Open Data IEEE Test Systems Implemented in SimpowerSystems for Education and Research in Power Grid Dynamics and Control

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***Abstract*— This paper presents three IEEE standardized power system benchmarks developed in SimPowerSystems, a MATLAB/Simulink package. The simulation models can be used for baselining and testing new control techniques and protection algorithms for renewable and micro grids integration studies. Analytical examples as well as static, time domain, and frequency analysis are presented to support the correctness of the implementation. The models are available in MATLAB-Central file exchange for power system education and research worldwide.**

***Keywords*— IEEE Standardized Benchmarks, MATLAB SimPowerSystems, power system simulation and modelling, Education and Research**

I. Introduction

Interconnected power systems are the biggest and the most complex infrastructures that have been conceived and built in last decades. As a result, teaching power system can be very challenging since there are no easy ways to perform actual experiment on the studied object. Growing population, economic growth, climate change, adoption of new technologies, and many other advanced topics have made this task even more complicated by introducing intermittency in generation, responsiveness in demand, and interlinks between power system communication and information. Educators and researchers are now required to demonstrate their concepts and inventions on realistic reduced-scaled power system with several scenarios in order to enable new solutions for providing reliable, affordable, and sustainable electricity.

Implementing an idea on real power system must first undergo complete investigation by extensive simulations to prevent any instability issue and catastrophic consequence. Simple IEEE standardized benchmark systems are considered by experts to be fair enough for understanding, developing, and deploying any new solutions, as long as the components' dynamic behaviors are represented without undue simplification.

To this aim, several programming environments can be used for studying power system dynamics and control [1]. SimPowerSystems (SPS), a MATLAB/Simulink based package developed and maintained by Mathworks and Hydro-Québec Research Centre (IREQ), provides a wide range of specialized component libraries and analysis tools for modelling and simulating power systems. It is well-known worldwide and appears to be the prime study environment among the academic and industrial researchers [2]. Graphically-oriented package allows the users to easily create and simulate power system models by simple "click and drag'' procedure. SPS is seamlessly integrated to the Simulink environment and can be used in conjunction with Simulink tools to design and to optimize any control scheme.

Generally, test systems are available in book appendices, IEEE papers, or on the web in flat ascii files of specific software file format, making them hard to use and to disseminate. The authors decided to provide more widespread use of realistic test systems in power system teaching and research, namely, data accessibility and openness, easy availability, transparency, modifiability and re-usability of models including electromechanical components (machines, lines, etc.) controls (governors, excitation systems, etc.) and measurements (voltage and current transformers). The authors opted to develop in a systematic way, all commonly used power system benchmark test systems in SPS, starting with the following popular choices: **(1)** The IEEE 10 generator 39 bus test system [3], known also as New England 39 bus, **(2)** The three-area IEEE Reliability Test System (RTS) 1996 [4] and **(3)** The Australian simplified 14 generators [5]. These systems have been prioritized from IEEE working groups' reports [6] and fully modelled based on corresponding references. The SPS test networks can be used in phasor mode and in time domain simulation mode for stability studies. They also include various models of governors, excitation systems, and power system stabilizers according to the references, with the option of adding more, using Simulink programming facilities.

The main objective is to use them for baselining and testing new control techniques such as fuzzy-logic based controls and new protection algorithms, especially for wide-area information based schemes using PMU. The test systems are also suitable for renewable and micro grids integration studies. The models are offered in MATLAB central file exchange, making them widely available for power systems education and research worldwide.

Section II of this paper describes benchmarks with SPS including relevant information for applied components and control devices, and section III discusses some analytical examples on benchmarked systems as well as static, time domain, and frequency analysis to support the correctness of the implementation.

