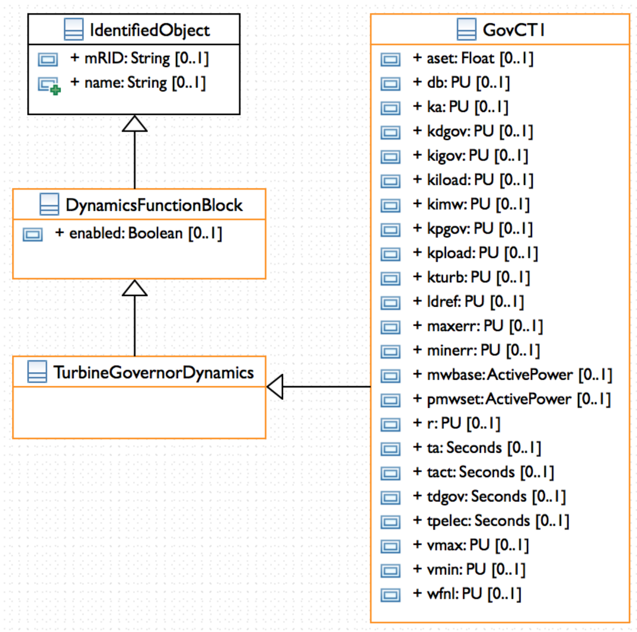


FIGURE 3. Information model of the gas turbine model GovCT1 without information related to the turbine.

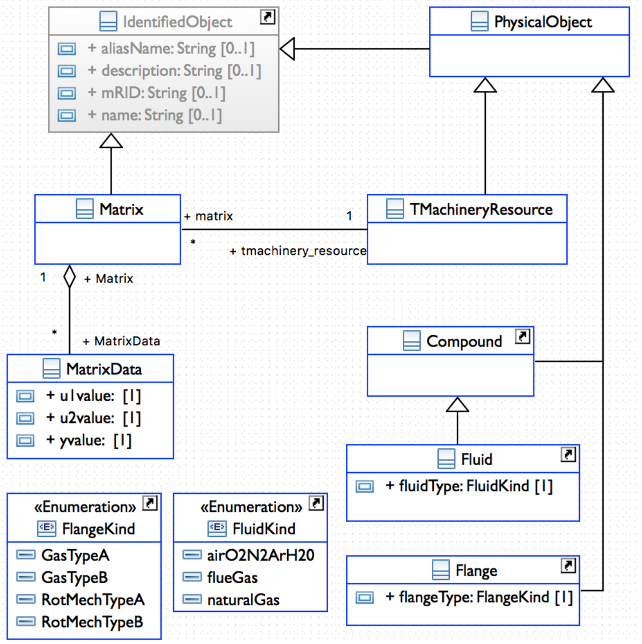


FIGURE 4. UML Class diagram with classes from the Core package, extended from the ISO 15926 standard definitions.

implementation of CIM-RDF artifacts, as described by the IEC 61970-501 standard [32], is considered.

B. UML EXTENSIONS TO SUPPORT MULTI-DOMAIN MODELING IN CIM

To enhance the CIM representation of non-electrical energy sources, such as Turbine models, CIM semantics are taken as a reference to include new turbo-machinery data. To illustrate this idea, the GovCT1 model that constitutes the entire turbine governor group of the GGOV1-based governor models, is taken as an example. GovCT1 class attributes are restricted to governor parameters and a simple representation of the turbine.

To create a harmonized multi-domain semantic representation of gas turbine models, some of the physical data types defined by the CIM Domain package can be reutilized. Furthermore, the "Domain" package can be extended with ISO-based units, referred by this standard as "Property" classes (see Table 2).

TABLE 2. Combining CIM Domain with ISO properties information.

