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Design and tuning of FACTS stabilizers for dynamic stability enhancement in multimachine power systems

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This contribution discusses and compares different control techniques for damping undesirable electromechancial oscillations in power systems by means of power system stabilizer and Series / Shunt FACTS controllers. The linearized model of the power system is derived with FACTS controllers and the problem of small signal stability enhancement is formulated as an optimization problem to maximize the damping ratio of critical electro mechanical modes in the power system. Particle swarm optimization (PSO) technique is applied to tune the controller parameters of the PSS and FACTS controllers. The following FACTs controllers are taken for analysis (i) Static Var Compensator (SVC) (ii) Static Compensator (STATCOM) (iii) Thyristor Controlled Series Capacitor (TCSC) (iv) Unified Power Flow Controller (UPFC) .

Keywords: *Small Signal Stability, Power system oscillations, SVC, STATCOM, TCSC, UPFC, Particle Swarm Optimization.*

1.0 INTRODUCTION

As power systems became interconnected, areas of generation were found to be prone to electromechanical oscillations**.** Theseoscillations have been observed in many power systems worldwide. As the level of power transmission rose, largely through existing interconnections, which were becoming weak and inadequate, load characteristics added to the problem causing spontaneous oscillations. The oscillations may be local to a single generator or generator plant (local oscillations, 1.0 – 2 Hz), or they may involve a number of generators widely separated geographically (interarea oscillations0.2 –0.8 Hz). If not controlled these oscillations may lead to total or partial power interruption. [1]. Electromechanical oscillations are generally studied by modal analysis of a linearized system model. Power System stabilizer (PSS) is possibly the first measure that has been used to improve damping and is well described in [10]. Classical control theory was used for designing controllers and PSS were suggested with speed signals being fed to voltage regulators [2,11].

The availability of flexible ac transmission system (FACTs) controllers such as static Var compensators (SVCs), Static Compensator (STATCOM), Thyristor Controlled Series Compensators (TCSCs), Static Synchronous Series Compensators (SSSC) and Unified Power Flow Controllers (UPFC) has led their use to damp electro mechanical oscillations.[9] Ref [3] compares damping capabilities of the controllable reactive power elements namely SVC and Controllable Series Capacitor (CSC).A nonlinear control scheme for the TCSC (thyristor controlled series capacitor) for the enhancement of transient stability is proposed in Ref[15]. Energy function approach is used for comparing the damping capabilities of STATCOM and SSSC in Ref [14].

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Recently Particle Swarm Optimization technique is used for maximizing system loadability with FACTs devices.

The objective of the present work is to optimize the controller parameters of FACTS stabilizers to enhance small signal stability of a multimachine power system and to determine the dynamic rating of Series /shunt FACTS controllers namely TCSC, UPFC, SVC, STATCOM. The paper is organized as follows: Section 2 presents power system modeling and analysis concepts used throughout this paper. The modeling and control of Power System Stabilizer and FACTS devices is discussed. Section 3 presents the basic concepts and problem formulation PSO. Section 4 presents the Simulation Results. Conclusions and Future work is given in section V.

2.0 POWER SYSTEM AND FACTS CONTROLLER MODELLING

In general, power systems are modeled by a set of differential and algebraic equations (DAE), that is

$$\dot{x} = f(x, y, \lambda, p)$$
$$0 = g(x, y, \lambda, p) \qquad ....(1)$$

is the vector of state variables associated with the dynamic states Generators, loads and other system controllers; $y \in R^m$ is a vector of algebraic variables associated with steady state variables resulting from neglecting fast dynamics (e.g., load voltage phasor magnitudes and angles); $\ddot{e} \in R^l$ is a set of uncontrollable parameters, such as variations in active and reactive power of loads; and $p \in R^k$ is a set of controllable parameters such as tap and AVR settings, or controller reference voltages. [4].