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II. BENCHMARK MODELS

This section describes the key features of the three test systems. General concepts which have been considered in the process of modelling are as follows:

- Three-phase PI section line blocks are used to represent transmission lines. Positive- and zero-sequence resistances, inductances, capacitances, and line length can be set.
- All loads are represented by three-phase parallel RLC load in PQ type (Y grounded configuration) since corresponding references provided load data in active and reactive demands. Different types of connection configuration and types are available.
- Three-phase transformer block are used to model all the transformers of the test systems. Y-Y connection for interconnecting transformer and Δ-Yg connection for generator transformer can be set.
- Generators are modelled by three-phase synchronous machine in dq rotor reference frame while d-axis and q-axis time constants vary to best fit with given data.
- If applied, single mass tandem compound steam prime mover including speed regulator, steam turbine and a shaft is set to model steam turbine and governor.
- If applied, hydraulic turbine combined to a PID governor system is used for hydro power plants.
- Different types of well-known IEEE synchronous machine voltage regulators and exciters are used to model excitation systems.
- Each generator equipped with three types of Power System Stabilizers (PSSs), Multi-Band PSS (MBPSS), Delta omega generic PSS, and Delta Pa generic PSS.

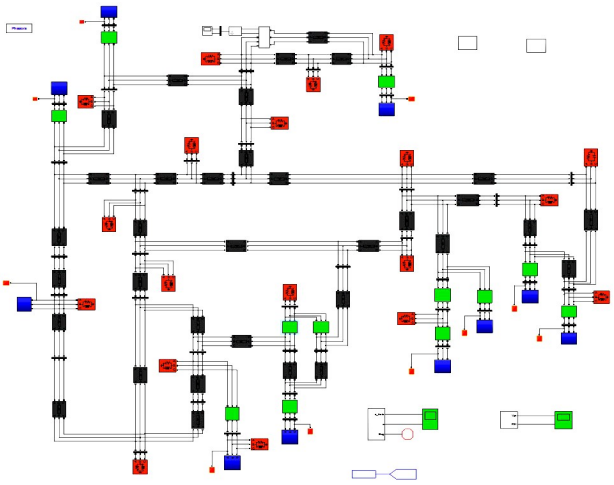


Fig. 1. The IEEE 10 generator 39 bus test system.

A. *The IEEE 10 generator 39 bus test system (NE39bus)*

The IEEE 10 generator 39 bus test system is well known also as New England 39 bus (NE39bus) in some literatures. This benchmark has 39 buses, 19 loads, and 10 generators with generator one, connected to bus 39, represents the aggregation of a large number of generators. It is widely used for small signal stability studies and dynamic stability analysis. Fig. 1 shows the modelled system.

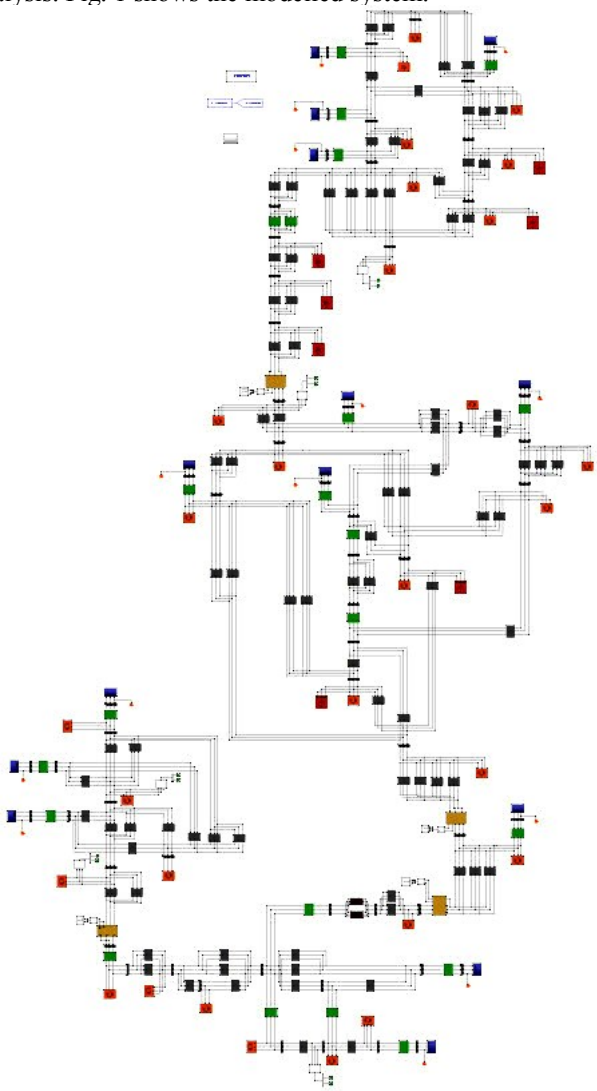
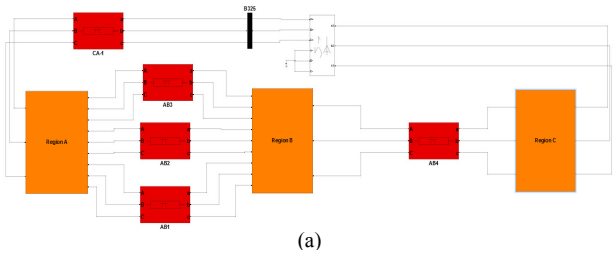


