A UNIFIED FRAMEWORK FOR NONLINEAR DYNAMIC SIMULATION AND MODAL ANALYSIS FOR CONTROL OF LARGE-SCALE POWER SYSTEMS

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Abstract – This paper presents a framework which allows an easy parallel use of both nonlinear and linear approaches to analyze and damp power oscillations in interconnected power systems. For this, the Small-Signal Stability tool SMAS3 was interconnected to the dynamic simulation tool EUROSTAG so that one can use in SMAS3 the linearized model of the grid and machines along with their regulations computed by EUROSTAG. Any control solutions synthesized in SMAS3 can be pulled-up into the nonlinear model of EUROSTAG to validate their efficiency in a nonlinear dynamic simulation. The final solution can thus be obtained after a sufficient number of iterations of complementary linear/nonlinear analysis and synthesis and this assess the oscillation damping and make sure that the solution proposed by synthesis methods based on the linearized model is still satisfactory in the actual nonlinear context. This framework is used to do the eigenvalue analysis of a large-scale representation of the European power system and to design in a coordinated manner controllers to damp the power oscillations. Starting from this grid, a benchmark to test the performance of the modal analysis algorithms in case of very large scale grids is proposed.

Keywords: nonlinear dynamic simulation, small-signal stability, modal analysis, coordinated PSS tuning for damping power system oscillations

1 INTRODUCTION

The phenomenon of electromechanical oscillations in power systems is not new. Electric power systems are increasingly vulnerable to poorly damped low-frequency oscillations due to the increase of the size of the synchronous areas and to the fact that interconnections are more used to maximize the electricity trade between the existing power markets.

Several approaches are well-established to analyze the pattern of oscillations and to propose control solutions to damp them (see [1] for a general presentation). Most of the existing solutions are based on a linear representation of the grid along with its regulations. Indeed, eigenvalues of the linearized model provide the frequency and damping of the oscillations. In addition, their right and left eigenvectors are the basis of tools to design controllers to damp the oscillations such as power system stabilizers (PSS).

However, the analysis results as well as the control solution obtained with the linear approximation of the power grid behavior have to be validated on the actual nonlinear power system. This parallel nonlinear time-domain analysis is important especially in case of growing size grids (complex load models, time delays for the transmission of the information) with complex regulations (dead-bands, hysteresis) where the damping of oscillations can be assessed by a complementary linear/nonlinear analysis.

As a matter of fact, we propose here a framework in which the final solution is obtained after a sufficient number of iterations of modal analysis and control synthesis and nonlinear time-domain validations. For this, the Small-Signal Stability tool SMAS3 [2] was interconnected to the dynamic simulation tool EUROSTAG [3]. Thus, one can use in SMAS3 the linearized model of the grid and machines along with their regulations computed by EUROSTAG around a given operating point. Any control solutions synthesized in SMAS3 (location and tuning of PSSs) can be pulled-up into the nonlinear model of EUROSTAG to validate their efficiency in a nonlinear dynamic simulation. The main advantage of this approach is that both analysis are carried out on precisely the same power system: first, the model used in the small-signal stability analysis is directly obtained from the linearization of the actual grid with no data conversion or approximation for the operating point and models of the machines and their regulations. Next, the control solutions provided by the linear approach are directly integrated into the nonlinear simulation model of the actual power system.

The paper is organized as follows: in Section 2 we briefly describe the tools SMAS3 and EUROSTAG. Section 3 details the input/output data of the nonlinear and linear analysis and the way in which the two tools are interfaced. Section 4 describes how the Eurostag-SMAS3 interconnection has been validated. Section 5 applies the resulting framework to improve the damping of the electromechanical oscillations in a large-scale representation of the European power system. In Section 6 the grid above is transformed in order to get a benchmark for modal analysis of very large scale interconnected electrical grids. Section 7 is devoted to final remarks.

2 TOOLS DESCRIPTION

2.1 Eurostag

Eurostag is a time domain simulation program for transient and long term phenomena in power systems (time constants from tens of milliseconds to hundreds of seconds) [3]. Machines are represented by Park's state models whilst frequency sensitive impedances and passive or dynamic components are used for the grid and loads. The tool is particularly flexible in modeling the control loops. Indeed, in addition to a library of the standard regulators (like, e.g., IEEE AVRs and speed governors), HVDC links and FACTS devices, it provides a friendly graphical user's interface, called macroblock editor, to define any continuous-time control scheme. The user can thus input in an exact manner any particular regulation scheme. Protections are also represented.

The overall power system is thus represented by a set of (nonlinear) differential-algebraic equations

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{f}(\mathbf{x},\mathbf{r}) \\ \mathbf{0} &= \mathbf{g}(\mathbf{x},\mathbf{r}) \end{aligned} \tag{1}$$

The variables of the dynamics (1) are split into two classes: the first one denoted by $\mathbf{x}$ and called differential variables in the sequel, is composed by state-variables of the dynamic devices (synchronous machines and their regulators, induction machines, HVDC links, FACTS devices, etc.) while the second one, denoted by $\mathbf{r}$ and called algebraic variables, describe both the interconnection of the elementary components of the dynamic devices and the interconnection of the dynamic devices through the network. Instances of the algebraic variables are the field voltage and the mechanical torque of the synchronous machines and the real and imaginary components of the bus voltages.

