Coordinated Design of TCSC and PSS for Mitigating Inter-Area Oscillation

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Abstract: *Interconnection of electric power systems is becoming increasingly widespread as part of the power exchange between countries as well as regions within countries in many parts of the world. These long distance power transfers cause, however, the system low-frequency oscillations to become more lightly damped. As a result, many power network operators are taking steps to add supplementary damping devices in their systems to improve the system security by damping these undesirable oscillations.*

The objective of this paper is to study the power system stability enhancement via power system stabilizers (PSSs) and Flexible AC Transmission System (FACTS) based controller namely thyristor controlled series capacitor (TCSC).This study includes possible coordination between PSSs and TCSC. This paper utilizes a control scheme to mitigate inter-area oscillations in power systems using FACTS controller. The nonlinear time-domain simulation is carried out to validate the effectiveness of the proposed coordination controllers to damp system oscillations. The performance of control strategy of stabilizing controller using PSS and TCSC has been tested by simulation study. Simulation results on two area multi-machines test system show that the power system critical mode of oscillations are damped out effectively after disappearing the disturbance in the system and the controller's performance is robust to changes in operating condition of the system.

Keywords: *Power system,interarea oscillations,PSS,FACTs devices,TCSC*

1. INTRODUCTION

Today's Power system is a complex network, sometimes made of thousands of buses and hundreds of generators. Available power generation usually does not situated near a growing of load centre. In order to meet the growing power demand, utilities have an interest in better utilization of available power system capacities, existing generation and existing power transmission network, instead of building new transmission lines and expanding substations. On the other hand, power flows in some of the transmission lines are overloaded, which has as an overall effect of deteriorating voltage profiles and decreasing system stability and security. In addition, existing traditional transmission facilities, in most cases, are not designed to handle the control requirements of complex and highly interconnected power systems. This overall situation requires the review of traditional transmission methods and practices, and the creation of new concepts, which would allow the use of existing generation and transmission lines up to their full capabilities without reduction in system stability and security.

Series capacitor, shunt capacitor, and phase shifter are different approaches to increase the power system loadability. In past decades, all these devices were controlled mechanically and were, therefore, relatively slow. They are very useful in a steady state operation of power systems but from a dynamical point of view, their time response is too slow to effectively damp transient oscillations. If mechanically controlled systems were made to respond faster, power system security would be significantly improved, allowing the full utilization of system capability while maintaining adequate levels of stability. This concept and advances in the field of power electronics led to a new approach introduced by the Electric Power Research Institute (EPRI) in the late 1980 Called Flexible AC Transmission Systems or simply FACTS, it was an answer to a call for a more efficient use of already existing resources in present power systems while maintaining and even improving power system security[10]. In [6], the author introduced this new concept, initiating a new direction in power system research. Developments in the field of high voltage power electronics have made possible the practical realization of FACT controllers.

The potential benefits of using Flexible AC Transmission system (FACTS) controllers for enhancing power system stability are well known. The use of these controllers gives grid planners and operators a greater flexibility regarding the type of control actions that can be taken at any given time. Thyristor Controlled Series Capacitors (TCSC), in particular, have been widely studied and reported in the technical literature, and have been shown and used in practice to significantly enhance system stability [1], [2].

There have been a number of attempts to derive an accurate analytical model of a TCSC that can be employed in system stability studies and controller design [3,4,5,8]. The model presented in [3] uses a special form of discretisation, applying Poincare mapping, for the particular Kayenta TCSC installation. The model derivation for a different system will be similarly tedious and the final model form is not convenient for the application of standard stability studies and controller design theories especially not for larger systems. A similar final model form is derived in [4], and the model derivation is improved since direct discretisation of the linear system model is used, however it suffers other shortcomings as the model in [3]. The modeling principle reported in [5] avoids discretisation and stresses the need for assuming only line current as an ideal sine, however it employs rotating vectors that might be difficult to use with stability studies, and only considers the open loop configuration. The model in [5] is also oversimplified because of the use of equivalent reactance and equivalent capacitance that might be deficient when used in wider frequency range. Most of these reported models are therefore concerned with a particular system or particular type of study, use overly simplified approach and do not include control elements or Phase Locked Loops (PLL)[10].

