An STATCOM-based Hybrid Shunt Compensation Scheme Capable of Damping Subsynchronous Resonance

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ABSTRACT

The paper presents the potential use of supplemental control of a new economical phase imbalanced shunt compensation concept for damping sub synchronous resonance (SSR) oscillations. In this scheme, the shunt capacitive compensation in one phase is created by using a Single-Phase Static Synchronous Compensator (STATCOM) in parallel with a fixed capacitor (C_C), and the other two phases are compensated by fixed shunt capacitor (C). The proposed arrangement would, certainly, be economically attractive when compared with a full three-phase STATCOM which have been used/proposed for power swings and SSR damping. SSR mitigation is achieved by introducing a supplemental signal into the control loops of single phase STATCOM. The validity and effectiveness of the proposed structure and supplemental control are demonstrated on a modified version of the IEEE second benchmark model for computer simulation of sub synchronous resonance by means of time domain simulation analysis using the Matlab program.

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1. INTRODUCTION

Series compensation of long ac transmission lines improves the transmission capacity by enhancing the transient stability of the power system. As a result, the compensation techniques have been widely utilized in the power systems [1]. However, it is well known that sub-synchronous resonance (SSR) can occur when thermal power plants are connected to the grid through a series compensated transmission line [2-5].

To prevent the generator shaft from damages of un-damped sub-synchronous oscillations, various devices such as: power system stabilizers (PSSs) [6] and flexible AC transmission systems (FACTSs) [7–10] as possible approaches have been proposed. In [7] a phase imbalance scheme for stabilizing torsional oscillationsa have been proposed or in [8] a WAMS based SSR damping controller is proposed for FACTS devices to SSR mitigation. In [9] a novel control strategy have been proposed based on increasing the network damping at critical frequencies of the generator shaft. This has been acquired by controlling the sub-synchronous frequency of the line current to zero. In [10], two separate controllers have been granted to the conventional controllers of the SVC and the TCSC in order to damp the SSR in a series compensated wind farm. Furthermore, the damping controller of the SVC is a conventional lead-lag controller and the damping characteristic of the TCSC have been added through constant current control of the TCSC.

Although it was shown that utilizing a feedback auxiliary control, in addition to the FACTS device main control, can greatly improve system, but it is well known that FACTS devices 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 [11-13].

In [11-13] two economical phase imbalanced series compensation concept has been introduced and their ability for power system dynamic enhancement and power system 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* compensation concept and investigating its ability for power system dynamic enhancement and SSR 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 (C_C). Certainly, the proposed arrangement would, be economically attractive when compared with a full three-phase STATCOM which have been used/proposed for power swings and subsynchronous resonance oscillations damping. Furthermore, reducing the number of thyristor valves and VSC to one-third will also have a positive impact on equipment reliability. The power system dynamic stability enhancement and SSR damping would be achieved by adding an auxiliary damping controller to the main control loop of the single phase STATCOM. To optimize the parameters of the designed Damping Controller 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 [14], [15]. The Fast Fourier Transform (FFT) and simulation results have been implemented to validate performance of proposed structure.

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 [16].

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 [16].

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:

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

$$Q_c = Q_{Cc} + Q_{STATCOM} \quad (2)$$

During any other frequency, Fe

$$Q_c = Q_{Cc} + Q_{STATCOM} + \Delta Q_{STATCOM} \quad (3)$$

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 SSR 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 SSR. Time domain simulations were conducted on a benchmark network using the Matlab.

