Comparison of Industrial-Grade Analytical Tools Used in Small-Signal Stability Assessment

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ABSTRACT

There are several analytical tools used for small-signal stability studies commercially available on the market. These tools are time-consuming to master. In most cases the input data cannot be transferred from tool to tool and the user has to learn anew how to introduce them. Hence, most users rely on results obtained with only one tool; these results are seldom validated with field measurements and, in most of the cases, they are not compared with results obtained with similar industrial-grade tools.

The tools differ with regard to: 1) components modelling, 2) numerical methodology; therefore, for the same benchmark network, different tools give different solutions. Understanding why the solutions differ is not a trivial issue. It requires time and a lot of forensic effort to understand the modelling techniques and the algorithms used in each tool.

*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, SSAT (DSA PowerTools), and MatNetEig. Some of the features we compared 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. Our results show that the method of constructing the **A** matrix affects the frequency of oscillation and the turbine model output affects the damping.*

1. INTRODUCTION

The advancement of computer technology has permitted the development of many powerful power system analytical tools. Hence, there are several tools commercially available on the market. However, they are time-consuming to learn and as a result, most users prefer to stick to one tool. The results are neither validated with field measurements nor compared with results obtained using other tools.

From our investigation, it appears that only few studies are comparing the results of analytical tools used in power system modal analysis [1-4]; most of them are limited in scope and in number of investigated tools.

The tools differ in their components modelling and numerical methodology; therefore, for the same benchmark network, different tools give different results.

In this paper, we compare eigenvalue results, obtained with five industrial-grade tools, for a well known two-area benchmark system [5]. We analyse some features of the tools that could explain the differences between numerical results.

For software comparison, we have used the following features:

(i) **Model availability:** generators and loads.
(ii) **Numerical 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 modelling and numerical 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: 2) Components modelling, 3) Numerical methodology, 4) Software flexibility, 5) Case study, 6) Conclusions.

2. COMPONENTS MODELLING

2.1. SYNCHRONOUS GENERATOR

We investigated the following aspects related to the generator model.

2.1.1. ORDER OF COMPLEXITY

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 [6]. 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).

All investigated tools include a 6^{th} order generator model. 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 ($p.u.$) stator terminal voltage, E_t is expressed as

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

where:

e_d, e_q - d- and q-axis components of terminal voltage
Ψ_d, Ψ_q - d- and q-axis components of stator flux linkage
i_d, i_q - d- and q-axis components of stator current
ω_r - rotor angular velocity
R_a - stator resistance

In stability studies, network transients are neglected because they decay very fast. Therefore, for modelling consistency, the terms representing stator transients ($d\Psi/dt$ terms in (1)) are also neglected. In [5], it is shown that both the stator transients and effect of speed variations on stator voltages should either be included or neglected (ω_r = 1.0 $p.u.$).

In [2], the authors show that if the stator transients are neglected and the effect of speed variations on the stator voltage is included, complex eigenvalues shift to the right on the complex plane.

PSS/E, DIgSILENT, and EUROSTAG neglect the stator transients but include the effect of speed variations on stator voltage; SSAT and MatNetEig neglect both effects.

2.1.3. REPRESENTATION OF TURBINE MODEL OUTPUT

From the investigated literature and from vendors' software documentation, it is not clear whether the turbine model output should be mechanical power P_m or mechanical torque T_m. For example, reference [5] recommends T_m output whereas reference [7] recommends P_m output.

If speed variations are neglected (ω_r = 1 $p.u.$), $T_m = P_m$ $p.u.$ The swing equation may be expressed in terms of either torque or power without affecting the eigenvalue results.

However, if the rotor speed variations are taken into consideration ($\omega_r \neq 1$ $p.u.$), $T_m \neq P_m$ $p.$u. The variables T_m and P_m are related as shown in equation (2).

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

The swing equation, expressed in terms of torque, is given in (3). If the turbine model output is P_m, expression (2) for evaluating T_m is substituted in (3). The resultant equation is linearised around the equilibrium point.

$$2H\frac{d\omega_r}{dt} = T_m - T_e - K_D\omega_r \qquad (3)$$

where:

H - inertia constant
T_e - air-gap torque
K_D - damping constant representing friction.

All the tools utilise the linearised form of swing equation (3). In SSAT, the user can choose a swing equation expressed in terms of power.

Turbine models with P_m output and rotor speed variations taken into consideration give results that exhibit better damping than models that use T_m [1],[2].