The objective of this paper is to investigate the power system stability enhancement via power system stabilizers (PSSs) and Flexible AC Transmission System (FACTS) based controller. This study includes coordination design between PSSs and FACTS-based controller. The procedure to achieve the objective is as follows:

1. The existing system is studied with and without local PSS by simulating on MATLAB tools.
2. The system is studied with PSS and after incorporating TCSC.
3. A comparison is made for above cases by simulating on MATLAB tools.

2. POWER SYSTEM STABILIZERS

The Power System Stabilizer (PSS) is a device that improves the damping of generator electromechanical oscillations. Stabilizers have been employed on large generators for several decades; permitting utilities to improve stability constrained operating limits. Although the main objective of PSS is to damp out oscillations it can have strong effect on power system transient stability. As PSS damps oscillations by regulating generator field voltage it results in swing of VAR output [1]. So the PSS gain is chosen carefully so that the resultant gain margin of Volt/VAR swing should be acceptable. To reduce this swing the time constant of the wash-out filter can be adjusted to allow the frequency shaping of the input signal [4]. Again a control enhancement may be needed during the loading /un-loading or loss of generation when large fluctuations in the frequency and speed may act through the PSS and drive the system towards instability. A modified limit logic will allow these limits to be minimized while ensuring the damping action of PSS for all other system events. Apart from the low frequency oscillations the input to PSS also contains high frequency turbine- generator oscillations which should be taken into account for the PSS design. So emphasis should be on the study of potential of PSS-torsional interaction and verify the conclusion before commission of PSS [7].

When disturbed by a sudden change in operating conditions, the generator speed and electrical power will vary around their steady-state operating points.

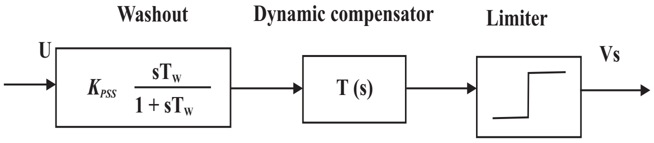

Fig. 1. Basic block diagram of a PSS

The relationship between these quantities can be expressed in a simplified form of the "swing equation":: The "Swing Equation" where:

$$\frac{2H}{\omega 0}\frac{d^2\delta}{dt^2} = T_m - T_e - K_D\Delta\omega_r$$

For small deviations in rotor speed, the mechanical and electrical torques are approximately equal to the respective per unit power values. The base value of power is selected to be equal to the generator nameplate MVA.

Unfortunately improvements in synchronizing torque are often achieved at the expense of damping torque, resulting in reduced levels of oscillatory or small-signal stability. To counteract this effect, many units that utilize high-gain automatic voltage regulators are also equipped with power system stabilizers to increase the damping coefficient (TD) and improve oscillatory stability.

3. Thyristor Controlled Series Capacitor (TCSC)

Thyristor Controlled Series Capacitor (TCSC) is a series FACTS device which allows rapid and continuous changes of the transmission line impedance. It has great application potential in accurately regulating the power flow on a transmission line, damping inter-area power oscillations, mitigating subsynchronous resonance (SSR) and improving transient stability [2].

In dynamic applications of TCSC, various control techniques and designs have been proposed for damping power oscillations to improve system dynamic response, whereas for steady state control, the main interest of users and researchers has been the use of the this controller for power flow control in transmission lines, usually considering optimal scheduling strategies (e.g. [3], [4])

A. ANALYSIS OF THE TCSC

The following "approximate" analysis of TCSC operation in the vernier-control mode is performed based on the simplified TCSC circuit shown in Fig. 2 [2]. Transmission line current is assumed to be the independent-input-variable and is modeled as an external current source, i_S (t). Moreover, it is assumed that the line current is sinusoidal, as field tests have demonstrated that very few harmonics exist in the line current [3].

