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Comparison Between Facts Devices and Damping Resistance to Damp the Sub-synchronous Resonance

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Abstract

Sub synchronous resonance (SSR) poses a serious stability problem to the modern power system. In this paper, most popularly known FACTS devices (STATCOM, SSSC, UPFC) and a dynamic resistance bank are used to mitigate the occurrence of sub-synchronous phenomenon. Fuzzy logic controller with inputs as rotor speed deviation and its derivative are used as a control strategy in order to damp out the sub-synchronous oscillation more efficiently caused by the series compensation of transmission network and Eigen value technique is used to analysis the stability of the system. Simulation in MATLAB is carried out on the IEEE second benchmark to validate the effectiveness of the proposed schemes under the condition of three phase fault at infinite bus. Time domain simulation and Eigen values are used to observe the superior ability of UPFC when compared with other FACTS devices to damp sub-synchronous oscillation.

Keywords: FACTS Devices: SSSC, STATCOM, UPFC, Torsional Oscillation Fuzzy Controller, Dynamic Resistance

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1. Introduction

Modern power systems are widely inter-connected while this inter-connection leads to the operational economy and reliability through mutual assistance. They also contribute to the stability of the system. One of the major challenges faced by the power engineers are process or events which are vulnerable to power system disturbances. One such event is the occurrence of Sub-synchronous resonance(SSR). Sub-synchronous resonance is an electrical power system phenomenon in which the electrical network transfers energy to the turbine generator network. [1]

The turbine-generator network in power system can be considered as a spring-mass system in which the masses (i.e. Generator, Low pressure turbine, High pressure turbine) are tandem on a single shaft (fig 1).

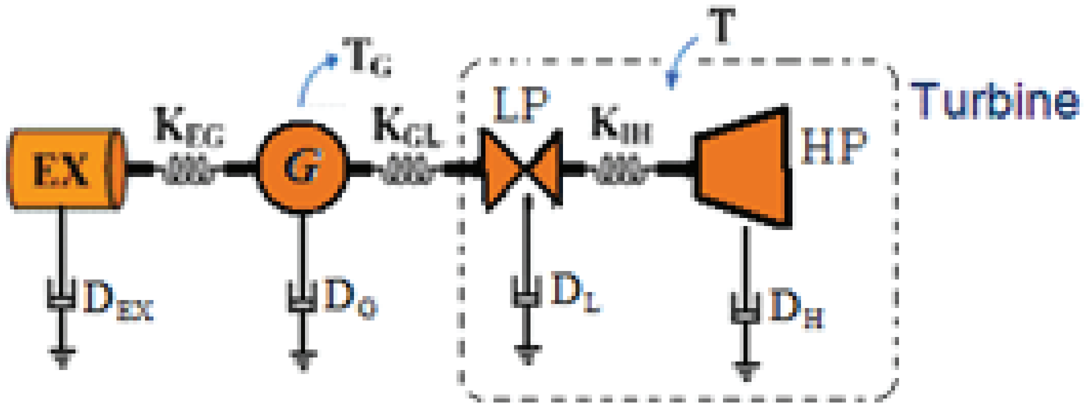


Figure 1: Turbine-Generator Network.

Under the normal operating conditions when the shaft is rotating at its synchronous frequency. These masses have their natural frequency of oscillation which can be calculated by the equation

$$fn = \frac{1}{2 * \prod} * \left(\frac{k_{12}}{(H1 * H2)/(H1 + H2)} \right)^{1/2}$$

Where fn gives the natural frequency of oscillation in a spring mass system. As the turbine- generator network is considered as a spring mass system. Natural oscillation frequency is given by the equation above where 'k' represents the stiffness constant of the spring (shaft) and the H1 and H2 represents the inertia constant of masses (i.e. generator, LP turbine and HP turbine).

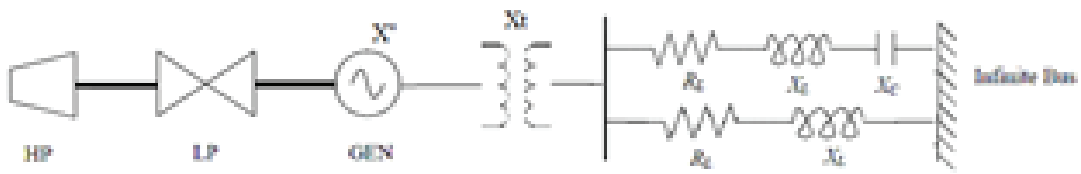


Figure 2: Single line diagram of the IEEE second benchmark model.

