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POWER SYSTEM STABILITY ENHANCEMENT USING A NSPSO DESIGNED UPFC DAMPING CONTROLLER

M. Sedighizadeh [1] B. Minooie [2] M. Sarvi [3]

1. Faculty of Electrical and Computer Engineering, Shahid Beheshti University, Tehran, Iran, m_sedighi@sbu.ac.ir
2. Faculty of Engineering, Sanandaj Branch, Islamic Azad University, Sanandaj, Iran, minooei.behzah@yahoo.com
3. Faculty of Engineering and Technology, Imam Khomeini International University, Qazvin, Iran, sarvi@ikiu.ac.ir

Abstract- In this paper, a control technique based on simultaneous regulation of all control coefficients for Unified Power Flow Controller (UPFC) and Power System Stabilizer (PSS) is proposed. Non-Dominated Sorting Particle Swarm Optimization (NSPSO) has been used for parameter optimization. Studies in time and frequency domains for single machine infinite bus power system (SMIB) in different operational conditions are performed. In the control system, local state variables are choose as inputs to control blocks and simultaneous regulation of control parameters established out through NSPSO algorithm led to appealing results and some advantages over the control systems used formerly in similar settings. Different scenarios are simulated in this learn and compared to the proposed control system using the characteristics of the objective function in time domain and the position of system poles in frequency domain. The efficiency of the proposed system is established under different conditions for disturbance and variations of loads in the simulation.

Keywords: PSS, UPFC, Non-Dominated Sorting Particle Swarm Optimization, Improvement of Damping.

I. INTRODUCTION

The budding of wants and load for electrical power on one hand, and limitations on power making and conduction lines as well as economic exploitation for power systems, on the other hand, lead to pains for deployment of power systems about their stability regions. The load facility of large solid power systems is often degraded due to their pitiable damping ability mainly on low frequency oscillations and this stuff leads to some researches about power system stability in new position. Such a problem leads to the argument of low-frequency oscillations (LFO) stability in power systems. Ranging 0.2-3 Hz, in the absence of plenty damping, the oscillations might boost and this can in turn, result in contravention of transmission lines by safeguard systems.

In order to damp these power system oscillations and to raise the system oscillation stability, the mechanism of Power System Stabilizer (PSS) is both reasonable and efficient. The PSSs have been used for various years to add damping to electromechanical oscillations. though, in PSSs experience a weakness of being trustworthy to cause great variations in the voltage profile and they may even result in leading power factor function and losing system stability under sever turmoil, especially those three-phase faults which may occur at the generator terminals [2]. The modern advances in power electronics and growth of FACTS opened approaches for new methods of stabilization based on these plans. Copious studies are conducted based on better stability using FACTS control systems in the lack of disturbance.

SVC, as an FACTS device which is lengthily applied, mainly stabilizes the voltage level of the power system through convenient paralleled reimbursement mechanism in order to advance the stability of the power system. TCSC device, as an significant member of FACTS, can adjust the reactance of the controlling paralleled payment device slickly in at large range, so that it could develop the transmit capacity and system stability of the long-distance transmit system, control the tidal up to date neatly, condense the range of voltage. Commonly speaking, FACTS device contain low frequency oscillation during ad system damping and adjust power position of the line. Conversely, the Unified Power Flow Controller (UPFC) device could supply another efficient answer to contain low frequency oscillation and UPFC collect all the advantages mentioned above. It can control the line impedance, terminal voltage and power angle roundly. It restrains low frequency oscillation through maintain the given value of line power [3, 4].

In addition, UPFC has been used in modern power systems to advance reliability, obstruction management and efficient utilization of power systems. Several studies have been carried out on steady-state and small-signal or forceful modeling of UPFC [5-7]. Wang et al. projected a modified linear model based on Heffron-Phillips model with linking UPFC to power systems [8, 9]. Encountering with the miscellany of loads in power systems - concerning the type of loads (e.g. amount of inductive - resistive loads), formation of loads (e.g. static or dynamic loads), and the interval for which the load is connected to system - the loads are nonlinear completely and power system designer are faced with a highly nonlinear situation. Hence, adjustment of controller parameters based on classic control methods for humanizing oscillation damping is not sufficient for controlling UPFC parameters. This justifies the use of controllers which can adjust variations. Neural networks have been studied as an implement for improving damping in UPFC systems [10, 22]. Another approach is employing fuzzy controllers based on fuzzy logic to adjust UPFC parameters and advance damping [11].

