COMPARATIVE ANALYSIS AND NUMERICAL VALIDATION OF INDUSTRIAL-GRADE POWER SYSTEM SIMULATION TOOLS: APPLICATION TO SMALL-SIGNAL STABILITY

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Abstract — Several industrial-grade power system simulation tools are commercially available on the market. They are expensive to acquire and time-consuming to learn. As a result, very few institutions (utilities, academic/research organizations) can afford to use more than one power system simulation tool. The tools employ slightly different component models, analytical algorithms, and numerical approaches; therefore for the same benchmark electrical network, different tools can give different numerical results.

This paper presents the experience gained in comparing a number of industrial-grade power system simulation tools. We carried out an eigenvalue analysis of the two-area four-generator system using PSS/E, DIgSILENT, EUROSTAG and Power System Toolbox (PST). We validated the results using time domain simulations. Some of the features used for comparison are 1) modelling adequacy, 2) linearisation method used by the software's solver, 3) capability of accessing system matrices, and 4) data exchange flexibility and capability.

Keywords: Eigenvalue Analysis, simulation tools, software comparison, numerical validation

1 INTRODUCTION

In large-scale transmission networks and power systems, it is difficult to perform field experiments. To investigate power system stability we rely increasingly on the new multidisciplinary, computational approach and on simulation tools. The tools play a critical role in decision-making: planning and real-time operation. Electric power systems are expected to be highly reliable. Therefore, the simulation tools should accurately and reliably replicate the real-life systems. The quality of a simulation depends mainly on (i) system components modelling, (ii) solution methodology, and (iii) system input data.

Due to the differences in components modelling and solution methodology, for the same investigated power system, different simulation tools could give different results. Understanding why the solutions differ is not a trivial issue. At present there are no industry-accepted standards for comparing the power system simulation tools available on the market. The power system engineering literature, in this domain, is scarce. We consider that there is a need to develop expertise in power system software comparison.

In this paper we focus on small-signal stability using the well known two-area benchmark system [1]. We compare the results obtained with the following industrial-grade simulation tools: (i) PSS/E, (ii) DIgSILENT, (iii) EUROSTAG and (iv) PST. We analyze some features of the tools that could explain the differences between numerical results. In addition to frequency-domain and linear analysis, we use the PSCAD time-domain and non-linear analysis software for validating our results.

For software comparison, we have used the following features:

(i) **Model availability:** generators, transmission lines, and loads.
(ii) **Solution methodology:** Linearisation and eigenvalue calculation methods.
(iii) **Software flexibility:** Data input/output.

In order to reduce the complexity of the task and the amount of data, we focused mainly on generator modeling and solution methodologies. We will continue to incorporate in our study other devices and controller models (e.g. excitation system, governor).

The paper is organized as follows. In section 2, we discuss components modelling; section 3, solution methodology; section 4, software flexibility. In section 5, we describe the case study and discuss the simulation results. In section 6, we present the conclusions.

2 COMPONENTS MODELLING

2.1 Synchronous generator

We investigated the following aspects related to the generator model.

2.1.1 Equivalent circuit

In power system dynamic studies, the synchronous generator is commonly represented using the *dq*-axes. The generator is represented using models of varying degrees of complexity the simplest being the classical (2^{nd} order) model that assumes a constant voltage behind transient reactance. The sixth order model has been found adequate for representation of round rotor generators in stability studies [2]. This model has four rotor circuits: a field winding, a damper winding on the *d*-axis, and two damper windings on the *q*-axis. Salient pole generators are represented using a similar model but with only one damper winding on the *q*-axis (5^{th} order).

The 6^{th} order generator model is included in all investigated tools. In Table 1 we present the complete picture of the software capabilities with respect to generator models.

