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POWER OSCILLATION DAMPING USING QPSO BASED CONTROLLER FOR STATCOM

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Abstract- In this paper, a novel damping controller based on Quantum based Particle Swarm Optimization (QPSO) method is proposed for the STATCOM in order to damp the Low Frequency Oscillations (LFO) of the power system which caused by fault. The proposed controller is utilized in a three areas power system which has two inter-area modes of oscillation. As a result, the two stage damping controller is implemented to cover both modes of oscillations. To examine the proposed controller comprehensively, another damping controller which is optimized by PSO algorithm is also designed and supplemented to the STATCOM's normal controller. Simulation results are performed in three different operating points to assess the capability of proposed QPSO based damping controller in LFO suppression. Moreover, a Performance Index (PI) analysis is also carried out for various cases to compare two proposed controllers analytically.

Keywords: Low Frequency Oscillations (LFO), Static Compensator (STATCOM), Quantum Based Particle Swarm Optimization (QPSO), Performance Index (PI).

I. INTRODUCTION

By interconnecting the large power systems, utilities have achieved more reliability and economic viability. However, low frequency oscillations (LFO) with the frequencies in the range of 0.2-2 Hz are one of the direct results of the large interconnected power systems. The power oscillations may come up to entire rating of a transmission line, as they are superimposed on steady state line flow. Hence, these oscillations would limit the total and available transfer capability (TTC and ATC) by requiring higher safety margins. These electromechanical modes of oscillations are usually weakly damped which may increase the risk of instability of power system. Thus, in order to maintain the stability of the system, it is essential to damp the power oscillations as soon as possible [1, 2].

Different methods have been proposed to alleviate the oscillations in the power system. Power system stabilizer (PSS) has been one of the traditional devices which have been used to damp out the oscillations so far [3]. It has been found that during some operating conditions, PSS may not mitigate the oscillations effectively; hence, other effective alternatives are suggested in addition to PSSs [4]. Recently, the advent of Flexible AC Transmission System (FACTS) has directed the way to a new and more versatile approach to control the power system in a desired manner [5, 6]. FACTS controllers provide a set of interesting capabilities such as: power flow control, reactive power compensation, voltage regulation, damping of oscillations, and so on [7-11]. STATCOM is a shunt FACTS device which is generally used for voltage support or reactive compensation, but with an auxiliary controller it is capable of Low Frequency Oscillation (LFO) and SSR damping [12].

The most common type of damping controller is traditional lead-lag damping controller. 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 [13-15]. Recently, Particle Swarm Optimization (PSO) method is 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 [16-18]. PSO not only eliminates the deficiencies of other conventional optimization methods, but also, it utilizes a few parameters and is easy to implement.

In this paper, the QPSO algorithm which is the advanced version of PSO algorithm is utilized to design a robust LFO Damping controller for the STATCOM. The QPSO algorithm is not suffering from the PSO algorithm's deficiencies (PSO cannot be considered for global convergent, and lack insurance of velocity and position of particles simultaneously) and it provides many benefits. In order to better analyze the performance of proposed controller, a comparison is also adopted between proposed QPSO based damping controller and PSO based damping controller in various cases. For this aim, several case studies are conducted in a three areas six machines power system. Simulation results and Performance Index (PI) analysis with Matlab verify the effectiveness of the proposed QPSO based controller.

II. POWER SYSTEM MODELING

The power system configuration for this scheme is revealed in Figure 1. It is three areas six machines power system which can be used for nonlinear time domain simulation of the power system. This scheme is dedicated to verify the capability of proposed QPSO based damping controller in LFO suppression even in nonlinear condition. Shunt capacitors are implemented in buses 7, 9 and 15 in order to keep the initial bus voltage profiles within 1±0.03 p.u. The Matlab/Simulink is used as the simulation study tool.

For the nonlinear time domain simulation, the generators are represented in the d-q-o reference frame and the transmission lines are modeled as a PI sections which is available in Matlab. It should be noted that, the dynamic of the generator excitation is also included in the simulation. The data about the system is comprehensively included in [19]. The rotor angle oscillation modes of the modified system, obtained by the Eigenvalue analysis, consist of five oscillation modes: three local and two inter-area modes [19].