Class	Unit	Source Standard
PU		CIM
Boolean		CIM
Float		CIM
Seconds		CIM
Rotation Speed	rad/s	CIM
Area	m2	CIM
Absolute Pressure	Pa	ISO
Absolute Temperature	K	ISO
Density	kg/m3	ISO
Mass Flow Rate	kg/s	ISO
Heat Capacity	J/K	ISO

The proposed ISO/UML representation has the *PhysicalObject* entity as the super-class for all physical concepts, and can be viewed as an extension to the CIM model to include the specific Generation and Load asset information. For naming and identification purposes, this class directly inherits the attributes from the CIM *IdentifiedObject* class. Instances of other thermo-mechanical concepts and classes are thus identified by their inheritance from the *PhysicalObject*. A *TMachineryResource* is created to distinguish only those *PhysicalObject* instances used to model a gas turbine element with flanges. In this way, classes such as *Fluid* and *Compound* are isolated from other dynamic components classes without removing their direct inheritance from *PhysicalObject* (see FIGURE 4).

The *TMachineryResource* class inherits from the *PhysicalObject* class, instead of directly inheriting from the *IdentifyObject* class following the definition provided by the ISO standard for *PhysicalFunctionObjects* as *PhysicalObjects*.

The classes *Matrix* and *MatrixData* though, are manually created from scratch based on the modeling concepts of the *ThermoPower* Modelica library and by following the same modeling principle from the CIM classes *Curve* and *CurveData*. In this case, *Matrix* and *MatrixData* are aimed to represent the look-up tables of each gas turbine component characteristic maps [33].

The *Flange* class is included to model the connectivity between several turbo-machines equipment, where an enumerator *FlangeKind* specifies the kind of connection, such as inlet shaft or outlet gas flow.

This resulting connectivity model mimics the relationship *Terminal-Connectivity Node* of the CIM model. In the context

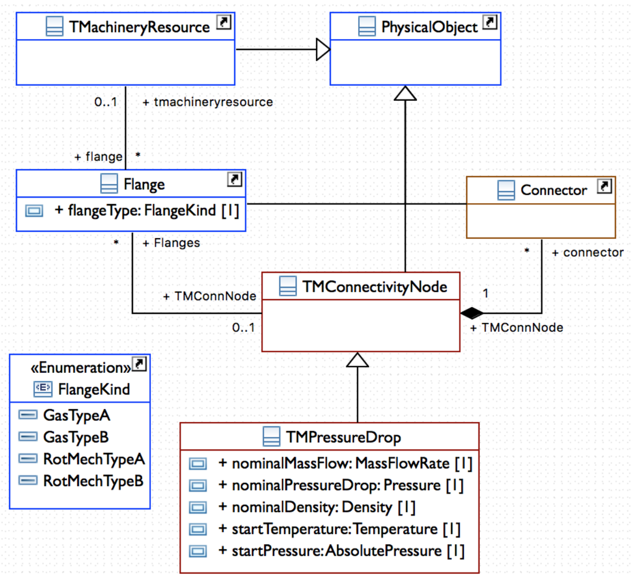


FIGURE 5. UML Class diagram with classes modeling the topology of turbo-machinery equipment, inspired by the ISO 15926 standard definitions.

of gas turbines, the suggested connectivity is expressed in terms of a *Flange-TMConnectivityNode* connection (see FIGURE 5).

Relevant to this work, a total of six packages have been created to classify the set of new classes to be used for the proposed semantic modeling approach (see FIGURE 6).

