DAMPING SUB-SYNCHRONOUS OSCILLATIONS USING UPFC

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This paper investigates the effect of using unified power flow controller (UPFC) on reduction of the sub-synchronous resonance (SSR) effects. In this paper, a new control method is used for the UPFC eigenvalues sensitivity theorem, actually used methods are robust against parameter changes. An UPFC is employed at the generator terminal. Then two feedback signals have been obtained using the basis of eigenvalues sensitivity theorem to produce two complementary damping signals. In this theorem, by appropriate choice of SSR damping controllers (SSRDC) coefficients, an appropriate value has been achieved for system eigenvalues, which shows the robustness of the used method. This method has been implemented in single-machine system connected to an infinite bus and shows the capability of UPFC and proposed controller. Simulation results in this paper have been obtained by using the MATLAB/SIMULINK software.

Keywords: Sub-synchronous resonance (SSR), Unified power flow controller (UPFC), Eigenvalues sensitivity theorem, Eigenvalues analysis

1. Introduction

The task of power system is the supply of electrical energy with high reliability that much of this energy produces with converting mechanical energy to electrical energy by generators. Generator is composed of various components. Electrical and mechanical torques imposed over different parts of the generator make different angles and speeds in various components of the machine which lead to torsional oscillations [1]. Torsional oscillations are not problematic themselves, but if they interfere with other frequencies of system, lead to sub-synchronous resonance (SSR) phenomena [2].

The task of electrical energy transmission is by transmission lines which the lines use series compensation during long distances [3]. Although series compensating is a simple and effective way to increase the capacity of power transmission and improve the system stability, but it is possible to make sub-synchronous resonance to the system. In SSR, electrical oscillations modes interact with the mechanical modes and lead to dynamic instability [4-5]. Sub-synchronous resonance can cause tensional interaction, induction generator effect or transient torque [6].

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The first two shaft failures due to sub-synchronous resonance (SSR) occurred at the Mohave station in 1970 and 1971.However, sub-synchronous oscillations were first discussed in 1937 and until 1971 turbine shaft oscillations were neglected [7]. Here, a major concern is because of rotor shaft damage possibility which can be cumulative effects of low amplitude and lengthy torque or effects of high amplitude and transient torque [8].

Detection and opposition against SSR in power systems is an important issue and has great operational importance. One way to reluctate the SSR is using flexible AC transmission Systems (FACTS) devices. FACTS devices technology is based on using controlled power electronic devices. Transfer of power through a transmission line is determined by line impedance, voltage magnitude and angles of both ends of the line. Thus, the fundamental purpose of FACTS devices is controlling of the three main parameters of voltage, phase angle and impedance. These devices allow transmission lines to load without a significant change in the structure of power systems and improve controllability and system reliability. One of these devices is unified power flow controller (UPFC) that has been used for sub-synchronous damping [9].

UPFC is a special FACTS device that is designed for real-time controlling, dynamic compensation, system oscillation damping and provides a multi-functional flexibility. UPFC controls all parameters in power flow and can control impedance, phase angle and voltage and also can control active and reactive power on the transmission line and bus voltage simultaneously and independently. UPFC incorporated the abilities of Static Synchronous Series Compensator (SSSC) and Static Synchronous Compensator (STATCOM) with different parameters controlling of the network and is used as an instrument installation and consists of a shunt connected voltage source converter and a series connected voltage source converter. Series converter injects a series voltage while shunt converter is controlled to inject reactive current [10]. As mentioned, Research on this subject began after two rotor fractures of the Mohave power plant and different methods were discussed to deal with SSR. Researchers have offered many articles in order to suppressing this phenomenon since beginning the labors to minimize the SSR and also they have tried to use the UPFC for reducing the effects of this phenomenon except the mentioned features. In [11] a method has been proposed for risk assessment of SSR in compensated AC networks that it has considered SSR severity and probability of network configuration in different operational modes of Turbine Generator. In [12] reducing model of the SSR has been introduced with appropriate series control of capacitors that it is an attractive and interesting approach because this method does not incur additional costs, but constrains some limitations. In [13] damping SSR with SSSC and in [14] a new method have been presented for sub-synchronous damping controller design based on nonlinear optimization and using a STATCOM. In [15] the characteristics of SSR with UPFC based on frequency domain method, eigenvalues method and transient simulation has discussed and in [16] UPFC controller has been used for system oscillations damping by using H_2 model. These mentioned methods have been studied oscillation damping by using various control methods, but they didn't have pay to robustness of control method against network parameters changing and failing to take advantage of parallel and series combination controls.