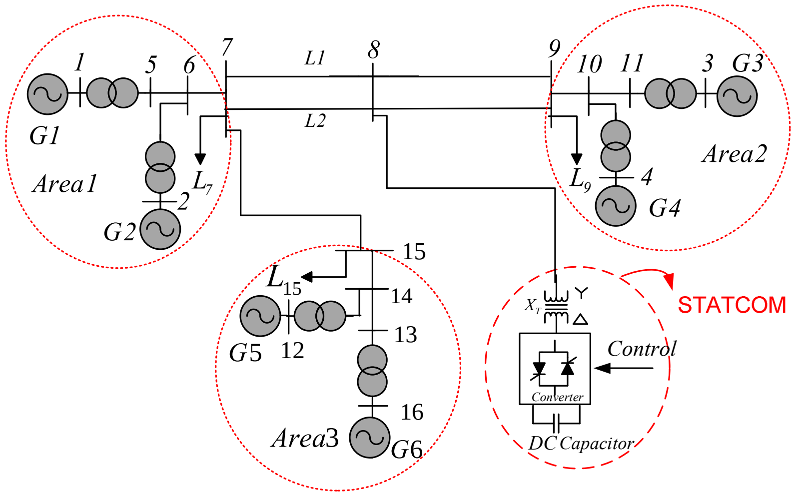

Figure 1. The investigated test system equipped with an STATCOM

The inter-area mode 1 is characterized by having a slightly higher frequency (0.78 Hz) than mode 2 (0.46 Hz). Mode 1 consists of generators of area 1 (G_1 and G_2) swinging against those of area 3 (G_5 and G_6). While, mode 2 consists of generators of area 2 (G_3 and G_4) swinging against those of areas 1 and 3 (G_1, G_2, G_5, and G_6). A simple two-stage classic controller is proposed which is represented in Figure 2.

It is apparent that to damp out multi-mode oscillations, a suitable supplementary signal containing both modes of oscillations is necessary. In order to modulate the STATCOM's AC voltage for damping two inter-area oscillation modes, each kind of input signals that has good modal observability of inter area oscillation can be used like a line power between two area or angle differences between two buses in two area or etc. Here for damping the inter-area mode 1 (0.78 Hz), classic 1 is used whose input is $\Delta\omega_{15}$. Also, classic 2 is employed to damp out the oscillation mode 2 (0.46 Hz) with input of $\Delta\omega_{13}$. Finally, the output of two stage damping controller aims to modulate the reference value of the AC voltage of STATCOM in Figure 3.

Note that in Figure 2, for the aggregated damping signal, the output is obtained according to (1). Weighting factors W_1 and W_2 are chosen inversely proportional to the normalized damping ratio of their dominant mode obtained from the Prony analysis (W_1=1.15, W_2=1) [2].

$$output = W_1 \Delta V_{q1} + W_2 \Delta V_{q2} \qquad (1)$$

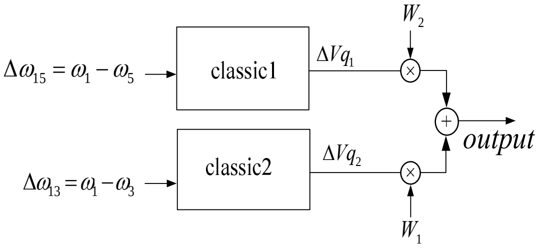

Figure 2. The two-stage damping controller designed for three-area power system

III. APPLICATION OF THE STATCOM IN THE INVESTIGATED POWER SYSTEM

A. STATCOM Concept

The STATCOM is a power electronic based Synchronous Voltage Generator (SVG) that generates a three-phase voltage in synchronism with the transmission line voltage from a DC capacitor. Generally, it is connected to the transmission line by a coupling transformer. By controlling the output voltage magnitude of the STATCOM, the reactive power will be exchanged between STATCOM and the transmission system [6]. The STATCOM is based on the principle that regulates the voltage at its terminal with managing the amount of reactive power injected to or absorbed from the power system. When the system voltage is going to decrease, it generates a reactive power (capacitive mode) and in a similar manner, if the system voltage is high, it will absorb reactive power (inductive mode).

