

# Simultaneous Coordinated Tuning of PSS and FACTS Controller for Damping Power System Oscillations in Multi-Machine Systems

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**Abstract**—This paper deals with the simultaneous coordinated tuning of the FACTS (Flexible AC Transmission Systems) POD (Power Oscillation Damping) controller and the conventional PSS (Power System Stabilizer) controllers in multi-machine power systems. Using the linearized system model and the parameter-constrained nonlinear optimization algorithm, interactions among FACTS controller and PSS controllers are considered. Furthermore, their parameters are optimized simultaneously. Simulation results of multi-machine power system validate the efficiency of this new approach. The proposed algorithm is an effective method for the tuning of multi-controllers in large power systems.

**Index Terms**— Comprehensive Damping Index (CDI), Coordination, Damping control, FACTS, Interaction, Nonlinear optimization, POD, PSS, Tuning.

## I. INTRODUCTION

DAMPING of power system oscillations between interconnected areas is very important for the system secure operation. Besides PSS, FACTS devices are also applied to enhance system stability [3,8,13]. Particularly, in multi-machine systems, using only conventional PSS may not provide sufficient damping for inter-area oscillations. In these cases, FACTS POD controllers are effective solutions. Furthermore, in recent years, with the deregulation of the electricity market, the traditional concepts and practices of power systems have changed. Better utilization of the existing power system to increase capacities by installing FACTS devices becomes imperative. FACTS devices are playing an increasing and major role in the operation and control of competitive power systems.

However, uncoordinated local control of FACTS devices and PSSs always causes destabilizing interactions. To improve overall system performance, many researches were made on the coordination between PSSs and FACTS POD controllers [7-11]. Some of these methods are based on the complex nonlinear simulation [7,8], the others are based on the linearized power system model.

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In this paper, an optimization based tuning algorithm is proposed to coordinate among multiple controllers simultaneously. This algorithm optimizes the total system performance by means of sequential quadratic programming method. By minimizing the objective function in which the influences of both PSSs and FACTS POD controllers are considered, interactions among these controllers are improved. Therefore, the overall system performance is optimized.

This paper is organized as follows: Following the introduction, the test system comprising a series FACTS and 16 generators equipped with PSS is described. In section 3, the PSSs and FACTS POD controllers are introduced. In section 4, the simultaneous tuning method is discussed in detail. The simulation results are given in section 5. Finally, brief conclusions are deduced.

## II. MULTI-MACHINE TEST SYSTEM

A 16-machine 68-bus system [1] modified with series FACTS devices, as shown in Fig. 1, is simulated in this study. Each generator is described by a 6<sup>th</sup> order model and the FACTS devices are simulated using power injection model [5,7].

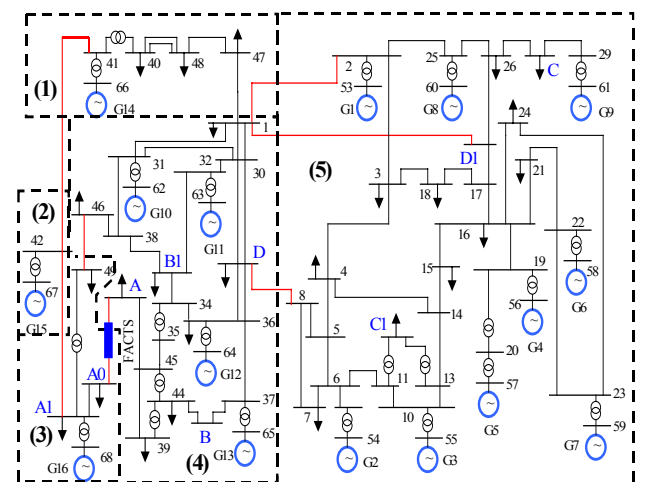


Fig. 1. 16-machine five areas power system

By means of the modal analysis, this system is divided into 5 areas [1]. Because there are three tie lines between area 4

and area 5, the main inter-area oscillation is between area 3 and area 4.

Series FACTS devices are the key devices of the FACTS family and are recognized as an effective and economical means to damp power system oscillation. Therefore, in this research, the series FACTS device is employed for damping of inter-area oscillations. It is located between bus A and bus A0 (on the tie line between area 3 and area 4). The location is determined using the residue algorithm for damping of inter-area oscillations [4].