Authors in [12, 13] employed forceful control methods adjust UPFC parameters and improve damping in oscillation. However, the main problem in these methods is the prerequisite for sure number of trials and errors to adjust output parameters in the controller. In large systems with top degree, it is not sensible to use these models because they significantly increase the level of computational pains. In [14], GA has been used in adjustment of UPFC parameters of PI controller for humanizing stability of the system. PSO is another optimization method used for UPFC parameters adjustment [15, 24]. In [16, 17], it is argued that parameters simultaneous regulation for FACTS and PSS devices are necessary for improving system competence and stability. Moreover, in [1], PSO has been used for improved damping and simultaneous adjustment of UPFC parameters by PSS.

In this study, different the previous researches, we use four independent controllers to adjust four main parameters at UPFC input: δ_E , m_E , δ_B , m_B . Using these controllers down with simultaneous adjustment of PSS controlling parameters significantly improves stability compared to situations that UPFC and PSS parameters are adjusted singly or situation that simultaneous adjustment are used but only one main output to UPFC (usually δ_E) is controlled. Non-dominated sorting particle swarm optimization (NSPSO) is used in the current study for optimization and simultaneous adjustment of parameters. A propos to the nonlinear character of the power system, an ancillary controller is proposed to increase the generated damping torque of the UPFC. In this study, in order to have a near-global set of damping controller parameters the NSPSO algorithm is engaged. The capability of this algorithm is used under various operating conditions and due to a severe commotion. Observing the time domain based results verifies the stoutness and efficiency of the NSPSO based designed controllers. Moreover, through a comparison the most powerful control signal of UPFC is also identified.

The main objectives of this examine are as following:

- Provide a control system for simultaneous adjustment of control coefficients for input parameters $(\delta_E, m_E, \delta_B, m_B)$ and PSS control coefficients to reach improved stability.
- To calculate the performance of the proposed controller concerning various aspects such as balancing the generated and consumed power based on simulation in time domain, To generate small-signal (e.g. in short circuits) and to appraise the performance of the system under different loading conditions (e.g. normal, light, or heavy loads).

NSPSO algorithm is in employment for tuning control parameters regulation. The system is evaluated under different working conditions in frequency domain by decisive the state-space + atmosphere and system modes.

II. NON-DOMINATED SORTING PARTICLE SWARM OPTIMIZATION

The goal of our multi-objective hybrid algorithm is to combine single-objective PSO with NSGA-II operations without losing performance on establishing the Pareto-front. The NSPSO combines the strengths of the these advanced operations (A fast non-dominated sorting approach, crowding distance ranking, elitist strategy, mutation and selection operations) with single-objective PSO search. The hybrid algorithm is presented below:

- Step 1: Generate an initial population *P* (Population size = *N*) and velocity for each individual (agent or particle) in a feasible space; Set the maximum speed max i_v (max i_v equals its upper bound minus lower bound) for a variable.
- Step 2: Sort the population based on the non-domination and crowding distance ranking.
- Step 3: Do rank-based selection operator.
- Step 4: Assign each individual a fitness (or rank) equal to its non-domination level (assume fitness minimization).
- Step 5: Randomly choose one individual as *gbest* for *N* times from the non-dominated solutions, and modify each searching point using previous PSO formula and *gbest*, where rand() is a random number between (0, 1). The constriction factor approach can generate higher quality solutions than the conventional PSO approach [13]. If current position outside the boundaries, then it takes the upper bound or lower bound and its velocity is generated randomly ($0 \le V_{k+1} \le V_{\max}$) and multiplied by -1 so that it searches in the opposite direction.
- Step 6: Do mutation operator.
- Step 7: Combine the offspring and parent population to form extended population of size 2*N*.
- Step 8: Sort the extended population based on non-domination and fills the new population of size *N* with individuals from the sorting fronts starting to the best.
- Step 9: Modify the *i*th *pbest* of each searching point: If current rank of the new individual (offspring) P_{k+1} is smaller than or equal to the previous one (parent) in *R*, replace the $pbest_i$ with current individual; otherwise keep the previous *i*th *pbest*.
- Step 10: Perform step (2) to (9) until the stopping criterion is met.

