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Robust Tuning of PSS in Power Systems with Different Operating Conditions

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Abstract--**This paper presents a new approach to deal with the problem of robust tuning of PSS in multimachine power systems with different operating conditions of load, topology and generation scheduling. The proposed method is based on the formulation of an optimization problem, solved by an evolutionary programming algorithm. The effectiveness of the proposed approach is demonstrated through modal analysis and nonlinear simulations of two test systems, carried out using Matlab and PSS/E software package.**

Index Terms--**Power system small signal stability, PSS, Robust tuning, Evolutionary programming algorithms**

I. Introduction

THE power system dimension growth and the increased operating constrains (economic, environmental, regulatory, technical, etc.) are leading to more tight stability margins and to the arise of conditions propitious to low damped oscillations. Such conditions can also be precipitated by contingencies, such as line outages, or high load levels. Hence, even systems that have adequate damping in normal operation, can often suffer from these problems during abnormal conditions. When this happens, additional damping may be required.

A valuable contribution to increase system damping is given by Power System Stabilizers (PSS), if correctly tuned. The first methods used to find out the parameters of PSS assumed that such tuning could be made using an approach where the generator was connected to an infinite bus. Although interesting and simple, it was early seen that it did not respond to the needs of modern large interconnected systems and a multimachine model was required to provide adequate solutions. However, the solution of the PSS tuning problem can be quite complex in multimachine power systems, due to the dimensionality problem.

It is well known that power systems dynamic behavior may be quite different at different operating conditions. Consequently, a set of parameters that produces satisfactory damping for a given operating condition may no longer be the desirable one in a different operating scenario. These facts show that search for robust solutions, which are able to produce satisfactory results for the all set of different operating conditions, is very much needed.

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Several techniques have been proposed to deal with this problem. An interesting approach exploits the concept of sensitivity, which comprises two steps: the design of the phase compensation network and the computation of the gain. In [1] it is suggested to minimize the sum of the weighted PSS gain increments, after the compensation design. The weighting coefficient constitutes a way to bias the solution in favor of the most effective stabilizers, based on previous analysis. In [2] the concept of sensitivity is introduced in the calculation of the PSS gain, giving to the algorithm the ability of selecting the most efficient stabilizers. In both cases, the problem is formulated and solved as a Linear Programming (LP) problem.

However, the use of LP approaches has several limitations and is not flexible enough. The use of meta-heuristics provided a powerful tool to overcome some of the LP limitations. In [3]-[5] it is introduced the use of meta-heuristics to solve this problem. In this approach, the objective function used lead to the maximization of the mode damping, providing simultaneously the determination of the compensation networks and gains, but having the inconvenience of the need of a previous selection of the PSS locations.

The method presented in this paper, is intended to be a new tool to assist in PSS tuning, by trying to combine the best features of the approaches mentioned above. The problem is formulated as an optimization one, where the objective function consists in the minimization of total amount of control actions, subject to a set of restrictions. EPSO - Evolutionary Particle Swarm Optimization - is used here as optimization motor [6],[7], to identify robust solutions in the search space.

In the following sections, the problem formulation is presented and some results of its application to the well-known Two-Area and New England test systems are described. Finally, the quality of the results is evaluated with time domain nonlinear simulations using the PSS/E software package.

II. Power System Modeling

A linear model of the power system, in a state space form, is used in this research [8]. The canonical description given by equations (1) was obtained from the analytical linearization of differential equations that define the state model. This model allows the use of classical approach to analyze the stability conditions of the power system, which consists in computing the eigenvalues of the state matrix, from which are then calculated the damping conditions associated to each oscillation mode.

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du \quad (1)$$

The generator model to be used depends on the needed detail. When a six order model is adopted, the state variables are the speed deviation, rotor angle and d-q flux linkages. If a fourth order model is considered, two of the flux variables are ignored. The voltage regulator and governors were represented by typical IEEE models adequate to the requirements.