2.1.2 Stator voltage equations

Based on the dq-axis machine representation, the per unit (pu) stator terminal voltage, E_t is given by equation (1).

$$\left.\begin{aligned} \widetilde{E}_t &= e_d + je_q \\ e_d &= \frac{d\psi_d}{dt} - \omega_r\psi_q - R_a i_d \\ e_q &= \frac{d\psi_q}{dt} + \omega_r\psi_d - R_a i_q \end{aligned}\right\} \qquad (1)$$

where

ω_r – rotor angular velocity

Ψ_d, Ψ_q - d-, q-axis flux linkage

i_d, i_q - d-, q-axis armature winding current

R_a - armature resistance

In [1], it is shown that both the stator transients ($d\Psi/dt$) and effect of speed variations on stator voltages should either be included or neglected ($\omega_r = 1.0$ pu). In [3] the authors show that if the stator transients are neglected, while the effects of speed variations are included, complex eigenvalues shift to the right.

All the investigated tools consider the effect of speed variations, but neglect the stator transients.

2.1.3 Representation of mechanical input

If the turbine/governor set is not modelled, the generator mechanical torque input, T_m is assumed to be constant. If a generator is modelled with mechanical power input P_m, and rotor speed variations are ignored ($\omega_n/\omega_r = 1$), then $T_m = P_m$ pu. However, if P_m input is chosen and rotor speed variations are taken into consideration, $T_m \neq P_m$ pu. The variation of T_m with machine speed is given by equation (2); the assumption, T_m is constant does not hold.

$$T_m = \frac{\omega_n}{\omega_r} P_m \qquad (2)$$

where ω_n and ω_r are the synchronous speed and rotor angular speed respectively.

Generator models with P_m input give results that exhibit better damping than models that use T_m [3], [4].

PSS/E, DIgSILENT and PST generator models have P_m input and the rotor speed variations are considered, whereas EUROSTAG and PSCAD models use T_m as input.

2.1.4 Rotor angle reference

If the system matrix is defined in terms of absolute rotor speed and angle deviations, one or two zero eigenvalues result if the system has no infinite bus model. One of the zero eigenvalues appears due to lack of uniqueness of absolute rotor angles. The second zero eigenvalue appears if all generator torques are assumed to be independent of speed deviations [1], [5], [6]. To eliminate the zero eigenvalues, one of the generators can be chosen as a reference and the angle and speed deviations of all the other machines are measured with respect to the reference. The relative values become the new state variables replacing the absolute ones.

In EUROSTAG, the rotor angle reference is a virtual centre of inertia that rotates at an angular speed ω_{coi} given by equation (3) [7]. The user may also choose a reference rotating at the network nominal frequency ω_n.

$$\omega_{coi} = \frac{1}{M_T}\sum_{j=1}^{n} M_j\omega_j \qquad (3)$$

where $M_j = H_j S_{Nj}$ and $M_T = \sum_{j=1}^{n} M_j$

n : number of generators

H_j : generator j's inertia constant

S_{Nj} : generator j's apparent power rating

In PSS/E and PSCAD the reference rotates at nominal frequency ω_n. In DIgSILENT, the program automatically chooses one of the generators (ω_j) to be the reference. In PST the user may choose one of the generators as reference.

2.1.5 Magnetic saturation

The calculated initial values of flux linkages and field voltages are affected by the modeling of machine saturation [8]. Saturation may be assumed to affect either (i) d-axis only or (ii) d-axis and q-axis. In [9] it is illustrated that the method of saturation modelling may be an important factor in the determination of system damping performance.

EUROSTAG allows saturation characteristics to be modelled either on d-axis only or on d-axis and q-axis. In PSS/E and DIgSILENT both d- and q-axis parameters are assumed to be saturated. In PSCAD and PST, saturation is assumed to be on the d-axis only.

In PSS/E, DIgSILENT, and PST the user specifies two saturation parameters $S_{1.0}$ and $S_{1.2}$ corresponding to 1.0 and 1.2 pu terminal voltage (flux linkage) respectively. These saturation parameters are determined from the open circuit characteristic (OCC) curve of the generator as described in [10].

The saturation characteristics may be represented using several functions e.g. two-piece linear, exponential, quadratic. The choice of function has little effect on the accuracy of the model [9]. In PSS/E, the user may choose a generator model with quadratic or exponential function.