Equations (1) are integrated using a variable step algorithm in order to capture different time-scale phenomenon. In this way one can simulate the response of the power system at a wide range of usual disturbances: steps on the set-points of the AVRs/AGCs, short-circuits, lines/generators outages, load evolution, etc.

2.2 SMAS3

Selective Modal Analysis of Small-Signal Stability (SMAS3) is a program package that incorporates the state-of-the art of the techniques for small signal stability analysis and control in large electric power systems [2]. SMAS3 computes both all system eigenvalues of small-scale systems and a reduced number of eigenvalues of large-scale systems. Eigenvalues of large-scale systems are computed using algorithms for reduced order. Several algorithms of reduced order eigenanalysis are available in SMAS3:

- Generalized Selective Modal Analysis [4].
- Modified Arnoldi Method [5].
- Dominant Pole Spectrum Eigensolver [6].

SMAS3 provides not only the eigenvalues but also the participation factors [7] and a number of eigenvalue sensitivities (i.e., residues [8]) and controllability and obserbability factors. Eigenvalue sensitivities are the basis of the approach to design power system damping controllers in SMAS3 [9].

SMAS3 also includes efficient algorithms for linear time response and frequency response.

The model used can be expressed as a collection of linear dynamic subsystems (the generation units along with their regulations), interconnected through a set of static constraints (the grid along with the loads)

$$\begin{bmatrix} \Delta\dot{\mathbf{x}} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} \\ \mathbf{A}_{21} & \mathbf{A}_{22} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{x} \\ \Delta\mathbf{V} \end{bmatrix} + \begin{bmatrix} \mathbf{B}_1 \\ \mathbf{B}_2 \end{bmatrix} \Delta\mathbf{u} \tag{2}$$

where $\Delta\mathbf{V}$ is the vector of the real and imaginary components of bus voltages and $\Delta\mathbf{u}$ is the vector of the input variables which will be specified in Section 3.2. $\mathbf{A}_{11}$, $\mathbf{A}_{12}$, $\mathbf{A}_{21}$, $\mathbf{B}_1$ and $\mathbf{B}_2$ are block diagonal matrices whereas $\mathbf{A}_{22}$ is a large sparse matrix which corresponds to the network admittance matrix expanded to its real and imaginary parts including the static models of the dynamic devices and the models of the static loads.

Any chosen output variable can be defined as a linear combination of the state variables, the components of the bus voltages and the control variables:

$$\Delta\mathbf{y} = \begin{bmatrix} \mathbf{C}_1 & \mathbf{C}_2 \end{bmatrix} \begin{bmatrix} \Delta\mathbf{x} \\ \Delta\mathbf{V} \end{bmatrix} + \mathbf{D}\Delta\mathbf{u} \tag{3}$$

3 INTERCONNECTION EUROSTAG-SMAS3

3.1 Eurostag linearization

It is possible to get by user's demand at any given simulation time the linear approximations of the functions f and g which define the power system equations (1) in the vicinity of the current point $(\mathbf{x}_0,\mathbf{r}_0)$:

$$\begin{aligned} \mathbf{f} &= \mathbf{f}_0 + \left.\frac{\partial \mathbf{f}(\mathbf{x},\mathbf{r})}{\partial \mathbf{x}}\right|_{(\mathbf{x}_0,\mathbf{r}_0)} \Delta\mathbf{x} + \left.\frac{\partial \mathbf{f}(\mathbf{x},\mathbf{r})}{\partial \mathbf{r}}\right|_{(\mathbf{x}_0,\mathbf{r}_0)} \Delta\mathbf{r} = \mathbf{f}_0 + \mathbf{J}_1\Delta\mathbf{x} + \mathbf{J}_2\Delta\mathbf{r} \\ \mathbf{g} &= \mathbf{g}_0 + \left.\frac{\partial \mathbf{g}(\mathbf{x},\mathbf{r})}{\partial \mathbf{x}}\right|_{(\mathbf{x}_0,\mathbf{r}_0)} \Delta\mathbf{x} + \left.\frac{\partial \mathbf{g}(\mathbf{x},\mathbf{r})}{\partial \mathbf{r}}\right|_{(\mathbf{x}_0,\mathbf{r}_0)} \Delta\mathbf{r} = \mathbf{g}_0 + \mathbf{J}_3\Delta\mathbf{x} + \mathbf{J}_4\Delta\mathbf{r} \end{aligned} \tag{4}$$

where $\mathbf{f}_0 = \mathbf{f}(\mathbf{x}_0,\mathbf{r}_0)$ and $\mathbf{g}_0 = \mathbf{g}(\mathbf{x}_0,\mathbf{r}_0)$.

