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Low Frequency Oscillations Suppression via CPSO based Damping Controller

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ABSTRACT

In this paper, the Unified Power Flow Controller (UPFC) is enhanced with a Chaotic Particle Swarm Optimization (CPSO) Damping Controller in order to mitigate the Low Frequency Oscillations (LFO) in a Single Machine Infinite Bus (SMIB) power system. The designed damping controller is an optimized lead-lag controller, which extracts the speed deviation of the generator rotor and generates the output feedback signal, which aims to modulate the reference values of the UPFC normal controller to achieve the best damping of LFO. In order to examine the better damping option, the damping controller is applied to both series and shunt converter of the UPFC and the results are comprehensively compared in three different operating points. Simulation results are performed in MATLAB/Simulink in three different cases and a Performance Index (PI) analysis is carried out.

KEYWORDS: Chaotic Particle Swarm Optimization, Flexible AC Transmission Systems, Single Machine Infinite Bus, UPFC.

1. INTRODUCTION

In recent years, the power system design, high efficiency operation and reliability of the power systems have been considered more than before. Due to the growth in consuming electrical energy, the maximum capacity of the transmission lines should be increased. Therefore, the stability and security of the power system even in normal condition is a critical point. For many years, power system stabilizers (PSSs) have been one of the most common control approaches used to damp out the oscillations in the power systems [1, 2]. However, in some operating conditions, the PSS may fail to stabilize the power system, especially in low frequency oscillations [3]. As a result, other alternatives have been suggested to stabilize the system accurately.

The rapid improvement of the high power electronics industry has made the flexible AC transmission systems (FACTS) as an appropriate selection for utility applications. FACTS devices have been proven to be more effective in power flow control, voltage stability and power swing damping [4-8]. UPFC is one of the most complex FACTS devices in a power system, which is being implemented today. Its preliminary duty is to control the active and reactive power independently. It has been shown that all three parameters that can affect the real and reactive power in the power system can be simultaneously and independently controlled just with possible switching from one control scheme to another one in UPFC. Moreover, the UPFC can be implementted for voltage support and transient stability improvement by damping of sub-synchronous resonance (SSR) or LFO. For example, in [6] it has been shown that the unified power flow controller is capable of inter-area oscillation damping by means of directly controlling the UPFC's sending and receiving bus voltages. In [8], particle swarm optimization (PSO) method is utilized for the optimization of parameters of damping controllers of the UPFC to enhance power system stability.

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Therefore, the main aim of the UPFC is to control the active and reactive power flow through the transmission line with emulated reactance. It is widely accepted that the UPFC is not capable of damping the oscillations with its normal controller. As a result, the auxiliary damping controller should be supplemented to the normal control of the UPFC in order to retrieve the oscillations and improve the system stability.

The most common type of damping controller is traditional lead-lag damping controller due to its ability to tune on-line and assurance of the stability by some adaptive or variable structure methods. Furthermore, it has been shown that the damping of oscillations will be improved with appropriate selection of controller parameters. Unfortunately, existence of more than one local optimum for lead-lag damping controllers is the main drawback of these controllers. Hence, the conventional optimization techniques are not suitable for this problem. Thus, the heuristic methods, which are widely implemented for the global optimization problems are developed [9-11].

Recently, particle swarm optimization method has been appeared as a promising algorithm for managing the optimization problems. PSO is a population based stochastic optimization algorithm, prompted by social behavior of bird flocking or fish schooling [12-14]. PSO not only eliminates the deficiencies of other conventional optimization methods, but also, it utilizes a few parameters and is easy to implement. Employing optimized controllers to achieve better performance of UPFC has emerged a vast range of researches in the literature [15-19]. Optimization algorithms such as PSO [14, 15], genetic algorithm (GA) [16, 19], quantum PSO (QPSO) [17], and chaotic optimization algorithm [18] are examples of these approaches.

