International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 7, No. 4, December 2016, pp. 1172~1180
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v7i4.pp1172-1180

Inter-area Oscillation Damping using an STATCOM based Hybrid Shunt Compensation Scheme

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Article Info

Article history:
Received May 31, 2016
Revised Nov 5, 2016
Accepted Nov 17, 2016

Keyword:
Compensator (STATCOM)
Inter-area oscillations
Power system stability
Shunt compensation
Static synchronous

ABSTRACT

FACTS devices are one of the latest technologies which have been used to improve power system dynamic and stability during recent years. However, widespread adoption of this technology has been hampered by high cost and reliability concerns. In this paper an economical phase imbalanced shunt reactive compensation concept has been introduced and its ability for power system dynamic enhancement and inter-area oscillation damping are investigated. A hybrid phase imbalanced scheme is a shunt capacitive compensation scheme, where two phases are compensated by fixed shunt capacitor (C) and the third phase is compensated by a Static Synchronous Compensator (STATCOM) in shunt with a fixed capacitor (CC). The power system dynamic stability enhancement would be achieved by adding a conventional Wide Area Damping Controller (WADC) to the main control loop of the single phase STATCOM. Two different control methodologies are proposed: a non-optimized conventional damping controller and a conventional damping controller with optomised parameters that are added to the main control loop of the unbalanced compensator in order to damp the inter area oscillations. The proposed arrangement would, certainly, be economically attractive when compared with a full three-phase STATCOM. The proposed scheme is prosperously applied in a 13-bus six-machine test system and various case studies are conducted to demonstrate its ability in damping inter-area oscillations and power system dynamic enhancement.

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1. INTRODUCTION

Low frequency inter-area oscillations have been observed when large power systems are interconnected by relatively weak tie lines. These oscillations may sustain and grow to cause system separation if no sufficient damping is available [1]-[2]. Traditional power system stabilizers (PSSs) have been widely studied to solve the problem [3]. However, PSSs suffers a trouble of being liable to cause considerable variations in the voltage profile and they may even result in leading power factor operation and losing system stability under severe disturbances, especially those three phase faults which may happen at the generator terminals. In recent years, the fast progress in the field of power electronics had opened new opportunities for the application of the Flexible AC Transmission Systems (FACTS) devices as one of the most effective ways to improve power system operation controllability and power transfer limits [4]-[5]. Through the modulation of bus voltage, phase shift between buses, and transmission line reactance, FACTS devices can cause a substantial increase in power transfer limits during steady-state. Because of the extremely fast control action associated with FACTS device operations, they have been very promising candidates for utilization in power system damping enhancement. It is well known that utilizing a feedback auxiliary control, in addition to the FACTS device main control, can greatly improve system damping [6]-[8] and can also improve system voltage profile, which is advantageous over PSSs. Besides many merits which are provided with FACTS devices, they are suffering from high initial costs, device complexity and low reliability of these devices which means if a single point of failure occurs in a system, the system will be entirely shut down. These barriers have convinced the researchers to search out for a solution and, in the literature some new structures and systems have been introduced [9]-[15]. In [9]-[12] the Distributed FACTS (D-FACTS) technology has been introduced. This newly born technology points a way to a novel approach for achieving the power flow control, voltage stability, system oscillation damping and whole system reliability.

The distributed nature of the suggested system makes it possible to achieve fine granularity in the system rating. Moreover, it is possible to expand the system with the growing demand. This gives a salient benefit in planning the system, which allows the planner to have control on available transfer capacity (ATC). It is done in a way that the growing needs in power transfer (equal to 2% for every year) are satisfied by installing new D-FACTS modules in the line for 10 years; this is done in order to meet project growth needs without having to invest all the capital at the start of the project implementation or in [13]-[15] two economical phase imbalanced series compensation concept has been introduced and their ability for power system dynamic enhancement and inter-area oscillation damping have been investigated where the series capacitive compensation in one phase is created using a single-phase TCSC (Scheme I) or a single-phase SSSC (Scheme II) in series with a fixed capacitor, and the other two phases are compensated by fixed series capacitors. The TCSC and SSSC controls are initially set such that their equivalent compensations at the power frequency combined with the fixed capacitor yield a resultant compensation equal to the other two phases. These two schemes would, definitely, be economically attractive when compared with a full three-phase TCSC or SSSC, which have been used/proposed for power oscillations damping. Furthermore, reducing the number of thyristor valves and VSC to one third will also have a positive impact on equipment reliability.