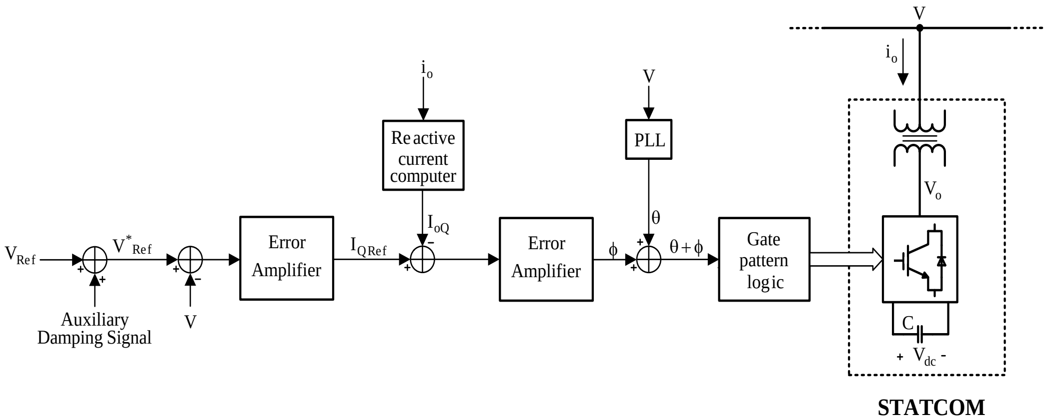

Figure 1. STATCOM control system

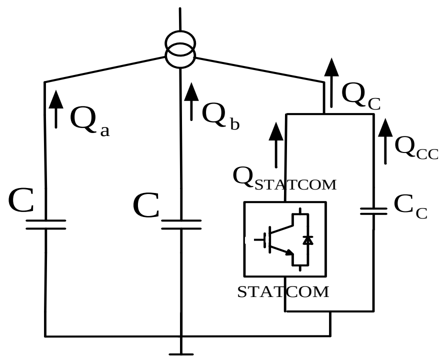

Figure 2. Schematic diagrams of the hybrid shunt compensation schemes

3. POWER SYSTEM UNDER STUDY

The structure of the power system that has been utilized for SSR study is shown in Figure 3. The IEEE Second Benchmark Model combined with an unbalanced shunt compensator in bus 1 is considered for SSR analysis [17]. The system composed of a synchronous generator supplying power to an infinite bus via two parallel transmission lines. It is a Single Machine Infinite Bus (SMIB) power network that has two transmission lines, and one of them is compensated by a series capacitor. A 600 MVA turbine-generator is connected to an infinite bus, and the rated line voltage is 500KV, while the rated frequency is 60Hz. The proposed unbalanced shunt compensator is shunt connected to bus 1 by step up transformer. The mechanical system consists of four masses: a high pressure turbine (HP), and low pressure turbine (LP), the generator (Ge) and rotating exciter (EX). All masses are mechanically connected to each other by elastic shaft. The complete mechanical and electrical information for the study system are demonstrated in [17].

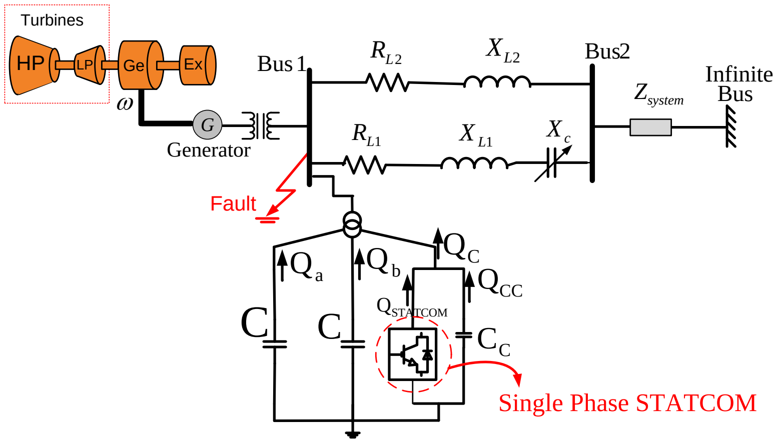

Figure 3. The IEEE second benchmark model combined with unbalanced shunt compensator for SSR analysis

Due to the high level of compensation (52%), a small type of instability such a fault will pass the system unstable and the SSR is more likely to happen at this situation. First of all, to show how unfavorable these oscillations will be, the unbalanced shunt compensator just existed in the power system and the single phase STATCOM has not been enhanced with damping controller. A three-phase to ground fault will happen at Bus 1 of IEEE-SBM at time 0.1sec and it will be removed after two cycles. Firstly, the system will be simulated to obtain the oscillatory modes of the rotor shaft and consequently, the sub-synchronous mode.