In EUROSTAG, saturation parameters are defined as m and n calculated from $S_{1.0}$ and $S_{1.2}$ (4).

$$m = S_{1.0} \text{ and } n = \frac{\ln\left(\frac{S_{1.2}}{S_{1.0}}\right)}{\ln(1.2)} \qquad (4)$$

In PSCAD the OCC curve is defined through ten user defined points.

2.2 Transmission line

All the tools under investigation use a nominal π model of transmission line. PSS/E and PSCAD in addition have an equivalent π model.

2.3 Load

Load models are broadly classified as static and dynamic. In our study, we used the static load model and thus we limit our discussion to this model.

The static load at a bus may be modelled by either an exponential function (5) or polynomial function (6) also known as *ZIP* model [1]. These models account for both voltage and frequency dependency of loads.

$$\left.\begin{aligned} P &= P_0(\overline{V})^a(1+K_{pf}\Delta f) \\ Q &= Q_0(\overline{V})^b(1+K_{qf}\Delta f) \end{aligned}\right\} \tag{5}$$

$$\left.\begin{aligned} P &= P_0[p_1\overline{V}^2 + p_2\overline{V} + p_3](1+K_{pf}\Delta f) \\ Q &= Q_0[q_1\overline{V}^2 + q_2\overline{V} + q_3](1+K_{qf}\Delta f) \end{aligned}\right\} \tag{6}$$

$$\overline{V} = V/V_0 \quad \text{and} \quad \Delta f = f - f_0$$

where:

- P, Q - active, reactive components of load corresponding to bus voltage magnitude V. Subscript $_0$ denotes the initial values of the respective variables.
- f - bus voltage frequency
- K_{pf}, K_{qf} - active power, reactive power frequency dependency.

The parameters of the exponential function are a and b. If these parameters are equal to 0, 1, or 2, the model represents constant power, constant current or constant impedance characteristics respectively.

The coefficients p_1, p_2 and p_3 (q_1, q_2 and q_3) in the *ZIP* model define the proportion of constant impedance (*Z*), constant current (*I*) and constant power (*P*) components respectively.

All the tools except PST can model the frequency dependency of loads. The static load models available in each tool are given in Table 1.

3 SOLUTION METHODOLOGY

3.1 Linearisation of system equations

In PSS/E, the linearisation of the system equations is numerical [8]. The program starts from an equilibrium point with state vector $\boldsymbol{x_0}$ i.e. the derivative $\dot{x}_0 = 0$. A vector $\boldsymbol{x_j}$ in which all the elements except the j^{th} one are equal to those of $\boldsymbol{x_0}$ is evaluated. The j^{th} element differs from the corresponding value in $\boldsymbol{x_0}$ by Δx_j. If Δx_j is sufficiently small, the j^{th} column of $\boldsymbol{A}$ matrix, A_j is estimated from:

$$\dot{x}_j - \dot{x}_0 = \dot{x}_j = A_j \Delta x_j \tag{7}$$

$\dot{x}_j$ is evaluated from the system of non-linear differential algebraic equations (DAE). By sequentially perturbing all the elements of $\boldsymbol{x_0}$, the columns of $\boldsymbol{A}$ are calculated using (7).

The user has to specify the perturbation size Δx_j. Its value affects the $\boldsymbol{A}$ matrix and hence the eigenvalues. The perturbation size Δx_j should be small enough to ensure correct linear approximation but it should not be too small to cause a null column in $\boldsymbol{A}$. A typical value of Δx_j is 0.0001.

Once a perturbation has been applied to a given state variable, the network solution has to be re-converged prior to calculating the state variable derivatives. The value of network solution tolerance affects the $\boldsymbol{A}$ matrix.

PST uses a similar linearisation procedure as in PSS/E. The differences between the two tools are: (i) PSS/E user chooses perturbation size Δx_j; PST user does not choose the perturbation size. (ii) In PSS/E Δx_j is fixed; PST chooses Δx_j to be the greater of 0.0001 and (0.001*state variable) [12].

