Simscape Power Systems Benchmarks for Education and Research in Power Grid Dynamics and Control

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***Abstract*—This paper introduces a MATLAB/Simulink package including two well-known power system benchmarks developed in Simscape Power Systems. The simulation models can be employed for base-lining and for testing new control techniques and protection algorithms for renewable and micro-grids integration studies. Different simulation scenarios including time-domain and small-signal analysis are presented to support the correctness of the implementation. Furthermore, we present a frequency measurement (phasor) block to measure the frequency in a Simscape Power Systems model running in phasor mode. The models are available in MATLAB-Central file exchange for power system education and research worldwide.**

***Index Terms*—IEEE Standardized Benchmarks, MATLAB Simscape Power Systems, power system simulation and modeling, Education and Research**

I. Introduction

Electric power systems turned into interconnected power grids a long time ago. Interconnected systems stabilize the grid, while reducing the overall cost of providing reserves and the chance of undesirable load shed situations. These complex infrastructures make power system analysis so challenging since there are no direct ways to perform actual experiment on the studied object. These complications are becoming more highlighted by introducing intermittency in generation, responsiveness in demand, and interlinks between power system communication and information. Educators and researchers are now searching for new solutions for modeling and studying power system dynamics and control [1].

Simscape Power Systems, a MATLAB/Simulink based package developed and maintained by Mathworks and Hydro-Québec Research institute (IREQ), provides a modern design tool via a Simscape-based and Simulink-based environments [2]. Specialized Technology libraries (SPS-ST) provide components and technology specifically developed for electrical power systems. They contain models of typical power equipment such as transformers, lines, machines, and power electronics. The validity of the SPS-ST components is based on the experience of the Power Systems Testing and Simulation Laboratory of Hydro-Québec, a large North American utility located in Canada.

In general, test systems can be found in book appendices, IEEE papers, or on the web in flat ascii files of specific software file format, making them difficult to work with and to disseminate. Overcoming these limitations, the authors opted to develop in a systematic way, all commonly used power system benchmarks in SPS-ST. The work initiated with modeling the IEEE 10 generator 39 bus test system, known also as New England 39 bus, the three-area IEEE Reliability Test System (RTS) 1996, and the Australian simplified 14 generators [3]. In this paper, we extend the test systems MATLAB/Simulink package [3] to include phasor simulation models of the western North American Power System (wNAPS) as well as the Western System Coordinated Council (WSCC). These standard power system models are employed in many publications as a research demonstration model for stability limited issues [4], [5]. Furthermore, the proposed benchmarks are using frequency measurement blocks to allow users to measure the frequency in various points of the network. The Control and Measurements library of SPS-ST contains Phase-Locked Loop (PLL) and PMU blocks that compute the frequency of a signal in discrete or continuous simulation modes. The proposed block is designed to work in phasor mode.

The rest of the paper is constructed as follows: Section II describes the power systems benchmarks with SPS including relevant information for applied components and control devices. Section III introduces the frequency measurement (phasor) block. Simulation results and analysis are presented in Section IV, while the conclusion is drawn in Section V.

II. Benchmark Models

This section describes the main built-in components of the simscape power systems benchmarks:

- Power system transmission lines are modeled using three-phase PI section line blocks, where we define the positive- and zero sequence resistances, inductances, capacitances, and line length.
- All loads are modeled using three-phase parallel RLC PQ load blocks (Y grounded configuration).
- Power systems transformers are modeled using three-phase transformer blocks, where we define the Y-Y (Δ-Yg) connection for interconnecting transformer (generator transformer).
- Three-phase Salient-pole or Round (cylindrical) synchronous machine blocks in dq rotor reference frame represent the power system generators.
- All generators are equipped with comprehensive model of

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TABLE I
DATA SHEET OF THE TEST SYSTEMS

System Settings	Nb of Buses	Nb of Gens	Nb of Loads	Installed Gen	Installed Load	Losses
WSCC: 100 (MVA), 345 (KV)	9	3	3	320.19 (MW)	315 (MW)	4.5 (MW)
wNAPS: 100 (MVA), 500 (KV)	41	16	11	88200 (MW)	53000 (MW)	2150.56 (MW)