For obtaining the oscillatory modes of the rotor shaft and consequently the sub-synchronous mode, the FFT analysis is performed on the system which is shown by Figure 3. The FFT plot of generator rotor speed in time interval of 0 to 1.5sec is described in Figure 4. Percentage of compensation (the proportion of series capacitive reactance to line reactance $= \frac{X_C}{X_{L1}} \times 100$) is set to 52% to excite the oscillatory mode of the generator rotor shaft. It is founded by FFT analysis with MATLAB that, three modes exist in the rotor speed in this situation. As shown in Figure 4, it can be deduced that, due to the chosen level of series compensation, the electrical resonance happens at 25Hz. From FFT analysis of the mechanical system, the oscillatory modes of the generator shaft are 1.667, 25, 32.33Hz. Furthermore, maximum destabilization is for 25Hz mode, or in other way, the dominant mode which has sub-synchronous frequency is 25Hz.

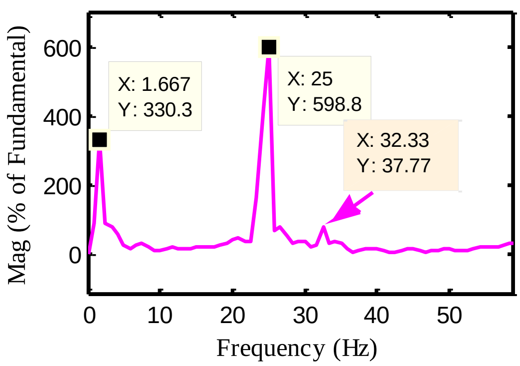

Figure 4. FFT analysis on generator rotor shaft in order to confirm the dominant mode

The FFT plot of the generator rotor speed is illustrated in Figure 5 during four separate interval after the fault happening. It is worth mentioning that, after the fault, as the times goes on, the Sub-Synchronous mode will be increased in amplitude and the other modes will be decreased. Moreover, after a few seconds, the dominant mode with the frequency of 25 Hz, namely the sub-synchronous mode, has increased upto a great value which will make the system unstable if this condition is going to continue. There should be a controller in the power system to mitigate these oscillations and make the system stable. From Figure 5, it can be observed that, the rotor shaft has the sub-synchronous mode with frequency of 25 Hz which if is not mitigated, will be led to harsh shaft failures.

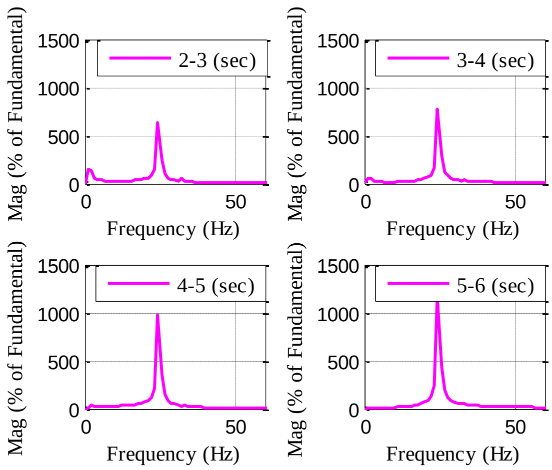

Figure 5. The FFT analysis on the generator rotor speed without damping controller in 2-6 sec with the time division of 1 second

To better assess the subject of SSR, simulation results for generator rotor speed deviation (delta w), the torque between generator and low pressure turbine, and the torque between the Low pressure Turbine and High pressure turbine is illustrated in Figure 6. It can be observed that, after the fault, large flactuations will be appeared in the power system that will definitely damage the rotor shaft.