Fig. 2. The Australian simplified 14 generators test system (AU14gen).

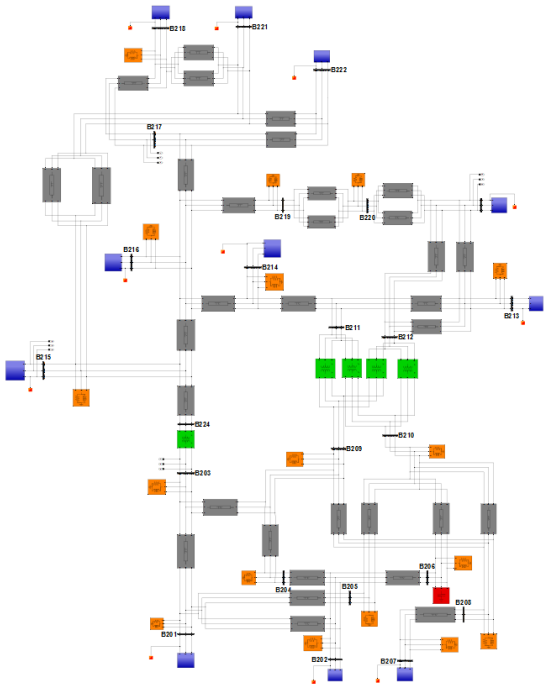
B. *The Australian simplified 14 generators (AU14gen)*

The Australian simplified 14 generators benchmark is inexactly based on the southern and eastern Australian power system. This model is developed by the University of Adelaide for research-oriented studies and educational purposes. The AU14gen model of the Australian power system has 59 buses, 14 generators, and 29 loads (see Fig. 2).

The purpose of creating this model was to provide a benchmark for small signal analysis and design of controllers in a multi-machine power system. This model also has five Static VAR Compensators (SVCs) providing the opportunity for studying the performance of FACTS devices in power systems. At this point it should be mentioned that turbine and governor model were not included in the current version given by the University of Adelaide. For this reason, some critical disturbances such as loss of generation and loss of load cannot be simulated. This gap has been filled in the MATLAB/ Simulink version of the Australian test system by including suitable models for turbine and governor system based on common parameters.



(a)



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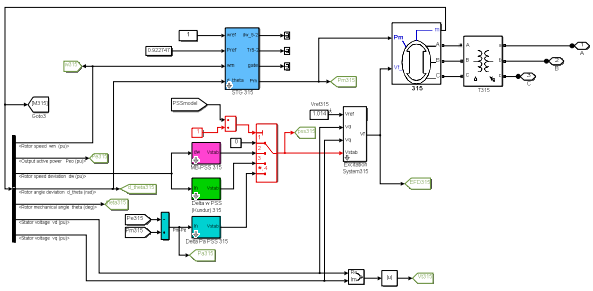

(c)

Fig. 3. (a) The IEEE Reliability Test System 1996 (RTS96) (b) The network of area B (c) Inside generating unit 315.