The main contribution of this paper is introducing an economical phase imbalanced shunt capacitive compensation concept and investigating its ability for power system dynamic enhancement and inter-area oscillation damping. A shunt hybrid phase imbalanced scheme is a shunt capacitive compensation scheme, where two phases are compensated by fixed shunt capacitor (C) and the third phase is compensated by a single phase Static Synchronous Compensator (STATCOM) in shunt with a fixed capacitor (CC). Certainly the proposed arrangement would, certainly, be economically attractive when compared with a full three-phase STATCOM. The power system dynamic stability enhancement would be achieved by adding an auxiliary damping controller to the main control loop of the single phase STATCOM. In designing damping controller, the feedback signals could either comprise wide-area information through utilization of PMUs dispersed over the network or be limited to merely local data captured at the line's sending end. Since this paper concentrates on the inter-area phenomenon on which is inherently a global issue, wide area signals are used for the damping controller input signal [16]-[17]. To optimize the parameters of the designed Wide Area Damping Controller (WADC) the Particle Swarm Optimization (PSO) method is utilized. The PSO is a population based stochastic optimization algorithm, prompted by social behavior of bird flocking or fish schooling [18]-[19]. In order to assess the capability of the PSO based damping controller in oscillations suppression, a nonoptimized conventional damping controller is also designed and enhanced to the main control loopof the unbalanced STATCOM to suppress the oscillations.Finally the proposed approach is prosperously applied in a 16-bus six-machine test system and various case studies are conducted to demonstrate the potential of the proposed approach.

2. PHASE IMBALANCED SHUNT COMPENSATION SCHEME

The STATCOM is a well-known shunt connected FACTS controller based on voltage source converter (VSC). As illustrated in Figure 1, a typical STATCOM is realized with a three-phase VSC, a dc link capacitor and an interfacing transformer. Also a filtering stage (not shown) is considered at the output of the VSC for alleviating the harmonic pollution in the injected voltage [4].

The STATCOM is capable of generating or absorbing reactive power. By varying the amplitude of the produced output voltages, the reactive power exchange between the converter and the ac system can be controlled; hence, it gives the opportunity to control some specific parameters (e.g. voltage) of an electric power system. To address in more details, the STATCOM main task is to control the voltage dynamically. However, it is commonly expected to yield some ancillary duties such as power oscillation damping, transient stability enhancement, voltage flicker control and so forth. Figure 1 also displays the main control system of the single phase STATCOM considered here. From this figure it can be seen that the control system requires three input signals including ac system bus voltage, V, converter output current i_o and the bus reference voltage V_{Ref} . As illustrated, voltage V operates a phase-locked loop (PLL) which determines the basic synchronizing signal, angle θ. The reactive component of the output current I_{oQ} is extracted and compared to the produced reactive current reference, I_{QRef} . Ultimately the obtained error signal is utilized to provide angle ϕ , which determines the necessary phase shift between the output voltages of the converter and the ac system voltage. In the sequel when ϕ is calculated, the dc link capacitor is charged or discharged to the dc voltage level required [4].

A phase imbalanced STATCOM is a shunt compensation scheme, where two phases are compensated by fixed shunt capacitor (C) and the third phase is compensated by a single phase STATCOM paralleled with a fixed capacitor (C_C) as shown on Figure 2. The phase imbalance of proposed Scheme can be explained mathematically as follows. At the power frequency, the reactive power for phases a, b and c are given by:

$$Q_a = Q_b = Q_c \tag{1}$$

$$Q_c = Q_{Cc} + Q_{STATCOM} \tag{2}$$

During any other frequency, Fe

$$Q_c = Q_{Cc} + Q_{STATCOM} + \Delta Q_{STATCOM} \tag{3}$$

The first terms in (2) and (3) are different because of the difference in frequency. The third term in (3) represents the change in effective reactive power of the single phase STATCOM due to the action of the STATCOM supplementary damping controller that has been added to yhe main control loop of STATCOM to inter area oscillation mitigation. As said on section 1 this scheme would, definitely, be economically attractive when compared with a full three-phase STATCOM. This paper introduces this economical scheme and evaluates the effectiveness of the scheme in damping oscillations. Time domain simulations were conducted on a benchmark network using the Matlab.