### III. PSS AND FACTS POD CONTROLLER

#### A. PSS

PSS acts through the excitation system to import a component of additional damping torque proportional to speed change. It involves a transfer function consisting of an amplification block, a wash out block and two lead-lag blocks [1]. The lead-lag blocks provide the appropriate phase-lead characteristic to compensate the phase lag between the exciter input and the generator electrical torque. The structure of the used PSS is illustrated in Fig. 2.

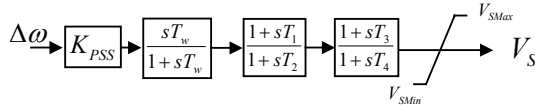


Fig. 2. PSS controller

#### B. FACTS POD Controller

In general, the structure of series FACTS POD controller, as shown in Fig. 3, is similar to the PSS controllers [3].

Commonly, local signals of FACTS devices are applied for the damping control. In this simulation, the active power flow through the series FACTS device  $P_{line}$  is employed. The output is  $V_{Series}$  which represents the controlled variable of the series FACTS devices. For example, for TCSC (Thyristor Controlled Series Capacitor) it is the value of the series capacitance [3] and for UPFC (Unified Power Flow Controller) it is the series injected voltage, which is in perpendicular to the line current [14,15].

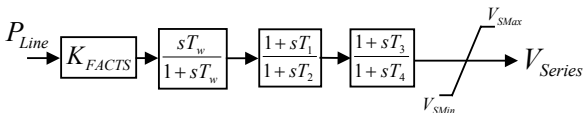


Fig. 3. FACTS POD controller

#### C. Allocation and Parameter Tuning of PSS and FACTS Controllers — Conventional Approach

Originally, the aim of tuning FACTS controllers is to damp power system oscillations on the tie lines where the FACTS devices are installed. The intention of PSSs tuning is

particularly the damping of local modes. Well-designed PSS and FACTS POD controllers can provide damping over a wide range of system operating conditions. Based on modern control theory, the design methods for PSS and FACTS controllers are well developed for single-machine systems [3]. However, the design of PSS and FACTS controllers in multi-machine systems is much more complicated than that in single machine system. Commonly, the conventional tuning methods are always based on the modal analysis and the process is shown as follows [12]:

Firstly, the locations of PSS and FACTS devices can be determined using participation factors and residue method respectively. Then, FACTS and PSS controllers are designed based on their selected locations [1,4,12]. For this design, different methods can be used [3,7,8]. Furthermore, the settings of the controller will be verified under various operating conditions. Finally non-linear simulations under critical faults will also be simulated in validating the performance of the controller settings.

In order to minimize the adverse interactions among PSS and FACTS controllers, parameters of each controller are always determined sequentially and separately. However, these so determined controller parameters cannot achieve the global optimal damping behavior. Moreover, the damping task is not properly allocated to each controller.

### IV. SIMULTANEOUS TUNING METHOD

Many researches were made on the parameter tuning. In [8], non-linear optimization based global tuning procedures are introduced for minimizing the interactions among the FACTS and PSS controllers. The non-linear model based tuning method considers complex dynamics of power system, especially during critical faults [8]. However, these non-linear simulation based methods need much more time than linear methods [7]. Therefore, in practice, modal analysis based methods are more common.

In this section, an optimization based method for simultaneous tuning of the FACTS and PSS controllers is presented.

The objective of the simultaneous parameter tuning is to globally optimize the overall system damping performance. This requires the simultaneous optimization and coordination of the parameter settings of the FACTS and PSS controllers to maximize the damping of all modes of oscillations: for instance local modes, inter-area modes, exciter modes and other controller modes.

In this work, the parameters of each PSS and FACTS POD controller are determined simultaneously using nonlinear programming technique [7]. The main procedure is as follows:

1. System linearization for analyzing the dominant oscillation modes of the power system;
2. Allocation of controllers based on the participation factors and the residue method;
3. Using the parameter constrained non-linear optimization to optimize the global system behavior.

This paper focuses on the last point concerning the optimization based parameter setting. Furthermore, in order to cope with the non-linear nature of the power system, a particular range of system operating conditions will also be studied to verify the capability of the optimized controller setting.