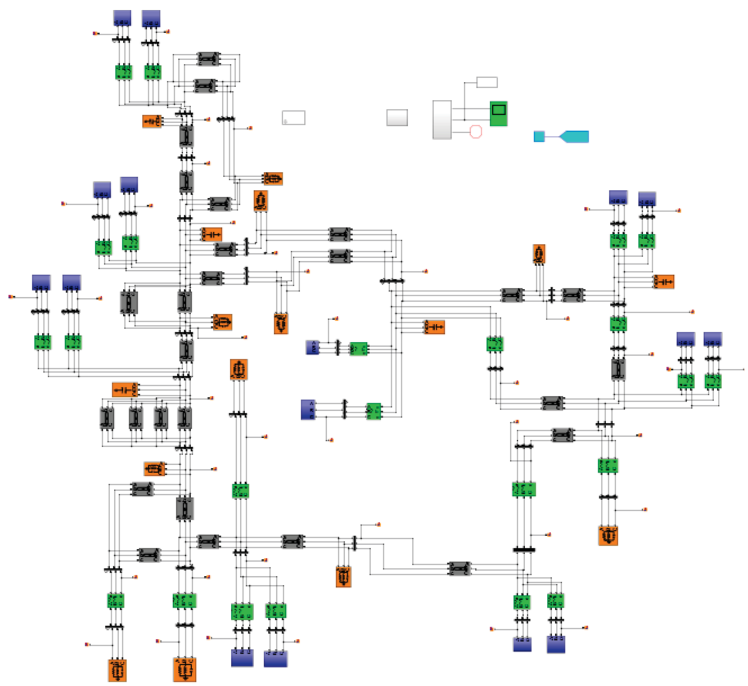

Fig. 1. Schematic of Western North American Power Grid .

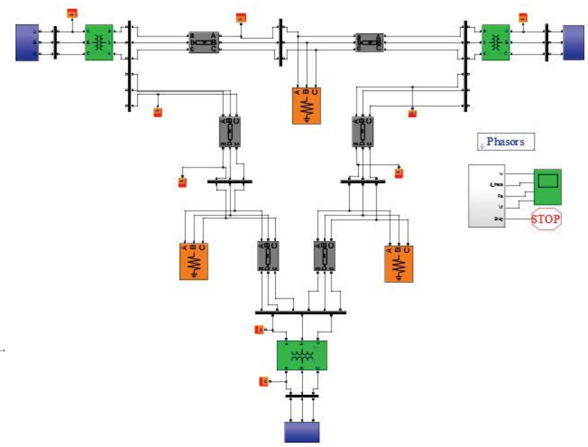

Fig. 2. Schematic of WSCC 3-Machines 9-bus system

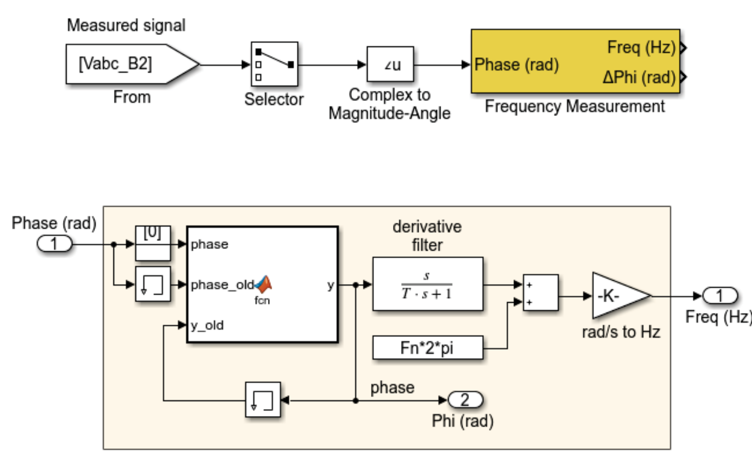

Fig. 3. Frequency Measurement Unit Block Model.

Steam/Hydraulic turbine governor models.