In this research, a typical stabilizer with the rotor speed deviation as the input signal was considered. The transfer function is the following:

$$u(s) = K\frac{sT_W}{1+sT_W}\cdot\left(\frac{1+sT_1}{1+sT_2}\right)^N\cdot\Delta\omega(s) \quad (2)$$

Where K is the PSS gain and T_w is the washout time constant. There are also N lead-lag blocks with time constants T_1 and T_2, to provide the necessary phase compensation.

After setting up a system of equations like (1), the eigenvalues $\lambda_i = \sigma_i \pm j\omega_i$ of the state matrix are calculated. For each eigenvalue, damping is defined as:

$$\xi_i = \frac{-\sigma_i}{\sqrt{\sigma_i^{\,2} + \omega_i^{\,2}}} \quad (3)$$

Of course, the oscillation mode does not contain all information. The influence of each state variable in system behavior can be assed by analyzing mode-shape (right eigenvector) and participation factors. From the eigenvectors, we can calculate the participation factors, which are defined as the product of the *j-th* element of the right v_{ji} and left w_{ji} eigenvectors, corresponding to the *i-th* oscillation mode [9],[10]:

$$P_{ji} = w_{ji}v_{ji} = \frac{\partial\lambda_i}{\partial a_{jj}} \quad (4)$$

An interesting property of the participation factors is that they are dimensionless, what makes them suitable for PSS location. If a_{jj} is the generator speed, the participation factor can be interpreted as the sensitivity of the oscillation mode to the location of an ideal PSS. An ideal PSS introduces a torque in phase with the speed deviation [11].

III. Problem Formulation

The purpose of the approach described in this paper is to identify a reduced number of PSS to be installed in power system generators, and, for each one of these PSS, to determine the set of parameters that provides a robust solution, producing in this way a satisfactory global damping, for all less damped oscillation modes and for the all set of considered operating conditions.

The engineering problem consists therefore in the minimization of the total system control actions. Mathematically, the problem can then be formulated as a minimization one, where the objective function – OF ($\underline{X}$) – consists in the weighted sum of the PSS gains, subject to a set of restrictions, (namely damping of the oscillation modes should be smaller than a given bound and control variables should be within allowable physical limits). If necessary, other restrictions, like maximum tolerable frequency deviation, can be added to the problem.

$$\text{min} \qquad OF(\underline{X}) = \sum_{k=1}^{nc}\sum_{i=1}^{nm}\sum_{j=1}^{n}(1-p_{ji})K_j \quad (5)$$

$$\text{subject to} \qquad \xi_j \geq \xi_{j.\min} \quad (6)$$

$$\underline{X}_{j.\max} \geq \underline{X}_j \geq \underline{X}_{j.\min} \quad (7)$$

Where:

- $\underline{X}$ - is the solution of the problem (set of control variables to be used in each PSS to be installed);
- p_{ji} - is the normalized speed participation factor of generator *j-th* in oscillation mode *i*;
- K_j - is the PSS gain of the *j-th* generator;
- n - total number of generators;
- nm - number of electromechanical oscillation modes;
- nc - number of system scenarios.

The control variables (solution of the problem) are, for each PSS, the gain K, the number of lead-lag blocks N and the time constant values ($T = T_1$ and $\alpha = T_1 / T_2$) of each of these blocks. Limits are also imposed to the gains of the stabilizers and to the time constants in the lead-lag blocks. The washout time constant is specified previously to the PSS designs and is not adjusted.

The generators where the gain value of the PSS, determined with this approach, present a value different from zero are the ones selected for PSS installation.

The factor $w_{ji} = (1-p_{ji})$ correspond to the weighting coefficient. As mentioned in [9],[11], the participation factor provides a good and simple indication of the best location to install PSS. The participation factor of generators speed can be seen as the mode sensitivity to the installation of an ideal PSS using speed as input. To weight properly the gain, the speed participation factor of each generator in an oscillation mode was divided by the sum of the participations, described by (4).