We did not have information on the linearisation methods used in DIgSILENT and EUROSTAG.

3.2 Calculation of eigenvalues

The eigenvalues of the $\boldsymbol{A}$ matrix are calculated using the QR method in all the simulation tools.

4 SOFTWARE FLEXIBILITY

4.1 Data Input

PSS/E, DIgSILENT, EUROSTAG and PSCAD have graphical user interface. Through this interface, the user can draw the system one-line diagram (or three phase in PSCAD) and populate the system with data using the pop-up windows.

In PSS/E, the user can also introduce data in text format. The program reads load flow data separately from the dynamic data. These are given as two distinct raw data files. In PST, data can be introduced only in text format.

4.2 Data output

PSS/E and PST results are eigenvalues, frequency of the oscillatory modes and the damping ratio. DIgSILENT and EUROSTAG do not give the values of frequency and damping ratio.

Accessibility to the system matrices is important for controller design and parameter setting purposes e.g. design of PSS and AVR. The $\boldsymbol{B}$ and $\boldsymbol{C}$ matrices are of interest in the formulation of the mode controllability and observability matrices. PSS/E and PST allow the user access to all four system matrices, EUROSTAG only allows $\boldsymbol{A}$ matrix. DIgSILENT does not allow access to any of the matrices.

The eigenvectors and participation factors are important for placement of power system support devices.

PSS/E gives the normalised complex right eigenvectors from which the user can deduce local area and interarea electromechanical modes of oscillation. The program also gives the normalised participation factors for all the system modes.

PST gives both the left and right eigenvectors and normalised complex participation factors.

DIgSILENT gives the normalised complex participation factors but only for the machine state variables i.e. does not include controllers and other devices state variables. In addition to the numerical values, the program gives a graphical representation of the participation factors. Users can easily deduce local area and inter-area electromechanical modes of oscillations from the graphical representation.

EUROSTAG does not give eigenvectors and participation factors. Users have to use other programs to determine the electromechanical modes of oscillations.

Table 1 summarises the comparison of simulation tools.

		Standard PSS/E	DIgSILENT	EUROSTAG	PST	PSCAD
Components models	Generator models	2nd, 3rd, 5th, 6th	5th, 6th	3rd, 5th, 6th	2nd, 4th, 6th	5th, 6th
	Generator saturation parameters	$S_{1.0}$, $S_{1.2}$	$S_{1.0}$, $S_{1.2}$	n, m	$S_{1.0}$, $S_{1.2}$	Specify points on OC curve
	Generator mechanical input	P_m	P_m	T_m	P_m	T_m
	Rotor angle reference angular speed	ω_n	ω_j	ω_{coi} or ω_n	ω_j	ω_n
	Transmission line	Nominal π and equivalent π	Nominal π	Nominal π	Nominal π	Nominal π and equivalent π
	Load models	Exponential and *ZIP*	Exponential	Exponential	*ZIP* - voltage dependent only	Exponential
Solution methodology	Linearisation of system equations	Numerical differentiation	Information not available	Information not available	Numerical differentiation	N/A
	Perturbation size	User specified	Information not available	Information not available	Chosen by program	N/A
	Eigenvalue calculation method	QR	QR	QR	QR	N/A
Software flexibility	Data input	Graphical user interface with pop-up windows or text	Graphical user interface with pop-up windows	Graphical user interface with pop-up windows	Text	Graphical user interface with pop-up windows
	Accessibility of system matrices	A, B, C, D matrices available	Not available	A matrix only	A, B, C, D matrices available	N/A
	Eigenvectors	Right only	Not available	Not available	Right and left	N/A
	Participation factors	Available	Available	Not available	Available	N/A

Table 1: Summary of software comparison

5 CASE STUDY – TWO AREA SYSTEM

5.1 Two area system

We used the two-area power system as shown in figure 1 [1] for the case study. The system consists of two similar areas, connected by a weak tie line. Each area has two generators, G1 and G2 in area 1, and G3 and G4 in area 2.