#### A. Linearized System Model

Once the optimal locations of the controllers are chosen, the total linearized system model extended by PSS and FACTS devices can be derived and represented by the following equation:

$$\begin{aligned} \dot{\Delta \mathbf{x}} &= \mathbf{A}\Delta \mathbf{x} + \mathbf{B}\Delta \mathbf{u} \\ \Delta \mathbf{y} &= \mathbf{C}\Delta \mathbf{x} + \mathbf{D}\Delta \mathbf{u} \end{aligned} \quad (1)$$

From (1), the eigenvalues  $\lambda_i = \sigma_i \pm j\omega_i$  of the total system can be evaluated. The proposed method is to search the best parameter sets of the controllers, so that a Comprehensive Damping Index (CDI) (2) can be minimized:

$$CDI = \sum_{i=1}^n (1 - \zeta_i) \quad (2)$$

where  $\zeta_i = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}}$  is the damping ratio and  $n$  is the

total number of the dominant eigenvalues which include the inter-area modes, local modes, exciter modes and controller modes, as shown in Fig. 4. This index includes the influences of both FACTS POD controller and PSS controllers.

Among the dominant eigenvalues, only those, which have a damping ratio less than 0.1 are considered in the optimization. The objective of the optimization is to move the total considered eigenvalues to left, and thus to maximize the damping ratio as much as possible.

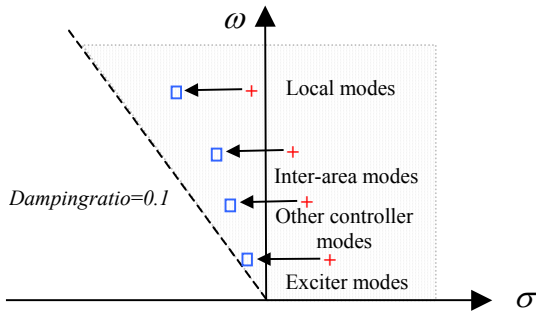


Fig. 4. Objective of the optimization based tuning  
 + : Eigenvalues before the optimization  
 ■ : Eigenvalues after the optimization

In order to minimize (2), the nonlinear optimization technique implemented in Matlab is employed.

#### B. Non-Linear Optimization Technique

The objective of the parameter optimization can be formulated as a nonlinear programming problem expressed as follows:

$$\begin{aligned} \min. \quad & f(\mathbf{z}) = CDI = \sum_{i=1}^n (1 - \zeta_i) \\ \text{s.t.} \quad & E(\mathbf{z}) = 0 \\ & F(\mathbf{z}) \geq 0 \end{aligned} \quad (3)$$

where  $f(\mathbf{z})$  is the objective function defined as (2).  $\mathbf{z}$  is a vector, which consists of the parameters of the PSSs and FACTS POD controllers have to be tuned. In this paper,  $\mathbf{z}$  contains the amplification part of the FACTS POD controller ( $K_{FACTS}$ ) and those of all PSS controllers ( $K_{PSS}$ ).

$E(\mathbf{z})$  are the equality functions and  $F(\mathbf{z})$  are the inequality functions respectively. For the proposed method, only the inequality functions  $F(\mathbf{z})$ , which represent the parameter constrains of each controller, are necessary.

The above-mentioned objective is a general parameter-constrained nonlinear optimization problem and can be solved successfully. In this paper, the Matlab Optimization Toolbox is applied [6].

The flow chart of the optimization based coordinated tuning algorithm is shown in Fig. 5.

