Benchmark Models for the Analysis and Control of Small-Signal Oscillatory Dynamics in Power Systems

IEEE Task Force on Benchmark Systems for Stability Controls

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***Abstract*—This paper summarizes a set of six benchmark systems for the analysis and control of electromechanical oscillations in power systems, recommended by the IEEE Task Force on Benchmark Systems for Stability Controls of the Power System Dynamic Performance Committee. The benchmark systems were chosen for their tutorial value and particular characteristics leading to control the system design problems relevant to the research community. For each benchmark, the modeling guidelines are provided, along with eigenvalues and time-domain results produced with at least two simulation softwares, and one possible control approach is provided for each system as well. Researchers and practicing engineers are encouraged to use these benchmark systems when assessing new oscillation damping control strategies.**

***Index Terms*—Benchmark system, damping controller, electromechanical oscillations, power system stabilizer, small-signal stability.**

I. Introduction

A major root cause of large-scale power system blackouts is poorly-damped or unstable electromechanical oscillations which are inherent to interconnected power systems. Therefore, reliable planning and operation of power systems to ensure satisfactory damping performance is of considerable practical interest. Indeed, due to a number of factors including the increasing size, dynamic complexity and utilization of power systems provision of adequate damping remains an important research challenge [1]–[3]. In this context, the paper summarizes the set of six carefully chosen benchmark power system models as recommended by the IEEE Task Force (TF) on Benchmark Systems for Stability Controls established by the Power System Stability Controls Subcommittee of the Power System Dynamic Performance Committee [4]. A ‘benchmark system’ comprises a model of the power system together with a set of conventional power system stabilizers (PSSs) whose parameters are soundly tuned in accordance with one of several techniques that are widely applied in practice. Thus, these benchmark systems provide a basis for assessing the damping performance of novel damping controls and/or tuning methodologies to the research community.

Installing PSSs to increase the damping component of the electrical torque of a synchronous generator through the modulation of its excitation voltage, has been the industry practice for many decades to improve the small-signal stability of interconnected power systems [5]. Many variants of the phase compensation designs of the 1970s have been proposed to minimize possible adverse dynamic effects of this controller at non-electromechanical frequencies [3], [6]. The advances in robust control theory over the years have also led to a number of alternative PSSs, all acting through the automatic voltage regulator (AVR) and exciter of the synchronous machines [2]. Controllers with structures other than the lead-lag phase compensation and/or applied to FACTS devices have been termed power oscillation dampers (PODs) [7].

Many methods to tune the parameters of conventional PSSs and PODs have been proposed and continue to appear in the literature. The performance of the new controller is usually verified by digital simulations and compared to that of a conventional PSS using a test system built mainly to highlight the advantages of the new controller. In such cases there is a tendency to over-emphasize the benefits of the new controller in comparison with well applied conventional solutions. Thus, there is a clear need for a set of benchmark systems with soundly tuned conventional PSSs to provide a common basis for fairly evaluating the performance of novel damping controllers and/or PSS tuning methods in comparison with conventional approaches.

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The prime objectives of the TF on Benchmark Systems are:

1) Select a set of power system models that has tutorial value and present challenges from the perspective of small-signal stability analysis and control.
2) Propose at least one possible conventional damping control approach for each system model based on common industry practices.
3) Implement the system models and their respective damping control solutions in at least two simulation software packages that have the capability of performing eigen-analysis and time-domain simulations.
4) Validate the benchmark models by confirming (i) that the damping performance of the system with the proposed damping controllers is satisfactory; and (ii) there is close agreement between the results obtained with the respective simulation packages.

As mentioned earlier, each selected system model along with its proposed conventional damping control solution is referred to as a benchmark system.

The criteria used for selecting the benchmark systems are outlined in Section II, while Section III presents the proposed damping control solutions for all the benchmark systems. Section IV describes the procedure used for implementing and validating the benchmark systems, and Section V summarizes the paper.

II. The Benchmark Systems and Their Selection Criteria

Single machine infinite bus (SMIB) test systems have been extensively used for the study of electromechanical oscillations [8]. The SMIB model effectively considers many of the practical aspects related to the field commissioning and testing of stabilizers, in which it is usually not possible to excite inter-area modes [9]. However, the simplifications inherent to the SMIB model limits its applicability to the study of system-wide (inter-area) oscillations in large interconnected power systems [3]. Other important aspects that may require a detailed multi-machine power system representation include: (i) the coordination of multiple controllers to simultaneously damp several modes; and (ii) robust damping of these electromechanical modes for a range of operating conditions.

The following requirements were considered for the selection of a power system model as a benchmark system:

1) The system must have multiple machines and exhibit a combination of local and inter-area modes. Other types of modes (e.g., intra-plant modes) can also be present to better reflect practical system conditions. One or more of the electromechanical modes must be poorly damped without damping controls.
2) The system must be provided with at least one soundly implemented conventional damping control approach whose action results in satisfactory damping performance.
3) Consistent with the TF objectives the system must have been validated by comparing its eigenvalues and nonlinear time-domain responses from at least two different simulation software packages.