To better understand how the participation factor introduces a localization index in the objective function, let us analyze the result for extreme values of p_{ji}. If $p_{ji} = 1$, it is because only generator *j-th* has influence on mode *i*. This results in $w_{ji} = 0$, which means that the PSS gain of *j-th* generator can take any value between its limits, since no other generator can damp mode *i*. On the other hand, if $p_{ji} = 0$, it is because generator *j-th* has no influence over mode *i*. In this way, the gain will be minimized with $w_{ji} = 1$. Of course, a real occurrence should be between these two extreme cases.

The system damping is determined calculating the eigenvalues of the state matrix, but only the electromechanical modes are considered to identify the problem solution. The eigenvalues determination is obtained by using MATLAB QR method routines. Therefore, this approach is limited by the capabilities of the routine used.

The solution of this problem can also be oriented just to deal with the poorly damped modes of the system.

By considering an objective function of this kind, it is then possible to indicate admissible locations to install PSS and let the algorithm select the best ones. This is an advantage relatively to other methods, which need a specification regarding where PSS are to be installed. By specifying such location, one is limiting the search space and eliminating solutions that could be more interesting.

The use of a tool such as the one described here has increased interest is situations where it is difficult to identify a "worst case" scenario, to design afterwards the PSS solution.

IV. Optimization Module

The determination of the solution of this problem is performed here using an Evolutionary Particle Swarm Optimization (EPSO) algorithm, inspired in both Evolutionary and in Particle Swarm Optimization algorithms, as described in [6],[7]. This method provides a very effective meta-heuristics searching approach in the solution searching space defined by the control variables.

The EPSO algorithm, recently developed, is quite robust and has the advantage of dealing easily either with continuous variables, which is the case of most of the variables involved in this PSS tuning problem, or with discrete variables (number of lead/lag blocks, in this case).

The solution of the objective function within the EPSO algorithm is obtained by adding a penalty to the objective function defined by equation (5), such that this penalty is proportional to the square deviation of the violated restrictions (in this case the system oscillation modes damping).

Each particle – a potential problem solution - is composed by the control variables of generators where it is possible to install PSS.

The particles are oriented towards the best solutions by adding to the present position (solution) a factor, called particle velocity. As in classical PSO, the velocity is defied as the sum of three factors (inertia, memory and cooperation), in this case weighted by self-adaptative parameters. This increases the robustness of the algorithm [6],[7].

The initial particles were selected randomly. In some cases, a particle, representing a good solution, may be given to the algorithm at the beginning of the searching procedure. This increases convergence speed but may also lead to a local optimum instead of the global optimum.

V. Numerical Results IN Test Systems

Two test systems have been used in this research to demonstrate the effectiveness of the developed approach. A simple two-area test system was used first to get a good view of the problem and of the results provided by the approach used. A larger system was exploited afterwards to show that good results could also be obtained independently of the dimension of the problem.

A. Two-Area System

A test system widely used for small signal stability studies was used here to demonstrate the performance of the used approach. This simple two-area system is shown in Fig. 1. Network and generator data can be found in [8].

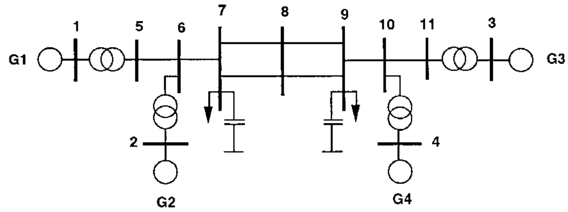

Fig. 1. Two-area test system

Synchronous generators are modeled using a six order model with magnetic saturation neglected. It was assumed that generators are equipped with a typical DC excitation system, modeled with an IEEE type 1 AVR model. The governor system was not represented. The complete system, without PSS, was therefore represented with 36 variables. All active and reactive loads are modeled using constant impedances.

In addition to the operating condition defined in [8], it was considered two additional different scenarios. The operating conditions studied are characterized by:

- OC1 – Base case;
- OC2 – A single line between bus 7 and 8;
- OC3 – Load decrease of 1000 MW.

