Phasor Time-Domain Power System Modeling and Simulation using the Standardized Modelica Language: Conventional and Power Electronic-Based Devices

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Electric Power Systems Dept.
Royal Institute of Technology (KTH)
December 2014
Abstract

Modern electric power systems are complex networks that ensure continuous supply of electricity. For the planning and operation of these complex networks, modeling and simulations are essential to satisfy operational requirements or planning constraints. Traditionally, dynamic modeling and simulation of power systems is performed by using different and mostly incompatible software packages. This issue is currently being addressed through the Common Information Model (CIM) for power system applications, however, there are still many challenges for Power system dynamic modeling and simulation without any ambiguity.

To overcome these challenges, this thesis develops unambiguous models for consistent model exchange, which are compatible in different simulation environments that support the Modelica language. Modelica, an object-oriented equation-based standardized language, is proposed as possible solution to these challenges as it can represent and exchange dynamic models with a strict mathematical description.

In this thesis, modeling and simulation of controllable power electronic-based components and conventional components for phasor time-domain simulation is carried out using Modelica. The work in this thesis contributes to a Modelica power systems library being developed by KTH SmartTS Lab under the FP7 iTesla project and other projects supported by Statnett SF. Both software implementation in Modelica of each component, and software-to-software validation against PSAT is carried out.
Sammanfattning

Moderna elkraftsystem r komplexa ntverk som skerstller en kontinuerlig tillfrsel av elkraft. Fr att kunna uppfylla de tekniska krav och begrnsningar som stlls vid planering och drift r modellering och simulering av dessa komplexa ntverk av avgrande betydelse. Vanligtvis sker modellering och simulering av kraftsystemets dynamik i olika och oftast inkompatabla programvaror. Detta problem sker Common Information Model (CIM) fr kraftsystemkomponenter att lsa, men mnga hinder kvarstr innan dynamisk modellering och simulering av kraftsystemet kan ske utan tvetydigheter.

Fr att lsa dessa utmaningar s utvecklar detta examensarbete entydiga modeller fr ett konsekvent utbyte av modeller mellan simuleringsprogramvaror som stdjer modelleringssprket Modelica. Modelica, ett standardiserat, objektorienterat och ekvationsbaserat sprk, fersls som en mjlig lsning fr dessa utmaningar d det kan representera och utbyta modeller genom en strikt matematisk beskrivning.

I detta examensarbete utfrs modellering och simulering i Modelica av bde styrbara kraftelektronik och konventionella kraftsystemkomponenter fr tidssimulering med fasvektorer. Detta examensarbete bidrar till det Modelica bibliotek fr elkraftsystem som utvecklas av KTH SmartTS Lab i FP7 projektet iTesla och andra projekt som stttas av Statnett SF. Modellerna som utvecklas i Modelica valideras med hjlp av mjukvaru-validering med PSAT som referens.
I am grateful to Assoc. Prof. Dr.-Ing. Luigi Vanfretti for giving me the opportunity as his master thesis student, he has been a great support during the whole work. In addition, special gratitude and thank to my supervisor Francisco Gómez for his generous help, warm encouragement and support.

I would like to thank my program coordinator, Assoc. Prof. Hans Edin, for his guidance for the past two years of my master’s program. In addition, special thank to EIT/KIC-InnoEnergy for funding my studies in Smart Electrical Network and Systems (SENSE) program.

I would like to thank all the people who helped me and supported me during this project and special thank to Apostolis Kristal, Md Jahidul Islam Razan, Le Qi, Yuwa Choompoobutrgool, Wei Li, Jan Lavenius and all the members of the SmarTS Lab. Without the help from the group members, the completion of this thesis would not have been possible. Finally, I would like to thank my beloved family for their support, as well as all of my friends.
# Contents

List of Figures xiii

List of Tables xiv

1 Introduction 2

1.1 Background .................................................. 2
1.2 Problem Definition .......................................... 4
1.3 Objectives ..................................................... 5
1.4 Overview of the Report ...................................... 5