TABLE I
Summary of the Benchmark Systems

System	Buses	Gens	Damping Control Issue
1	6	3	Simultaneous damping of intra-plant, local (inter-plant) and inter-area modes
2	7	5	Poor controllability due to zeroes in the vicinity of the critical electromechanical mode
3	11	4	Simultaneous damping of local and inter-area modes in a highly symmetrical system
4	39	10	Coordination of multiple stabilizers to damp electromechanical modes within a control area
5	59	14	Simultaneous damping of local and inter-area modes, small- and large-disturbance analysis of a system for multiple operating conditions.
6	68	16	Coordination of multiple stabilizers to damp multiple local and inter-area modes

The choices of the simulation packages used in the validation processes were made by the volunteers in charge of it for each system and were based on their experiences to work in those platforms. However, reference [4] provides a full documentation of each benchmark, in such a way that future users should not be constrained by a prescribed set of packages that may not be available to them.

The addition of a stabilizer to a generating plant in a system under expansion is usually made in coordination with the previously existing stabilizers, and the simultaneous design of several stabilizers is rarely required in practice. Therefore, approaches comprising the design of just a few stabilizers were proposed for the benchmarks since these are of more practical interest.

The selected benchmarks are small-scale test systems that are simple and easy to handle, while still maintaining the characteristics of interest. Most of the benchmark systems do not assess the performance of the stabilizers with respect to changes in the system operating condition or to nonlinear behavior due to large disturbances. Such assessments are, of course, necessary in practice.

Based on the aforementioned criteria, six systems were chosen, each focusing on an issue of practical interest to oscillation damping. During model validation sometimes unavoidable discrepancies between the results from the different simulators (due to different built-in models offered by different software, for example) were highlighted and their probable source discussed where appropriate.

The main damping control issues of the six benchmark systems are briefly described in Table I. Results from extensive validation activities, as well as the complete set of data for each of the benchmark systems, can be found in [4] or, alternatively, retrieved from the TF website whose URL is ewh.ieee.org/soc/pes/psdpc/PSDP_benchmark_systems.htm.

Finally, it is worth emphasizing that the TF does not recommend or endorse the use of a specific model or any particular simulation software to perform the linear analyses or the nonlinear simulations in order to reproduce the reported results. For the analysis of a particular benchmark, the TF recommendation is to use a software that produces results close to those reported herein and in [4].

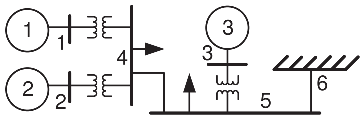

Fig. 1. Single-line diagram of the 3MIB system.

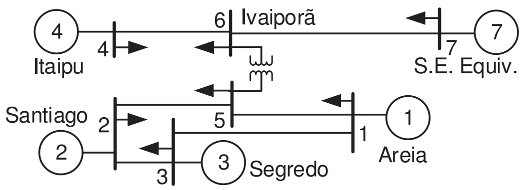

Fig. 2. Single-line diagram of the 7-bus system.

III. Description of the Benchmark Systems

This section describes the structure and the electromechanical oscillation problem posed by the benchmark systems, along with one possible damping control solution for each of them.

A. Benchmark 1: Three-Machine Infinite-Bus (3MIB) System

This system is comprised of 6 buses and 3 generators, as shown in Fig. 1, in which generators 1 and 2 are identical parallel units of the same power plant. The 3MIB system exhibits all three types of electromechanical modes, which can be classified into intra-plant (between generating units 1 and 2), inter-plant or local (parallel units 1 and 2 against generator 3), and inter-area (the three generators oscillating coherently against the infinite bus 6). It bears some similarities to the 3-machine system in [5] and poses the challenge of providing robust and simultaneous damping to the three modes from controllers located in a single power plant.

The challenge presented by the 3MIB benchmark system, of exerting effective damping control from a single power plant, has been tackled using the method described in [9]. In this method a family of SMIB systems is produced, whose line reactances are chosen so as to produce electromechanical modes whose frequencies are close to those of the 3MIB system. The phase angle that should be ideally compensated by the PSS circuitry is calculated at the electromechanical frequency of each system in the family. These phase angles are then used to define a phase compensation band in the electromechanical frequency range, which allows for the PSS dynamic phase shaping that can be conducted either manually or using an optimization procedure. The resulting PSSs are robust and compatible with the PSS circuitry from practice.

B. Benchmark 2: Brazilian 7-Bus Equivalent System

This system, shown in Fig. 2, is a 7-bus, 5-machine equivalent model of the South-Southeastern Brazilian system configuration in the 1990s, in which generator-7 is an equivalent of the south-eastern area.