The study of a small number of operating conditions allows, on a first stage, to demonstrate the performance of the proposed method while keeping the analysis simple.

The oscillation modes, for both operating conditions without PSS, are shown in Table I. The structure of the oscillations can be identified with a classical participation factor and mode shape analysis. For this system, the behavior of the initial oscillation modes is well known [8]-[10]. The higher frequency modes are associated to local oscillations. In contrast, the lower frequency mode is an inter-area mode, since it has a significant participation of all generators. The generator with greatest participation in inter-area mode is generator 3, which makes it the most suitable generator to install a PSS.

TABLE I
Electromechanicall Modes Without PSS

OC	No.	Real	Imag.	Damp. (%)	f(Hz)
1	1	-0.5604	7.0133	7.96	1.12
	2	-0.5569	6.7901	8.17	1.08
	3	-0.0146	3.3532	0.43	0.53
2	1	-0.5701	6.9805	8.14	1.11
	2	-0.5706	6.7551	8.42	1.08
	3	0.0050	2.5685	-0.20	0.41
3	1	-0.6474	6.7335	9.57	1.07
	2	-0.0591	4.1858	1.41	0.67

The approach described before was then used to find out a robust solution in terms of PSS and their parameters, such that the oscillations damping would increase for values larger than 10%. The PSS adopted are assumed to have a transfer function like the one described in (2). The PSS parameters were adjusted considering also typical limits, as described in literature. In the optimization process, the following limits were used: K = [0, 10], T = [2, 0.2] and α = [1, 30]. It was also assumed a fixed T_w = 5 s. Table II presents the results obtained with this approach.

The generators where the gain value of the PSS presents a value different from zero are the ones selected for PSS installation. Of course, the solution may not be the optimum one. Like any other algorithm based on meta-heuristics, this method does not guarantee that the global optimum value is found.

TABLE II
PSS PARAMETERS WITH PSS TUNED SIMULTANEOUSLY

Generator	K	N	T	α
1	0.26	2	2.00	30
2	0		Not Used	
3	1.03	2	1.99	18
4	0		Not Used	

In this example, only two generators were selected for PSS installation (generator 1 and 3). This corresponds to the expectations, since generator 3 has the highest participation on inter-area mode. It is also necessary to install a PSS on generator 1 because the effect of generator 3 in the local mode of area 1 is not significant.

With PSS parameters adjusted according to the values shown in Table II, the system modes are now the ones presented in Table III.

TABLE III
ELECTROMECHANICAL MODES WITH PSS TUNED SIMULTANEOUSLY

OC	No.	Real	Imag.	Damp. (%)	f(Hz)
1	1	-0.7640	7.4561	10.19	1.19
	2	-0.6887	6.8552	10.00	1.09
	3	-0.3320	3.3014	10.01	0.53
2	1	-0.7813	7.4269	10.46	1.18
	2	-0.7042	6.8186	10.27	1.09
	3	-0.3210	2.3455	13.56	0.37
3	1	-0.7808	6.7995	11.41	1.08
	2	-0.9863	4.2044	22.84	0.67

It is obvious that the designed PSS produced now the desired result, and the damping of all electromechanical modes increased to values above 10%. Next figure shows the movement of all oscillation modes on the s-plane, which confirm that all modes are shifted to the left half plane, (to the left of the 10% damping ratio line). It is worth to be mentioned that frequency of electromechanical modes does not change significantly, that indicates proper phase compensation, near 180 degrees.