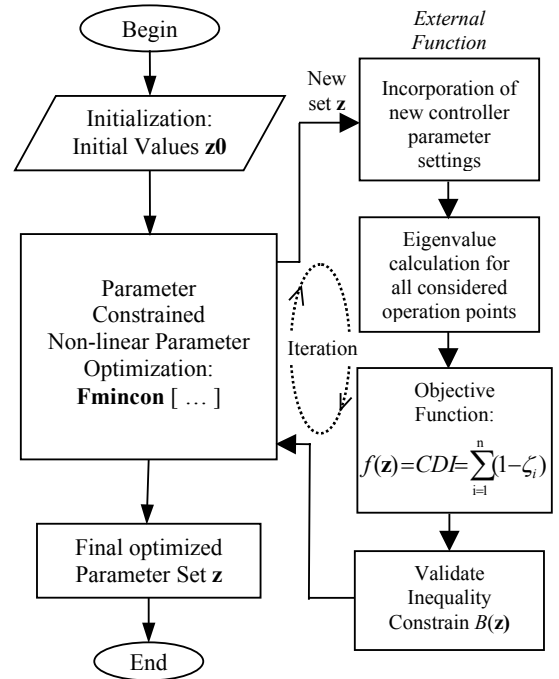


Fig. 5. Flow chart of optimization based coordinated tuning

The optimization starts with the pre-selected initial values of the controllers:  $\mathbf{z}_0$ . Then the nonlinear algorithm is employed to adjust the parameters iteratively, until the objective function (2) is minimized. These so determined parameters are the optimal settings of the FACTS POD controller and PSS controllers.

The proposed method allows considering several operating points of the system simultaneously. In this case, the CDI is calculated for each state successively and added to a global CDI provided for the optimization algorithm.

### C. Application

In comparison with the approach in [7,8], this algorithm calculates more rapidly for every state of the power system. It is an effective method for tuning of controllers in large power systems.

Particularly, the optimized setting of PSS and FACTS controllers should produce a damping torque over a wide range of operation conditions. Therefore, in practice, it is necessary to optimize the controller settings under different possible operating conditions, which can be done simultaneously. Thus, the proposed tuning method provides robust solutions.

## V. SIMULATION RESULTS

To verify the performance of the proposed tuning method, the algorithm is tested in a multi-machine system as shown in Fig. 1. In this system, all machines are equipped with static exciters and PSS. The series FACTS device is located between the bus A and bus A0.

### A. Dominant Eigenvalues.

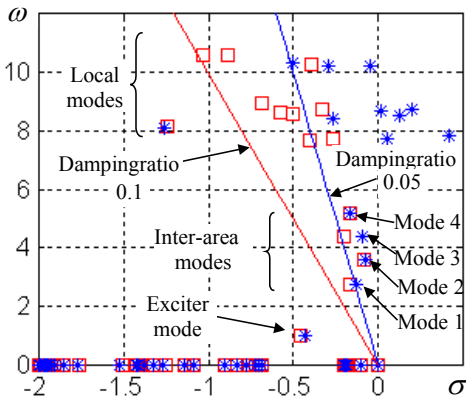


Fig. 6. Results of the conventional controller tuning  
\* Eigenvalues without any controller.  
□ Eigenvalues with PSS and FACTS controllers.

First, the test system is evaluated without FACTS and PSS controllers. As shown in Fig. 6, the examined system is unstable.

After the conventional sequentially design of PSS and FACTS controllers, i.e. without coordinated tuning, the power system becomes stable. However, the damping ratio of some local modes (1.2111Hz, 1.4426Hz and 1.7528Hz mode) and some inter-area modes (Inter-area mode 2, 3 and 4) are not satisfactory.

### B. Root-locus

The root locus for varying the gain of series FACTS controller  $K_{FACTS}$  from 0 to 100, is shown in Fig. 7. It is obvious that a gain of 100 sufficiently increases the damping of the 0.43168Hz mode (Inter-area mode 1). However, when  $K_{FACTS}$  is beyond 70, the damping ratio of the 0.56863Hz mode (Inter-area mode 2) and 0.68184Hz mode (Inter-area mode 3) will be lightly reduced again. Furthermore, with the increase of the gain of FACTS controller, the damping ratio of exciter mode (0.1588Hz) is reduced significantly and will be unstable.

It is also clear that the FACTS POD controller has little influence on the local modes whereas some PSSs have significant influence on the inter-area modes. Therefore, the simultaneous coordinated tuning between FACTS POD controller and PSS controllers is necessary.