In this paper, an optimized lead-lag controller has been designed to suppress the low frequency oscillations of UPFC system. In order to reduce the control cost and complexity, the control goal has been considered to design just one optimized series/shunt controller to stabilize the UPFC system. Next, the performance of the developed controller has been evaluated in different working conditions in the cases of employing either series or shunt controllers. The employed optimization algorithm is the chaotic PSO (CPSO) method. In CPSO, the chaotic logistic map is employed as the initial population generator unit, which in turn results in faster convergence and more promising optimal solution with respect of the other PSO variants [20]. Furthermore, there is an average optimal solution in the CPSO method, which can search the optimal particle more effective than PSO method. Up to knowledge of authors, it is the first attempt to study the designing and implementing the CPSO approach for optimizing the parameters of the damping controllers of FACTS devices. In order to formulate the problem to be solved, the linearized model of a SMIB power system aggregated with UPFC has been considered for controller design and the Philips-Heffron equations of the power system have been obtained through nonlinear equations of the system. Next, nonlinear system model has been employed for simulations. As the UPFC has two main controllers namely series and shunt controllers, the CPSO based damping controller is granted to both types of controllers in order to compare the two controllers and obtain the best option of damping controller installation. The performance of the proposed damping controllers will be examined in three different cases of study. Furthermore, to prove the superior performance of the proposed CPSO based damping controller in different conditions, a Performance Index (PI) based on the dynamics of the power system is also defined and calculated.

The remainder of the paper is organized as follows. In section 2, basic configuration of UPFC is presented. Section 3 describes the linearized model of system. In section 4 damping controller design is expressed and the simulation results are brought in section 5. The presented performance index is defined in section 6. A comparison between PSO and CPSO methods has been provided in Section 7. The paper is concluded in section 8.

2. BASIC CONFIGURATION OF UPFC

Generally, UPFC consists of two back-to-back voltage source converters (VSCs), and a common DC link between them. One of the two VSCs of the UPFC, connected in series and another connected in parallel with transmission line. The series converter provides the main function of UPFC by injecting an AC voltage with controllable magnitude and angle, in order to control the power flow transmitted from the transmission line. The shunt converter exchanges a current of controllable magnitude and power factor angle with the power system. Furthermore, it can adjust the reactive power flow in disturbances, in order to achieve the best damping of oscillations. The transmission line current flows through series converter and therefore, it exchanges the active and reactive power with the AC system.

If the active power flows from series converter into AC system, the DC link voltage will be discharged and if the active power flows from AC system into series converter, the DC link voltage will be charged. So in order to keep the DC link voltage fixed, the shunt converter is used to provide the power demanded by series converter through a common DC link.

Furthermore, since the converters are connected to a common DC link, only the active power can be exchanged among them and there is no reactive power flow between them. It means that the reactive power can be controlled independently in both converters. Generally, the shunt converter is implemented to support the voltage; and series converter has the duty of independent active and reactive power flow control. Figure 1 demonstrates the basic configuration of UPFC in power system including parallel and series transformers and two VSC with common DC link, where P, Q are the total power transmitted from transmission line, V_{seinj} is the voltage injected by series converter, T_{se} and T_{sh} are the series and shunt transformers of UPFC, respectively [21].

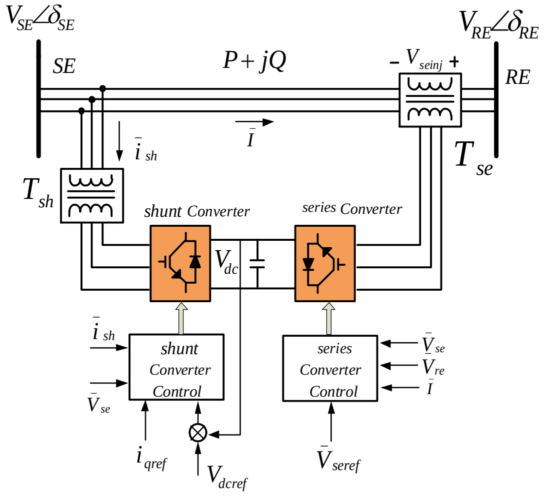

Fig. 1. Block diagram of the UPFC.