2.1 Generators

In power system dynamic studies, the synchronous generators are commonly represented by using models of varying degrees of complexity the simplest being the classical (2[nd] Order) model that assumes a constant voltage behind transient reactance. The sixth order model has been found adequate for representation in stability studies. This model has four rotor circuits: a field winding, a damper winding on the d-axis and two damper windings on the q –axis.[8].

2.2 Power System Stabilizers

A PSS can be viewed as an additional block of a generator excitation control or AVR, added to improve the overall dynamic performance, especially for the control of electromechanical oscillations. Thus, the PSS uses auxiliary stabilizing signals such as shaft speed, terminal frequency and /or power to change the input signal to the AVR. The block diagram of the PSS used in the paper is depicted in Figure 1.

FIG. 1 POWER SYSTEM STABILIZER

In large power systems, participation factors corresponding to the speed deviation of generating units can be used for initial screening of generators on which to add PSS. However, a high participation is necessary but not a sufficient condition for a PSS at the given generator to effectively damp oscillation. Following the initial screening, a more rigorous evaluation using residues and frequency response should be carried out to determine the most suitable locations for the stabilizers.

2.3 Static Var Compensators

Static Var Compensator(SVC(is basically a shunt connected static Var Generator /Absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power system variables; typically, the controlled variable is the SVC bus voltage. One of the major reasons for installing a SVC is to improve dynamic voltage control, and thus, increase, increase system loadability. An additional stabilizing signal, and supplementary control, superimposed on the voltage control loop of a SVC can provide damping of system oscillation. Figure 2 shows the main voltage control loop and the stabilizing loop, which uses SVC bus voltage as the stabilizing signal.

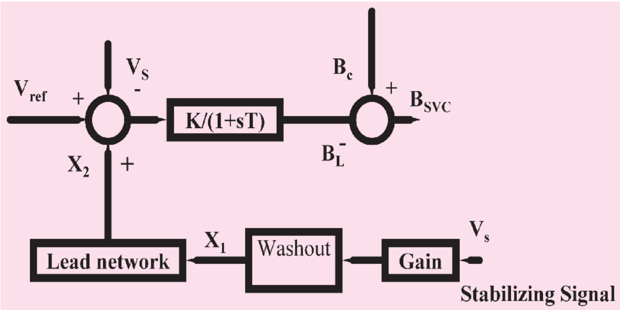

FIG. 2 DYNAMIC MODEL OF SVC

2.4 Statcom

The STATCOM resembles in many respects a synchronous compensator, but without inertia. The basic electronic block of a STATCOM is the voltage source converter (VSC), which in general converts an input dc voltage into a three-phase output voltage at fundamental frequency, with rapidly controllable amplitude and phase. The STATCOM is modeled here using the model described in [13]. α is the phase shift between the controller VSC ac voltage and its bus Voltage V. The shunt controller of the STATCOM includes a pulse width modulation (PWM) based AC voltage magnitude controller (Figure 3) which controls the modulation index of the shunt inverter. (m_{sh}). [4]

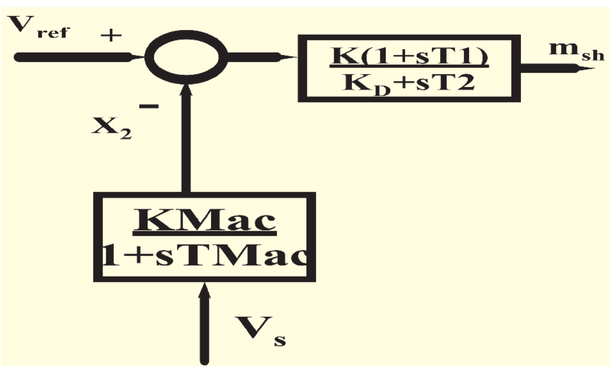

FIG. 3 PWM VOLTAGE MAGNITUDE CONTROLLER OF STATCOM

The DC voltage magnitude controller is directly controlled by the phase angle, alpha which basically determines the active power flowing into the controller and charging and discharging of the DC capacitor (Figure 4).