The main differences of our approach with respect to the other proposals existing in the literature [4, 5, 6] are:

- We add selection operator to the multi-objective particle swarm algorithm.
- We don't need external repository to save *pbest*, *gbest*.
- Selection regime for the choosing of global best (*gbest*) and personal best (*pbest*) for swarm members is based on elitist operation.
- The programming code is much short compared with the other proposals and simple to implement to any optimization problem.

III. DESCRIPTION OF CASE STUDY

A. SMIB Nonlinear Model with UPFC

Figure 1 shows an SMIB power system and its UPFC. The synchronous generator is equipped with PSS and transfers its generated power to an infinite bus through two identical parallel transmission lines and the UPFC.

The UPFC contains Pulse Width Modulation (PWM) convertors, an Excitation Transformer (ET), a Boosting Transformer (BT), a DC link capacitor and two 3-phases Voltage Source Converters (VSC). UPFC Input signals are $\delta_E, m_E, \delta_B, m_B$.

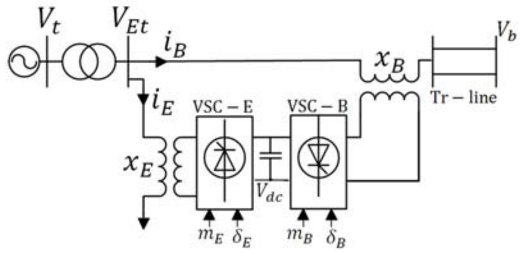

Figure 1. SMIB power system equipped with UPFC

$$\begin{bmatrix} V_{Etd} \\ V_{Etq} \end{bmatrix} = \begin{bmatrix} 0 & -x_E \\ x_E & 0 \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_E v_{dc} \cos\delta_E}{2} \\ \dfrac{m_E v_{dc} \sin\delta_E}{2} \end{bmatrix}$$
$$\begin{bmatrix} V_{Btd} \\ V_{Btq} \end{bmatrix} = \begin{bmatrix} 0 & -x_B \\ x_B & 0 \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_B v_{dc} \cos\delta_B}{2} \\ \dfrac{m_B v_{dc} \sin\delta_B}{2} \end{bmatrix} \quad (1)$$

$$\frac{dv_{dc}}{dt} = \frac{3m_E}{4C_{dc}} \begin{bmatrix} \cos\delta_E & \sin\delta_E \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + $$
$$+ \frac{3m_B}{4C_{dc}} \begin{bmatrix} \cos\delta_B & \sin\delta_B \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} \quad (2)$$

SMIB power system which is equipped with UPFC model as shown in Figure 1 is described by [18]:

$$\begin{aligned} &\dot{\delta} = \omega_0(\omega - 1) \\ &\dot{\omega} = (P_m - P_e - D\Delta\omega)/M \\ &\dot{E}_{fd} = (-E_{fd} + K_a(V_{ref} - v + u_{PSS}))/T_A \\ &\dot{E}'_q = (E_{fd} - (x_d - x'_d)i_d - E'_q)/T'_{do} \end{aligned} \quad (3)$$

where

$$\begin{aligned} &P_e = v_d i_d + v_q i_q \\ &v = (v_d{}^2 + v_q{}^2)^{1/2} \\ &v_d = x_q i_q \\ &v_q = E'_q - x'_d i_d \\ &i_d = i_{Ed} + i_{Bd} \\ &i_q = i_{Eq} + i_{Bq} \end{aligned} \quad (4)$$

where P_m and P_e are the mechanical and electrical power respectively; M and D the inertia constant and damping coefficient, respectively; ω_0 the synchronous speed; δ and ω the rotor angle and speed, respectively; E'_q, E'_{fd} and v the generator internal, field and terminal voltages, respectively; T'_{do} the open circuit field time constant; x_d, x'_d and x_q the d-axis reactance, d-axis transient reactance, and q-axis reactance, respectively; K_A and T_A the exciter gain and time constant, respectively; v_{ref} the reference voltage; and u_{PSS} the PSS controlling signal [18].