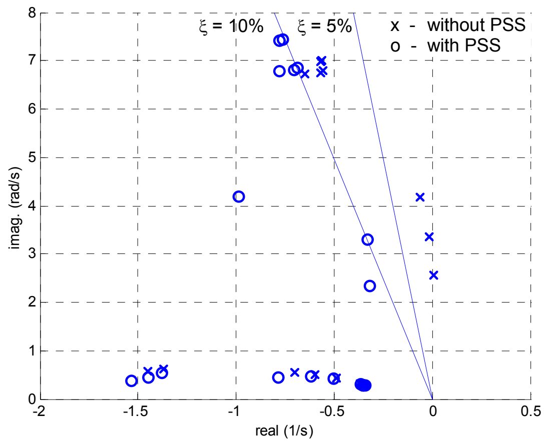

Fig. 2. Pole map of the operating conditions for two-area system

A different approach to solve the proposed problem would be tuning the PSS considering one scenario – "worst case" – instead of a simultaneous tuning. To identify the "worst case", it is clear that the best guess would be the contingency scenario, because of the higher transfer reactance and the existence of an instable mode in the initial operating condition. However, by analyzing Table III, we may observe that damping in operating condition 1 is lower, which does not agree with the guess.

To determine if OC2 is the "worst case", the proposed method was applied just to this scenario. Therefore, if the guess is correct, it is expected that the solution found produces satisfactory results in the other scenario. The PSS parameters obtained are presented in Table IV and the resulting modes in both scenarios are shown in Table V.

TABLE IV
PSS PARAMETERS WITH PSS TUNED FOR OC2 ONLY

Generator	K	N	T	α
1	0.22	2	2.00	30
2	0		Not Used	
3	0.95	2	2.00	30
4	0		Not Used	

TABLE V
ELECTROMECHANICAL MODES WITH PSS TUNED FOR OC2 ONLY

OC	No.	Real	Imag.	Damp. (%)	f(Hz)
1	1	-1.1993	7.3170	16.18	1.16
	2	-0.6694	6.8459	9.73	1.09
	3	-0.2828	3.2133	8.77	0.51
2	1	-1.2175	7.2797	16.50	1.16
	2	-0.6840	6.8089	10.00	1.08
	3	-0.2315	2.3043	10.00	0.37
3	1	-0.7612	6.7898	11.14	1.08
	2	-0.7285	3.8579	18.55	0.61

One can observe that with the adjustments of Table IV the damping of modes for OC1 (described in Table V) are bellowing the requirement (over 10% damping). On other side, if we perform the PSS adjustment only with scenario 1, the results obtained are not significantly different from the ones obtained with simultaneous design.

From these results, it is possible to conclude that the guess was wrong: the “worst case” is scenario 1. These results demonstrate that is not always possible to identify the “worst case” base on simple rules. When applying PSS there are several factors involved other than damping of initial scenario. For instance, it has to be considered the influence that a PSS will have on damping. This can be done with a careful analysis of the speed participation factors for the inter-area mode. For the operating conditions considered, we verify that, although normalized participation factor does not change significantly, the absolute value (in p.u.) is larger when transmission system is weaker. It should not be forgotten that phase compensation also varies with operating conditions.

Although modal analysis is a powerful tool, it should be kept in mind that power systems are nonlinear. Therefore, to demonstrate the effectiveness of the presented method, and the validity of results produced, it was simulated a disturbance in the system, with and without the PSS. Fig. 4 and Fig. 5 describe the oscillation obtained after a disturbance in the system, using the PSS/E simulation package, for some of the considered scenarios. Solid lines describe the system behavior before installing PSS and dashed lines describe it after installing these devices. It can be observed from these figures that, after installing the PSS with the parameters identified with the described approach, the system increased considerably its damping.

Finally, it should be mentioned that the EPSO performance was essential to the success of the proposed approach. As mentioned, the problem of PSS robust tuning is complex, and requires heavy computation.

B. New England System

In this part of the study, the 10 machines 39 bus power system, known as New England Test System, is used to demonstrate the effectiveness of the proposed method in larger systems. The one-line diagram is shown on Fig. 6. and details of system data can be found in [12]. Generator 1 represents an equivalent of a large system. Electrical generators are represented here with a fourth order model. Excitation system was represented with an IEEE type 1 AVR model. The governor system was represented considering typical models. This results in a state matrix with a dimension of 94x94. All active and reactive loads are represented with a constant impedance model.