If the Eurostag linearization is carried out such that $(\mathbf{x}_0,\mathbf{r}_0)$ is an equilibrium point, the matrices given by (4) define the linear dynamics of the overall power system:

$$\begin{bmatrix} \Delta\dot{\mathbf{x}} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} \mathbf{J}_1 & \mathbf{J}_2 \\ \mathbf{J}_3 & \mathbf{J}_4 \end{bmatrix} \begin{bmatrix} \Delta\mathbf{x} \\ \Delta\mathbf{r} \end{bmatrix} = \mathbf{J} \begin{bmatrix} \Delta\mathbf{x} \\ \Delta\mathbf{r} \end{bmatrix} \tag{5}$$

The easiest way to ensure this is to trigger the linearization procedure at steady-state, i.e., when all variables are constant. The user is assisted by an automatic test to detect the steady-state conditions and a warning is generated along with the linearization result if the variation of the variables is greater than a minimal threshold.

3.2 Definition of transfer functions in EUROSTAG

For the modal analysis we are interested in transfers between some specific input variables and output ones. Those variables can be separated into two classes. First, if the standard transfer functions of a power system are considered, their inputs are the standard set-points of the generator regulation loops, i.e., the speed, voltage excitation and mechanical torque references while the outputs are the usual physical variables like, e.g., machine speed, electrical power and terminal voltage, line transit, etc.. Next, the user could like to investigate transfer functions between particular specified points of the regulation loops. This is the case for the robust control synthesis when the sensitivity and complementary sensitivity transfer functions must be studied. For the example of the voltage regulation of one generator, this reduces to open the control loop between the AVR and the generator in order to consider the transfer from a signal injected at that point and the EFD signal of the generator (sensitivity function) on one hand and, on the other hand, to the AVR output (complementary sensitivity function). These special inputs can be easily specified by placing additional set-points in any desired location of an EUROSTAG macrobloc regulation scheme. Also, any desired output variable which is not a standard electrical variable or a state-variable (output of an integrator) can be added to the list of algebraic variables if a name (label) is associated to it in the macrobloc scheme.

Therefore, the vector of algebraic variables contains the vector of the dynamic device algebraic variables $\Delta\mathbf{z}$, the vector of dynamic device input variables $\Delta\mathbf{u}$ and the vector of bus voltage components $\Delta\mathbf{V}$.

Matrices of dynamics (5) can be repartitioned according to:

$$\begin{bmatrix}\Delta\dot{\mathbf{x}}\\ \mathbf{0}\\ \mathbf{0}\\ \mathbf{0}\end{bmatrix}=\begin{bmatrix}\mathbf{J}_{11} & \mathbf{J}_{12} & \mathbf{J}_{13} & \mathbf{J}_{14}\\ \mathbf{J}_{21} & \mathbf{J}_{22} & \mathbf{J}_{23} & \mathbf{J}_{24}\\ \mathbf{J}_{31} & \mathbf{J}_{32} & \mathbf{J}_{33} & \mathbf{J}_{34}\\ \mathbf{J}_{41} & \mathbf{J}_{42} & \mathbf{J}_{43} & \mathbf{J}_{44}\end{bmatrix}\begin{bmatrix}\Delta\mathbf{x}\\ \Delta\mathbf{z}\\ \Delta\mathbf{u}\\ \Delta\mathbf{V}\end{bmatrix} \tag{6}$$

3.3 Conversion of the EUROSTAG model to the SMAS3 model form

If the equation (6) is rewritten while eliminating the equations corresponding to the input variables, it results in:

$$\begin{bmatrix}\Delta\dot{\mathbf{x}}\\ \mathbf{0}\\ \mathbf{0}\end{bmatrix}=\begin{bmatrix}\mathbf{J}_{\mathrm{A11}} & \mathbf{J}_{\mathrm{A12}} & \mathbf{J}_{\mathrm{A13}}\\ \mathbf{J}_{\mathrm{A21}} & \mathbf{J}_{\mathrm{A22}} & \mathbf{J}_{\mathrm{A23}}\\ \mathbf{J}_{\mathrm{A31}} & \mathbf{J}_{\mathrm{A32}} & \mathbf{J}_{\mathrm{A33}}\end{bmatrix}\begin{bmatrix}\Delta\mathbf{x}\\ \Delta\mathbf{z}\\ \Delta\mathbf{V}\end{bmatrix}+\begin{bmatrix}\mathbf{J}_{\mathrm{B1}}\\ \mathbf{J}_{\mathrm{B2}}\\ \mathbf{J}_{\mathrm{B3}}\end{bmatrix}\Delta\mathbf{u} \tag{7}$$

In addition, the output variables are defined as:

$$\Delta\mathbf{y}=\begin{bmatrix}\mathbf{J}_{C1} & \mathbf{J}_{C2} & \mathbf{J}_{C3}\end{bmatrix}\begin{bmatrix}\Delta\mathbf{x}\\ \Delta\mathbf{z}\\ \Delta\mathbf{V}\end{bmatrix}+\mathbf{J}_{D}\Delta\mathbf{u} \tag{8}$$