The system has two inter-area modes and exhibits a modal controllability problem in which a single generator (Itaipu plant), despite having a relatively high modal observability and controllability over the unstable inter-area mode (i.e., large transfer function residue), is unable to provide sufficient damping via excitation control to stabilize this mode. Control difficulties of this type might be present in other multi-machine systems. In this benchmark, the PSS action is impaired by the presence of a non-minimum phase (NMP) complex-conjugate pair of zeroes in the scalar (SISO) open-loop transfer function for the stabilization loop. From the root locus plot, it can be verified that the unstable open-loop poles tend to the NMP transfer function zeroes as the PSS gain is increased.

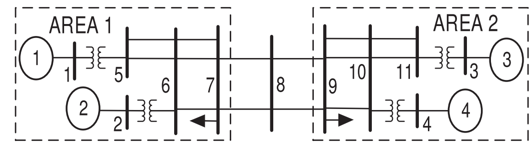

Fig. 3. Single-line diagram of the 4-generator system.

Reference [10] gives, in the body of the paper as well as the accompanying discussions and closure, a physical explanation as to the existence of the NMP complex pair of zeros in this benchmark system, as well as to the fact that they are readily removed by the addition of PSS to a second generator in the system. These two facts can be explained from basic linear control system concepts: 1) the location of the open-loop, scalar transfer function zeros determines the ease or difficulty with which a system can be stabilized by feedback damping controller; 2) the existing NMP zeros in a scalar transfer function to be feedback-compensated may disappear when considering instead a multivariable feedback control system, which effectively augments system controllability and observability.

Therefore, the elimination of the problematic NMP zeros of the Itaipu damping control loop in order to allow the PSS to push the unstable open-loop pole into the left-half plane of the complex plane, involved installing another PSS to a second machine. In the proposed damping control solution for this benchmark, PSSs are installed to all generators, except at generator 7 (given that it is an area equivalent). Each PSS was tuned independently (with the PSSs of the other generators disabled) with the objective of providing maximum damping to the two inter-area modes. A classical PSS design technique was used for tuning the PSSs [5].

C. Benchmark 3: 2-Area, 4-Generator System

This is a two-area symmetric system with 5 buses and 2 machines in each area, plus an intermediate tie-line bus to total 11 buses. This test system [11] has been studied extensively and is thoroughly documented in [1]. Fig. 3 shows the single-line diagram of this system.

Due to its symmetric structure, the two local modes related to areas 1 and 2 can have almost identical frequencies (depending on the power flow conditions, among other factors [11]). The inter-area oscillation between areas 1 and 2 has a lower frequency than the local modes, as expected. This benchmark has historical value and was intended to show that well designed PSSs may effectively promote the simultaneous damping of

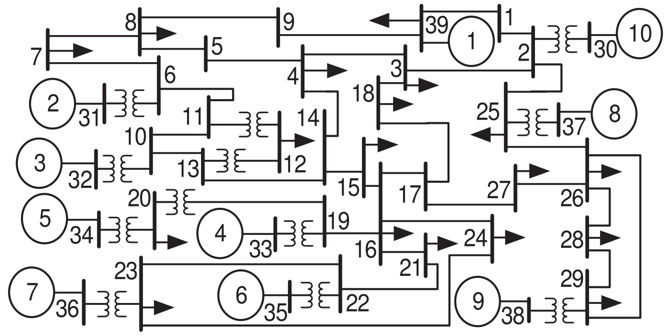

Fig. 4. Single-line diagram of the 39-bus system.

inter-area as well as local electromechanical modes having very close frequencies.

Reference [4] presents the parameter set for the original PSSs [11] and also proposes a modified set designed by classical methods [8], [5] which have the practical advantage of allowing easy tuning verification during the PSS commissioning tests. All modes in the benchmark can be properly damped simply by a suitable coordination of PSSs. Given that conventionally tuned PSSs can provide effective damping to this system the justification for a novel POD or PSS tuning method for this system would need to be particularly compelling.

D. Benchmark 4: 39-Bus New England Test System (NETS)

The NETS, shown in Fig. 4, was first used in [12], and since then it has been extensively employed in the oscillation damping control literature. It is comprised of 39 buses and 10 generators. Generator 1 is an area-equivalent that represents the New York system to which the New England system is interconnected [13].

Almost all electromechanical modes in this system have local or regional nature, except for one that is observed as the oscillation of generators 2 to 10 against generator 1. This latter mode has the lowest frequency and should be regarded as a New England versus New York inter-area mode, with all generators within the New England area oscillating coherently against the New York equivalent (generator 1).

This system does not present much of a challenge from the small-signal stability stabilization viewpoint and is included herein mostly for historical reasons and for the sake of verifying the compatibility of results from different software. The emphasis in this study was to avoid detrimental interactions among the multiple generators equipped with PSSs that have to provide adequate damping for both the local mode of their respective generators and the inter-area mode that involves all generators against the New York equivalent.

