Optimization Based Coordination of PSS and TCSC Controllers for Improving Power System Dynamic Stability

ABC*, and EFG**
* University of XYZ, abc@xyz.ac.ir
** University of XYZ, efg@xyz.ac.ir

Abstract: *This paper investigates the simultaneous coordination of power system stabilizers and the Thyristor Controlled Series Capacitor (TCSC) damping controller to improve the overall dynamic stability of power system. The phase compensation-root locus method is used for linear sequential design of Power System Stabilizers (PSS) and TCSC controllers using remote signals. It is necessary to coordinate the controllers in order to achieve the best damping performance of the system controllers. An objective function is proposed for the coordinated design of power system controllers and the Genetic Algorithm is used to solve the optimization problem. Time domain simulations are performed on a multi-machine test system for verification of the effectiveness of the proposed method.*

Keywords: Coordinated design of power system controllers, genetic Algorithm based optimization, PSS design, TCSC damping controller.

1. Introduction

Power systems are increasingly being more stressed due to the need for more power transfers over tie lines. The competitive environment of power markets has made utilities to deploy the maximum capacity of the transfer system to trade power with the neighbouring power pools. This has pushed power systems toward their stability margins. When huge amount of power is transferred over weak tie lines inter area oscillations are likely to happen [1, 2]. Many incidents of power system instability due to low damped oscillations have been reported [3]. The most common method to damp power systems' low frequency oscillation has been the use of Power System Stabilizers (PSS) for a long time [1]. Conventional PSS have proved to be quite effective in damping local oscillatory modes but when it comes to damping of inter area modes they seem to lack the desirable efficiency. This is mainly due to the low observability of inter-area oscillatory modes in PSS local signals such as rotor speed deviations or generator's power deviations [5]. Flexible AC Transmission System (FACTS) devices were initially devised for mitigating power system's steady state performance such as voltage regulation and power flow capacity increase. Later they proved to be efficient in damping power systems' oscillatory modes [8]. One main issue in designing controllers for FACTS is the selection of the feedback signal. The feedback signal should have the most observability of the low damped oscillatory mode in order to achieve the best damping performance. This signal might be a remote one. Remote signals are not popular among control engineers for designing reliable control systems because of the shortcomings of communication infrastructures in power systems and the stochastic delay of the transmitted signals. The newly developed Wide Area Measurement System (WAMS) which is based on Phasor Measurement Units (PMU) technology has facilitated data transmitting over long distances in power systems [6]. The inherent delay of these signals is still a considerable problem. Extensive research work has been conducted by researchers in the recent years to deal with remote signals delays and to design controllers that are robust against delay.

Considering all PSSs, FACTS and HVDC controllers there are lots of controllers in a typical power system. Coordination of these controllers is essential for their efficient performance. The conventional method for tuning different controllers in a power system has been the linear sequential method (LSM) in which controllers are tuned and installed one after another considering a specific oscillatory mode to be damped by each single controller [7]. The main shortcoming of the LSM is that controllers are tuned disregarding the effect of the next controllers. Installation of a new controller inevitably affects the performance of previously installed controllers and may decline the damping performance of a specific controller. Optimization Based Coordination of controllers has been proposed for amelioration of this drawback. In this method the optimum performance of all controllers of a system is sought through optimization of an objective function [9, 10]. The objective function should be defined in such a way that its minimization results in the desired performance criteria of the overall control system such as fulfilling a minimum damping ratio for all oscillatory modes or acquiring a definite time response criteria. Different objective functions have been proposed in the literature based on eigenvalue shifting or damping ratio maximization of oscillatory modes [7]. The optimization problem then could be solved either by gradient-based nonlinear optimization techniques such as dynamic programming method or by the use of evolutionary algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization technique (PSO) and etc. Evolutionary algorithms have attracted much attention in the recent decade due to their ability in solving non-linear non-differentiable optimization problems and finding global or near global optimal points of the objective function [11]. An objective function based on eigenvalue shifting is proposed in this paper for investigating the effectiveness of optimization based coordination of PSS and TCSC controller parameters in improving the overall dynamic performance of the power system. The simulations are performed on New-England 39 bus 10 machine test system to verify the effectiveness of the method.