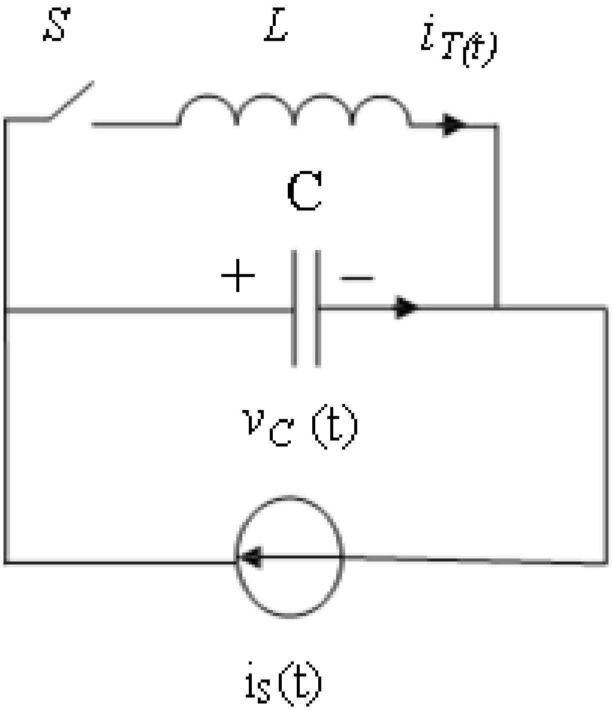

Fig. 2. A simplified TCSC circuit.

The current through the fixed-series capacitor, *C*, is expressed as

$$C\frac{d_{vc}}{dt} = is\ (t) - ir\ (t).\ u \tag{1}$$

The switching variable *u* is equal to 1 when the thyristor valves are conducting (switch S is closed). When the thyristor valves are blocked (switch S is open), *u* = 0. The thyristor current, i_T(t)can be described as

$$L\frac{di_r}{dt} = v_c.\ u \tag{2}$$

Let the line current, i_S(t) be represented by

$$i_S\ (t) = I_m \cos \omega t \tag{3}$$

Equations (2) and (3) can be solved with the knowledge of the instants of switching. In equidistant firing-pulse control, for balanced TCSC operation, the thyristors are switched on twice in each cycle of the line current at instants *t1* and *t3* given by

$$t_1 = -\frac{\beta}{\omega} \tag{4}$$

$$t_3 = \frac{\pi - \beta}{\omega} \tag{5}$$

where â is the angle of advance (before the forward voltage becomes zero). Or,

$$\beta = \pi - \alpha; 0 < \beta < \beta \text{ max} \tag{6}$$

The firing angle á is generated using a reference signal that can be in phase with the capacitor voltage. The thyristor switch S turns off at the instant *t2* and *t4* defined as:

$$t_2 = t_1 + \frac{\sigma}{\omega} \tag{7}$$

$$t_4 = t_3 + \frac{\sigma}{\omega} \tag{7}$$

where σ is the conduction angle and,

$$\sigma = 2\beta \tag{9}$$

Solving the TCSC equations (1 to 3) results in the steady-state thyristor current *iT* (t),as:

$$t_r\,(i) = \frac{k^2}{(k^2-1)}\,\text{Im}\left[\cos\omega t - \frac{\cos\beta}{\cos k\beta}\cos\omega_r t\right]; -\beta < wt < \beta \tag{10}$$

where,

$$\omega_r = \frac{1}{\sqrt{LC}} \tag{11}$$

$$k = \frac{\omega r}{\omega r} = \sqrt{\frac{1}{\omega L}\;\frac{1}{\omega C}} = \sqrt{\frac{Xc}{XL}} \tag{12}$$

and *XC* is the nominal reactance of the fixed capacitor only. The steady-state capacitor voltage at the instant ωt = – β is expressed by:

$$vc_1 = \text{Im}\,\frac{wc}{k^2-1}\,(\sin\beta - k\cos\beta\tan k\beta) \tag{13}$$

At ωt = β, ir = 0 and the capacitor voltage is given by:

$$v_c\,(\omega_t = \beta) = vc_2 = vc_1 \tag{14}$$

The capacitor voltage is finally obtained as:

$$v_c(t) = \text{Im}\,\frac{X_c}{k^2-1}\left[-\sin\omega t + k\frac{\cos\beta}{\cos k\beta}\sin\omega rt\right]; -\beta \le wt \le \beta \tag{15}$$

$$v_c\,(t) = vc_2 + \text{Im}\,X_c\,(\sin\omega t - \sin\beta);\ \beta < \omega t < \pi - \beta \tag{16}$$