- The excitation systems are modeled using the IEEE type 1 synchronous machine voltage regulator combined to an exciter.
- Different types of Power System Stabilizers (PSSs), including Multi-Band PSS (MBPSS), $\Delta\omega$ generic PSS, and ΔP generic PSS can be used in the simulation.

A. Western North American Power System Model (wNAPS)

wNAPS is shown in Fig. 1, and it's data sheet is given in Table I. The foundation case data are also presented in [6]. This system has been employed in many publications as a research demonstration model for stability limited issues [4], [5]. The power system includes major generation buses 17 thru 24, while loads are distributed in load buses 31 thru 41. Each generation bus has two generators connected to it. Generators 9, 10, 14, and 16 are driven by hydro turbines, while generators 11, 12, 13, and 15 are driven by faster acting steam turbines. All generators are equipped with fast-acting voltage regulators and PSS units. Furthermore, the loads can be set to act as constant impedance, constant current, constant power, or as dynamic load models.

B. Western System Coordinated Council Model (WSCC)

The well-known WSCC system is shown in Fig. 2, while it's data sheet is given in Table I. The foundation case data are presented in [6]. WSCC system is widely used for transient stability study. The synchronous machines are equipped with voltage regulators combined with an exciter and comprehensive model of steam turbine and governors.

III. FREQUENCY MEASUREMENT (PHASOR) BLOCK

The frequency is an important operational parameter of a network. The frequency of a feed system is normally constant if the sum of all loads and losses is equal to the total power system generation. However, the system frequency decreases if the total generation is less than the sum of charges and losses. On the other hand, the frequency of the system increases when the total production exceeds the sum of charges and losses. It is very important to be able to maintain the frequency of a feeding system very close to its nominal frequency. Frequency changes that cannot be tolerated in a system must be addressed by control systems. It is therefore important to present a reliable and representative frequency measuring instrument. Phase-Locked Loop (PLL) and PMU blocks are the frequency measurement units in the Control and Measurements library of SPS-ST. They only work in discrete or continuous simulation modes. The proposed block is therefore designed for simulations running in phasor mode.

The phasor solution method is mainly employed to study electromechanical oscillations of power systems involving large generators and motors. This technique is not limited to the study of transient stability of machines. It can be applied to any linear system. Phasor solution method computes voltages and currents as phasors (complex numbers at a particular frequency). They can be expressed either in cartesian coordinates (real and imaginary) or in polar coordinates (amplitude and phase). As the electrical states are ignored, the phasor solution method is much faster to execute since it does not require a particular solver to solve the electrical part of the system.

The frequency measurement (phasor) block implements a device that measure the frequency by derivative of input phase angle variation ($\Delta\phi$) with respect to a synchronous phasor rotating at nominal frequency.

The first output of the block gives a measure of the frequency, and the second output gives the unwrapped $\Delta\phi$ phase angle (without 2π discontinuities). The input of the block is a measure of the phase of a complex phasor signal. Users can monitor three-phase abc phasor voltage or current using sequence analyzer blocks as shown in Fig. 3. The block requires specifying the nominal frequency of the network and the time constant of the derivative filter used inside block's model.

IV. Simulation and Analysis

In this section we demonstrate the capability of the both frequency measurement block and SPS benchmarks using time-domain and small-signal analysis.

A. Measurement Unit Validation Using Kundur Test System

The Kundur's test system (Fig. 4) consists of two fully symmetrical areas linked together by two 230 kV lines of 220 km length. The load is represented as constant impedances and split between the areas in such a way that area 1 is exporting 413MW to area 2. At t = 4s one of the two tie-lines is removed by opening the breakers.

Although it is normally believed that the system frequency is a global value throughout the system and usually measured as the average machines frequency, there are some differences in bus frequency values. Figure 5 represents the global system frequency (average machines frequency) versus the buses frequency values. As can be seen in the figure, the values are almost the same in steady state condition. However, after removing the first tie-line by opening the breakers the frequency of area 1 increases because of the power surplus in this area, while in the second area frequency decreases.