TABLE I
DATA SHEET OF THE TEST SYSTEMS

System	Nb of Busses	Nb of Gens	Nb of Loads	Installed Gen (MW)	Installed Load (MW)	Total Losses (MW)
NE39bus	39	10	19	10000	6096	45
AU14gen	59	14	29	33333	14810[a]	232
RTS96	72	33	51	8998	8550	174

[a] according to studied case 4 [5]

C. *The IEEE Reliability test system 1996 (RTS96)*

The IEEE RTS96 was developed by adapting and updating the original IEEE reliability test system. The main idea is to allow comparative studies on new reliability techniques especially in the case of multi-area power systems. This benchmark has three identical areas which are connected by interconnections (see Fig. 3a), 72 buses, 33 generators, and 51 loads (peak load at winter). One prototype area is sketched in Fig. 3b. Each generating unit comprises several blocks. Fig. 3c shows inside the generating unit 315. The network also includes three synchronous condensers at buses 114, 214, and 314.

Table I lists a summary of test systems.

III. SIMULATION AND ANALYSIS

The following common studies have been simulated to show the capability of the benchmarked systems. Simulations are performed in phasor mode.

A. *Time domain Analysis*

Application of PSSs for resolving oscillatory stability issues goes back to years ago. During last decades, the good performance and capabilities of PSSs have been shown in many literatures and even in real world applications. Therefore, PSS models are important features required in any power systems simulation tool.

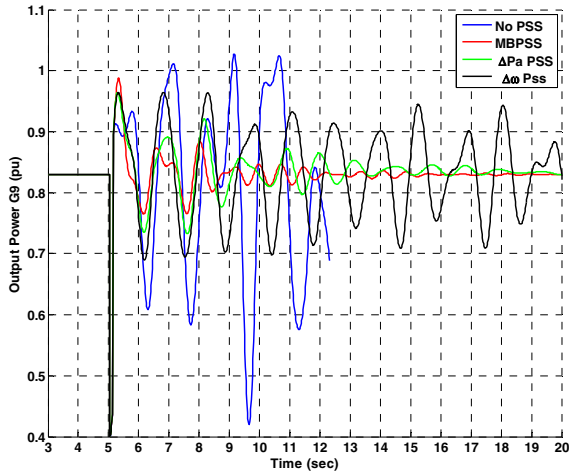

Fig. 4. Active power of G9 at NE39bus with/without PSSs [Three-phase fault to ground at t=5s cleared after 6 cycles].

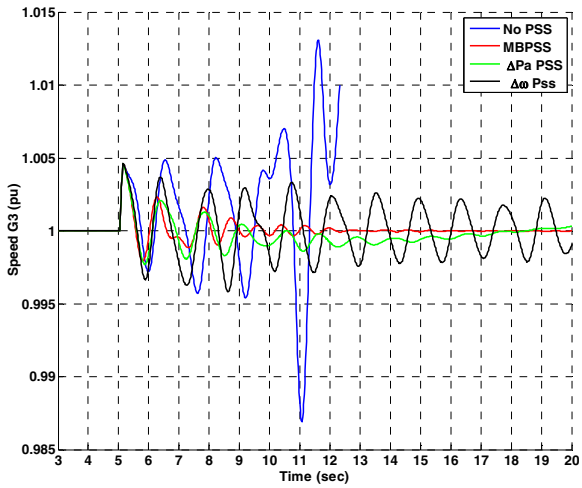

Fig. 5. Speed of G3 at NE39bus with/without PSSs [Three-phase fault to ground at t=5s cleared after 6 cycles].

Three different types of PSSs in SimPowerSystems have been included in the test systems. Figs. 4 and 5 illustrate the performance of New England 39 bus in the case of a severe

fault applied close to the bus 16. Three-phase fault, at t=5s cleared after 6 cycles, without losing any equipment is simulated. In the absence of PSSs (No PSS), the test system losses the synchronism after t=12s. Having PSSs, the test system will not collapse. Moreover, the performance of MBPSS is superior compared to other types of PSSs.