3. LINEARIZED MODEL OF THE SYSTEM

A single machine infinite bus (SMIB) power system aggregated with the UPFC is considered in this study, as shown in Fig. 2. In this figure, R and L represent the resistance and the reactance of the transmission line, V_t and V_b are the generator terminal and infinite bus voltages, respectively. The UPFC is installed in the transmission line and tries to inject a voltage in series with the line in order to control the power flow and reactive power in the line. The UPFC is assumed to be controlled directly based on pulse width modulation (PWM) converters. The nominal parameters of the system are provided in [22].

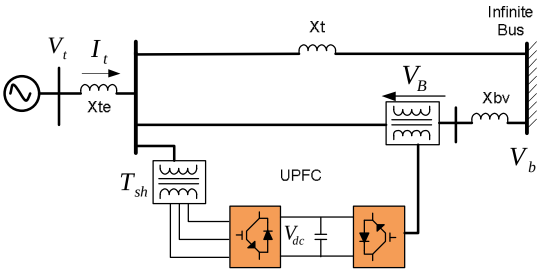

Fig. 2. The SMIB aggregated with the UPFC.

By neglecting the resistance of the components of the system (generator, transformers, transmission lines and converters of UPFC) and the transient of the transmission line and UPFC transformer, the non-linear dynamic model of the system can be achieved. The non-linear dynamic model of the system with UPFC can be expressed as [22]:

$$\dot{\omega} = \frac{(P_m - P_e - D\Delta\omega)}{M} \tag{1}$$

$$\dot{\delta} = \omega_0(\omega - 1) \tag{2}$$

$$\dot{E}'_q = \frac{(-E_q + E_{fd})}{T'_{do}} \tag{3}$$

$$\dot{E}_{fd} = \frac{-E_{fd} + k_a(V_{ref} - V_t)}{T_a} \tag{4}$$

$$V_{dc} = \frac{3M_E}{4C_{dc}}(\sin(\delta_E)I_{Ed} + \cos(\delta_E)I_{Eq}) + \frac{3M_B}{4C_{dc}}(\sin(\delta_B)I_{Bd} + \cos(\delta_B)I_{Bq}) \tag{5}$$

For designing the electromechanical mode damping stabilizer, the linearized model of the system is commonly employed. By linearizing the non-linear dynamic model around the nominal operating condition, the Philips-Heffron model of the power system will be obtained. As a result, the linear model of the proposed system is given by [22]:

$$\Delta\dot{\delta} = \omega_0\Delta\omega \tag{6}$$

$$\Delta\dot{\omega} = \frac{(-\Delta P_e - D\Delta\omega)}{M} \tag{7}$$

$$\Delta\dot{E}'_q = \frac{(-\Delta E_q + \Delta E_{fd})}{T'_{do}} \tag{8}$$

$$\Delta\dot{E}_{fd} = -\frac{1}{T_A}\Delta E_{fd} - \frac{k_A}{T_A}\Delta V \tag{9}$$

$$\Delta\dot{V}_{dc} = k_7\Delta\delta + k_8\Delta E'_q - k_9\Delta V_{dc} + k_{me1}\Delta m_e + k_{\delta e1}\Delta\delta_e + k_{me2}\Delta m_B + k_{\delta e2}\Delta\delta_B \tag{10}$$

where:

$$\Delta P_e = k_1\Delta\delta + k_{pd}\Delta V_{dc} + k_2\Delta E'_q + k_{me3}\Delta m_e + k_{\delta e3}\Delta\delta_e + k_{me4}\Delta m_B + k_{\delta e4}\Delta\delta_B \tag{11}$$

$$\Delta E_q = k_4\Delta\delta + k_{qd}\Delta V_{dc} + k_3\Delta E'_q + k_{me5}\Delta m_e + k_{\delta e5}\Delta\delta_e + k_{me6}\Delta m_B + k_{\delta e6}\Delta\delta_B \tag{12}$$

$$\Delta V_t = k_5\Delta\delta + k_{vd}\Delta V_{dc} + k_6\Delta E'_q + k_{me7}\Delta m_e + k_{\delta e7}\Delta\delta_e + k_{me8}\Delta m_B + k_{\delta e8}\Delta\delta_B \tag{13}$$

where:

ω, ω_R, and δ are the speed, the synchronous speed and rotor angle, respectively.