Turbine models in PSS/E, DIgSILENT, and SSAT have P_m output and the rotor speed variations are considered. EUROSTAG and MatNetEig models have T_m output.

2.2. 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 (4) or polynomial function (5) also known as *ZIP* model [5]. These models account for both voltage and frequency dependency of loads.

$$\left.\begin{aligned} P &= P_0(\overline{V})^a(1+K_{pf}\Delta f) \\ Q &= Q_0(\overline{V})^b(1+K_{qf}\Delta f) \end{aligned}\right\} \qquad (4)$$

$$\left.\begin{aligned} P &= P_0[p_1\overline{V}^2 + p_2\overline{V} + p_3](1+K_{pf}\Delta f) \\ Q &= Q_0[q_1\overline{V}^2 + q_2\overline{V} + q_3](1+K_{qf}\Delta f) \end{aligned}\right\} \qquad (5)$$

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

where:

P, Q - active, reactive components of load corresponding to bus voltage magnitude V
P_0, Q_0 - initial values of active, reactive power
f - frequency
V_0, f_0 - initial values of bus voltage magnitude and 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 MatNetEig can model the frequency dependency of loads. The static load models available in each tool are given in Table 1.

3. NUMERICAL METHODOLOGY

3.1. LINEARISATION OF SYSTEM EQUATIONS

The dynamic behaviour of the power system is expressed through a system of non-linear differential and algebraic equations (DAE) (6). In order to study the system's response to a small disturbance, these equations are linearised (7) in the vicinity of an equilibrium point ($\boldsymbol{x_0}$).

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{f}(\boldsymbol{x},\boldsymbol{u}) \\ \boldsymbol{y} &= \boldsymbol{g}(\boldsymbol{x},\boldsymbol{u}) \end{aligned} \tag{6}$$

$$\begin{aligned} \Delta\dot{\boldsymbol{x}} &= \boldsymbol{A}\Delta\boldsymbol{x}+\boldsymbol{B}\Delta\boldsymbol{u} \\ \Delta\boldsymbol{y} &= \boldsymbol{C}\Delta\boldsymbol{x}+\boldsymbol{D}\Delta\boldsymbol{u} \end{aligned} \tag{7}$$

Where

- $\boldsymbol{x}$ - nx1 vector of state variables
- $\dot{\boldsymbol{x}}$ - derivative of $\boldsymbol{x}$ with respect to time
- $\boldsymbol{f}$ - nx1 vector of non-linear functions
- $\boldsymbol{u}$ - mx1 vector of inputs
- $\boldsymbol{y}$ - px1 vector of outputs
- $\boldsymbol{g}$ - px1 vector of non-linear functions
- Δ - denotes a small deviation
- $\boldsymbol{A}$ - n x n state matrix
- $\boldsymbol{B}$ - n x m input matrix
- $\boldsymbol{C}$ - p x n output matrix
- $\boldsymbol{D}$ - p x m feed-forward matrix

System stability is deduced from the eigenvalues of the $\boldsymbol{A}$ matrix. The elements of the $\boldsymbol{A}$ matrix are partial derivatives evaluated at the equilibrium point $\boldsymbol{x_0}$.

$$A = \begin{pmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{pmatrix}_{x=x_0} \tag{8}$$

The investigated tools use, for constructing the $\boldsymbol{A}$ matrix, the following two methods: (i) numerical differentiation (PSS/E and DIgSILENT), (ii) analytical differentiation (EUROSTAG, SSAT, and MatNetEig).

3.1.1. NUMERICAL DIFFERENTIATION

The elements of $\boldsymbol{x_0}$ are sequentially perturbed by an amount Δx_j. If Δx_j is sufficiently small, the j^{th} column of $\boldsymbol{A}$, A_j can be approximated by (9). This linearisation scheme is defined as a one-sided difference method.

$$A_j = \frac{\partial f(x_0,u_0)}{\partial x_j} = \begin{bmatrix} \frac{\partial f_1}{\partial x_j} \\ \vdots \\ \frac{\partial f_n}{\partial x_j} \end{bmatrix} \approx \frac{f(x_0+\Delta x_j,u_0)-f(x_0,u_0)}{\Delta x_j} \tag{9}$$

To evaluate A_j, equation (6) is recalculated with the new argument $\boldsymbol{x_0+\Delta x_j}$.

The accuracy of (9) depends on the perturbation size Δx_j, and the tolerance to which $\dot{x}_j$ is evaluated.