The applied solution was based on a classical tuning method, which involved the calculation of the GEP(s) function of each of the system generators and the determination of PSS gains and phase compensation parameters according to the guidelines given in [5].

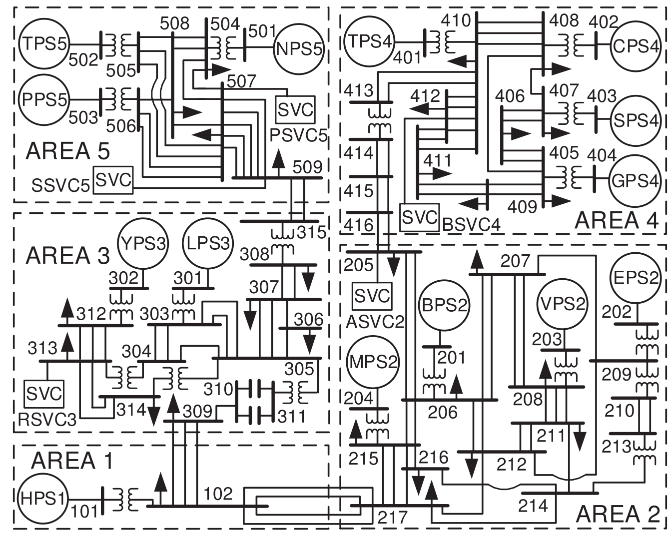

Fig. 5. Single-line diagram of the 14-generator system.

E. Benchmark 5: Australian 14-Generator Equivalent System

This simplified model of the southern and eastern Australian system, shown in Fig. 5, consists of 59 buses, 14 generators and 5 areas. The system also includes five static VAr compensators (SVCs) and a series compensated transmission line. This system is characterized by four weakly connected regions resulting in three inter-area modes of oscillation as well as 10 local area modes. Base cases are provided for an encompassing set of six different system operating conditions representing a range of system loading and interconnection power flow conditions. A comprehensive set of transient stability analysis results for two-phase to ground faults at all system buses are provided for each of the six study cases via [4].

The challenge posed by this system is simultaneous damping of all the local and inter-area modes using PSSs such that the damping remains robust for multiple operating points. As mentioned, PSS performance following large disturbances is also assessed.

The solution chosen in this case is based on the "P-Vr" PSS-design method [14] which is applied widely in practice. The $\mathrm{P\text{-}Vr}$ characteristic of a generator is the frequency response from the AVR voltage reference "Vr" to the electric-torque (or equivalently electrical power output "P") with the shaft dynamics of all machines disabled [14]. The $\mathrm{P\text{-}Vr}$ characteristic is computed for each generator in each study case. For the ith generator one of the $\mathrm{P\text{-}Vr}$ characteristics from the six study cases is selected as representative for the purpose of PSS tuning. A "best fit" low-order transfer-function representation, $H_i(s)$, of the selected $\mathrm{P\text{-}Vr}$ characteristic is found for the ith generator. Tuning of the PSS compensation is based on the concept that the damping-torque coefficients introduced by the PSS fitted to the ith generator are given by $D_i(s) = De_i.\, B_i(s) = H_i(s).\, G_i(s)$ in which De_i is the desired damping torque coefficient to be introduced by the PSS over the frequency range of electromechanical modes (typically 0.2 to 2 Hz), $B_i(s)$ is a pass band filter with unity gain and near zero phase in the above frequency range and $G_i(s)$ is the PSS transfer-function. Note that this method not

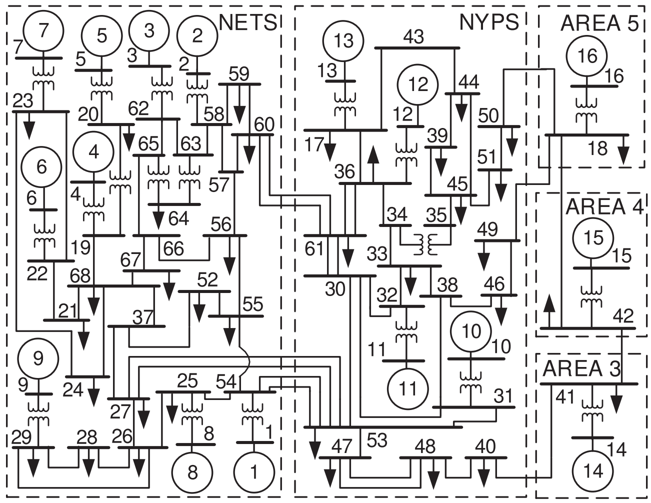

Fig. 6. Single-line diagram of the 68-bus system.

