

KTH INSTITUTE OF TECHNOLOGY

MASTER THESIS

Modelica Driven Power System Modeling, Simulation and Validation

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Abstract

Power system simulation is an important tool for the planning and operation of electric power systems. With the growth of large-scale power systems and penetration of new technologies, the complexity of power system simulation has increased. In this background, achievement of valuable simulation results in the simulation has become one of the important research questions in electrical power engineering field.

The most effective solution of this question is to develop accurate models for the power system. However, the complexity and diversity of power system components make the accurate modelling difficult while the simulation is time consuming. To cope with the problem, powerful modelling language which can realize not only accurate model representation, but increase computational efficiency of model simulation is required.

In this thesis, power system modelling and simulation is achieved using an object-oriented, equation-based modelling language, Modelica. Firstly, some essential component models in power systems are developed in Modelica. The software-to-software validation of the models are performed. To serve this purpose, different software environments are exploited depending on software used for the model development. Moreover, four different-scale test systems are implemented, simulated and validated with the developed models. Through the investigation of the simulation results, the performances of Modelica in undertaking power system simulations are evaluated.

In addition, since imprecise parameter values in the models are also problematic for accurate model representation, system identification is performed to obtain accurate parameter values for the models. The parameters of a model are identified based on measurement data. This thesis also illustrates the application of Modelica on model exchange, and the combination of Modelica and FMI technology on system identification.

Finally, examples of application of the RaPIId Toolbox on measurement-based power system identification are provided.

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Notations

PSAT	P ower S ystem A nalysis T ool
PSS/E	P ower S ystem S imulator for E ngineer
EMT	E lectro M agnetic T ransient
FMU	F unctional M ock-up U nit
FMI	F unctional M ock-up I nterface
DAE	D ifferential A lgebraic E quations
ODE	O rders D ifferential E quations
ODAE	O verdetermined D ifferential A lgebraic E quations
AVR	A ntomatic V oltage R egulator
TG	T urbine G overnor
PSS	P ower S ystem S tabilizer
AVR	A ntomatic V oltage R egulator
GUI	G raphic U ser I nterface
CLI	C ommand L ine I nterface
PF	P article F ilter
PSO	P article S warm O ptimization

Chapter 1

Introduction

1.1 Background

1.1.1 Power system modelling and simulation

The design, construction and operation of electric power systems is carried out to achieve three main goals: the quality of supply, safety of operation and economy [6]. To achieve the objectives, power system modelling and simulation are two steps this thesis is focused on. Power system simulation has to be performed to assess the response of the system after changes or influence of disturbances. Power system simulation can be classified into two main categories:

- **Static Simulation.** Static power system simulation, commonly known as power flow analysis, is essentially the computation of a system equilibrium, in which all parameters and variables are assumed to be constant during the observation period. Static simulation is fast, but the dynamic evolution between the before and after disturbance is neglected.
- **Dynamic simulation.** Dynamic power system simulation is essentially the computation of system response through time. The dynamic simulation can cover different kinds of time-scales: slowly changing dynamic corresponding to normal load

change or the action of automation controls, and transient dynamic corresponding to electromechanical oscillations of machines, actions of primary voltage and speed controls [6, 7]. Corresponding to different dynamics, dynamic simulation can be further classified according to the specific time-scale.

In Contrast with static simulation, since dynamic simulation focuses on the system evolution between before and after disturbance, it is always time consuming.

To obtain satisfactory and valuable simulation results, the models of components and systems used in the simulation are playing important roles. Different kinds of models are designed to meet different simulation requirements. The emphasis of modelling, and the level of models' complexity mainly depends on the type of studies to be carried out [8]. Here include some commonly used models:

- Electro-Magnetic Transient (EMT) models. This kind of model reflects the electro-magnetic behavior of power system components. Relevant studies are the analysis of transients after asymmetrical faults, or operations of power electronics converters [9]. EMT model is the most detailed type of power system models.
- Phasor models. This kind of model is used in positive sequence time-domain simulation, which utilizes a simplified representation of power system components [8, 9].
- Quasi Steady State models. This kind of model uses a further simplified representation of power system components, which can be used in long-term dynamic simulation.

Specific types of model are used to perform simulations to meet different study requirements. Traditionally, domain-specific simulation tools are used in different cases of power system simulations. In this thesis, the models are developed for power system dynamic simulations.

1.1.2 Power system modelling software

According to specific kind of studies, the traditional used software tools can be classified into the following three categories:

- Electro-mechanical transient simulation tools: **PSS/E, Eurostag, Simpow, PSAT**, etc. This kind of software tools mainly simulates and investigates the response of system after large or small disturbances, such as short-circuit fault, opening of transmission lines, loads and generators. These tools also study the system ability to maintain stable operation [2, 3].
- Electro-magnetic transient (EMT) simulation tools: **EMTP-RV, PSCAD/EMTDC**, etc. EMT simulation tools mainly studies the electro-magnetic transient of the system after large or small disturbances, in the time scale between microseconds and seconds.

Electro-magnetic transient simulation must take the magnetic and nonlinear characteristics of the devices into consideration. The devices include generators, transformers and inductors. Thus the models used in this kind of tools are described by algebraic, differential and partial differential equations. The simulation is achieved by utilizing numerical methods [10].

- Combination tools: **DIgSILENT PowerFactory, SimPowerSystems**, etc. This kind of simulation software tools consider the first two cases synthetically, and can provide simulation results in a broader time range [11].

Combination tools provide us the possibilities of obtain more detailed and accurate simulation solutions. However, the combination tools are limited available, and the libraries integrated in the tools are commonly closed for modifications, which limit the flexibility of the simulation to some extent. Furthermore, the simulation considering both electro-mechanical and electro-magnetic transient is time consuming, especially for large systems [12].

1.1.3 Power system model validation

Validation of power system models is an essential step to make sure the models are accurate. Since models are the foundation of power system simulations, they must represent all necessary aspects of power system correctly to predict power system performance. If

a particular model can not represent the observed phenomena on the power system with accuracy, the study performed on that model will have no confidence.

In this thesis, the models are validated against two kinds of reference: measurement data and simulation results from power system simulation software. For measurement-based validation, presently there is no systematic model validation process can be taken through for entire interconnected power system models. The current approach to model validation is limited to individual power system components. However, component level validation is a crucial step and necessary part of system wide measurement-based model validation [1, 13].

Figure 1.1 illustrates the validation loop for power system models. The process can be divided into three main steps:

1. Collect measurement data. The measurement data includes both steady-state power flow data, and also dynamic system responses to the disturbances.
2. Adjusting the conditions in the power system model to match the collected data of the actual power system. This step is the major task of the validation. The model should represent the initial steady-state conditions for the moment in time just prior to the event that is used for the validation. After a specific event (e.g. disturbance), various aspects of a model should be matched with the measurement data: node voltages, angles, and key inter-tie power flows during and after event.
3. Make refinement to the model. The refinement of model can be performed both in model structure and parameters.

In this thesis, most models are validated against provided reference model, which are developed in software environment other than Modelica. Normally identical test systems are implemented in two environments (Modelica environment and reference software), and simulation results from reference software are used to replace the measurement data in the loop shown in figure 1.1.

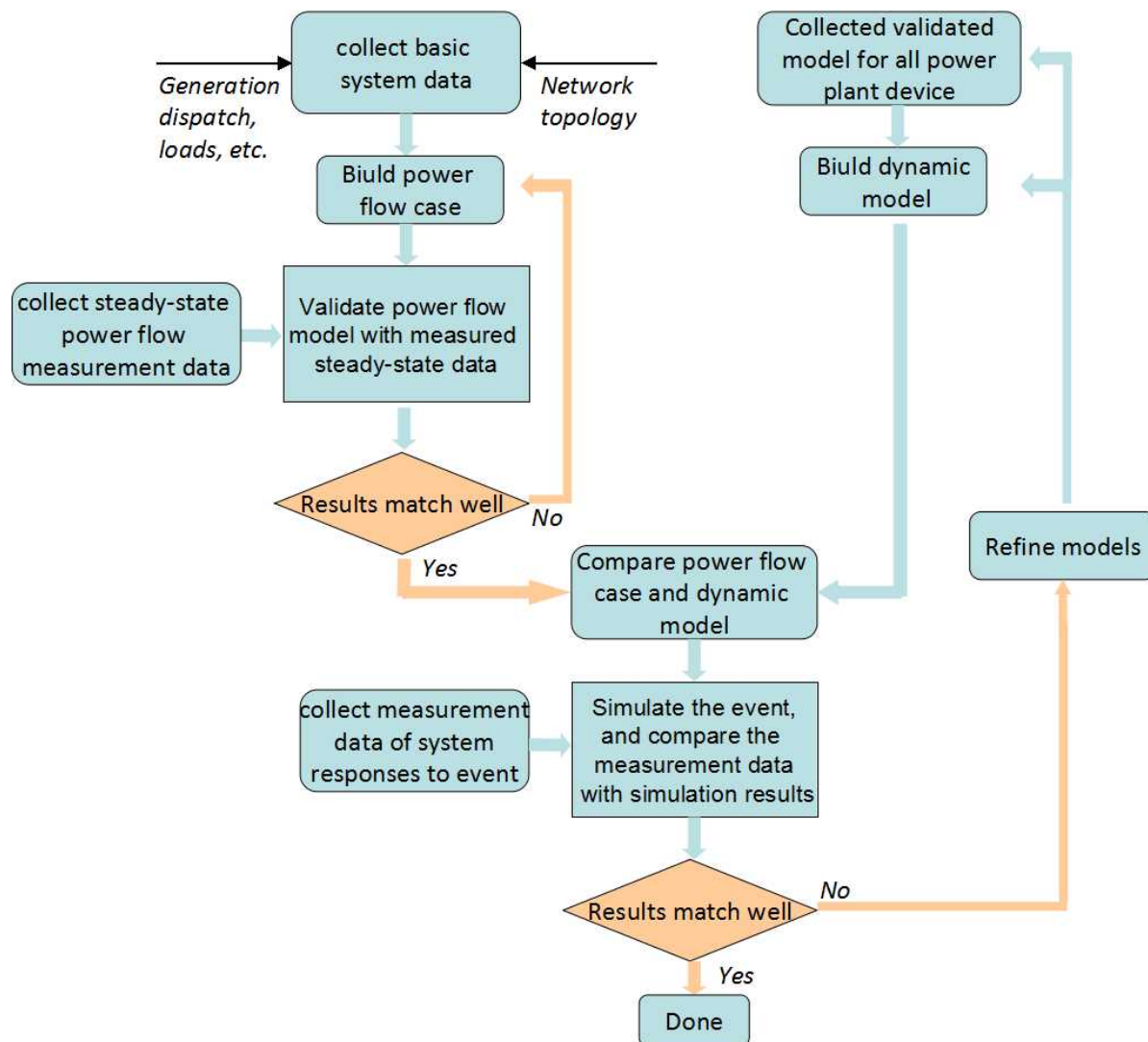


FIGURE 1.1: Validation loops for system models [1]

1.1.4 New challenges

With the rapid development of smart-grid technologies, simulation of power systems is facing new challenges. The problem mainly lies in the following four aspects:

- The expansion of the grid. Large-scale power systems are constructed by the interconnection of small networks. These large power systems always include a considerable number of variables and DAE equations. For instance, the western European main transmission grid (ECTE area) include 15226 buses and 21756 branches, 3483 synchronous machines and 7211 other models (equivalent of distribution systems,

induction motors and loads). There are 146239 DAE states in total [7]. The simulation of this kind of power systems will be apparently very time-consuming.

- The need of information sharing and exchanging. The operation of large-scale power systems needs the coordination of multiple transmission system operators (TSOs). In this case, the harmonization of operational methods and procedures are critical. However, most TSOs across Europe are using different software tools with specific data format and strong coupling of models and numerical solvers. Since the divergences between different software are not acceptable, it is required to re-implement and tune the models in each software to achieve consistent simulation results, which is apparently inefficient. Therefore, there is a need for a standardized simulation tool to achieve the information exchange and modelling consistency between software tools [14, 15].

- The utilization of increasing number of control components. In recent years control components are playing important roles in the operation of power systems. For instance, the generators in one single power plant are controlled by excitation systems, over excitation limiters, voltage regulators, power system stabilizers, speed governors and turbines.

Control components not only control the operation of devices where they are installed, but also will affect the response of system after disturbances. To give an example, it can be found in voltage stability analysis that the operation of over excitation limiters may lead to voltage collapse after disturbance [5]. Therefore, it is necessary to consider the effects of these components in the simulation, which will surely increase the computation burden.

- The penetration of new devices. With the development of power electronic technologies, FACTS and HVDC devices have been developed to increase the operation efficiency and reliability of power systems. In addition, the increasing numbers of wind power plants and hybrid electrical cars are also penetrating into the grids. This kind of new devices will also bring new questions to power system modelling and simulation.

In summary, even though there are many approaches available for power system modelling and simulation, the need of new simulation tools is still increasing.

1.2 Problem definition

As elaborated in Section 1.1, an approach to achieve accurate and fast power system simulation is needed. In order to meet this demand, a new modelling and simulation tool, *Dymola*, based on the *Modelica* language is adopted in this project. In general, to evaluate the validity of the chosen approach, a number of power system simulation tests should be conducted, and the simulation results should be validated.

A few attempts for power system modelling and simulation using Modelica has been made in recent years [16–19]. However, some libraries are not complete or closed for modifications, which means one can not modify or improve the models. For this reason, it is necessary to develop a new power system library in which modification and maintenance are available. Presently, such power system library is under development at SmarTS Lab within the FP7 iTesla project [20].

In order to conduct specific experiments in the test system, additional models for the corresponding devices should be included to the power system library. For instance, the model of load tap changers (LTC) is required for the voltage stability tests. At the same time, to obtain the best simulation results, the models must be mathematically correct and have a good match with the actual behavior. The software-to-software validation will be done between Modelica-based models and the reference software in which the power system components were developed.

In order to guarantee that the components models can function well in simulations of large-scale systems, some representative test systems should be implemented, and simulation will be conducted to these test systems. The test system models are also validated against references.

Additionally, since another objective to adopt Modelica is to serve as a solution to the problem of model exchange and co-simulation between different software environments,

the application examples of model exchanging are required to prove the feasibility of the solution.

The problems this thesis focuses on are:

- Make a contribution to the development of Modelica power system library by providing validated models.
- Provide validated test system models to be used in model validation tasks primarily, and other tasks related to dynamic security assessment in FP7 iTesla project.
- Apply system identification methods for estimation and calibration of power system components parameters based on the measurements.

1.3 Objectives

In order to deal with the problems listed in Section 1.2, the following objectives were set:

- Perform a literature review.
- Be familiar with the Modelica language and usage of Dymola.
- Learn the model implementation specifics, develop the models for the components, and perform software-to-software validations by developing small-scale system models.
- Implement test system models with developed component models, and perform software-to-software validation.
- Perform measurement-based model validation if no generic model parameters specified in the reference.
- Propose methods to improve the simulation speed and accuracy for large system models in Dymola.

The objectives will be achieved in order to evaluate Modelica-based modelling advantages, and will be the foundation of future work in the area of dynamic security assessment.

1.4 Contributions

This thesis project is a part of the European Project iTesla, in particular work packages 3.3 and 3.4. All the information in this report is a direct contribution towards it.

The model developed in this thesis contribute to the Power-System Open-Source Modelica library, which is being developed in collaboration with “Grupo AIA (Spain)”, “RTE (France)” and “KTH SmarTS Lab”, with Prof. Luigi Vanfretti as work-package leader.

In addition, the test power system models developed in this thesis will be used in model validation tasks and other tasks related to dynamic security assessment in iTesla project.

1.5 Overview of the report

The report will be divided into three parts:

- Introduction to Modelica and Dymola.
- Power system modelling and simulation using Modelica-based tools: implementation of power system models, power system simulation and validation, also parameter identification of the power system components.
- Discussion and evaluation of the results.

The first part is the overview of the thesis contents. In Chapter 2, an introduction to the Modelica-based tools is provided.

The main part of the thesis is dedicated to the practical application of Modelica in power system. Firstly in Chapter 3, the concrete procedures of implementing and validating models for components is presented, and validation results is provided. A few representative models are selected to show the procedures.

Secondly, the experiences of modelling and simulating large power systems are presented in Chapter 4. Four system models of different scale are implemented and validated, with

the simulation results analyzed. At last in Chapter 5, applications of measurement-based system identification methods for parameter estimation are provided.

The last part is the conclusion part of this thesis. The application of Modelica is discussed and assessed, and the experiences of power system simulation and model validation using Modelica are summarized.

Chapter 2

Modelica based modelling, simulation and model validation

2.1 Introduction to Modelica

Modelica is an object-oriented, declarative, multi-domain language for the modelling of complex systems, such as the physical systems containing mechanical, electrical, hydraulic, thermal, electric power or process-oriented sub-components, and also the control elements of the sub-components [21].

Modelica language is designed to support effective library development and model exchange. It is a modern language built on a causal modeling with mathematical equations and object-oriented constructs to achieve the reuse of modelling knowledge [21].

The Modelica language is developed by the non-profit Modelica Association. The Modelica Association also has developed free Modelica Standard Library that includes about 1360 generic model components and 1280 functions in various domains. Now the library is updated to the version 3.2.1.

A lot of commercial and free software tools based on Modelica is now available for industrial and academic usage, as summarized in Table 2.1. The main difference between

different software is the interface and solvers. While some open-source environments (e.g. Scicos) are using a sub-set of Modelica for component modelling.

TABLE 2.1: Software environment based on Modelica

Commercial software	Free software
AMESim	JModelica.org
Dymola	OpenModelica
CyModelica	Scicos
Wolfram SystemModeler	
SimulationX	
MapleSim	

In this thesis, Dymola was chosen as the modelling and simulation environment. Compared with other Modelica environments, Dymola is more user-friendly, and has efficient implementation of solvers which allows faster simulation of the large systems. It enables the users to create a graphical representation of physical systems, which is advantageous in the implementation of power system networks.

Moreover, models in Dymola can be exported into the FMU format which can be perceived by other software (e.g. Simulink), meaning it is possible to realize co-simulation and information exchange with other simulation tools.

2.2 Main characteristics

The motivation of adopting Modelica as the modelling language is that it owns many unique capabilities which are beneficial to power system modelling, as summarized as following:

1. **Object-oriented.** Power systems are composed of plenty kinds of components, therefore it will be convenient to model the components independently, based on

the specific description of each component. Traditional object-oriented modelling language such as C++ and Java, support programming with operations on stored data. The stored data of program include variable values and object data. The numbers of object often change dynamically.

Different from these languages, Modelica is object-oriented in a different way: it emphasizes structured mathematical modelling [22]. Modelica is object-oriented by using a general class concept, which unifies classes and general sub-typing into a single language construct. This facilitates reuse of components and evolution of models.

2. **Re-usability.** As mentioned above, Modelica is object-oriented in a general class concept, with variables and parameters of each class defined locally. Thus the models in Modelica are independent of the environment where they are developed. Except through connectors, all information in a model is independent from the environment.

This characteristics of Modelica will simplify the modelling of large power systems, for the model of each components can be reused without being changed or affected by the introduction of other components.

3. **Equation-based.** In Modelica, the dynamic model properties are described in a declarative way through equations [22]. The use of logarithms is allowed, but in a way to regard the algorithm section as a system of equations.

This characteristic of Modelica offers the possibility of modelling power system components and networks directly with equations. In most cases, power systems are represented by Differential Algebraic Equations (DAE) system in the form of equation 2.1:

$$\begin{cases} \dot{x} = f(x, y) \\ 0 = g(x, y) \end{cases} \quad (2.1)$$

Where x is the vector of differential variables, y is the vector of algebraic equations and \dot{x} denotes the derivative of x with respect to time. The derivative equations describe the constrains imposed by network topology, while the derivative equations describe the dynamic phenomena affecting transients [16].

The equations can be directly declared to represent the model in Modelica, which guarantees both the accuracy and flexibility of modelling. In addition, since the models are acasual and there exists no assignment statements, no certain data flow is prescribed, so a better reuse of models are permitted.

4. **Multi-domain modelling.** Power system is a hybrid system contains not only electrical components, but also mechanical, hydraulic, thermal and control components [23]. Therefore there is a need to develop models with components from different domains. In Modelica, the components from different domains (e.g. hydro turbines and generators) can be connected and co-simulated without affecting each other.
5. **Model exchange.** Today's simulation tools do not allow model exchange (especially on equation-level), which leads to differences in simulation results between tools. In Modelica, the dynamic models can be stored as Functional Mock-up Units (FMU), and utilized by other modelling and simulation environments. The models are independent of the target simulator for they do not use a simulator specific header file as in other approaches.

2.3 Application example

This section shows an example of Modelica's main constructs used to specify DAEs encountered in power system models. Figure 2.1 and 2.2 show the icon, text and diagram view of a transformer model respectively. In icon view, the graphic appearance of the model can be designed. In text view, the parameters, variables and equations will be defined by code. In diagram view, the user can drag and drop existing models (model of connectors in this example) to construct a new model. When the content of any view is changed, other two will be changed simultaneously.

There are three important principles to be considered in the model development: the concept of class and connectors, declarations and equations, and initialization of models.

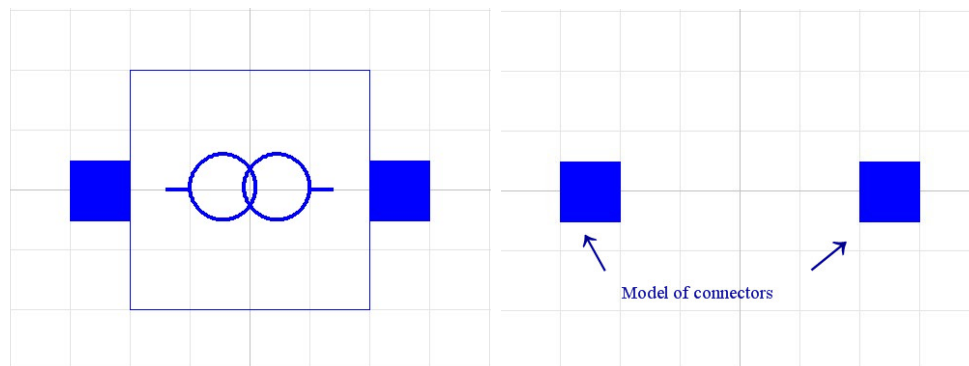


FIGURE 2.1: Icon and diagram view of transformer model

```

class PwTransformer2
  Connectors.PwPin p
  Connectors.PwPin n
  parameter Real R "Resistance";
  parameter Real X "Reactance";
  parameter Real G "Shunt conductance";
  parameter Real B "Shunt susceptance";
  parameter Real r "Transformation ratio";

  equation
    r*(G*n.vr - B*n.vi - n.ir)=p.ir;
    r*(G*n.vi + B*n.vr - n.ii)=p.ii;
    R*p.ir - X*p.ii=r*r*p.vr - r*n.vr;
    R*p.ii + X*p.ir=r*r*p.vi - r*n.vi;
  end;
end PwTransformer2;

```

Model of connectors

Declaration of parameters and variables

Equations

FIGURE 2.2: Text view of transformer model

2.3.1 Classes and connectors

Modelica is object-oriented by using the “class” concept to represent models. Normally, one class can be regarded as a independent model. The collection of basic models can form a “library”, and the models in library can be connected or assembled into implement new models.

Models are connected by connectors. Connectors are special Modelica classes, which define the rules for the connection of two or more components [16]. As shown in Figure 2.1, connector models are used for the connection of transformer and other power system components. Two models of connectors are commonly used: *PwPin* connectors for electrical components and *Impin* connectors for non-electrical components.

In order to connect components “electrically” by *PwPin* connectors, variables vr , vi and ir , ii are defined to present the real and imaginary parts of the voltage and current respectively. Two types of connection rules are applied to connect the variables: equality rule is applied to voltage variables, and sum-to-zero rule is applied to current variables, as stated in Figure 2.3 and equation 2.2:

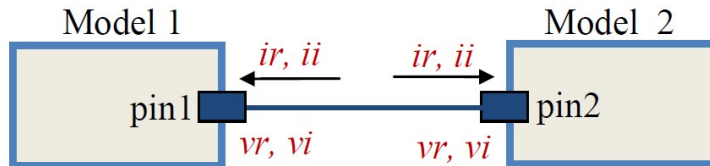


FIGURE 2.3: Connection of two models using *PwPin* connectors

$$\begin{aligned}
 \text{pin1.vr} &= \text{pin2.vr} \\
 \text{pin1.vi} &= \text{pin2.vi} \\
 \text{pin1.ir} + \text{pin2.ir} &= 0 \\
 \text{pin1.ii} + \text{pin2.ii} &= 0
 \end{aligned}
 \tag{2.2}$$

2.3.2 Declarations and equations

As shown in Figure 2.2, a Modelica model is composed of an equation section and a declaration section. In equation section the equations of the model are specified. In declaration section parameters and variables are declared according to their data type. In this example, no additional variable is declared, so the variables in the connector model ($p.vr$, $p.vi$, $p.ir$, $p.ii$) are the variable of the transformer model. All declared variables are function of the independent variable *time*. The variable *time* is a built-in variable available to all models.

In addition, the equations of a model follow the *synchronous data flow principle*: all variables keep their current values until they are explicitly changed, and in every time point the relation described by the equation must be fulfilled [16, 24].

2.3.3 Initialization of models

Before the simulation for a model is started, initialization takes place to assign consistent values for all variables presented in the model [16]. During this procedure, the derivatives ($\text{der}(x)$) are considered as unknown algebraic variables [25]. If a model has derivative expressions, the number of algebraic variables is larger than the number of equations in initialization problem. Thus additional constraints have to be provided in the initialization process.

In most cases, the model is initialized from a steady state, which means to set $dx/dt = 0$ as initial state. Then the initial value x_0 can be obtained by solving $f(x, t) = 0$. Initialization can be done by adding initial equation in equation section, and also by using *start = value* expression in declaration section.

2.4 Simulation parameters

The setting of simulation parameters is important before starting the simulation. The setting will affect the simulation result to a large extent. There are three groups of simulation parameters:

1. **Simulation interval.** The time interval of simulation is set by start time and stop time, as shown in Figure 2.4.
2. **Output interval.** The length of output intervals can be set in two ways: intervals length and number of intervals, as shown in Figure 2.4. One can get smooth plots by setting small interval length, but the simulation time will increase; on the other hand if interval length is too large, the plot may be distorted to some extent, but the simulation time will decrease.
3. **Integration algorithm.** Dymola provides a number of different integration methods for the simulation of dynamic systems. The commonly used algorithms are summarized in Table 2.2. In the table, “model type” means the type of equation

systems describing the model. “Stiff” shows if the method can be used in stiff system or not ¹.

Integration step can be set manually for constant step solvers. If constant step solver is used, the integration step will have large effect on the simulation results. Choosing a large step will shorten the simulation time, but the accuracy will be decreased; on the other hand if the integration step is too small, the simulation time will increase, but the accuracy of results will be improved.

It is worth noting that one should not rely on just one integration method for simulation experiments. Instead, two or three other (different) integration methods should be applied to find a better result [26]. The choice of integration method has large effect on the speed and accuracy of power system simulations.

TABLE 2.2: Integration algorithms

Integrator	Model Type	Stiff
DASSL	DAE	yes
LSODAR	ODE	both
Euler	ODE	no
DEABM	ODE	no
ODASSL	OADE	yes
MEXX	OADE	no

¹For a dynamic process described by differential equations, if the process contains sub-processes interacting with each other, but the rate of change is different with great disparity, such process is called stiff process, system containing stiff process is called stiff system [26].