Because the non-sinusoidal capacitor voltage, *vC*, has odd symmetry about the axis ùt=0, the fundamental component, *VCF*, is obtained as:

$$V_{CF} = \frac{4}{\pi}\int v_c\,(t)\sin\omega td\,(\omega t) \tag{17}$$

$$x_{rcsc} = \frac{V_{CF}}{\text{Im}} = X_c - X^2c\,\frac{(2\beta + \sin 2\beta)}{(X_c - X_L)\,\pi} + 4X^2c\cos^2\beta$$

$$\frac{(k\tan k\beta - \tan\beta)}{(X_c - X_L)\,(k^2-1)\pi} \tag{18}$$

The net reactance of the TCSC in per unit of *XC*, denoted by *Xnet* (= *XTCSC/XC*, sometimes called the boost factor) can be expressed as:

$$X_{net} = 1 - \frac{X_c\,(\sigma + \sin\sigma)}{(X_c - X_t)\,\pi} + \frac{4X_c\cos^2 0.5\,\sigma}{(X_c - X_L)\,(k^2-1)}$$

$$\frac{(k\tan 0.5\sigma\,k - \tan 0.5\,\sigma)}{\pi} \tag{19}$$

4. Description of the Study System

A. Two Area (4 machine ,11 bus)system

The two-area system shown in Fig.6 has been studied extensively [1]. Two generation and load areas are interconnected by two parallel transmission lines. Each area is equipped with two identical round rotor generators rated 20 kV/900 MVA. The synchronous machines have identical parameters except for inertias which are H = 6.5s in area 1 and H = 6.175s in area 2. Dynamic data for generation and excitation system are used in the study. The load is represented as constant impedances and split between the areas in such a way that area 1 is exporting 413MW to area 2. Since the surge impedance loading of a single line is about 140 MW the system is somewhat stressed, even in steady-state.

From the open loop system eigenvalue and participation factor analysis shown in Table 1, the system exhibits three electromechanical modes:

- An inter-area mode, with a frequency of 0.5098 Hz, in which the generating units in one area oscillate against those in the other area.

Table 1: Two area eigen value analysis

Eigenvalues	*Freq.*	*Mode*	*Damping Ratio*	*Machines Participation Factor*			
				G1	**G2**	**G3**	**G4**
-0.660 ±6.9904i	1.1125	Local	0.094	0.7544	1	0.0015	0.0088
-0.7375 ±6.8742i	1.0941	Local	0.1067	0.0133	0.0016	0.8438	1
0.0279 ± 3.2030i	0.5098	Inter-Area	-0.0087	1	0.7869	0.3891	0.2432

- Local mode, in area 1, with a frequency of 1.1125 Hz. In this mode the machines in Area 1 oscillate against each other.

- Local mode, in area 2, with a frequency of 1.0941 Hz. In this mode the machines in Area 2 oscillate against each other.

The Table shows that the two generating units in each area have close participation factor in the inter-area mode. The same is also true for the two local modes. This is to be expected, since all units are identical, and units in each area are electrically close. The table also shows that the units in Area 1 (the receiving end) have higher participation factor than the units in Area 2 (sending end) to the inter-area mode. It can also be seen that, the inter-area mode has negative damping ratio at this operating condition.

5. SIMULATION RESULTS

The Power system shown in Fig. 3 is studied through the computer simulation using the MATLAB/ Simulink in MATLAB environment. The speed deviations, change in rotor angles, electrical power outputs, machine terminal voltages, and PSS's controllers responses, respectively, for a 6-cycle three-phase fault at bus 10 of the two-area system without PSS & TCSC is shown in Fig.4.