The voltage source converter (VSC) which is linked to secondary side of the coupling transformer contributes to perform the variations of the reactive power. The VSC uses forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to create a voltage from a DC voltage source [6].

B. STATCOM Control

In order to control the power electronic switches, Sinusoidal Pulse Width Modulation (SPWM) is utilized. This algorithm is implemented to synthesize a sinusoidal wave form proportional in magnitude to the modulation gain (k) and shifted by the phase angle α. The supreme merit of pulse width modulation is that, both parameters k and α can be independently controlled. As the phase angle of the voltage on converter side is changed with respect to the phase angle of AC system voltage, the STATCOM will attempt to generate or absorb active power form the AC system. The exchanged active power will charge or discharge the internal DC capacitors [6].

The primary duties of a STATCOM are to control the AC line voltage (V_s) and the DC capacitor voltage (V_{dc}). The AC voltage control is achieved by filtering out the second harmonic and the low frequencies of the AC voltage and then a lead-lag and PI controller are applied to the voltage error in order to attain the modulation phase shift α. The DC capacitor voltage error is put through a PI controller to provide the modulation index gain k. Figure 3 shows the control block of the STATCOM [6].

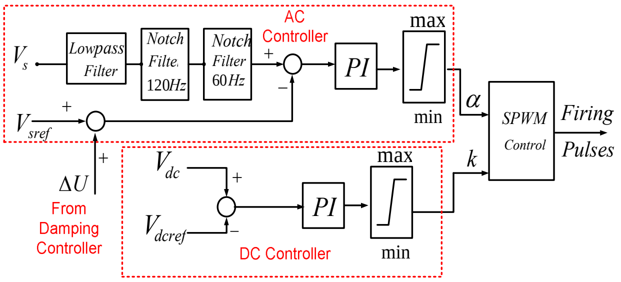

Figure 3. Block control of STATCOM

IV. POD CONTROLLER DESIGN

A. POD Controller Design

In this paper, a POD controller has been designed based on conventional lead-lag controllers. It should be noted that classic 1, and classic 2 both are lead lag damping controllers. Conventional Lead-Lag controllers have been widely used in industry because of their simple structure, easy to design, robust performance in the linear system and low cost [9]. In this investigation, because the aim is to mitigate the inter-area oscillations, the speed deviation of generators from different areas has been utilized as input signal of damping controller.

As shown in Figure 4, $\Delta\omega$ has been implemented as an additional signal to mitigate the oscillations. The auxiliary 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 so that to produce the damping torque. The limiter block tends to restrict the output of controller when it is going to decrease or increase from specific range. The output of the damping controller is therefore sent to the STATCOMAC voltage regulator in Figure 3 in order to regulate the V_{DCref}. The parameters T_w and limiter parameters are set manually but the other parameters will be optimized by QPSO algorithm in order to yield the proper damping.

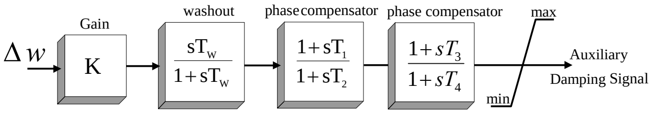

Figure 4. Auxiliary Damping Controller Structure

B. PSO Algorithm

PSO which is first developed by Kennedy and Eberhart in 1995 is a population based stochastic optimization method. It is inspired by social behavior of bird flocking or fish schooling [18]. It usually is implemented to improve the speed of the convergence and also to detect the global optimum value of the objective function. It can be utilized to solve many same problems as other kinds of algorithms such as Genetic Algorithm (GA). In comparison with GA, the PSO is easy to implement, needs fewer adjustable parameters, is suitable for the nature of the problem, and is easy for coding[17, 18]. So, with consideration of these merits toward other methods, the researchers have been convinced to use this method widely. The PSO is launched with some initial random particles and searches for the optimal point with updating the generations.