2. Power System Modeling and Modal Analysis

2.1 Modal Analysis

The differential algebraic equations (DAE) of power system are derived by writing the system's differential equations describing the dynamics of its components such as generators, AVRs, governors, and the algebraic equations describing load flow. The resulting DAE is as follows:

$$\begin{aligned} \dot{x} &= f(x,u) \\ y &= g(x,u) \end{aligned} \qquad (1)$$

These equations are highly non-linear. Linearization of the system around a nominal operating point yields:

$$\begin{aligned} \Delta\dot{x} &= A\Delta x + B\Delta u \\ \Delta y &= C\Delta x + D\Delta u \end{aligned} \qquad (2)$$

Eigenvalues of the state matrix A are derived using equation: $det(A - \lambda I) = 0$, where $\lambda = \sigma \pm j\omega$. The damping ratio of the i_{th} eigenvalue is defined as:

$$\xi = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \qquad (3)$$

The system is stable if all eigenvalues of the system have negative real parts. Furthermore, for the system to settle, in a proper time, to a new steady state after occurrence of a fault or a disturbance, a minimum damping ratio of 10% is mandated by most of the utilities [7].

A linear transformation is applied to equation1 to separate the differential equations. Replacing $x = \varphi z$ in equation (2) yields:

$$\begin{aligned} \Delta\dot{z} &= \Lambda\Delta z + B'\Delta u \\ \Delta y &= C'\Delta z + D\Delta u \end{aligned} \qquad (4)$$

Where $\Lambda = \varphi^{-1}A\varphi$ is a diagonal matrix and $C' = C\Phi$ and $B' = \Phi^{-1}B$ are called the controllability and the observability matrices, respectively. As a result, the state equations are separated. Λ is the modal matrix and the equation set (4) is the modal equations of the system. Let $D=0$, then the transfer function from input Δu to output Δy is:

$$G(s) = \frac{\Delta y(s)}{\Delta u(s)} = c(sI - A)^{-1}b \qquad (5)$$

$G(s)$ could be expanded in partial fractions as:

$$G(s) = \sum_{i=1}^{i=n} \frac{R_i}{s - \lambda_i} \qquad (6)$$

,where $R_i = c\varphi_i\psi_i b$ is the residue of the transfer function at the i_{th} eigenvalue. Residue is a measure of the controller's ability to move the i_{th} eigenvalue of the system toward the left half plane and is commonly used for finding the best controller location and the best feedback signal [12].

2.2 PSS structure

PSS provides additional damping to the system by acting through the excitation system. PSS imports damping torque to the excitation system by compensating the phase lag between its input signal and the reference voltage of the AVR. A conventional $\Delta\omega$ input PSS model is used in this study. The PSS comprises of a washout filter to eliminate the steady state error, an amplifier gain block K_{PSS} and two lead-lag blocks to provide the necessary phase compensation. The PSS structure is depicted in figure below.

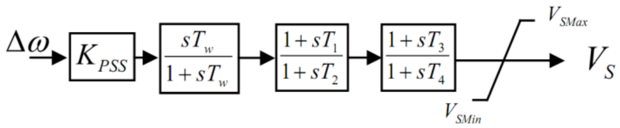

Fig. 1: PSS structure [9]

2.3 TCSC damping controller structure

The structure of the TCSC damping controller is similar to the structure of a PSS. Usually the power or current of the tie lines is selected for the controller input. The selected signal should have a good observability of the oscillatory mode. The controller's output is a signal that adds to the controlled variable of the TCSC, for example the value of the series reactance (ΔX_{se}) in this case. The structure of a TCSC damping controller is depicted in Fig. 2.

