POWER SYSTEM STABILITY STUDY USING MODELICA

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ABSTRACT

This paper is concerned with power system modeling using the Modelica language in comparison to a traditional simulation tool. Though most common power system simulation tools are computationally efficient and reasonably user-friendly, they have a closed architecture. Thus, there is motivation to use an open-source modeling language to describe electric networks, such as Modelica. A well-established benchmark for power system studies was analyzed. Regarding the voltage as a function of time, a reasonable agreement was found between the simulation results of the used simulation tools for long-term voltage stability. However, a comparison of faster electromechanical mechanisms, such as rotor angle stability, demands more detailed models in the Modelica tool.

Keywords: Power system modeling and control, PSS®E, Modelica, Dymola, Voltage stability, Rotor angle stability, Frequency stability

NOMENCLATURE

P	Active power [W]
S	Apparent power [VA]
AVR	Automatic Voltage Regulator
GOV	Governor
δ	Load angle
$OLTC$	On-Load Tap-Changer
OXL	Over eXcitation Limiter
PSS	Power System Stabilizer
Q	Reactive power [VAr]
f	System frequency [Hz]
V	Voltage [V]

INTRODUCTION

The modeling of power system components and networks is important for planning and operating electric networks, as they provide insight into how the power system will respond to both changing power demand and to various types of disturbances.Traditional tools for power system modeling are usually tied to a certain time frame (e.g., 1 sec to 15 min) depending on the phenomenon being investigated. Different time frames often limit the applicability and/or validity of the models to a specific kind of study [1]. A broad range of time constants results in specific domain tools for simulations. Traditionally, simulation of stability in power systems has been constrained to tools developed specifically for this purpose, as PSS®E, EUROSTAG and PowerFactory [2]. Though most of these tools are computationally efficient and reasonably user-friendly, they have a closed architecture in which it is difficult to view or change most of the component models. The implementation of new network component models in PSS®E requires editing of the FORTRAN source code. PSS®E has the capability to export a linearized representation of the system for further analysis, but the full nonlinear representation

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remains hidden to the user. Thus, there is motivation to use an open-source modeling language, such as Modelica, to describe electric networks.

In this paper, power system modeling was performed using the Modelica language with the tool Dymola [3] as well as PSS®E, to analyze stability. PSS®E is one of the most widely used commercial programs of its type. Modelica effectively allows multi-domain modeling, including electrical, mechanical, and control systems. Thus, this paper presents power system stability simulations from an analysis of a simple power system to compare modeling tools.

The paper is organized as follows. Section 2 provides a brief overview of phenomena within power system stability. Section 3 introduces and describes the test system, and the simulation results are presented in Section 4. The results of the simulations are discussed in Section 5, and conclusions and future perspectives are presented in Section 6.

POWER SYSTEM STABILITY AND CONTROL

Two important highly nonlinear characteristics of power system stability are two pairs of strongly connected variables: reactive power Q and voltage V, and active power P and power angle δ. The power angle is often referred to as the load angle and associated with the system frequency f. These variables need to be monitored and controlled within certain limits to secure stable power system operation [1]. The TSO (Transmission System Operator) Statnett gives functional requirements in the power system [4] and has the overall supervision responsibility and physical control as regards Norway‘s power system. TSO ensures normally a power grid frequency of 50 Hz (or 314.16 rad/s) $\pm 2\,\%$ and a voltage interval of $\pm 10\,\%$ according too [5]. The system frequency of an interconnected power system has the same value everywhere in the system; in other words, it is independent of the location. A similar "‘system voltage" does not exist the voltage amplitude depends strongly on the local situation in the system. Power system stability is understood as the ability to regain an equilibrium state after being subjected to a physical disturbance, and it can be divided into:

- Voltage stability
- Rotor angle stability
- Power imbalance (frequency stability)

Different types of disturbances are classified in the literature [1]. Only the large disturbances given in Table 1 will be addressed in this paper. Determination of large-disturbance stability requires examination of the nonlinear dynamic performance of a system over a period of time sufficient to capture interactions between the devices to be investigated. To manage these stability phenomena, synchronous generators in power systems are often protected or controlled by devices, such as an automatic voltage regulator (AVR), power system stabilizer (PSS), turbine governor (GOV) and over-excitation limiter (OXL). A simplified control structure for these different devices is illustrated in Figure 1 and will only be presented here briefly. The turbine governor controls either the speed or output power according to a preset active power-frequency characteristic (droop control). This control is achieved by opening/closing control valves to regulate the water-flow (e.g., hydropower) through the turbine, forcing the generator to rotate, converting mechanical energy into electricity. The excitation (or field) current required to produce the magnetic field inside the generator is provided by the exciter and controlled by an AVR. The AVR is designed to automatically maintain a constant voltage; it may be a simple "feedforward" design or may include negative feedback control loops and implemented as a PI or PID controller. The AVR, in cooperation with the PSS, regulates the generator terminal voltage by controlling the amount of current supplied to the generator field by the exciter.