P_m and P_e are the mechanical and electrical power of the system, respectively.

E_{fd} and E'_q are the field voltage and the internal voltage respectively.

T'_{do} is open circuit field time constant.

X_d and X'_d are the d axis reactance and transient reactance of the generator, respectively.

I_d and I_q are the d and q axis component of the current.

V_t is the generator terminal voltage.

T_A and K_A are the gain and time constant of the excitation system, respectively.

The corresponding block diagram model of the Philips-Heffron model of a single machine infinite bus system with UPFC is shown in Fig. 3. Numerous constants are provided in the figure by k_{ij}. These constant's parameters are functions of parameters and the initial operating condition.

The control vector U in Fig. 3 can be expressed as:

$$U = [\Delta m_e \; \Delta\delta_e \quad \Delta m_B \quad \Delta\delta_B]^T \tag{14}$$

where:

Δm_e is deviation in pulse width modulation index of the series inverter.

$\Delta\delta_e$ is deviation in phase angle of the voltage of the series inverter.

Δm_B is deviation in pulse width modulation index of the shunt inverter.

$\Delta\delta_B$ is deviation in phase angle of the voltage of the shunt inverter. In Fig. 3, some factors can be defined as:

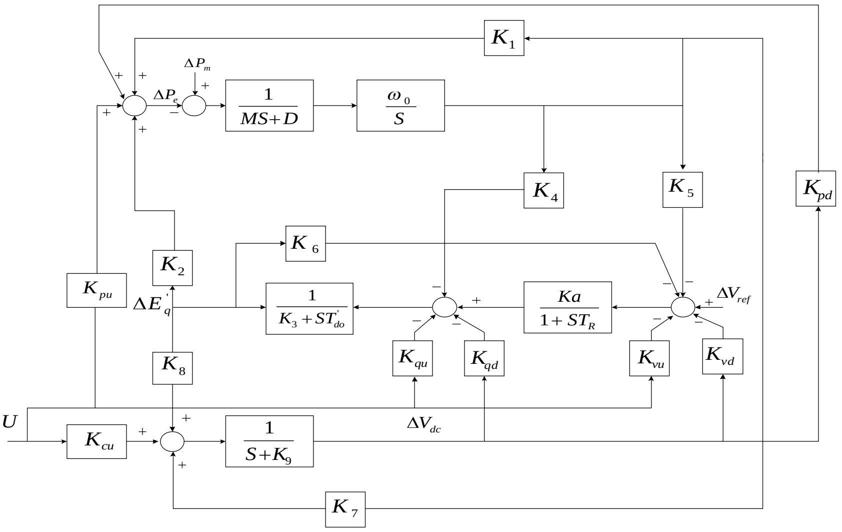

Fig. 3. The Philips-Heffron model of a single machine infinite bus power system with UPFC.

$$\begin{aligned} k_{pu} &= [k_{me3}\ k_{\delta e3}\ k_{me4}\ k_{\delta e4}] \\ k_{qu} &= [k_{me5}\ k_{\delta e5}\ k_{me6}\ k_{\delta e6}] \\ k_{vu} &= [k_{me7}\ k_{\delta e7}\ k_{me8}\ k_{\delta e8}] \\ k_{cu} &= [k_{me1}\ k_{\delta e1}\ k_{me2}\ k_{\delta e2}] \end{aligned} \tag{15}$$

The damping controller can be supplemented to each part of the proposed block in order to increase the damping performance of the UPFC.

4. DAMPING CONTROLLER DESIGN

As the UPFC has two separate kinds of controllers namely series and shunt converters, in this section, two separate kinds of damping controllers will be designed based on classical lead-lag damping controllers for each of UPFC controllers. The parameters of the auxiliary damping controllers will be optimized by the CPSO algorithm which is an advanced version of PSO algorithm. In the following, the brief explanation of CPSO method will be described.