C. RDF SCHEMA TO SUPPORT MULTI-DOMAIN MODELING IN CIM

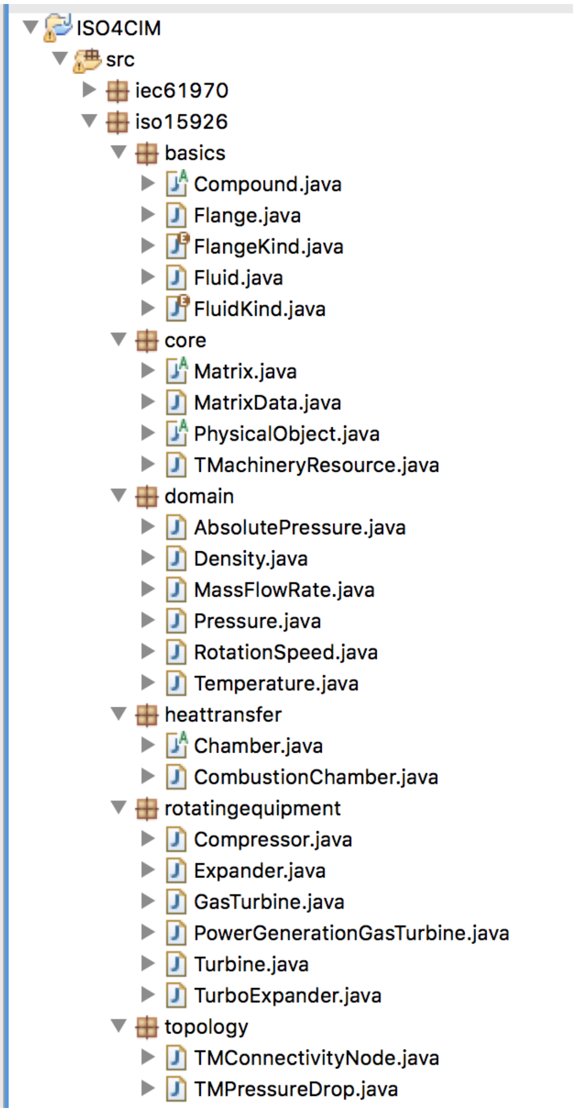
Following the class definitions from the previous section (see FIGURE 4, FIGURE 5 and FIGURE 6) the serialization of these classes has been implemented in JAVA with the Apache JENA library [34].

To comply with RDF implementation of new classes under the CIM definitions, an extra package has been created with a *vocabulary* definition that includes both IEC 61970 concepts and new concepts extracted from ISO 15926 (see FIGURE 7).

This implementation is used to create the RDF-triple prototype model representation, shown in the graph-like representation of FIGURE 8, which shows part of the basic definition of a Gas Turbine model.

As shown in FIGURE 9, RDF and CIM namespaces have been used to guarantee that the proposed enhancements comply with the naming and data structure definitions of their respective standards.

An additional namespace has been created which points to the proposed new semantics. This namespace comprises the new components required to define detailed models from the turbo-machinery domain. The resulting RDF model shows how the implementation follows the CIM object definitions and the unique identifiers for each object.



- ISO4CIM
  - src
    - iec61970
    - iso15926
      - basics
        - Compound.java
        - Flange.java
        - FlangeKind.java
        - Fluid.java
        - FluidKind.java
      - core
        - Matrix.java
        - MatrixData.java
        - PhysicalObject.java
        - TMachineryResource.java
      - domain
        - AbsolutePressure.java
        - Density.java
        - MassFlowRate.java
        - Pressure.java
        - RotationSpeed.java
        - Temperature.java
      - heattransfer
        - Chamber.java
        - CombustionChamber.java
      - rotatingequipment
        - Compressor.java
        - Expander.java
        - GasTurbine.java
        - PowerGenerationGasTurbine.java
        - Turbine.java
        - TurboExpander.java
      - topology
        - TMConnectivityNode.java
        - TMPressureDrop.java

FIGURE 6. Prototype implementation for package classification of ISO concepts, following an Object-Oriented approach.

IV. MULTI-DOMAIN EQUATION-BASED MODELING

This section addresses the equation-based modeling and simulation of multi-domain systems, which are pre-requisite to apply an automated model transformation method to transform the model from CIM to Modelica.

The OpenIPSL library [27] is used herein for the creation of a benchmark power network model used to perform dynamic simulations of a multi-domain power system model. This multi-domain model combines models of typical network components (e.g. generator and governor) with the turbine model from the turbo-machinery domain. The turbine model was developed using the *ThermoPower* library [35]. The naming convention from this library present similarities with the information from the ISO15926, and has also been used to define some of the parameters of the proposed information model in Section III.