Series capacitor is highly effective and economical means of improving power transfer [2]. It is mainly used to compensate the reactance in the long transmission lines. However this could lead to the occurrence of Sub-Synchronous resonance which is one of the main factors which could hinder the stability of the system. The capacitor has its own resonant frequency which is calculated by the equation.

$$fer = fo\sqrt{\frac{Xc}{x'' + Xt + Xe}}$$

where x" is the sub transient reactance of the generator , Xt is the leakage reactance of the transformer Xe and Xc are the external inductive and capacitive reactance's respectively (fig 2) since $fm < fo$ and $fer < fo$ .Thus for some particular levels of series compensation it is possible that

$$fer \approx fo - fm$$

If under transient condition the resonance frequency of a series compensated system is equal to the complement of the natural mode of the turbine generator system then these will enhance the torsional vibrations of the different modes of the turbine-generator network.

2. Eigen Values

Stability of any power system can be proven by the calculation of the eigen values.[3, 4]. From the Eigen values we can determine the state for our system. The following dynamic equation are obtained which the system is solved empirically

$$\frac{d\delta_i}{dt} = w_i - w_0 \tag{1}$$

$$2 * \frac{H_i}{w_0} * \frac{dw_i}{dt} = T_{mi} - T_e - K_i * (\delta_i - \delta_{(i+1)}) \tag{2}$$

where '$\delta_i, \delta_{(i+1)}$' : represents the twist angle of the ith mass to the (i+1)th mass between Generator and the HP masses.

'w_i': represents the angular Frequency of the ith mass between Generator and the HP masses.

'w_o': represents the bass angular Frequency (60Hz)

'H_i': represents the Inertia Constant of the ith mass between Generator and the HP masses.

'K_i': represents the stiffness Constant of shaft of the ith mass between Generator and the HP masses.

'T_{mi}': represents the magnetic Torque of the ith mass between Generator and the HP masses.

'T_e': represents the Electrical Torque of the i^{th} mass between Generator and the HP masses.

$$\dot{X} = \begin{bmatrix} \delta_i \\ w_i \\ \delta_{(i+1)} \\ w_{(i+1)} \\ .. \\ . \\ . \\ \delta_n \\ w_n \end{bmatrix} = [A]X + [B]u$$

The above equation gives set of Torsional mode of the turbine-generator mechanical system in the state-space form. Where A is the state co-efficient matrix and u is the forcing torque vector.

3. Control Strategy

In recent years, Fuzzy Logic Damping controllers (FLDCs) have been appeared as an effective tool to stabilize the power network [5, 6]]. The main advantage of fuzzy logic controller is that it doesn't require the exact mathematical model. They act with inaccurate inputs, control nonlinearity and are more robust and effective than the conventional damping controllers in the power system. [5]. Several works has been carried on damping the SSR with the help of PID controllers. [7]. In this paper Fuzzy Logic Damping Controllers has been incorporated as a common damping strategy to compare the efficiency of the FACTS devices and damping resistance technique to damp the Sub-synchronous oscillation arising in the series compensation transmission network under the faulted circumstances. Time domain simulation is carried out on the IEEE second benchmark model[8] to validate the effectiveness of the proposed technique.

4. Design of Fuzzy Logic Damping Controller (FLDC) for FACTS Devices

FACTS technologies offer competitive solutions to today's power system in term of increased power flow transfer capability, enhancing continuous control over the voltage profile, improving system damping, minimizing losses [,9,10,11]. FACTS technology consists of high power electronics based equipments with its real time operation control.

4.1. STATCOM (Static compensator)

STATCOM has a fast and smooth control performance. [12, 13] It can be used to damp SSR, STATCOM's reactive power output should use the generator speed as a reference. For single generator suffered from SSR, when its shaft speed rises, the STATCOM should be controlled to improve the bus voltage. Output of the generator will correspondingly change so as to in-cooperate the changes in the bus voltage which is modulated through the control of reactive power output of the STATCOM., thereby giving an induced additional electromagnetic torque on the generator shaft. Under certain control adjustments this additional induced electro-magnetic torque could be used to damp the torsional oscillation arising in the turbine-generator network. [12, 13]

4.2. SSSC (Static series synchronous compensator)

Static Synchronous Series Compensator (SSSC) is one of the important series FACTS devices and with a suitable design can be used for improving the effectiveness in damping low frequency power oscillation in the power network [14]. SSSC injects an almost sinusoidal voltage, of variable magnitude in series with the transmission line. The injected voltage is almost in quadrature with the line current. Most of the injected voltage, emulates an inductive or a capacitive reactance in series with the transmission line. This emulated variable reactance, influences the electric power flow through the transmission line. A SSSC operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted active power.