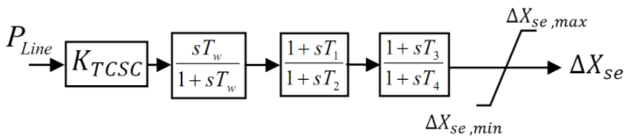

Fig. 2: TCSC damping controller structure

3. Controller Design

The proposed controller is designed in two stages. First, PSS and TCSC controllers are designed using linear sequential method. Then all of the controller parameters are coordinated for the best damping performance using the optimization based technique by genetic algorithm.

3.1 Coordination using Linear Sequential Method

For the first round of tuning a linear sequential tuning of controllers using the phase compensation-root locus method for controller design is applied to the system. If *H(s)* is a feedback controller between output *y* to input *u*, the sensitivity of the i_{th} eigenvalue to the gain of this controller is proportional to the residue of the open loop transfer function between *y* and *u* [6].

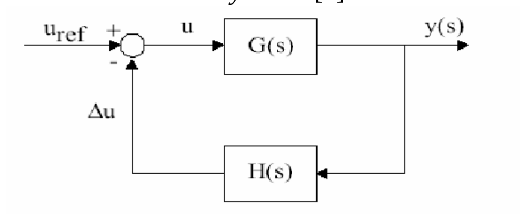

Fig. 3: plant and the controller [12]

$$\frac{\partial\lambda_i}{\partial K} = R_{\mathrm{i}}\frac{\partial(K.H(s))}{\partial K} = R_{\mathrm{i}}H(s) \tag{7}$$

$$\Delta\lambda_i = R_{\mathrm{i}}H(s).\Delta K \tag{8}$$

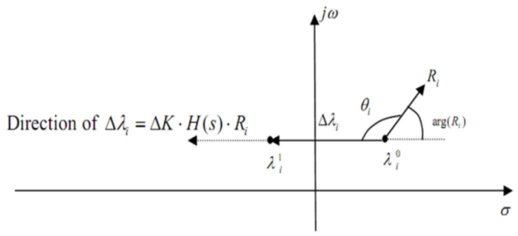

Fig. 4: residue based phase compensation [12]

The desired controller is expected to move the oscillatory modes eigenvalues toward the left half plane as they leave the open loop poles by increasing the controller's gain. To achieve this goal the controller should provide a phase compensation of $\theta_i = 180^{\circ} - arg(R_i)$. As discussed earlier:

$$H(s) = K\frac{sT_w}{1+sT_w}\left(\frac{1+sT_1}{1+sT_2}\right)^n \tag{9}$$

for both the PSS and the TCSC controller where $T_w$is selected a number between 1 to 20 [3].Since the maximum phase compensation for a lead-lag block is suggested to be 60°[7],the number of the lead-lag blocks needed to provide the necessary phase compensation is calculated as $n = \lceil {}^{\theta}/_{60} \rceil$, where $\lceil x \rceil$ is the smallest integer number bigger than x. T_1 and $T_2$are then calculated using the following formula:

$$\alpha = \frac{T_1}{T_2} = \frac{1-\sin(\frac{\theta_i}{n})}{1+\sin(\frac{\theta_i}{n})} \tag{10}$$

$$T_2 = \alpha T_1\,, T_1 = 1/(\omega_i\sqrt{\alpha}) \tag{11}$$

where ω_i is the frequency of the oscillatory mode to be damped and n is the number of the needed lead-lag blocks. After T_is are calculated the controller gain is calculated using the root locus method with the help of the *sisotool* toolbox in MATLAB. In controller tuning using linear sequential method the first controller is tuned for achieving the maximum damping ratio for the first oscillatory mode. The second controller is then tuned with the first controller installed in the system. This procedure goes on until the desirable damping for all modes is acquired or all of the controllers are exhausted [7].After all PSSs are installed, residue based phase compensation method is used for TCSC controller design. The signal with the largest residue is used as the feedback signal to the controller which is the power of line 4-14 in the test system. After the feedback signal is selected the controller is designed in a similar way as the PSS design procedure described earlier.