There exist other libraries that provide turbine models, such as the NPSS project [36]. The NPSS is

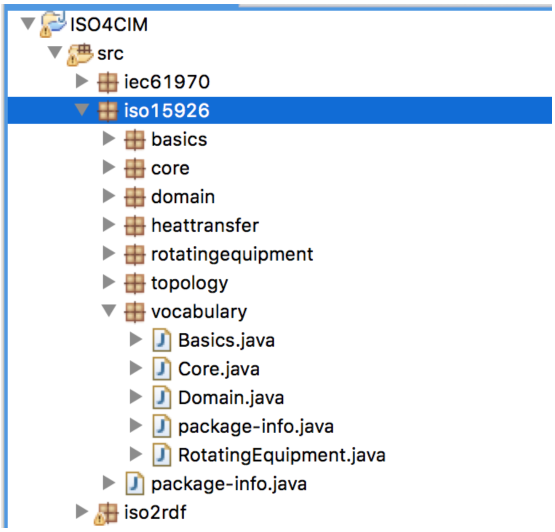


FIGURE 7. Prototype for package classification of ISO concepts and vocabulary.

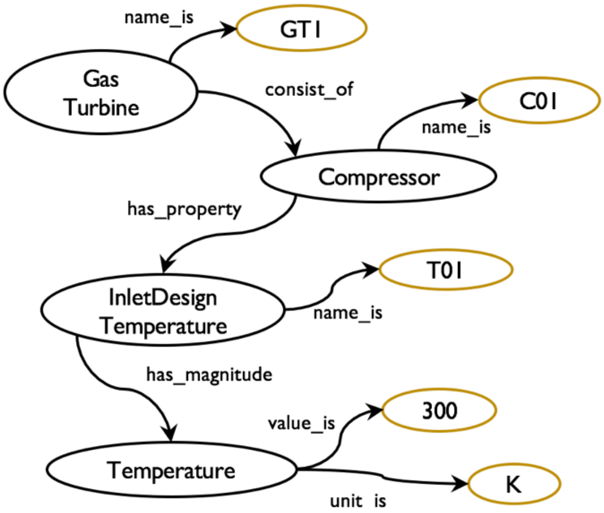


FIGURE 8. Subset of the graph for the compressor model of the gas turbine corresponding to the RDF representation.

```
<?xml version="1.0" encoding="UTF-8"?>
<rdf:RDF
    xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
    xmlns:cim="http://iec.ch/TC57/2013/CIM-schema-cim16#"
    xmlns:iso15="https://alsetlab.github.io/iso/15926/ISO_CIM-
schema_cim16#">
  <iso15:GasTurbine rdf:about="_7c1ae276-2bb8-11b2-80e9-
8acfb8612c06">
    <iso15:TMachineryResource.Compresor
rdf:resource="#_7c1ae277-2bb8-11b2-80e9-8acfb8612c06"/>
    <cim:IdentifiedObject.aliasName>GT01</cim:IdentifiedObject
.aliasName>
  </iso15:GasTurbine>
  <iso15:Compresor rdf:about="_7c1ae277-2bb8-11b2-80e9-
8acfb8612c06">
    <iso15:Compresor.InletDesignTemperature
rdf:resource="#_7c1ae278-2bb8-11b2-80e9-8acfb8612c06"/>
    <cim:IdentifiedObject.aliasName>CP01</cim:IdentifiedObject
.aliasName>
  </iso15:Compresor>
  <iso15:Temperature rdf:about="_7c1ae278-2bb8-11b2-80e9-
8acfb8612c06">
    <iso15:Temperature.unit>K</iso15:Temperature.unit>
    <iso15:Temperature.value>300.0</iso15:Temperature.value>
    <cim:IdentifiedObject.aliasName>T01</cim:IdentifiedObject.
aliasName>
  </iso15:Temperature>
</rdf:RDF>
```

FIGURE 9. Detail of RDF model, as a prototype for a multi-domain model combining CIM information and ISO 15926 information.

a component-based object-oriented engine cycle simulator that supports detailed aero-thermo-mechanical computer simulations, suitable for aircraft engines studies [37]. This project provides models for high and low-pressure turbines, for engine propulsion operations. But these components are tool-dependent, i.e. the solution of models' behavior is dependent on the mathematical solver implemented within the same NPSS simulation engine. Furthermore, while NPSS provides integration for other disciplines such as aerodynamics and heat transfer, there is not yet any proof of concept for its application in power system studies.