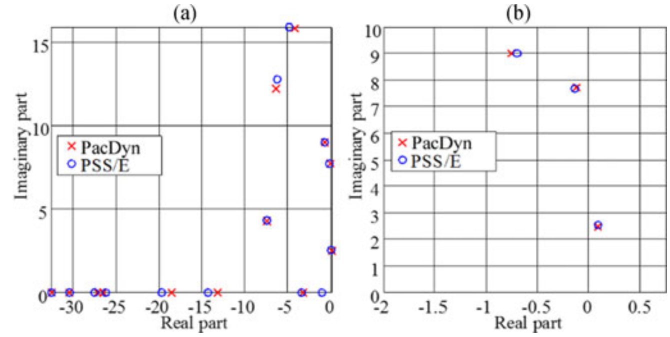

Fig. 7. 3MIB system eigenvalues: (a) Complete spectrum without PSSs; (b) enlarged view of the electromechanical modes.

only provides phase compensation but also provides a meaningful basis for specifying the PSS gain in terms of desired torque coefficient De_i. Because of the more-or-less invariant nature of the P-Vr characteristics over a wide range of operating conditions, the corresponding designed PSS is robust [14], [15].

F. Benchmark 6: 68-Bus System

The 68-bus 5-area system is a reduced order equivalent of the interconnected NETS and New York power system (NYPS) as shown in Fig. 6. There are four inter-area modes present in the system, and have high participation from the electromechanical states of generators 14, 15, and 16 (which represent areas 3, 4, and 5, respectively).

The challenge in this system resides in the difficulty to damp its local and inter-area modes relying only on PSSs, considering that three of its largest machines are system equivalents and not actual power plants.

The 68-bus system is a widely studied system [2], and several solutions for robust damping of all the electromechanical modes in the system are available ([16] and [17] are examples). Out of these solutions, only [17] relies solely on PSSs for providing robust damping. A shortcoming of [17] is the assumption that all the generators in the system can be controlled using PSSs, but generators 13 to 16 are area-equivalents and PSSs cannot be practically located on these generators. Also, as the inter-area modes have high participation from generators 13 to 16, it is highly probable that these modes cannot be damped by PSSs alone and hence wide area measurement systems (WAMS) and wide area control-device(s), such as FACTS devices, are needed to adequately damp them. As resorting to WAMS or FACTS is outside the scope of this TF, the study and validation of this system has been performed considering only PSSs on generators 1 to 12. GEP-based classical methods have been used for PSS design for this system [5], but some inter-area modes remained poorly damped.

IV. Modeling and Validation

The dynamic elements of the benchmark systems are modeled according with the guidelines from IEEE standards. Unless noted elsewhere, all the generators are modeled according to IEEE Std. 1110 [18], while excitation systems and PSSs are modeled as per IEEE Std. 421.5 [19]. Salient pole generators are represented by the fifth order IEEE 2.1 model, while round rotor units are represented by the sixth order IEEE 2.2 model. The models were implemented on at least two widely used power system simulation software packages. The results of power-flow, eigenvalue calculation and non-linear time-domain simulations are summarized in [4]. In general, the assessment was performed at a single operating point.

The non-linear simulations involved applying step changes to the AVR set points (V_{ref}) or to the mechanical power references of the generators, and also by the connection of a shunt reactor at a judiciously chosen bus. The disturbances were selected to excite particular electromechanical modes and assess the damping effectiveness of the proposed stabilizers.

A benchmark system is deemed to be validated if its simulated results, when obtained by at least two software packages, show good agreement. The details of modeling, implementation and validation for each benchmark system are available in [4], and a brief summary of the validation activities is outlined as follows.

A. Benchmark 1: 3MIB System

Generators 1 and 2 are salient pole units, while generator 3 has a round rotor. Each generator is equipped with a static excitation system and a rotor speed-based PSS, represented by the simplified ST1A and PSS1A models, respectively. The two loads are represented by a combination of constant impedance and constant power static models.

The 3MIB model was implemented on the software PSS/E [20] and PacDyn/ANATEM [21], [22]. For the time-domain validation, the simulated disturbances were: (a) a $+2\%$ step applied to V_{ref} of all generators at $t = 1$ s; (b) connection (at $t = 1\,\mathrm{s}$) of a 50 MVAr reactor to bus 5, removing it at $t = 1.1\,\mathrm{s}$. Sample results from the simulations in the two softwares are compared in Figs. 7 and 8, showing a good matching and validating the benchmark system.

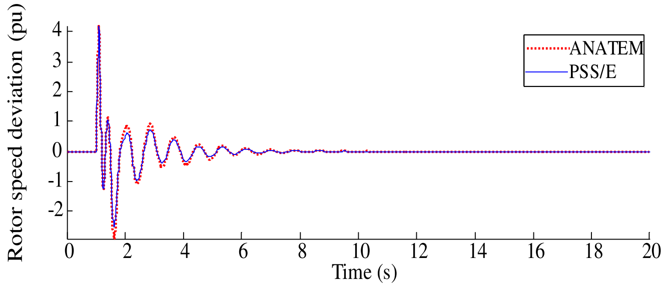

Fig. 8. 3MIB system: Simulation results for case (a). Results for generator 1 (With PSS on all generators).