The central difference scheme (equation 10) [8] improves the results' accuracy.

$$A_j = \frac{\partial f(x_0,u_0)}{\partial x_j} \approx \frac{f(x_0+\Delta x_j,u_0)-f(x_0-\Delta x_j,u_0)}{2\Delta x_j} \tag{10}$$

PSS/E employs the one-sided difference method. The program requires, from the user, to specify the size of the perturbation Δx_j. The magnitude of Δx_j should be small enough to ensure correct linear approximation but it should not be too small to cause a null column in $\boldsymbol{A}$. For our test case, we used the size of the perturbation equal to 10^{-4}.

DIgSILENT employs the central difference scheme. The program automatically defines the size of the perturbation equal to 10^{-3}.

3.1.2. ANALYTICAL DIFFERENTIATION

The elements of the $\boldsymbol{A}$ matrix are obtained by applying standard rules of differentiation on the system equations. The partial derivatives are evaluated at the equilibrium point $\boldsymbol{x_0}$.

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

All the tools have graphical user interface. Through this interface, system data are entered using data-input windows.

In PSS/E, SSAT, and MatNetEig, the user can also introduce data in text format.

4.2. DATA OUTPUT

All the tools give eigenvalue results. In addition, PSS/E, SSAT and MatNetEig give 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. 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, SSAT, and MatNetEig allow the user access to all four system matrices, EUROSTAG only allows ***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 and SSAT give the normalised complex right eigenvectors from which the user can deduce local area and inter-area electromechanical modes of oscillation. The programs also give the normalised participation factors for all the system modes.

MatNetEig gives both 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 state variables for controllers and other devices.

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.

		PSS/E	DIgSILENT	EUROSTAG	SSAT	MatNetEig
Components models	***Generator model order of complexity***	2nd, 3rd, 5th, 6th	5th, 6th	3rd, 5th, 6th	2nd, 5th, 6th	2nd, 5th, 6th
	Saturation parameters	$S_{1.0}$, $S_{1.2}$	$S_{1.0}$, $S_{1.2}$	*n, m*	$S_{1.0}$, $S_{1.2}$	$S_{1.0}$, $S_{1.2}$
	Turbine model output	P_m	P_m	T_m	P_m	T_m
	Swing equation	Torque	Torque	Torque	Torque or power	Torque
	Load models	Exponential and *ZIP*	Exponential	Exponential	Exponential and *ZIP*	Exponential
Numerical methodology	***Construction of A matrix***	Numerical differentiation	Numerical differentiation	Analytical differentiation	Analytical differentiation	Analytical differentiation
	Perturbation	User specified	10^{-3}	N/A	N/A	N/A
Software flexibility	***Data input***	Graphical user interface with data-input windows or text	Graphical user interface with data-input windows	Graphical user interface with data-input windows	Graphical user interface with data-input windows or text	Graphical user interface with data-input windows or text
	Accessibility of system matrices	A, B, C, D matrices available	Not available	A matrix only	A, B, C, D matrices available	A, B, C, D matrices available
	Eigenvectors	Right only	Not available	Not available	Right only	Right and left
	Participation factors	Available	Available	Not available	Available	Available

Table 1: Summary of software comparison

5. CASE STUDY

5.1. TWO AREA SYSTEM

We used the two-area power system as shown in figure 1 [5] 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 6th order generator model. The governor and excitation system are not included in this study. We computed the machine saturation parameters $S_{1.0}$ and $S_{1.2}$ as described in [9].

We represented 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.

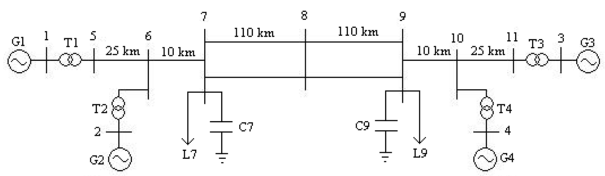

Figure 1: Two-area system

We performed eigenvalue analysis using the following programs: (i) PSS/E, (ii) DIgSILENT, (iii) EUROSTAG, (iv) SSAT, (v) MatNetEig; similar results presented in [5] were used for comparison.

5.2. SIMULATION RESULTS AND DISCUSSION

The simulation of the system represented in figure 1 gives a total of 24 eigenvalues. The system has three electromechanical modes; two local area modes, and one inter-area mode. The amount of output data from the five tools investigated is quite voluminous. Because the inter-area mode is of interest, we therefore present only the results of this mode.

Figure 2 shows location of the inter-area mode in the upper complex plane. The results in reference [5] are included for comparison.