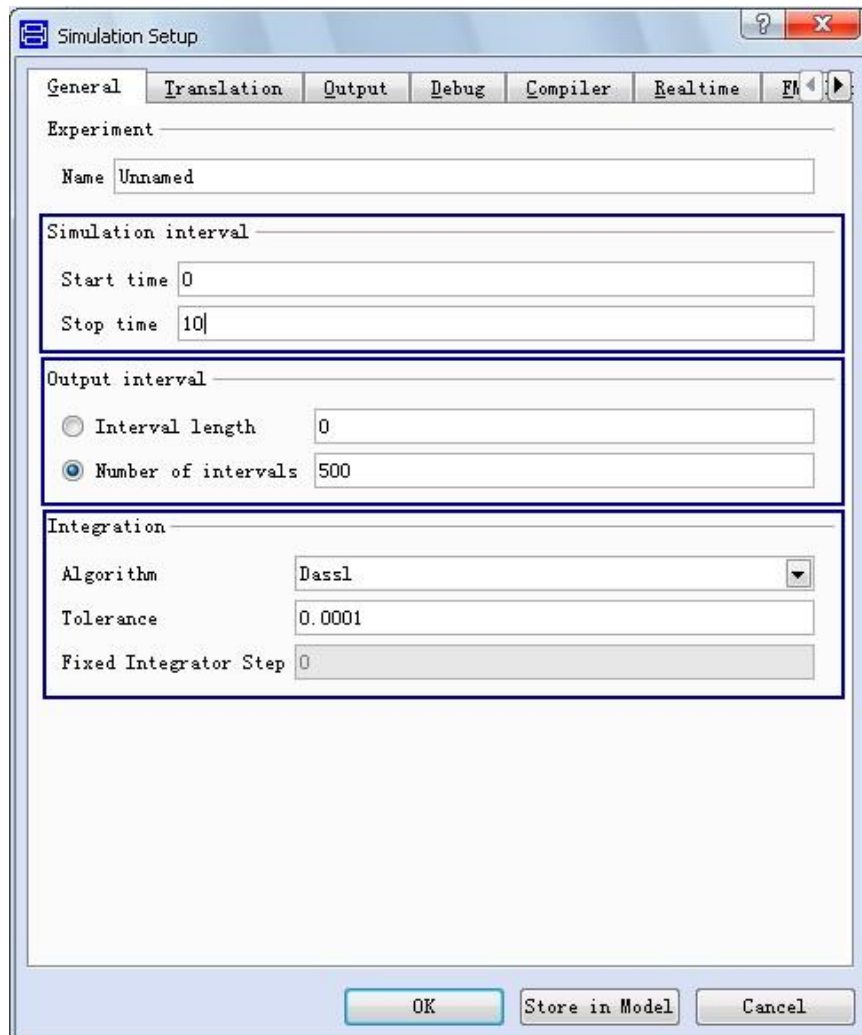


FIGURE 2.4: Simulation parameters in Dymola

Chapter 3

Modelling of Power System Components in Modelica

3.1 Introduction

This chapter presents the detailed modelling procedures and validation results of power system components in Modelica. The objective of the modelling is to create correct and reusable models that can function well with other power system models. Since some basic models (e.g. buses, transmission lines, transformers etc.) are available from former works [27], the emphasis of this thesis is on the modelling of control components in power system.

In order to model the components correctly, the modelling are based on other software, which are used as references. The referenced software in this thesis are PSAT, PSS/E and Simulink. Since the ways reference software working are completely different from Modelica, a new modelling approach needs to be taken. The steps to achieve a successful modelling are as following:

1. Read the specification of the model, understand the conceptual background of the model.
2. Identify the equations that describe the dynamic behaviour of the model.

3. Write the model in Modelica.
4. Initialize the model.
5. Perform software-to-software validation of the Modelica model against the reference model.

In order to present the basic processes, a few models are presented in this chapter. The models include:

- Synchronous generator models (reference software: PSAT)
- Turbine governor TG1 (reference software: PSAT)
- Excitation system EXAC1 (reference software: PSS/E)
- Power system stabilizer (reference software: PSS/E)
- Load tap changers (reference software: Simulink)

The rest models and validation results can be found in appendix A.

3.2 Power system components modelling principles

As stated above, the objective of modelling is to create correct and reusable models for power system components. To achieve this objective, the following principles need to be followed:

- **Define the model in the most direct and easiest way.** Modelica allows defining a model using other models, thus when constituent models are available, the user can simply connect models together to form a new model, without transferring the entire model into equations. Therefore the first step of modelling is to find the most direct way to represent the model.

- **Define and state parameters, constants, and variables clearly.** In Modelica, constants do not change with time and cannot be modified; whereas parameters are constant with time but can be modified; and variables are varied with time and commonly used in equations. The type of model inputs and outputs must be defined and stated distinctly.
- **Place the parameters on the top layer of a model block.** In order to reuse the models conveniently, the model parameters must be displayed on the top layer of the block to be modified easily. Especially for the models made up of other components, parameters of the constituent components must be propagated onto the top layer.
- **Use connectors as input and output interfaces.** The model inputs and outputs must be verified before the modelling, and corresponding types of connectors are used as interface to other models.
- **Select the proper initialization method.** One can initialize models either through auxiliary parameters, or through initial equations.
- **Design the model appearance concisely.** The model should be one simple block. If the model is formed by connecting other models, one must aggregate them in one block or icon.
- **Organize the models in packages.** Package is an easy method to organize models in a structured way. Models can be grouped of similar type in one package, which makes it easier to find a particular model in the applications.

3.3 Implementation of models in Modelica

3.3.1 Synchronous generators

This section describes the modelling of synchronous generators. Two different generator models are implemented according to the mathematical models in PSAT [2]. In PSAT

generator models, various simplifications can be applied, and the models are divergent from the basic model with only classical swing equation to an eight order model with field saturation. In the two models presented in this section, the dynamic of transient and sub-transient voltage are additionally considered. The models differ mainly in the differential equations.

The algebraic equation system for synchronous generator models is specified in Appendix A.1.1, as shown in equation A.2 - A.7.

3.3.1.1 Forth Order

The variables and parameters of the forth order generator model are detailed in Table A.1 and A.2. Other than parameters and variables, auxiliary parameters are defined to initialize the variables. The models are initialized after power flow computations. Once the power flow solution are determined, v^0 , θ^0 , p^0 , q^0 , and v_f^0 at the generator bus are used for initializing the variables. The initial values of variables are specified in Table A.3.

In this model, besides the classical electro-mechanical model, lead-lag functions are used for modelling the d and q-axix inductances. Electromagnetic flux dynamics is neglected, thus leading to a fourth order system in the state variables δ , ω , e'_q and e'_d . The differential equations are:

$$\begin{aligned}
 \dot{\delta} &= \Omega_b(\omega - 1) \\
 \dot{\omega} &= (P_m - P - D(\omega - 1))/M \\
 \dot{e}'_q &= (-e'_q - (x_d - x'_d)i_d + v_f^*)/T'_{d0} \\
 \dot{e}'_d &= (-e'_d + (x_q - x'_q)i_q)/T'_{q0}
 \end{aligned} \tag{3.1}$$

Where

$$\begin{aligned}
 \Omega_b &= 2\pi f_n \\
 v_f^* &= v_f + K_\omega(\omega - 1) - K_p(P - P_0)
 \end{aligned} \tag{3.2}$$

The voltage and current link is described by the equation:

$$\begin{aligned} e'_q &= v_q + r_a i_q + x'_d i_d \\ e'_d &= v_d + r_a i_d - x'_q i_q \end{aligned} \quad (3.3)$$

Equation A.2 - A.7 and 3.1 - 3.3 form the equations of fourth order generator model.

3.3.1.2 Sixth Order

The variables and parameters of the sixth order generator model are detailed in Table A.1 and A.2. As same as the fourth order model, auxiliary parameters are defined to initialize the variables. The model is initialized using power flow solutions v^0 , θ^0 , p^0 and q^0 . The initial values of each variable are detailed in Table A.3.

The sixth order model is obtained assuming the presence of a field circuit and an additional circuit along the d-axis and two additional circuit along the q-axis. Electromagnetic flux dynamics is neglected, thus leading to a sixth order system in the state variables δ , ω , e'_q , e'_d , e''_q , and e''_d . The differential equations are:

$$\begin{aligned} \dot{\delta} &= \Omega_b(\omega - 1) \\ \dot{\omega} &= (P_m - P - D(\omega - 1))/M \\ \dot{e}'_q &= (-e'_q - (x_d - x'_d - \frac{T''_{d0} x''_d}{T'_{d0} x'_d}(x_d - x'_d))i_d + (1 - \frac{T_{AA}}{T'_{d0}})v_f^*)/T'_{d0} \\ \dot{e}'_d &= (-e'_d + (x_q - x'_q - \frac{T''_{q0} x''_q}{T'_{q0} x'_q}(x_q - x'_q))i_q)/T'_{q0} \\ \dot{e}''_q &= (-e''_q + e'_q - (x'_d - x''_d + \frac{T''_{d0} x''_d}{T'_{d0} x'_d}(x_d - x'_d))i_d + \frac{T_{AA}}{T'_{d0}}v_f^*)/T''_{d0} \\ \dot{e}''_d &= (-e''_d + e'_d + (x'_q - x''_q - \frac{T''_{q0} x''_q}{T'_{q0} x'_q}(x_q - x'_q))i_q)/T''_{q0} \end{aligned} \quad (3.4)$$

Where

$$\begin{aligned} \Omega_b &= 2\pi f_n \\ v_f^* &= v_f + K_\omega(\omega - 1) - K_p(P - P_0) \end{aligned} \quad (3.5)$$

$$\begin{aligned} e_q'' &= v_q + r_a i_q + x_d'' i_d \\ e_d'' &= v_d + r_a i_d - x_q'' i_q \end{aligned} \quad (3.6)$$

3.3.2 Turbine Governor

Turbine governors define the primary frequency control of synchronous machines. The turbine governor model (TG1) implemented in Modelica is shown in Figure 3.1. The reference model is originally developed in PSAT. As shown in the block diagram, the model has three input signals: the actual rotor speed ω , the reference rotor speed ω_{ref} , and the reference active power p_{ref} . Output of the model is the mechanical power P_m to be applied to generator.

The governor regulates the speed of the generator by comparing its output with a predefined reference. When $R \neq 0$ and $R < \infty$, the governor regulates the speed proportionally to its power rate. In the mechanical part, two lead-lag filters are used to stand for the servo motor and the reheat mechanism.

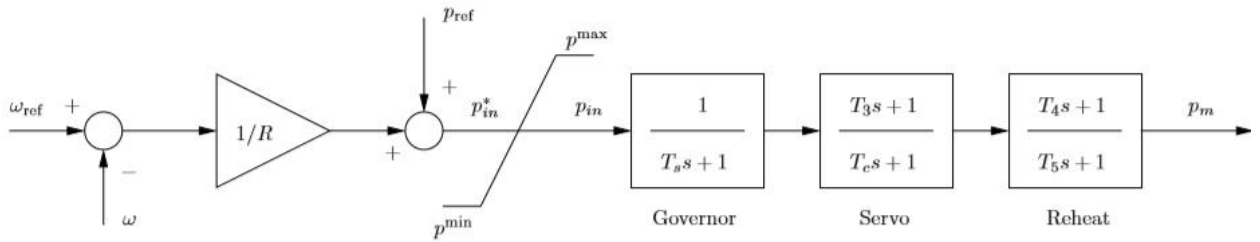


FIGURE 3.1: Block diagram of turbine governor model TG1 [2]

The variables and parameters of the turbine governor model are detailed in Table A.4 and A.5. Auxiliary parameters are also defined to initialize the variables of the model. The initial values of each variable are the values at the equilibrium point (e.g. ω_0 and p^0). The initialization parameters are detailed in Table A.6.

The model can be described by the following equations:

$$\begin{aligned}
 p_{in}^* &= p_{ref} + \frac{1}{R}(\omega_{ref} - \omega) \\
 p_{in} &= \begin{cases} p_{in}^* & \text{if } p^{min} \leq p_{in}^* \leq p^{max} \\ p^{max} & \text{if } p_{in}^* > p^{max} \\ p^{min} & \text{if } p_{in}^* < p^{min} \end{cases} \\
 x_{g1} &= (pin - x_{g1})/T_s \\
 x_{g2} &= ((1 - \frac{T_3}{T_c})x_{g1} - x_{g2})/T_c \\
 x_{g3} &= ((1 - \frac{T_4}{T_5})(x_{g2} + \frac{T_3}{T_c}x_{g1}) - x_{g3})/T_5 \\
 p_m &= x_{g3} + \frac{T_4}{T_5}(x_{g2} + \frac{T_3}{T_c}x_{g1})
 \end{aligned} \tag{3.7}$$

3.3.3 Excitation system

Exciter EXAC1 is one of the excitation system models developed in Modelica. The reference model is originally developed in PSS/E [3]. This model is the IEEE Type AC1A model correspond to a field-controlled alternator-rectifier exciter.

The exciter consists of an alternator main exciter with non-controlled rectifiers. The exciter does not employ self-excitation, and the voltage regulator power is taken from a source that is not affected by external transients. The diode characteristic in the exciter output imposes a lower limit of zero on the exciter output voltage, as shown in Figure 3.2 [28].

As shown in the block diagram, the model has three input signals: generator field current I_{FD} , generator terminal voltage E_C , and power system stabilizer (PSS) signal V_S . If no PSS is installed on the exciter, V_S can be set to zero. Output of the model is the field voltage E_{FD} to be connected to the generator.

Since the model is described originally by block diagram, it is implemented in Modelica by using developed components, as showed in Figure 3.3. The parameters of the excitation system model are detailed in Table A.7.

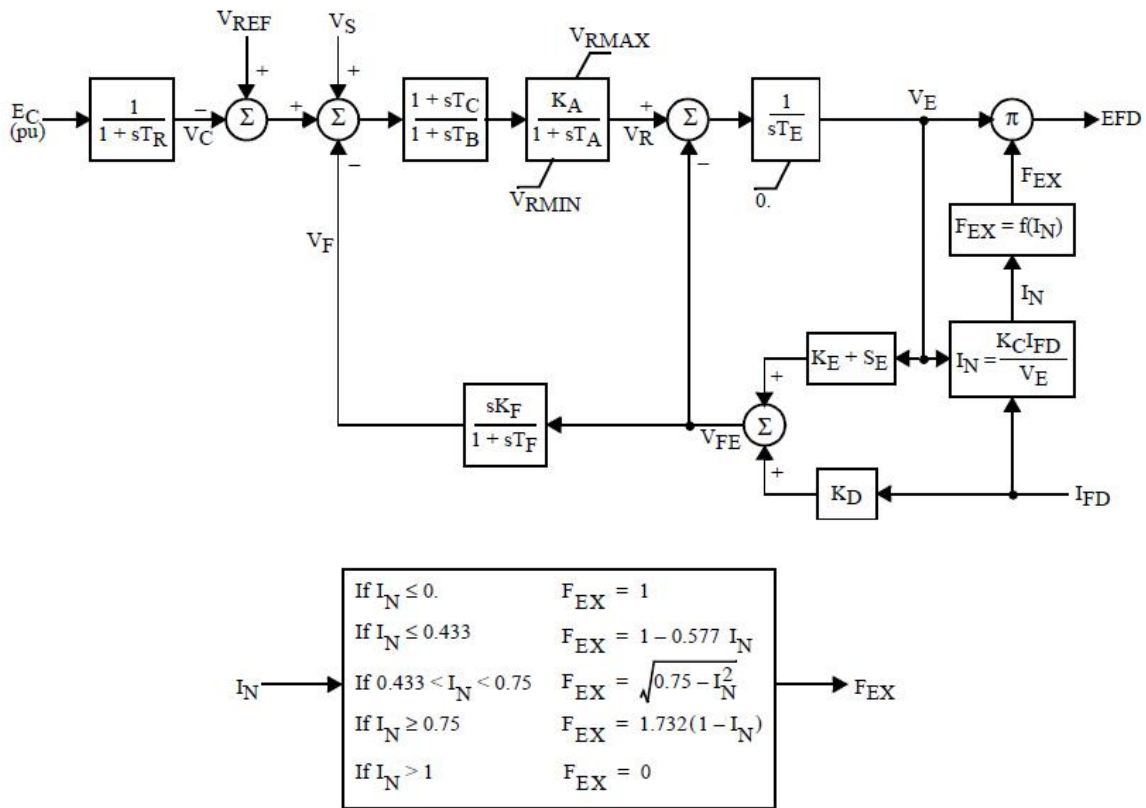


FIGURE 3.2: Block diagram of excitation system model EXAC1 [3]

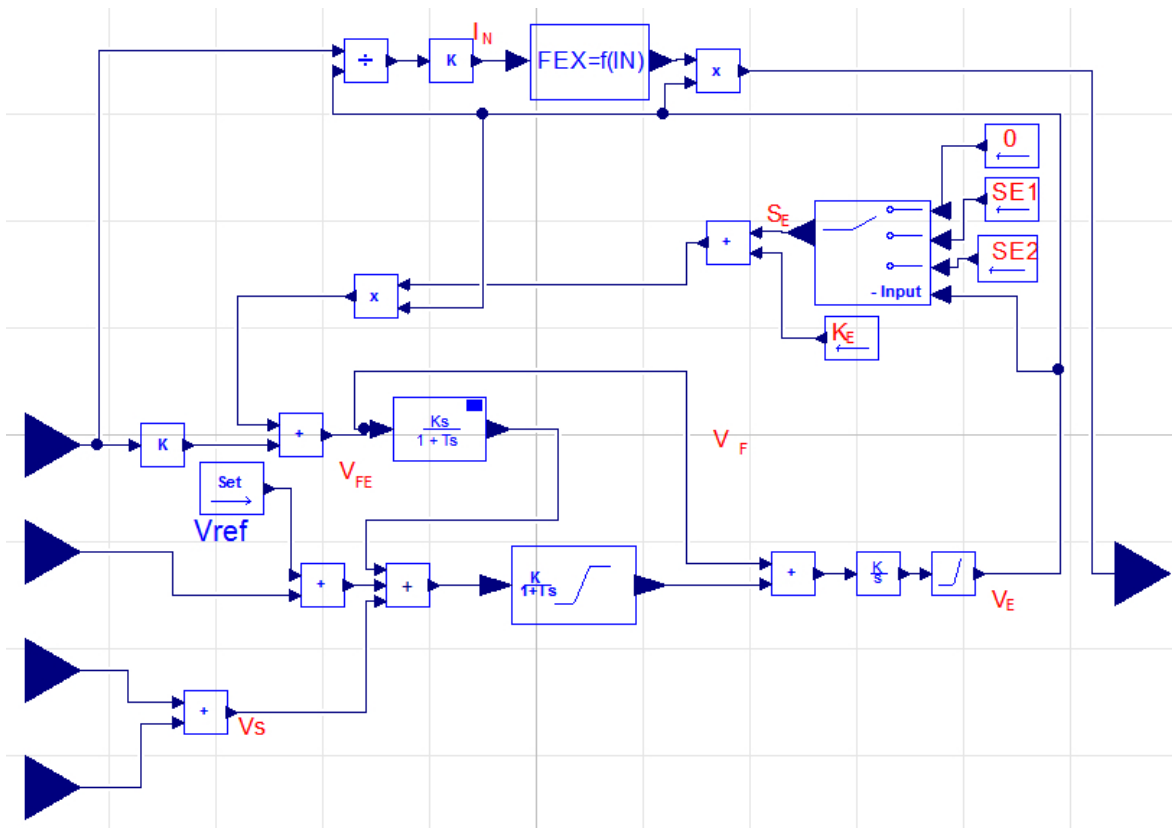


FIGURE 3.3: Excitation system model EXAC1 in Modelica

3.3.4 Power system stabilizer

Power system stabilizer (PSS) is another important component in power system. With PSS installed, electromechanical oscillations can be damped by adding the PSS output as additional input signal to the excitation system. The reference model is originally developed in PSS/E [3].

The PSS model (PSS2B) implemented in Modelica is shown in Figure 3.4. This model is the IEEE type PSS2B-Dual-Input PSS, which commonly uses the combinations of power and speed or frequency to derive the stabilizing signal [28].

As shown in the block diagram, the model has two input signals: speed deviation $\Delta\omega$ (or frequency deviation Δf) and active power P_e . Output of the model is the PSS signal V_{OTHSG} to be connected to the exciter.

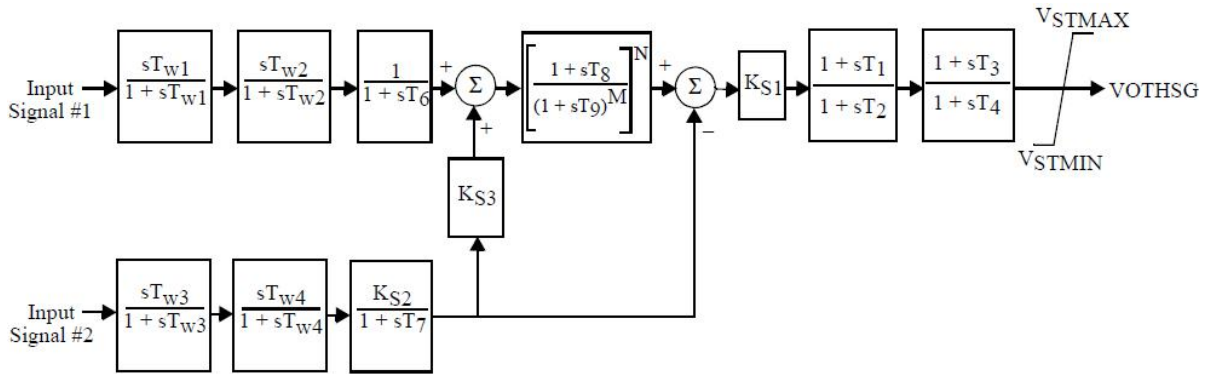


FIGURE 3.4: Block diagram of PSS model PSS2B [3]

Since the model is described originally by block diagram, it is implemented in Modelica by using existing models, as showed in Figure 3.5. The parameters of the excitation system model are detailed in Table A.8.

3.3.5 Load tap changer

An load tap changer (LTC) is a connection point selection mechanism along a power transformer with variable turns-ratio (or tap changer, i.e. n). The function of LTC is to automatically control load voltage by changing n . The representation of the effect of LTC

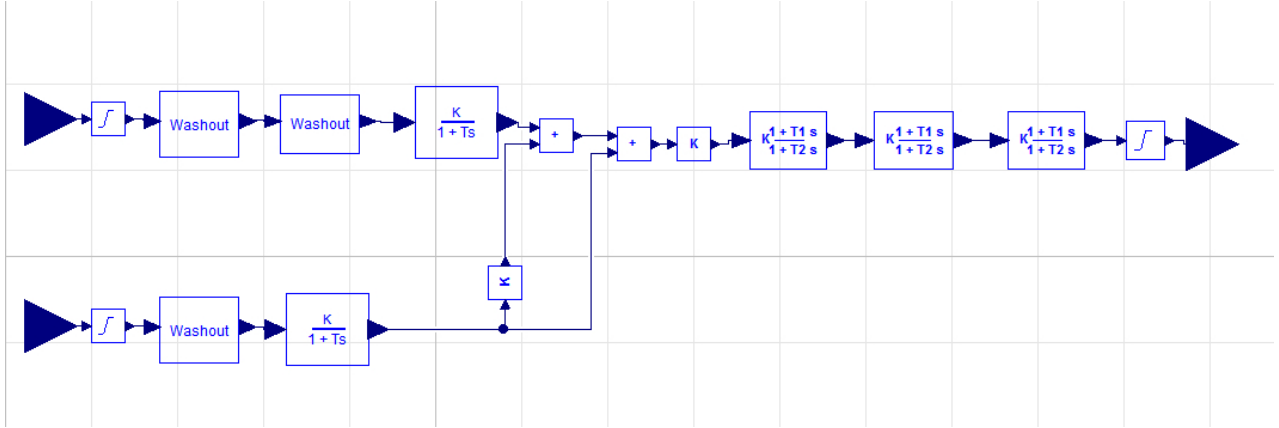


FIGURE 3.5: PSS model PSS2B in Modelica

transformer is particularly important for the analysis of slow voltage collapse phenomena [29].

The dynamic of LTC is described by a discrete tap changing logic. To keep the load voltage in the deadband $[V_{min}, V_{max}]$ p.u., the LTC adjusts the transformer ratios in the range $[n_{min}, n_{max}]$ over N positions (thus from one position to the next, the ratio varies by $(n_{max} - n_{min})/(N - 1)$).

The LTC has intentional delays. When the load voltage leaves the deadband at time t_0 , the first tap change takes place at time $t_0 + \tau_1$ and the subsequent changes at times $t_0 + \tau_1 + k\tau_2$ ($k = 1, 2, \dots$). The delay is reset to τ_1 after the controlled voltage has re-entered (or jumped from one side to the other of) the deadband. The values of τ_1 and τ_2 differ from one transformer to another in order to avoid unrealistic tap synchronization [5].

The LTC model implemented in Modelica is shown in Figure 3.6. As shown in the block diagram, input and output of the model are the load voltage v_l and turns-ratio n . The parameters of the LTC model are detailed in Table A.9.

3.4 Model validation

To assure the accuracy of modelling, software-to-software validation is carried out by designing different test scenarios. This procedure requires to compare outputs of two

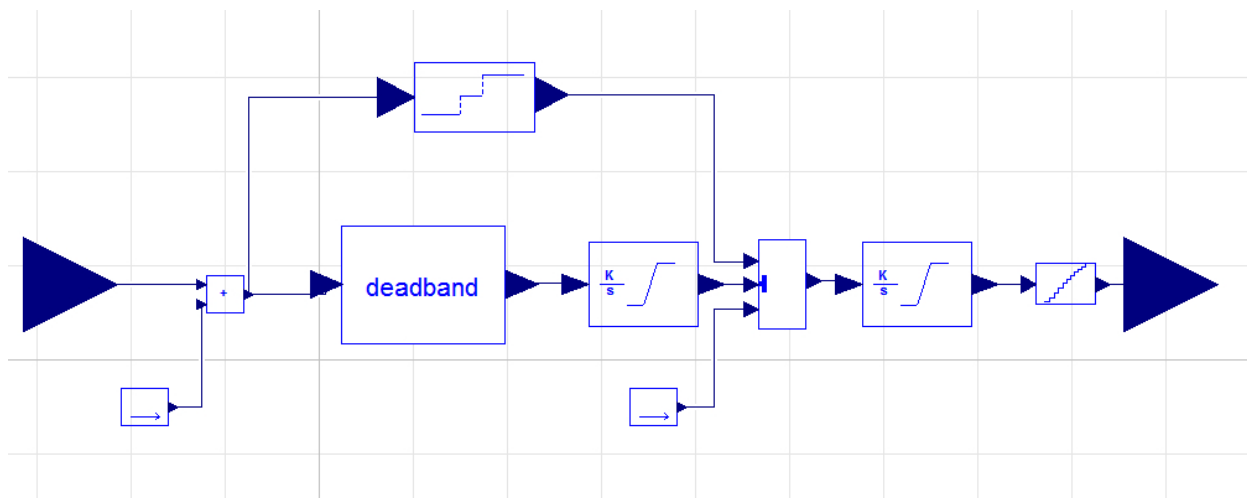


FIGURE 3.6: Block diagram of LTC model

validation systems given the same input and the same system structure (parameters). A correct model will provide a one to one match between the corresponding output signals.