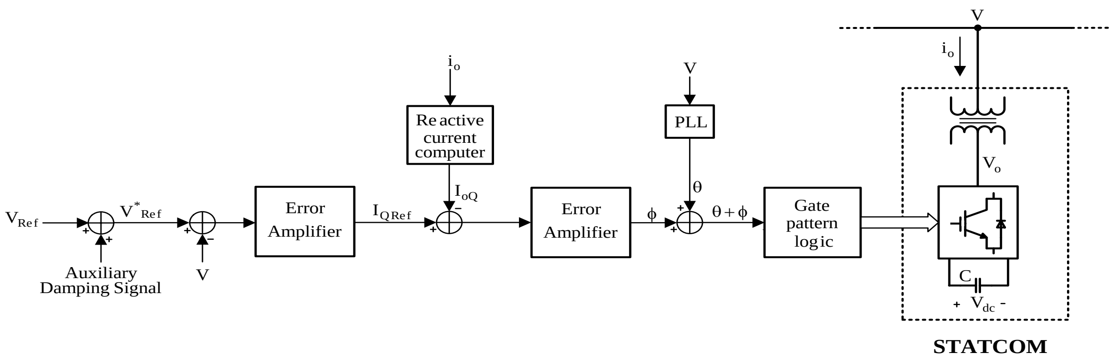

Figure 1. STATCOM Control system

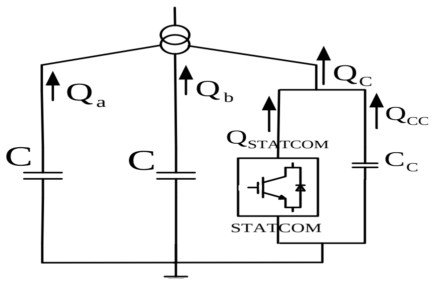

Figure 2. Schematic Diagrams of the Hybrid Shunt Compensation Schemes

3. STUDY SYSTEM

The power system adopted for this study is illustrated in Figure 4 [13]-[14] and [17]. It has originally 15 buses and six machines in three areas. Although this is a test system, it well serves to illustrate the concept, which remains the same for large systems. To keep the voltage profile of the system constant, shunt capacitors are installed at buses 7, 9, and 15. For the nonlinear time domain simulation, generators are modeled in the d-q-o reference frame and transmission lines are represented in the π model. It is worth mentioning that the dynamics of generator excitation is also considered in the simulation. The comprehensive data of the power system are given in the Appendix A. For applying the phase imbalanced shunt compensator in the system, a single phase STATCOM is installed instead of one phase of shunt capacitor that installed on bus 7 and the STATCOM contribution in the hybrid compensated phase is 0.5 p.u. of the total reactive compensation. However, the optimal location of reactive power compensator in practical and large power systems is vital point and requires comprehensive studies [21].

The power system under study has five distinct oscillatory modes: three local modes and two inter-area modes which have been obtained by the Eigen value analysis. 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 swinging against those of area 3. While, mode 2 consists of generators of area 2 oscillating against those of areas 1 and 3 [14]. As a result, in order to mitigate the unstable oscillation modes, a PSO-based is designed and added to the main control loop of the unbalanced STATCOM.

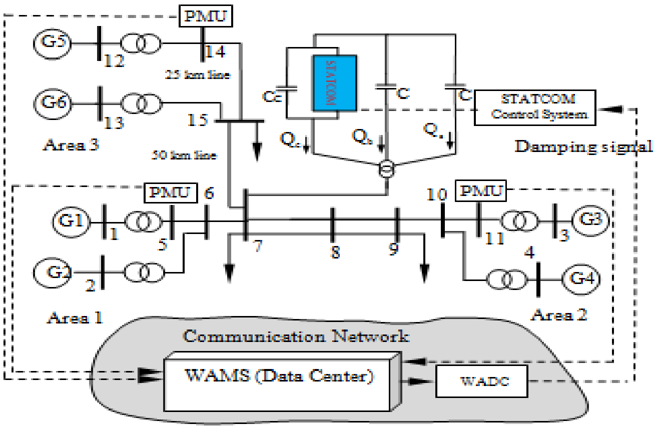

Figure 4. Three-Area Six-Machine Power System Aggregated with an Unbalanced STATCOM