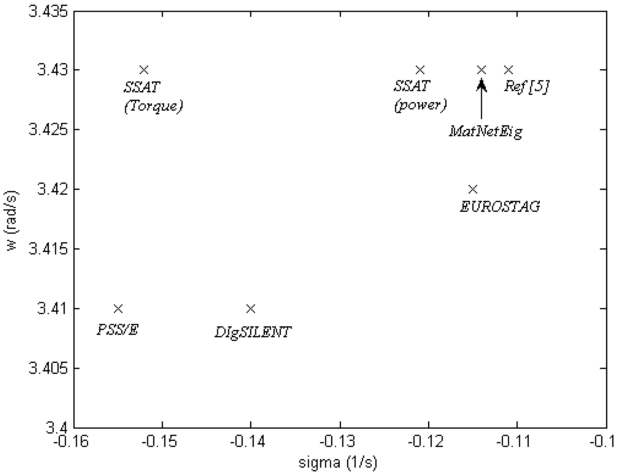

Figure 2: Loci of the inter-area mode in the complex plane. Results obtained with five analytical tools (PSS/E, DIgSILENT, EUROSTAG, SSAT, and MatNetEig)

Table 2 presents the damping ratio ζ (in percentage) of the inter-area oscillatory mode.

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \times 100 \qquad (11)$$

where σ and ω are the real and imaginary parts, respectively.

Tool	***Damping ratio, ζ (%)***
PSS/E	4.53
DIgSILENT	4.10
EUROSTAG	3.36
SSAT (torque option)	4.43
SSAT (power option)	3.52
MatNetEig	3.33
Ref [5]	3.23

Table 2: Damping ratio of the inter-area mode

From figure 2;

- The results obtained with the tools employing analytical differentiation (EUROSTAG, SSAT, and MatNetEig) for construction of the ***A*** matrix exhibit higher frequency of oscillation than those obtained with the tools employing numerical differentiation (PSS/E and DIgSILENT).
- The results obtained with the torque option in SSAT exhibit more optimistic damping than those obtained with the power option.

The difference in frequency of oscillation obtained with different tools is marginal; the difference between the highest and the lowest value is less than 1%. Hence, the variations observed in the damping ratio results are mainly due to differences in damping.

The difference between PSS/E and DIgSILENT, with regard to the method used for constructing the ***A*** matrix, consists in the perturbation method as explained in section 3.1.1. It is difficult to deduce to what extent the perturbation method affects the results because there are other modelling differences between the two programs.

In PSS/E and DIgSILENT the turbine model output is P_m. The torque option in SSAT is similar to PSS/E and DIgSILENT i.e. turbine model output is P_m and the swing equation is solved using torque (variable mismatch). As in PSS/E and DIgSILENT, the results obtained with this option exhibit high damping ratio. This may be attributed to the choice of turbine model output as discussed in section 2.1.3.

The power option in SSAT is similar to EUROSTAG and MatNetEig i.e. turbine model output variable matches the swing equation variable. In SSAT, turbine model output is P_m and the swing equation variable is power; in EUROSTAG and MatNetEig turbine model output is T_m and the swing equation variable is torque.

EUROSTAG gives results that exhibit lower frequency of oscillation compared with that obtained with other tools that model turbine output as T_m. This may be due to the inclusion of the effect of speed variations in the stator voltage equation.

The conservative value of damping ratio given in reference [5] may be due to the fact that, [5] takes into account incremental saturation whereas all the investigated tools take into account total saturation.

6. CONCLUSIONS

In this paper we have compared five industrial-grade power system analytical tools. All the tools use, for the calculation of eigenvalues, the QR method. Therefore the differences among eigenvalue results are not related to the mathematical routines used in these programs.

We highlight the following modelling features of the programs as possible causes of variations in eigenvalue results:

- Representation of turbine model output, P_m or T_m
- Form of generator swing equation, power or torque
- Representation of stator terminal voltage; inclusion of effect of speed variations on stator voltage.

We did not investigate the effect of saturation modelling on our results; this is part of our future work.

Further investigation of the effect of perturbation methods used in PSS/E and DIgSILENT is necessary.

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 reached 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).

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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	$\psi_{T1} = 0.9$
$R_a = 0.0025$	$T'_{qo} = 0.4$ 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***)
$r = 0.0001$ *p.u./km* $x_L = 0.001$ *p.u./km*
$b_C = 0.00175$ *p.u./km*

Transformers
Rating; 900 MVA, 20/230 kV
$X = j0.15$ p.u.
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