The device algebraic variables $\Delta\mathbf{z}$ can be written from (7) in terms of the state variables, the bus voltages and the input variables:

$$\begin{aligned}&\mathbf{0}=\mathbf{J}_{\mathrm{A21}}\Delta\mathbf{x}+\mathbf{J}_{\mathrm{A22}}\Delta\mathbf{z}+\mathbf{J}_{\mathrm{A23}}\Delta\mathbf{V}+\mathbf{J}_{\mathrm{B2}}\Delta\mathbf{u}\\ &\mathbf{J}_{\mathrm{A22}}\Delta\mathbf{z}=-\mathbf{J}_{\mathrm{A21}}\Delta\mathbf{x}-\mathbf{J}_{\mathrm{A23}}\Delta\mathbf{V}-\mathbf{J}_{\mathrm{B2}}\Delta\mathbf{u}\\ &\Delta\mathbf{z}=-\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{A21}}\Delta\mathbf{x}-\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{A23}}\Delta\mathbf{V}-\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{B2}}\Delta\mathbf{u}\end{aligned} \tag{9}$$

and next eliminated from (7) and (8)

$$\begin{aligned}\Delta\dot{\mathbf{x}}&=\mathbf{J}_{\mathrm{A11}}\Delta\mathbf{x}+\mathbf{J}_{\mathrm{A12}}\Delta\mathbf{z}+\mathbf{J}_{\mathrm{A13}}\Delta\mathbf{V}+\mathbf{J}_{\mathrm{B1}}\Delta\mathbf{u}\\ \mathbf{0}&=\mathbf{J}_{\mathrm{A31}}\Delta\mathbf{x}+\mathbf{J}_{\mathrm{A32}}\Delta\mathbf{z}+\mathbf{J}_{\mathrm{A33}}\Delta\mathbf{V}+\mathbf{J}_{\mathrm{B3}}\Delta\mathbf{u}\\ \Delta\mathbf{y}&=\mathbf{J}_{\mathrm{C1}}\Delta\mathbf{x}+\mathbf{J}_{\mathrm{C2}}\Delta\mathbf{z}+\mathbf{J}_{\mathrm{C3}}\Delta\mathbf{V}+\mathbf{J}_{\mathrm{D}}\Delta\mathbf{u}\end{aligned} \tag{10}$$

which become:

$$\begin{aligned}&\Delta\dot{\mathbf{x}}=\mathbf{J}_{\mathrm{A11}}\Delta\mathbf{x}\\ &+\mathbf{J}_{\mathrm{A12}}\left(-\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{A21}}\Delta\mathbf{x}-\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{A23}}\Delta\mathbf{V}-\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{B2}}\Delta\mathbf{u}\right)\\ &+\mathbf{J}_{\mathrm{A13}}\Delta\mathbf{V}+\mathbf{J}_{\mathrm{B1}}\Delta\mathbf{u}\\[1em] &\mathbf{0}=\mathbf{J}_{\mathrm{A31}}\Delta\mathbf{x}\\ &+\mathbf{J}_{\mathrm{A32}}\left(-\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{A21}}\Delta\mathbf{x}-\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{A23}}\Delta\mathbf{V}-\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{B2}}\Delta\mathbf{u}\right)\\ &+\mathbf{J}_{\mathrm{A33}}\Delta\mathbf{V}+\mathbf{J}_{\mathrm{B3}}\Delta\mathbf{u}\\[1em] &\Delta\mathbf{y}=\mathbf{J}_{\mathrm{C1}}\Delta\mathbf{x}\\ &+\mathbf{J}_{\mathrm{C2}}\left(-\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{A21}}\Delta\mathbf{x}-\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{A23}}\Delta\mathbf{V}-\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{B2}}\Delta\mathbf{u}\right)\\ &+\mathbf{J}_{\mathrm{C3}}\Delta\mathbf{V}+\mathbf{J}_{\mathrm{D}}\Delta\mathbf{u}\end{aligned} \tag{11}$$

or:

$$\begin{aligned}\Delta\dot{\mathbf{x}}=&\left(\mathbf{J}_{\mathrm{A11}}-\mathbf{J}_{\mathrm{A12}}\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{A21}}\right)\Delta\mathbf{x}\\ &+\left(\mathbf{J}_{\mathrm{A13}}-\mathbf{J}_{\mathrm{A12}}\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{A23}}\right)\Delta\mathbf{V}\\ &+\left(\mathbf{J}_{\mathrm{B1}}-\mathbf{J}_{\mathrm{A12}}\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{B2}}\right)\Delta\mathbf{u}\\[1em] \mathbf{0}=&\left(\mathbf{J}_{\mathrm{A31}}-\mathbf{J}_{\mathrm{A32}}\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{A21}}\right)\Delta\mathbf{x}\\ &+\left(\mathbf{J}_{\mathrm{A33}}-\mathbf{J}_{\mathrm{A32}}\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{A23}}\right)\Delta\mathbf{V}\\ &+\left(\mathbf{J}_{\mathrm{B3}}-\mathbf{J}_{\mathrm{A32}}\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{B2}}\right)\Delta\mathbf{u}\\[1em] \Delta\mathbf{y}=&\left(\mathbf{J}_{\mathrm{C1}}-\mathbf{J}_{\mathrm{C2}}\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{A21}}\right)\Delta\mathbf{x}\\ &+\left(\mathbf{J}_{\mathrm{C3}}-\mathbf{J}_{\mathrm{C2}}\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{A23}}\right)\Delta\mathbf{V}\\ &+\left(\mathbf{J}_{\mathrm{D}}-\mathbf{J}_{\mathrm{C2}}\mathbf{J}_{\mathrm{A22}}^{-1}\mathbf{J}_{\mathrm{B2}}\right)\Delta\mathbf{u}\end{aligned} \tag{12}$$