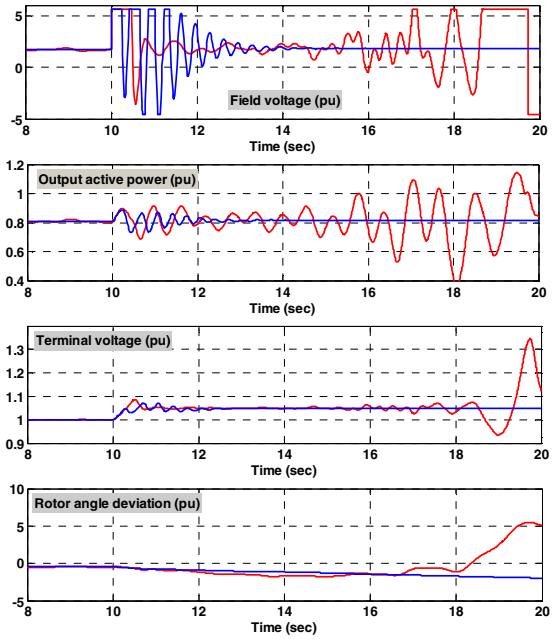

Fig. 6. Key variables of BPS_2 at AU14gen with/without its MBPSS [5% step change in AVR reference voltage of BPS_2 at t=10s] (Red: Without MBPSS, Blue: With MBPSS).

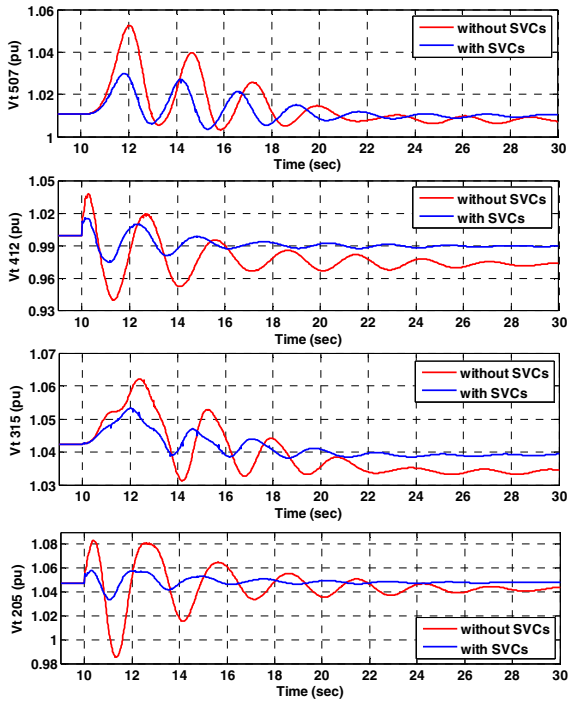

Fig. 7. Buses' voltages (AU14gen) [Loss of Load at t=10s].

The impact of MBPSS on local generating unit variables is another issue that needs to be investigated. Fig. 6 illustrates key variables of generating unit BPS_2 at AU14gen case due to the small-step change in its AVR reference voltage. The presence of MBPSS at this unit adds supplementary damping to variables' oscillations. In the absence of MBPSS the generating unit is not able to follow new voltage's set point.