B. SMIB Linearized Model with UPFC

Linearization of the nonlinear model around the system working point is obtained by [1]:

$$\begin{aligned} &\Delta\dot{\delta} = \omega_0 \Delta\omega \\ &\Delta\dot{\omega} = (-\Delta P_e - D\Delta\omega)/M \\ &\Delta\dot{E}'_q = (-\Delta E_q + \Delta E_{fd})/T'_{do} \\ &\Delta\dot{E}_{fd} = (K_A(\Delta v_{ref} - \Delta v) - \Delta E_{fd})/T_A \\ &\Delta\dot{v}_{dc} = K_7\Delta\delta + K_8\Delta E'_q - K_9\Delta v_{dc} + K_{ce}\Delta m_E + \\ &+K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B \\ &\Delta P_e = K_1\Delta\delta + K_2\Delta E'_q + K_{pd}\Delta v_{dc} + K_{pe}\Delta m_E + \\ &+K_{p\delta e}\Delta\delta_E + K_{pb}\Delta m_B + K_{p\delta b}\Delta\delta_B \\ &\Delta E'_q = K_4\Delta\delta + K_3\Delta E'_q + K_{qd}\Delta v_{dc} + K_{qe}\Delta m_E + \\ &+K_{q\delta e}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta b}\Delta\delta_B \\ &\Delta V_t = K_5\Delta\delta + K_6\Delta E'_q + K_{vd}\Delta v_{dc} + K_{ve}\Delta m_E + \\ &+K_{v\delta e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B \end{aligned} \quad (5)$$

where $K_1, K_2, \ldots, K_9, K_{pu}, K_{qu}$ and K_{vu} are constant coefficients. The coefficients are extracted from modified Heffron-Phillips model of SMIB system with UPFC. This model has been described in [19].

C. State-Space Modeling

The state space equations for a Linear Time Invariant (LTI) system have the following form:

$$\dot{X} = AX + BU \quad , \quad Y = CX \quad (6)$$

where X is state vector, U is input vector (e.g. control signals), and Y is vector of outputs.

$$\begin{aligned} &X = \begin{bmatrix} \Delta\delta & \Delta\omega & \Delta E'_q & \Delta E_{fd} & \Delta V_{dc} \end{bmatrix}^T \\ &U = \begin{bmatrix} \Delta u_{PSS} & \Delta m_E & \Delta\delta_E & \Delta m_B & \Delta\delta_B \end{bmatrix}^T \end{aligned} \quad (7)$$

Using dynamic equations of the power system, UPFC equations, and Park transformation, A and B can be simplified as Equation (8).

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ -\dfrac{K_1}{M} & -\dfrac{D}{M} & -\dfrac{K_2}{M} & 0 & -\dfrac{K_{pd}}{M} \\ -\dfrac{K_4}{T'_{do}} & 0 & -\dfrac{K_3}{T'_{do}} & \dfrac{1}{T'_{do}} & -\dfrac{K_{qd}}{T'_{do}} \\ -\dfrac{K_A K_5}{T_A} & 0 & -\dfrac{K_A K_6}{T_A} & -\dfrac{1}{T_A} & -\dfrac{K_A K_{vd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \quad (8)$$

$$B=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{K_{Pe}}{M} & -\frac{K_{P\delta e}}{M} & -\frac{K_{Pb}}{M} & -\frac{K_{P\delta b}}{M} \\ 0 & -\frac{K_{qe}}{T'_{do}} & -\frac{K_{q\delta e}}{T'_{do}} & -\frac{K_{qb}}{T'_{do}} & -\frac{K_{q\delta b}}{T'_{do}} \\ \frac{K_A}{T_A} & -\frac{K_A K_{ve}}{T_A} & -\frac{K_A K_{v\delta e}}{T_A} & -\frac{K_A K_{vb}}{T_A} & -\frac{K_A K_{v\delta b}}{T_A} \\ 0 & K_{ce} & K_{c\delta e} & K_{cb} & K_{c\delta b} \end{bmatrix}$$

In addition to time-domain analysis based on nonlinear objective function for UPFC and PSS parameters simultaneous adjustment under different conditions, we also have studied the poles of the system, which are the eigen values of state matrix (A).

In normal conditions, all poles have negative real parts and therefore the system is stable. In the presence of disturbance, pole excitation may result in instability or, in other words, positive real parts for some poles. In this case, for regaining stability, the unstable pole is pushed toward the left-half plane by optimum adjustment of controller parameters based on the feedback taken from control variables.

Time-domain analyses are carried out by evaluation of $\Delta\omega$ oscillations after the disturbance, while frequency-domain analyses, for SMIB with UPFC after the disturbance, are performed based on the state-space matrix for closed-loop system:

$$\dot{X} = A_C X \\ A_C = A + BGC \tag{9}$$

If control parameters are chosen properly, then, not only improved damping in time domain will be observed, but also all poles in frequency domain should be placed at the left-half plane, in this research which is also studied here.