For all four generators we used the sixth order generator model. The governor and excitation system are not included in this study. We computed the machine saturation parameters $S_{1.0}$ and $S_{1.2}$, and the points on the saturation curve as described in [10].

We represented all the transmission lines using nominal π models and the loads using static models. The active components of the loads are modelled as constant current; the reactive components as constant impedance.

The system data are given in the appendix.

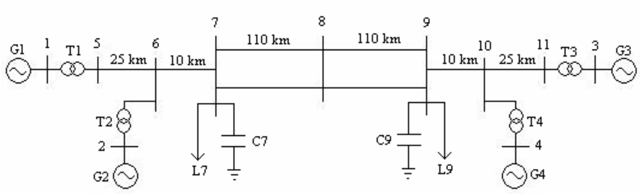

Fig.1: Two-area system

We performed frequency-domain analysis using the following programs: (i) PSS/E, (ii) DIgSILENT, (iii) EUROSTAG, (iv) PST; similar results presented in [1] were used for comparison.

To validate the eigenvalue analysis results, we performed time domain simulations using PSCAD. We simulated a small disturbance in the system by applying a three-phase short circuit fault at bus 7 for 5 ms [13].

5.2 Small-signal stability simulation

5.2.1 Eigenvalue analysis results

The results of the eigenvalue analysis using PSS/E, DIgSILENT, EUROSTAG and PST are shown in table 2. The results given in [1] are also included for comparison purposes. The first three oscillatory pairs represent: (i) area 1 local mode, (ii) area 2 local mode, and (iii) inter-area mode respectively.

PSS/E	DIgSILENT	EUROSTAG	PST	Ref [1]
-0.613 ± j6.76 (ζ = 0.090; f = 1.075 Hz)	-0.626 ± j6.67 (ζ = 0.093; f = 1.062 Hz)	-0.558 ± j6.58 (ζ = 0.085; f = 1.047 Hz)	-0.581 ± j6.79 (ζ = 0.085; f = 1.080 Hz)	-0.492 ± j6.82 (ζ = 0.072; f = 1.087 Hz)
-0.631 ± j6.94 (ζ = 0.090; f = 1.105 Hz)	-0.636 ± j6.90 (ζ = 0.092; f = 1.097 Hz)	-0.570 ± j6.77 (ζ = 0.084; f = 1.077 Hz)	-0.589 ± j6.98 (ζ = 0.084; f = 1.111 Hz)	-0.506 ± j7.02 (ζ = 0.072; f = 1.117 Hz)
-0.155 ± j3.41 (ζ = 0.045; f = 0.543 Hz)	-0.140 ± j3.41 (ζ = 0.041; f = 0.542 Hz)	-0.115 ± j3.42 (ζ = 0.034; f = 0.544 Hz)	-0.123 ± j3.42 (ζ = 0.036; f = 0.544 Hz)	-0.111 ± j3.43 (ζ = 0.032; f = 0.545 Hz)
+0.187 ± j0.163 (ζ = -0.754; f = 0.026 Hz)		-0.0998 ± j0.030 (ζ = 0.957; f = 0.005 Hz)	-0.075 ± j0.020 (ζ = 0.965; f = 0.003 Hz)	-37.89 ± j0.142 (ζ = 1.000; f = 0.023 Hz)
-0.149 ± j0.067 (ζ = 0.912; f = 0.011 Hz)	-37.34 -37.28			-38.01 ± j0.038 (ζ = 1.000; f = 0.006 Hz)
	-35.15	-37.10	-37.23	
	-34.35	-37.01	-37.15	-0.00076 ± j0.0022 (ζ = 0.331; f = 0.0003 Hz)
-37.17	-33.11	-34.61	-36.19	
-37.08	-32.99	-33.13	-36.03	
-35.85	-26.89	-31.37	-34.80	-35.53
-35.67	-25.66	-31.20	-33.41	-34.07
-34.70	-5.582	-24.22	-30.39	-32.45
-33.33	-5.546	-22.35	-28.89	-31.03
-29.94	-4.254	-5.992	-4.697	-5.303
-28.45	-3.523	-5.964	-4.656	-5.287
-5.190	-0.396	-4.706	-3.280	-4.139
-5.183	-0.226	-3.812	-2.362	-3.428
-3.860	-0.219	-0.218	-0.231	-0.276
-2.967	-0.069	-0.204	-0.214	-0.265
-0.572	-0.031	-0.026	-0.019	-0.117
-0.233	0	0	+0.027	-0.096