3.4.1 Software-to-software validation

3.4.1.1 Generator and turbine governor

For validating the generator and TG models developed in Modelica, two identical systems are implemented in the reference software (PSAT) and Dymola, as shown in Figure 3.7 and 3.8. The model of generator and TG model are connected to a 4-bus-system with two constant PQ loads. To investigate the dynamic response of the models, two kinds of disturbance are applied to the system:

1. A three-phase short-circuit fault lasting 100ms is located on bus 4.
2. One of the parallel transmission lines between bus 2 and bus 4 is tripped for 100ms from $t = 3s$ to $t = 3.1s$.

This structure was chosen in order to avoid locating the fault directly on the generator terminal, thus the fault is less severe.

In order to commence the dynamic simulation, the model needs to be initialized. Power flow solution can be used to present the equilibrium point before the disturbance. Since

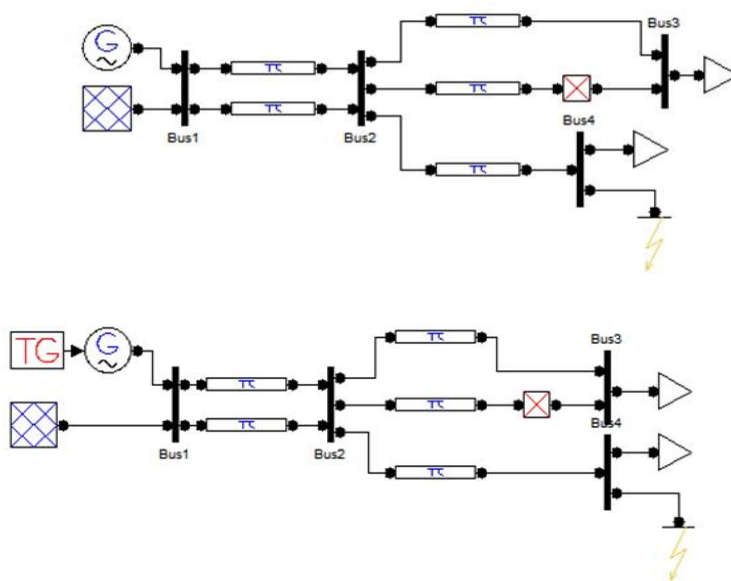


FIGURE 3.7: Reference model for generator and TG models in PSAT

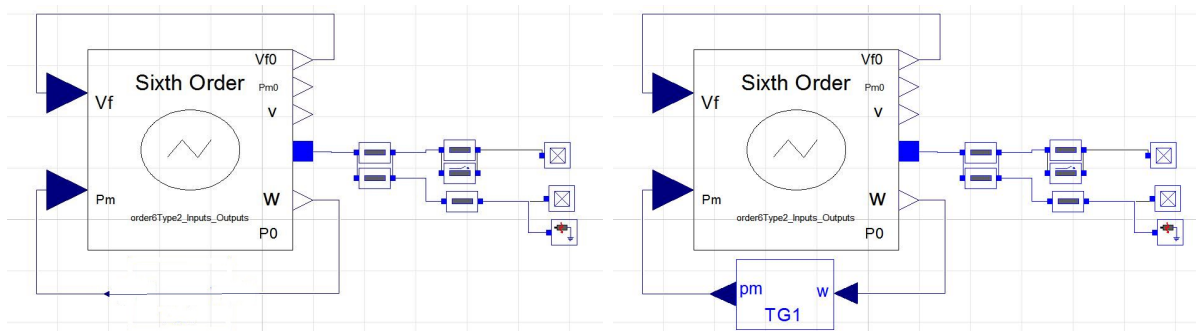


FIGURE 3.8: Modelica model for generator and TG models in Dymola

generator is the only model needed to be initialized in this system shown in Figure 3.8, the voltage magnitude, phase angle, active and reactive power on the generator bus (bus 1) is needed. The power flow calculation can be done in the reference software PSAT, in this way the two systems are starting from same equilibrium point.

3.4.1.2 Excitation system and PSS

For validating the excitation system and PSS models developed in Modelica, two identical systems are implemented in the reference software (PSS/E) and Dymola, as shown in Figure 3.9 and 3.10.

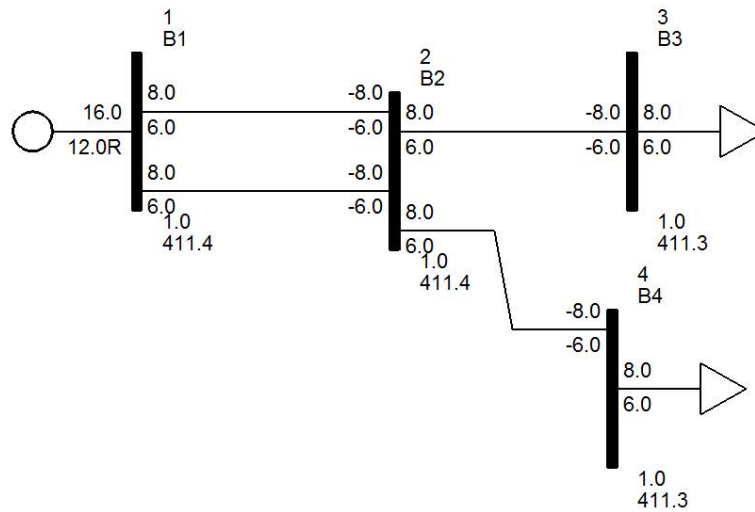


FIGURE 3.9: Reference model for excitation system and PSS models in PSS/E

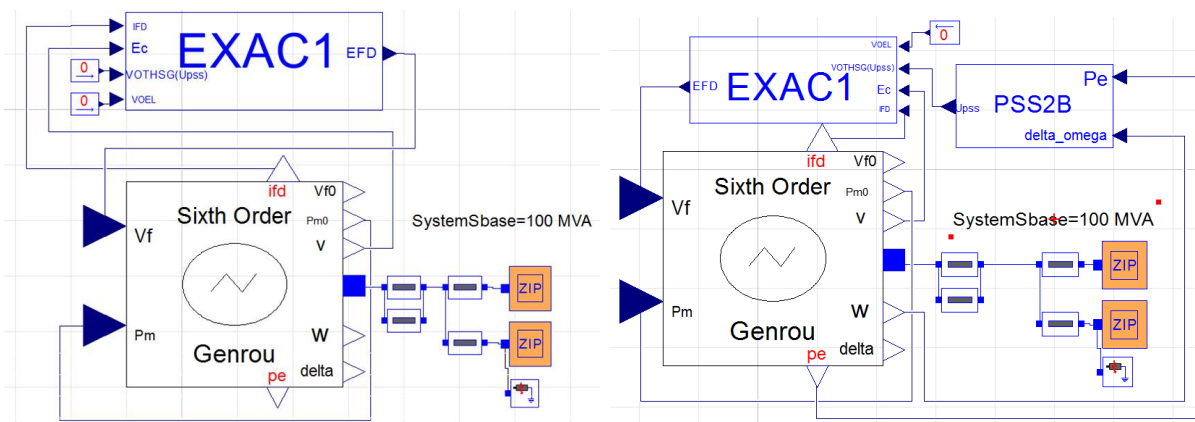


FIGURE 3.10: Modelica model for excitation system and PSS models in Dymola

Similar to the validation system for generator and TG models, the system is a 4-bus-system with one sixth order generator and two constant PQ loads. However in order to simplify the simulation process in PSS/E, one of the disturbances is omitted. In another words, only the short-circuit fault on bus 4 is applied to the system. The fault is also lasting for 100ms.

Power flow solution is used in the initialization process of the system similarly. The data of voltage magnitude, phase angle, active and reactive power on the generator bus (bus 1) is used. The power flow calculation are performed in the reference software PSS/E, so that the two systems are starting from the same equilibrium point.

3.4.1.3 LTC

The reference software of LTC model is MATLAB Simulink. In Simulink, generators and models are modeled using mask blocks. As shown in Figure 3.11, inputs of the generator and load models are bus voltages, while the outputs of the models are injected currents to the system.

S-function is used to establish the connection between currents and voltages. Output of the S-function are voltage on each bus, which is calculated based on the inputs (currents) of the system according to the equation $I = YV$. The bus admittance matrix Y is calculated based on the impedance contribution of machines, branches and loads.

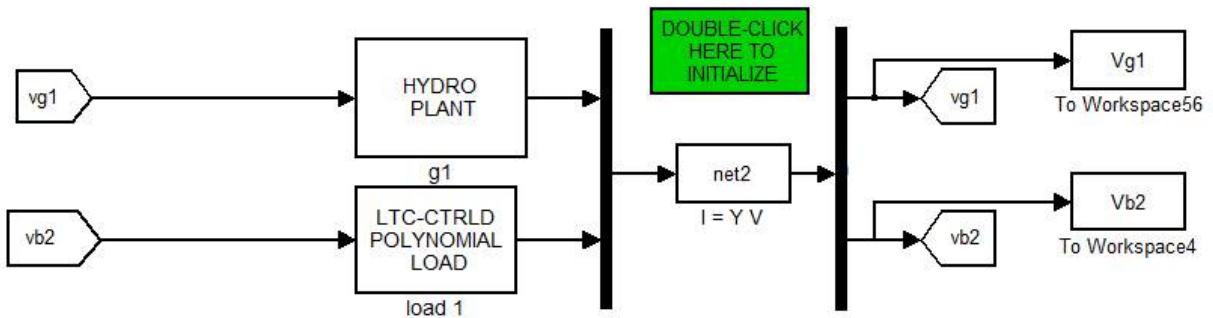


FIGURE 3.11: Reference model for LTC model in Simulink

In the simulation, it can be found that Simulink takes more time to simulate than PSAT and PSS/E. Therefore in order to increase computational efficiency, the system is simplified as much as possible. As shown in Figure 3.11 and 3.12, the model is a 2-bus-system, containing only one generator and one load. The LTC is installed on the transformer between the load bus and transmission line.

It is worth noting that no fault is applied in the system, but a different equilibrium point from the power flow solution is used in the initialization. So the dynamic response of the system is observed from $t = 0s$. Since for Simulink every model in the system needs initialization, the voltage magnitude, phase angle, active power and reactive power on each bus is given before the simulation.

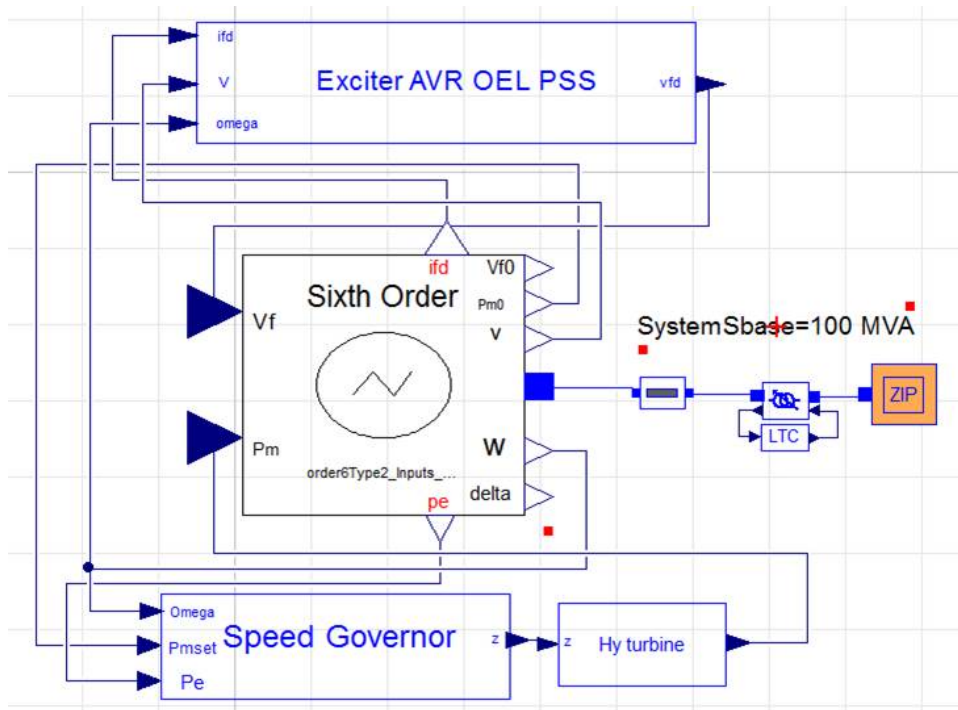


FIGURE 3.12: Modelica model for LTC model in Dymola

3.4.2 Validation results

In this section the validation results of the models described above are presented. In the results outputs from the reference software and Dymola are compared. When the corresponding output signals match each other, one can say the model is validated.

Validation results of all models can be found in Appendix A.

3.4.2.1 Forth Order generator

For the forth order generator model, the output signals compared are active power P , reactive power Q , d-axis transient voltage e'_d , q-axis transient voltage e'_q , generator terminal voltage v_g and rotor speed ω . The plots are shown in Figure A.1.

Discussion: After the disturbances applied at $t = 3s$ and $t = 12s$, the two systems response in the identical way. Since the model provide an one-to-one match between the corresponding output signals, the forth order generator model can be concluded as validated.

3.4.2.2 Sixth Order generator

For the sixth order generator model, the output signals compared are active power P , reactive power Q , d-axis transient voltage e'_d , q-axis transient voltage e'_q , d-axis sub-transient voltage e''_d , q-axis sub-transient voltage e''_q , generator terminal voltage v_g and rotor speed ω . The plots are shown in Figure A.2.

Discussion: After the disturbances applied at $t = 3s$ and $t = 12s$, the output signals match each other perfectly, including the sub-transient response. Thus the sixth order generator model can be concluded as validated.

3.4.2.3 Turbine governor

For the turbine governor model TG1, the compared output signals are P_m and ω . P_m is the mechanical power applied to generator, which is the only output of the governor model; while ω is the generator rotor speed, which is the state variable directly controlled by the governor. The plots are shown in Figure A.3.

Discussion: The outputs from two systems are identical. After the disturbances applied at $t = 3s$ and $t = 12s$, the turbine governor controls the mechanical power to stabilize the rotor speed. After 15 seconds, the rotor speed is stabilized at $\omega = 1 p.u.$, and the mechanical power is stabilized at $P_m = 0.16 p.u.$, equal to the values before the disturbances.

It is worth noting that the CPU-time for integration is 0.525 seconds in Dymola, while is 15.9799 seconds in PSAT. It can be seen that Modelica allowed a reduction of the integration step without increasing the computation time, thus providing smoother and more accurate results.

3.4.2.4 Excitation system

For the excitation system model EXAC1, the compared output signals are v_f and v_g . v_f is the field voltage applied to generator, which is the only output of the excitation

system. v_g is generator terminal voltage, which is the state variable directly controlled by the excitation system. The plots are shown in Figure A.4.

Discussion: The two systems response in the identical way. After the short-circuit fault applied at $t = 2s$, the terminal voltage v_g decreases instantaneously. To recover the system voltage, the excitation system increases field voltage v_f , then the generator terminal voltage is controlled and stabilized at $v_g = 1 p.u.$ after 3 seconds.

It can be observed that there exist small differences between the initial conditions in Figure A.4. The reason of the different initial condition is that the initialization processes of generator models in Modelica model and PSS/E model are not exactly the same. However it can be seen that after 0.5's fluctuation, the steady-state condition before disturbance of two system models are the same. The deviation does not influence the validation of excitation system model.

3.4.2.5 PSS

For the power system stabilizer model PSS2B, the outputs of PSS model U_{pss} are compared. The plots are shown in Figure A.5.

Discussion: As seen in Figure A.5, the two output signals match well. After the short-circuit applied at $t = 2s$, the PSS is activated to provide stabilizing signal; after $t = 8s$, the oscillation in the system is damped, resulting in U_{pss} turning back to 0.

3.4.2.6 LTC

For the load tap changer model LTC, the compared output signals are v_{load} and r_b . v_{load} is the load bus voltage, while r_b is the transformer ratio controlled by LTC. The plots are shown in Figure A.6.

Discussion: As shown in Figure A.6, the output signals from two systems match well. Since the initial value of V_{load} is above the deadband, the LTC adjusts the transformer ratios from $r_b = 1$. The first tap change takes place at $t = t_0 + t_1 + \tau_1 = 0 + 10 = 10s$, and the subsequent changes at times $t_0 + \tau_1 + k\tau_2$ ($k = 1, 2, \dots$) = 15s, 20s, 25s, \dots .

After the actions of LTC, the load bus voltage is adjusted at $v_{load} = 0.996 \text{ p.u.}$, which is within the deadband.

The CPU-time for integration is 0.435 seconds in Dymola, while is 28 seconds in Simulink. It is proved that Modelica computation power allows a reduction of the integration step without increasing the computation time.

Chapter 4

Modelling and Dynamic Simulation of Power Systems in Modelica

4.1 Introduction

With necessary component models prepared, it is theoretically feasible to implement and simulate integral power system models in Modelica. This chapter presents the experiences of power system modelling and dynamic simulation in Modelica.

In this thesis, four systems of different scale are implemented. The systems models will be used in future work in studying different aspect of problem, such as voltage stability analysis, instability detection and control.

- KTH Nordic 32 system: a conceptualization of the Swedish power system and its neighbors circa 1995, with some adjustment of the system model [4].
- IEEE Nordic 32 system: the IEEE Nordic 32 voltage stability test model
- iGrGen system: a model of a generator plant in Greece
- INGSVC system: a model of a sub-set of National Grid's network including two SVCs

The test systems are originally developed in different softwares. For instance, KTH Nordic 32 system model was developed in PSAT, whereas INGSVC system model was described specifically in PowerFactory. In the modelling process, the original models implemented in other software are regarded as references.

Software-to-software validation of the system models is done through the comparison of simulation results from different software. Given the same system structure, component model and critical system data, the system in Modelica should respond in a same manner as the reference system. Nevertheless, it is worth noting that for large scale systems, it is more difficult than small scale systems to obtain exactly same responses. In this case the criterion of validation should be revised on a case-by-case basis.

4.2 Power system modelling principles

As stated above, the objective of modelling is to create integral and correct test system models which can be used as benchmark systems in different studies. To achieve the objectives, the following five principles need to be followed:

1. The study purposes of the test system need to be determined

Test systems for one particular study should include specific representation of power system elements that have significant impact on the study. Therefore the usage of test systems must be determined clearly at the start of modelling to avoid omitting important elements. For instance, the IEEE Nordic 32 system is designed for voltage stability analysis and security assessment. Therefore the system model should include elements with the following characteristics [30–32]:

- *Generator characteristics* with excitation system models and its operating limits. Over excitation limiter (OEL) should be explicitly represented in order to account for the enforcement of generator limits.
- *Transmission system reactive compensating devices characteristics* or network compensation devices such as shunt capacitors, regulated shunt compensation, and series capacitors. Effect of transmission level LTC transformers should be accounted.

- *Load characteristics* with voltage dependence of loads and load restoration mechanisms (through the actions of load tap changers on transformers feeding the distribution system, and other load restoration mechanism such as those involving thermostat and some other load regulation devices). It is also important to account the effects of reactive power sources in the distribution systems.
- *Other protection and controls* which include armature overcurrent protection, transmission line overcurrent protection, reactive power source controls, and undervoltage load shedding.

Depend on different power system characteristics and prevailing operation conditions, it may be also necessary to include frequency dependence of loads, explicit model of automatic generation control (AGC), phase-shifting regulators, account the effect of adjustable ratio of generator step-up transformers and secondary voltage control.

2. Make appropriate simplification to the system model

Modern interconnected electric power systems cover very large geographic areas, include a large amount of electrical or non-electrical devices. To do one particular kind of study in the systems, it is neither practical nor necessary to model in detail the entire interconnected system [33]. It is common practice to represent parts of the system by some form of simplified model. The desired characteristics of the simplified model depends on its application and usage.

For most applications, two simplification approaches are commonly used. The first one is network simplification using equivalent techniques. In this approach, the interconnected power systems are partitioned into a studied area that needs to be well represented, and external areas that can be replaced by equivalent models [34]. Through this approach, the scale of the system can be reduced significantly.

The second commonly used approach is simplification of generator models. Generator is one of the most complex models in power system modelling. Thus by simplifying the model into several reduced orders, the amount of state variables in the system model will be decreased.

3. Use power flow solution to initialize the system model

The simulation of power system commonly starts from a equilibrium point, in which the system status can be presented by power flow solutions. The power flow calculation can be done in the reference software. To initialize the system model conveniently, the initialization parameters should be placed on top level of the system model.

4. The configuration of system model should be concise and compact

In the modelling of large scale power systems, it is important to organize the model in a concise and compact manner. It is common to include dozens of buses and hundreds of components in one system model, only one fault in the connection will lead to failed simulation. Thus for the convenience of double checking the configuration of the model should be as concise and compact as possible.

5. Implement the system model in a hierarchical approach

Modelica provides the possibility to implement power system models in a hierarchical way. Because of Modelica models can be implemented by connecting other models, some parts of power system (such as power plant models with generators and other control elements, and transformers with LTC) can be integrated into one compact model and used in the modelling of system. Figure 4.1 shows an example of hydro power plant model in Modelica. The models of generator, hydro turbine and speed governor are integrated into the hydro plant model, which can be used directly in the modelling of power system.

The system models are originally developed in PSAT, Simulink and Powerfactory. Since the modelling method in reference software are different from Modelica, a new set of procedures needs to be followed . The steps to achieve a successful modelling are as following:

1. Read the specification of the system. If detailed component models are not provided, select components to be included in the system model according to the application and use.

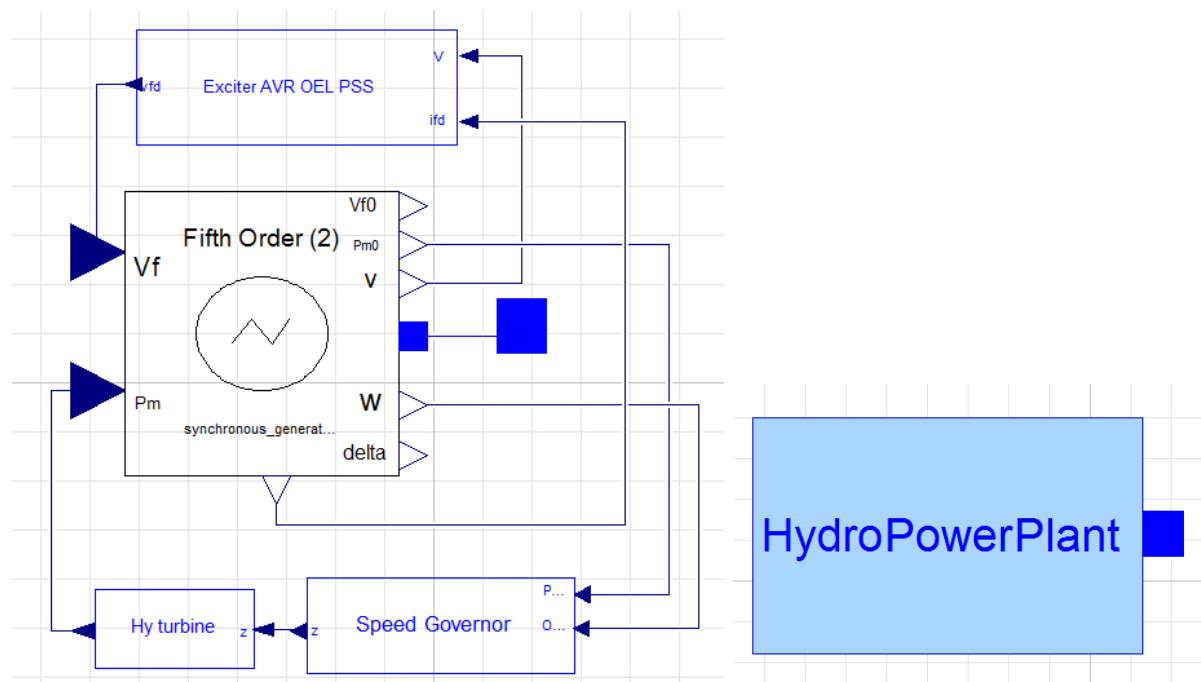


FIGURE 4.1: Icon view and diagram view of hydro power plant model in Modelica

2. Determine the parameters for the included models. If parameter and data are not given in the specification, other parameter identification methods (e.g. measurement-based parameter identification) need to be used.
3. Implement the model in Modelica.
4. Collect power flow solution data and initialize the system model.
5. Perform the simulation, compare the simulation results with the reference system model.

4.3 KTH Nordic 32 system

4.3.1 System overview

The first test system implemented in this thesis, KTH Nordic 32, is a variant of the so-called Nordic 32 test system [29]. The system is fictitious but similar to the Swedish and Nordic system (at the time of setting up the test system). The one-line diagram of KTH Nordic 32 system is shown in Figure 4.2.

The system involves 20 generators, 32 transmission and 22 distribution buses, for a total of 74 buses. The test system is divided into four areas:

- “North” with hydro generation and some load
- “Central” with much load and thermal power generation
- “Equiv” connected to the “North”, it includes a simple equivalent of an external system
- “South” with thermal generation, rather loosely connected to the rest of the system

Among the 20 generators in the system, 12 of which are hydro generators located in the North and Equivalent areas, whereas the rest are thermal generators located in the Central and South area. The system is heavily loaded with large transfers essentially from North to Central areas, which easily leads to system instabilities.

The nominal frequency is 50 Hz. Frequency is controlled by the speed governors in the hydro power plant in the North and Equiv areas. G_{20} is an equivalent generator, with a large participation in primary frequency control. The thermal units of the Central and South areas do not participate in this control.

The maximum power that can be delivered to the Central loads is strongly influenced by the reactive power capabilities of the Central and some of the Northern generators. Their reactive power limits are enforced by over excitation limiters (OELs). If, after a disturbance (such as a line outage), the power that need to be delivered is larger than the generator limits, voltage instability will be resulted.

The KTH Nordic 32 system is originally implemented in PSAT, which is considered as reference for the system model in Modelica.

4.3.2 Model and data

1. **Buses:** The system has 52 node buses, 20 of which are generator buses. There are four level of voltages; 15 kV for generator buses, 20kV for distribution buses, 130 kV, 220 kV and 400 kV for transmission buses.