4. POWER OSCILLATIONS DAMPING CONTROLLER DESIGN

As explained in Section III, the system under study has five distinct modes. These oscillatory modes are to be damped by an auxiliary damping controller that is added to the main control loop of the unbalanced STATCOM. Among crucial requirements of implementing auxiliary damping controllers is figuring out its best location. This task should be done with two major objectives: (i) providing an effective damping of oscillations and (ii) minimizing the possible interactions between STATCOM reactive power and damping controllers.

One of the fundamental issues in designing the damping controller is the selection of feedback signals to achieve the best modal observability and optimal oscillation damping [22]. Any kind of input signal with sufficient modal observability of inter-area oscillation can be used; amongst are the active power of tie lines, voltage angle differences between areas, rotor angular speed differences between generators, etc. Generally, the damping controller input signals can be classified in twofold groups: local signals and wide-area ones. As a result, two sorts of solutions exist for designing damping controllers: the decentralized approach based on local signals and the centralized approach exploiting wide-area information. The main advantage of the former solution comes from the fact that no telecommunication infrastructure is needed. The expense of this method is that it will suffice to economically and efficiently satisfy the damping requirements of the present/future heavily stressed networks with credible inter-area oscillation modes. In contrast, the centralized technique offers more effective outcomes at the expense of having fast communication infrastructure. Clearly, in a practical environment, selection of either centralized or decentralized solution depends on a given power system characteristics and its communication facilities. With respect to Figure 4 the power system under study equipped with PMUs, wide area signals used as damping controller input signal. Opposite to the conventional measurement devices, PMUs are synchronized respect to each other through the one pulse per second signals of the global positioning system. This new opportunity realized the true concept of measuring phase angles which inherently encompass valuable information of the system stress situation. The huge infrastructure which is in charge for gathering the PMUs' data in a central location(s) is referred to as WAMS. Autonomous control including oscillation damping is among advanced functionalities imagined for WAMS. Clearly, the WAMS potential in feeding WADCs is directly dependent to the number and location of PMUs deployed in the grid. The PMU placement problem is a broadly investigated research area and various aspects of this problem have been so far digested in dept [23]-[25]. Intuitively, it can be deduced that for oscillation damping objective a limited number, but geographically distributed, of PMUs would work sufficiently. The numerical studies presented in the following support this conclusion.

One of the main advantages of WADCs is its capability in designing multi-band damping controllers. Each band of the WADC has its own global input signal for damping one of the oscillation modes. As the system under study has two inter-area modes, a simple two-band classic controller is considered which is represented in Figure 5. Each controller is a conventional damping controller that is shown in Figure 6. Band controllers are denoted by WADC1 and WADC2 and the whole unit is recognized by WADC.

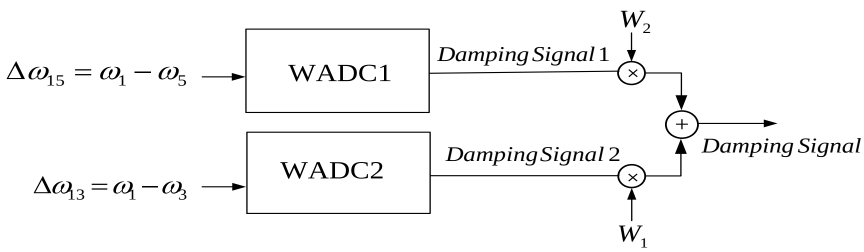

Figure 5. The Two-Band WADC Designed for the Three-Area Power System

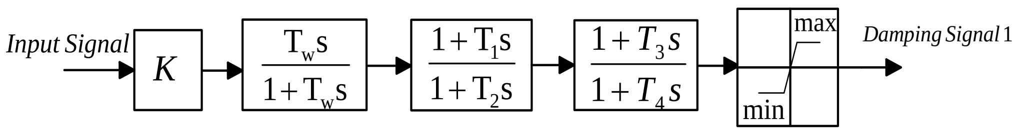

Figure 6. The Block Diagram of the Classical Damping Controller

It is apparent that to damp out multi-mode oscillations, two suitable supplementary signals containing both modes of oscillations are necessary. Any kind of input signal that has a good modal observability of inter-area oscillation can be used such as the power of tie line interconnecting two areas, frequency difference between two areas, angle difference of two buses in two areas, etc.