Table 2: Eigenvalues for the two-area system

Generally, the eigenvalue analysis results obtained using the various tools agree well amongst themselves and with those in [1]. However, some differences in results are observed, arising due to the variations in the modelling and solution methodology used by the tools. Factors that may have caused the variation of the results from those given in [1] include: (i) Stator transients: Reference [1] considers them; investigated programs ignore them. (ii) Saturation: Reference [1] considers incremental saturation; investigated programs consider total saturation.

In DIgSILENT and EUROSTAG one of the eigenvalues is zero. The zero eigenvalue may be due to the use of absolute deviations of rotor speed and angle as state variables in the formation of system matrices [1][5]. In PST and PSS/E, the zero eigenvalues are not computed exactly and the eigenvalues have a positive real part. This may be associated with round-off errors in calculation of the state matrix and mismatches in the load flow solution. Time domain simulations of the system using PST and PSS/E confirmed the system is stable. A similarity transformation of the system matrix as described in [5] also confirmed the stability of the system.

The oscillatory electromechanical modes obtained using PSS/E, DIgSILENT and PST are better damped than in EUROSTAG. This may be attributed to the choice of generator mechanical input as discussed in section 2.1.3.

Results obtained using PST have lower damping than those obtained using PSS/E and DIgSILENT. This may be due to differences in the modelling of generator magnetic saturation: in PST, saturation is modelled on the *d*-axis only while in PSS/E and DIgSILENT saturation is modelled on both *d* and *q* axes.

The difference between PSS/E and PST, with regard to linearisation, consists in the choice of the perturbation size. In PST, the perturbation size may vary depending on the value of the perturbed state variable as described in section 3.2. In PSS/E the perturbation size is fixed at the user specified value. It is difficult to deduce that it is the choice of the perturbation size that affects the results because there are other modeling differences between the two programs.

We do not know what the linearisation methods used in DIgSILENT and EUROSTAG are. We are therefore unable to compare the results comprehensively in terms of differences in linearisation methods among the tools.

We imported in MATLAB, from PSS/E and EUROSTAG, the **A** matrices and recalculated the eigenvalues; the results closely match those obtained directly from the two industrial-grade tools. PST uses the MATLAB solver for eigenvalue calculation. Therefore we conclude that the differences among eigenvalue results are not related to the mathematical routines used in these programs.

Δx_j = 0.0001		
***NST*= 1e-4**	***NST*=1e-5**	***NST* = 1e-7**
-0.617 ± j6.95	-0.587 ± j6.96	-0.631 ± j6.94
-0.605 ± j6.76	-0.610 ± j6.75	-0.613 ± j6.76
-2.488 ± j2.61	-0.177 ± j3.19	-0.155 ± j3.41
-0.620 ± j2.25	-3.096 ± j1.22	+0.187 ± j0.163
-37.20	-37.16	-0.149 ± j0.067
-37.15	-37.09	
-35.80	-35.84	-37.17
-35.56	-35.68	-37.08
-34.91	-34.70	-35.85
-34.03	-33.31	-35.67
-28.81	-29.95	-34.70
-25.78	-28.45	-33.33
-5.889	-5.235	-29.94
-5.170	-5.178	-28.45
-5.143	-3.811	-5.190
-2.170	+2.976	-5.183
+0.325	-0.231	-3.860
-0.241	-0.224	-2.967
-0.223	-0.167	-0.572
-0.171	-0.008	-0.233