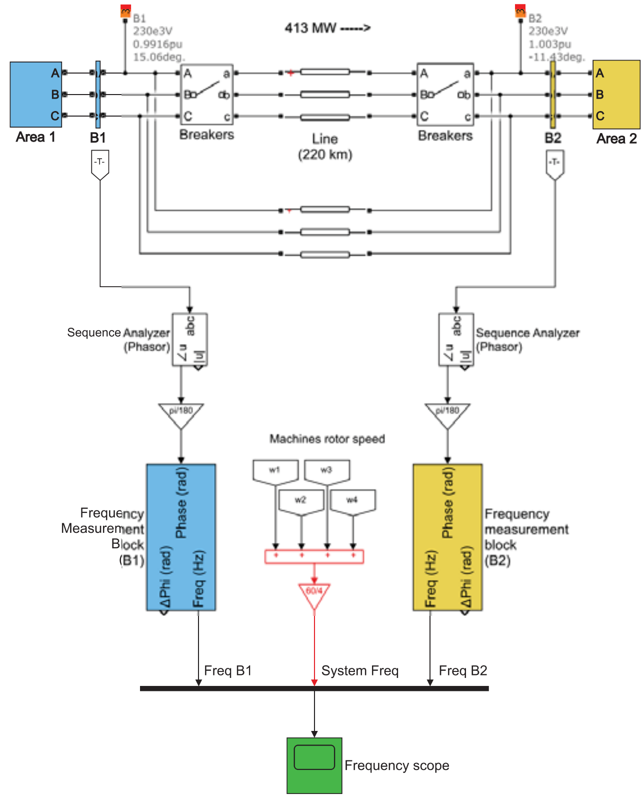

Fig. 4. Kundur Test System with Frequency Measurement Unit Blocks

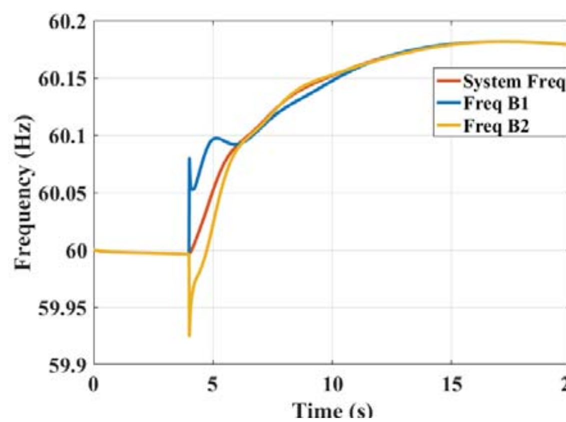

Fig. 5. Frequency Response of The Two-areas Test System

B. SPS Benchmarks Validation Using Time-demain Analysis

1) First Contingency (Three Phase Fault):

The first disturbance event is a severe three phase to ground fault applied (close to the bus 22 of wNAPS) at t=5s, and cleared after 5 cycles. As shown in Fig. 6, in the absence of PSSs (No PSS), the test system losses the synchronism after t=15s, while having PSSs, the test system will not collapse. The power output of G5 (shown in Fig. 7) again confirms the effectiveness of PSS in improving the oscillatory behavior of power systems.

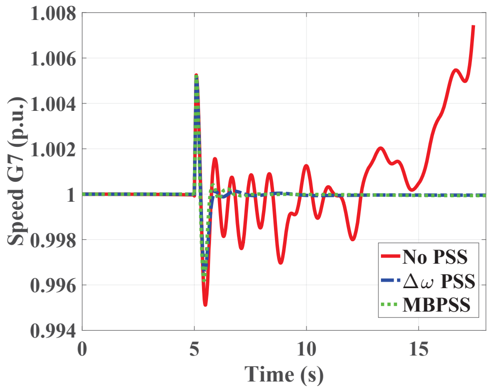

Fig. 6. Speed of G7 at wNAPS with/without PSSs [Three-phase fault to ground at t=5s cleared after 5 cycles].