In the PSO technique, by dynamically regulating the velocity of each particle according to its own movement and the movement of the other particles, the trajectory of each individual in the search space is altered. The velocity vector and the position of ith particle in the D-dimensional search space can be expressed as: $V_i=(V_{i1},V_{i2},...,V_{id}), X_i=(X_{i1},X_{i2},...,X_{id})$, respectively.

Consider a predefined objective function by the user; the best objective function obtained by ith particle at time (Pbest), can be expressed as: $P_i=(P_{i1},P_{i2},...,P_{id})$. Furthermore, the overall best value of the objective function obtained by the particles at time (*gbest*) is calculated through the algorithm. By using the following equations, the new velocity and new position of each particle can be achieved [16, 18]:

$$V_{id}(t)=w\times V_{id}(t-1)+c_1r_1\times(p_{id}(t-1)- \\ -X_{id}(t-1))+c_2r_2\times(p_{gd}(t-1)-X_{id}(t-1)) \tag{2}$$

$$X_{id}(t)=X_{id}(t-1)+cV_{id}(t) \tag{3}$$

where, P_{id} and P_{gd} are *pbest* and *gbest* respectively. c_1 and c_2 are positive constants which are responsible for alternation of the particle velocity toward *pbest* and *gbest*. r_1 and r_2 are two random constants between 0 and 1.

In order to balance the local and global searches and also to decrease the number of iterations, the w, or inertia weight is defined. The definition of inertia weight is expressed as [17]:

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} \times iteration \qquad (4)$$

where, $iter_{\max}$ is the maximum number of iterations and iteration is the current number of iteration. The new inertia weight is updated through Equation (3), where, $w_{\max}$ and $w_{\min}$ are initial and final weights. The flowchart of the proposed PSO algorithm for POD study is shown in Figure 5.

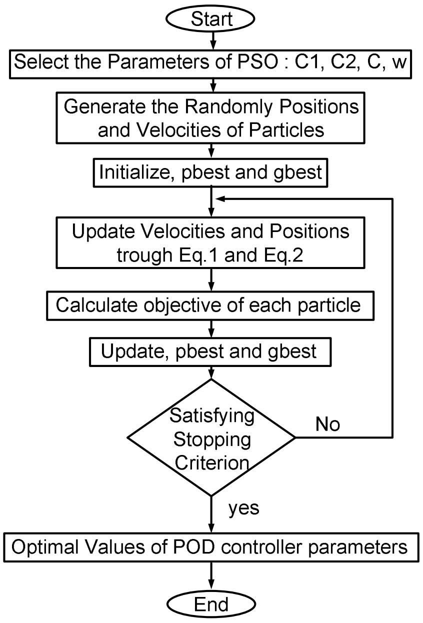

Figure 5. Flowchart of the PSO algorithm

C. QPSO Based Damping Controller

The main drawback of the PSO algorithm has convinced the researchers to improve this optimization method. The drawback can be mentioned as it cannot be considered for global convergent. In traditional PSO technique, the trajectory of the particle is determined through its position vector X_i and velocity vector V_i. The main problem is that the exact values of the X_i and V_i cannot be determined because the dynamic characteristics of the particle is different from that is considered in traditional PSO.

According to uncertainty principle, the X_i and V_i of each particle cannot be specified simultaneously. So, the term trajectory has no meaning in quantum world. As a result, if a particle in a PSO system has quantum behavior, the PSO algorithm will be bound to work in a different manner. In a quantum based PSO, terms position and velocity are eliminated and the state of a particle is defined by wave function $\psi(x,t)$. By using the Monte Carlo method, the particles will move according to these equations [20]:

$$X_{id}(t+1) = p + \beta.\left|Mbest_i - X_i(t)\right|.\ln(\frac{1}{u}) \text{ , if } K \le 0.5 \qquad (5)$$

$$X_{id}(t+1) = p - \beta.\left|Mbest_i - X_i(t)\right|.\ln(\frac{1}{u}) \text{ , if } K > 0.5 \qquad (6)$$