2 Modeling Languages 6

2.1 Modelica ...................................................... 6
2.2 Modelica Features ........................................... 7
2.3 Modelica Simulation Environment .......................... 7
2.4 Modelica Programming ...................................... 8
2.5 Power System Analysis Toolbox (PSAT) ................. 9

Bibliography 11
List of Figures

1.1 Time frame of different power system dynamics. . . . . . . . . . . . . . . . 3

2.1 Examples of Modelica Models [24]. . . . . . . . . . . . . . . . . . . . . . 6

2.2 Textual programming in Modelica. . . . . . . . . . . . . . . . . . . . . . 9

2.3 Graphical User Interface of PSAT. . . . . . . . . . . . . . . . . . . . . . 10
List of Tables

2.1 Modelica based software environments. .......................... 8
# Notations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSAT</td>
<td>Power System Analysis Toolbox</td>
</tr>
<tr>
<td>EMT</td>
<td>Electro-Magnetic Transient</td>
</tr>
<tr>
<td>DAE</td>
<td>Differential and Algebraic Equation</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
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<tr>
<td>ODE</td>
<td>Ordinary Differential Equation</td>
</tr>
<tr>
<td>TCSC</td>
<td>Thyristor Controlled Series Compensator</td>
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<tr>
<td>STATCOM</td>
<td>Static Synchronous Compensator</td>
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<tr>
<td>SSSC</td>
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<td>UPFC</td>
<td>Unified Power Flow Controller</td>
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<td>ULTC</td>
<td>Under Load Tap Changer</td>
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<td>PST</td>
<td>Phase Shifting Transformer</td>
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<tr>
<td>TWT</td>
<td>Three Winding Transformer</td>
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<tr>
<td>AVR</td>
<td>Automatic Voltage Regulator</td>
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<tr>
<td>FACTS</td>
<td>Flexible AC Transmission System</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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Chapter 1

Introduction

1.1 Background

Today’s electric power systems are large and complex. These systems consist of many kinds of interconnected components to generate, transmit and distribute electrical energy continuously to a large consumers spread over the vast geographical area. Due to the interconnection of many individual components in these systems there exist a large variety of dynamics which can affect the system as a whole in many ways. These dynamics can be divided into groups distinguished by their cause, consequence, time frame, physical character or the place in the system where these dynamics occur [1]. The different Power System dynamics are:

- Electromagnetic Transients
- Electromechanical Transients
- Quasi-Steady state Dynamics

Power system modeling and simulation is essential to satisfy operational requirements or planning constraints [2]. In power system analysis, to deal with different dynamics, different kinds of models are used to simulate each of the dynamic phenomena shown in figure 1.1.
• **Electro-Magnetic Transient Model:** Electro-magnetic transient phenomena occurs in less than of a microsecond and involves the power systems response to events such as lightning strikes, switching operation etc. To model these phenomena, Electro-magnetic transient models are used. These models are described mathematically by differential and algebraic equations. To use these mathematical models in digital simulation the methods used are: state variable analysis and difference equation’s [3], [4]. A well known simulation software used to analyze these models is EMTP-RV [5].

• **Electro-mechanical Transient Model:** Electro-mechanical transients occur in the range of millisecond to seconds. An example of such transient is the oscillation of the rotating masses of the generators and motors that occurs following a disturbance or due to the operation or a of protection system. The mathematical models of electro-mechanical transients are simplified or averaged from electro-magnetic transient models. This simplified mathematical models are used in digital modeling. This simulation approach is known as phasor time domain simulation. The simulation software packages used to analyze this kind of models are PSAT [6], EUROSTAG [7], PSS/E [8], PSCAD [9] etc.

• **Quasi-Steady State Model:** Quasi-steady state (QSS) dynamics occur for more than one second. An example of QSS is the thermodynamic change of the boiler control action in steam power plants to meet the demand of automatic generation controls. Mathematically, in these kind of models electro-magnetic transients are neglected and the system is modeled by algebraic equations [10]. The only tool used in practice for this kind of simulations is astre [11].