Table 3: PSS/E eigenvalue results; effect of varying network solution tolerance (*NST*)

***NST* = 1e-7**		
Δx_j = 0.001	Δx_j = 0.0001	Δx_j =0.00001
-0.625 ± j6.95	-0.631 ± j6.94	-0.684 ± j6.88
-0.613 ± j6.75	-0.613 ± j6.76	-0.577 ± j6.82
-0.152 ± j3.42	-0.155 ± j3.41	-0.140 ± j3.46
+0.051 ± j0.172	+0.187 ± j0.163	-0.067 ± j0.113
-37.16	-0.149 ± j0.067	-0.233 ± j0.020
-37.08		
-35.86	-37.17	-37.11
-35.67	-37.08	-37.06
-34.72	-35.85	-35.84
-33.33	-35.67	-35.65
-29.94	-34.70	-34.69
-28.47	-33.33	-33.37
-5.210	-29.94	-30.03
-5.178	-28.45	-28.54
-3.862	-5.190	-5.182
-2.985	-5.183	-5.074
-0.346	-3.860	-3.890
-0.230	-2.967	-3.021
-0.214	-0.572	-1.409
-0.037	-0.233	+1.195

Table 4: PSS/E eigenvalue results; effect of varying perturbation size (Δx_j)

Table 3 shows the effect of varying network solution tolerance (*NST)* with Δx_j constant in PSS/E. As *NST* is changed, there is no consistency in eigenvalues change. *NST* should be reduced until there is no significant change in the eigenvalues for a given value of Δx_j.

Table 4 shows the effect of varying Δx_j for a fixed *NST* in PSS/E. We observe slight differences between the results obtained with Δx_j = 0.0001 and 0.001. When Δx_j is reduced to 0.00001, the eigenvalues obtained deviate from those obtained with larger values of Δx_j. We consider that such eigenvalue results indicate a numerical instability related to the choice of a too small perturbation step as discussed in section 3.1.

5.2.2 Time domain results

PSCAD simulation results are shown in figure 2 and figure 3. In figure 2 it is observed that all the system generators swing together after the disturbance. Thus the system is stable as deduced from the eigenvalues.

The applied disturbance excites area 1 local mode and the interarea mode. Area 1 mode dies out before the inter-area mode. This observation agrees with the eigenvalue analysis results, which show this local mode has a higher damping factor than the interarea mode.

Figure 2 and figure 3 show the inter-area mode oscillates with a period T12 = 1.85 s (damped natural frequency = 0.541 Hz). From the eigenvalue analysis results obtained using different tools, the oscillation frequency for this mode ranges between 0.542 Hz and 0.544 Hz (table 2 un-shaded boxes). Area 1 local mode shown in figure 2 has a period T1 = 0.95 s (frequency of oscillation = 1.053 Hz). This value compares reasonably well with the eigenvalue analysis results, which ranges between 1.047 Hz and 1.080 Hz (table 2 shaded boxes).

PSCAD results confirm, in time-domain, the stability of the power system; these results are consistent to the results obtained, in frequency-domain, with the other four industrial-grade simulation tools.