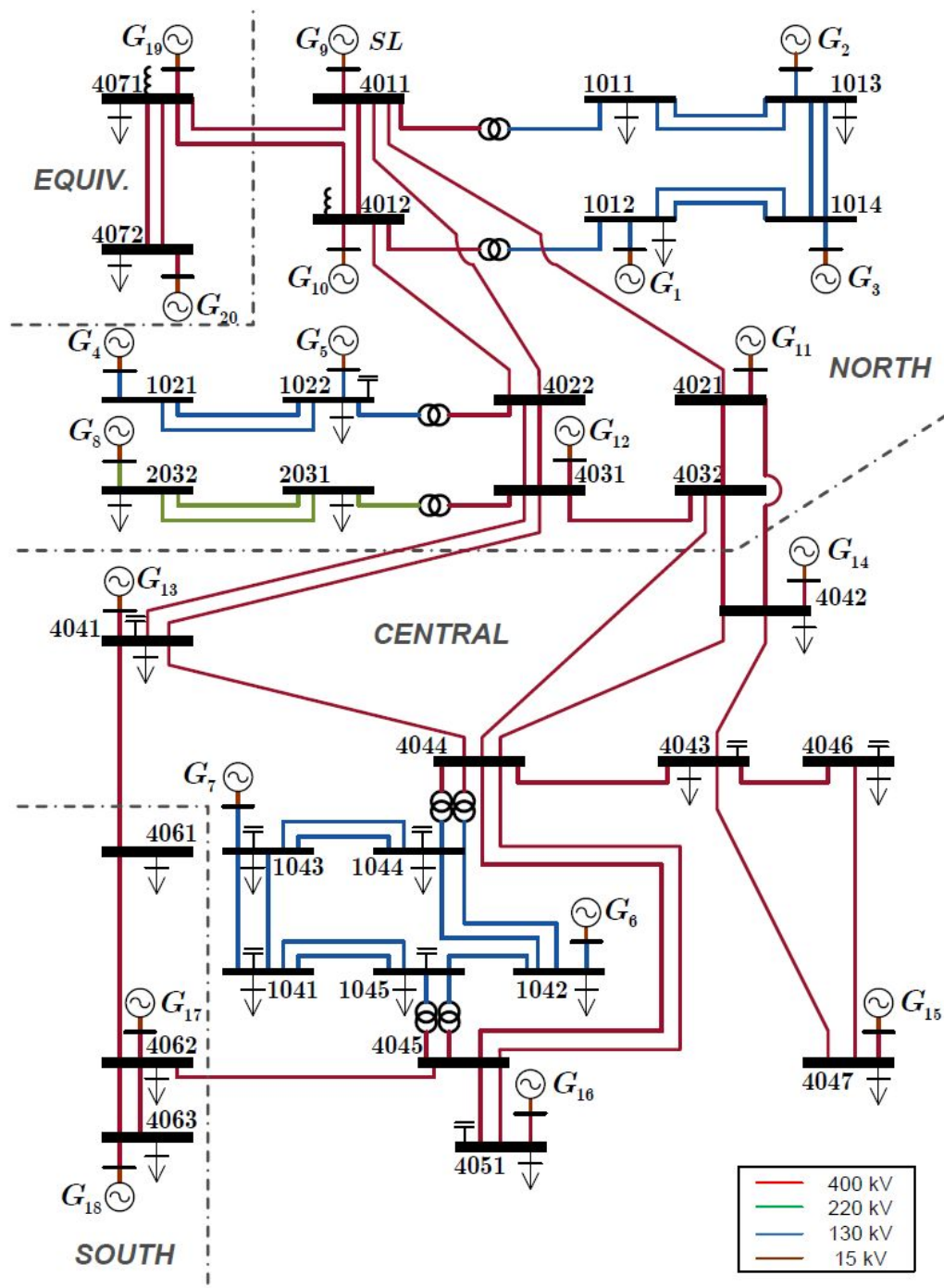


FIGURE 4.2: KTH Nordic 32 system [4]

2. **Transmission lines:** The system has 52 transmission lines in total. The transmission line model is based on the π -equivalent circuit. The values for resistance r , reactance x and susceptance b are in per unit. Shunt conductance is not considered in this model.
3. **Loads:** The loads in the system are modeled as constant impedance loads. In the initialization of the model, with node voltage magnitude U_0 , load active power P_0 and reactive power Q_0 from power flow solution are transformed into constant impedances R_l and X_l :

$$P_0 = \frac{R_l U_0^2}{R_l^2 + X_l^2}, \quad Q_0 = \frac{X_l U_0^2}{R_l^2 + X_l^2} \quad (4.1)$$

4. **Shunts:** The system has 11 shunts, 9 of which are capacitor banks and the rest are inductor banks. The capacitive shunts are represented by positive susceptance b , whereas the inductive shunts are represented by negative b . The description of the shunt model can be seen in appendix A.4.
5. **Synchronous generators:** Two synchronous generator models are used in the system: three rotor windings for the salient-pole machines of hydro power plants (Order V Type 2) and four windings for the round-rotor machines of thermal power plants (Order VI). All data follows Van Cutsem's proposed data [35], except for the nominal apparent power of G_{18} that is changed to 1600 MVA. Saturation effects are neglected.
6. **Turbine governors:** Two types of turbine governors are employed in the system. TG Type I is used for the thermal generators while TG Type II is used for the hydro generators. The data for hydro TGs is provided in [35], whereas recommended values are applied for the thermal TGs. The TG Type II model is depicted in Figure 4.3, and the TG Type I model is described in Chapter 3.3.2.
7. **Automatic voltage regulators:** Automatic voltage regulators (AVR) are used for all generators to control the field voltage v_f . The AVR model used in the system is AVR Type III [2]. The AVR model is depicted in Figure 4.4, and the parameters are the recommended values provided in [36].

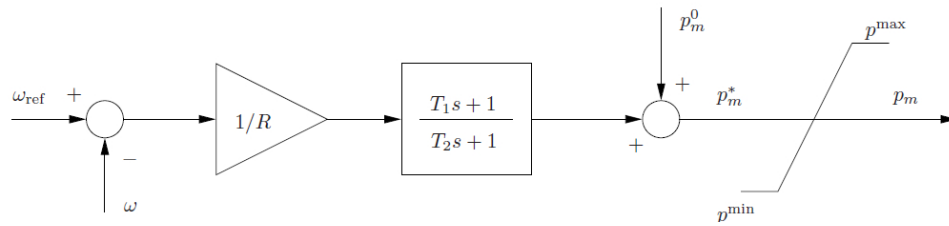


FIGURE 4.3: Turbine governor Type II model [2]

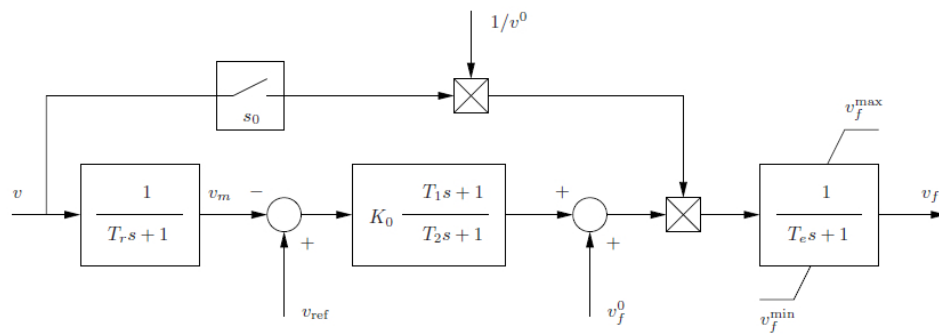


FIGURE 4.4: AVR Type III model [2]

8. **Over excitation limiters:** Each generator is equipped with an over excitation limiter (OEL) to keep its field current within limits. Since the focus is on overexcited generators, lower excitation limitation is not included. As seen in Figure 4.5, the OEL is modeled as a pure integrator with anti-windup hard limits. The OEL is not activated unless the field current i_f is larger than its limit i_f^{lim} . The field current is calculated based on generator terminal voltage v_g , active power p_g and reactive power q_g . The OEL model is detailed in appendix A.4.

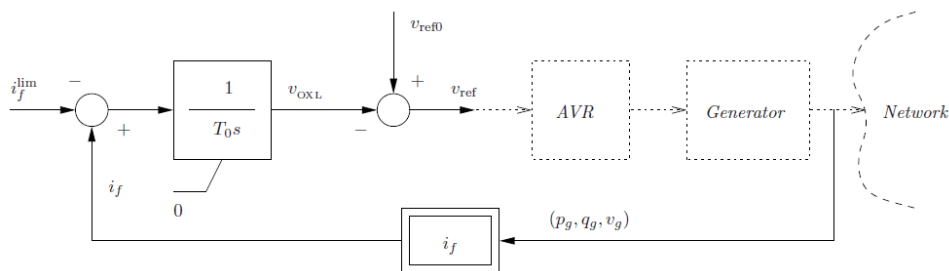


FIGURE 4.5: OEL model [2]

The system model in Modelica is shown in Figure 4.6.

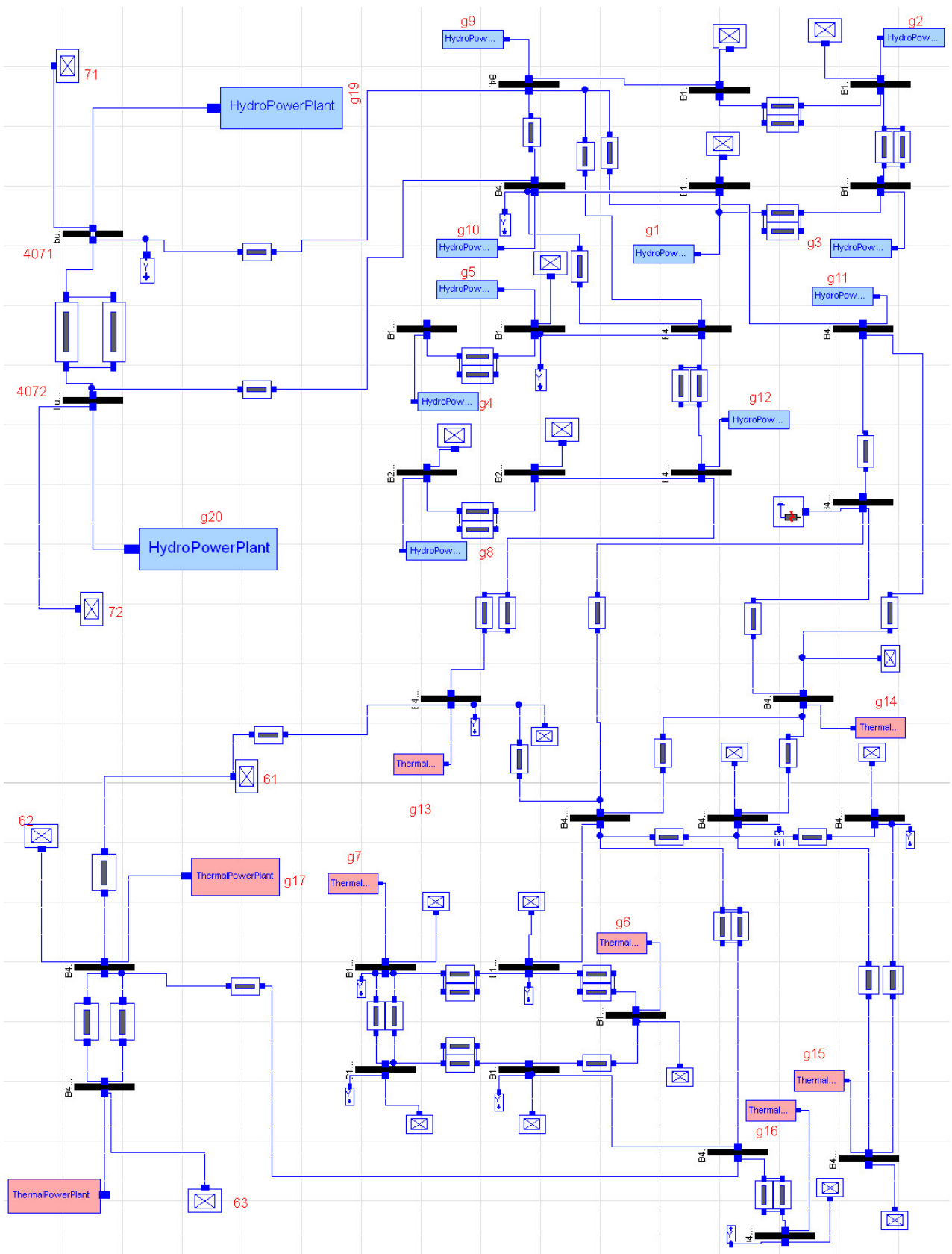


FIGURE 4.6: KTH Nordic 32 system model in Modelica

4.3.3 Simulation and validation

To investigate dynamic response of the system, a three-phase short-circuit fault is applied on “Bus2032” at $t = 15 - 15.1s$, with the fault impedance $Z_{fault} = 0.0001 + j0.001$. The fault is set on this bus to decrease the influence on critical generators, and avoid affecting the dominant power flow.

The system model validation is done by comparing responses of two systems from Dymola and PSAT. The system response after fault is investigated by observing the following outputs, as shown in Figure 4.7, 4.8 and 4.9:

- Distribution bus voltage: $V_{B4022}, V_{B2032}, V_{B4012}$ (NORTH) $V_{B1041}, V_{B1043}, V_{B1045}$
 V_{B4041} (CENTRAL)
- Generator terminal voltage: V_{G8}, V_{G12} (NORTH) V_{G6}, V_{G13} (CENTRAL)
- Generator rotor speed: ω_8 (NORTH) ω_6 (CENTRAL)

Discussion: As the distribution bus voltages show in Figure 4.7, in response to the short-circuit fault applied to one of the generator bus at $t = 15s$, the system exhibits damped electromechanical oscillations that die out in 10 seconds. Since the fault is applied to “BUS2032”, which is a non-critical generator bus far from the North-Central corridor, the fault does not affect the dominant power flow. Thus the fault does not lead to voltage collapse in the system.

For the system is closely connected by the 400 kV transmission lines between North and Central areas, the voltage oscillation can be observed in both areas. Nevertheless since the fault is applied to a bus in North area and does not cause large-scale power outage in Central area, the oscillations in Northern buses are more severe.

The generator terminal voltages are presented in Figure 4.8. Since AVRs are installed on every generator, the terminal voltage is controlled to keep constant. It can be seen that the AVRs function well. Similarly because the generators in North area are more influenced than those in Central area, the voltage oscillations in G_8 and G_{12} are more severe than G_6 and G_{13} .

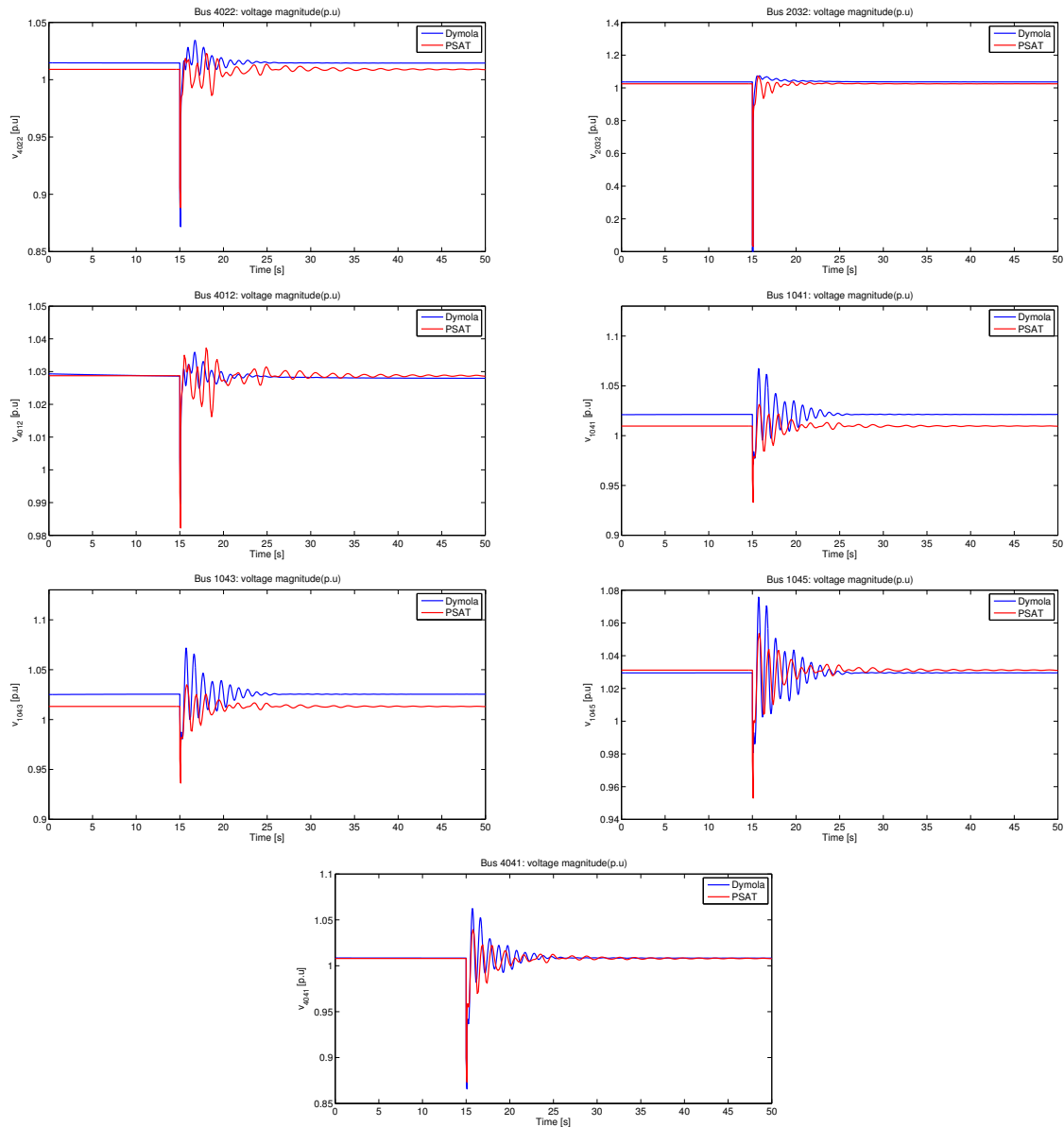


FIGURE 4.7: Distribution bus voltages in KTH Nordic 32 system

The effect of frequency control is shown in Figure 4.9. The generator rotor speed of G_8 (located in North) and G_{13} (located in Central) are kept around 1 p.u. by the governor installed on the generator.

In addition, from the comparison between the outputs from two systems, it can be found that two systems response to the disturbance in a fairly similar way. There are small deviations between the oscillation processes, the reason lies in the differences between the numerical solvers of two software.

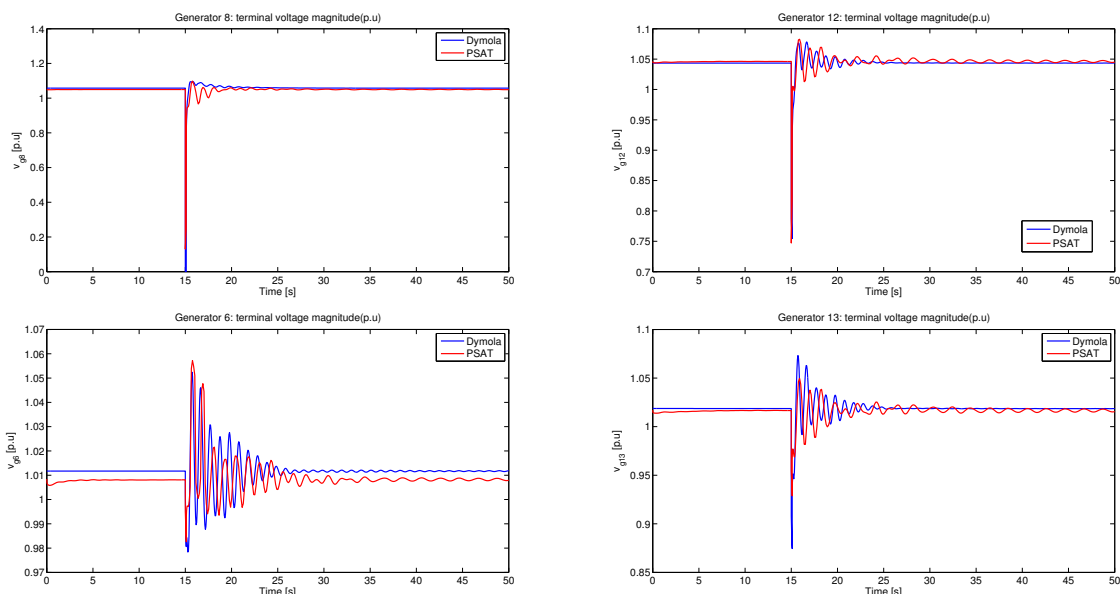


FIGURE 4.8: Generator terminal voltages in KTH Nordic 32 system

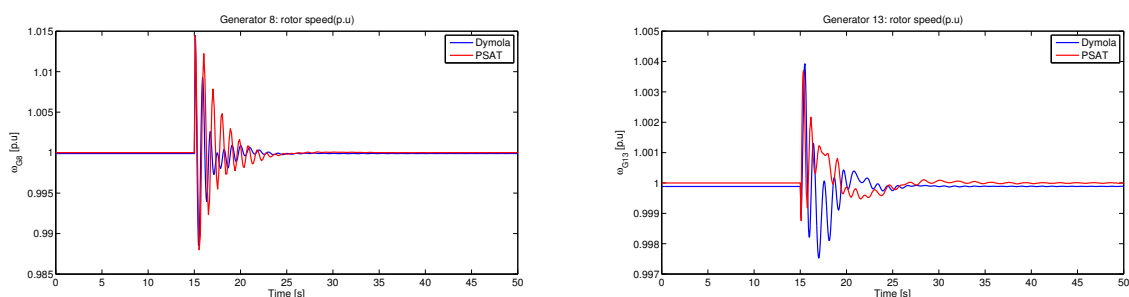


FIGURE 4.9: Generator rotor speeds in KTH Nordic 32 system

4.4 IEEE Nordic 32 system

4.4.1 System overview

The IEEE Nordic 32 system is another variant of the Nordic 32 system with some models adjusted. IEEE Power and Energy Society Task Force has done voltage stability analysis on the Nordic 32 system, and provided detailed model description, data and simulation results in the task force report [5]. The IEEE Nordic 32 system in this thesis is implemented based on the information provided in the report.

The one-line diagram of the system is as same as the KTH Nordic 32 system, as shown in Figure 4.2. The differences in IEEE Nordic 32 system in comparison to KTH Nordic 32 system are:

- Saturation is modelled in all machines.
- Different generator control elements (governors and excitation systems) are used.
- Power system stabilizers (PSS) are included in the excitation system.
- Load tap changers (LTCs) aiming at restoring distribution voltages are included.

The IEEE Nordic 32 system is originally implemented in Simulink, which is considered as reference model in Modelica.

4.4.2 Model and data

The models of buses, transmission lines and shunts are the same as in KTH Nordic 32 system, the description can be seen in Section 4.3.2. In this section only different models are focused on.

1. **Synchronous generators:** Salient-pole generators are represented by Order V Type 2 model, whereas round-rotor generators of thermal plants are represented by Order VI model. Saturation is modelled in all generators. The standard saturation curve relating the no-load armature voltage V_{nl} and field current i_{fd} is given in Figure 4.10. The saturation characteristics is given by:

$$k = \frac{|AB|}{|AC|} = 1 + m(V_{nl})^n \quad (4.2)$$

The following data apply to all generators:

- For $V_{nl} = 1$ p.u., $k = 1.1$ which yields $1.1 = 1 + m$ and hence $m = 0.1$
- For $V_{nl} = 1.2$ p.u., $k = 1.3$ which yields $1.3 = 1 + 0.1 \times 1.2^n$ and hence $n = 6.0257$
- Unsaturated leakage reactance $X_l = 0.15$ p.u. in both axes.

2. **Exciter, PSS and OEL:**

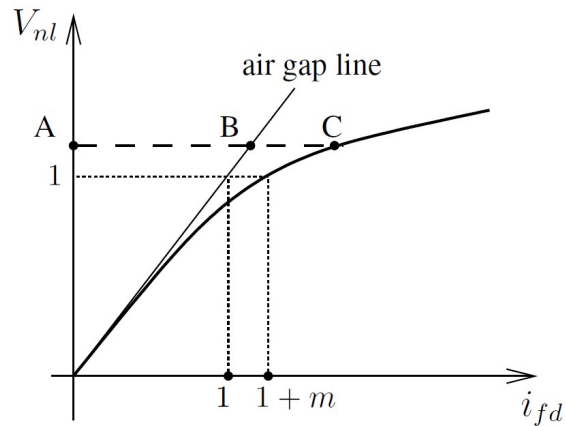


FIGURE 4.10: Saturation characteristics [5]

In figure 4.11 shows the model of excitation system for generators, including exciter, PSS and OEL is shown. The model is used for all generators but with different parameters. The exciter is represented by a first-order system with a time constant of 0.1 s and a non-windup limits on the field voltage. A transient gain reduction has been included, to limit the overshoot in terminal voltage following a step change in voltage reference when the generator operates in open circuit.

All generators (except G_{13} , G_{19} and G_{20}) are equipped with PSS using the rotor speed ω as inputs. Each PSS includes a washout filter and two identical lead-lag filters in cascade. The PSS provides damping for oscillation between 0.2 Hz and 1 Hz.

In addition, all generator are equipped with OELs keeping their field current within limits. For small generators, namely G_6 , G_7 , G_{11} and G_{12} , the OELs have a fixed operation time of 20s. All other OELs are modelled with inverse time characteristics, i.e. the higher the field current, the faster the limitation takes place.

3. Turbine and governor

The models of turbine and speed governor used in the system are shown in Figure 4.12. The governor model includes a measurement, a PI controller and a servomotor. The turbine model is lossless. The models of excitation system, turbine and governor are detailed in Appendix A.3.

4. Load tap changers

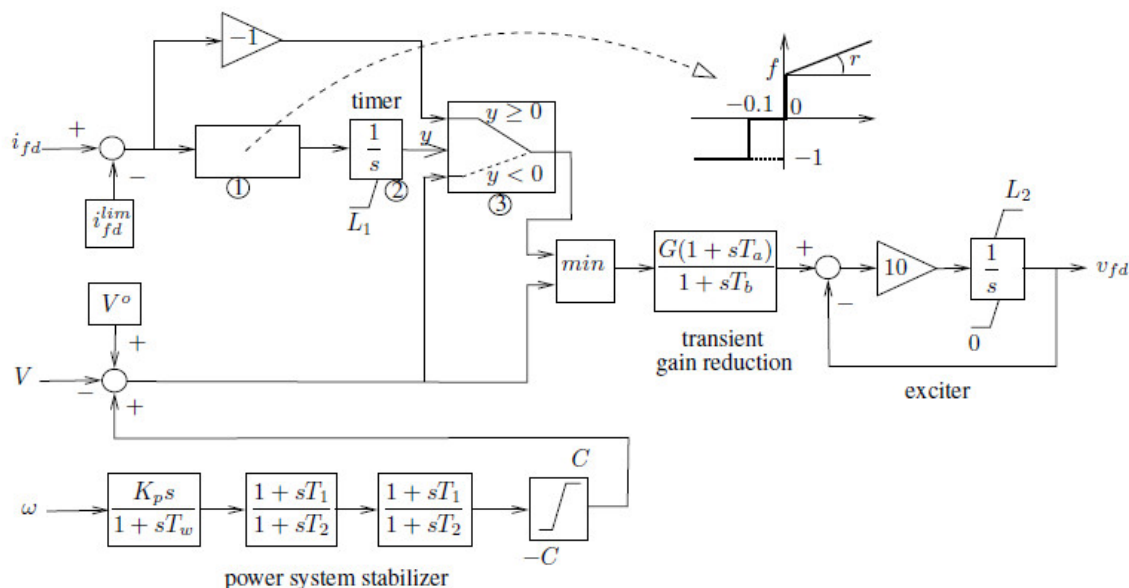


FIGURE 4.11: Model of exciter, PSS and OEL [5]

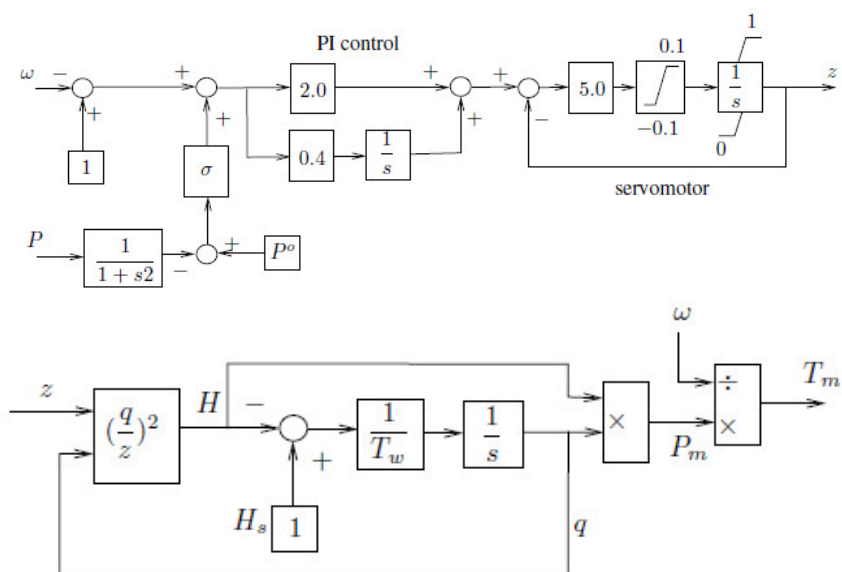


FIGURE 4.12: Model of speed governor and turbine [5]

All distribution transformers are equipped with LTCs. The LTC model is detailed in Chapter 3.3.5. In Modelica, the LTC is installed on the transformer by bringing in a new “transformer-LTC” model, as shown in Figure 4.13. The transformers are connected to the grid through electrical connectors, whereas the transformer ratios are controlled through non-electrical connectors. The distribution bus voltage V_l is exported by a 3-phase potential transformer, and the power transformer ratio r_b is an independent variable which can be controlled externally.