4.3. UPFC (Unified power flow controller)

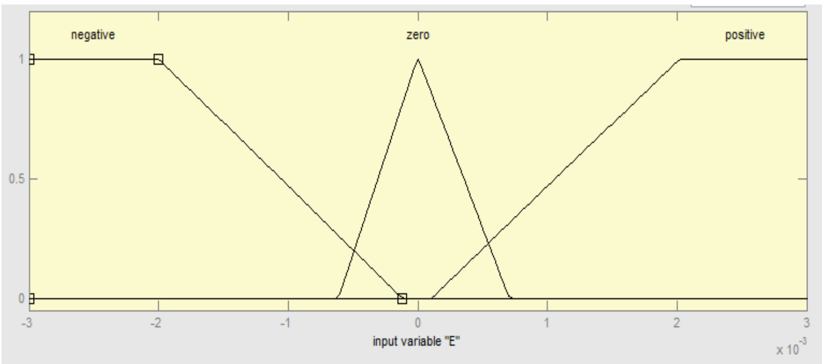
The UPFC is the most versatile of FACTS controller capable of control of three system parameters; voltage, power angle and transfer impedance. UPFC consists of a shunt connected voltage source converter and a series connected voltage source converter(VSC2. Series voltage converter injects a series voltage while Shunt voltage source converter is controlled to inject reactive current. The series and shunt branches of UPFC can generate/absorb reactive power independently and the two branches can exchange active power. The injection of series reactive voltage provides active series compensation while the injection of the shunt reactive current can be controlled to regulate the voltage at the bus where shunt voltage source converter is connected. The injection of series real voltage (in-phase with the line current) can be controlled to regulate the reactive power in the line or the voltage at the output port of the UPFC [15]

The mitigation of the sub synchronous resonance has been performed by the FACTS devices using fuzzy logic controller. The rotor speed deviation and it's derivative has been taken as the input to the fuzzy logic controller and the output of the fuzzy logic controller acts as the Reference voltage to the FACTS devices i.e. STATCOM, SSSC & UPFC. The fuzzy logic controller is designed in such a way that only if the rotor speed deviates outside from a certain limited constraints then only the fuzzy logic controller will be activated and then only will the power injection or adsorption will take place.

Rotor speed deviation (Δw) and its derivative (($\partial \Delta w / \partial t$)(fig 3:(a),(b)) is used as an input to the fuzzy controller input and voltage ref is taken as the output of the fuzzy controller.(fig 3(c))

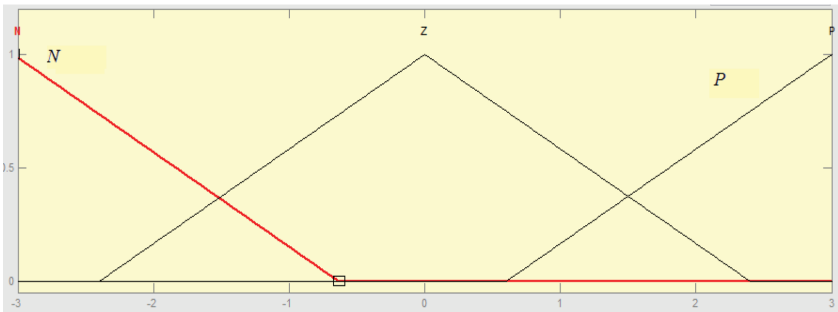
The Fuzzy rule of the controller are showed below. The fuzzy sets have been determined as: N: negative, Z:zero, P: positive for the input membership function and S: small, B: Big for the output Membership function.

1. If (Δw is N) and ($\partial \Delta w / \partial t$) is N) then (Gate is S)
2. If (Δw is N) and ($\partial \Delta w / \partial t$) is Z) then (Gate is B)
3. If (Δw is N) and ($\partial \Delta w / \partial t$) is P) then (Gate is B)
4. If (Δw is Z) and ($\partial \Delta w / \partial t$) is P) then (Gate is S)
5. If (Δw is Z) and ($\partial \Delta w / \partial t$) is Z) then (Gate is S)
6. If (Δw is Z) and ($\partial \Delta w / \partial t$) is N) then (Gate is S)

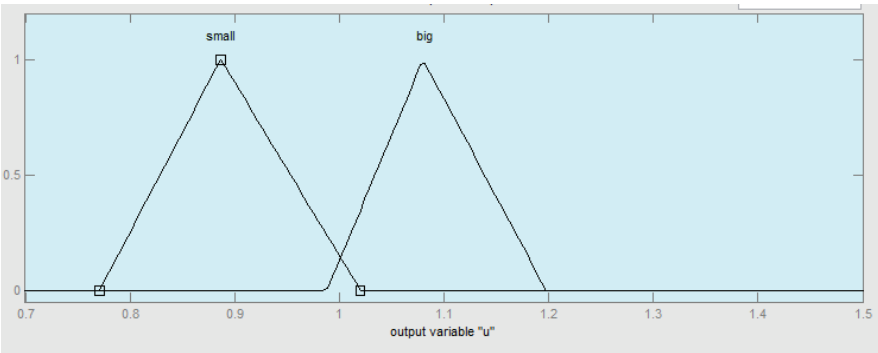


(a)

Output Membership Function



(b)



(c)