3.2 Optimization based coordination

The main drawback of the linear sequential method is that each controller is designed regardless of the interactions of that controller with the next controllers. This could be improved by simultaneous design of all controllers using an optimization based technique. The objective of the simultaneous parameter tuning is to globally optimize the overall damping performance. This could be achieved by minimizing a properly defined objective function that its minimization corresponds to acquiring the desired location for the critical modes. As mentioned before the damping of an oscillatory mode is $\xi = \frac{-\sigma}{\sqrt{\sigma^2+\omega^2}}$. Hence as the real part of an oscillatory mode moves toward the left half of the complex plain its damping ratio will increase, if the oscillation frequency is kept constant. The objective function used in this research is described below. $f(z)$ would be minimal when the real-part of the oscillatory mode σ_i is placed on the desired real-part value σ_{des}. The constraints are exerted for practical considerations. Time constants are limited in order to make it easier for the optimization solver to find the answer and the gains of the controllers are limited to 100 to prevent noise amplification and controller saturation due to high controller gains.

$$\begin{gathered} min\, f(z) = \sum_{i=1}^{n} w_i(\sigma_{des} - \sigma_i)^2 \\ s.t.: \begin{cases} 0 < T_{jk} < T_{j\,max} \\ 0 < K_p < K_{p\,max} \end{cases} \end{gathered} \tag{12}$$

Weighting coefficients are assigned in such a way that the optimization solver focuses more on shifting the real-part of the low-damped modes. The complex plain is split into three zones as depicted in Fig. 5. Zone 1 pertains to the critical modes that their eigenvalues must be shifted to the left of the complex plain with a high priority. Zone 2 pertains to the fairly-damped oscillatory modes and zone 3 pertains to the well-damped modes that their damping ratio is more that 20%. No more control effort is needed to be spent on the modes in zone 3 to further shift their eigenvalue to the left. These weighting coefficients accent the importance of the more critical modes in the objective function and prevent the optimization solver from spending the control effort where it is not necessary.

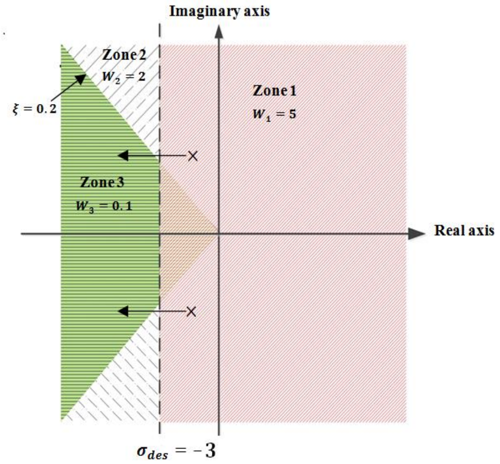

Fig. 5: Zones for allotting proper weight coefficients

Based on the objective function and the weighting zones above the following flow chart is used for solving the optimization problem using the genetic solver in MATLAB optimization toolbox.

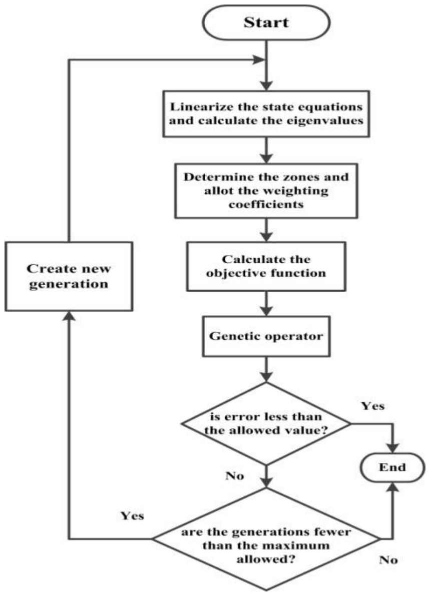

Fig. 6: Flow chart for the optimization based controllers tuning

4. Test System Description and Simulation Results

IEEE 10machine 39bus system [Fig. 7] is used for time domain simulations and verification of the proposed method effectiveness in multi machine power systems. The system is modelled in Power System Analysis Toolbox (PSAT) which is an open-source MATLAB toolbox. All generators are modelled with a 3rd order synchronous generator model equipped with AVRs and turbine governors. The system is described in detail in [12]. The load at bus 15 and bus 16 is increased 70% and the generators G4 and G5 are regulated to provide more power to compensate for the increased need of load. A TCSC is installed on the line connecting bus16 and bus19 to compensate for 40% of line reactance