Therefore, the matrices of the SMAS3 implicit linear model (2)-(3) are:

$$
\begin{aligned}
\mathbf{A}_{11} &= \mathbf{J}_{A11} - \mathbf{J}_{A12}\mathbf{J}_{A22}^{-1}\mathbf{J}_{A21} \\
\mathbf{A}_{12} &= \mathbf{J}_{A13} - \mathbf{J}_{A12}\mathbf{J}_{A22}^{-1}\mathbf{J}_{A23} \\
\mathbf{A}_{21} &= \mathbf{J}_{A31} - \mathbf{J}_{A32}\mathbf{J}_{A22}^{-1}\mathbf{J}_{A21} \\
\mathbf{A}_{22} &= \mathbf{J}_{A33} - \mathbf{J}_{A32}\mathbf{J}_{A22}^{-1}\mathbf{J}_{A23} \\
\mathbf{B}_{1} &= \mathbf{J}_{B1} - \mathbf{J}_{A12}\mathbf{J}_{A22}^{-1}\mathbf{J}_{B2} \\
\mathbf{B}_{2} &= \mathbf{J}_{B3} - \mathbf{J}_{A32}\mathbf{J}_{A22}^{-1}\mathbf{J}_{B2} \\
\mathbf{C}_{1} &= \mathbf{J}_{C1} - \mathbf{J}_{C2}\mathbf{J}_{A22}^{-1}\mathbf{J}_{A21} \\
\mathbf{C}_{2} &= \mathbf{J}_{C3} - \mathbf{J}_{C2}\mathbf{J}_{A22}^{-1}\mathbf{J}_{A23} \\
\mathbf{D} &= \mathbf{J}_{D} - \mathbf{J}_{C2}\mathbf{J}_{A22}^{-1}\mathbf{J}_{B2}
\end{aligned}
\tag{13}
$$

This linear model has the advantage to automatically inherit all details and particularities of the power system which can be modeled in EUROSTAG. As an example, special regulation schemes, as well as detailed (voltage and/or frequency dependent) load behaviours can thus be taken into account.

4 VALIDATION OF THE EUROSTAG-SMAS3 INTERCONNECTION

The interconnection of EUROSTAG and SMAS3 has been validated using small- and large-scale power systems. In case of small-scale power systems the validation of the interconnection was done comparing the results of the full eigenvalue analysis provided by the two tools. In case of large-scale systems the validation cannot be done is such way. As SMAS3 also includes efficient algorithms for linear time response, the validation can be addressed comparing the time responses to small disturbances provided by both EUROSTAG and SMAS3.

As instance of a large-scale system a realistic model of the interconnected European power system will be considered in this paper. Such model contains about 400 generators and 2000 buses. The linear model is described by 7473 state variables.

The interconnected European system exhibits a low damped inter-area oscillation of 0.23 Hz in which the generators of the eastern part of the grid are oscillating against the generators of the western part (see, e.g., [10] and [11]). This mode was retrieved using the EUROSTAG-SMAS3 framework; Figure 1 shows its geographical mode shape.

The time responses to a step increase of 0.1% of the reference of the excitation system of the generator with greatest participation in the slowest inter-area mode (the mode above) computed using both EUROSTAG and SMAS3 are given in Figure 2. The solid line corresponds to the response computed by SMAS3 whereas the dotted line corresponds to the response computed by EUROSTAG. Both responses agree exactly when only the slowest inter-area mode is visible in the response (from 0 to 15 seconds in Fig. 2). When the oscillations of the speed deviation are dominated by another mode (beyond 15 seconds in Fig. 2) the linear and the nonlinear simulations exhibit some discrepancy. Despite such small discrepancy, the validation could be considered as satisfactory.

Figure 1: Mode shape of the slowest inter-area mode of the European interconnected system.

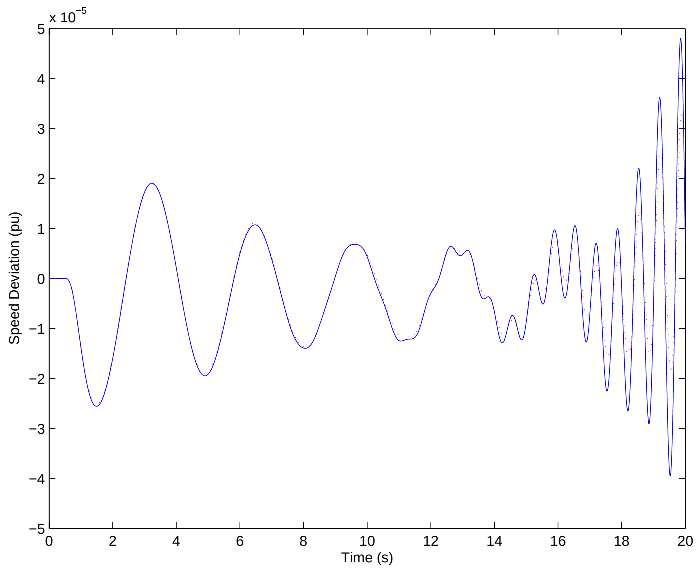

Figure 2: Comparison of the time responses provided by EUROSTAG and SMAS3.