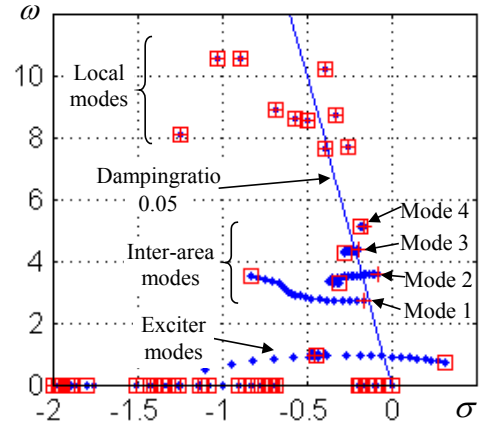


Fig. 7. Results of the conventional controller tuning  
• Root locus when  $K_{FACTS}$  vary from 0 (+) to 100 (□).

### C. Optimized System Performance

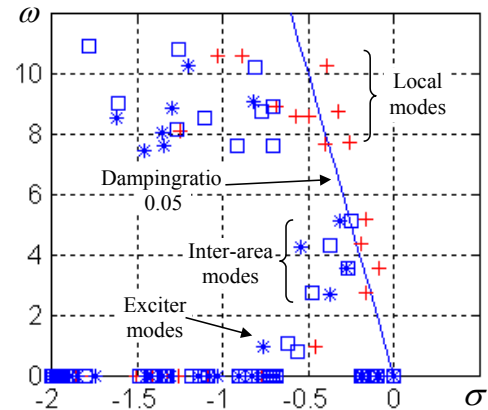


Fig. 8. Optimization based coordinated tuning results  
+ Eigenvalues before optimization;  
\* Eigenvalues after optimization;  
□ Eigenvalues when loss of two tie-lines between area 4 and area 5.

After the coordinated tuning, as shown in Fig. 8, local

modes, inter-area modes and the exciter modes of oscillations are now well damped. All the damping ratios of dominant modes are more than 5%. Simulation results demonstrate the improvement in damping of overall power oscillations in the system. The detailed controller parameters are shown in Appendix A and the final dominant modes, damping ratios and frequencies are given in Appendix B.

#### D. System Performance under Different Operating Conditions

In practice, in order to achieve the robustness of the coordinated tuning, the controller settings need to be optimized under different possible operation conditions.

In this study two tie-lines (line 1-2, line D-8) between the areas 4 and area 5 are disconnected to verify the performance of the optimized controller settings.

The eigenvalues for this state is also shown in Fig. 8. In the new operating point, the damping ratio of inter-area mode 1 (0.43168Hz mode) is improved but the damping ratios of the other three modes of inter-area oscillations are reduced. Although the eigenvalue of inter-area mode 3 (0.68184Hz mode) moves to the right side significantly, its damping ratio remains in a sufficient range. Even if some local modes are also changed, their damping ratios are still favorable.

#### E. Non-linear Simulation Result

In order to validate the performance of the coordinated tuning, large disturbances were simulated in the test system. In this paper, a three-phase short circuit of 100ms duration is simulated at bus A in area 4.

For evaluation of the system damping behavior, the corresponding center of power angles (COA) [2] of each area ( $\delta_{Area3}$ ,  $\delta_{Area4}$ ) are employed:

$$\begin{aligned}\delta_{Area3}(t) &= \frac{\sum_{k \in Area3} S_k H_k \delta_k(t)}{\sum_{k \in Area3} S_k H_k} \\ \delta_{Area4}(t) &= \frac{\sum_{k \in Area4} S_k H_k \delta_k(t)}{\sum_{k \in Area4} S_k H_k}\end{aligned}\quad (7)$$

where

$H_k$  — The inertia constant of the  $k^{\text{th}}$  generator;

$S_k$  — The base power of the  $k^{\text{th}}$  generator.

The simulation results in Fig. 9, validates the proposed tuning method under large disturbance. It can be seen that not only the damping behavior but also the transient stability, which is characterized by the first swing magnitude, is improved significantly.