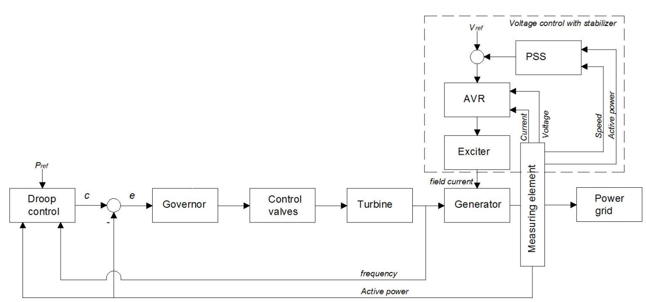

Figure 1: Single generator voltage and frequency control

10-BUS TEST SYSTEM

This paper presents the results from an analysis of a simple 10-bus[1] power system described in [1]. Typically nominal SI-voltage levels are used in simulations. The system is a well-established benchmark for exploring voltage stability issues [6]. This small system shares some of its characteristics with the Nordic system studied in [7]. In both systems, most generation occurs in a remote area that is connected to a main load area through five transmission lines. In addition to voltage stability, the frequency and rotor angle stability will also be visualized in this paper. The system has three synchronous hydro-power generators; one generator is connected to a slack-bus to represent inter-area power exchange. Both generators 1 and 2 are remote generators that supply power to the loads through five parallel feeders, and generator 3 is a local generator. A one-line diagram of the test system that will be used to illustrate some of the mechanisms of power system instability in a time simulation is shown in Figure 2.

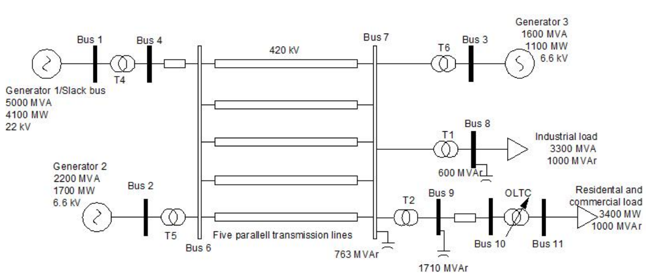

Figure 2: 10 bus case (BPA test system [1]).

The purpose of the simulations is to visualize how the generators in a power system respond when a momentary disturbance occurs in the power balance between the electrical power consumed in the system, the mechanical power delivered by the turbines, and the equivalent power from the slack-bus. The simulations were performed in Dymola [3] and compared with PSS®E Dynamic Simulation module [8] . An overview of simulations and countermeasures[2] carried out in this paper is shown in Table 1.

[1] In an electrical power system the bus is an electrical junction (node) where conductors terminate. It is usually made of copper bar.

[2] After an disturbance, measures are taken by different control components to stabilize voltage, frequency and rotor oscillations.

Test model constructed using PSS®E and Dymola

Power system parameters can be given in International System of measurement (SI) or per-unit system (pu). The pu system is used in power system modeling in which each parameter is expressed as a decimal fraction of its respective base. A minimum of two base quantities is required to completely define a pu system. For example, apparent power S and voltage V are fixed and then the current and impedance (or admittance) set arbitrarily. The pu bases used in the models developed in this paper were both "system base" (100 MVA) and a different "machine base".

PSS®E

The dynamic simulations of PSS®E are based on power-flow calculations in steady-state. The equipment used in dynamic simulations needs to be defined in power-flow. The main skeleton of PSS®E contains logic for data input, output, numerical integration, and electric network solutions but contains no logic related to differential equations for specific equipment [9]. The equipment used in this paper included standard PSS®E models and was defined in so-called subroutines in PSS®E. The model subroutines are called whenever the main skeleton logic needs numerical values of time derivatives. Dynamic models that are used for developing the test system are listed in Table 2. The models in PSS®E are restricted to block diagrams with input and outputs (casual), whereas in Modelica models can be acasual.