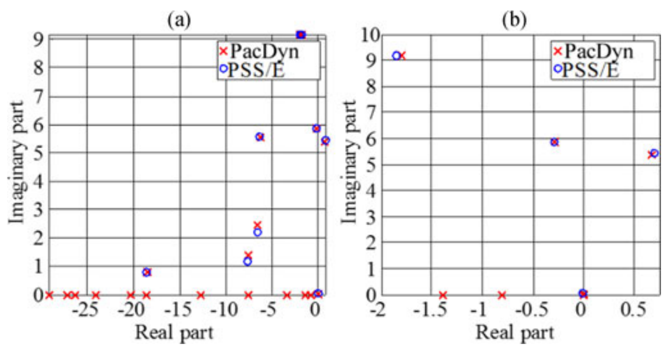

Fig. 9. 7-bus system eigenvalues: (a) Complete set without PSSs; (b) enlarged view in the region of electromechanical modes.

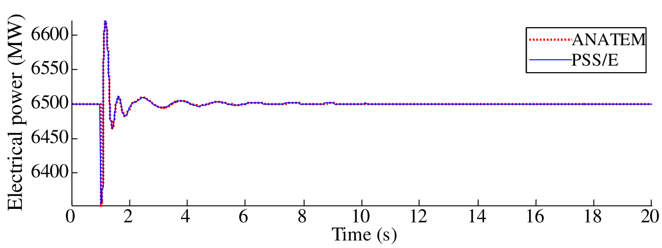

Fig. 10. 7-bus system: Simulation results for case (a). Results for generator 4 (With PSS on all generators, except generator 7).

B. Benchmark 2: 7-Bus System

In this system, all the generators are salient pole units, and except for generator 7 (which is an area equivalent), have a static excitation system ST1A and a PSS1A stabilizer. The loads have a constant current characteristic for the active part and constant admittance for the reactive part.

This system model was implemented on PSS/E and PacDyn/ANATEM. The simulated perturbations were: (a) a $+2\%$ step in $V_{\rm ref}$ of generator 4 (Itaipu) at $t = 1$ s; (b) connection (at $t = 1$ s) and removal (at $t = 10.1$) s of a 500 MVAr reactor to bus 6. Both disturbances excite an inter-area mode of 0.85 Hz, which is unstable without PSSs. Sample results of simulations from the two softwares are pictured in Figs. 9 and 10, showing a good matching and validating the benchmark system.

C. Benchmark 3: 4-Generator System

In this system, all the generators are round rotor units represented by the sixth order IEEE 2.2 model. Each generator is equipped with a slow DC excitation system (DC1A) and PSS (PSS1A). The loads have a constant current characteristic for active power and a constant admittance characteristic for reactive power.

TABLE II
4-Generator System: Comparison of Eigenvalues

Mode type	PSS/E	PacDyn
Local mode-Area 1 $(\mathrm{G1} \times \mathrm{G2})$	$-0.656 \pm \mathrm{j}7.09$	$-0.639 \pm \mathrm{j}7.08$
Local mode-Area 2 $(\mathrm{G3} \times \mathrm{G4})$	$-0.660 \pm \mathrm{j}7.29$	$-0.639 \pm \mathrm{j}7.28$
Inter-area mode-$((\mathrm{G1}+\mathrm{G2}) \times (\mathrm{G3}+\mathrm{G4}))$	$0.006 \pm \mathrm{j}3.84$	$0.022 \pm \mathrm{j}3.82$

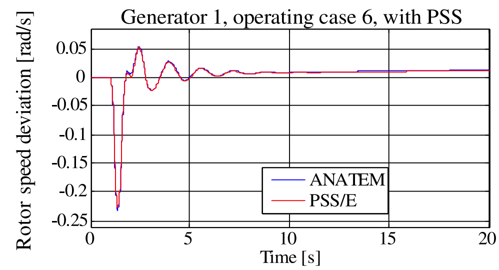

Fig. 11. 4-generator system: Some simulation results.

This system has been implemented and validated on PSS/E and PacDyn/ANATEM for the six operating conditions taken from [1]. The comparisons of the electromechanical modes for operating case 5 are shown in Table II. The eigenvalues calculated by PacDyn are considered herein as references because the software carries out an analytically-based linearization procedure and produces results that match closely those from other software for other benchmark systems. Therefore, the mismatch observed particularly in the real parts of the eigenvalues in Table II might be attributed to the perturbation method used by the PSS/E subpackage LSYSAN, which was utilized here for eigenvalue calculation.