Five operating conditions were considered:

- OC1 – Base case;
- OC2 – Lines 3-18 and 25-26 out of service;
- OC3 – Lines 17-16 and 4-14 out of service;
- OC4 – Line 6-11 out of service;

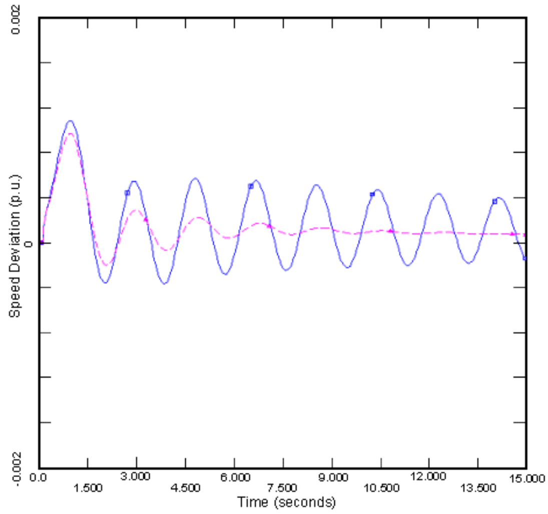

Fig. 3. Response of generator 3 speed deviation to a three-phase fault in bus 7 (10ms duration) for two-area system OC1

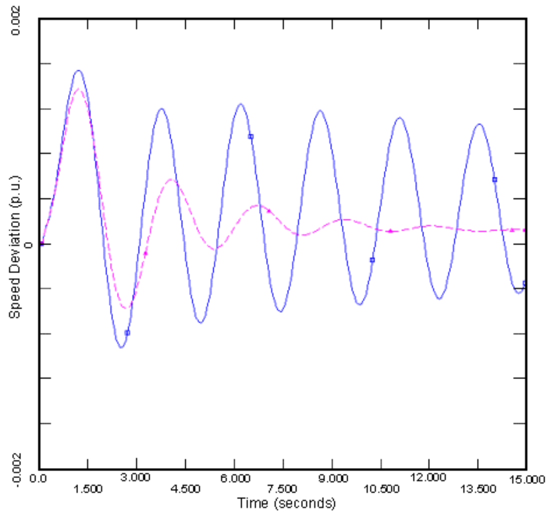

Fig. 4. Response of generator 3 speed deviation to a three-phase fault in bus 7 (10ms duration) for two-area system OC2

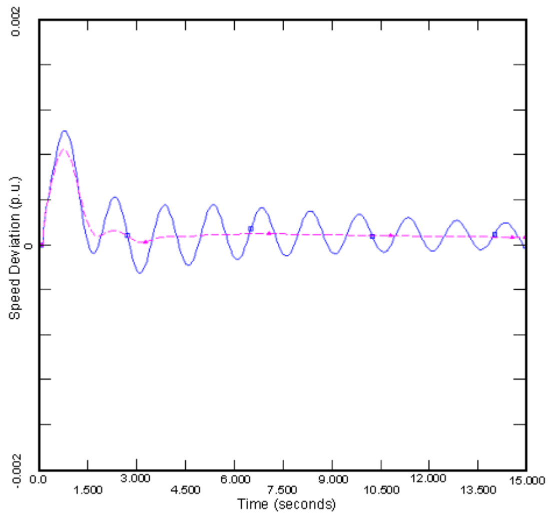

Fig. 5. Response of generator 3 speed deviation to a three-phase fault in bus 7 (10ms duration) for two-area system OC3

- OC5 – 15% Load increase;
- OC6 – 30% Load decrease.

Without PSS the system exhibits low damped modes. The lower frequencies correspond to inter-area modes characterized by oscillations between groups of generators.