The choice for turbine models from the ThermoPower library is that they are more appropriate for the modeling of of power generation units in power systems, and their performance do not depend on the chosen simulator. Moreover, ThermoPower is also written in Modelica, which allows its use in more than one particular tool. Finally, the integration with the OpenIPSL is straight-forward, as described in the next section.

A. MODELICA MULTI-DOMAIN MODEL

In the power system domain, a gas turbine and governor system is typically described using the GGOV1 model, where the turbine part is combined with the governor part and modeled from a power systems perspective.

The Modelica implementation of GGOV1 can be found in the OpenIPSL library, under the *OpenIPSL/Electrial/Control/PSSE/TG/GGOV1/GGOV1.mo* file. Meanwhile, the turbine model from the *ThermoPower* library is used separately, providing more detailed equations and parameters from the turbo-machinery perspective.

A new design of the GGOV1 model was obtained by refactoring each of the three controls logics forming the GGOV1 model: (1) A block for the load limiter; (2) a block for the acceleration limiter; and (3) a block for the main governor.

A fourth block was created to represent only the turbine (see FIGURE 10), which can be removed and replaced by the turbine model from the *ThermoPower* library as previously stated. Thus, the new GGOV1 model design is better suited from an Object Oriented (OO) perspective, obtaining a convenient way to re-use the models when a certain study requires only the turbine and the governor, instead of having an all-in-one-simplified model with turbine controls and protections.

An additional interface block was created to allow the connection between the electro-mechanical generator model and the detailed gas turbine model. It provides a matching Modelica implementation of the *TMConnectivityNode class* using the *Flange* and *Connector* classes of the proposed

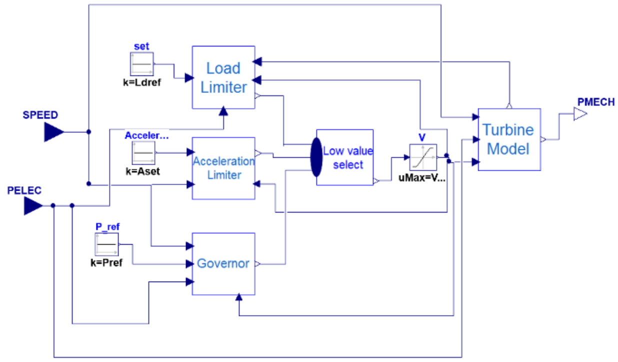


FIGURE 10. Refactored OpenIPSL GGOV1 governor model, where control logics and the turbine model are split in different blocks.

topology information model presented in Section III.B. This connection relates the rotational mechanics (flange internal variables) of the gas turbine model with the generator mechanical power and speed, as shown in FIGURE 11.

```
model TM2EPConverter "Interface between OpenIPSL
generators and ThermoPower gas 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;
```

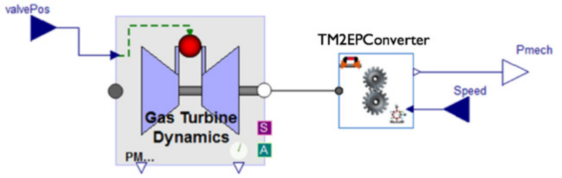


FIGURE 11. Detailed gas turbine model from ThermoPower library, connected to the interface block. Its code is in the top of the figure.

The power system model is assembled by using OpenIPSL components of the synchronous generator, transformers, transmission lines, loads and buses, as shown in FIGURE 12.

B. SIMULATION RESULTS

The multi-domain model consists of a "generation group" template (which it can be used for different sets of component configurations) connected to the grid model, the *ThermoPower* turbine and a governor block model from the power system domain.

The governor block uses the implementation from FIGURE 10, thus its turbine model is substituted by and externally connected with the physical model of a gas turbine from the *ThermoPower* library (see FIGURE 11).