IV. UPFC AND PSS CONTROLLERS

A lead-lag controller is used for PSS as shown in Figure 2. Input signal to this controller is the speed deviation of synchronous generator ($\Delta\omega$), which is passed through the controller and compared with v_{ref} and generate the PSS control signal which eventually modifies excitation voltage for the synchronous generator.

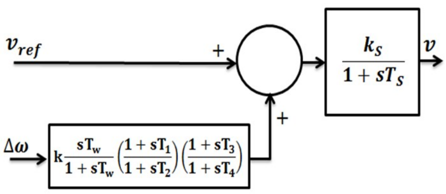

Figure 2. Block diagram of PSS controller

As mentioned earlier, a separate controller is designed for each UPFC parameters $(\delta_E, m_E, \delta_B, m_B)$. The overall structure for these controllers is the same as shown in Figure 3.

Control inputs to UPFC are divided to two parts; a lead-lag controller is used to control oscillations in speed deviation and the other part contains a DC link capacitor voltage which is compared to $V_{DC(ref)}$, passes through a PI controller, and the lead-lag controller final output are added together and merged into the reference value to make control signals for $\delta_E, m_E, \delta_B, m_B$.

The most important point in this study is performing simultaneous adjustment of control parameters for UPFC and PSS and optimization of the objective function without any assumption about the fixed position of zeros or poles or determination of other control coefficients based on this assumption.

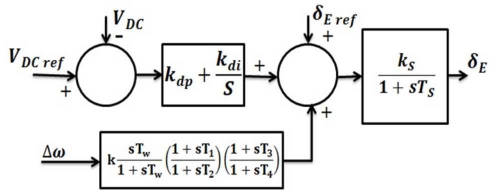

Figure 3. Block diagram of UPFC controller with DC voltage regulator

V. OBJECTIVE FUNCTION

The following objective function Integral of Time multiplied absolute value of the error ($ITAE$) was used for optimization in this study:

$$J_1 = \sum_{m=1}^{n} \int_0^{t_{end}} t\left|\Delta\omega_m\right| dt \tag{10}$$

where t_{end} is the simulation time and "n" is number of optimization points.

System eigenvalues (SE) are used in frequency domain. Second objective function can be given as:

$$J_2 = \max\{\mathrm{real}(\lambda_{ir})\} \tag{11}$$

where λ_{ir} is the real part of nearest pole to $j\omega$ axis. The optimization purpose is minimizing the objective function bounded to following constraints.

minimize J subject to:

$$K^{\min} \le K \le K^{\max} \\ T_1^{\min} \le T_1 \le T_1^{\max},\ T_2^{\min} \le T_2 \le T_2^{\max} \\ T_3^{\min} \le T_3 \le T_3^{\max},\ T_4^{\min} \le T_4 \le T_4^{\max} \tag{12}$$

The problem constraints are the optimized parameter bounds. Typical ranges of the optimized parameters are [0.01 100] for K and [0.01 1] for T_1, T_2, T_3 and T_4. The proposed approach employs NSPSO algorithm to solve this optimization problem and search for an optimal set of controller parameters.

The above nonlinear objective function (J_1) has been evaluated to use time-domain simulation. The system operating conditions are presented in Table 1.

Table 1. System operating conditions

Condition	P_e	Q_e
Normal	0.8	0.2
Light	0.2	0.1
Heavy	1.2	0.4

VI. SIMULATION

To assess effectiveness of the proposed controller using NSPSO, parameter adjustment has been investigated under different conditions (e.g. disturbance presence or absence, working conditions changes, loading (light, normal, and heavy loads), fault clearing time and conditions, etc.).

A. Simulation Scenario

The efficiency of the proposed control system was evaluated for small-signal disturbance at t=1 by applying imbalance of 0.1 pu between generation and consumption power at normal, light, and heavy loads and the results are compared to those obtained by other control systems (e.g. only PSS control, only UPFC control, PSS-UPFC control, and control over only one parameter of UPFC with PSS, that is δ_E).

To prove the efficiency of the proposed control system for small-signal disturbance working conditions, the two objective functions are evaluated. Damping in speed deviation of generator in the same condition and under nominal, light, and heavy loads are evaluated and compared to other control methods.