Figure 3: (a) Membership function of input1. (b): Membership function of input2. (c): Membership function of the output

7. If (Δw is P) and ($\partial \Delta w/\partial t$) is N) then (Gate is B)

8. If (Δw is P) and ($\partial \Delta w/\partial t$) is Z) then (Gate is B)

9. If (Δw is P) and ($\partial \Delta w/\partial t$) is P) then (Gate is S)

5. Design of Fuzzy Logic Damping Controller (FLDC) for Dynamic Resistance

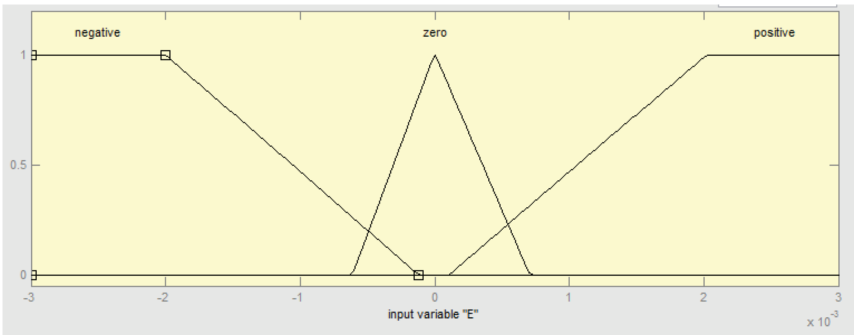
A three phase resistance bank is placed in the turbine-Generator network to damp out sub synchronous oscillations.. Rotor speed deviation (Δw) (fig 4(a)) and its derivative ($(\partial \Delta w / \partial t)$ (fig 4(b)) is used as an input to the fuzzy controller input and the gate signal to the GTO thyristor is taken as the output(fig4(c)) of the fuzzy controller which is connected to a 3-phase resistive load of 10 MW rating. This resistive load absorbs the active energy exchange between the mechanical and electrical network under the circumstance of fault occurrence which might lead to permanent shaft damage if the torsional modes of the turbine and generator network are not damped.

The Fuzzy rule of the controller is showed below. The fuzzy sets have been determined as: N: negative, Z:zero, P: positive for the input membership function and S: small, B: Big for the output Membership function.

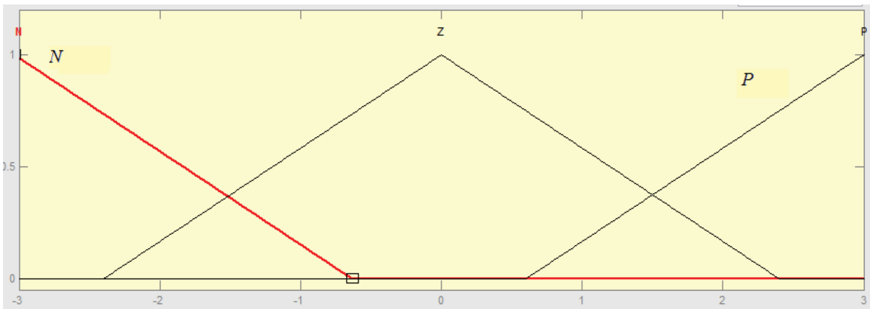
1. 1If (Δw is N) and $(\partial \Delta w / \partial t)$ is N) then (Gate is S)
2. If (Δw is N) and $(\partial \Delta w / \partial t)$ is Z) then (Gate is B)
3. If (Δw is N) and $(\partial \Delta w / \partial t)$ is P) then (Gate is B)
4. If (Δw is Z) and $(\partial \Delta w / \partial t)$ is P) then (Gate is S)
5. If (Δw is Z) and $(\partial \Delta w / \partial t)$ is Z) then (Gate is S)
6. If (Δw is Z) and $(\partial \Delta w / \partial t)$ is N) then (Gate is S)
7. If (Δw is P) and $(\partial \Delta w / \partial t)$ is N) then (Gate is B)
8. If (Δw is P) and $(\partial \Delta w / \partial t)$ is Z) then (Gate is B)
9. If (Δw is P) and $(\partial \Delta w / \partial t)$ is P) then (Gate is S)

6. Results and Discussion

In order to prove the effectiveness of the applied control strategy and to compare the strength of various facts devices to damp the Sub-synchronous resonance oscillation simulation is carried out for which IEEE second benchmark model is used in Matlab/Simulink domain[6]. For the purpose of comparison the series compensation level is kept at 55% and the 3-phase line-line fault occurrence in the transmission network from 0.00169 to 0.0022 seconds in the simulation.