Dymola

Larsson [7, 10] created the freely available power system library ObjectStab, which is intended for power system stability simulations written in Modelica, a general-purpose object-oriented modeling language. The "Electric Power Library" (EPL) [10] in Dymola by Modelon AB was used to develop the test system in this paper. The EPL contains models of standard power system components, including the control of generators, exciters for synchronous machines (generators), and turbine GOVs. To investigate the stability phenomena in this paper, some additional components were made. An

Table 1: Simulations

Case	Stability	Countermeasures/Devices	Disturbance
A1	Voltage	Tap changer and OXL at G2 and G3	Loss of line
A2	Voltage	Tap changer and OXL at G3	Loss of line
B	Rotor angle	Power system stabilizer	3-phase fault and line trip
C	Frequency	Governor/Tie-line/load shedding	power imbalance

IEEE ST1A bus-fed thyristor excitation system with PSS and OXLs with inverse-time characteristics was built with logic blocks in Modelica. The ST1A has a PSS using only generator speed as the input signal. This stabilizer is simpler than the one used in PSS®E, which uses both speed and active power as the input. The ST1A was setup similar to a transient stability analysis of a power system in Kundur [1]. An On-Load Tap-Changer (OLTC) was also created as an state machine based on [11]. Generator G1 was modeled as an infinite bus (voltage with a constant amplitude and phase) and generators G2 and G3 using 6th-order models. The loads at bus 8 and bus 11 were modeled as constant impedance. The load at bus 11 was connected through the OLTC at T6. The GOVs were implemented as PI controllers (first-order transfer functions with limiter) using speed and power as reference values (set points).

For the comparison with PSS®E, some parameters needed to be correlated in EPL. This was done mainly at the transformer ratio and transmission line parameters (resistance, inductance, and capacitance).

SIMULATIONS

The simulations are designed to visualize the three main stability phenomena within power systems. Voltage instability/collapse is a major security concern for power system operation. This phenomenon is often preceded by a slow process of load restoration and limitation in generators reactive power supply, after some initial disturbances [12]. If each bus in a system elevating both the voltage (V) and reactive power (Q) after a disturbance the system is voltage-stable. On the other hand, if the voltage decreases and reactive power increases at one or more buses we have voltage instability. This phenomenon can be seen in case A1 in Figure 3 (only Dymola) and case A2 in Figure 4 (Dymola and PSS®E). A disconnect between one of the five parallel lines occurred in the simulation at 100 s. At approximately 115 s, the short-term dynamics including the generator electromechanical and load recovery dynamics settled. As the voltage at bus 11 was below the OLTC deadband, its internal timer started. As seen from the figures, the OLTC reacted and slightly increased the voltage at bus 11 (secondary side) and decreased the voltage at bus 10 (primary side). In Figure 3, OXLs were implemented at G3 (at 140 seconds) and G2 (at 160 seconds). Bus 10 exhibited voltage instability until the OXL started to limit the reactive power after 140 seconds. In Figure 4, the OXL was only implemented at generator 3. The OXL limited the field voltage by ramping down the field voltage (or current), ensuring that G3 did not overheat. Consequently, the necessary voltage support was not dispatched locally and a power system "blackout" occurred. The use of a tap-changer as a countermeasure is often referred to as secondary voltage control. Another countermeasure for voltage instability is load shedding, but it is not presented in this case.

As seen in Figure 3, similar trend was observed for both PSS®E and Dymola. However, the voltage before disturbance was not the same due to how the power system was constructed in the different simulation tools. Also the OXL characteristic in PSS®E (MAXEX1) was slightly more complex than that implemented with EPL.

Rotor angle stability

In Figures 5 and Figure 6, the rotor angle stability phenomena and countermeasures are visualized by showing the speed deviation in pu from synchronous speed of generator G3 with and without stabilizer

Table 2: Test system in PSS®E and Dymola

Equipment	PSSE	Dymola
Governor G1 (Slack bus)	GENCLS	Infinite bus
Governor G2 and G3	GENROU	6-th order dq
Exciter G2 and G3	SEXS	IEEE ST1A
Overexcitation limiter at G3	MAXEX1	Inverse-time characteristic with ramping
Overexcitation limiter at G2	None	Constant maximum limit
Transformer tap changer at bus 11	OLTC1T	OLTC
Power system stabilizer at G2	PSS2A	Simplified PSS
Load at bus 8 and 11	Constant impedance	Impedance (Load at nominal voltage)

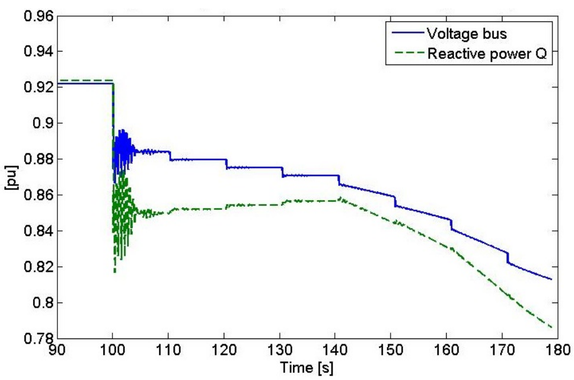

Figure 3: Case A1: Voltage instability at bus 10 with OXL implemented both at G2 and G3