5 APPLICATION OF EUROSTAG-SMAS3 INTERCONNECTION TO THE DAMPING OF ELECTROMECHANICAL OSCILLATIONS IN THE EUROPEAN INTERCONNECTED SYSTEM

A meaningful application of the interconnection of Eurostag and SMAS3 is the design of controllers (namely PSSs) for the improvement of the damping of low frequency electromechanical oscillations in a large scale system such as the European interconnected power system. Low frequency oscillations were detected in measurements and confirmed by both nonlinear time domain simulations and eigenvalue computations ([10]-[11]). This paper shows how the results of the eigenvalue analysis can be used to design PSSs to improve the damping of several modes. The objective is to simultaneously damp three inter-area modes: the two slowest European inter-area modes and a low frequency one with Spanish system. For this, PSS are tuned in a coordinated manner for some Spanish generators.

5.1 Eigenvalue analysis

The slowest European inter-area mode (around 0.23Hz) depends significantly on the power exchanged between France and Spain [10]. It becomes poorly damped when Spain increases the power exports to France. The base case of this study was chosen to represent the most unfavourable case when the transit from Spain to France is 800MW.

The three modes which will be studied are given in the first line of Table 1. The first two ones are the slowest inter-area modes of the European power system which has been extensively studied in the past (see, e.g., [10] and [11]). Mode 1 is an east-west mode while mode 2 is a center-extreme one. Together they are representative of the European inter-area oscillation problems. Mode 3 has a slightly different nature; it is an inter-area mode of the Spanish system, or, in other words, an intra-area of the European system, so that it concerns mainly generators of the Spanish system (Figure 3). It is also a mode at a slightly higher frequency (0.9Hz) that the first two ones.

Figure 3: Mode shape of the Spanish inter-area mode.

5.2 Coordinated design of power system stabilizers

The identification of the most suitable generators for damping the slowest inter-area mode of the European system has been already investigated in [10]. Two generators in Spain (PGR and ALMARAZ) were selected. This set will be completed with another generator in Spain because of its participation in the Spanish east-west mode: COFRENTES.

The objective of the coordinated design of PSSs is to improve the damping of both the slowest inter-area mode and the Spanish one whereas the damping of the second slowest inter-area mode is not deteriorated. The coordinated design provides the time constants of the phase compensation networks and the gains to achieve such purposes. Speed deviation power system stabilizers are assumed. The time constant of the washout filter is also assumed.

$$V_s = K_s \frac{1+T_1 s}{1+T_2 s} \frac{1+T_3 s}{1+T_4 s} \frac{T_5 s}{1+T_5 s} \Delta\omega \qquad (14)$$

Table 1 provides the results of the eigenvalue analysis corresponding to the three modes of interest. The original modes, the expected values of the modes due to the PSSs effect as estimated by the eigenvalue sensitivities and actual values of the modes. The damping of the both the slowest and the Spanish modes are improved while the damping of the second slowest mode is hardly affected.

Table 2 contains the parameters of the stabilizers. They are obtained in a two step approach based on the first order sensitivities of the eigenvalues of the power system linear model [9]: first, the independent design of phase compensation networks of the controllers and, next, the coordinated design of the gains of the controllers.

Table 1: Modal analysis results.

	Mode 1		Mode 2		Mode 3	
Case	$\varsigma(\%)$	$f(Hz)$	$\varsigma(\%)$	$f(Hz)$	$\varsigma(\%)$	$f(Hz)$
Without PSS	3.87	0.23	11.7	0.24	6.25	0.91
Expected with PSS	10.37	0.23	9.82	0.25	9.71	0.93
Realized with PSS	8.43	0.23	9.97	0.25	11.53	0.86

Table 2: PSS parameters.

	$T_1 = T_3$	$T_2 = T_4$	K_s
PGR	0.61	0.061	0.54
COFRENTES	0.58	0.058	5.74
ALMARAZ	0.21	0.021	2.43

Table 3: Slowest modes of the very large scale benchmark.

Mode	Eigenvalue	$\varsigma(\%)$	$f(Hz)$	Generator with greatest participation
1	-0.2062±j0.6070	32.16	0.097	Gravelines zone 2
2	-0.2062±j0.6070	32.17	0.097	Gravelines zone 3

5.3 Nonlinear dynamic analysis and validation

The contribution of the designed PSSs is further evaluated with nonlinear time domain simulations. A three phase fault is applied at PGR grid side connection. Figure 4 shows the time evolution of the speed of the machines equipped with PSSs (dashed lines) in comparison with the ones obtained when no PSS are used for the three selected generators (solid lines). Figure 5 details such responses. They confirm the improvement of the damping of both the slowest mode and the Spanish mode.