(a)



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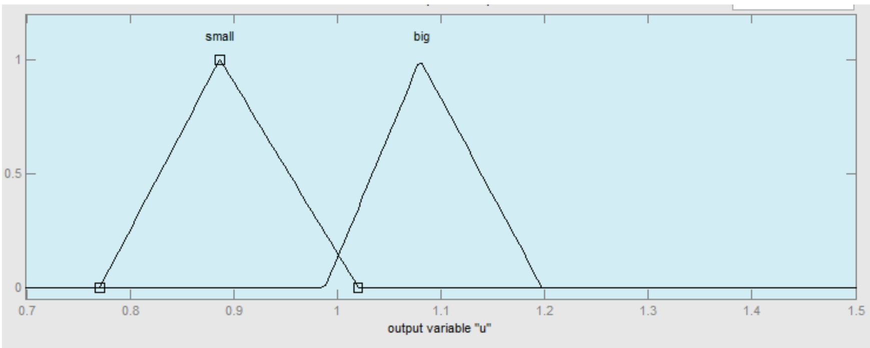
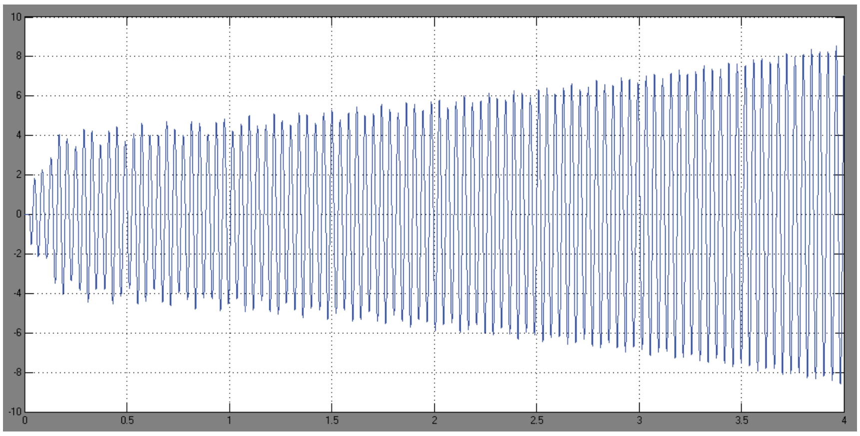


(c)

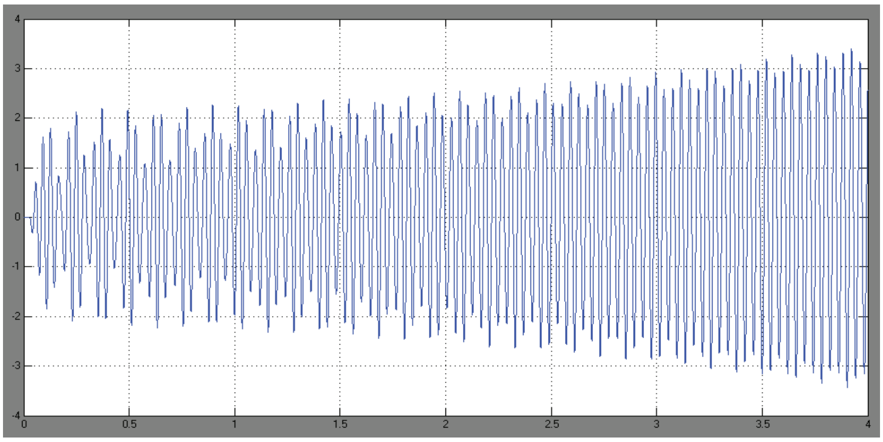
Figure 4: (a) : Membership function of input1. (b) : Membership function of input2. (c): Membership function of the output.

Simulation which shows the occurrence of the Sub-synchronous phenomenon is listed. From fig 5 it is clearly seen that both the torsional oscillation between HP-LP turbine and LP – Generator is violently enhanced on the occurrence of fault. Even the eigen value suggest the same (shown in table 1)

Fig 6 shows the behavior of our studied system under the influence of fuzzy damping controller connected to a dynamic resistance. Damping of the torsional oscillation is achieved. The speed rotor deviation is brought into steady limits.



(a)