Mode No.	Controller Status	Eigen value	Frequency (Hz)	Damping Ratio
1	Without controller	-0.39± j9.59	1.53	4 %
	PSS only	-3.62± j9.71	1.55	34.9%
	PSS + TCSC	-2.22± j10.54	1.68	20.4%
	Coordinated	-2.45± j10.12	1.61	23.5%
2	Without controller	-0.40 ± j9.48	1.51	4.2%
	PSS only	-2.81± j9.11	1.45	29.5%
	PSS + TCSC	-2.78 ± j9.16	1.46	29.1%
	Coordinated	-3.65 ± j9.32	1.48	36.5 %
3	Without controller	-0.66± j9.45	1.50	7%
	PSS only	-3.73± j9.43	1.50	36.8%
	PSS + TCSC	-3.92 ± j9.16	1.45	39.3%
	Coordinated	-2.96 ± j 9.27	1.47	30.4%
4	Without controller	-0.28 ± j8.06	1.28	3.3%
	PSS only	-0.84± j8.13	1.29	10.3%
	PSS + TCSC	-0.79 ± j8.05	1.28	9.8%
	Coordinated	-1.21 ± j 8.72	1.39	13.7%
5	Without controller	-0.27± j7.78	1.24	3.5%
	PSS only	-1.89± j8.28	1.31	22.4%
	PSS + TCSC	-1.85 ± j8.31	1.32	21.7%
	Coordinated	-3.18 ± j 7.09	1.13	40.1%
6	Without controller	-0.28± j7.19	1.14	3.9%
	PSS only	-2.31± j7.17	1.14	30.1%
	PSS + TCSC	-2.36 ± j7.12	1.13	31.5%
	Coordinated	-2.78 ± j 8.05	1.28	32.6%
7	Without controller	-0.21± j6.53	1.04	3.2%
	PSS only	-0.71± j6.43	1.02	11%
	PSS + TCSC	-2.05± j5.57	0.89	34.5%
	Coordinated	-3.14 ± j 5.35	0.85	50.6%
8	Without controller	-0.23± j6.22	0.99	3.7%
	PSS only	-2.29± j6.65	1.06	32.6%
	PSS + TCSC	-1.95 ± j5.96	0.95	31.1%
	Coordinated	-3.05 ± j 6.45	1.03	42.6%
9	Without controller	-0.07± j4.03	0.64	1.7%
	PSS only	-0.73± j3.75	0.59	19 %
	PSS + TCSC	-0.71± j3.62	0.58	19.2%
	Coordinated	-1.12 ± j 4.35	0.69	24.9%

TABLE I: oscillatory modes in different control statuses

and facilitate the huge power transfer over the line. The small-signal analysis shows the presence of 9 lowly-damped oscillatory modes. TABLE I shows the modes eigenvalue, damping ratio in different controller statuses. Power system stabilizers are installed on all machines except for Gen1, Gen5 and Gen10 due to a low controllability measure of these machines of the