Generally, in the PSO approach there is a search space with some simple entities named particles. Each particle at its current position calculates the objective function and then determines its movement through the search space. When all the particles have been moved, the next iteration will be created. At last, the swarm as a whole is likely to move toward an optimum of the objective function [13, 14]. Consider a predefined objective function by the user; the best objective function obtained by the i^{th} particle at time, can be expressed as *Pbest*. Furthermore, the overall best value of the objective function obtained by the particles at time (*gbest*) is calculated through the algorithm. The PSO updates each particle's velocity and position and when the stopping criterion is achieved, the final values of parameters of LFODC will be achieved. This optimization algorithm demonstrates an outstanding performance under complicated problems, but still sometimes faces with some problems such as get tin stuck at local optima and stagnation. Thus, various improvements have been introduced in order to solve these problems. The first approach was the inertia weight, which was introduced by Eberhart [23-25] in order to improve the performance of the PSO approach by controlling the local and global exploration behavior of the population.

Later, various hybrid and innovative approaches were introduced in order to get rid of the PSO barriers. One of the main important solutions for obtaining the local optimum of the PSO algorithm is the chaos particle swarm optimization (CPSO).

The CPSO method is based on chaos theory which is recognized as very useful theory in many engineering applications. An essential feature of chaotic system is that small changes in the parameters or the starting values for the data lead to different future behavior, such as stable fixed points, periodic oscillation, bifurcations and ergodicity. These behaviors can be analyzed based on the meaning of Lyapunov exponents and the attractor theory [26, 27].

Optimization algorithms based on the chaos theory are stochastic search methodologies that differ from any of the existing evolutionary algorithms. Due to the non-repetition of chaos, it can carry out overall searches at higher velocities than stochastic ergodic searches that depend on probabilities. In the PSO design, the main advantage of chaotic optimization approach is the maintenance of population diversity in the problem of interest. In CPSO sequences are generated by the logistic map rather than random parameters such as r_1 and r_2 in conventional PSO. These parameters (r_1 and r_2) are modified by the logistic map based on the following equation [26]:

$$C_r(t+1) = k \times C_r(t) \times (1 - C_r(t)) \tag{16}$$

In this equation, $C_r(0)$ is generated randomly for each independent run, with $C_r(0)$ not being equal to [0, 0.25, 0.5, 0.75, 1] and k equal to 4. The driving parameter k of the logistic map controls the behavior of $C_r(t)$ as the time goes to infinity. The equation of velocity for CPSO method can be obtained by:

$$\begin{aligned} V_i(t+1) &= W \times V_i(t) \\ &+ C_1 \times C_2 (p_{best} - X_i(t)) \\ &+ C_2 \times (1 - C_r)(g_{best} - X_i(t)) \end{aligned} \tag{17}$$

In this equation, C_r is a function based on the results of the logistic map with values between 0 and 1. The overal step by step function of CPSO method can be expressed as [28]:

- Randomly initialize the particle swarm.
- Randomly generate the C_r (0).
- While the number of iteration of stopping criteria is not meet, evaluate the fitness of particle swarm.
- Calculate the pbest and gbest of the swarm at the current iteration.
- Update the chaotic C_r using (16) .
- Update the velocity and position of particles using (17).
- Create next generation until the stopping criteria is achieved.

In order to improve the ability of the UPFC in LFO suppression, an extra controller should be implemented in addition to the conventional controller of the UPFC. The main structure of the proposed auxiliary damping controller which is the conventional lead-lag controller is shown in Fig.4. As shown in Fig. 4, $\Delta\omega$ has been implemented as an additional signal to mitigate the unstable modes. An auxiliary signal extracted from the rotor speed $(\Delta\omega)$ is implemented in damping controllers. Output signal of supplementary controller (Δu) of shunt converter of the UPFC is used to adjust reactive power in the UPFC with modulation of reference value of the DC link voltage for effective LFO damping. The same process will be organized to modulate the modulation angle of the series converter controller of the UPFC to aim the LFO suppression.

The auxiliary LFO damping controller consists of five blocks: a washout filter, two phase compensator blocks, limiter block, and a gain block. The washout filter is used to prevent the controller from responding to the steady-state changes of the input signal. The phase compensator block presents the suitable lead-lag features to produce the damping torque.