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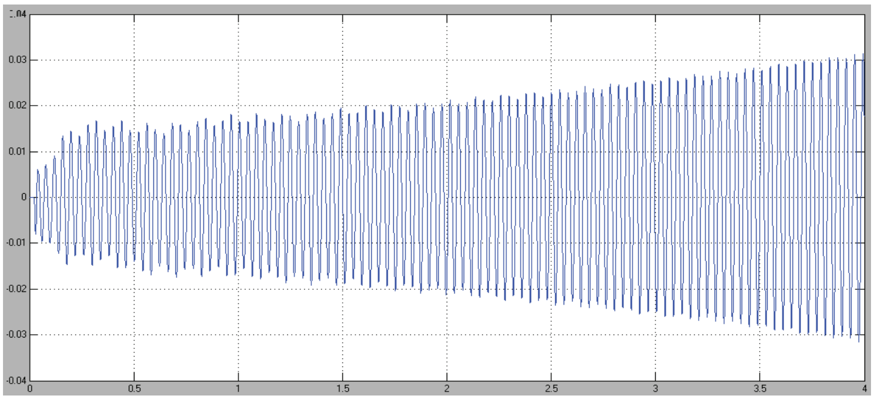
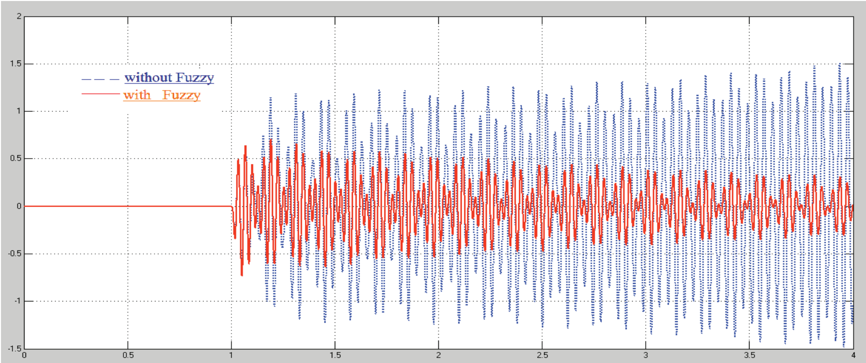


(c)

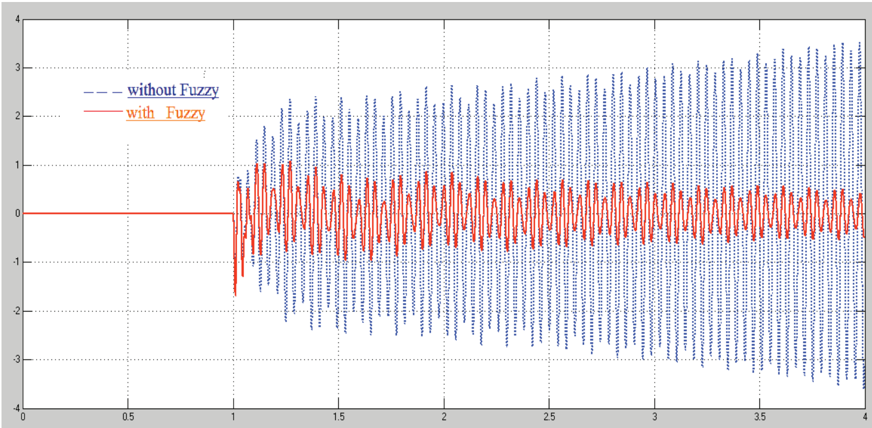
Figure 5: Simulation for the un-damped mode: (a) Variation of Torques B/w LP turbine and Generator, (b) Variation of Torque B/w HP – LP turbine, (c) Rotor Speed Deviation at the occurrence of fault.

Table 1: Eigen Values of undamped mode.

Eigen values	Comments
-0.037 ± 8.28j	Low frequency mode
-0.53 ± 204.6j	Sub synchronous mode
0.84 ± 202.92j	Sub synchronous mode



(a)



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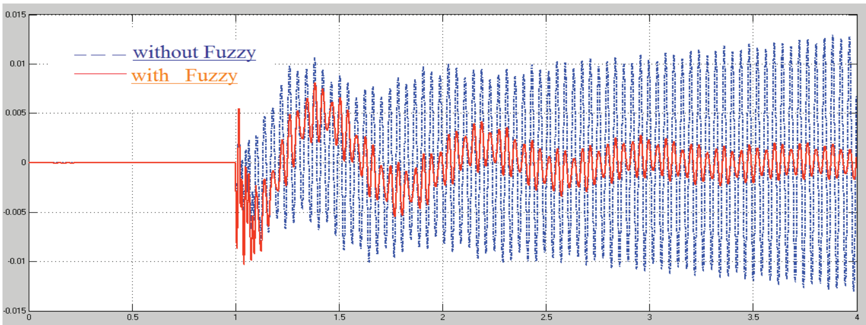
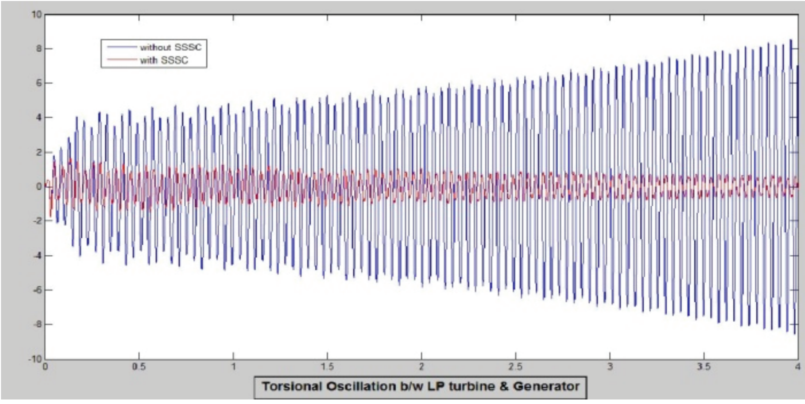