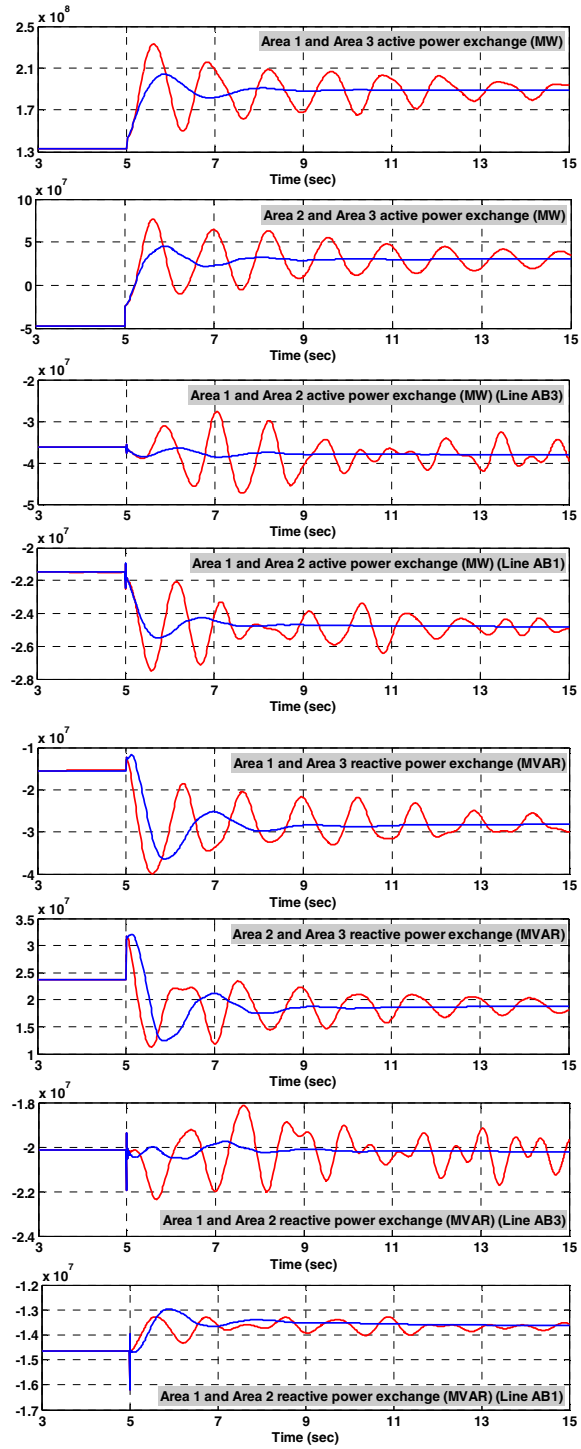

Fig. 8. Inter-area exchanges at RTS96 with/without MBPSSs [Loss of generating unit 315 at t=5s] (Red: Without MBPSSs, Blue: With MBPSSs).

FACTS devices have also gained interest due to the recent advancement in power electronic area. They are used to increase power transfer capability and to enhance the stability and controllability of modern power systems. SPS offers some models for FACTS devices. SVCs are part of the FACTS device family used for voltage regulation, power factor

correction, and stabilizing the system. The main advantage of SVCs is fast response to any variations in the system voltage.

The Australian 14 generator test system takes benefit from several distributed SVCs. The scenario of loss of load is simulated with AU14gen benchmark. The load 405 is disconnected completely at t=10s. The voltages amplitudes of some selected buses shown in Fig. 7 demonstrate the damping capability of SVSs.

Regarding the RTS96 in time domain analysis, performances of the MBPSS in the case of loss of generating unit 315 are studied. The results of Fig. 8 give another solid reason of MBPSS global approval in the domain of power system stability.

B. Frequency Domain analysis

In several studies, frequency domain analysis is used to explain the nature of power system over a range of frequencies. In this type of study, the equations of power system are presented as functions of complex frequency which provides useful information about its dynamic behavior. MATLAB/Simulink control design has a quite powerful linearization tool. It can be used to linearize a nonlinear model that is valid around small area of operation point. Exact linearization of a power system model produces the opportunity to identify several key specifications of power system as well as electromechanical modes, mode shapes, controllability, and observability. Some results of frequency domain analysis over the aforementioned test systems are presented in this paper.

Fig. 9 shows that, using MBPSS, the unstable modes on the right side of Y-axis may become stable, relocated to left side of Y-axis. Fig. 10 presents that rotor speed shapes of G10 and G8 oscillate against each other which means itself this is a local mode. Concerning Fig. 11, all the generating units oscillate against the generator one, the aggregation of a large number of generators. In other words, this mode is an inter-area mode between the entire power system against the external connected network.