Generally, the PMU firstly receives the sinusoidal waveforms of three-phase voltages and currents, then converts the sampled digital data to the phasor values, and finally sends the information to the regional or system control center [26]. Although the PMU computed frequency and its rate of change are based on local voltage measurements, there are several approaches to calculate the generator speed through local PMU measurement [27]-[29]. Frequency is a key indicator for the system stability and generation/demand balance. This parameter or its derivatives such as rotor speeds and their rates of change are usually implemented as the damping controller feedback signal [11]-[12] and [17]. To this end, high voltage buses associated with G1, G3 and G5 are assumed to be equipped with PMUs and $\Delta\omega_{13} = \omega_1 - \omega_3$ and $\Delta\omega_{15} = \omega_1 - \omega_5$ are chosen as global feedback signals. For damping the inter-area mode 1 (0.78 Hz), WADC1 is used whose input is $\Delta\omega_{15}$ and WADC2 is responsible for damping the oscillation mode 2 (0.46 Hz) with input of $\Delta\omega_{13}$. As shown in Figure 5, the output of WADCs are weighted and summed up to generate the WADC output, which is

$$Damping\ Signal = W_1 * (Damping\ Signal\ 1) + W_2 * (Damping\ Signal\ 2) \quad (4)$$

W1 and W2 are weighting factors and are chosen inversely proportional to the normalized damping ratio of their dominant mode obtained from the Prony analysis (W1=1.15, W2=1) [14]. The WADC output is finally employed for modulating the reactive power loop of the STATCOM (see Figure 1).

It has to be noted that the communication system is thus far assumed to be delay free in the design process which is not the case in real world observations and the communication latency should be considered in design procedure. The authors intend to work on this issue in future while many good pioneer research is available presently [18] and the controller designed in this paper is an ideal WADC without considering latency in wide area signals. The proposed WADC is implemented in the simulation setup and its parameters are tuned through the PSO technique. İn the following a quiet explanation about optimisation of WADC parameters has been presented.

4.1. PSO Algorithm

In the PSO technique, there are some simple entities (particle) which their trajectory in the search space can be adjusted by dynamically regulating the velocity of each particle. Generally, a predefined objective function will be defined by the user, and then the best value of the objective function that is achieved by the i^{th} particle is expressed as *Pbest*. Furthermore, the overall best value of the objective function obtained by the particles at every time step (*gbest*) is calculated through the algorithm. Then, each particle's velocity and position is being updated by [18]-[19]:

$$V_{id}(t+1) = wV_{id}(t) + c_1 r_1 (P_{id} - X_{id}(t)) + c_2 r_2 (P_{gd} - X_{id}(t)) \tag{5}$$

$$X_{id}(t) = X_{id}(t-1) + cV_{id}(t) \tag{6}$$

Where, V_{id} is the velocity of the i^{th} particle, $X_{id}$is the position of the i^{th} particle, $P_{id}$and P_{gd} are *Pbest* and *gbest*, respectively. c_1 andc_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 and c is a factor which can modify the velocity of the particle to adjust the position of each particle in the next iteration. w, inertia weight, is defined to balance the local and global searches. Hence, the PSO algorithm searches for the optimal minimum value of the objective function and updates the velocity and particle's location in each iteration. The iterative process will be terminated when the stopping criterion is met.