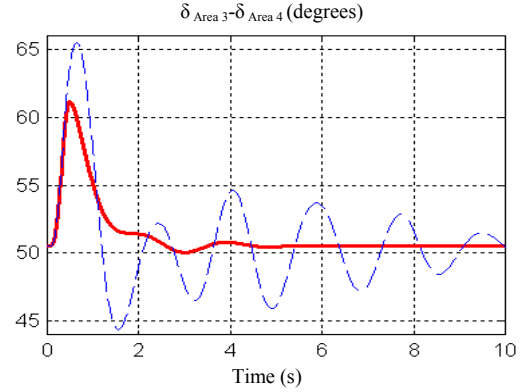


Fig. 9. Non-linear simulation results  
 --- System behavior before the coordinated tuning  
 — System behavior after the coordinated tuning

## VI. CONCLUSIONS

This paper presents an algorithm for the simultaneous coordinated tuning of the series FACTS POD controller and PSS controllers in multi-machine system. The algorithm is based on the linearized power system model and parameter constrained nonlinear optimization technique. Using this method no system simplifications are required, and therefore, the overall system performance will be optimized. Non-linear simulation has proved that with the calculated controller settings the system will be stable and power system oscillations are well damped also in case of large operation discursions. The method is also simple and easy to be realized in large power systems.

Although only the series FACTS device is simulated in the proposed multi-machine system, the algorithm is generally applicable to other types of FACTS devices too.

## VII. APPENDICES

### Appendix A: Results of the Coordinated Tuning

TABLE I  
OPTIMIZED CONTROLLER PARAMETERS

No.	Type.	Gain	$T_w$	$T_1$	$T_2$	$T_3$	$T_4$
G1	PSS	85.8	10	0.08	0.01	0.08	0.01
G2	PSS	85.8	10	0.08	0.01	0.08	0.01
G3	PSS	90.55	10	0.04	0.02	0.1	0.01
G4	PSS	70.66	10	0.08	0.02	0.08	0.02
G5	PSS	66.72	10	0.05	0.01	0.08	0.02
G6	PSS	66.72	10	0.05	0.01	0.08	0.02
G7	PSS	66.72	10	0.05	0.01	0.08	0.02
G8	PSS	87.15	10	0.08	0.01	0.08	0.02
G9	PSS	89.69	10	0.05	0.01	0.05	0.02
G10	PSS	92.74	10	0.08	0.01	0.08	0.02
G11	PSS	60.00	10	0.08	0.03	0.05	0.01
G12	PSS	85.8	10	0.08	0.01	0.08	0.01
G13	PSS	80.55	10	0.04	0.01	0.05	0.01
G14	PSS	80.55	10	0.04	0.01	0.05	0.01
G15	PSS	80.55	10	0.05	0.01	0.04	0.01
G16	PSS	75.06	10	0.03	0.02	0.05	0.01
17	FACTS	76.00	10	0.05	0.01	0.05	0.02

## Appendix B: Dominant Oscillation Modes

TABLE II  
DOMINANT OSCILLATION MODES

	Eigenvalues After Optimization	Frequency (Hz)	Damping Ratio	
			Before Optimization	After Optimization
<b>Exciter Mode</b>	-0.77±0.99i	0.1588	0.42299	0.60833
<b>Inter-Area Modes</b>	-0.37±2.71i	0.43168	0.061066	0.1359
	-0.28±3.57i	0.56863	0.023607	0.076861
	-0.55±4.28i	0.68184	0.04534	0.12672
	-0.32±5.13i	0.81645	0.032769	0.061816
<b>Local Modes</b>	-10.1±6.78i	1.0795	0.83104	0.82941
	-1.46±7.48i	1.1901	0.82323	0.19182
	-10.4±7.51i	1.1953	0.052032	0.80991
	-1.34±7.61i	1.2111	0.034204	0.17397
	-1.35±8.05i	1.2811	0.80398	0.16554
	-8.41±8.05i	1.2815	0.15185	0.7225
	-1.62±8.53i	1.3581	0.76757	0.18628
	-7.997±8.8i	1.3992	0.058226	0.67288
	-1.3±8.89i	1.4144	0.066857	0.14482
	-2.53±8.96i	1.4257	0.76674	0.27133
	-0.82±9.06i	1.4426	0.037742	0.090167
	-9.28±9.82i	1.5622	0.076926	0.68684
	-1.2±10.24i	1.6308	0.69868	0.11671
	-9.08±10.8i	1.7258	0.038234	0.64183
	-3.5±10.9i	1.7388	0.084028	0.3049
-5.4±11.89i	1.8915	0.097096	0.41557	

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## IX. BIOGRAPHIES



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