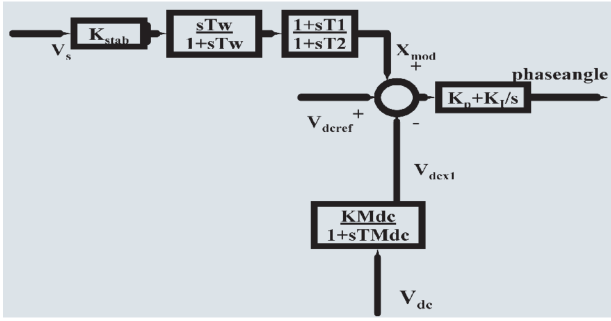

FIG. 4 PI PHASE ANGLE CONTROLLER OF THE STATCOM

2.5 Thyristor Controlled Series Capacitors (TCSC)

Thyristor controlled series Capacitor schemes typically use a thyristor-controlled reactor in parallel with a capacitor to vary the effective compensating reactance. In practice, several capacitor banks, each with its own thyristor-controlled reactor, may be used to meet the specific application requirements. For the purpose of analysis, the TCSC, regardless of its practical implementation, can be considered simply as a continually variable capacitor whose impedance is controllable in the range of

$0 \le X_{TCSC} \le X_{TCSCMAX}$

The TCSC is modeled using the variable reactance model as shown in Figure 5. [7]

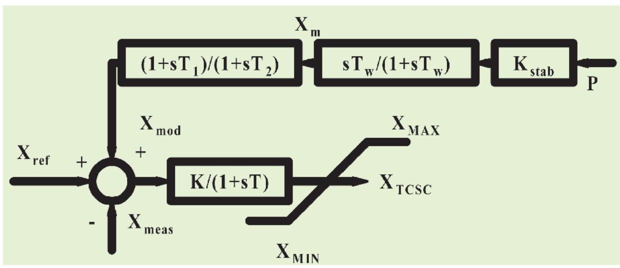

FIG. 5 TCSC MODEL FOR DYNAMIC ANALYSIS

2.6 Unified Power Flow Controller

The UPFC is the most versatile FACTS controller developed so far, with all encompassing capabilities of voltage regulation, series compensation, and phase shifting [12]. It can independently and very rapidly control both real and reactive power flows in a transmission line. It comprises of two Voltage Source Converters coupled through a common dc link. The series converter (VSC2) [is controlled to inject a voltage phasor Vs, in series with the line, which can be varied from 0 to V_{smax}. Moreover the phase angle of Vs can be independently varied from 0 to 360 [6].

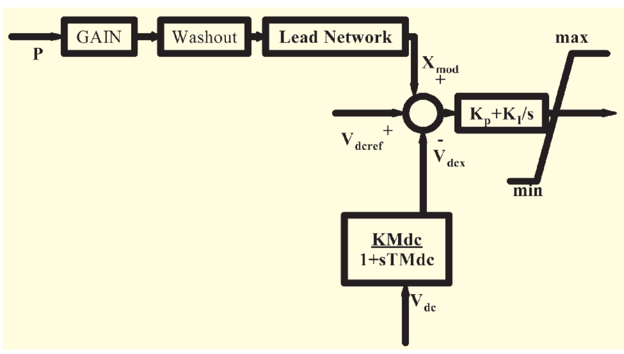

FIG. 6 DC VOLTAGE CONTROLLER OF UPFC

The shunt controllers of the UPFC have the same configurations as the control strategy used for the control of modulation and phase angle of the shunt inverter in a STATCOM (Figures 3 and 4).