The transformer-LTC model is connected with a LTC model in the manner shown in Figure 4.14. Based on the value of V_l , LTC adjusts the transformer ratio to control the distribution bus voltage.

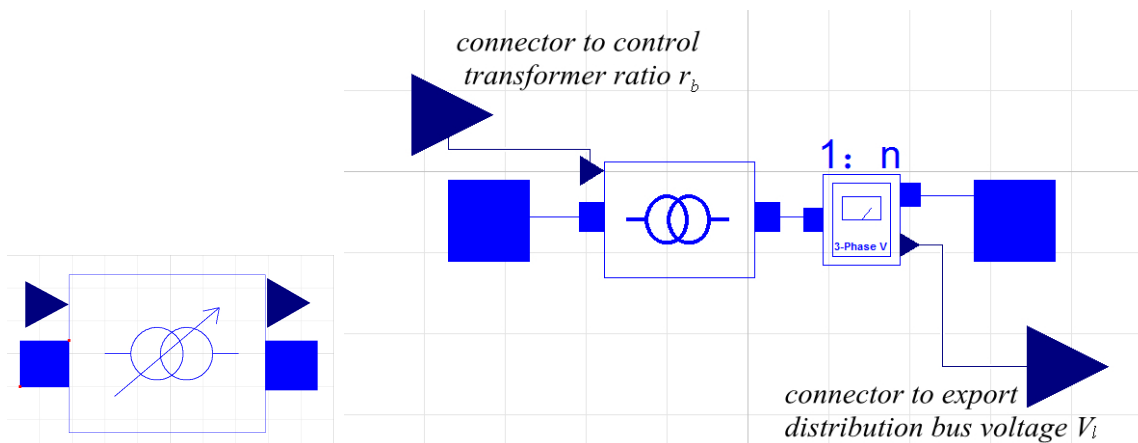


FIGURE 4.13: Diagram and icon view of transformer-LTC model

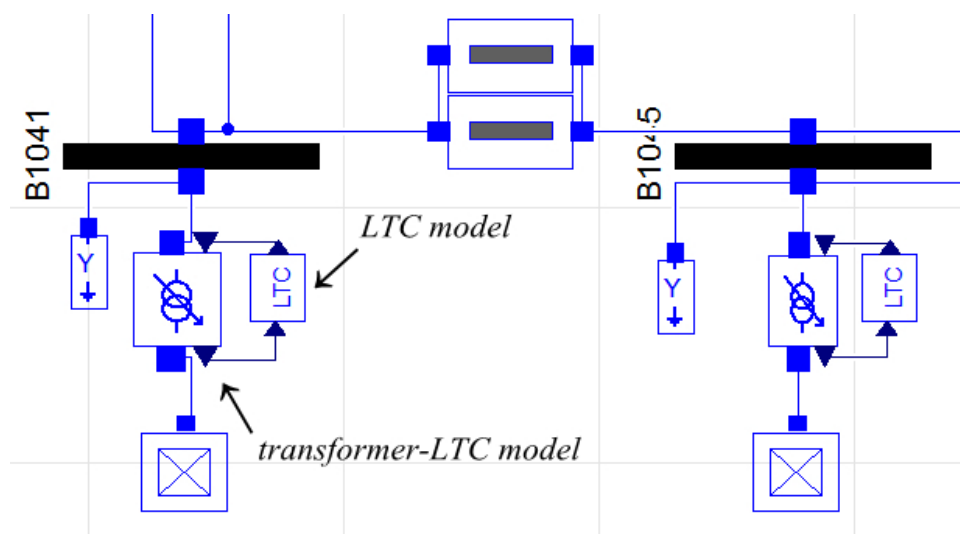


FIGURE 4.14: Connection of LTC to the system model

4.4.3 Simulation and validation

To investigate dynamic response of the system, a three-phase short-circuit fault is applied on “Bus2032” at $t = 40 - 40.1s$, with fault impedance $Z_{fault} = 0.0001 + j0.001$. By applying the fault on bus 2032, critical generators will not be affected seriously, and dominant power flow will not be influenced.

The system model validation is done by comparing responses of two systems from Dymola and Simulink. The system response after fault is investigated by observing the following outputs, as shown in Figure 4.15, 4.16 and 4.17:

- Distribution bus voltage: V_{B4022} , V_{B4032} (NORTH) V_{B1044} , V_{B1045} (CENTRAL)
- Generator terminal voltage: V_{G14} , V_{G15} (CENTRAL)
- LTC operation: Transformer 1 connecting bus 1011 and load 1, transformer 17 connecting bus 4051 and load 51

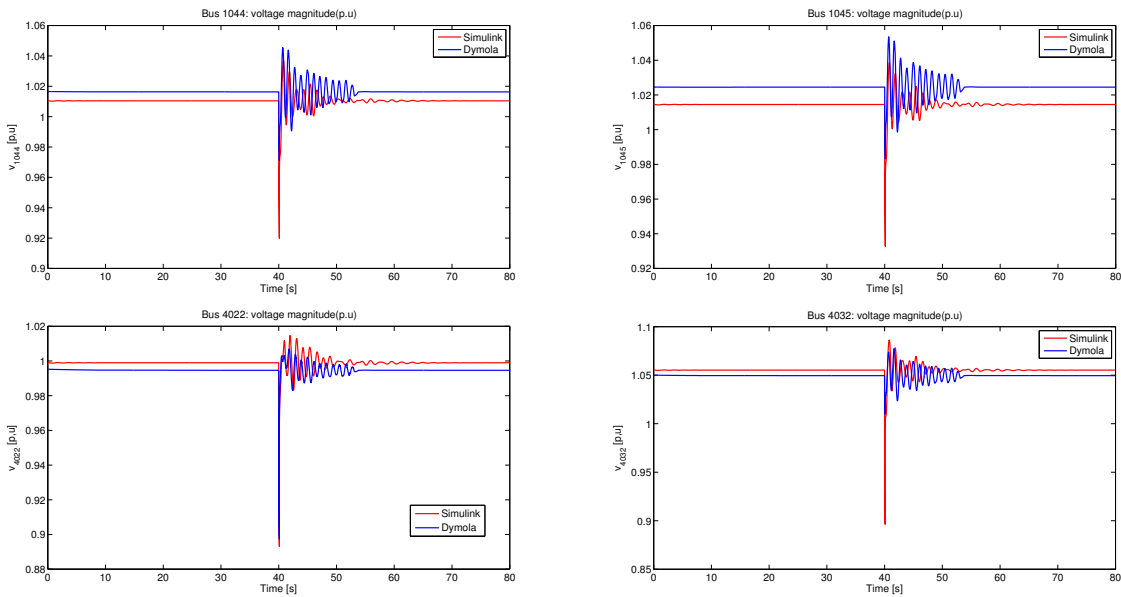


FIGURE 4.15: Distribution bus voltages in IEEE Nordic 32 system

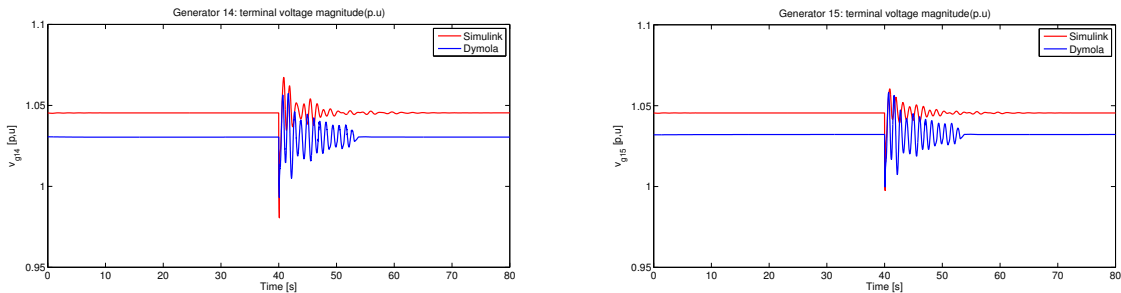


FIGURE 4.16: Generator terminal voltages in IEEE Nordic 32 system

Discussion: As shown by distribution bus voltages in Figure 4.17, in response to the distribution applied on bus 2032 at $t = 40 - 40.1s$, the system exhibits damped electromechanical oscillations that die out in 15 seconds. Since the fault is applied in North area, the voltages in Central buses are less influenced than Northern buses.

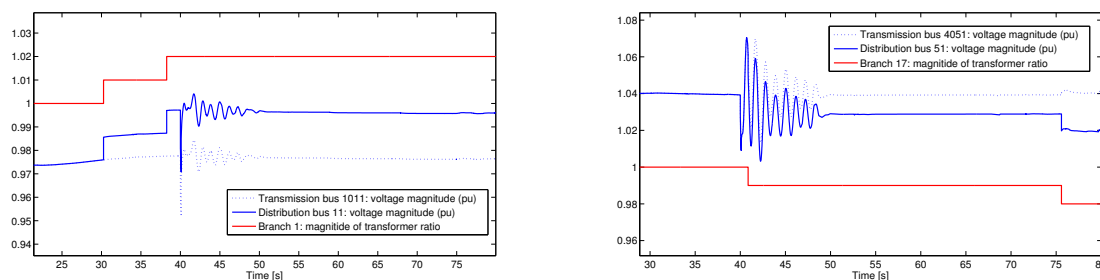


FIGURE 4.17: LTC operations in IEEE Nordic 32 system

In Figure 4.16, generator terminal voltages are controlled to keep constant. Compared with the generator terminal voltages of KTH Nordic 32 system shown in Figure 4.8, it can be found that when the same disturbance is applied on Nordic 32 system, although generators are equipped with different excitation system and governor models, effects of the control are similar.

In addition, from the comparison between the outputs from two systems in Dymola and Simulink, it can be seen that two systems response to the disturbance in a fairly similar way. The small deviations between the oscillation processes are caused by the differences between numerical solvers in two softwares.

Consideration of LTC operations is a major difference between KTH Nordic 32 and IEEE Nordic 32 system. To present the effect of LTC operations, the dynamics of transformer ratio and distribution bus voltage are shown in Figure 4.17. The figures show the successful attempt of LTC to bring distribution voltages back within the $[0.99, 1.01]$ deadband. The solid and dashed lines in the figure are distribution and transmission bus voltages respectively. As seen in the figure, when distribution bus voltage is above the limitation, LTC will keep changing the transformer ratio after a certain delay, until distribution bus voltage is within the acceptable range.

4.5 iGrGen - Greece Generator system

4.5.1 System overview

The Greece generator system is a Combined Cycle Power Plant (CCPP). The power plant consists of a gas turbine, a steam turbine and a synchronous generator on a single shaft arrangement. The one-line diagram of iGrGen system is shown in Figure 4.18.

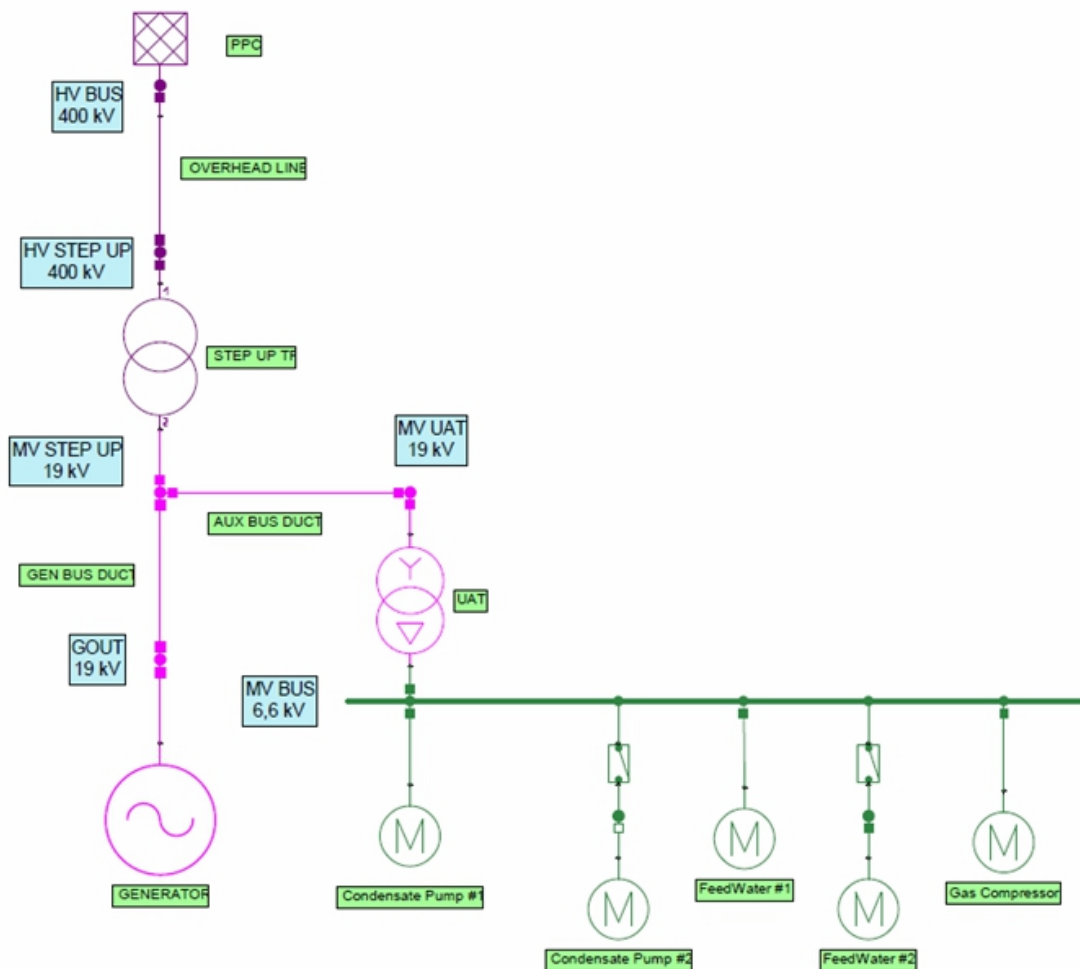


FIGURE 4.18: One-line diagram of iGrGen system

As the figure shows, the step-up transformer (STEP UP TR) connects the generator to the 400 kV busbar (HV BUS) with a overhead transmission line. The system also includes auxiliary loads (medium voltage motors), which are connected to the 6.6 kV busbar (MV BUS). The auxiliary load bus connects to the generator with an auxiliary transformer

(UAT). The nominal power output of the generator is 533.4 MVA, and the total rated power of the medium voltage auxiliary loads is 8.66 MW.

4.5.2 Model and data

1. **Synchronous generator:** In order to include the transient reactances (x'_q , x'_d) and sub transient reactances (x''_q , x''_d) in the generator model, Order VI generator model is used. The generator excitation system is AVR Type III as depicted in Figure 4.4, according to the specification in PSAT [2].

The generator is also equipped with a power system stabilizer (PSS) in order to enhance damping of power system oscillation through excitation control. The model is PSS Type II according to PSAT specification, as shown in Figure 4.19. The gas and steam turbine of the generator are controlled through a speed governor, the used model is TG Type I.

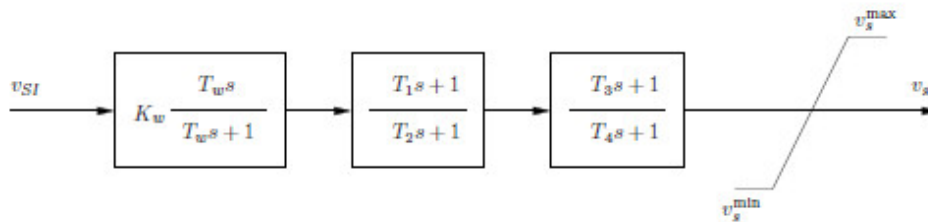


FIGURE 4.19: PSS Type II model [2]

2. **Step-up transformer:** The step-up transformer “STEP UP TR” is a three-phase, oil immersed, outdoor type transformer. The rated power of the transformer is 500 MVA, and the short circuit voltage is 15%.
3. **Auxiliary transformer:** The rated power of the auxiliary transformer “UAT” is 23 MVA and the nominal voltage ratio is 19/6.9 kV. The short circuit voltage is 7.25%.
4. **Overhead transmission line:** The step-up transformer is connected to HV BUS with a typical single circuit 400 kV overhead transmission line with ACSR 550/70 conductors. The length of the line is 70 m.

5. **Auxiliary loads:** The main auxiliary loads of the system are five medium voltage motors with their rated characteristics given in table 4.1. Two of the motors (Feed Water #2 and Condensate motor #2) are used as backup. The auxiliary loads also consist of 32 low voltage motors. The rated power of low voltage motors is estimated as 4.69 MW and 2.91 MVar. The total auxiliary power of the system is approximately 8.2 MW.

TABLE 4.1: Medium voltage motors

Motor	P_m (MW)	Speed (rpm)	Load moment of inertia	No. of motors
Feedwater	3.2	2986	0.499	2
Condensate	0.43	1486	2.449	2
Gas compressor	1.4	2980	1.443	1

6. **Equivalent network behind the substation:** The equivalent network behind the HV busbar (the rest of the power grid) is modeled as an equivalent large impedance load as well as an infinite bus with constant voltage magnitude and phase angle.

The iGrGen system model in Modelica is shown in Figure 4.20.

4.5.3 Simulation and validation

To investigate dynamic response of the system, two disturbances are applied to the system. The first disturbance is a three-phase fault on MV BUS applied at $t = 10 - 10.2s$, the fault impedance is $z_{fault} = 0.0001 + j0.3$. The second disturbance is another three-phase fault on the auxiliary transformer UAT applied at $t = 30 - 30.2s$, with the same fault impedance $z_{fault} = 0.0001 + j0.3$.

In order to validate the model of the system, an identical system is implemented in PSAT with the same system structure and parameters. The system responses from two systems are investigated by comparing the following outputs, as shown in Figure 4.21 and 4.22:

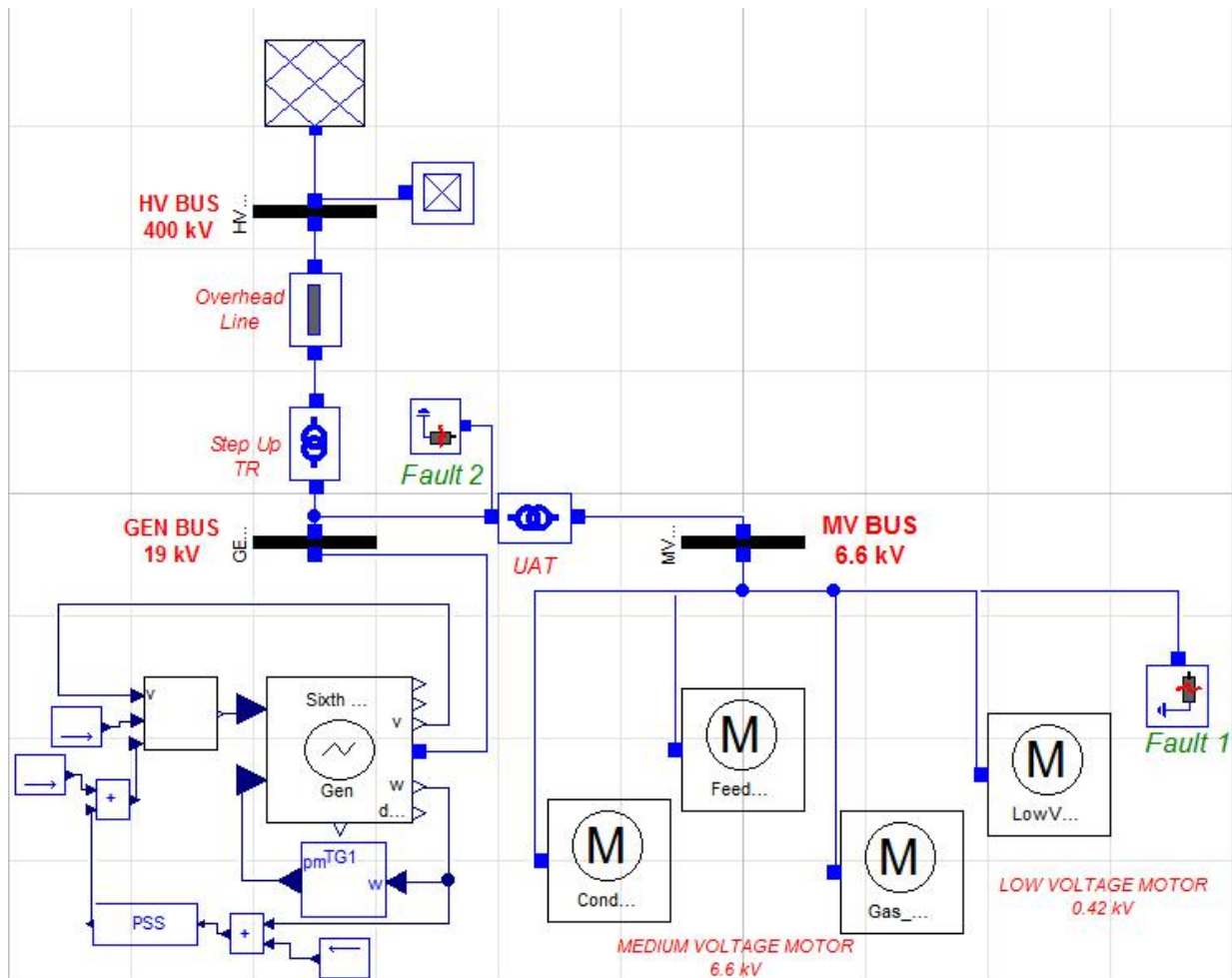


FIGURE 4.20: iGrGen system model in Modelica

- Bus voltage: V_{MVBUS} , V_{GENBUS}
- Generator power: P_G , Q_G
- Generator mechanical power: P_m
- Generator field voltage: v_f

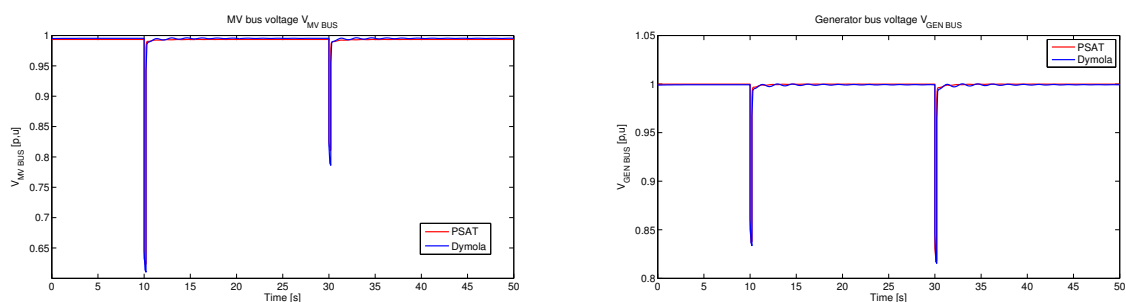


FIGURE 4.21: Bus voltages in iGrGen system

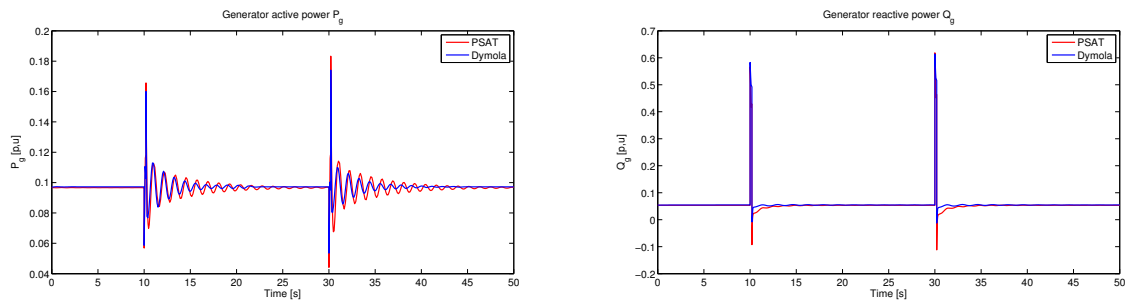


FIGURE 4.22: Generator power in iGrGen system

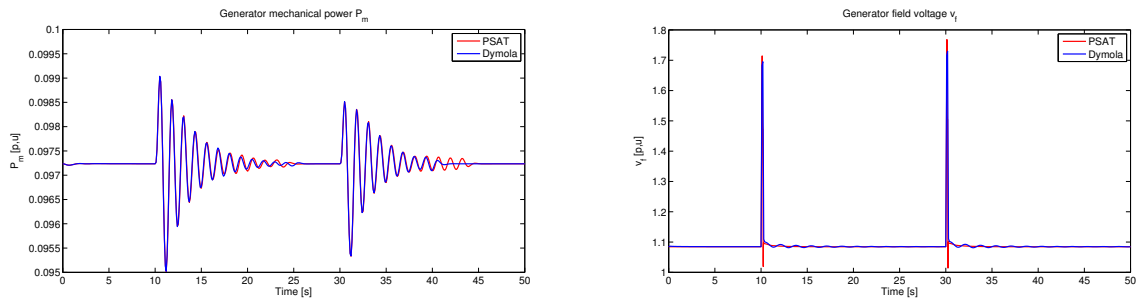


FIGURE 4.23: Generator mechanical power and field voltage in iGrGen system

Discussion: According to the MV BUS and GEN BUS voltages shown in Figure 4.21, since the faults are not severe, the bus voltages are recovered quickly and voltage dips after the fault in the system do not cause voltage instability. In addition, due to the presence of the speed governor and AVR, the generator power P_G and Q_G , and terminal voltage V_{GENBUS} are regulated after the faults.