The limiter block tends to restrict the output of the controller when it is going to decrease or increase from specific range. Thus, the output of the LFO damping controller is sent to the conventional controller of UPFC in order to modulate the reference settings of series and shunt converters. In order to ameliorate the overall system dynamic stability in a robust way, the parameters of the proposed damping controller should be tuned.

The parameter T_w and limiter parameter are set manually but the other parameters will be optimized by CPSO algorithm in order to yield the LFO suppression.

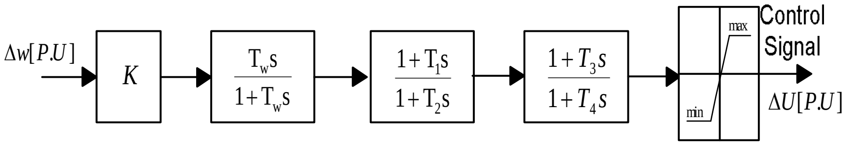

Fig. 4. LFO damping controller bock diagram.

In this study, an objective function, which comes from the speed deviation of the rotor shaft is utilized in order to yield the fittest output parameters for LFO damping controller. The mentioned objective function is an integral of time multiplied absolute value of the speed deviation expressed as:

$$J = \int_0^{t_{sim}} t \,.\left|\Delta \omega\right| .dt \tag{18}$$

where, t_{sim} is the simulation time and $\Delta\omega$ is the speed deviation of the rotor shaft in SMIB aggregated with UPFC. The main aim of optimization is to minimize the objective function due to some constrains:

$$\begin{aligned} &k^{\min} \le k \le k^{\max} \\ &T_1^{\min} \le T_1 \le T_1^{\max} \\ &T_2^{\min} \le T_2 \le T_2^{\max} \\ &T_3^{\min} \le T_3 \le T_3^{\max} \\ &T_4^{\min} \le T_4 \le T_4^{\max} \end{aligned} \tag{19}$$

The CPSO algorithm searches for the optimal values of above parameters in range of [0.001-200] for K and [0.001-3] for T_1, T_2, T_3, T_4. By implementing the time domain simulation model of the power system on simulation period, the objective function is computed and after reaching to specified criterion, the optimal parameters of the controller will be achieved. Parameters of the proposed CPSO based damping controllers for series and shunt converters are as follows.

- LFO damping controller for series converter:

  $k = 5.55$, $T_w = 2$, $T_1 = 0.9106$, $T_2 = 0.0497$, $T_3 = 0.3892$, $T_4 = 0.7757$, $\max = 0.15$, $\min = -0.15$

- LFO damping controller for shunt converter:

  $k = 4.33$, $T_w = 2$, $T_1 = 0.45012$, $T_2 = 0.1133$, $T_3 = 0.4539$, $T_4 = 1.7424$, $\max = 0.15$, $\min = -0.015$

5. SIMULATION RESULTS

The simulations and the optimization of state feedback controller parameters are performed in MATLAB software [29]. To verify the capability of the proposed CPSO based damping controllers the performance of the system will be compared in three different cases:

Case A: Light loading condition P=0.65 p.u. and Q= 0.1 p.u.

Case B: Nominal loading condition P=0.9 p.u. and Q= 0.13 p.u.

Case C: Heavy loading condition P=1.2 p.u. and Q= 0.25 p.u.

The dynamic responses of the rotor speed variation and power deviation are illustrated for each case of study in Figs. 5 to 10. It is worth mentioning that a three-phase to ground fault will be occured in time 10 sec and it will be lasted up to 3 cycles. It is widely accepted that, after clearing the fault, large fluctuations will be faced with the power system.

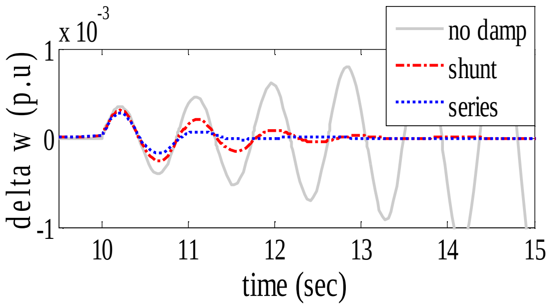

Fig. 5. Rotor speed deviation for nominal load condition.