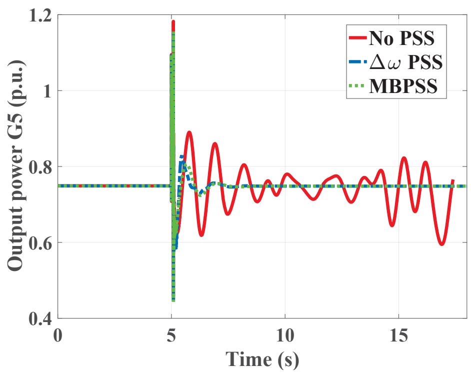

Fig. 7. Active power of G5 at wNAPS with/without PSSs [Three-phase fault to ground at t=5s cleared after 5 cycles].

2) Second Contingency (Load Variation):

The second contingency is dedicated to an unexpected load increase in WSCC and wNAPS power systems.

– The active power of the load in bus 5 of WSCC , is suddenly increased by 63MW at t=5s.

– The active power of the load in bus 39 of wNAPS , is suddenly increased by 900MW at t=2s and t=10s.

Different load control strategies are simulated and compared in terms of frequency-based performance metrics. Refer to [7], [8], and [9] for detailed information on each control approaches. The quadratic cost function of $c_j(d_j) = \frac{d_j^2}{(2\alpha_j)}$ is considered as the disutility of controllable loads in Conventional OLC with $\alpha_j = 100$ and the absolute maximum ΔP_j allowed at each bus is $\pm 20\%$. We employ the Formula-based load tuning method by Kalsi et al. [10] [1] to adjust the feedback gain factor (α_j) at load control substations. We also set $K_1 = 20$ and $K_2 = 50$ for Virtual inertia-based load control approach [2]. As shown in Fig. 8 and 9, the load control approaches lead to a damping torque which improves the power system frequency regulation.

[1] $\alpha_j = \frac{pct_{max,load} P_{load,sys}}{\Delta f_{min}} \times \frac{pct_{cont,ON,j} P_{cont,j}}{P_{cont,sys}}$ [10]
[2] $K_1 \times \frac{d\Delta f_{bus}}{dt} + K_2 \times \Delta f_{bus} = \Delta P_{bus}$ [9]

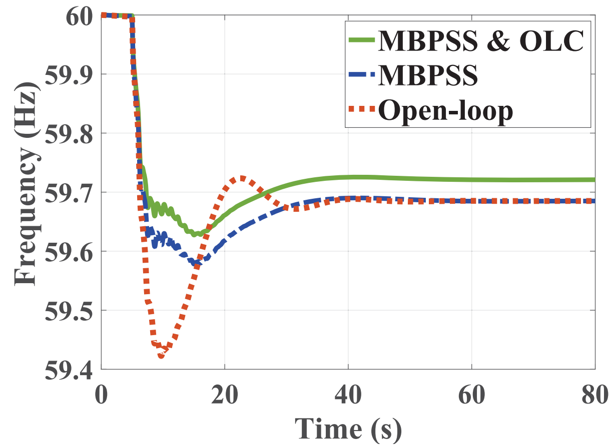

Fig. 8. Frequency response of WSCC system for load variation contingency.

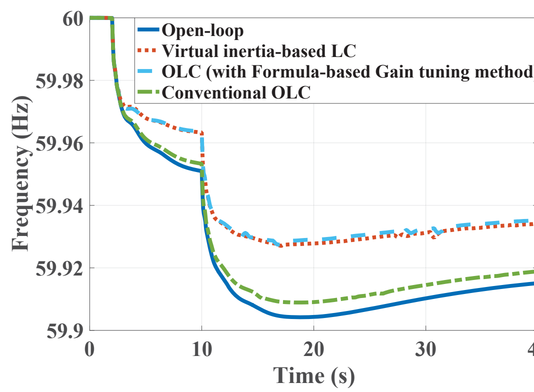

Fig. 9. Frequency response of wNAPS for load variation contingency.

C. SPS Benchmarks Validation Using Small-signal Analysis

Linear analysis is employed using MATLAB Linearization Toolbox to evaluate the power system oscillatory behavior [11], [12]. As shown in Fig 10, the unstable modes of wNAPS may become stable, relocated to left side of Y-axis using PSS units. Similarly, the open-loop system's critical mode damping ratio is increased from -0.3117 to 0.199 using PSS units.