In the comparison between the responses from Dymola and PSAT, it can be concluded that the system model in Dymola is correct, and provides a one to one match between the corresponding output signal from PSAT model.

4.6 INGSVC - SVC part of National grid system

4.6.1 System overview

INGSVC is an equivalent model of a 400 kV substation with a Static Var Compensator (SVC) connected to the busbar. Since SVC can generate and absorb reactive power, it

is installed in the substation mainly for voltage control. The SVC is connected to the substation bus bar through a transformer and a circuit breaker, as shown in Figure 4.24.

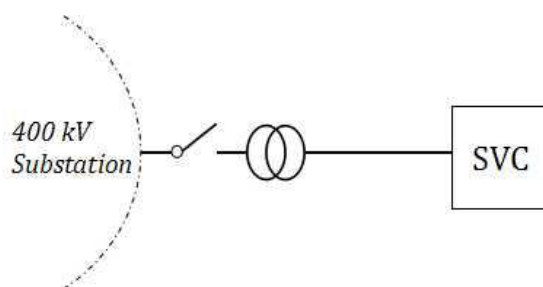


FIGURE 4.24: INGSVC system

4.6.2 Model and data

In INGSVC system model, the substation is equivalent to a infinite bus with constant voltage amplitude and phase angle. The effect of circuit breaker is modelled as a transmission line, connected through the transformer and the infinite bus. The INGSVC model in Dymola is shown in Figure 4.25.

Different from other systems, the parameters of INGSVC system are not given with the system description. Thus the parameters of the model are estimated using the measured data with the application of system identification methods. The available measurements is the response of SVC to a busbar fault. The parameter estimation and simulation results of INGSVC model are detailed in Chapter 5.

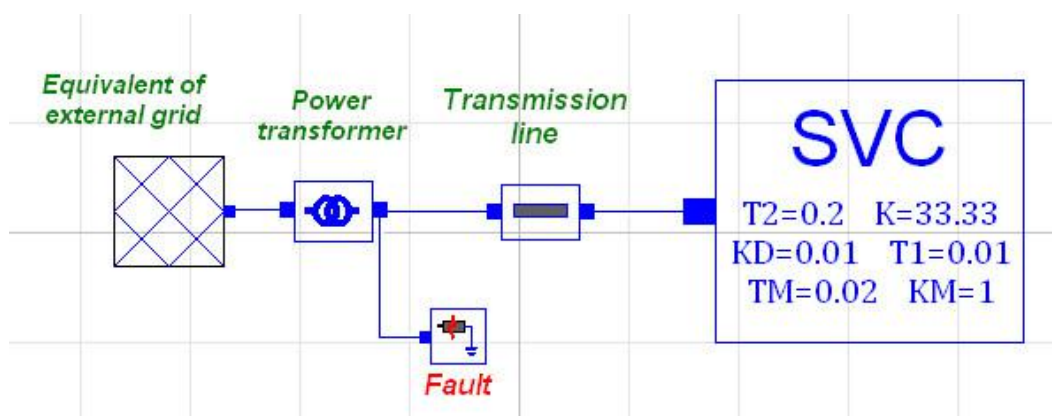


FIGURE 4.25: INGSVC system model in Dymola

Chapter 5

System identification

5.1 Introduction

System identification is a number of methods to build valid mathematical models for a dynamic system based on measurement data [37]. Particularly, a system model is identified by estimating and adjusting parameters until its outputs match the measured outputs with acceptable error.

System identification is an important task in power system modelling and simulation. The system model may have been developed with a reference component, and the validity of such model is directly linked to the fidelity of the parametrization. In most cases, the parameters are not given with a system model; even for the models with parameters, the available parameters may not correspond to real values due to several reasons: the model may have been validated against a different component; the parameter value have changed over time, etc. [8].

In this chapter, experience of power system identification is provided with the aid of iTesla RaPID toolbox developed by SmarTS Lab. Two system models are identified against measurement data: the Greece generator system iGrGen, and the National Grid SVC system INGSVC. Since system identification requires different computational methods, two kinds of optimization algorithms are used, and the obtained results are analysed

involving two widely-used technologies: fitness function calculation and statistical analysis (confidential interval).

5.1.1 System identification using Modelica and FMI

In this project, system identification and parameter estimation is realized with the help of RaPIId toolbox. RaPIId is a parameter estimation toolbox developed by SmartTS Lab Within the FP7 funded iTesla project. The main operation principle of RaPIId is illustrated in Figure 5.1.

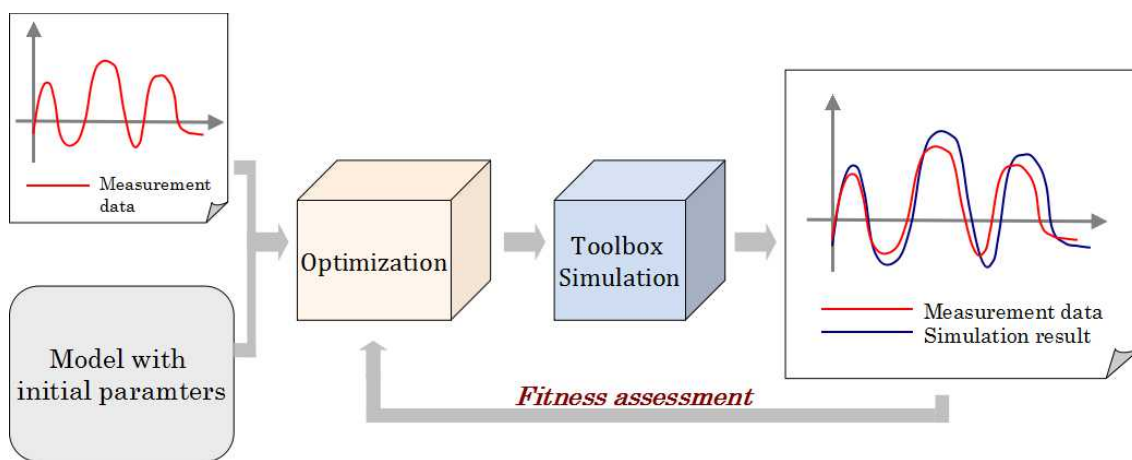


FIGURE 5.1: Operation principle of RaPIId toolbox

The system model and measurement data are the input to the toolbox. In the first step of parameter estimation, the model is simulated using a set of initial system model parameters. Then the correctness of the initial guess is assessed by evaluating the fitness function, which is composed by comparing the simulation result with a reference model response (or measurement data) provided as input to the toolbox. Next, according to the fitness function, an updated set of parameters is generated using chosen optimization algorithms. On next iteration, the power system model will be simulated again and fitness function will be evaluated. The optimization process will continue until the error between model output and measurement data is within an acceptable range. This range can be defined by engineer according to the validation protocols.

It is worth noting that besides model parameters, the parameters of chosen algorithms can also be optimized, according to the estimation correctness and efficiency.

The RaPIId toolbox is developed in MATLAB. The top-level MATLAB code acts as a wrapper to provide interaction with several other tools [38]. The interaction of the tools are realized in the following pattern:

- **MATLAB:** MATLAB combines all the software to realize the toolbox's simulation and optimization functions. It provides a Graphical User Interface (GUI) and a Command Line Interface (CLI) for the user of the toolbox. Built-in parameter optimization algorithms are also developed in MATLAB, and several MATLAB toolboxes are used within RAPID toolbox.
- **Simulink:** Simulink is used to configure the models used by RAPID, and generate simulation results used by RaPIId toolbox for fitness assessment.
- **Modelica:** The system model is developed and identified in Modelica language.
- **FMU:** System model is compiled into a Flexible Mock-up Unit (FMU) according to the FMI standard. FMU is a C-object containing the methods for simulation. FMU is used as input to RaPIId toolbox.

5.1.2 Optimization algorithms

To find the parameters which minimize the error between the measurement data and the simulation results, different optimization algorithms are used in the parameter estimation showed in Figure 5.1. There are six algorithms integrated in RaPIId toolbox in total, among which the following two algorithms are applied for the parameter estimation in this thesis:

- **Particle swarm optimization algorithm:** The PSO method is a meta-heuristic algorithm for global random optimization. No prior assumptions are made in this algorithm and it can search in a large space of candidate solutions, thus it is not guaranteed that the optimal solution can be found [39].

The algorithm works by having a group of candidate solutions (normally called particles). At the beginning these particles are distributed randomly around the

solution space, in each position the particle evaluates its own fitness. In every iteration, the particle changes its position according some criteria, according to the algorithm implementation.

- **Particle filter algorithm:** Particle filter algorithm is a posterior density estimation algorithm that estimate the posterior density of the state-space by directly implementing the Bayesian recursion estimation equations. Recursive Bayesian estimation is a general probabilistic approach for estimation unknown probability density function recursively over time using incoming measurements and a mathematical process model [40]. The advantage of the algorithm is that it performs well in finding global solutions.

5.1.3 Power system parameter estimation

In this section, the specified steps used to identify parameters of power system using RaPIId toolbox is presented. The main steps in this process are the following:

1. Collect measurement data
2. Implement power system model using Modelica language
3. Compile the Modelica model into FMU format
4. Create a Simulink model, load the previously complied Modelica model into the Simulink model using the FMI toolbox for MATLAB
5. Start the RaPIId Toolbox, and input the settings required by the toolbox (inputs, outputs, algorithm, parameters, etc.)
6. Run the parameter identification algorithms
7. Evaluate the results of identification

Collect measurement data

The measurement data in this context is a recorded output from the real world or a reference system. Collection of measurement data can be connected with the difficulties of the power system components stage tests. In the case of reference model, experiments set up and the measurement data collection is simpler and gives flexibility to the engineer.

In most cases the measurement data needs to pass through pre-processing before it can be used as input for the system identification. The reason for that is the presence of noise, and unnecessary data which does not characterized by parameters to be estimated.

Implement Modelica models, and compile it into FMU format

In this thesis the language chosen for power system identification is Modelica (as it was mentioned and shown below in Figure 4.20 and 4.25). In Dymola, the Modelica models can be compiled into FMUs. The RaPIId toolbox utilizes the compiled FMU as the mathematical model with parameters to be estimated of real system via the FMI toolbox for Matlab. The FMU is compliant with the FMI standard (Functional Mock-up interface), which is a tool independent standard for the exchange of dynamic models and for co-Simulation [41].

When compiling FMU, two kinds of FMU can be chosen:

- FMU for model exchange: generates lime C-Code or object code containing the dynamic system model in the form of blocks with input and output.
- FMU for co-simulation: similar to FMU for model exchange, but contains the solvers together with the model.

To simulate the model using the solvers provided by MATLAB/Simulink, FMU for model exchange is used.

Create a Simulink model and load the previously complied Modelica model

Simulink model is used as an interface for loading and configuring parameters in the model via FMI toolbox for MATLAB. Additional Simulink components are also used to serve as a link between FMU and RaPIId toolbox. For instance, *from workspace* and *to workspace* are utilized for monitoring the measurement data, and redirecting the simulation results

to RaPID toolbox; *scope* is used to monitor the simulation results in each iteration. As an example, the Simulink model built for system identification of iGrGen system is shown in Figure 5.2.

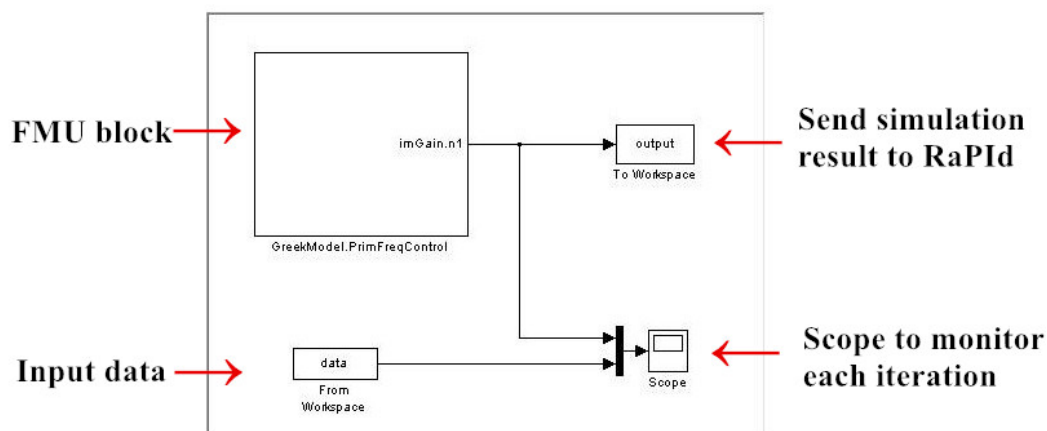


FIGURE 5.2: Simulink model with FMU of Modelica model

Start the RaPID Toolbox and input the required settings

To perform system identification, the RaPID toolbox plays an role of interface between the input data, optimization algorithms developed in MATLAB and Simulink model. It simulates the system model contained in the FMU, and optimizes the model parameters according to the fitness of the simulation results against measurement data. The RaPID toolbox paramters can be set up by Graphic User Interface (GUI, as shown in Figure 5.3) or by textual interface. There are four groups of required settings: the choice of optimization algorithm, the general parameters for simulation and parameters of algorithm, the path of input and output, and the path of the simulink model with loaded FMU.

Perform identification and evaluate results

After complete the RaPID setting up, the toolbox can perform estimation of the model parameters. To find the optimal parameters, the simulation needs to be performed in iterations. At the same time, different kind of optimization algorithms can be used or combined to find the optimal solution.

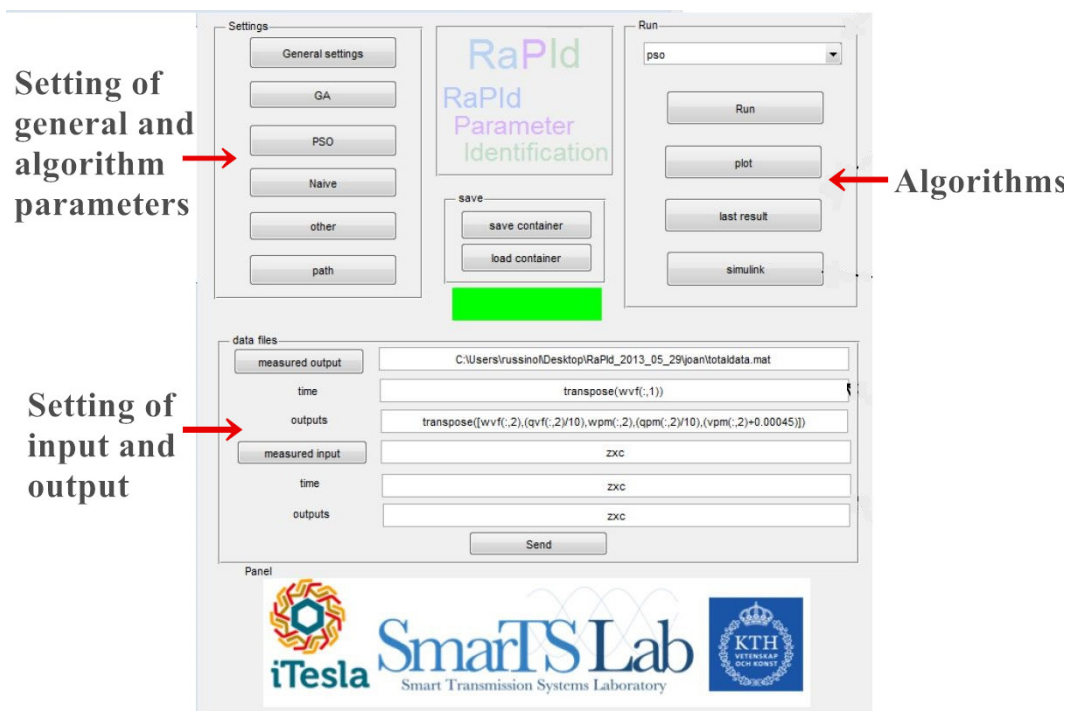


FIGURE 5.3: Main GUI of RaPIId toolbox

5.2 Parameter estimation case 1: Turbine parameters of iGrGen system model

The Greece generator system iGrGen is a Combined Cycle Power Plant containing a gas turbine, a steam turbine and a synchronous generator in a single shaft arrangement. A speed governor is used in gas turbine to control the system frequency. The iGrGen system is detailed in Chapter 4.5.1.

5.2.1 Experiment set-up

Measurement data

The measurement data used for system identification is obtained from experiments performed on the gas turbine governor. The purpose of the experiment is to demonstrate the response of generator turbine to system frequency deviation, thus the measured data is the turbine mechanical power output. If the system frequency decreases below rated frequency, the turbine will be controlled to increase the output mechanical power; if the

system frequency increases above the rated frequency, the turbine will reduce the power output.

It worth noting that the steam turbine in the power plant does not contribute initially to the primary frequency control because of the large thermal inertia.

Modelica model

The Modelica model of iGrGen system is shown in Figure 5.4. Incremental signal is injected to the frequency reference input of the governor to simulate the effect of variation of system frequency. The injected signals are in forms shown in Figure 5.5, with the frequency deviation $\Delta\omega = +/ - 0.2Hz$ ($0.004p.u.$).

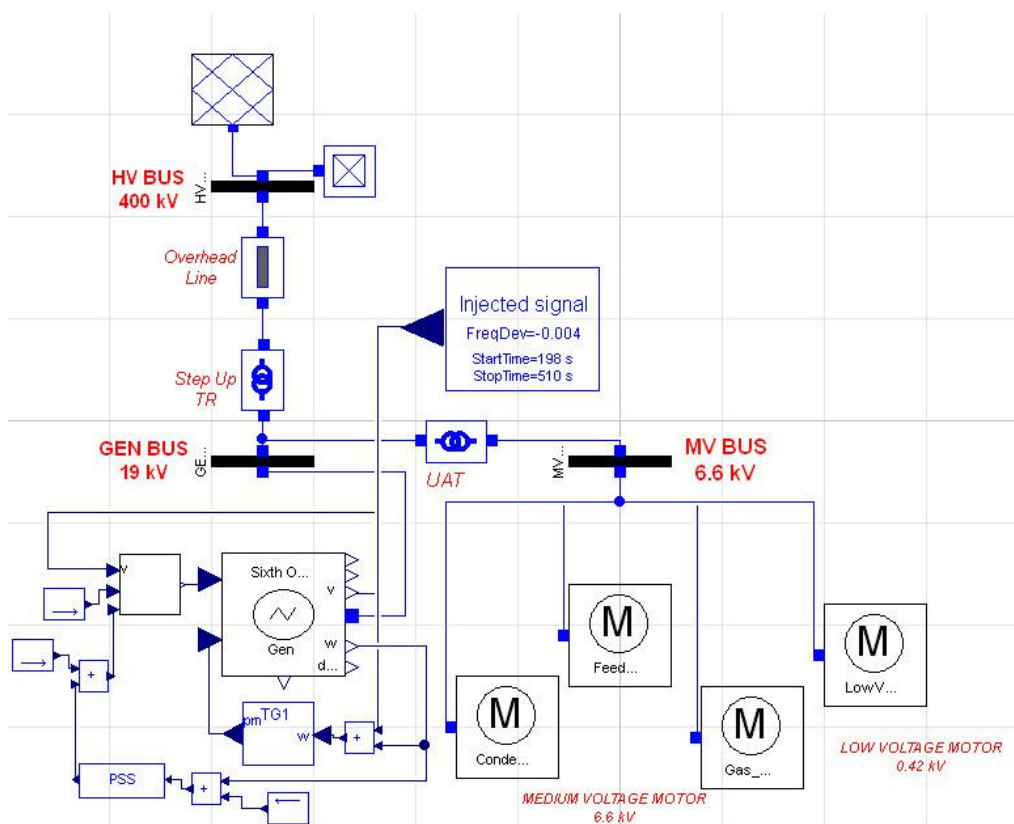


FIGURE 5.4: Modelica model of iGrGen system for system identification

Parameter estimation

The Simulink model with compiled FMU from the Modelica model is shown in Figure 5.2. Two kinds of algorithms are selected to find the optimal parameters: particle swarm optimization (PSO) algorithm and particle filters (PF) algorithm. The parameters to be estimated are listed in Table 5.1.

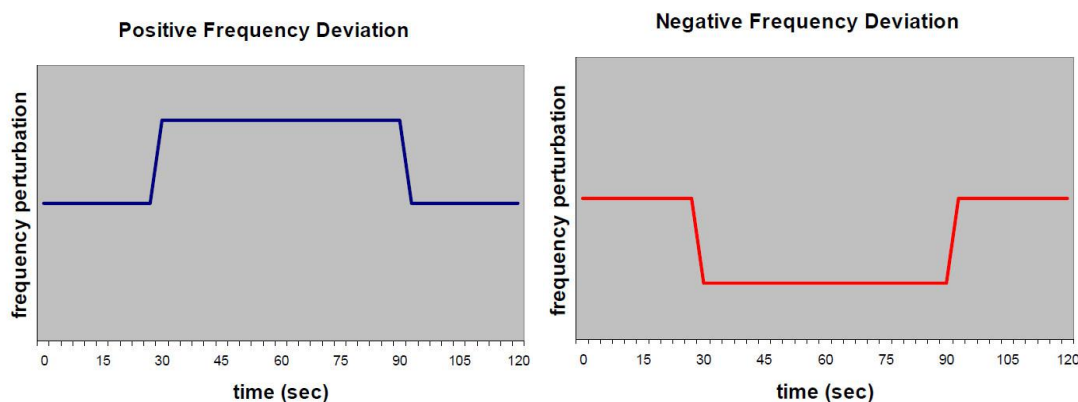


FIGURE 5.5: Injected signals to the system

TABLE 5.1: Parameters to be estimated

Parameter		Parameter	
R	Droop	T_s	Governor time constant
T_c	Servo time constant	T_3	Transient time constant
T_4	Power fraction time constant	T_5	Reheat time constant

5.2.2 Results

The numerical results of the generator parameter estimation process are shown in Table 5.2. Two kinds of optimization algorithm are used, and the performances are evaluated by comparing the mean squared error (MSE) and convergence time.

TABLE 5.2: Parameter estimation results

Algorithm	Parameter	Value	Parameter	Value	Time (s)	MSE
PSO +Gradient descent	R	0.3201	T_s	15.5085	189.999	4.7332
	T_c	0.3	T_3	0.04		
	T_4	5	T_5	4		
PF +Gradient descent	R	0.3145	T_s	15.8765	61.799	4.4792
	T_c	0.3	T_3	0.04		
	T_4	5	T_5	4		

The graphical comparison of measurement data and simulation results of the iGrGen system model is shown in Figure 5.6. The plot shows the primary response of the turbine, and the frequency deviation in the two cases: 0.2 Hz and -0.2 Hz (0.004 p.u) respectively.

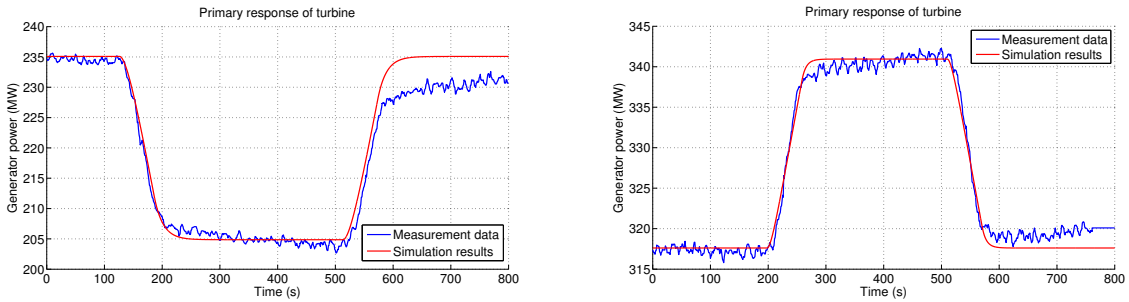


FIGURE 5.6: Simulation result and measurement data for the iGrGen system with 0.2 Hz and -0.2 Hz frequency deviation ($R = 0.3201$, $T_s = 15.5085$)

Discussion: From the values of the identified parameters, it can be seen the numerical value for all parameters are within the normal range. From the parameter values, it can be concluded that only the droop R and governor power time constant T_s play important role in the proposed experiment, the system frequency is not sensitive to the variation of other parameters.

In the graphical comparison shown in Figure 5.6, the simulation results and measurement data is not 100% match, but the error is acceptable. In the second case (with negative frequency deviation) the output signals match well, while in the first case (with positive frequency deviation) there is deviation between the two signals on the steady-state after the frequency change. In the real system, the turbine governor requires longer time to revive system frequency to nominal value, which may be caused by power variance in the process of real experiment.

Moreover, according to the comparison of two applied algorithms for system identification showed in Table 5.2, it can be found that particle filter (PF) algorithm can provide three times less convergence time than particle swarm optimization (PSO) algorithm, with the same or even higher precision as PSO.

5.3 Parameter estimation case 2: SVC parameters of INGSVC system model

INGSVC is an equivalent model of a 400 kV substation with a Static Var Compensator (SVC) connected to the busbar. The substation is modelled as an infinite bus, and the SVC model is connected to the bus with a transmission line and a transformer. The system is detailed in Chapter 4.6.1.

5.3.1 Experiment set-up

Measurement data

The measurement data used for system identification is obtained from experiment performed on the substation. In the experiment, a fault is applied on the substation busbar. The purpose of the experiment is to demonstrate the response of SVC to the fault, thus the measured data is the voltage and current on the terminal of SVC.

Modelica model

The Modelica model of the INGSVC system is shown in Figure 4.25. To simulate the effect of busbar fault, a fault is applied to the second side of transformer, leading to a voltage dip in the SVC terminal.

Parameter estimation

The Simulink model with compiled FMU from the Modelica model is shown in Figure 5.7. Similar to case 1, particle swarm optimization algorithm and particle filters algorithm are selected to find the optimal parameters. The parameters to be estimated are listed in Table 5.1.

5.3.2 Results

The numerical results of the generator parameter estimation are shown in Table 5.4. Similar to case 1, two kinds of optimization algorithm are applied and compared. The graphical comparison of measurement data and simulation results of the INGSVC system

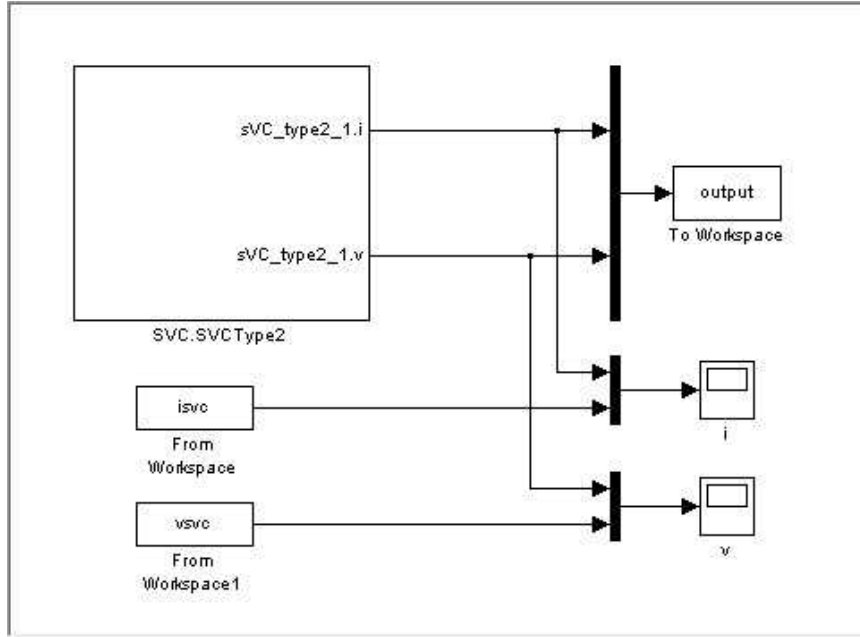


FIGURE 5.7: Simulink model with FMU of INGSVC system Modelica model

TABLE 5.3: Parameters to be estimated

Parameter		Parameter	
α_0	SVC firing angle	K	Regulator gain
K_D	Integral deviation	T_2	Regulator time constant
T_1	Transient regulator time constant	T_m	Measure time delay
K_m	Measure Gain	x_l	Reactance (inductive)
x_c	Reactance(capacitive)		

model is shown in Figure 5.8. The plots show the voltage and current responses of SVC to the fault applied on the substation busbar respectively.