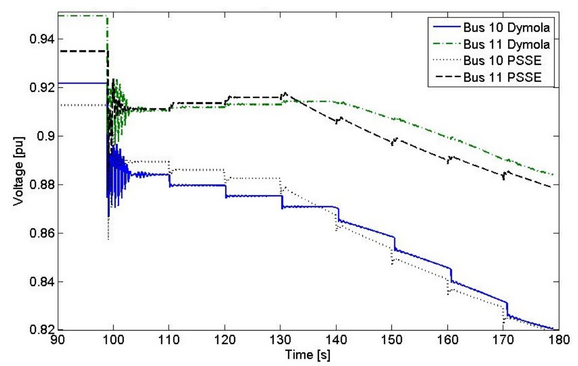

Figure 4: Case A2: Voltage level due to tap-changer transformer T6 with results from both Dymola and PSS®E

during a large disturbance. Rotor angle [3] stability is the ability of interconnected synchronous machines of a power system to remain in synchronism. PSS provided supplemental damping to the oscillation of synchronous machine rotors through the generator excitation as shown in Figure 1. A fundamental factor in this problem is the manner in which the power outputs of synchronous machines vary as their rotors oscillates.
The effect of this positive damping after an large disturbance in the grid can be seen in figure 5, where PSS is applied to the excitation system at G3.

As mentioned, PSS®E is using the PSS2A stabilizer measuring both speed and active power as input. This gives a greater positive damping by the stabilizer compared to the one in EPL with only speed as input. Also the generator oscillation behavior and amplitude are different due to different governor models. In both cases the stabilizer will lower the time for the system to settle in non oscillating state.

[3] the derivative of rotor angle is equal to the rotor angular velocity in [rad/s]

Frequency stability

If a large load is suddenly connected (disconnected) to the system, or if a generating unit is suddenly disconnected, a long-term distortion occurs in the power balance, changing the frequency in the system. In Figure 7 the frequency stability phenomena is visualized in Dymola by showing the rotor-dynamic oscillation at G2. In real-life applications, generators are protected against frequency instability by disconnecting equipment before a severe hazard. However, this protection was not implemented here and the simulations are only a theoretical approach for visualizing this phenomenon. When the

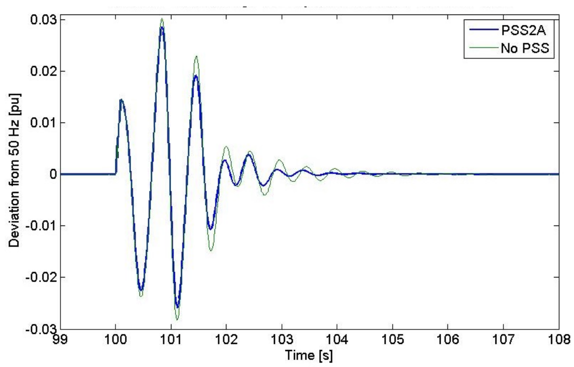

Figure 5: Rotor oscillations at G3 in PSS®E

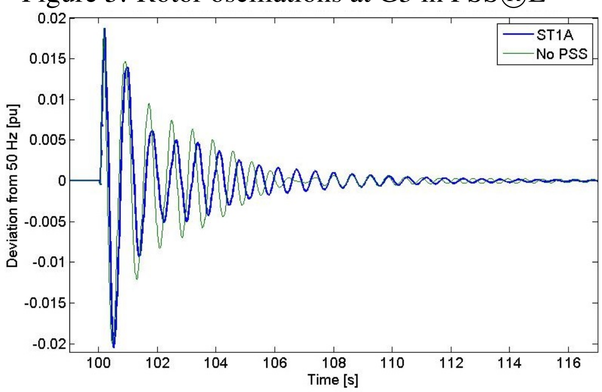

Figure 6: Rotor oscillations at G3 in Dymola

turbine generators are equipped with governing systems following a change in total power demand (or loss of a generator), the system is not able to return to the initial frequency on its own without any additional action. In Figure 7, generator G3 was disconnected from the system at 103 seconds. The G2 is now oscillating due to the generator rotor-dynamics. This rotor oscillation is a good representation of the frequency instability that would occur in the 10-bus system. The 10-bus system is now in power imbalance transferring more power through the slack-bus trying to stabilize the system. This is often refered to tie-line power. After 130 seconds the load at bus 11 was disconnected (load shedding) making the frequency equilibrate after approximately 160 seconds. Simulation in this case is done only with Dymola. How the infinte bus are constructed in EPL and PSS®E are different causing the system to behave differently.