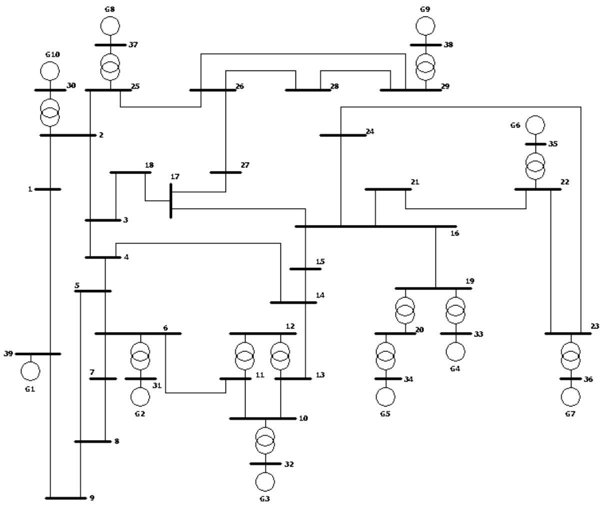

Fig. 6. New England test system

In this situation the selection of the "worst-case" scenario becomes even more difficult, due to the large dimension of the system. In the OC5 operating point the load of the system is larger, on the other hand, in the cases where lines were considered to be out of service, the transfer reactances are larger. Probably scenario OC6 would be the less problematic situation.

For this system, the following limits were used in the optimization process: K = [0, 100], T = [2, 0.2] and α = [1, 30]. It was also assumed a fixed T_w = 5 s.

The solution found corresponds to the installation of PSS in all the generators where this possibility was admitted by the approach. The PSS parameters obtained are presented in Table VI. The oscillation modes, for the 6 scenarios, obtained without and with the PSS, adjusted with the parameters obtained, are presented in next figure.

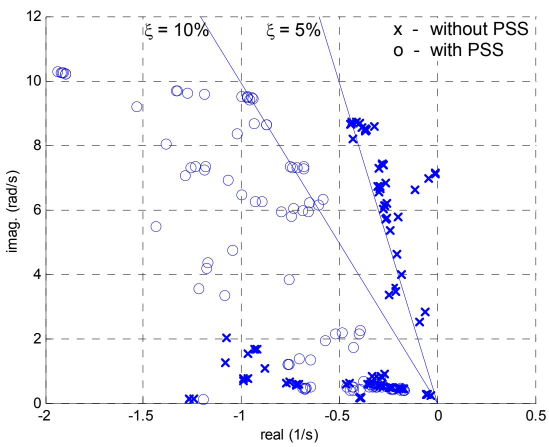

Fig. 7. Pole map of the operating conditions for New England system

It can be verified that after the installation of the PSS the oscillation modes are now well damped and with a damping generally large than 10%. However, in a very few cases it was not possible to obtain the specified damping conditions, although the obtained values were very near the project targets.

The frequency deviations in some modes are considerable high, as it can be observed from the imaginary values of the pole map presented in figures 7. In fact it was not considered any restriction regarding this kind of deviation in the initial problem formulation. However, if such a restriction would be included it would be expected a reduction in the obtained damping. This results from the difficulty in introducing the necessary phase compensation.

TABLE VI
PSS PARAMETERS FOR NEW ENGLAND SYSTEM

Generator	K	N	T	α
2	10.42	2	1.02	29
3	6.65	2	0.20	20
4	24.61	2	0.52	30
5	0		Not Used	
6	12.35	2	0.92	30
7	60.10	2	0.20	20
8	35.76	2	0.53	30
9	6.78	2	0.49	30
10	67.84	2	0.79	28

In order to validate and evaluate the quality of the results obtained, time domain simulations were also performed here. For that purpose a short-circuit was simulated in bus 28 with a duration of 100 ms. In Figures 8, 9 and 10 selected results are shown. As it can be observed the generator speeds become rapidly damped after the installation of the PSS tuned with the parameters determined used the described approach.

VI. CONCLUSIONS

The approach described here to identify the location of the installation of PSS and to produce their tuning, shown to be well succeeded in producing robust solutions to assure well damping characteristics in several operating conditions.

The adoption of EPSO, to deal with this optimization problem, also revealed excellent performance that contributed for the success of the described approach.

The results obtained lead to:

1. selection of a reduced number of generators where PSS should be installed;
2. considerable increase in damping of the electromechanical oscillations for all the scenarios considered.