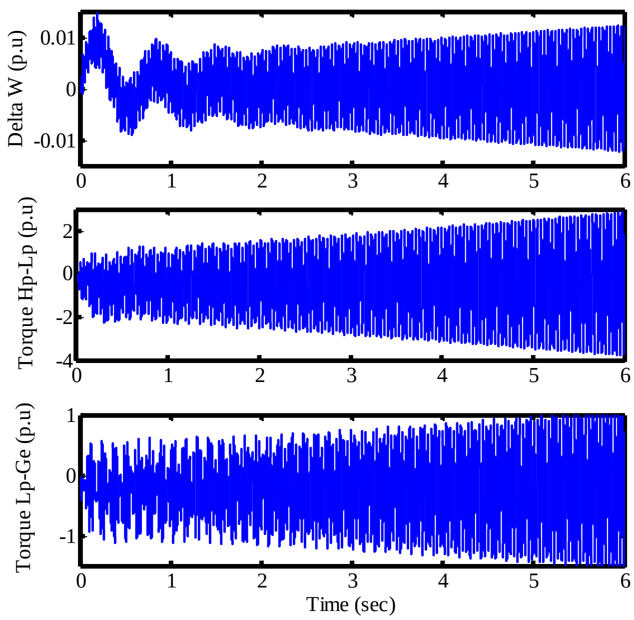

Figure 6. Simulation results for the IEEE-SBM without controllers

It is apparent that, the torque between the generator and the low pressure turbine reaches up to 4 p.u after few seconds and the sub-synchronous mode at the 25 Hz will face the system with large amplification of torques. In the next part, the damping controller will be enhaced to the proposed unbalanced compensator in order to retrieve the power system from suffering.

4. SSR DAMPING CONTROLLER DESIIGN

In this paper SSR damping controller designed based on conventional lead-lag 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 [2]. In this investigation, because the aim is to mitigate the SSR, the speed deviation of generator rotor has been utilized as input signal of SSR damping controller. As shown in Figure 7, $\Delta\omega\,[\mathrm{p.u}]$ has been implemented as an additional signal to mitigate the unstable modes. The auxiliary SSR 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. As show in Figure 7 and Figure 1, the output of the SSR damping controller is therefore send to the single phase STATCOM's AC voltage regulator. The parameters T_w and limiter parameters are set manual but the other parameters will be optimized by PSO algorithm in order to yield the SSR suppression.

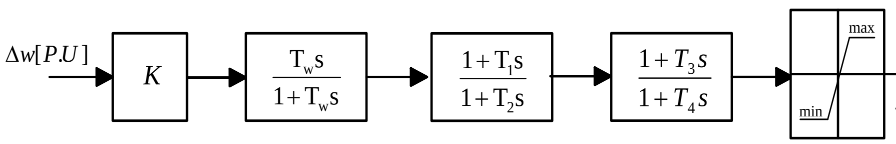

Figure 7. SSR damping controller block diagram

4.1. PSO algorithm

PSO which is first developed by Dr. Kennedy and Dr. 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 [14]. So, with consideration of these merits toward other methods, the researchers are 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 PSO algorithm, some simple entities which are named as particles are located in the search space of the problem or function. Each particle, at its current position, calculates the objective function and then determines its movement through the search space. The movement can be done by aggregating some facets of the history of each particle's current and the best positions by other particles or more members of the swarm with some random perturbations. When all the particles have been moved, the next iteration will be happened. At last, the swarm as a hole, just like school of fish which collectively searching for food, is likely to move toward an optimum of the objective function [19].

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: $V_i = (V_{i1}, V_{i2}, \dots V_{id}), X_i = (X_{i1}, X_{i2}, \dots X_{id})$, respectively. Consider a predefined objective function by the user; the best objective function obtained by ith particle at time (pbest), can be expressed as: $p_i = (p_{i1}, p_{i2}, \dots p_{id})$. 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 [18]:

$$V_{id}(t) = w \times V_{id}(t-1) + c_1 r_1 \times \left(p_{id}(t-1) - X_{id}(t-1)\right) + c_2 r_2 \times \left(p_{gd}(t-1) - X_{id}(t-1)\right) \quad (4)$$

$$X_{id}(t) = X_{id}(t-1) + cV_{id}(t) \quad (5)$$

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 [20]:

$$w = w_{max} - \frac{w_{max} - w_{min}}{iter\_max} \text{iteration} \quad (6)$$

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 6, Where, w_{max} and w_{min} are initial and final weights. The flowchart of the proposed PSO algorithm for SSR study is shown in Figure 8.