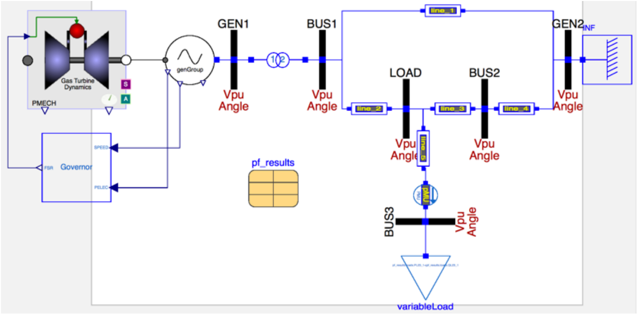


FIGURE 12. Multi-domain SMIB model with GGOV1-based governor model and a detailed Gas Turbine model.

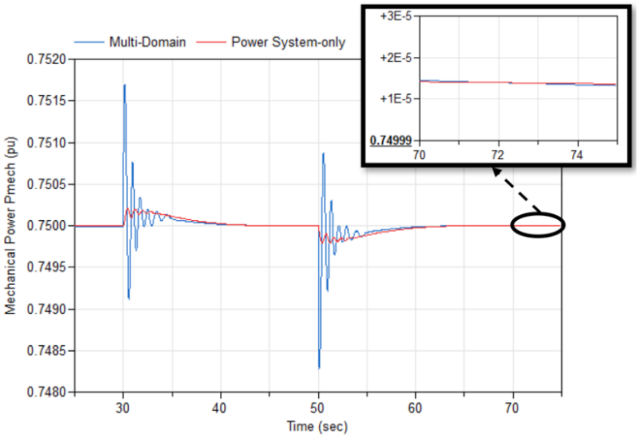


FIGURE 13. Comparison of the mechanical power response for the multi-domain and power systems-only models.

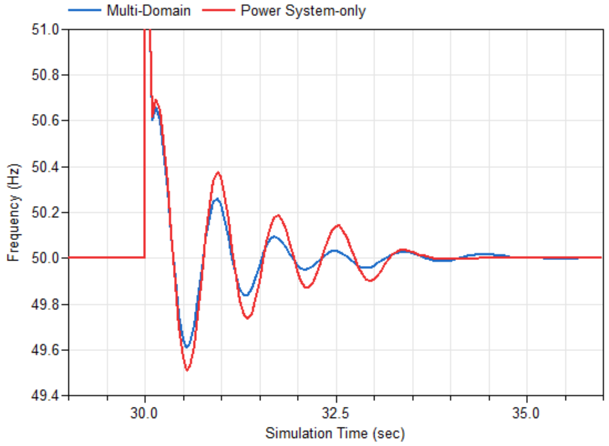


FIGURE 14. Comparison of the frequency response for the multi-domain and power systems-only models.

The multi-domain benchmark model in FIGURE 12 is simulated to study the dynamic behavior of the grid model when subject to different modeling detail of the turbine, as shown in FIGURE 13, FIGURE 14 and FIGURE 15. In addition, time-domain responses are to those from the same model described using components *only of the power system domain* are shown. Both multi-domain and power system-only models were subject to a load change event.

The simulation was executed for 100 seconds. The active power of the load was increased by 0.2 p.u. after 30 seconds

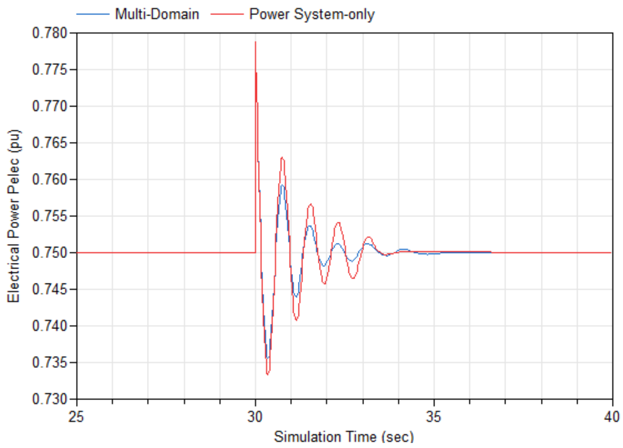


FIGURE 15. **Comparison of the electrical power response for the multi-domain and power systems-only models.**

of simulation, and was set back again to the original value after 20 seconds.