where *u* and *k* are values which are generated according to a uniform probability distribution in range, the parameter β is contraction or expansion coefficient which if be tuned will be able to control the convergence speed of the particle [20]. In order to guarantee the convergence of the particle, the β should be selected in range β<1.782 [20]. So, the equation 5 and 6 are the basic equations of the particle’s position in QPSO method. Furthermore, the QPSO needs no velocity vector and also has fewer parameters than PSO algorithm because only β should be controlled. So, this fewer parameters make the implementation of this algorithm easier. It is revealed by the manuscripts that the QPSO acts more efficient than the classic PSO algorithm [20]. In equations above, Mbest is the mean best position which is the mean of the Pbest of all particles:

$$Mbest = \frac{1}{N}\sum_{d=1}^{N} P_{id}(t) \qquad (7)$$

If each particle converges to its local attractor, the convergence of the QPSO algorithm will be achieved:

$$P = (c_1 P_{id} + c_2 P_{gd}) / (c_1 + c_2) \qquad (8)$$

In the following, the brief explanation of the procedure for implementation of the QPSO algorithm will be expressed:

1. A random distribution of positions will be initialized in *n*-dimensional space for each particle.
2. The fitness value of each particle is evaluated.
3. The fitness value which is obtained in the last section will be compared to *pbest*. If the fitness value is better than the *pbest*, then the *pbest* is set to current fitness value and location of *pbest* is set to the current location.
4. The fitness will be compared with the overall previous best of population. If the current value is better than *gbest*, then the *gbest* is set to current particle’s array index and value.
5. Calculate the *Mbest* through Equation (7).
6. The position of each particle will be changed through Equations (5) and (6). It should be noted that, c_1 and c_2 are two random numbers between 0 and 1.

If the convincible criterion is not achieved, the evolutionary cycle will be repeated. The criterion is usually a sufficient fitness, or a maximum number of iteration of process.

D. PSO and QPSO Based Damping Controller

In order to design the STATCOM lead-lag damping controller, QPSO technique is employed to determine the optimal parameters of the controller. In this study, an objective function which is come from speed deviation of rotor shaft is utilized in order to yield the appropriate output parameters for damping controller. The mentioned objective function is an integral of time multiplied absolute value of the speed deviation, and can be expressed by:

$$J = \sum_{1}^{iteration} \int_{0}^{t_{sim}} t.\left|\Delta\omega_{13} + \Delta\omega_{15}\right|.dt \tag{9}$$

where, t_{sim} is the simulation time, and $\Delta\omega$ is the speed deviations of the rotor shaft in generator number 1 with number 3 and number 5. The main aim of optimization is to minimize the objective function due to some constrains:

$$\begin{aligned} &K^{\min} \le K \le K^{\max} \\ &T_1^{\min} \le T_1 \le T_1^{\max} \\ &T_2^{\min} \le T_2 \le T_2^{\max} \\ &T_3^{\min} \le T_3 \le T_3^{\max} \\ &T_4^{\min} \le T_4 \le T_4^{\max} \end{aligned} \tag{10}$$

The QPSO algorithm searches for the optimal values of parameters above in range of: [0.01-200] for K and [0.0001-5] for T_1, T_2, T_3 and T_4. With implementing the time domain simulation model of the power system on simulation period, the objective function is computed and after reaching to a specified criterion, the optimal parameters of the controller will be achieved. It is worth mentioning that, the parameter β is set to 1.2 and c_1 and c_2 are set to 0.9 and 0.9. Finally, the Parameters of the proposed QPSO based classical controller are as follows:

- Classic 1: K = 86.8, T_W = 5, T_1 = 0.034, T_2 = 1.278, T_3 = 3.51, T_4 = 0.605, max = 500 and min = -500.

- Classic 2: K = 24.5, T_W = 5, T_1 = 0.223, T_2 = 2.13, T_3 = 0.081, T_4 = 0.58, max = 500 and min = -500.