The compass plot of the right eigenvector components associated with generators speed changes of wNAPS are also shown in Fig. 11. As shown in Fig. 11 (b), the rotor speed shapes of G12, and G4 oscillate against the rest of the system which means this is an inter-area mode. The bode diagram of WSCC is shown in Fig. 12, which clearly demonstrates the stability margins of the system under different conditions.

V. Conclusion

This paper introduced a MATLAB/Simulink package including two well-known power systems benchmarks implemented in SPS-ST toolbox on phasor mode, for baselining and testing new control techniques. Furthermore, a new frequency measurement unit have been proposed to measure the frequency in a power system model running in phasor mode. The developed models capability was clearly shown using time domain and small-signal analysis. The models can be found in

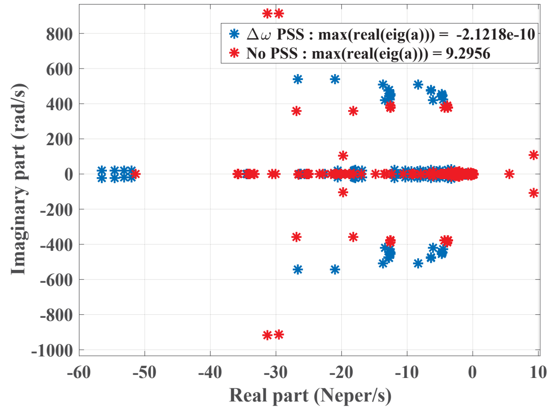

Fig. 10. Electromechanical modes of WNAPS with/without PSSs.

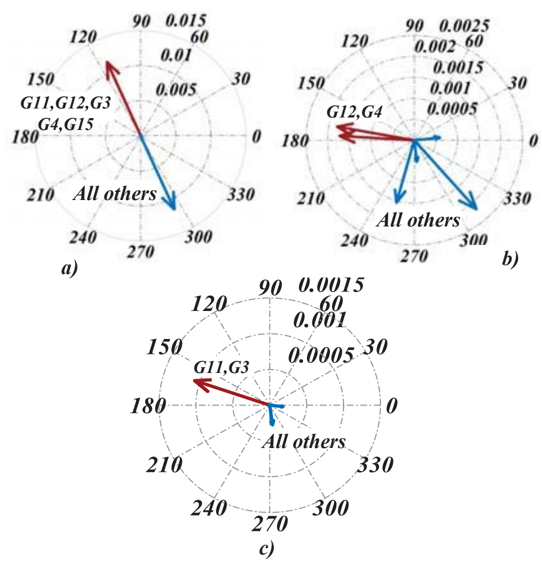

Fig. 11. Rotor speed mode shapes for the critical inter-area frequency mode: (a) wNAPS without PSS [0.0482^{Hz}: Damping = - 0.31174]. (b) wNAPS with PSS [0.8218^{Hz}: Damping = 0.199]. (b) wNAPS with PSS and Load control [0.848^{Hz}: Damping = 0.244].

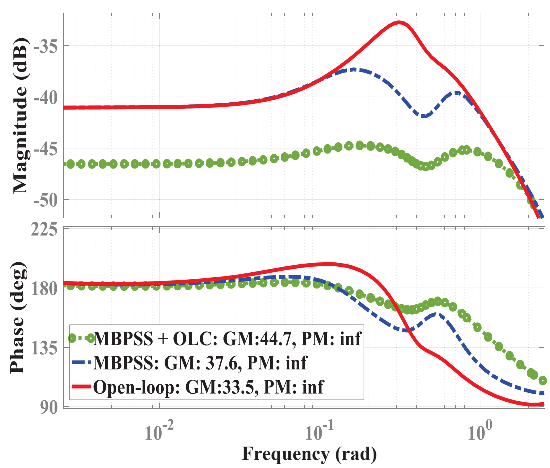

Fig. 12. WSCC System Bode diagram for damping low frequency oscillations.

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