In this case, other than the fitness indicated by MSE, another performance indicator: statistical analysis is used to evaluate the validity of identification results with the help of MATLAB statistics toolbox. From the results listed in Table 5.4, it can be found the main differences between two groups of parameters are the value of SVC firing angle α_0 and regulator gain K . To find the optimal value for the two parameters, the estimation is performed for 30 times with particle filter algorithm. The statistical analysis of the results is shown in Figure 5.9.

TABLE 5.4: Parameter estimation results

Algorithm	Parameter	Value	Parameter	Value	Time (s)	MSE
PSO +Gradient descent	α_0	0.2012	K	33.3301	256.988	7.128×10^{-4}
	K_D	0.01	T_2	0.2		
	T_1	0.01	T_m	0.02		
	K_m	1	x_l	0.2		
	x_c	0.1				
PF +Gradient descent	α_0	0.2030	K	32.9301	155.442	6.228×10^{-4}
	K_D	0.01	T_2	0.2		
	T_1	0.01	T_m	0.02		
	K_m	1	x_l	0.2		
	x_c	0.1				

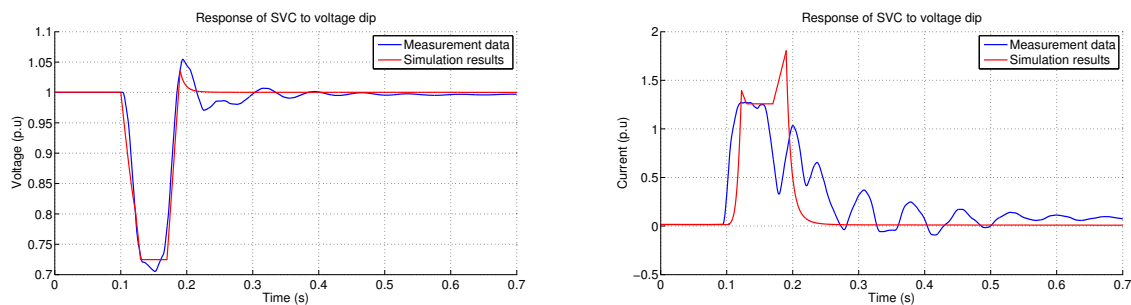


FIGURE 5.8: Simulation result and measurement data for the INGSVC system ($\alpha_0 = 0.2012$, $K = 33.3301$)

Discussion: From the numerical results of system identification, it can be found the values of the identified parameters are within the normal range. Apparently only the values of SVC firing angle α_0 and regulator gain K influence the SVC's response to the applied busbar fault.

In the graphical comparison shown in Figure 5.8, it can be seen that the simulation result and measurement data of SVC terminal voltage match well, but there exists large error between simulation and measurements in SVC terminal current. The reason are two-fold: first of all, the test system is a rough approximation of the real system; and many

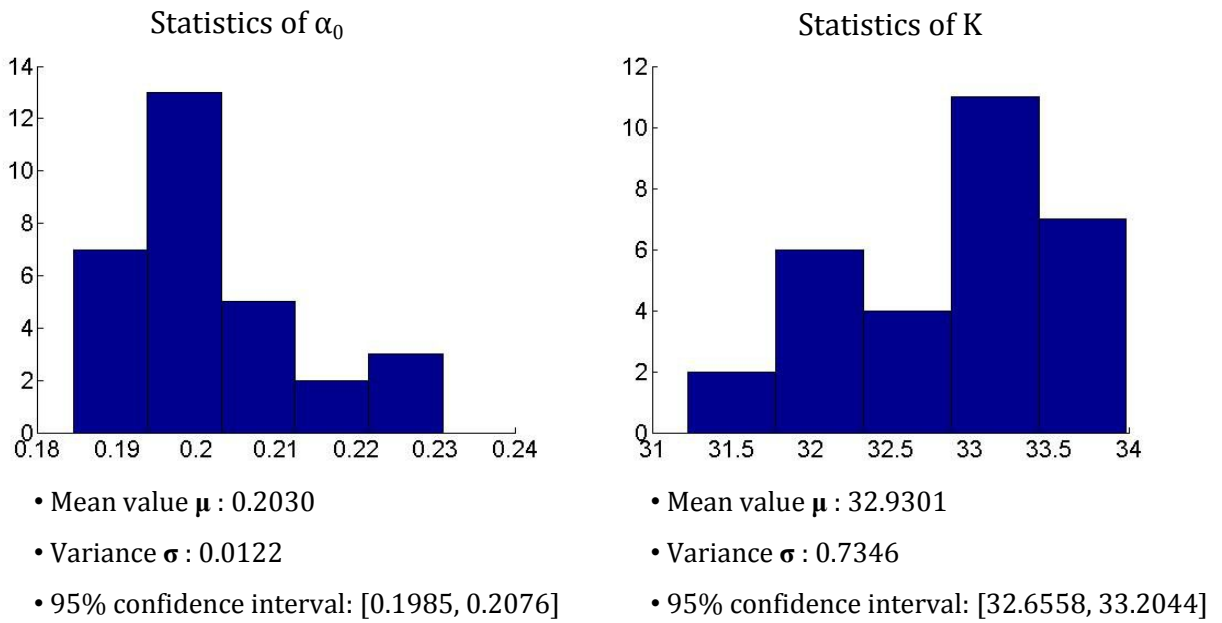


FIGURE 5.9: Statistical analysis for parameter estimation results

simplifications are made in the modelling of the SVC model, which may not respond to the system disturbance as a real component. Because of the simplifications, the SVC model may respond to the fault in form of instantaneous current changes other than oscillations, as shown in the left plot in Figure 5.8. Nevertheless, the model and the estimated parameters can still be used to investigate the effect of SVC on the overall system operation.

From the statistical analysis results presented in Figure 5.9, the confidence interval for α_0 is from 0.1985 to 0.2076, while for K the confidence interval is from 32.6558 to 33.2044. Figure 5.10 and 5.11 present the graphical comparisons of simulation results and measurement data with $\alpha_0 = 0.1985$, $K = 33.2044$ and $\alpha_0 = 0.2076$, $K = 32.6558$ respectively. By comparing the two groups of plots with different parameter values, it is observed that although the parameter values are at the edges of confidence interval, there exists no large deviation between the two cases, and the case shown in Figure 5.8. Thus the conclusion can be derived that any parameter value in the confidence interval is acceptable and can be applied on the model.

Similarly to case 1, according to the comparison of algorithms presented in Table 5.4, it can also be concluded that particle filter (PF) algorithm perform faster with the same or

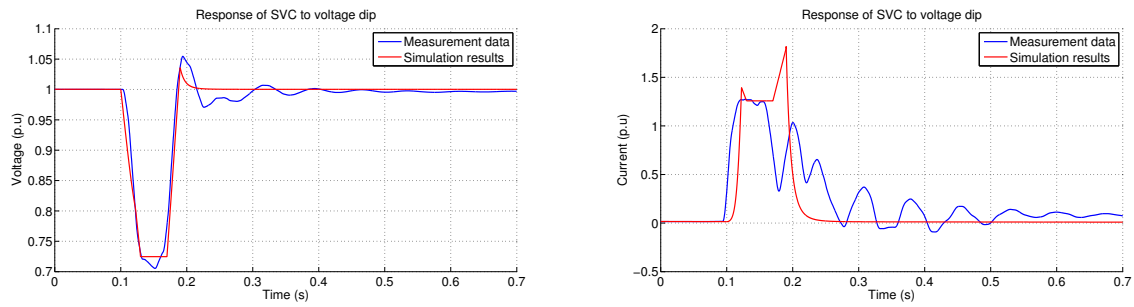


FIGURE 5.10: Simulation result and measurement data for the INGSVC system ($\alpha_0 = 0.1985$, $K = 33.2044$)

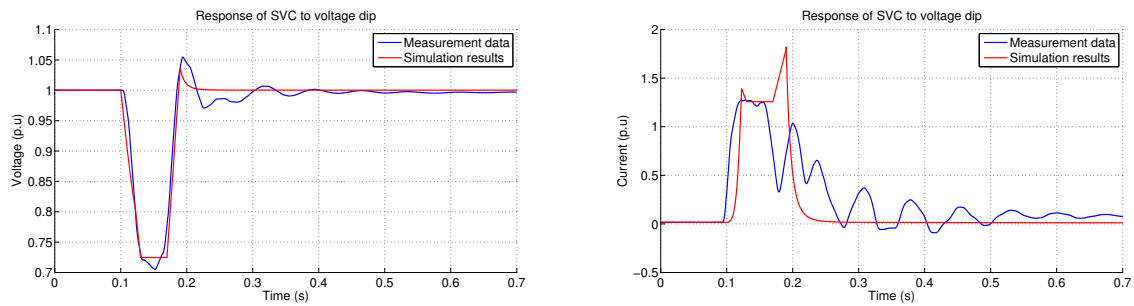


FIGURE 5.11: Simulation result and measurement data for the INGSVC system ($\alpha_0 = 0.2076$, $K = 32.6558$)

higher precision as particle swarm optimization (PSO) algorithm.

Chapter 6

Discussion

6.1 Modelica

In chapter 3 and 4, the experience of Modelica based power system modelling, simulation and validation are presented. In general, Modelica is advantageous compared with other modelling tools mainly in four aspects. First of all, it allows the implementation of high complexity models using simple mathematical language; secondly, model exchange between software environments and co-simulation is possible in Modelica; thirdly, the powerful mathematical solvers integrated in the Modelica simulation environments provides the user the freedom to select the optimal method to solve very complex systems; finally, as the validation results presented in chapter 3 and 4 show, Modelica has been proven to achieve identical results of other power system analysis specific tools, provided new extra features.

6.1.1 Modelling, simulation and validation of system components

Sixteen power system component models are developed in Modelica in this thesis. Since the validation results in chapter 3 and appendix A are positive, the potential of achieving accurate modelling of Modelica is proven. Considering the components modelled in this

thesis are mainly control elements, it is feasible to implement more complex power system models in Modelica.

Modelica also provides sufficient flexibility in power system modelling. The model can be described not only by mathematical equations, also by connecting other existing models. In addition, even though the models developed in this thesis are originally implemented in different software environments with different properties, Modelica is able to represent all necessary characteristics correctly in one single model.

6.1.2 Modelling and simulation of power systems

Chapter 4 presents the models and simulation results of four systems of different scale. The system models are validated against the reference models with satisfying results, which provides the possibilities of doing power system analysis, especially dynamic simulation in Modelica simulation environments.

Compared with other software tools, Modelica is advantageous for it simplifies the modelling process of power systems. Users can develop specific models and libraries according to the system characteristics, thus the problem of “lack of suitable models” in other software is no longer a restriction. Modelica also provides users the freedom to decide which solver to use in order to obtain the best results and the shortest simulation time.

Considering the limitation of Modelica in power system modelling, it is found that the simulation time will increase on a large scale with the model size and number of variables and equations. Therefore in order to achieve high simulation efficiency, the approaches of model reduction and simplification need to be investigated when implement large scale power system models in Modelica.

6.1.3 Model exchange

Chapter 5 shows the experience of system identification using the model exchange function provided by Modelica. In this point of view, Modelica is not only a modelling language, but also provides possibilities of re-utilization and sharing. The fact that any Modelica

model can be converted to an FMU and then be able to run in different software environment is a revolution. With the help of Modelica, the process of software-to-software modelling and validation can be simplified on a large scale.

As stated in chapter 1, the power systems simulation and analysis tools are commonly incompatible. For instance, a model developed in PowerFactory cannot be used in PSAT. This fact will cause problem when organizations using different tools need to collaborate, and will finally lead to economic losses. The results shown in chapter 5 can be seen as an evidence to solve this problem using Modelica.

6.2 System identification with RaPIId toolbox

In chapter 5, system identification and parameter estimation are performed in MATLAB environment with the help of RaPIId toolbox. Two system models are identified with estimated parameters, and the simulation results can match measured data well. RaPIId toolbox thus can be proven to be a very powerful tool to perform system identification, provided many optimization algorithms and the convenience to use.

However in the identification process, it can be found that the level of noise in measurement data will effect the convergence time and result accuracy to a large extent. For the measurements obtained from real experiments with high level of noise, it is hard for the toolbox to find optimal solution. Therefore, some signal processing methods are necessary to be integrated to the toolbox.

In the identification process, the results are evaluated according to two kinds of performance indicators: the best fitness of simulation results and measurement data (mean squared error), and statistical analysis. The best fitness method is faster and easier to evaluate the results, but statistical analysis can provide more information about validity of the results. In general, no matter which evaluation methods is used, it will be beneficial to perform the parameter estimation for several times to find the optimal solution.

Chapter 7

Conclusion and future work

7.1 Conclusions

This thesis provides a proof of the priority of a equation-based and object-oriented modelling language, Modelica, on the field of electric power system modelling, simulation and validation. The modelling and validation of power system components are successful. The success is a foundation for the future work of more complex power system modelling and simulation.

This thesis also proves the feasibility of implementing power system models, thereby doing dynamic simulation and other relevant power system analysis in Modelica-based simulation environment. Modelica allows users to develop specific model libraries according to the system characteristics, and the powerful mathematical solvers integrated in Modelica tools also provide the possibility to solve the problem more efficiently and accurately for complex and large power system models.

The measurement-based system identification task in this thesis not only presents an application of high-accuracy parameter estimation, but also a success in model exchanging and the usage of the FMI standard. This function provided by Modelica has a lot of potential and can be further applied to solve the incompatibility problems in the field of power system modelling and simulation.

7.2 Future work

Future work of this thesis would be focused on the following three aspects:

1. The completion of the power system library in Modelica, with an addition of more complex models utilizing new technologies, such as HVDC links and smart-grid devices, to achieve the modelling and simulation of recent electric power systems.
2. Investigation on the methods to perform simulations for large-scale power systems in Modelica environment. In order to achieve the simulation of interconnected systems, solutions must be proposed to simplify system model and increase simulation efficiency, without affecting the accuracy of simulation results.
3. Further application of model exchange and co-simulation function provided by Modelica on the power system modelling and simulation.

Appendix A

Models and validation results

A.1 Model information

A.1.1 Synchronous generator model

The electrical connectors are used as interface between the generator and the grid with four variables: v_r , v_i , i_r , and i_i . The link between the network phasors and the machine voltage is presented using the Park's transformation:

$$\begin{aligned}v_d &= v \sin(\delta - \theta) \\v_q &= v \cos(\delta - \theta)\end{aligned}\tag{A.1}$$

Equation A.1 can be transformed to the form shown in equation A.2 and A.3.

$$\begin{bmatrix} v_r \\ v_i \end{bmatrix} = \begin{bmatrix} \sin(\delta) & \sin(\delta) \\ -\cos(\delta) & \sin(\delta) \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix}\tag{A.2}$$

$$\begin{bmatrix} i_r \\ i_i \end{bmatrix} = - \begin{bmatrix} \sin(\delta) & \sin(\delta) \\ -\cos(\delta) & \sin(\delta) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix}\tag{A.3}$$

Besides the variables in equation A.2 and A.3, each generator model also includes four algebraic variables, namely active power P , reactive power Q , mechanical power P_m and

field voltage v_f . Thus each model will also include four more algebraic equations, which are:

$$P = (v_d + r_a i_d) i_d + (v_q + r_a i_q) i_q \quad (\text{A.4})$$

$$Q = (v_d + r_a i_d) i_d - (v_q + r_a i_q) i_q \quad (\text{A.5})$$

$$P_m = p^0 \quad (\text{A.6})$$

$$v_f = v_f^0 \quad (\text{A.7})$$

Equation A.2 - A.7 form the basic algebraic equation system for a synchronous generator model. The variables, parameters and initialization parameters of the fourth order generator model are detailed in Table A.1, A.2 and A.3.

TABLE A.1: Variables in synchronous generator model

Symbol	Variable	Symbol	Variable
δ	rotor angle	i_d	d-axis current
ω	rotor speed	i_q	q-axis current
v_r	node voltage magnitude (real)	P_m	mechanical power
v_i	node voltage magnitude (imaginary)	P	active power
v_d	d-axis voltage	Q	reactive power
v_q	q-axis voltage	e'_d	transient d-axis voltage
v_f	field voltage	e'_q	transient q-axis voltage
θ	node voltage angle	e''_d	sub-transient d-axis voltage(Order6)
		e''_q	sub-transient q-axis voltage(Order6)

A.1.2 Turbine governor

Table A.4 A.5, and A.6 show the variables, parameters and initialization parameters of the turbine governor model.

TABLE A.2: Parameter in synchronous generator model

Symbol	Parameter	Unit
S_n	power rating	MVA
V_n	nominal voltage	kV
f_n	frequency rating	Hz
x_l	leakage reactance	p.u.
r_a	armature resistance	p.u.
x_d	d-axis reactance	p.u.
x'_d	d-axis transient reactance	p.u.
x''_d	d-axis sub-transient reactance (Order 6)	p.u.
T'_{d0}	d-axis transient time constant	s
T''_{d0}	d-axis sub-transient time constant (Order 6)	s
x_q	q-axis reactance	p.u.
x'_q	q-axis transient reactance	p.u.
x''_q	q-axis sub-transient reactance (Order 6)	p.u.
T'_{q0}	q-axis transient time constant	s
T''_{q0}	q-axis sub-transient time constant (Order 6)	s
$M = 2H$	mechanical starting time	kWs/kVA
D	damping constant	-
K_w	speed feedback gain	gain
K_P	active power feedback gain	gain
$S(1.0)$	first saturation ratio at node	-
$S(1.2)$	second saturation ratio at node	-

TABLE A.3: Initialization parameter in synchronous generator model

Initialization	Value	Initialization	Value
v_{r0}	$v_0 \cos(\theta_0)$	i_{q0}	$i_{r0} \sin(\frac{\pi}{2} - \delta_0) + i_{i0} \cos(\frac{\pi}{2} - \delta_0)$
v_{i0}	$v_0 \sin(\theta_0)$	e'_{q0}	$v_{q0} + r_a i_{q0} + x'_d i_{d0}$
i_{r0}	$\frac{p_0 v_{r0} + q_0 v_{i0}}{v_{r0}^2 + v_{i0}^2}$	e'_{d0}	$v_{d0} + r_a i_{d0} - x'_q i_{q0}$
i_{i0}	$\frac{p_0 v_{i0} - q_0 v_{r0}}{v_{r0}^2 + v_{i0}^2}$	$e''_{q0}(\text{Order6})$	$v_{q0} + r_a i_{q0} + x''_d i_{d0}$
δ_0	$\arctan\left(\frac{v_{i0} + r_a i_{i0} + x_q i_{r0}}{v_{r0} + r_a i_{r0} - x_q i_{i0}}\right)$	$e''_{d0}(\text{Order6})$	$v_{d0} + r_a i_{d0} - x''_q i_{q0}$
v_{d0}	$v_{r0} \cos(\frac{\pi}{2} - \delta_0) - v_{i0} \sin(\frac{\pi}{2} - \delta_0)$	P_{m0}	P_0
v_{q0}	$v_{r0} \sin(\frac{\pi}{2} - \delta_0) + v_{i0} \cos(\frac{\pi}{2} - \delta_0)$	v_{f0}	$e'_{q0} + (x_d - x'_d) * i_{d0}$
i_{d0}	$i_{r0} \cos(\frac{\pi}{2} - \delta_0) - i_{i0} \sin(\frac{\pi}{2} - \delta_0)$		

TABLE A.4: Variables in turbine governor model TG1

Symbol	Variable
ω	generator rotor speed
p_m	mechanical power applied to generator
p_{in}^*	intermediate variable
p_{in}	intermediate variable
x_{g1}	intermediate variable
x_{g2}	intermediate variable
x_{g3}	intermediate variable

A.1.3 Excitation system

The parameters of the excitation system model are showed in Table A.7.

A.1.4 Power system stablizer

The parameters of the excitation system model are showed in Table A.8.

TABLE A.5: Parameter in turbine governor model TG1

Symbol	Parameter	Unit
ω_{ref}	reference speed	p.u.
p_{ref}	reference active power	p.u.
R	droop	p.u.
p_{max}	maximum turbine output	p.u.
p_{min}	minimum turbine output	p.u.
T_s	governor time constant	s
T_c	Servo time constant	s
T_3	transient gain time constant	s
T_4	power fraction time constant	s
T_5	reheat time constant	s

TABLE A.6: Initialization parameter in turbine governor model TG1

Initialization	Value
ω	ω_0
p_{m0}	p_0
p_{in0}^*	p_0
x_{g10}	p_0
x_{g20}	$(1 - \frac{T_3}{T_c})p_0$
x_{g30}	$(1 - \frac{T_4}{T_5})(x_{g20} + x_{g10}\frac{T_3}{T_c})$

A.1.5 Load tap changer

The parameters of the LTC model are showed in Table A.9.

TABLE A.7: Parameter in excitation system model EXAC1

Symbol	Parameter	Unit
T_R	voltage input time constant	s
T_B	AVR lead-lag time constant	s
T_C	AVR lead-lag time constant	s
K_A	AVR gain	p.u.
T_A	AVR time constant	s
V_{RMAX}	maximum AVR output	p.u.
V_{RMIN}	Servo time constant	p.u.
T_E	Exciter time constant.	s
K_F	Rate feedback gain	p.u.
V_{REF}	Reference terminal voltage	p.u.
T_F	Rate feedback time constant	s
K_C	Rectifier load factor	p.u.
K_D	Exciter demagnetizing factor	p.u.
K_E	Exciter field factor	p.u.
E_1	Exciter saturation point 1	p.u.
E_2	Exciter saturation point 2	p.u.
SE_1	Saturation at E1	-
SE_2	Saturation at E1	-

A.2 Validation results

1. Forth Order generator

The simulation results of Modelica model and reference model for forth order generator are shown in Figure A.1.

2. Sixth Order generator

The simulation results of Modelica model and reference model for sixth order generator are shown in Figure A.2.

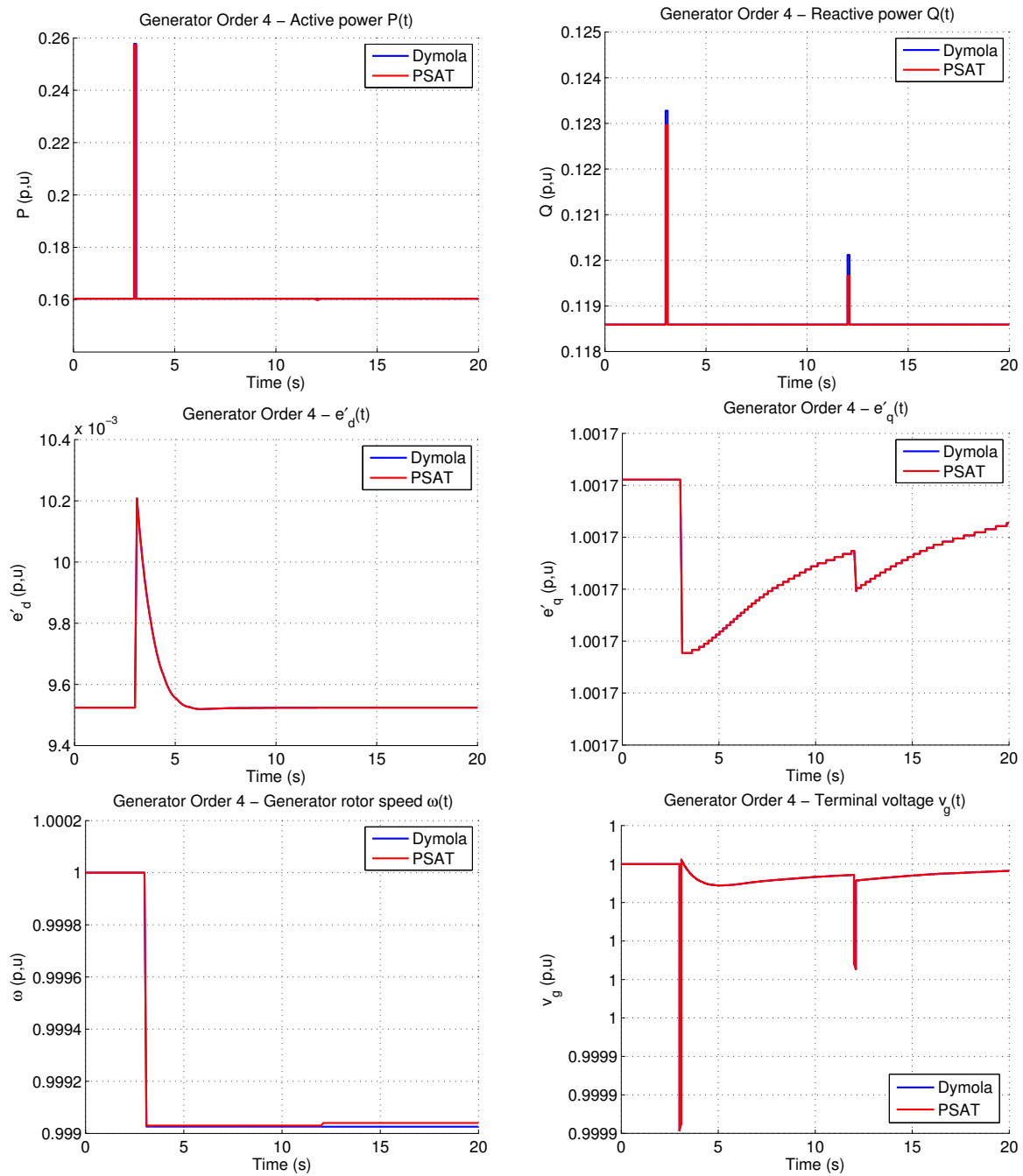


FIGURE A.1: Validation results of fourth order generator model

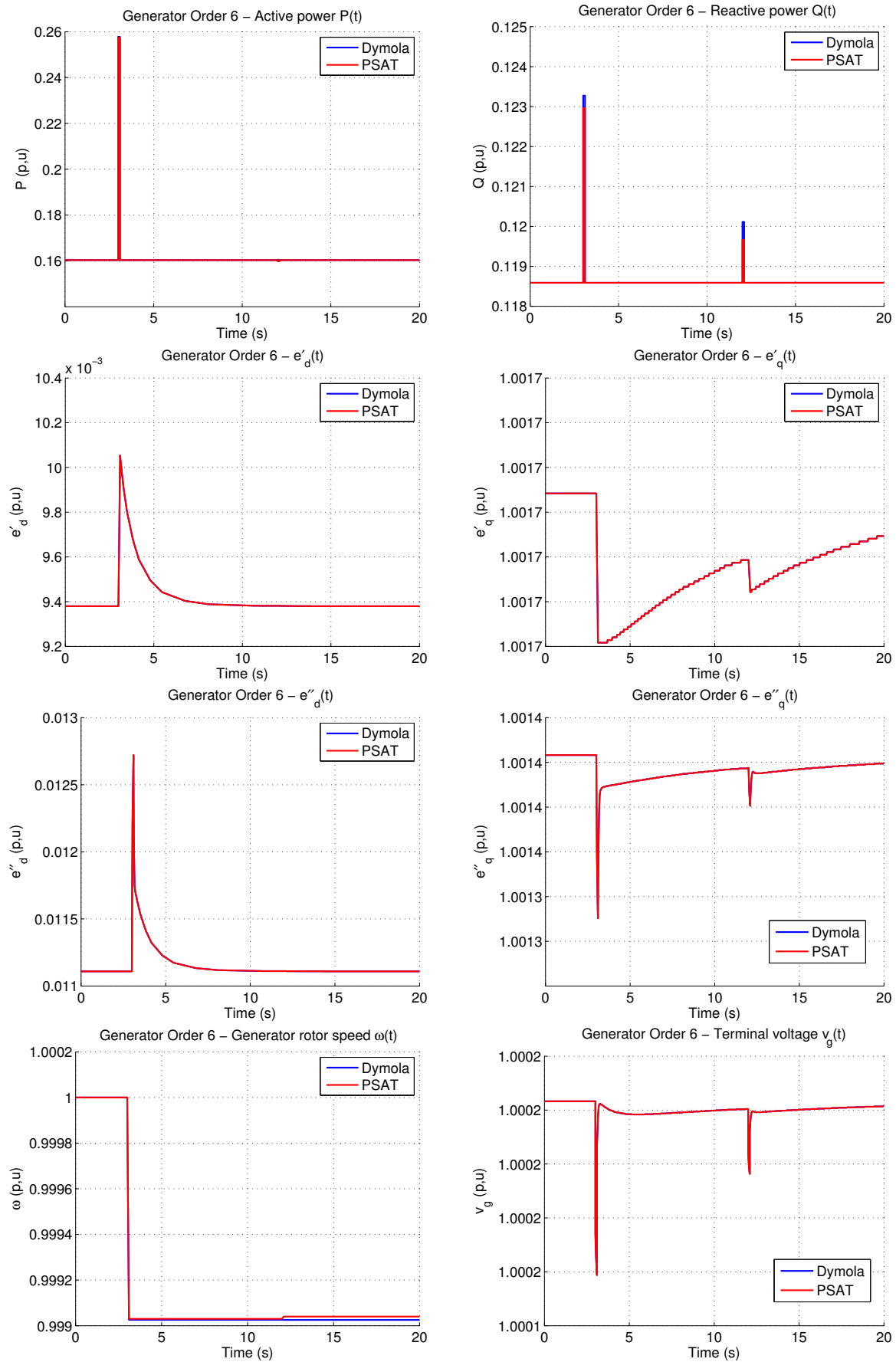


FIGURE A.2: Validation results of sixth order generator model

TABLE A.8: Parameter in PSS model PSS2B

Symbol	Parameter	Unit
T_{W1}	washout 1 time constant	s
T_{W2}	washout 2 time constant	s
T_{W3}	washout 3 time constant	s
T_{W4}	washout 4 time constant	s
T_6	lag 1 time constant	s
K_{S2}	Lag 2 gain, (practically T_7/H , H:inertia of the machine)	p.u.
T_7	lag 2 time constant	s
K_{S3}	gain	p.u.
K_{S1}	PSS gain	p.u.
T_8	ramp-tracking filter time constant	s
T_9	ramp-tracking filter time constant	s
T_1	leadlag 1 time constant	s
T_2	leadlag 1 time constant	s
T_3	leadlag 2 time constant	s
T_4	leadlag 2 time constant	s
T_{10}	leadlag 3 time constant	s
T_{11}	leadlag 3 time constant	s
V_{STMAX}	PSS output limiation	p.u.
V_{STMIN}	PSS output limiation	p.u.