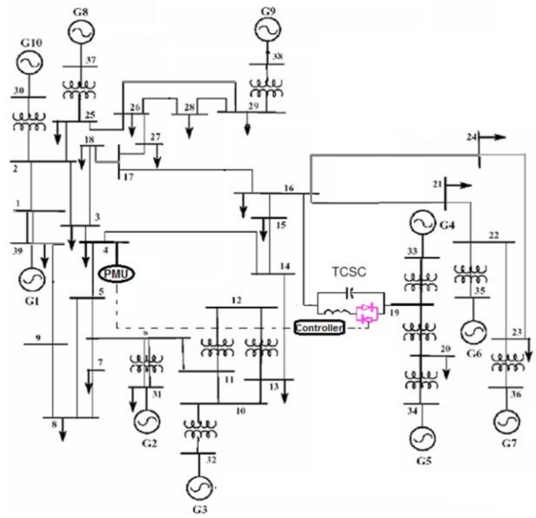

Fig. 6: IEEE 39 bus 10 machine test system

oscillatory modes and their ineffectiveness in improving the damping ratio of the oscillatory modes. After tuning of PSSs using the linear sequential method, the damping ratios of all oscillatory modes are considerably improved except for mode4 and mode7 that need more damping. The TCSC damping controller is designed with the purpose of improving the damping of mode7 which is an inter-area mode. Then the controllers are simultaneously tuned using the optimization based technique described in section 3. TABLE I shows the eigenvalues and the damping ratios of the oscillatory modes after tuning with linear sequential method and also with the optimization based tuning technique. Fig. 8-10 show the system variables oscillation after the occurrence of a three phase fault at bus3. The results verify the effectiveness of the optimization based controllers tuning technique for improving power systems dynamic performance.

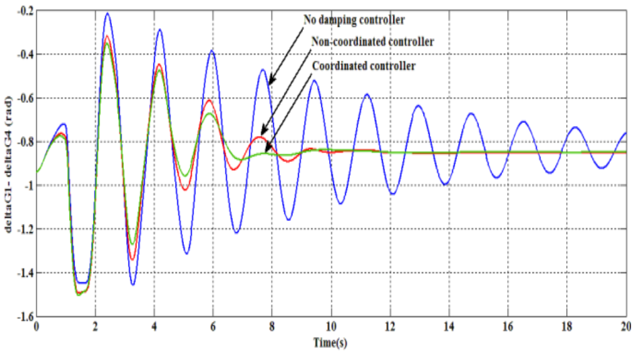

Fig. 7:G1 against G4 rotor angle oscillation after a fault at bus3

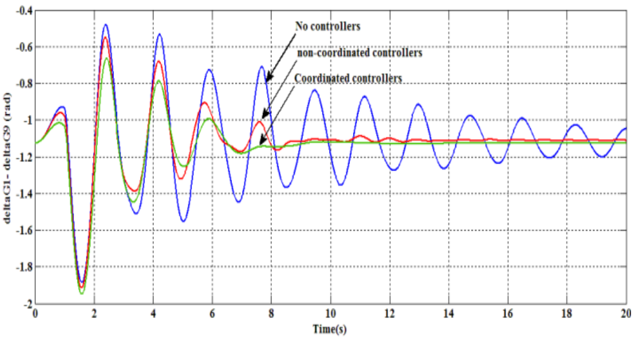

Fig. 8: G1 against G9 rotor angle oscillation after a fault at bus3

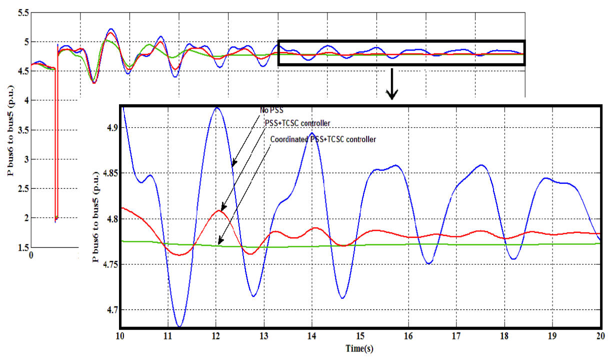

Fig. 9: Power oscillation in line 5-6 after a fault at bus3

5. Conclusion

An optimization based coordinated tuning of power system controllers was presented in this paper. The results were compared with the linear sequential method results for controllers tuning. The effectiveness of using remote signals for TCSC controller design for improving the damping of inter-area oscillations was verified. Genetic algorithm was used for optimization of the objective function. Results show that the optimization based technique enhances the overall dynamic stability of the system.

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