Five control systems have been defined in this paper. Simultaneous tuning of all control coefficients for PSS and UPFC is named "4UPFC&PSS" in all the simulations. Tuning of all control coefficients for UPFC, simultaneous tuning of δ_E and PSS parameters, tuning of just δ_E parameters and tuning of just PSS parameters are named "4UPFC", "delE&PSS", "only delE" and "only PSS", respectively.

B. Result

Firstly, the best objective function is selected between objective functions that are introduced in previous parts. To acquire this aim, the result of simulations in different condition of work for system equipped with "4UPFC&PSS" control system is presented. The values of objective functions in different working conditions are presented in Table 2.

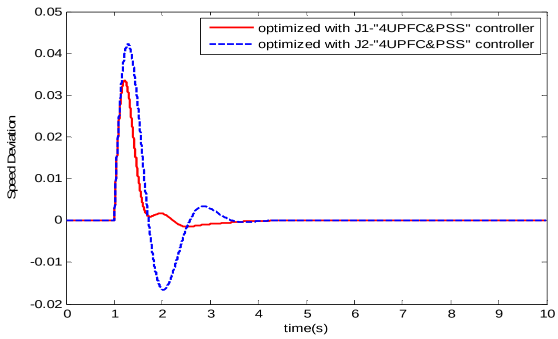

Figure 4. Dynamic response for small-signal disturbance at normal load

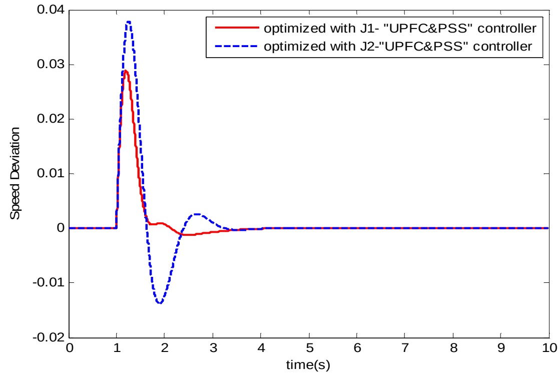

Figure 5. Dynamic response for small-signal disturbance at light load

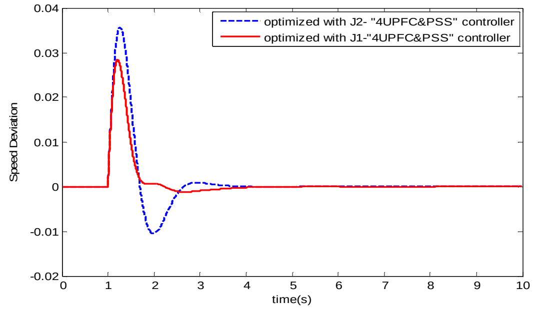

Figure 6. Dynamic response for small-signal disturbance at heavy load

It's considered that simulation based on nonlinear objective function is the most effective so other reports are presented based on J_1.

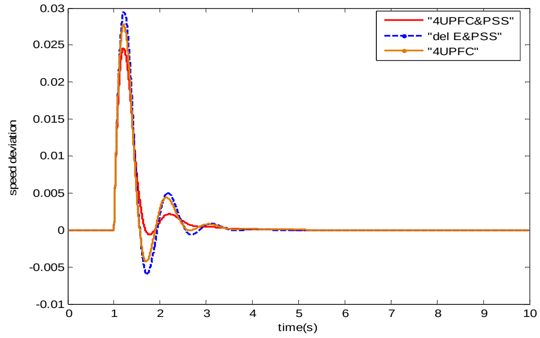

Figure 7. Dynamic response for small-signal disturbance at normal load

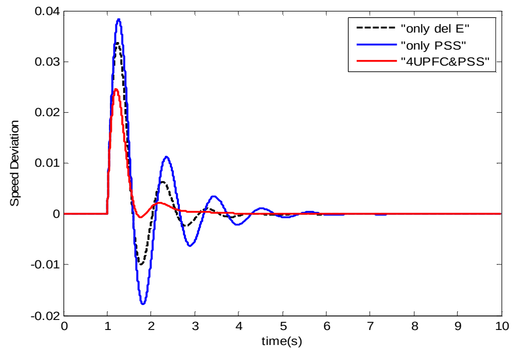

Figure 8. Dynamic response for small-signal disturbance at normal load

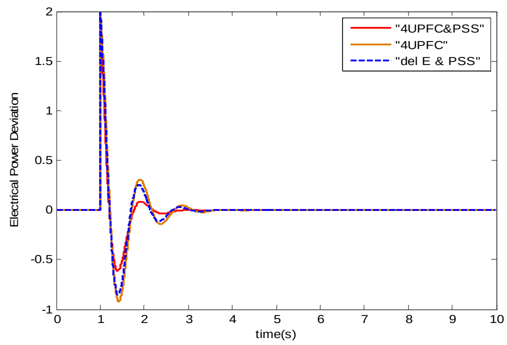

Figure 9. Dynamic response for small-signal disturbance at normal load (power electrical deviation)