(c)

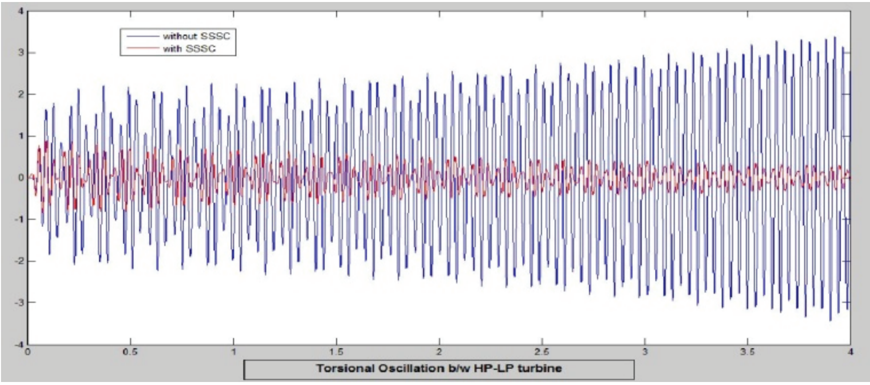
Figure 6: Simulation for the un-damped mode with dynamic resistance: (a) Variation of Torques B/w LP turbine and Generator, (b) Variation of Torque B/w HP – LP turbine, (c) Variation of Rotor speed deviation.

6.1. Results with FACTS devices

STATCOM, SSSC and UPFC are introduced into the transmission network separately and the torsional oscillation of the shaft of the turbine-generator network is observed. From Figure 7,8 & 9 it is noted that all devices i.e. STATCOM, SSSC & UPFC are effective in damping the oscillation. This can be verified from the eigen values as the real part which is the damping factor is positive (shown in table 2). To compare the efficiency of the FACTS Devices for the mitigation of SSR a peak to peak table is tabulated (table 3) which gives clear and cut idea that UPFC is damping the torsional oscillation better than other FACTS devices. Furthermore the damping factor (i.e. the real part) of the eigen values (table 4) of UPFC is more than the others in comparison which also signifies that the torsional oscillation are damping more effectively in case of upfc.



(a)



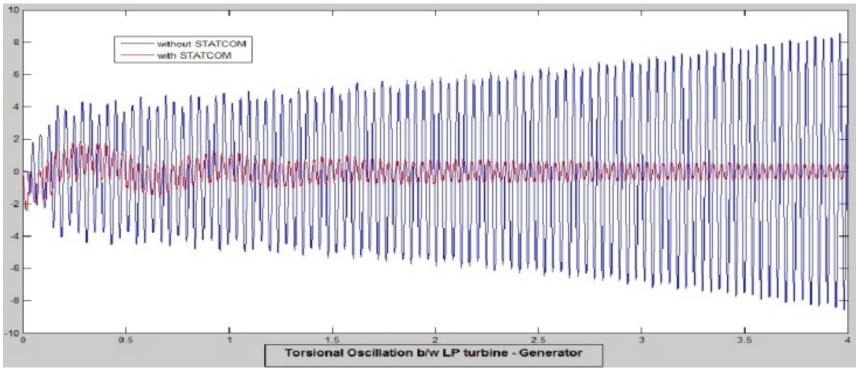
(b)

Figure 7: Simulation for the un-damped mode with SSSC : (a) Variation of Torques B/w LP turbine and Generator, (b) Variation of Torque B/w HP – LP turbine.

From table no 5 it can be noticed that the UPFC is the most efficient in damping the torsional oscillation. Damping of the torsional mode achieved by UPFC alone is more than 6000% when compared to the system under fault disturbance.

Table 2: Eigen values with SSSC.

Eigen values	**Comments**
-0.045 ± 7.85j	Low frequency mode
-0.51 ± 163.28j	Sub synchronous mode
-0.43 ± 207.24j	Sub synchronous mode



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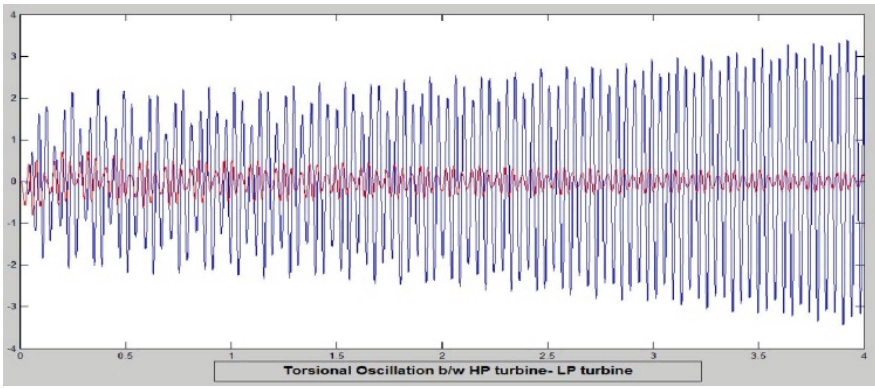