Figure 6 contains the time evolution of the terminal voltages of the machines on which the new PSSs are installed before (solid lines) and respectively after (dashed lines) their installation. No inadmissible over-voltages are found as a result of PSSs action.
The nonlinear simulation has confirmed the contribution of the designed controllers.

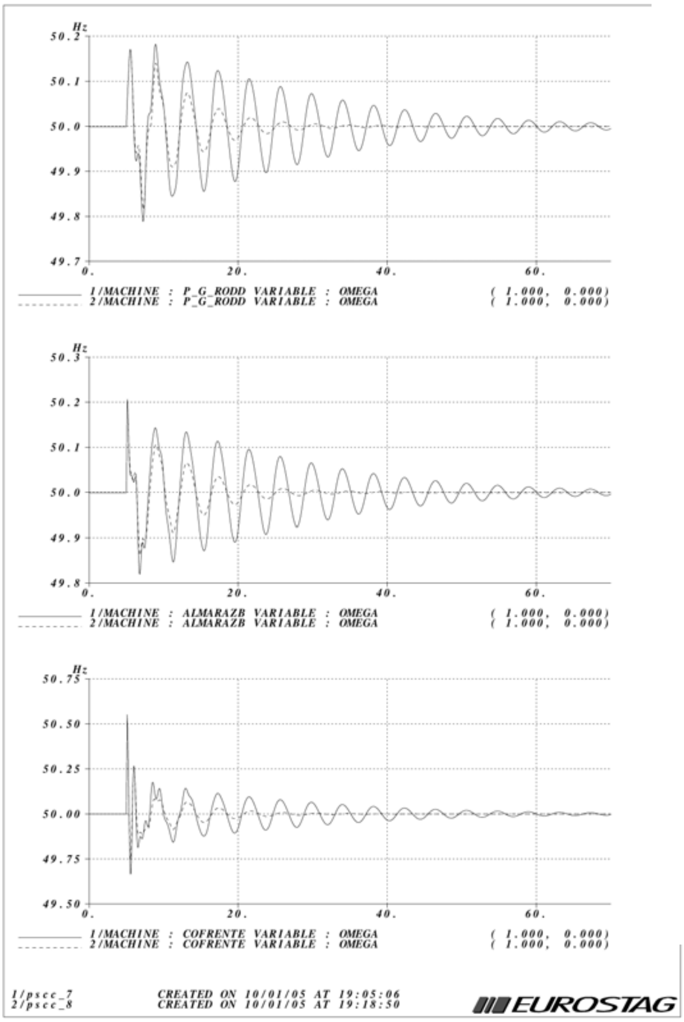

Figure 4: Nonlinear machine speed responses.

6 APPLICATION OF EUROSTAG-SMAS3 INTERCONNECTION TO A VERY LARGE SCALE POWER SYSTEM BENCHMARK

The power system model used in Sections IV and V is transformed in order to get a benchmark for modal analysis of very large-scale interconnected electrical systems. For this, the model is triplicated and the three resulting grids are interconnected as in Figure 7. The resulting benchmark is of size big enough (about 1200 machines and 22116 state variables) to test in advance the algorithms which are supposed to be used for instance to analyze further extensions of the European grid. As an example, 10 eigenvalues were successfully computed within 6 iterations of the Generalized Selective Modal Analysis Method [4] in a reasonable time (about 3 minutes on a medium fast machine). Two of those modes are presented in Table 3. They are inter-area modes of the new interconnection of the 3 grids associated with almost identical eigenvalues.