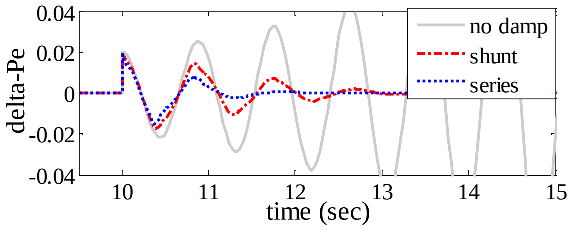

Fig. 6. Active power deviation for nominal load condition.

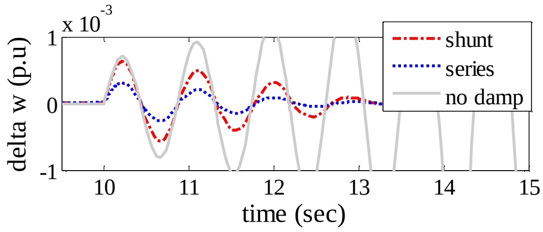

Fig. 7. Rotor speed deviation for low load condition.

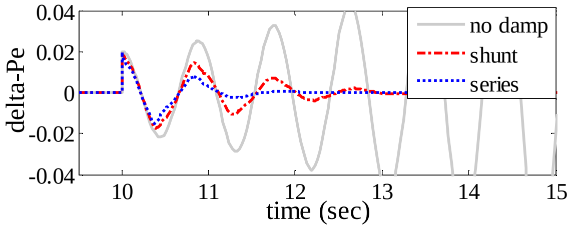

Fig. 8. Active power deviation for low load condition.

It is observed from Figs. 5 and 6 that in the nominal case of study, although the system is faced with moderate fluctuations, if the damping controller is removed from the system, the system will be unstable due to these increasing oscillations. Furthermore, when the system is enhanced with the damping controllers, it can greatly remove the oscillations in short time. Moreover, the performance of the CPSO based damping controller on series converter is superior than the CPSO based damping controller on shunt converter in mitigating the oscillations.

The system performance under low load condition has been shown in Figs. 7 and 8. It is observed from the figures that in low load condition the amplitude of oscillations are less than the nominal case, but the damping ratio is somewhat poor.

Moreover, when the system is enhanced with damping controllers, the oscillations will be mitigated quickly and similar to the previous case, the CPSO based damping controller on series converter acts superior than CPSO based damping controller on shunt converter. Figures 9 and 10 show the rotor speed deviation and power deviation of the proposed SMIB power system in heavy load condition. Although, in this situation the system faces with large increasing oscillations the CPSO based damping controller is greatly capable of damping these oscillations and it performs more robust than CPSO on shunt converter. As it can be observed, the shunt converter in this case fails to stabilize the power system and it provides very poor damping ratio. It means that in case of heavy load, the series converter is the best option as the damping controller.

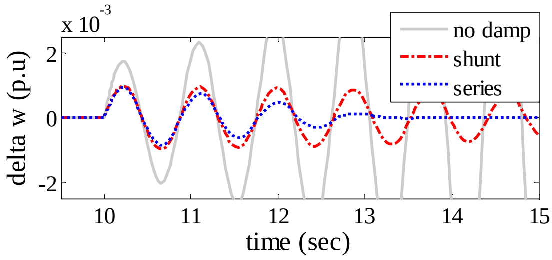

Fig. 9. Rotor speed deviation for heavy load condition.

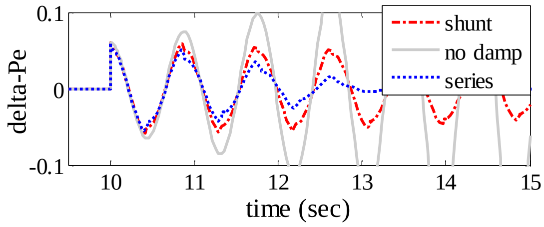

Fig. 10. Active power deviation for heavy load condition.