3.0 OPTIMIZATION APPROACH FOR DAMPING ENHANCEMENT

Through cooperation and competition among the population, population based optimization approached often can find very good solutions efficiently and effectively. Most of the population based random search approached as are motivated by evolution as seen in nature. PSO is an evolutionary computation technique developed by eberhart and Kennedy [16] in 1995, and was inspired by bird flocking and fish schooling. Instead of using evolutionary operators to manipulate the individuals, like in other evolutionary computational algorithms, each individual in PSO flies in search space with a velocity which is dynamically adjusted according to its own flying experience and its companions flying experience, Each individual is treated as volume- less particle in the search space. The i^{th} particle is represented as xi = (x_{i1}, X_{i2}, ---X_{in}). The best previous position (the position giving the best fitness value) of the ith particle is recorded and represented as P_i.(P_{i1},P_{i2}, ----P_{in}). The index of the best particle among all the particles in the population is represented by the symbol g.The rate of the position change (velocity) for particle i is represented as V_i=(V_{i1},V_{i2}, ------V_{in}). The particles are manipulated according to the following equation. At each iteration the velocity, position of a particle is determined by both the individual and group experience.

$$V_i(t) = W_i V_i(t-1) + C_1 rand_1 \left(P_i - X_i(t-1)\right) + C_2 . rand_2 \left(P_g - X_i(t-1)\right) \quad ....(2)$$

$$X_i(t) = X_i(t-1) + V_i(t) \quad ....(3)$$

where W_i is a positive number between 0 and 1.C_1, C_2 are two positive constants. $rand_1$and $rand_2$ are two random number generators [0,1]. P_i- best position found by the particle so far.

P_g- Global best position found by any particle in the swarm. The maximum allowable velocity for the particles is controlled by the parameter V_{max}.. If Vmax is too high, then particles tend to move beyond a good solution. On the other hand, if Vmax is small then particles can be trapped in local minima.

3.1 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.

$$\Delta \dot{x} = A\Delta x + B\Delta u$$
$$\Delta y = B\Delta x + D\Delta u \quad ....(4)$$

From (4) the Eigen values $ë_i = ó_i \pm jù_i$ of the total system is evaluated. The proposed method is to search the best parameter sets of the controllers. Since the objective is to maximize the damping ratio of the system the Problem is stated as follows.

$$s.t. K_{min} \leq K \leq K_{max}$$
$$T_{1MIN} \leq T_1 \leq T_{1MAX} \quad ....(5)$$

where ζ_i represents the damping ratio of the critical mode. K and T may denote the controller parameters of the power system stabilizer or Series /Shunt FACTS controllers. The dominant eigen values of the system are the one which have a damping ratio less than 0.1 which are taken and considered for optimization. The following steps are performed for optimizing the controller parameters of FACTS controllers and to enhance the small signal stability of the power system.

1. Get the Linearized model of the power system with FACTS controllers and PSS.[8]
2. Compute the Eigen Values. Identify the Dominant Eigen values.
3. Maximize the damping ratio of the critical electromechanical modeusing equation 5 and obtain the controllable parameters of the FACTs controller using Particle Swarm Optimization.
4. Run the small signal stability program with the controller parameters (K_{stab}, T_w,T_1, T_2,) obtained in step 3 and find the eigen values.

4.0 EIGENVALUE ANALYSIS RESULTS

The eigenvalue analysis results presented in this section are obtained for a two-area 4-machine power system [5] for the optimized values of PSO results of controller parameters. The single line diagram of a two-area system is shown in Figure 7.

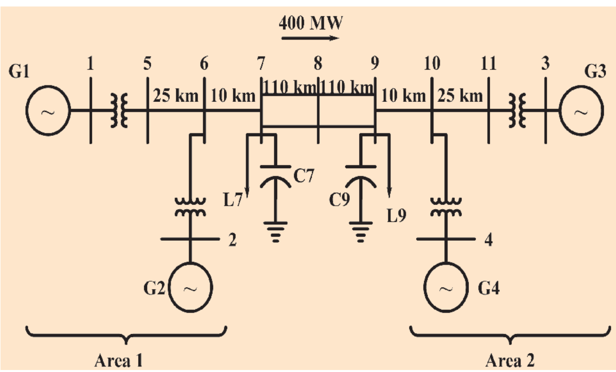

FIG. 7 4 GENERATOR TWO AREA POWER SYSTEM

The eigenvalue analysis of the two-area system is given in Table 1 without the FACTS controller, with PSS connected to each area (Generators G1and G3), series FACTS controllers connected in tie line 8-9, shunt FACTS controllers connected at Bus 8. Under Normal Operating Conditions, the power flow from area 1 to area 2 is 400 MW. The results show the presence of one lightly damped interarea mode and two reasonably damped local modes of oscillation.