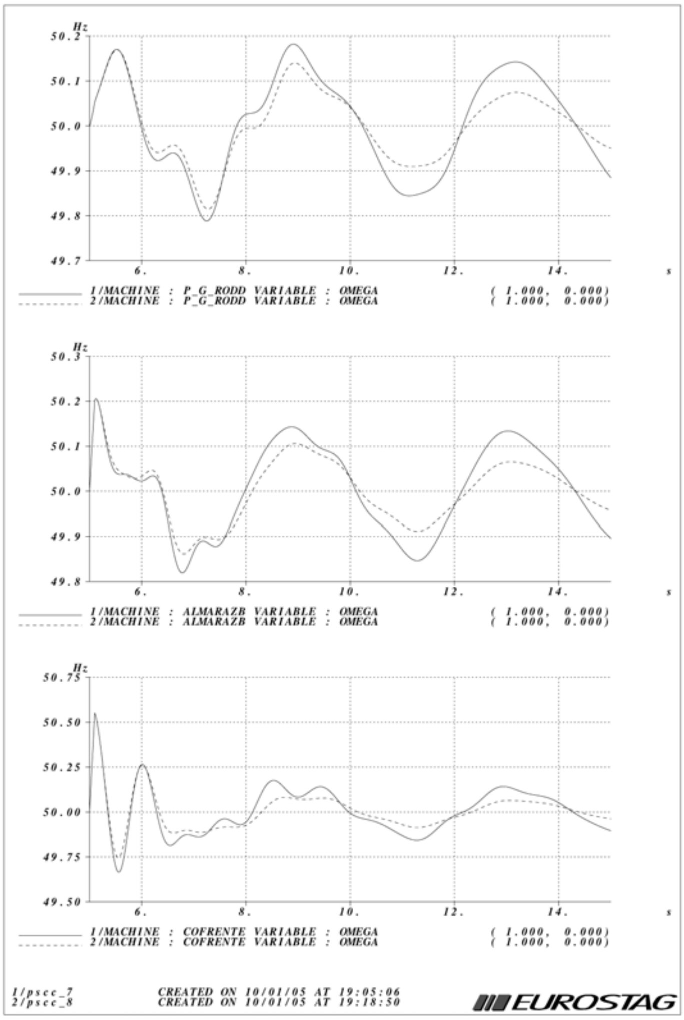

Figure 5: Detail of the nonlinear machine speed responses.

7 CONCLUSIONS

A new framework for parallel linear and nonlinear analysis of power systems is presented. It consists of the interconnection of EUROSTAG and SMAS3 packages which allows complementary modal analysis/synthesis of controls and dynamic nonlinear simulations. It is particularly useful to study and damp power oscillations in interconnected power systems and it presents the following advantages:
Both linear and nonlinear analysis are carried out on precisely the same power system since the link between the two software packages is the linearized model of the actual grid and regulations around the actual operating point without any data conversion or approximation.
The control solutions provided by the linear approach can be pulled-up into the actual nonlinear model to validate their efficiency and, if necessary, to be retuned. The solution obtained after such iterations of comple-

mentary linear/ nonlinear analysis and synthesis better assess the oscillation damping in case of large scale power systems.
This approach was illustrated on a realistic model of the European interconnected power system. The algorithms are also proven to be reliable for power systems much larger than the actual European one.

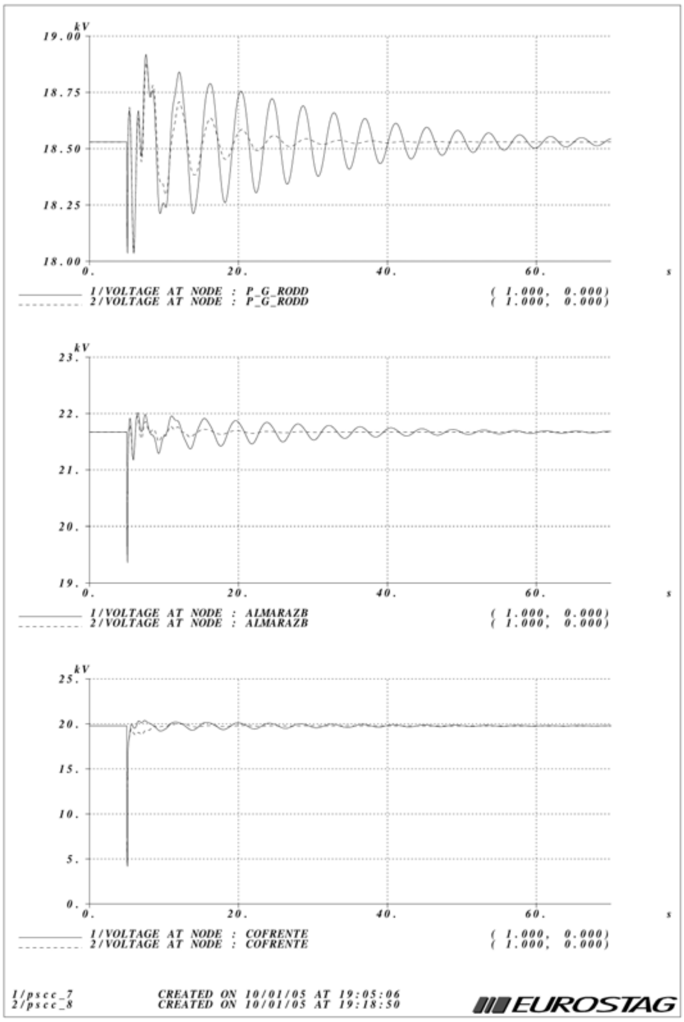

Figure 6: Nonlinear terminal voltage responses.

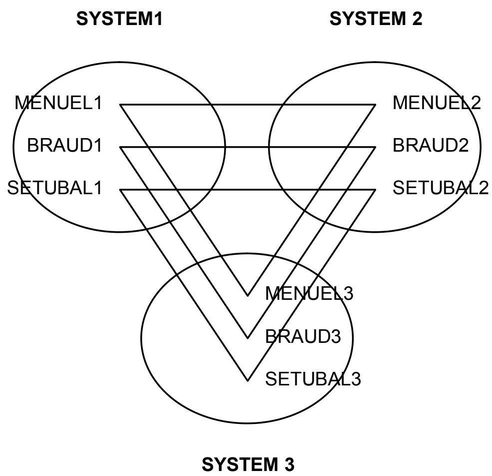

Figure 7: The benchmark grid.

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