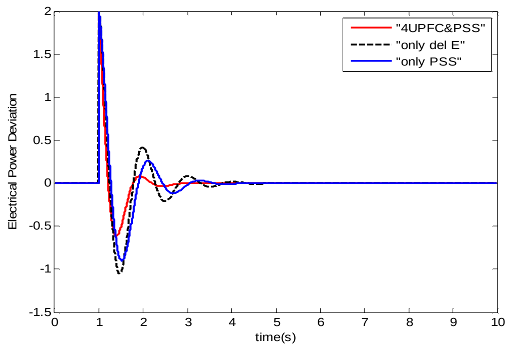

Figure 10. Dynamic response for small-signal disturbance at normal load (power electrical deviation)

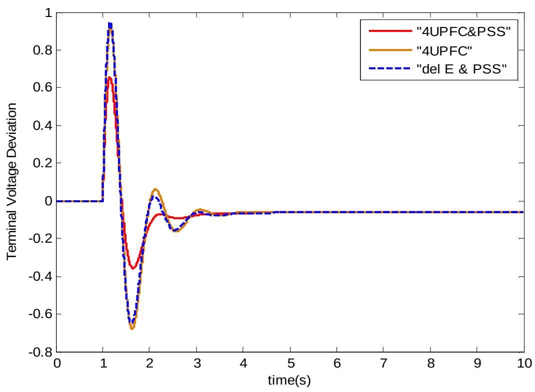

Figure 11. Dynamic response for small-signal disturbance at normal (terminal voltage deviation)

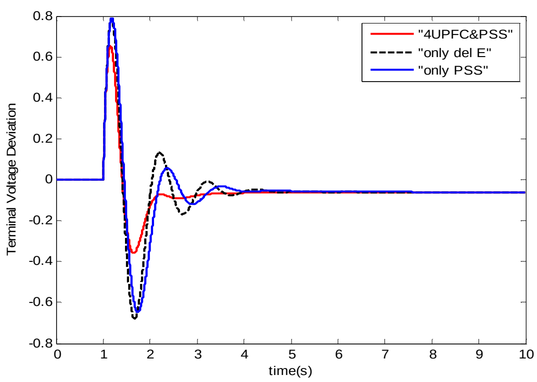

Figure 12. Dynamic response for small-signal disturbance at normal (terminal voltage deviation)

Table 2. The values of the objective functions

Disturbance	Load	J_1	J_2
small	normal	9.66E-4	-1.272
small	light	7.70E-4	-1.907
small	heavy	8.39E-4	-1.245

According to the results, It's obvious that the system outputs which is equipped with "4UPFC&PSS", "4UPFC",and "delE&PSS" are much better than the system outputs which is equipped with "only delE" or "only PSS" so other reports are presented based on "4UPFC&PSS", "4UPFC" and "delE&PSS". Table 3 shows the results for evaluation of J_1, J_2 at above simulations.