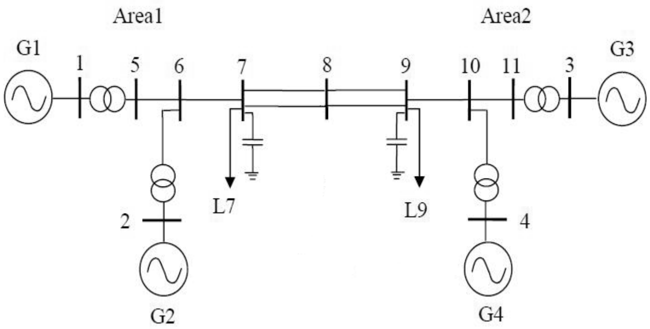

Fig. 3. Single line diagram of the two-area system

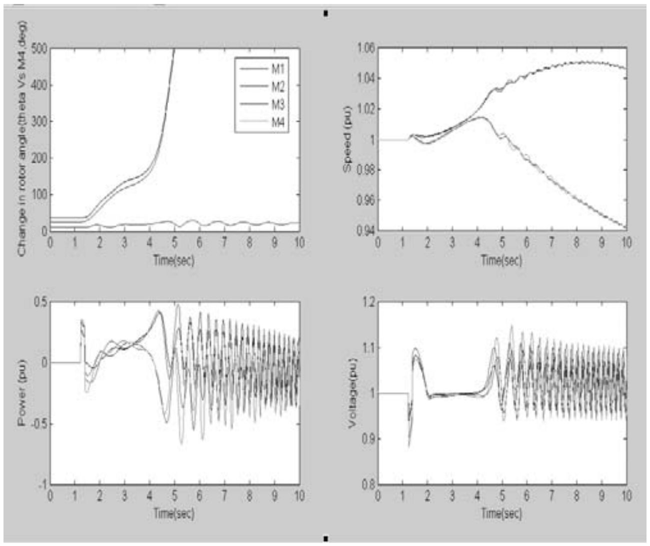

Fig. 4. Results w/o PSS & TCSC for Speed &Voltage

Fig. 5 shows the combined results with the proposed PSS's at each machine. The simulations with PSS and TCSC are shown in Fig.6. Moreover, the proposed coordination between PSS's and TCSC have been compared with those without PSS and TCSC and with PSS only and the same has been shown in Fig. 7 & 8.