6. PERFORMANCE INDEX

In order to compare the results of the proposed controller with conventional damping controller, a performance index is utilized based on the behavior of the power system. This index, which mainly consists of the integral of the time multiplied with the absolute value of the power system errors known as *ITAE* performance index. *ITAE* is a well-known performance index for optimized controller design for UPFC systems, which properly takes the properties of the UPFC system into account [15, 16]. This index can be defined as:

$$J = 100\int_0^{t_{sim}} t.(|\Delta\omega| + |\Delta\delta| + |\Delta P|).dt \quad (20)$$

where, $\Delta\omega$ is the speed deviation of generator, $\Delta\delta$ is angle deviation and ΔP is the power deviation of the generator. It should be noted that, the lower value of the PI, the better performance of the controller will be guaranteed. Numerical results for three cases of study included CPSO based damping controller for series and shunt converter are shown in Table 1.

Table 1. PI calculation for proposed controllers

Case	CPSO on series converter	CPSO on shunt converter
Low	1.223	1.824
Nominal	1.426	2.657
Heavy	2.680	10.236

It is observed that, the value of PI in all three cases including low, heavy and nominal loads for CPSO based damping controller and shunt converter is much greater than its counterpart CPSO for series converter. Furthermore, in the heavy load case, the PI for shunt converter is much greater than series converter. Thus, the CPSO based damping controller on series converter operates more efficiently than CPSO based damping controller on shunt converter.

7. COMPARISON BETWEEN PSO AND CPSO METHOD

In the last part, it has been mentioned and concluded that the series converter damping controller provides a better damping characteristic than its counterpart shunt converter. Here, in order to verify the capability of proposed CPSO based damping controller, a PSO based damping controller is also designed and granted to the series converter of the UPFC in order to mitigate the LFO in a normal condition. Figure 11 shows the results of simulation for this case.

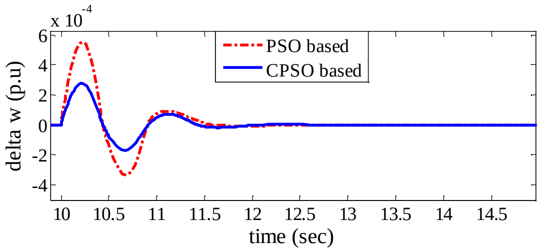

Fig. 11: The comparison of PSO and CPSO in optimal controller design.

It is worth mentioning that the proposed CPSO algorithm can provide a better time response and settling time than the PSO based damping controller in LFO suppression. Furthermore, the oscillations are going to be damped out in a superior manner when the UPFC is enhanced with CPSO based damping controller on series converter.

8. CONCLUSION

In this paper, two separate kinds of damping controllers have been designed and applied to UPFC to alleviate the power system oscillations. Damping controllers have been based on conventional lead-lag controllers which have superior performance in many different conditions.

The parameters of these conventional controllers have been optimized by new algorithm namely CPSO method which is an advanced version of PSO algorithm. These two separate controllers have been granted to the main controller of the UPFC to stabilize the power system oscillations. In order to achieve the model of the system, a linearized model of the single machine infinite bus power system aggregated with UPFC has been considered based on Heffron-Philips equations. To validate the claims, time domain simulations have been conducted in three different cases including low, nominal and heavy loading conditions. It has been revealed that the CPSO based damping controller on series converter of the UPFC provides better damping than CPSO based damping controller on shunt converter. To compare the results analytically, a performance index has been defined based on the system oscillation and calculated for three different cases of study. The results prove that the best option to enhance the UPFC is CPSO based damping controller on the series converter.

Finally, It should be emphasized that employing two damping controllers, simultaneously, may result in better performance and more reliability of the system. However, as the UPFC is a very expensive device, implementing two damping controllers would increase the equipment costs, as well. On the other hand, more complex control strategy results in more complex tuning methods as well as an increase in maintenance costs. Thus, if the control goal can be achieved by a single simpler controller, the underlying control strategy is superior with respect to the complicated one. Based on the above discussions, in this paper, the best operation of an optimized single series/shunt controller for stabilization of UPFC has been investigated. However, if more reliability is needed in the system, the shunt controller may be included as well.

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