If the parameters of damping controller are properly optimized, the damping of oscillation will be resulted effectively. For this reason, damping controller parameters will be optimized by the PSO algorithm. In this study, the objective function to be minimized by PSO is come from the generators rotor speed deviations. This objective function is an integral of time multiplied by the absolute value of the power deviation, that is

$$J = \int_0^{t_{sim}} t.\left|\Delta W_{13}\right|.dt \tag{7}$$

Where, t_{sim} is the total simulation time and ΔW_{13} is the generators rotor speed deviations. The optimization is subjected to parameter limits, i.e.

$$K_{\min} \le K \le K_{\max},\ T_{1\min} \le T_1 \le T_{1\max},\ T_{2\min} \le T_2 \le T_{2\max},\ T_{3\min} \le T_3 \le T_{3\max},\ T_{4\min} \le T_4 \le T_{4\max}$$

It has to be pointed out that the above parameters are associated with the damping controller and would be introduced in the next section. Here, the ranges for parameters are as follows. $K \in$[0.01-40] and T_1, T_2, T_3, $T_4 \in$[0.0001-2]. Associated with PSO algorithm, 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 and the final values of parameters are presented in Appendix B.

5. SIMULATION RESULTS

This section demonstrates the capability of the proposed STATCOM based hybrid shunt compensation scheme in damping inter-area oscillations. As seen on Figure 4, for this propose fixed capacitor of one phase installed on bus 7 is replaced with an unbalanced. The parameters of the unbalanced STATCOM are shown in appendix C. For the sake of simulation, it is assumed that in the system shown in Figure 4, a three-phase to ground fault occurs on bus 8 and lasts for 200 ms. this fault stimulates oscillation of the system. Figures 7 and 8 show the rotor speed difference between G1 and G3 and the rotor speed difference between G1 and G2 as well as their damping behavior in three situations of fixed shunt compensator and Hybrid shunt compensation with optimized and non-optimised damping controllers. The inter-area oscillation is measured by rotor speed difference of G1 and G3 and the local oscillation is measured by rotor speed difference of G1 and G2. As shown in Figures 7 and 8, in the case fix shunt compensation, the system experiences severe fluctuations with very low damping. However, in the case of hybrid shunt compensation that in one phase a STATCOMis placed instead of a fixed shunt capacitor, both supplementary controllers of unbalanced compensation system leads to damping of oscillations but an effective damping of oscillations after the event of fault is achieved when PSO based damping controlleris added to main controllers of unbalanced STATCOM. Moreover, in the figure legends, “Fixed” refers to the system performance with fixed capacitor compensation.

Figures 9 show the tie-line (7–9, line 1) power flow time responses of the test benchmark during and after disturbance. Comparing the responses of the fixed shunt compensation to the hybrid shunt compensation scheme in this Figure, the favorable contribution of the proposed hybrid scheme to the mitigation of the inter-area oscillations is very understandable. As it can be seen from Figures 7 and 9, the power oscillations damping controller decrease the first swing and effectively damps the subsequent oscillations.

In Figure 10, the bus voltage, and damping controller output signal of the STATCOM are plotted. As observed from these figures, unlike the fixed shunt compensation, the hybrid scheme effectively preserves the system stability after disturbance and damps both inter-area and local oscillations. The results of simulation obviously show that, in the case of PSO based WADC, the performances of damping controller is by far better than the case that WADC parameters is achieved by trial and error method. This is because the parameters of PSO based WADC tuned with an optimization method.