These steps have been implemented on the STATCOM enhanced with PSO method to compare the results comprehensively. It should be noted that, in designing the damping controller with PSO method: to achieve a better damping, the number of particles, number of iterations, c_1, c_2, c and w are set to 50, 200, 2, 2, 1, and 0.85, respectively. Final parameters of the proposed PSO based damping controller are expressed in below:

- Classic 1: K = 56.44, T_W = 2.25, T_1 = 0.674, T_2 = 0.04, T_3 = 0.28, T_4 = 0.03, max = 500 and min = -500.

- Classic 2: K = 56.44, T_W = 2.25, T_1 = 3.78, T_2 = 0.44, T_3 = 1.53, T_4 = 0.005, max = 500 and min = -500.

V. SIMULATION RESULTS

In order to clear perceptiveness of the proposed damping controllers, simulation results are carried out in three areas six machines power system in three different loading conditions. These three different operating points are illustrated in Table 1. A three-phase to ground fault is occurred between buses 9 and 7 in the middle of the line L_1 and it will be removed after 3cycles. Due to this fault, large fluctuations will be anticipated between different sections of the power system. So, the damping controllers should be implemented to alleviate these adverse oscillations as soon as possible. The performances of the proposed controllers in these situations are shown in Figures 6 to 8.

Table 1. Three different loading conditions

Case	Bus 7 (load)	Bus 9 (load)	Bus 15 (load)
Low	1755+j100-j260	1200+j100-j350	1440+j300-j240
Normal	1400+j100-j350	1800+j100-j500	1200+j300-j220
Heavy	1250+j100-j220	1700+j100-j400	1440+j300-j360

Table 2. The result of PI calculations performed for cases two and three with both designed controllers

Case	QPSO		PSO	
	PI_1	PI_2	PI_1	PI_2
Low	1.28	0.73	2.34	1.11
Medium	1.65	0.96	3.62	2.79
Heavy	2.12	1.26	5.46	3.98

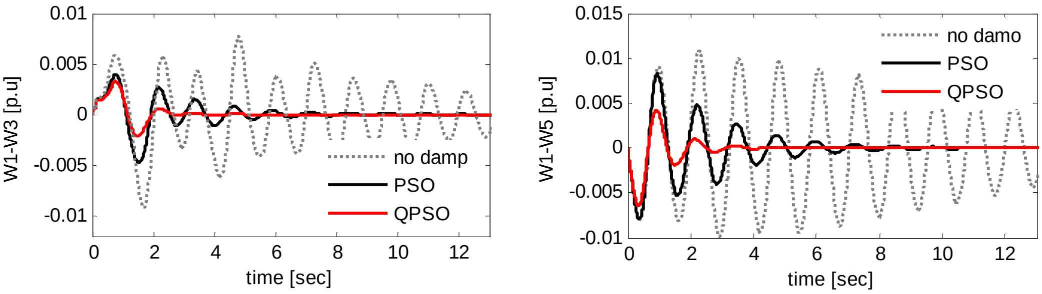

Figure 6. Simulation results for speed deviations of the generators from different areas in low load condition

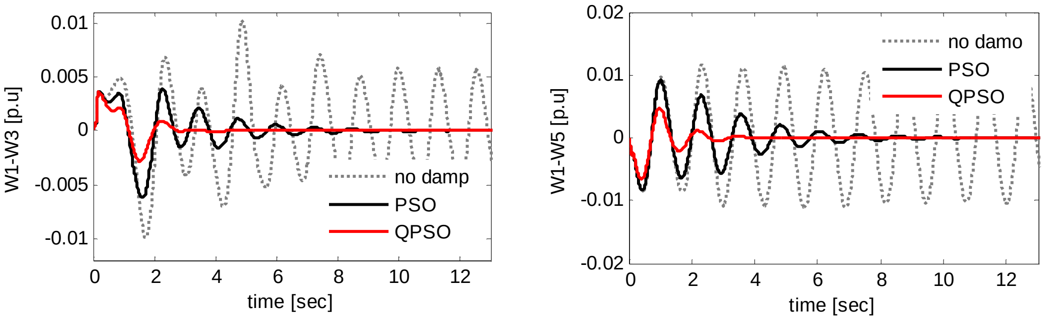

Figure 7. Simulation results for speed deviations of the generators from different areas in normal load condition