With respect to the non-linear time-domain simulations, the disturbances applied in all the operating cases correspond to simultaneous changes in $V_{\rm ref}$ of all the generators at $t = 1$ s. The changes are $+3\%$ for G1, –1% for G2, –3% for G3 and $+1\%$ for G4, and all $V_{\rm ref}$ set-points return to their original values at $t = 1.1$ s. These perturbations have been selected as they excite all the electromechanical modes in the system. The results for one of the generators (generator G1) for one of the operating cases (case 6) are shown in Fig. 11. The time-domain simulation results exhibit nearly perfect match for the two software packages, and it is concluded that the 4-generator benchmark system has been validated.

D. Benchmark 4: 39-Bus System

The Task Force has made a choice to adopt the original generation data for this system, as given in [12] and [13]. Hence, all of its generators are represented by the fourth order IEEE 2.0 model (each generator is a round rotor type unit). Each generator has a static excitation system (simplified ST1A) and a PSS (simplified PSS1A). All the loads are of constant impedance type.

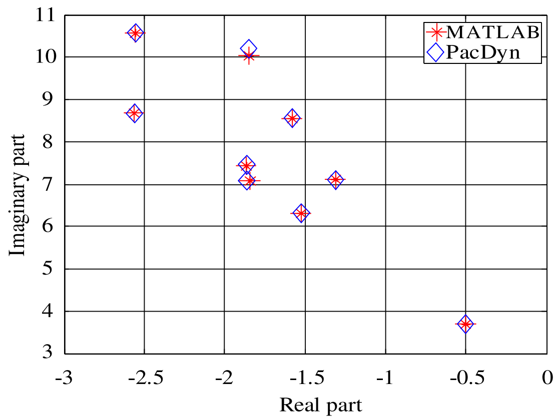

Fig. 12. 39-bus system: Electromechanical modes (with PSS).

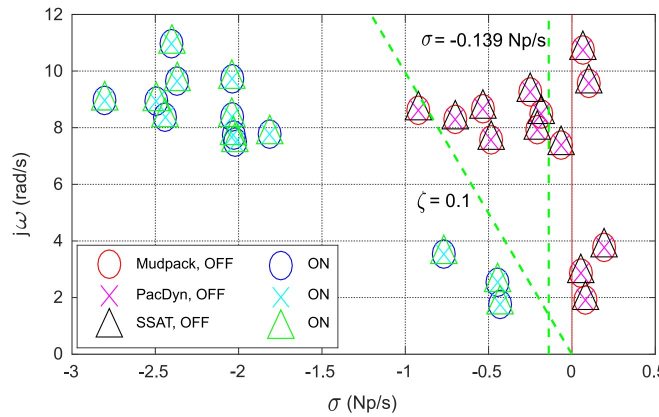

Fig. 13. 14-generator system, case 2: Comparison of electromechanical modes with PSSs in- (on) and out-of-service (off).

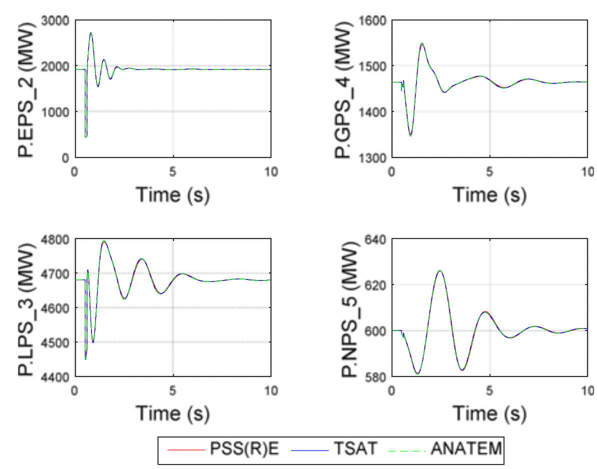

Fig. 14. 14-generator system, case 2: Comparison of generator power outputs with two-phase to ground fault applied to bus 209.

This system model was implemented on MATLAB [23], PacDyn and EMTP-RV [24]. Time domain simulations (available in [4]) were performed only on EMTP-RV (other software such as PSS/E or ANATEM did not have a built-in IEEE 2.0 model) and, hence, cannot be used for validation (as results from at least two packages are required). Exceptionally, eigenvalue analyses from MATLAB and PacDyn were chosen for validation. The nine electromechanical modes of this system are displayed in Fig. 12.

It can be observed that the two packages exhibit very good matching. The 39-bus system is validated as a strong matching is obtained for the rest of the eigenvalues of the system as well.

E. Benchmark 5: 14-Generator System

The generators are represented using the "Classical Parameter Model" as described in Section 4.2.13 of [14]. The salient-pole generators HPS1 and YPS3 are represented with two *d*-axis and one *q*-axis rotor winding and all others are round-rotor machines represented with two rotor windings in each axis. Generators EPS2, YPS3 and NPS5 have AC1A excitation systems. The rest of the generators has ST1A excitation systems. All generators are equipped with a PSS1A. All the loads are of constant impedance type.