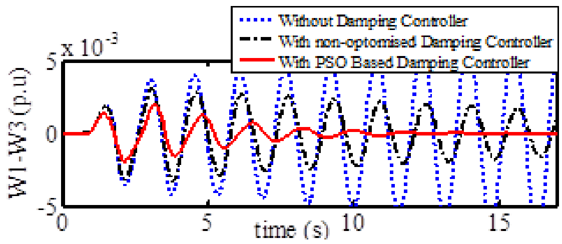

Figure 7. Rotor Speed Difference between G1 and G3, during and After Disturbance

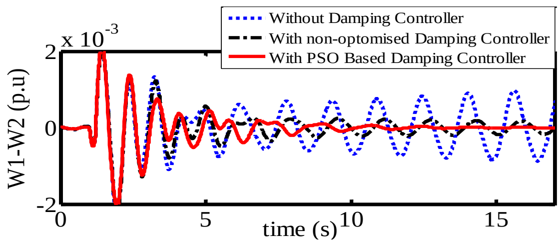

Figure 8. Rotor Speed Difference between G1 and G2, during and After Disturbance

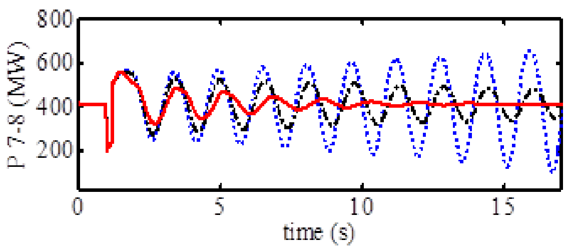

Figure 9. Tie-line power flow time responses during and after disturbance

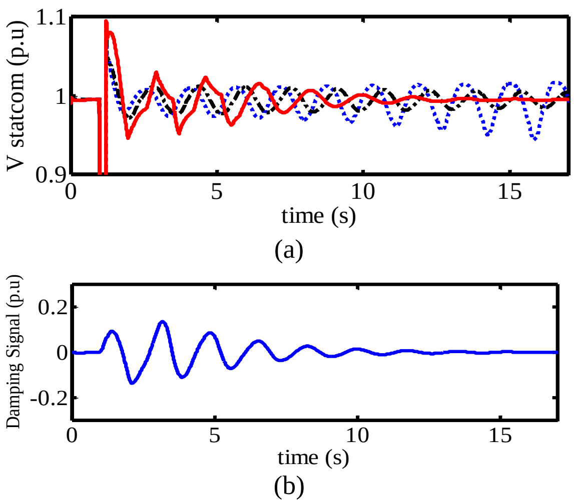

Figure 10. Performance of Unbalanced STATCOM during and After Disturbance: (a) STATCOM bus Voltage and (b) STATCOM Damping Controller Output Signal

6. CONCLOSION

This work is mainly dedicated to investigate the capability of a new “hybrid” shunt compensation schemes in damping inter-area oscillations. The presented hybrid shunt compensation schemes is easily achievable, technically sound, and have an industrial application potential. A six-machine three area power system is put under investigation in order to verify the proposed scheme capability on inter-area oscillation damping. The power system dynamic stability enhancement achieved by adding two wide area, damping controllers. A non-optimized conventional damping controller and a conventional damping controller with optomised parameters. The PSO algorithm is used to solve optimization problem. Both damping controllers are added to the main control loop of the proposed shunt compensator. With respect simulation illustrations, it was observed that as the time goes on, the proposed hybrid compensation equipped with auxiliary damping controller would damp all inter-area and locally oscillation modes; also the results of simulation showed that, in the case of PSO based WADC, the performances of damping controller was by far better than the case that WADC parameters were achieved by trial and error method.Hence, the effective performance of proposed unbalanced shunt compensation in the system oscillation damping was validated.

Appendix A Power System Data

Generator Data: 900 MVA, 20 kV, r_a = 0.0025 p.u., x_l= 0.2 p.u., x_d = 1.8 p.u., x_q = 1.7 p.u., x'_d = 0.3 p.u., x'_q = 0.55 p.u., x''_d = -0.25 p.u., x''_q = 0.25 p.u., T'_{do} = 8 s, T''_{do} = 0.03 s, T'_{qo} = 0.4 s, T''_{qo} = 0.05 s, $H(G_1\&G_2)$ = 6.5 s, $H(G_3\&G_4)$ = 6.175 s, H (G_5) = 5.5 s, $H(G_6)$ = 5 s.

Generator Steady State Data: G_1: V = 1.04 $\angle 0^o$ p.u., G_2: P = 700 MW, V = 1.01 p.u., G_5: P = 800 MW, V = 1.02 p.u., G_6: P = 780 MW, V = 1.01 p.u. Transmission Line Data: r = 0.053 Ω/km, Xseries = 0.53 Ω/km, Yshunt = 5.21 μS/km. Bus 7 load: 1400 + j100-j350, Bus 9 load: 1800 + j100 – j500, Bus 15 load: 1200 + j300 – j220.

Appendix B

Table 1. Parameters of the STATCOM based WADCs

Type	K	T_W	T_1	T_2	T_3	T_4	min & max
WADC1	9	2	0.012	0.89	1.11	0.011	±0.2
WADC2	16	2	0.032	1.3	0.014	0.044	±0.2

Appendix C STATCOM Data

Rated Power = 25 MVA, Rated Voltage = 26 KV, Frequency = 60 Hz, $X_{T(sh)}$ = 0.1 p.u. Switching Frequency = 15KHz.

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