(b)

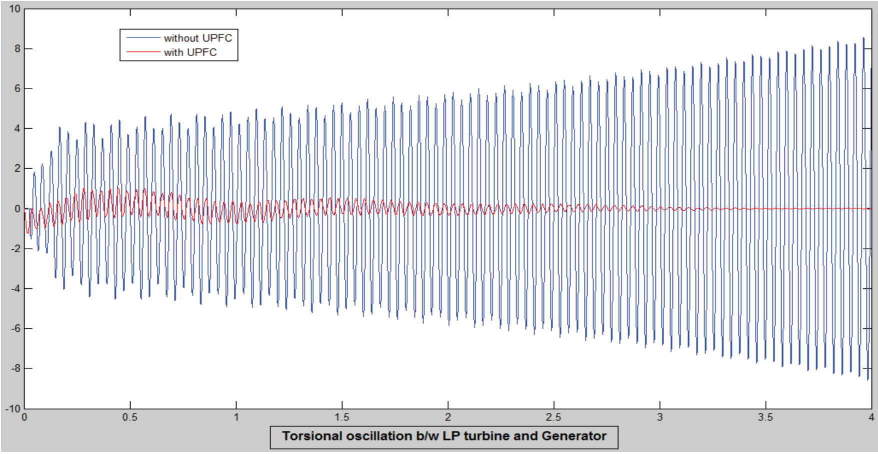
Figure 8: Simulation for the un-damped mode with STATCOM : (a) Variation of Torques B/w LP turbine and Generator, (b) Variation of Torque B/w HP – LP turbine.

Table 3: Eigen Values with STATCOM.

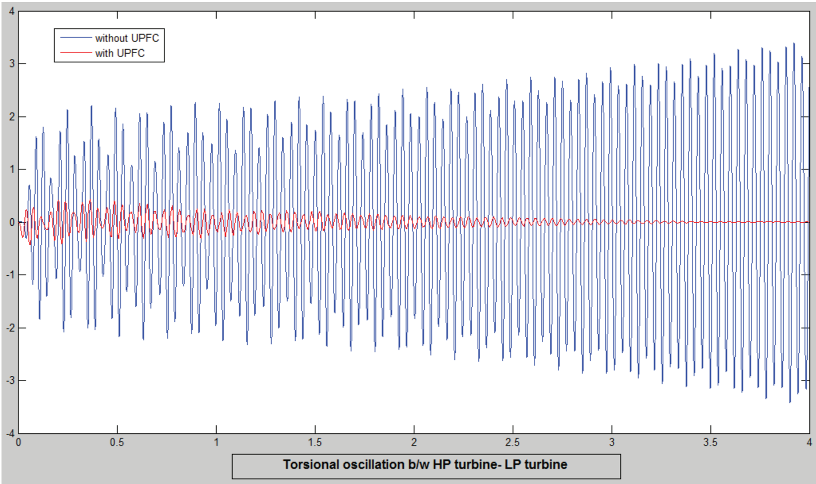
Eigen values	Comments
-0.046 ± 3.92j	Low frequency mode
-0..521 ± 155.13j	Sub synchronous mode
-0.681 ± 202.92j	Sub synchronous mode

Table 4: Eigen Values with UPFC.

Eigen Value	Comment
-0.057 ± 4.46j	Low frequency mode
-0.532 ± 156.043j	Sub synchronous mode
-0.761 ± 204.84j	Sub synchronous mode



(a)



(b)

Figure 9: Simulation for the un-damped mode with UPFC : (a) Variation of Torques B/w LP turbine and Generator, (b) Variation of Torque B/w HP – LP turbine.

Table 5: PEAK-PEAK COMPARISON.

Peak to peak torque(pu) at 3 seconds					
Section	Without Fact devices	Statcom	SSSC	UPFC	Dynamic Resistance
HP-LP	5.612	1.207	0.211	0.0856	0.3746
Gen-LP	12.945	2.403	0.221	0.124	0.5695

6.2. Discussion and conclusion

The proposed common strategy to compare the damping nature of FACTS device and dynamic resistance is highly efficient and reliable. The time domain analysis shows that UPFC (unified Power flow Controller) is the most efficient in damping the sub-synchronous oscillation. Damping of the sub-synchronous mode is achieved through all the proposed techniques, Future works on dynamic resistance technique can be related by the use of inductors so that the energy can be absorbed and used in some other processes, thereby increasing the efficiency of the plant.

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