3. Turbine governor

The simulation results of Modelica model and reference model for turbine governor TG1 are shown in Figure A.3.

4. Excitation system

The simulation results of Modelica model and reference model for excitation system EXAC1 are shown in Figure A.4.

TABLE A.9: Parameter in LTC model

Symbol	Parameter	Unit
V_{I0}	Initial load voltage	p.u.
r_0	Initial transformer ratio	-
V_{min}	maximum load voltage	p.u.
V_{max}	minimum load voltage	p.u.
n_{min}	minimum transformer ratio	-
n_{max}	maximum transformer ratio	-
N	number of positions	-
τ_1	first tap change delay	s
τ_2	subsequent tap change delay	s

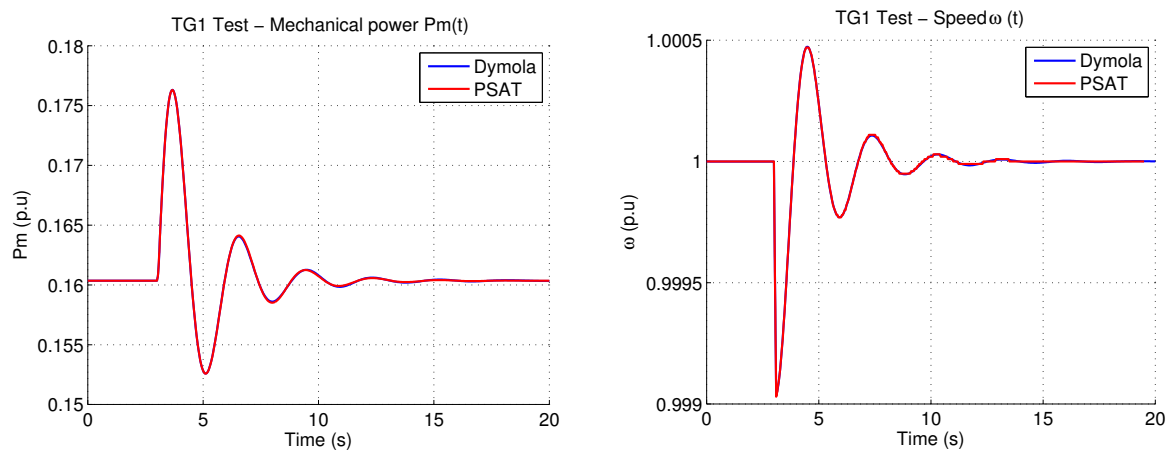


FIGURE A.3: Validation results of turbine governor model

5. PSS

The simulation results of Modelica model and reference model for PSS are shown in Figure A.5.

6. LTC

The simulation results of Modelica model and reference model for PSS are shown in Figure A.6.

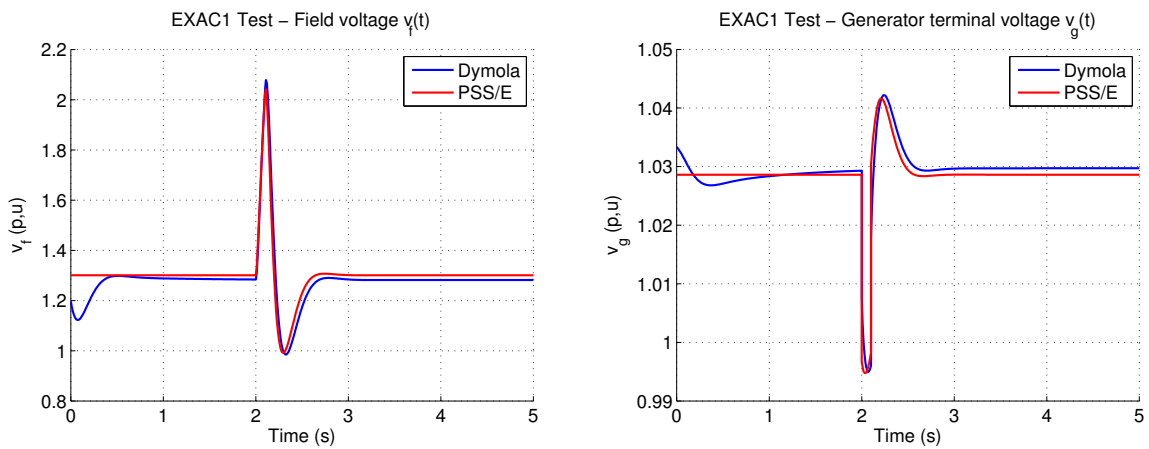


FIGURE A.4: Validation results of excitation system model

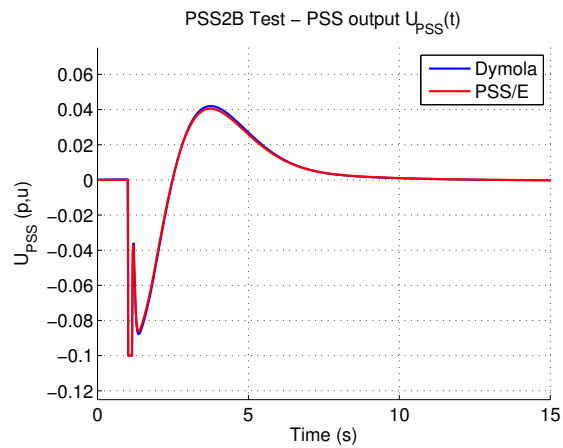


FIGURE A.5: Validation results of power system stabilizer model

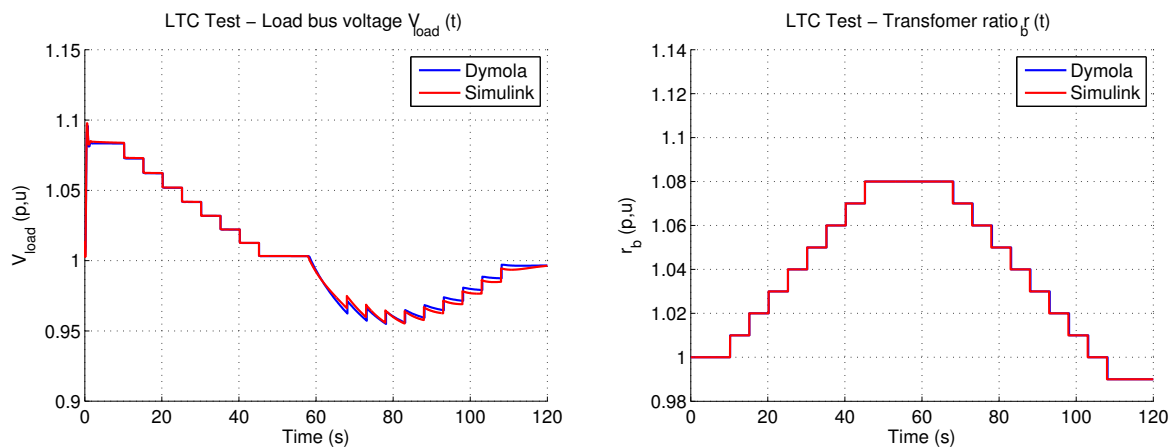


FIGURE A.6: Validation results of load tap changer model

A.3 Models validated vs Simulink

1. Excitation system with OEL and PSS

The excitation system shown in figure 4.11 consists of three components: Exciter (AVR), OEL and PSS.

- OEL: OEL model has two input signals: the generator field current i_{fd} and the generator terminal voltage. OEL has inverse time characteristics, i.e. the higher the field current, the faster the limitation takes place. In normal operating conditions, $i_{fd} < i_{fd}^{lim}$, the minimum gate passes on the $V^0 - V$ to the AVR; if $i_{fd} > i_{fd}^{lim}$, the minimum gate passes on the OEL output signal to the AVR.
- PSS: PSS uses the rotor speed ω as input. Each PSS includes a washout filter and two identical lead filters in cascade.
- AVR: The AVR is represented by a first-order system, and includes a transient gain reduction.

The validation results are shown in figure A.7.

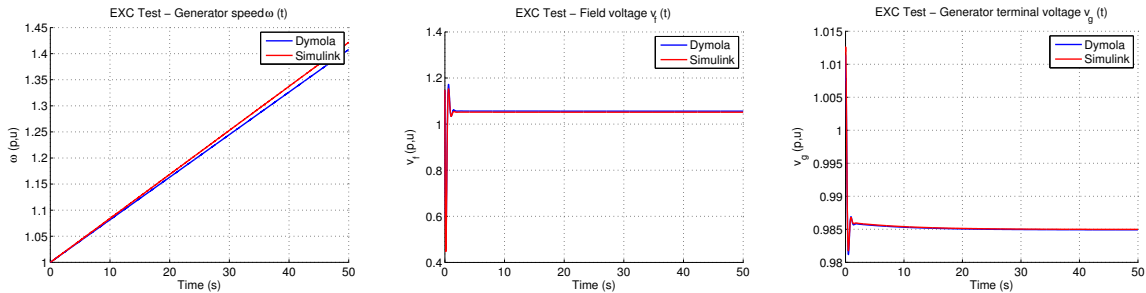


FIGURE A.7: Validation results of excitation system model

2. Turbine and speed governor

The governor model shown in figure 4.12 has two input signals: the generator active power P and the generator speed ω . The output of the block is the gate opening z that applied to the turbine. The turbine model has two input signals: the gate opening z and the generator speed ω . The output of the block is the torque T_m that applied to the generator. The validation results are shown in figure A.8.

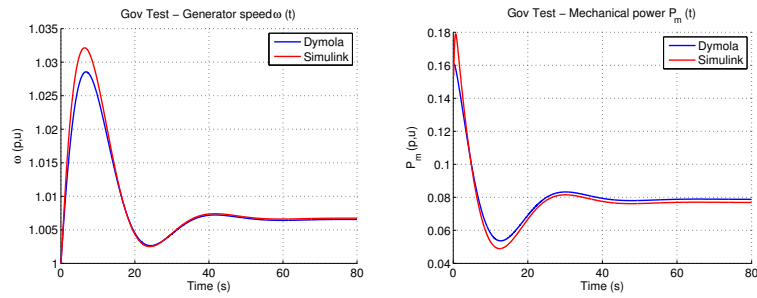


FIGURE A.8: Validation results of governor and turbine model

A.4 Models validated vs PSAT

1. AVR Type II

The AVR model shown in figure A.9 has two input signals: the terminal voltage v_g and the reference voltage v_{ref} . The output of the model is the field voltage v_f applied to the generator. The validation results are shown in figure A.10.

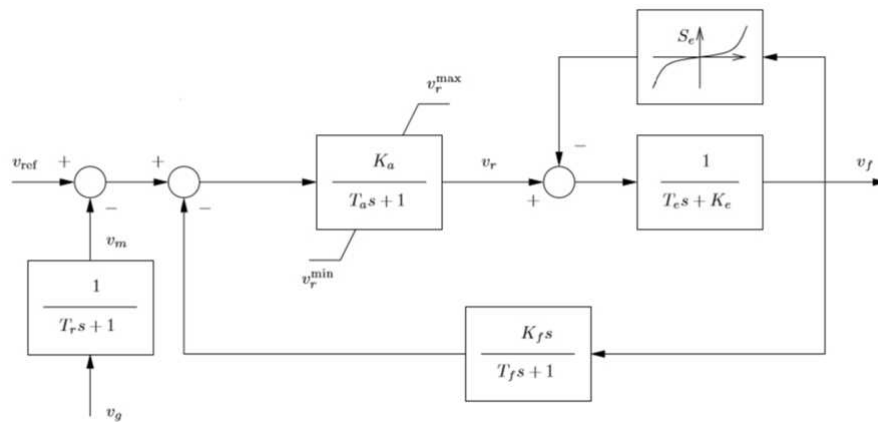


FIGURE A.9: AVR Type II model [2]

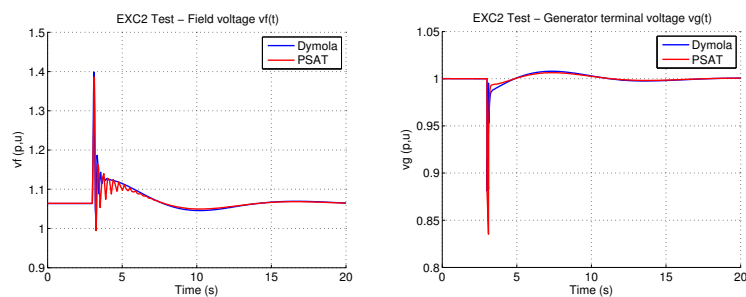


FIGURE A.10: Validation results of AVR Type II model

2. Over excitation limiter (OXL)

The OEL model shown in figure 4.5 provides an additional signal v_{OXL} to the reference voltage v_{ref} of AVRs. The generator field currents i_f is calculated according to the equation A.8.

$$i_f = \sqrt{(v_g + \gamma_q)^2 + p_2} + (x_d/x_q + 1) \frac{\gamma_q(v_g + \gamma_q) + \gamma_q}{\sqrt{(v_g + \gamma_q)^2 + p_2}} \quad (\text{A.8})$$

$$\gamma_p = x_q p / v_g, \quad \gamma_q = x_q q / v_g$$

The validation results are shown in figure A.11.

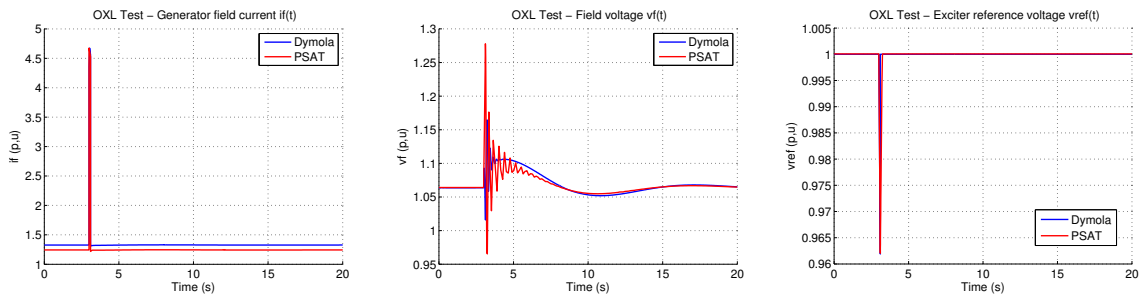


FIGURE A.11: Validation results of OXL model

3. Shunt

The shunt model is defined with a parameter Q_{nom} , which is the reactive power produced by the shunt element under a 1 pu voltage. Positive Q_{nom} relates to capacitors, whereas negative Q_{nom} relates to inductors. The validation results are shown in figure A.12.

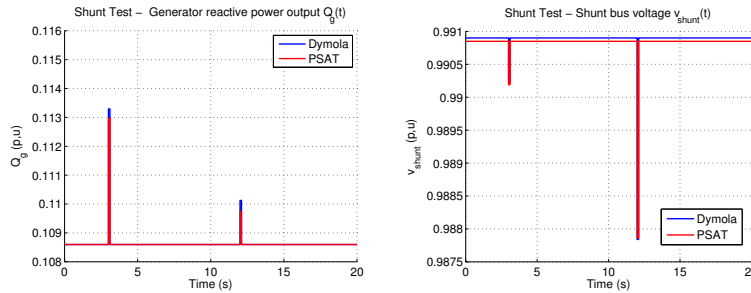


FIGURE A.12: Validation results of shunt model

A.5 Models validated vs PSS/E

1. Speed governor IEEEG1

The governor model shown in figure A.13 is designed for thermal turbines and governors. The input of the model is $\Delta\omega$, the variation of generator speed. Outputs of the model are mechanical power P_{MECHHP} and P_{MECHLP} to be connected to the generator. The validation results are shown in figure A.14.

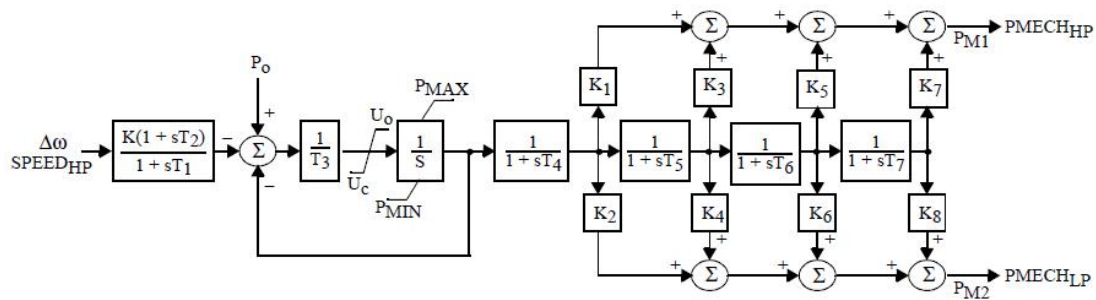


FIGURE A.13: Speed governor IEEEG1 model [3]

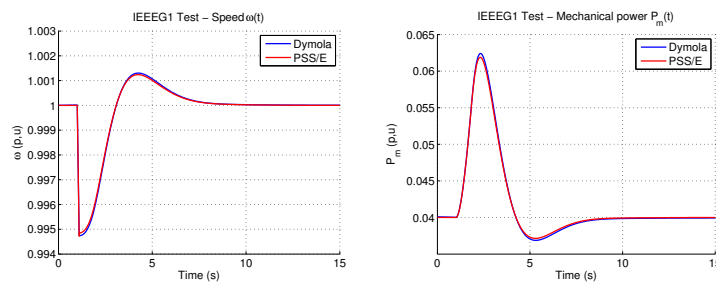


FIGURE A.14: Validation results of shunt model

Appendix B

Experiences in modelling and simulation of large-scale power systems

This appendix includes the experiences in the modelling, simulation and validation of large-scale power systems in the project: KTH Nordic 32 system and IEEE Nordic 32 system. In Section B.1 the critical steps are presented, and in Section B.2 the solutions to some common problems in the process are provided.

B.1 Critical Steps

B.1.1 Preparation

1. Before the implementation of system models, a few principles need to be followed. The principles are detailed in Chapter 4.2. Among the principles, the most important one are: “*Make appropriate simplification to the system model*”. The first knowledge one needs to know before the modelling of a power system is that a model cannot represent every aspect of a real system. The engineer needs

to decide which aspect is more important to represent according to the objective of the study, and make simplification to the models.

In this project, the types of critical models (generators, generator controllers, transformers, etc.) are already decided, thus there is no space for simplification.

2. After the simplification process, the component models used in the system model can be selected and prepared. An important task in this step is to make sure that all models are validated. One can use a small test system (for example: a system with 1-2 generator, 3-4 buses, 1-2 loads and 1-2 faults) to test if the component models are validated. ***“Make sure every component model is validated before the modelling large-scale system”*** is very important, since if an incorrect model is included in a large system model, it will be very difficult to figure out which model is the problem when the system model is giving incorrect responses.

After all component models are prepared, create a new package and include all component models in it. This step will solve the problem of incorrect path of models in the modelling process.

3. Another important principle is ***“Use power flow solution to initialize the system model”***. Other than the component models, another important preparation is the power flow solution data. The needed data include:

- Generator buses operating point data: Generated active power P_g , generated reactive power Q_g , initial voltage magnitude v_g , initial voltage phase angle θ_g .
- Transmission and distribution buses operating point data: Initial voltage magnitude v_b , initial voltage phase angle θ_b .

B.1.2 Modelling

1. Implement the model of power plants. Each power plant includes one or more generators and a number of controllers (AVR, governor, turbine, PSS, etc). Other than connecting all these component models to the system, it is better to integrate them in one single model first, and then connect it to the system. An example of the power plant model is shown in Figure 4.1.

2. Divide the system into a few parts, and develop independent models for each part. For instance, in the Nordic 32 system, the system is divided into four parts according to graphical area. It will make the modelling and simulation process easier to implement the system parts one by one.
3. Fill in the parameters (component parameters and initial parameters) into the models. This is the most important step in the modelling process. Even a small error in the parameters will cause problem in the simulation. It is better to fill in the parameters in the text view of the system model to avoid omitting any models.
4. Check and compile the model. If the components are correctly connected and all parameters are correctly filled in, there should not be any errors in this step. If there are errors, check the connection of component models, and the parameters of the models.

B.1.3 Simulation and validation

1. Simulate the models for each part (without faults). In this step, the external system can be replaced by one or more large loads, depending on how the system is connected. The simulation results will keep constant in the steady state values. Since the model includes less component models than the complete system model, it will be easier to find the reason of problem when the simulation cannot be run correctly.
2. If all parts can be simulated, it is time to connect all parts together to form the complete system. Simulate the system model (without faults), and the simulation results should also be constant, same as the steady state values.
3. Apply faults to the system, and simulate the model again. Revise the model according to the comparison of simulation results in reference software and Dymola. Solutions for possible problems in above two steps can be found in Section B.2.

B.2 Solutions to possible problems

1. **Q:** Fail to check the system model.

A: If the model is failed to be checked, there exist three possible reasons:

- The path of component models are not correct.
- The parameters of component models are not completely filled in.
- The models are not correctly connected.

2. **Q:** When trying to simulate one part of the system model, simulation cannot start.

A: In this case, the error information provided by Dymola may be: ***“Fail to start the model (simulation)”***. In most cases, initialization is the main problem.

Generally, there may be two reasons:

- There exist some variables divided by zero. Before the simulation begins, Dymola will calculate the initial values for all variables based on the provided initialization data, thus there may be situations in which the initial values for some variables are calculated to be zero.

In this case, check the detailed error information provided by Dymola, find the variables divided by zero, and revise the corresponding model.

- Initialization values conflict. This is a problem happens very frequently. When initialization information is provided for each model in a interconnected system, there may be situation in which initial values for a same variable (obtained in different models) conflict with each other.

In this case, the key is to find the models in conflict. One solution is to replace one kind of component model (e.g. load model) by another type of model. For instance, replace the constant current load models by constant impedance models. Next, run the simulation again, if the model can be initialized, then trying to find another method to initialize the constant current load model may solve the problem.

3. **Q:** When simulate one part of the system model without faults, cannot obtain constant simulation results.

A: If the simulation can start, but there are oscillations in the results even from the very beginning of the simulation, it shows that there still exists problem with the initialization, but not as severe as the case in Q2. The solution is similar: change the type of one particular model to see if the situation is improved.

4. **Q:** The simulation results of each small part of system model look fine, but when connect them together to form the complete system, the simulation cannot start.

A: The reason is similar: initialization conflict. Firstly start from connecting the smaller parts, try to find the models in conflict, and revise the initialization method in the model.

5. **Q:** The simulation results of complete system model look fine without fault, but when the fault is applied, the simulation cannot start.

A: Firstly, try different types of fault, and different positions to apply the fault. If it turns out that other types of fault can be simulated, or the fault can be simulated in other positions , then revise the fault model or model the fault in another way may solve the problem. If it turns out that no type of fault can be simulated, then change the fault to be less severe to see if the situation can be improved.

6. **Q:** The system model can be simulated, but cannot match the reference well.

A: Other than try to find problem in the models, change the simulation parameters may also help to improve the situation. The integration algorithm, integration step and output interval length can be changed. One should not rely on just one integration method, but two or three other integration methods can be applied to find a better result.

Other than the problems listed above, there may be a large number of possible problems in the modelling and simulation process. However, the solution can be general. When the reasons of problems are hard to found, the most practical method is: to change the models in every possible aspect, from the initialization data to the model description. Changes of models will bring variations in the simulation results, and these variations will show the right direction for the correction.

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