DISCUSSION

The simulations in Dymola were carried out with transient initialisation and simulations due to un-

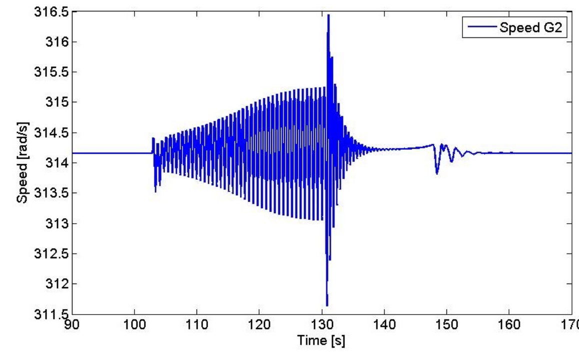

Figure 7: Case C in Dymola: Showing rotor-dynamic behavior at G2 influencing the grid frequency after an disturbance at time 103 seconds (oscillation starts) and countermeasure applied at 130 seconds.

certainty with the parameters of the power system and control components. There are two initialisation modes, transient (state variables with default-values) and steady-state. When choosing transient initialisation, no specific initial equations are defined. This type of transient simulation is only possible with feedback within the controllers. Periodically driven systems tend towards a periodic solution after some time. To get the periodic solution (after about 20 second simulation time in this paper) the initial limits of governor and AVR need to be greater than in balanced situations. Simulating transmission lines in steady-state was not possible in EPL due to some initializing problems.

The EPL's complexity (fully represents the actual physics of the components) demands the user to implement a huge amount of accurate parameters. Building a stable power system in the EPL with only limited knowledge of parameters is challenging, as some initial values need to be set explicitly to avoid guessing from the tool side. A real-life power system application with known parameters is recommended when comparing simulation tools with the EPL. When creating a large system model in Dymola, it is typically easier to build the system model through the composition of subsystem models that can be tested in isolation. However, connecting these well-posed subsystems together to create the full scale large power system may lead to instability and unwanted oscillations. A balanced power system, well posed initial equations, and accurate parameter values are of crucial importance to running transient power system simulations in Dymola.

The main advantages of using Modelica as a modeling language is the readability and re-usability of the code. Models within this library are based on a clear set of equations rather than a set of diagrams as in the PSS®E tool. In this sense the library has a didactic intention. FORTRAN is considered a procedural language (i.e., you tell the computer what to do step-by-step), whereas Modelica is a declarative language. Thus, rather than developing source code that lists a set of steps to follow in order to solve a problem, you only have to describe the mathematical structure of your problem [13]. The disadvantage is longer execution times compared to the FORTRAN model. For example, in long term simulations as shown in case A2, PSS®E use less than 3 second computation time on the 180 second simulation, while Dymola uses about 20 seconds on the same calculation (without the transient initialization process). For example if you want to simulate a state utility network (where the number of buses will be in thousands) you will need a robust software such as PSS®E. But if you want to execute a system with less number of buses and do in depth analysis you can use EPL and Dymola.

The different complexity of models used in PSS®E and Dymola affect the results. For example, the GOV used in the EPL is a PI control done as a transfer function block, whereas in PSS®E the Hydro-Turbine Governor (HYGOV) models both the GOV and hydraulic systems. This HYGOV model is a more complex structure than the EPL model. However, visualizing the stability phenomena in this paper, the controllers made in EPL had promising results compared to PSS®E. As seen in the long-term voltage stability simulations, this difference has a limited impact. A detailed hydraulic system model like HYGOV and an infinite bus such as GENCLS in PSS®E should be created with the EPL.
However, the modeling detail required for any given study depends on the scope of the study and the system characteristics [1]. A Hydro Power Library (HPL) is also available [14]. The EPL could be combined with the HPL in Dymola to also include waterway components and droop control.

CONCLUSION

Regarding the voltage as a function of time, a reasonable agreement was found between the simulation results obtained using Dymola and PSS®E for long-term voltage stability. However, a comparison of faster electromechanical mechanisms, such as rotor angle demands, requires more detailed models in EPL. In this paper, PSS®E was clearly the fastest simulator. However, PSS®E has an closed architecture in which it is difficult to view or change most of the component models. Using an open-source model with didactic intention for describing electric networks, such as Modelica, could be preferable for in-depth power system studies.

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