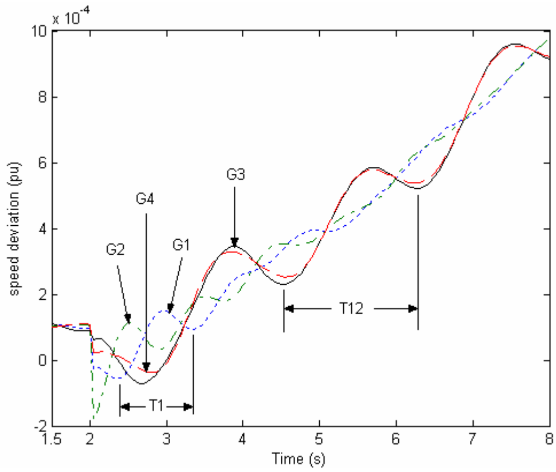

Fig. 2: Generators speed deviation

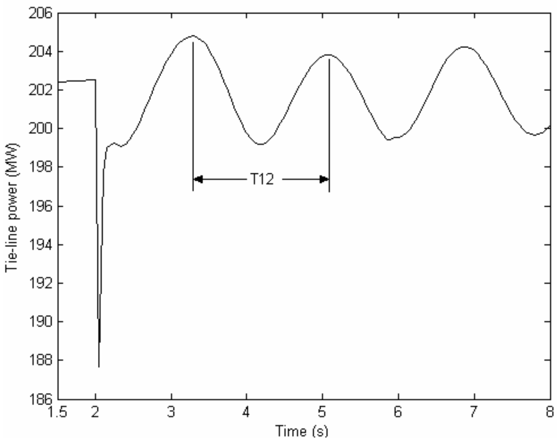

Fig. 3: Tie-line power flow

6 CONCLUSIONS

In this paper we have compared four industrial-grade power system simulation tools. The following modeling features of the programs have been highlighted as possible causes of variations in eigenvalue results:

- ♦ Representation of stator terminal voltage
- ♦ Saturation modelling; incremental or total saturation factors, *d*-axis only or *d* and *q* axes saturation effects
- ♦ Representation of generator mechanical input - P_m or T_m

Further investigation of the effect of fixed and variable perturbation size used in PSS/E and PST is necessary.

Additional information related to the linearisation methods and algorithmic approaches are necessary for more in-depth comparative analysis of the analytical tools used in power system simulation for small-signal stability.

Although we used a very small and simplified benchmark power system (without controlling devices), with different industrial-grade and state-of-the-art tools, different results (eigenvalues) were obtained. In a large and more complex system (real-life system) in which the power system components are modelled in details, the variations in results may be more pronounced. It is difficult to deduce from this investigation which modelling approach most accurately represents the behaviour of a real power system. Such a conclusion can only be made after comparing field measurements with the softwares' output results.

This paper presents results of an ongoing project related to comparison and validation of industrial-grade power simulation tools that are used in dynamic security assessment (stability). Further investigations include additional control systems (voltage controllers, stabilizers, governors).

APPENDIX

System data

Generator data

MVA base; 900 MVA, 20 kV, 60 Hz

$X_d = 1.8$	$X'_d = 0.3$	$X''_d = 0.25$	$A_{sat} = 0.015$
$X_q = 1.7$	$X'_q = 0.55$	$X''_q = 0.25$	$B_{sat} = 9.6$
$X_l = 0.2$	$T'_{do} = 8.0$ s	$T''_{do} = 0.03$ s	$\psi_{TI} = 0.9$
$R_a = 0.0025$	$T'_{qo} = 0.4$ s	$T''_{qo} = 0.05$ s	$K_D = 0$

$S_{1.0} = 0.039$ $S_{1.2} = 0.223$

$H = 6.5$ (for G1 and G2) $H = 6.175$ (for G3 and G4)

Air-gap line slope = X_d - X_l

Transmission lines

(***base: 100MVA, 230 kV***)

$r = 0.0001$ *pu/km* $x_L = 0.001$ *pu/km* $b_C = 0.00175$ *pu/km*

Transformers

Rating; 900 MVA, 20/230 kV

$X = j0.15$ pu

Off-nominal ratio = 1.0

Operating condition

G1	P = 700 MW	Q = 185 MVAr	$V_t = 1.03\angle 20.2°$
G2	P = 700 MW	Q = 235 MVAr	$V_t = 1.01\angle 10.5°$
G3	P = 719 MW	Q = 176 MVAr	$V_t = 1.03\angle -6.8°$
G4	P = 700 MW	Q = 202 MVAr	$V_t = 1.01\angle -17.0°$
Bus 7	$P_L = 967$ MW	$Q_L = 100$ MVAr	$Q_C = 200$ MVAr
Bus 9	$P_L = 1767$ MW	$Q_L = 100$ MVAr	$Q_C = 350$ MVAr

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