TABLE 1

EIGENVALUE ANALYSIS :BASE CASE

WITHOUT DAMPING CONTROLLERS	WITH PSS
-0.00145 ± 0.01742i ζ= 0.0829 f=1.05Hz	-0.00392 ± 0.02498i ζ= 0.155
-0.00138 ± 0.0176i ζ=0.0782 f=1.06Hz	-0.00218 ± 0.02046i ζ= 0.1059
-0.00033 ± 0.00865i ζ= 0.0381 f=0.519 Hz Interarea Mode	-0.00032 ± 0.00311i ζ=0.1024

From Table 1 it can be observed that for the base case two area system the damping ratio of the electro mechanical modes are low less than 0.1 The damping ratio of the inter area mode with a frequency of oscillation of 0.519 Hz is at a value of 0.0381 which is detrimental to the dynamic stability of the power system. The damping ratio of the swing modes increase to 0.1 with power system stabilizer in the network. The location of the power system stabilizer is chosen as machine G3 based on the participation factor matrix. [5]

TABLE 2	
EIGENVALUE ANALYSIS : SHUNT CONNECTED FACTS CONTROLLERS	
WITH SVC	**WITH STATCOM**
-0.0044 ± 0.02458i ζ =0.1762	-0.00649 ± 0.0248i ζ= 0.253
-0.00295 ± 0.02051i ζ= 0.1424	-0.00881 ± 0.02271i ζ= 0.3617
-0.00415 ± 0.01336i ζ= 0.2966	-0.0033 ± 0.01381i ζ= 0.2324

The damping ratio of the electromechanical modes increase to values greater than 0.1 with shunt connected FACTS controllers as shown in Table 2.From table 3 it is clear that the damping of inter area mode (ζ= 0.5402) has improved significantly compared to the one with TCSC in the tie line. The increase in damping ratio of the electromechanical modes with UPFC over TCSC is due to the fact that the compensation provided by the TCSC is dependent on the line current; alternatively the TCSC can control only the series capacitive reactance of the transmission line.

The damping ratio of the system with TCSC and STATCOM are almost comparable with the exception that the damping ratio for the interarea mode has increased to a comfortable value for the system with STATCOM.

TABLE 3	
EIGENVALUE ANALYSIS WITH TCSC /UPFC IN THE TIELINE	
With TCSC	**With UPFC**
-0.00333 ± 0.0143i ζ= 0.226	-0.00573 ± 0.01644i ζ= 0.3291
-0.00904 ± 0.02849i ζ= 0.3024	-0.01388 ± 0.0198i ζ= 0.574
-0.00249 ± 0.01402i ζ= 0.1749	-0.00502 ± 0.00782i ζ= 0.5402

5.0 CONCLUSION

This paper demonstrates that both interarea and local oscillations, which are typically damped through Power System Stabilizers, can be adequately damped using series /shunt connected FACTS controllers by properly placing them in critical tie lines/ nodes of the system. Particle swarm optimization technique is used to optimize the controller parameters and the state space model is computed after optimizing the controller parameter. The controllable outputs of FACTS controllers are modeled as state variables.

Even though it has been shown that UPFC and TCSC significantly increase the damping ratio of the oscillatory modes, a STATCOM is more preferable for the enhancement for small signal stability. However, when steady state continuous powers flow control is of prime importance UPFC is the preferred choice, if the cost of installation is not a constraint.

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