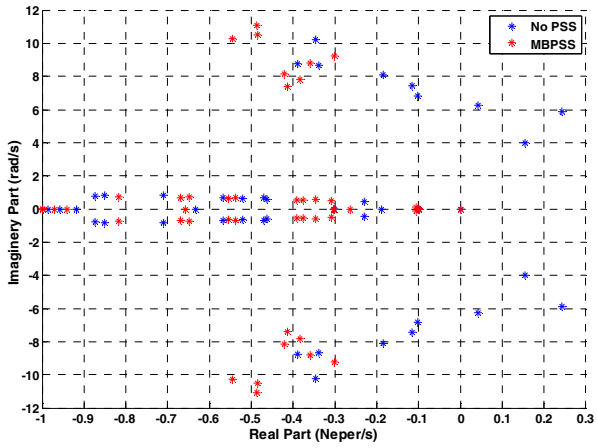

Fig. 9. Electromechanical modes of NE39bus with/without MBPSSs.

For the sake of transfer function creation, reference voltages of all the generating units and SVCs at AU14gen test system are set as input. On other hand, Active power exchanges between the areas are set as output. The goal is to determine the controllability and observability of the mode (Frequency: 0.48 Hz, Damping: 0.115) due to the selected inputs/outputs. Figs. 12 and 13 show the results for the inter-area mode. For example, it is 100% controllable with AVR reference voltage of generating unit 204 and 70% with the SVC located at bus 507. Finally, Figs. 14 shows the controllability of an output, inter-area exchange between region 4 and region 2, over a range of frequency using some selected generators.

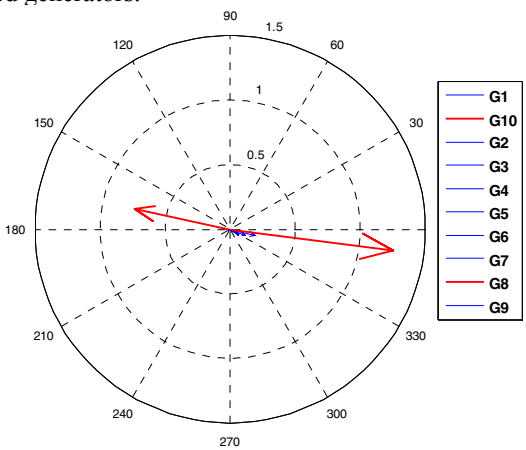

Fig. 10. Rotor speed mode shapes for the low frequency mode (NE39bus without MBPSSs) [Frequency 1.63 Hz, Damping: 0.034].

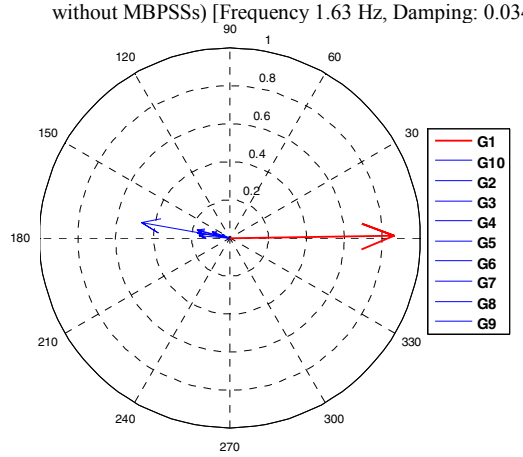

Fig. 11. Rotor speed mode shapes for the inter-area frequency mode (NE39bus) [Frequency 0.63 Hz, Damping: -0.039].