![Figure 1.1: Time frame of different power system dynamics.](image)
Chapter 1. Introduction

Though there exists a lot of simulation tools, the rapid change of grid and penetration of intermittent renewable sources making the simulation of power system challenging.

1.2 Problem Definition

Existing tools for power system phasor time domain simulation are exposed to certain limitations such as limited simulation features [2], limited abilities for consistent model exchange [12] or handling of penetration of new devices (FACTS).

Power system courses in the educational institutes deal with complex physical phenomena and detailed mathematical models of power systems. It is difficult to visualize the main concept of the cumbersome power system networks. Hence reproducing the complex power system phenomena through computer-based simulations is an efficient solution for educational and research purposes [13]. Commercially available power system simulation software packages are used in these educational institutes. Few problems with these software packages are: they do not allow changing the source code or adding new parameters [14]. In order to increase the flexibility of power system simulation softwares, an Open Source approach is taken by the power system academic community. Some examples of the Open Source software packages are UWPFLOW [15], PSAT [6], PowerWeb [16] and ObjectStab [17].

Modelica is a new promising modeling language. It is an equation based, object oriented, open source language, offering several advantages to the modeling community. It also offers a solution for covering model exchange challenges, easy modification of models, easy development of custom models and providing unambiguous simulation results among different tools [18]. One software that supports the Modelica language is OpenModelica.

At present a Power System library is developed by SmarTS Lab within the FP7 iTesla project [19]. Most of the power system component models have already been implemented in the library. Additional models are needed to perform time domain simulations of small and medium sized power system networks. The problems this thesis focuses are:

- Improving the iTesla power system library with the development of new Modelica models of power electronics based components for phasor time domain simulation.
- Validating the models and making validated test system models.
1.3 Objectives

Taking into account the problems described in the previous section, the following objectives are identified for this work:

- Literature review on power system simulation methods and the contribution of iTesla project in this field.
- How to use Modelica and PSAT for power system simulation.
- Develop the Modelica models of the Flexible AC Transmission System (FACTS) based devices, conventional power system devices (Transformers) which are used for hybrid electromagnetic and electromechanical power system models.
- Checking the validity of all the models against PSAT. PSAT contains the implementation of the models, which will be used in this work. So, a validation of the simulation outputs from the Modelica models is necessary to check the same behavior according to PSAT simulations.
- Prove the feasibility of the models into small and medium power system networks like IEEE 9-bus and IEEE 14-bus systems.

1.4 Overview of the Report

This report is divided into three sections. In the first section, involving chapter 1 and 2, background of the project with an introduction about Modelica and PSAT is given. In the second section, Power System component modeling in Modelica is discussed. In this section the modeling methodology, mathematical models of the components, implementation of the models, test system for the models and software to software validation results are given. This section covers the chapter 3 and 4. Finally in the third section, a small discussion about the experience with Modelica and future work are summarized. This part covers the chapter 5.
Chapter 2

Modeling Languages

2.1 Modelica

Modelica is an object oriented, acuasal, equation based, open source language for describing complex mathematical behavior. It supports dynamic modeling and simulation, for complex systems and applications from different domains such as Electrical, Mechanical, Hydraulic, Thermal, Control and Electric Power Engineering. Modelica models are described in schematics (see figure 2.1).

Figure 2.1: Examples of Modelica Models [24].
Modelica Design Group develops the free library for multi-domain modeling known as Modelica Standard Library. All the versions of the Modelica Language are available on-line (https://modelica.org/).

2.2 Modelica Features

Modelica offers several advantages to the modeling community both in academia and industry. Being a standard language, Modelica is supported by different modeling and simulation tools [23]. Most important features of Modelica are [20], [21]:

- Modelica is based on equation statements instead of assignment statements. That is why, it permits acausal modeling.

- Different domains such as Electrical, Mechanical, Thermodynamic, Hydraulic, Biological and Control applications can be connected and used in the same model.

- It provides hierarchical system architecture capabilities and visual component programming.

- Allows the exchange of the models among simulation solvers, which are able to compile Modelica code and provides unambiguous simulation results among different tools.