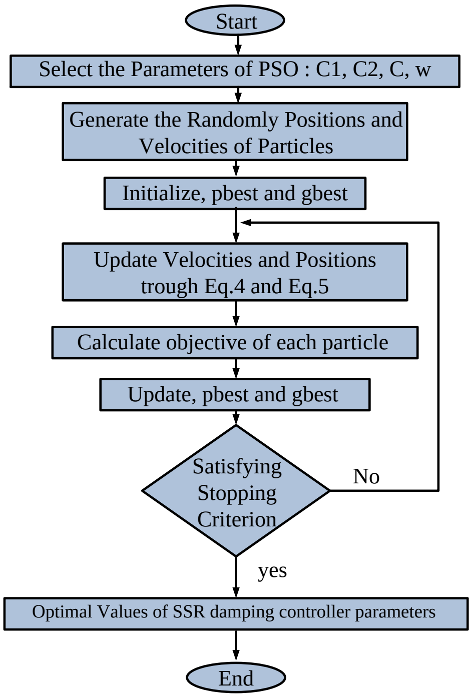

Figure 8. Flowchart of the PSO algorithm

4.2. Design of damping controller

In order to design the single phase STATCOM’s Lead-Lag damping controller, PSO 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 SSR damping controller. The mentioned objective function is an integral of time multiplied absolute value of the speed deviation, and can be expressed by:

$$J = \int_0^{t_{sim}} t.|\Delta\omega|.dt \quad (7)$$

Where, t_{sim} is the simulation time, and $\Delta\omega$ is the generator rotor speed deviation. The main aim of optimization is to minimize the objective function due to some constrains:

$$\begin{aligned} K^{min} &\le K \le K^{max} \\ T_1^{min} &\le T_1 \le T_1^{max} \\ T_2^{min} &\le T_2 \le T_2^{max} \\ T_3^{min} &\le T_3 \le T_3^{max} \\ T_4^{min} &\le T_4 \le T_4^{max} \end{aligned} \quad (8)$$

The PSO algorithm searches for the optimal values of parameters above in range of: [0.001-200] for K and [0.001-3] for T_1, T_2, T_3, 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 specified criterion, the optimal parameters of the controller will be achieved. The parameters yielded from PSO algorithm are included in Table 1.

Table1. Parameters Obtained from PSO Algorithm

parameter	kK	T_1	T_2	T_3	T_4
value	33	00.011	0.01	2.538	0.001

5. SIMULATION RESULTS

In order to better assess the capability of the proposed unbalanced shunt compensator in SSR damping, time-based simulation of the proposed system is utilized under disturbance. The three-phase to ground fault is occurred at time 0.1sec and lasts over two cycles. Figure 9 (a), (b), and (c) show the generator rotor speed deviation, the torque between High Pressure (H_P) and L_P turbine and the torque between Generator (Ge) and Low-Pressure (L_P) turbine respectively. Where, the dashed line corresponds to the condition in which there is no SSR damping controller in the system and the solid line corresponds to the situation in which the single phase STATCOM is enhanced with SSR damping controller. Due to these figures, it is revealed that, the sub-synchronous oscillations are greatly removed when the SSR damping controller operates.

Comparison of the results of our work and the results of previous work indicates that the SSR mitigation ability made by our proposed structure is like a three-phase STATCOM or other full 3 phase FACTS devices. it was shown that the proposed hybrid compensation equipped with auxiliary damping controller would damp all oscillatory modes like a complete FACTS device, While in terms of cost, The proposed structure is much cheaper and it is more affordable.