The approach described in this paper can be considered as a new tool for the identification of good solutions in the search space.

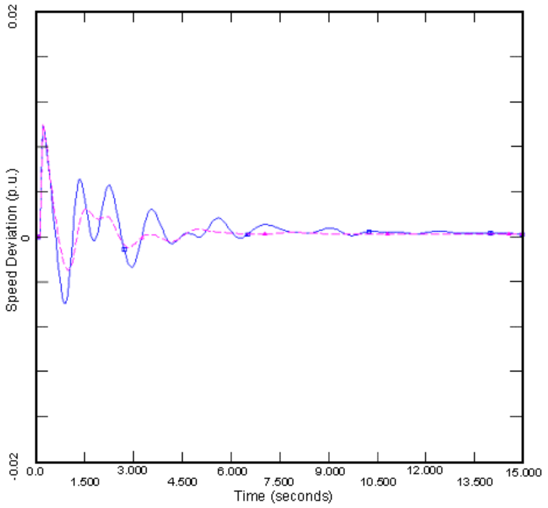

Fig. 8. Response of generator 9 speed deviation to a three-phase fault in bus 28 (100ms duration) for New England system OC1

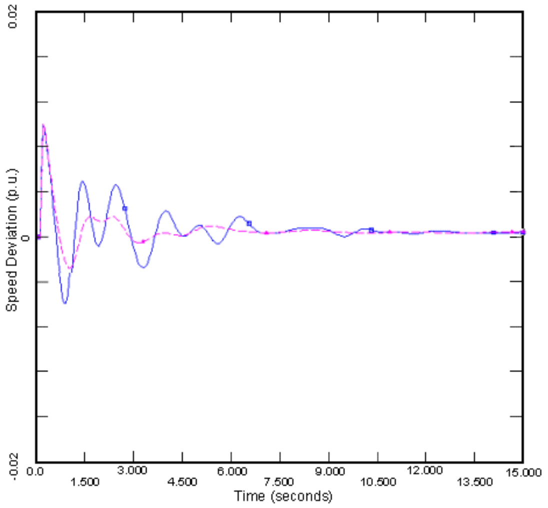

Fig. 9. Response of generator 9 speed deviation to a three-phase fault in bus 28 (100ms duration) for New England system OC4

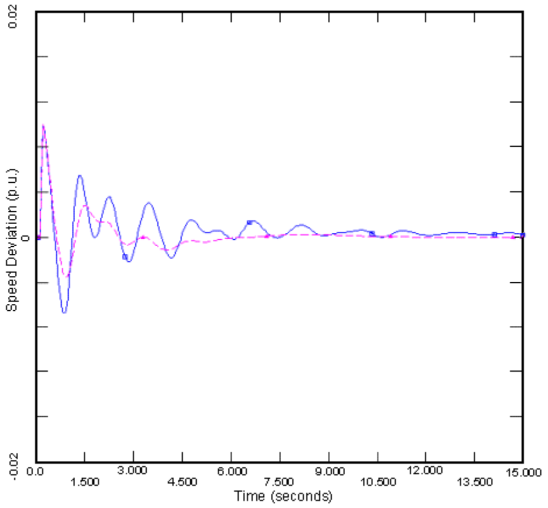

Fig. 10. Response of generator 9 speed deviation to a three-phase fault in bus 28 (100ms duration) New England system OC5

The adoption of such an approach to identify the parameters of PSS requires, however, a careful analysis of the obtained results in order to identify possible implementation difficulties.

VII. Acknowledgment

The authors want to express their deep gratitude to Mr. Nuno Fonseca and to Prof. Vladimiro Miranda, that developed the EPSO concepts and the optimization package used as optimization motor in this research.

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IX. Biographies

Ângelo Mendonça is a researcher at of the Power Systems Unit of INESC Porto. He obtained an Electrical Engineering degree (5 years course) in 2000 from Faculty of Engineering of University of Porto, and is currently in the final stages of the preparation of his MSc dissertation.

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