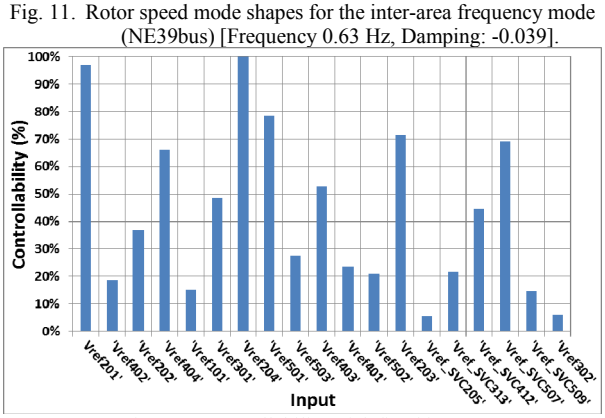

Fig. 12. Controllability of defined inputs.
[The mode: Frequency 0.48 Hz, Damping: 0.115] (AU14gen).

It is worth underlying that the examples presented above are just a small sample of the power system studies that can be setup and performed in SimpowerSystems taking advantage of the proposed test systems to speed-up the configuration and prototyping processes. Possible applications range from closed-loop testing of protective relays [7-8], fault detection

studies [9-12], Power electronic modelling and simulation [13-15], to wide-area control concept proving [16] and design of PMU based microgrids islanding schemes [17-18]. The test systems can be easily modified to introduce renewable generation in the form of wind or solar power plants. The ac interconnections in the RTS96 network can also be replaced by conventional or modular multilevel converters based multi-terminal HVDC systems to train students in power electronic for power systems applications [19]. In other words, the number of applications of the proposed test systems in dynamic performance applications is only limited by imagination of the researcher with the added benefit that these networks are well initialized and can be automatically linearized for control design and tuning purposes.

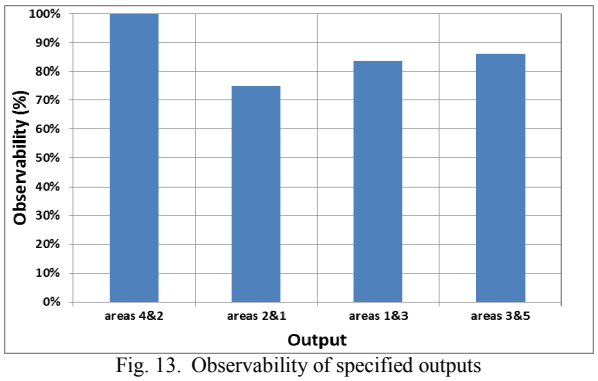

Fig. 13. Observability of specified outputs [The mode: Frequency 0.48 Hz, Damping: 0.115] (AU14gen).

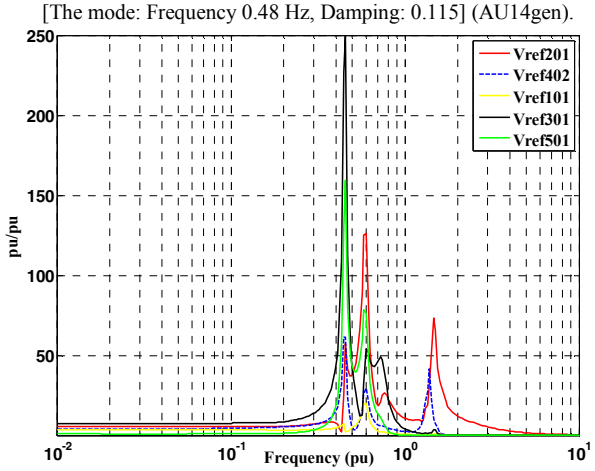

Fig. 14. Controllability of inter-area exchange power between region 4 and region 2 by some selected generators (AU14gen).

IV. Conclusion

Three IEEE standardized power system benchmark systems have been presented to illustrate the capability of the MATLAB/Simulink as the ideal prototyping platform for studying new power system models and for understanding complex control systems. The paper presented some typical time domain and frequency analysis on the test systems. The obtained simulation results have demonstrated the capability and usability of the developed models. Several other studies could have been presented. The readers are encouraged to download from MATLAB-Central the power system benchmark systems and use them to study and publish new concepts and scenarios for providing reliable, affordable, and sustainable electricity.

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