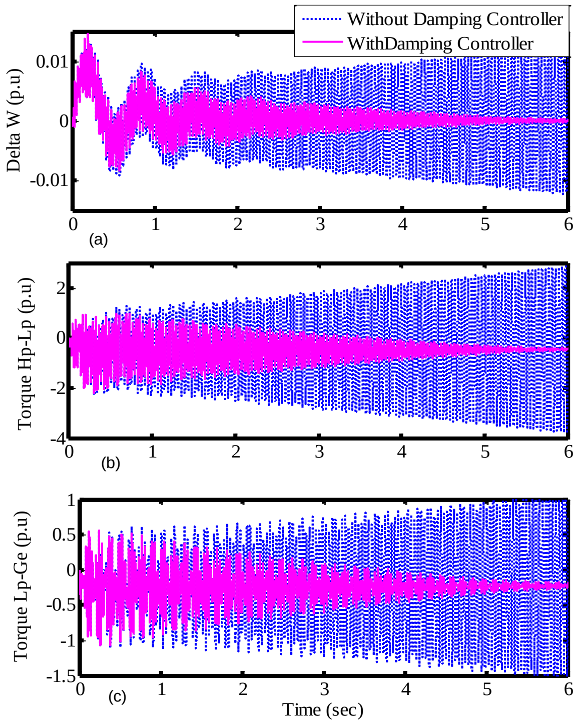

Figure 9. Simulation results for SSR damping with proposed unbalanced shunt compensator. (a) The generator rotor speed deviation (b) The torques between high pressure and low pressure turbine and (c) The torques between generator and low pressure turbine with and without damping controller

The FFT analysis on the generator rotor speed while damping controller is added to main control loopof phase STATCOM is depicted on Figure 10. It is observed from this figure that, the dominant torsional mode with frequency of 25Hz is diminishing as the time is going on and after 2sec it is completely eliminated from the generator rotor speed, which verifies the effectiveness of the proposed unbalanced compensator on SSR damping.

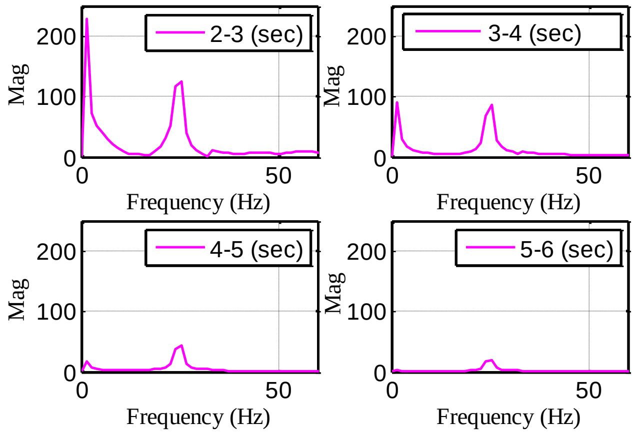

Figure 10. FFT analysis on rotor speed deviations when proposed compensator is enhanced with auxiliary damping controller

6. CONCLUSION

This work is mainly dedicated to investigate the capability of a new “hybrid” shunt compensation schemes in damping SSR. The presented compensation schemes is easily achievable, technically sound, and have an industrial application potential. The IEEE second benchmark model aggregated with proposed compensator is employed as the case study in order to verify the proposed scheme capability on SSR damping. In order to provide a comprehensive understanding of issue, Several FFT analyses are provided. It was found that for the selected level of series compensation, mode 2 (with the corresponding frequency around 25 Hz) has been the most dominant one which makes the system unstable. It was also shown that a zero mode with a frequency around 1.66 Hz appears in the system. The power system dynamic stability enhancement was by adding a PSO based auxiliary damping controller 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 oscillatory modes; hence, the effective performance of proposed unbalanced shunt compensation in SSR damping was validated. Comparison of the results of our work and the results of previous work indicates that the SSR mitigation ability made by our proposed structure is like a three-phase STATCOM or other full 3 phase FACTS devices while in terms of cost, the proposed structure is much cheaper and it is more affordable. With increasing importance of economic issues on power systems operation and control, designing of series or shunt compensators that are economically attractive with the purpose of whole system dynamic performance improvements is essential and requests vast research activities.

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