The system model was implemented and validated on MudPack [25], PSS/E, SSAT/TSAT [26] and PacDyn/ANATEM. As an example, Fig. 13 compares, for Case 2, the electromechanical modes with the PSSs in- and out-of-service obtained with Mudpack, PacDyn and SSAT. This reveals the significant left shift of the electromechanical modes due to the PSSs and the very close agreement between the three eigenanalysis packages. A range of time-domain simulations was conducted with the above software packages and close agreement between them has also been observed. Whenever there were differences, they could undoubtedly be attributed to specific differences in the modeling of some devices. One such comparison is shown in Fig. 14.

The 14-generator benchmark system is considered validated as the results of the six software showed very good matching.

F. Benchmark 6: 68-Bus System

In this system, all the generators are of round rotor type (represented by the sixth order IEEE 2.2 model). All generators have DC excitation systems (DC4B), except for generator 9 which has a static excitation system ST1A. Generators 1 to 12 are also equipped with PSSs (simplified PSS1A with three lead-lag stages). All the loads are of constant impedance type.

This system has been implemented and validated on MATLAB [27] and PacDyn. For the two cases simulated, in case (a) a step of 2% in V_{ref} is applied to the AVR of generator 3 at $\mathrm{t} = 1\,\mathrm{s}$, and –2% at $\mathrm{t} = 11\,\mathrm{s}$, while in case (b) a 50 MVAr reactor is added to bus 3 at $\mathrm{t} = 1\,\mathrm{s}$, and removed at $\mathrm{t} = 11\,\mathrm{s}$. Both disturbances excite the inter-area modes. Some results are shown for eigenvalue analysis and the nonlinear simulations in Figs. 15 and 16, respectively. The 68-bus benchmark system has been validated as it shows very high degree of matching in the results for the two software packages.

V. Summary

Six multi-machine systems were selected from the literature and recommended as benchmarks to allow comparison and validation of new methods for the analysis and control of small-signal dynamics in power systems. These benchmark systems have been described in the associated Task Force report "Benchmark Systems for Small-Signal Stability and Control"

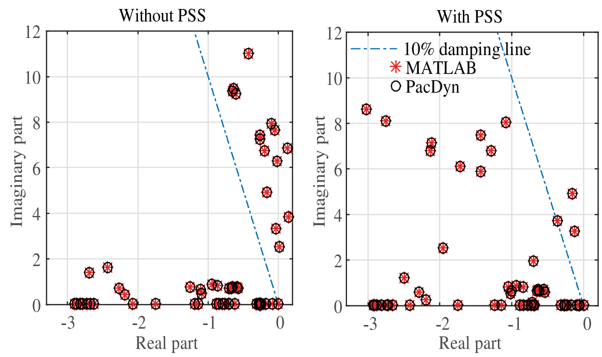

Fig. 15. 68-bus system: Plots of eigenvalues.

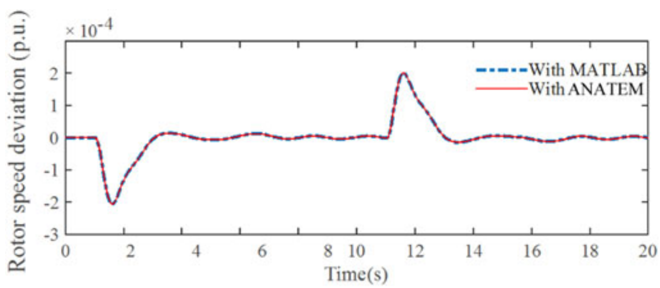

Fig. 16. 68-bus system: Nonlinear time-domain simulation results.

and their full dynamic data and ample simulation results made available at resourcecenter.ieee-pes.org/pes/product/technical-reports/PESTR18. Details on the structure, research challenge involved, control methodology, implementation and validation for each benchmark system can be found in the report. Also, files with data and simulation results can be downloaded from ewh.ieee.org/soc/pes/psdpc/PSDP_benchmark_systems.htm.

This paper provides a summary of the TF guidelines for ensuring adherence to minimum quality standards in future research in small-signal stability analysis and control. The proposed benchmarks may lead to the creation of other test systems for use in future research on power systems facing high penetration of intermittent generation or damping control alternatives derived from remote PMU signals, for example. An important by-product of this TF was to ascertain that the several softwares utilized produced equivalent dynamic simulation results for the benchmark systems. The consistent matching of results helped increase the confidence in power system simulation tools for dynamic and control studies.

Eventual updates and corrections to the TF documents and files might be made wherever necessary according to the feedback received from the users of the benchmark systems, and under the responsibility of the Working Group (WG) on Dynamic Security Assessment of the Power System Dynamic Performance Committee. Additional contributions and analyses regarding the modeling and the application of these benchmark systems are welcome by this WG.

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