Due to the thermodynamic model of the turbine, the multi-domain model provides a better representation of the dynamic behavior of the mechanical power, i.e. the transient response of the mechanical power is more accurate than the simulation from the equivalent power system-only model (see FIGURE 13). The responses of the frequency (see FIGURE 14) and the electrical power (see FIGURE 15), show the same period but with lower amplitude. It indicates a faster stabilization of the both signals, using the multi-domain model. The presence of mechanical-domain model parameters and equations within the model give more insight information of the physical behavior of the model components, which is of particular importance for control and protection system design.

V. CONCLUSIONS AND FUTURE WORK

In this paper, semantic information and data provided by the ISO 15926 has been analyzed with the aim of proposing a UML and RDF information modeling approach that can expand the CIM/CGMES, by providing more detailed information (e.g. parameters and structure) that are necessary to describe gas turbines with physical model principles from the thermos-mechanical domain. The context layer for CIM modeling has also been modified to incorporate further modeling resources, thereby expanding the capabilities of CIM.

The combination of semantic information from different domains is feasible and valuable for power systems dynamic studies. A multi-domain model has been derived, to allow detailed representations of gas turbines within power grid simulations. Although, open source software libraries (e.g. the *OpenIPSL* and the *ThermoPower*) are not widely used in the industry, 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 for power system analysis.

A simple network model has been developed as a proof of concept for this kind of modeling and simulation methodology. Although, the models are simple (due to the lack of publically available information), the turbine modeling approach provides a framework for future studies with multi-domain models in power systems. Thus, a better model that includes among other things the *valves dynamics* is desired as it would allow a better modeling of the fuel mass flow rate behavior. These kind of turbo-mechanical dynamics is not present in power system models, such as the GGOV1 turbine governor model.

The Single-Machine Infinite Bus (SMIB) model is configured to simulate typical scenarios that can be found in power system studies. Although, further work could be done regarding the behavior of multi-domain models within large power system models. However, this proof of concept leaves the door open for the analysis of larger models and the use of other Modelica-based libraries, such as the ThermoSysPro [38], which is developed and used by a major industry operators, Électricité de France. Moreover, these Modelica models could be combined with other tools, such as the NPSS, if they integrate and adopt the FMI standard for model-exchange and co-simulation.

Power system CIM models can be extended by achieving a harmonization between the CIM and information models from different domains. Although this work proposes an extension to include specific information of gas turbine power plants, the vocabulary can still be upgraded and enriched with more concepts from the ISO 15962. These changes can be materialized as an extension of the current CIM for Dynamics definitions. Available computation technologies make the definition of more complex models possible, so that information languages, such as the CIM, and mathematical languages, such as Modelica, can be incorporated within new tools that can utilize each language's strength. Relevant to multi-domain model dynamic simulations, a key step will be bridging the gap between information and equation-based models by developing new mapping rules that could be incorporated within the work presented in [14] for automated simulation models generation.

Note that within the CIM canonical model, a "fault" class exists and similarly to other CIM models in this paper, also inherits from the *IdentifiedObject* class. This class helps to model the basic parameters of an event affecting the grid. The CIM profile considered in this work is the Dynamics Profile, corresponding to the IEC 61970-302/457 packages, which does not include the "fault" class. Hence, in future work, the classes from the proposed design could be easily associated with the CIM fault class included in any CIM model. Together with mappings of the resulting enhanced CIM model proposed in this paper (grid and gas turbines) to the OpenIPSL library fault models (e.g. OpenIPSL/Electrical/Events/PwFault.mo), this can help to easily generate Modelica code [14] that can, in turn, be used to simulate the behavior of the multi-domain model under an array of fault scenarios.

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