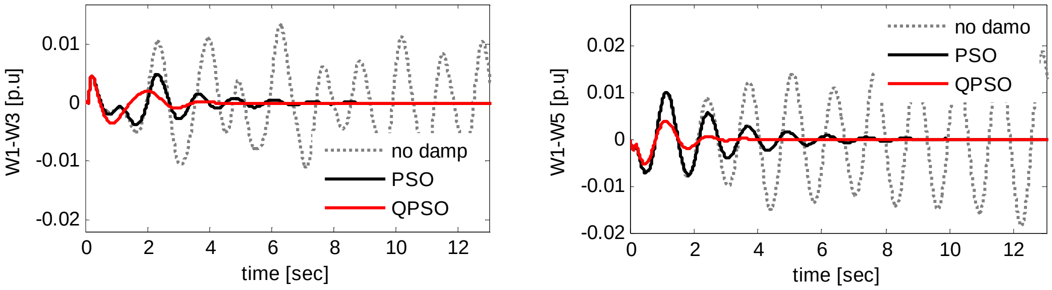

Figure 8. Simulation results for speed deviations of the generators from different areas in heavy load condition

It can be observed that the QPSO based damping controller achieves robus performance and provides superior damping in comparison with the PSO based damping controller. It should be noted that, in heavy load condition, without any damping controller, the performance of the system is purely unstable and the system will become unstable after few seconds.

But with implementation of the proposed damping controller, the system can retrieve from the fault and the QPSO based damping controller damps the power system oscillations a few seconds after the fault occurrence.

VI. PERFORMANCE INDEX

Now, in order to complete the clear perceptiveness about the system responses, two Performance Indexes (PIs) are defined on the system dynamics. These two performance indexes that reflect the settling time and overshoots can be defined as two separate objective functions for each designed controller.

If each performance index has the lower value with one of the proposed controllers, the controller will act efficiently and it will damp the oscillations quickly. Two performance indexes are expressed as:

$$PI_1 = 100 \int_0^{t_{sim}} t.(|\Delta\omega_{13} + \Delta\omega_{15}| + |\Delta\delta_{13} + \Delta\delta_{15}| + + |\Delta p_{13} + \Delta p_{15}|)dt \quad (11)$$

$$PI_1 = 100 \int_0^{t_{sim}} t.(|\Delta\omega_{13} + \Delta\omega_{15}|)^2 \, dt \quad (12)$$

where, t_{sim} is the simulation time, $\Delta\omega$ is the speed deviation of the generator rotor speed, $\Delta\delta$ is the angle deviation of the generator rotor and Δp is the power deviation of generator. The PI calculations are performed for cases two and three with both designed controllers, the results are shown in Table 2.

It is revealed that, for both cases, the PI related to the QPSO algorithm has lower value than the PI related to its counterpart PSO based damping controller. This demonstrates that the settling time and speed deviations of the generator rotor are greatly reduced by applying the proposed QPSO based damping controller. In other way, the proposed QPSO based damping controller provides good damping characteristic under various case studies.

VII. CONCLUSIONS

In this paper, the ability of STATCOM in mitigating the inter-area oscillations in a three areas power system is investigated. Due to the fact that the STATCOM’s duty in power system is voltage support or reactive compensation, it is not able to carry out other functional capabilities such as LFO damping. For this purpose, the STATCOM should be enhanced with supplementary controllers. So, a damping controller based on QPSO optimization algorithm is designed and enhanced to the conventional controller of the STATCOM to damp out the oscillations. In order to prove the effectiveness ofthe proposed damping controller, another damping controller based on PSO algorithm is also designed and supplemented to the STATCOM. Three different loading conditions are considered to compare the result of damping comprehensively, and the results have proved the superior performance of QPSO based damping controller in all three cases. Furthermore, the Performance Index analysis has been carried out to compare the results analytically. The results also have proved the better performance of QPSO than PSO in LFO suppression.

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