- Modelica models are solver independent.

- Modelica is an object-oriented language with universal class concept that unifies classes, generics-known as templates in C++ and general subtyping into a single language construct. This helps evolution of models.

2.3 Modelica Simulation Environment

Modelica language is used for modeling complex mathematical problems. Different Modelica simulation environments allow one to make these models using Graphical User Interface (GUI) editors, text-based editors or both. The currently available simulation environments for Modelica are given in the following table 2.1. In this work Dymola [22] and Open Modelica simulation environment is used.
Table 2.1: Modelica based software environments.

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2.4 Modelica Programming

Modelica programming can be done by using Graphical editor or writing the code in Textual editor. In graphical editor a new model can be created by dragging and dropping the models from the available models. Textual editor is used for writing the executable code. That means the programming is done in the textual editor to create the models. In the text editor model name is declared first, then the variables are declared. Finally, the equations are added with initialization. Detail programming in Modelica text editor can be found in [20], [21], [24].

The simulation editor is used to translate and simulate the models. Simulation editor also used to visualize the results. One of the simple example of Modelica code is given in figure 2.2.
2.5 Power System Analysis Toolbox (PSAT)

PSAT is a Matlab based toolbox for static and dynamic analysis of power system [6]. As a software tool for power systems analysis, PSAT offers various routines:

- Continuation Power Flow
- Optimal Power Flow
- Small Signal Stability Analysis
- Time Domain Simulations
- Phasor Measurement Unit (PMU) placement

```model Bus1
"First winding of Three Winding Transformer"

PowerSystems.Connectors.PwFin

PowerSystems.Connectors.PwFin n1

Name of the Model

Annotations (Hidden)

Connectors

parameter Real SystemBase=100;
parameter Real Sn=100 "Power rating MVA";
parameter Real Vbus=400000 "Rated bus voltage";
parameter Real Vn1=400000 "Voltage rating of the first winding, V";
parameter Real Vn2=100000 "Voltage rating of the second winding, V";
parameter Real Vn3=400000 "Voltage rating of the third winding, V";
parameter Real fn=50 "Frequency rating, Hz";
parameter Real Rl2=0.01 "Resistance of the branch 1-2, p.u.";
parameter Real Rl3=0.01 "Resistance of the branch 1-3, p.u.";
parameter Real Xl2=0.01 "Reactance of the branch 1-2, p.u.";
parameter Real Xl3=0.1 "Reactance of the branch 1-3, p.u.";
parameter Real Xl23=0.1 "Reactance of the branch 2-3, p.u.";
parameter Real m=0.98 "Fixed Tap ratio";

Real r1;
Real x1;
Real anglev2 "Angle of the fictitious bus";
Real vbus2 "Voltage of the fictitious bus";

equation

vbus2=sqrt(n1.vr^2+n1.vi^2);
anglev2=atan2(n1.vi, n1.vr);

r1=0.5*(Rl2+Rl3+Rl23);
x1=0.5*(Xl2+Xl3+Xl23);

r1*p.i-x1*p.i = (1/m)*p.vr - (1/m)*n1.vr;
x1*p.i+x1*p.i = (1/m)*n1.vi;

vbus2-n1.vr-x1*n1.vi = n1.vi - (1/m)*p.vi;
eq Bus1;
```

Figure 2.2: Textual programming in Modelica.
Chapter 2. Modeling Languages  2.5. Power System Analysis Toolbox (PSAT)

The main graphical user interface of PSAT is shown in figure 2.3. To make power system networks in PSAT, one can use data files or single-line diagrams via the GUI (using PSAT-simulink library). Then single line network or simulink diagram, is loaded via the data file field in the main GUI. The diagram must be saved before loading. After that this diagram is translated into PSAT readable data file and then any of available routines can be simulated.

Figure 2.3: Graphical User Interface of PSAT.

PSAT contains different power system components models that have not yet been modeled using Modelica. Thus, PSAT models are taken as the reference models, in order to compare their performance against the equivalent Modelica models, developed in this work.
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