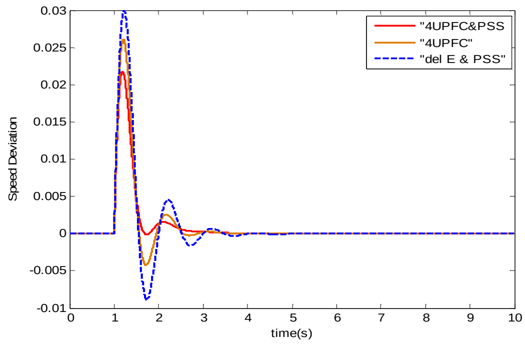

Figure 13. Dynamic response for small-signal disturbance at light load

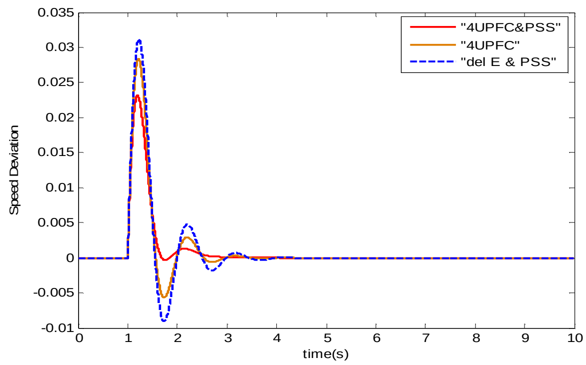

Figure 14. Dynamic response for small-signal disturbance at heavy load

Table 3. The values of *ITAE* and *FD* in simulations

Disturbance	Load	Control system	*ITAE* (J_1)	*FD*
Small	Normal	only PSS	17.33E-4	10.05342
Small	Normal	only delE	15.55E-4	13.00192
Small	Normal	4UPFC	14.07E-4	06.0853
Small	Normal	delE&PSS	14.19E-4	07.2591
Small	Normal	4UPFC&PSS	09.66E-4	03.8181
small	Light	4UPFC	09.93E-4	05.05945
small	Light	delE&PSS	11.23E-4	06.09363
small	Light	4UPFC&PSS	07.70E-4	03.51291
small	Heavy	4UPFC	10.56E-4	05.2298
small	Heavy	delE&PSS	09.77E-4	04.66230
small	Heavy	4UPFC&PSS	08.39E-4	03.3364

VII. CONCLUSIONS

Simultaneous adjustment of UPFC and PSS has been studied in this paper for improving stability of the power system in the disturbance presence. Four separate controllers have been considered for each UPFC parameters optimized simultaneously along with PSS control parameters using NSPSO. Simulated results in time domain and frequency domain for different types of disturbance and various loads (normal, heavy, light) have been described. Also the comparison of nonlinear objective functions and the position of poles (frequency-domain analysis) in different conditions based on *ITAE* and SE have been done. The suggested system performance and efficiency of the proposed control system in comparison to non-simultaneous adjustment or to the cases where Simultaneous adjustment is performed for UPFC and PSS parameters, but only one parameter of UPFC (δ_E) is controlled are more effective.

APPENDIX

The case study parameters are defined bellow:

Generator: M = 8, D = 4, f = 60 Hz, T'_{do}= 5.044 s, x'_d = 0.3, x_q = 0.6, x_d = 1, R_a = 0.

UPFC: C_{dc} =1, V_{dc} =2, m_E(min) = m_B(min) = 0, m_E(max) = m_B(max) = 2, δ_E(min) = δ_B(min) = 0, δ_E(max) = δ_B(max) = 2π, x_E = x_B = 0.1, K_S = 1, T_S = 0.05, K_{dp} = -10, K_{di} = 0.

Transformer and Transmission Line: X_T = 0.1, X_{L1} = X_{L2} = 0.3, V_b =1.

Excitation System: K_A = 50, T_A = 0.01, E_{fd}(min) = -7, E_{fd}(max) = 7.

PSS: U_{PSS} = -0.1 to U_{PSS} = 0.1, T_ω = 10 s.

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BIOGRAPHIES

Mostafa Sedighizadeh received the B.Sc. degree in Electrical Engineering from Shahid Chamran University, Ahvaz, Iran in 1996, and the M.Sc. and Ph.D. degrees in Electrical Engineering from Iran University of Science and Technology, Tehran, Iran, in 1998 and 2004, respectively. From 2000 to 2007 he was with Power System Studies Group of Moshanir Company, Tehran, Iran. Currently, he is an Assistant Professor in Faculty of Electrical and Computer Engineering, Shahid Beheshti University, Tehran, Iran. His research interests are power system control and modeling, FACTS devices, artificial intelligence, application of optimization in power systems and distributed generation.

Behzad Minooie received the M.Sc. degree in Electrical Engineering from Imam Khomeini International University, Qazvin, Iran in 2012. His research interests area are power system control and modeling, FACTS devices and optimization.

Mohammad Sarvi received the B.Sc. degree in Electrical Engineering Amirkabir Polytechnic University, Tehran, Iran in 1998, and the M.Sc. and Ph.D. degrees from Iran University of Science and Technology, Tehran, Iran in 2000 and 2004, respectively. Presently, he is an Assistant Professor at Imam Khomeini International University, Qazvin, Iran. His research interests include power electronics and renewable energy, FACTS and HVDC.