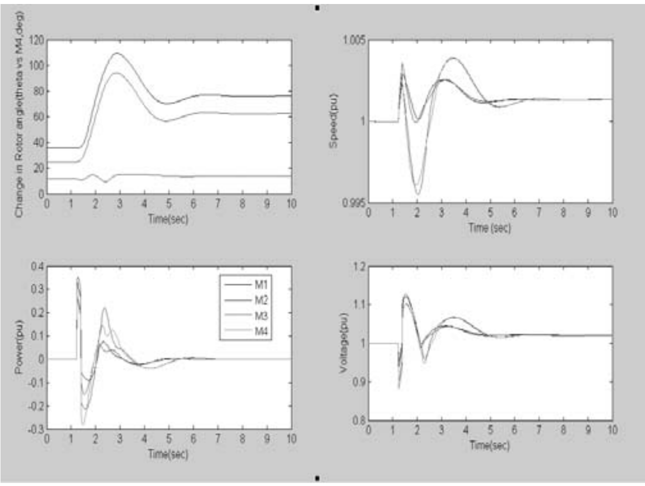

Fig. 5. Results after using PSS

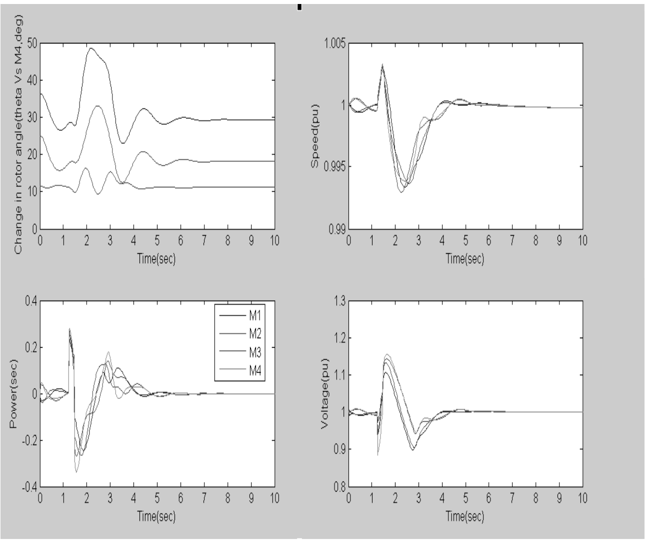

Fig. 6. Results after using PSS and TCSC

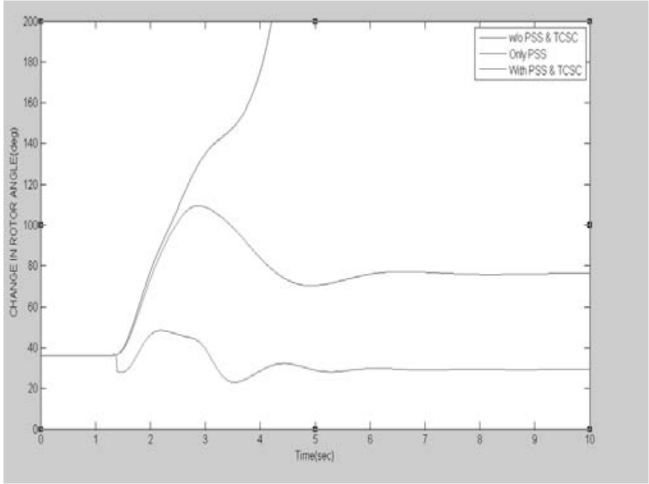

Fig. 7. Comparisons of results for change in rotor angle of Machine 1

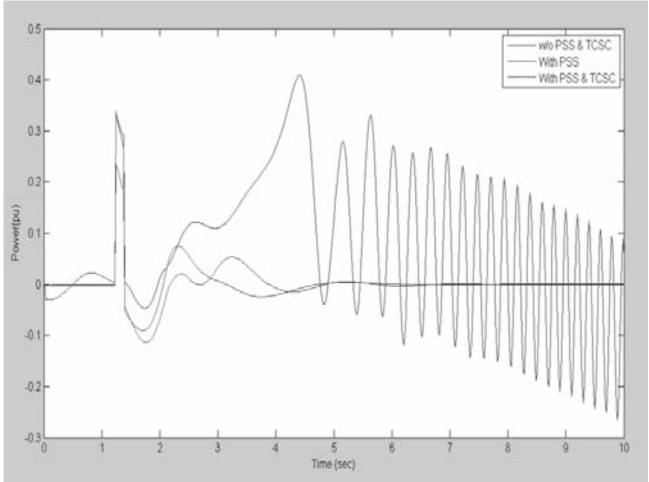

Fig. 8. Comparision of results for power of Machine 1

It can be readily seen that PSS's and TCSC are the most effective stabilizers in damping the electromechanical modes oscillations. This is in general, is consistent with eigenvalue analysis results. It is clear that the coordinated design of PSS's and TCSC-based stabilizer improves greatly the system damping compared to their individual application.

At 1.2s a 5% change in the reference impedance is applied. The response indicates that TCSC enables tracking of the reference impedance and the settling time is around 500ms. At 3.3s a 4% reduction in the source voltage is applied, followed by the return to 1p.u. at 3.8s. It is seen that the TCSC controller compensates for these disturbances and the TCSC impedance stays constant. The TCSC response time is 200ms-300ms.

Table2. Comparisons between model with PSS only and with TCSC and PSS.

Model	Eigenvalue	Damping Ratio	Freq	Settling Time
With PSS	-0.018±j3.27	0.005	0.52	2.427sec
With PSS & TCSC	-0.501±j3.77	0.13	0.60	1.786 sec

The two area four machine system has been analysed for the different modes of operation. The results for various parameters such as speed deviations, change in rotor angles, electrical power outputs, machine terminal voltages have been studied. The responses, respectively, for a 6-cycle three-phase fault at bus 10 of the two-area system without PSS & TCSC shows that the after the fault the system loses its synchronism and the oscillations appear in the system. After using PSS we see that the oscillations are reduced and a further improvement in damping the oscillations has been achieved by coordinated use of TCSC and PSS.

A comparative study of all the three above mentioned cases has been done and thus it has been demonstrated that the coordinated design of TCSC and PSS had reduced the damping ratio, settling time The eigen values confirm that system is more stable and the frequency of the system has improved.

The results obtained for two area, four machine systems reveal the following:

1. In the test system, all the Eigen-values have negative real parts for the cases without PSS, with PSS and with coordinated PSS & TCSC. However,

two modes in the case without PSS are under-damped (damping ratio less than 0.05).

With coordinated PSS & TCSC used, the system damping significantly improves. The latter case provides slightly better damping.

2. The transient response in test system shows that the system is oscillatory unstable without PSS and becomes stable with PSS and improves further after using TCSC.

6. CONCLUSION

In this paper, the power system stability enhancement via PSS and FACTS-based stabilizers when applied independently and also through coordinated application was discussed and investigated for a multimachine power system. For the proposed stabilizer design problem, an eigenvalue-based objective function to maximize the system damping ratio among all complex eigenvalues was developed.

In multimachine power system, the optimal locations of PSS's have been identified using participation factor technique, while the locations of TCSC has been selected based on its primary objectives such as voltage control and system power transmission capability.

The effectiveness of the proposed control schemes in improving the power system dynamic stability has been verified through eigenvalue analysis, and nonlinear time-domain simulations under different loading conditions and severe fault disturbances.

This paper demonstrates that TCSC controllers, appropriately tuned and located make them a viable alternative to traditional PSS controller or to enhance PSS controller for oscillation control.

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