In this paper, a new control method is proposed for UPFC using the eigenvalues sensitivity theorem, which is robust against parameter changes. In other words, it has been tried to implement the UPFC control properly to be able to damp sub-synchronous oscillations without changing transmitted power. Damping controller coefficients has been obtained based on the eigenvalues sensitivity theorem. This theorem is in a way that calculates eigenvalues sensitivity relative that robustness of control method against network parameters changing. In the following, modeling of power system is discussed.

2. Power system modeling without UPFC

The considered system in this paper is the IEEE first benchmark model that was created by IEEE working group on SSR in 1977 [17]. This model consists of a synchronous generator connected to an infinite bus through a series-compensated transmission line as shown in Fig1. Although it is a simple radial system, it is frequently used for SSR studies (The parameters are shown in Table 1). Modeling of the compensator that is used to reduce the SSR phenomenon will be discussed in the following.

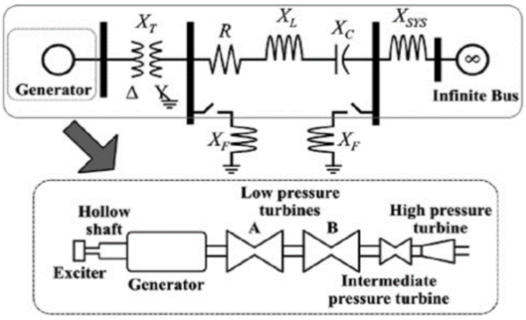

Fig. 1: IEEE first benchmark model

3. System modeling in presence of UPFC

3.1. UPFC structure and its location

UPFC schematic as part of a single machine system that has been connected to infinite bus is shown in Fig. 2. UPFC consists of a shunt voltage source converter (VSC-R) and a series voltage source converter (VSC-I). VSC-I injects series voltage while VSC-R is controlled to inject reactive current. The series and shunt branches of UPFC can generate or absorb reactive power independently and 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 VSC-R 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 voltage at the output port of the UPFC (UPFC can be viewed as a two port device on a single phase basis) [2]. The capacitor voltage is regulated at the specified value by dc voltage controller to keep balance the power between shunt and series branches.

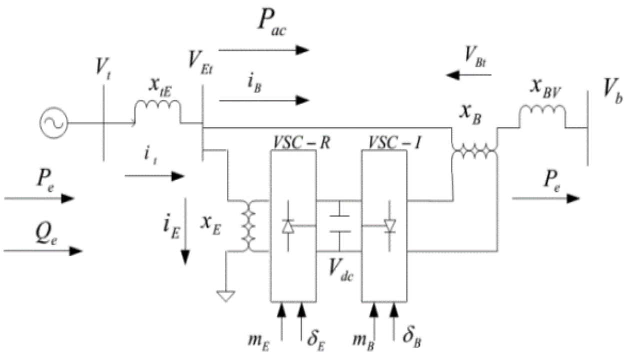

Fig. 2: UPFC schematic in the IEEE first benchmark model [20]

In this figure V_t and V_b are the generator terminal voltage and infinite bus voltage respectively. UPFC consists of a series transformer reactance x_B, a parallel transformer reactance x_E, two three-phase Gate Turn-Off (GTO) voltage source converters and a DC capacitor link. C_{dc} and V_{dc} are capacity and voltage of the DC link respectively. The four control signals of UPFC are consists of m_E, δ_E, δ_B and m_B that m_E is parallel excitation amplitude modulation index, m_B is series injection amplitude modulation index, δ_E is shunt excitation phase angle and δ_B is series injection phase angle. These are control parameters of UPFC for synchronization power compensation in a series line without external voltage source [20].

3.2. System equations in the presence of UPFC

When UPFC is located in the power system as Fig. 2 (on the sender side), system state equations are changed that new equations must be obtained to calculate the system eigenvalues. Also the capacitor voltage of DC link creates a differential equation. Generally, new equations are as follow [23]:

$$\dot{x} = Ax + Bu$$
$$x = \left[\Delta\delta, \Delta\omega, \Delta E_q^{'}, \Delta E_{fd}, \Delta V_{dc}\right]^T$$
$$u = \left[\Delta m_E, \Delta\delta_E, \Delta m_B, \Delta\delta_B\right]^T \qquad (1)$$

The X is the state variable δ and ω are the angle and angular velocity machines, respectively, $E^{'}_q$ and E_{fd} are the internal voltage and filed of voltage and V_{dc} is the capacitor voltage of the DC link . U is input control signals of UPFC. This needs to control the shunt and series converters and this operation lead to new state variables generation. The added variables will be discussed in the following.

3.3. UPFC control

In this section control circuits of UPFC to reduce the SSR are analyzed. As mentioned earlier, UPFC is composed of two inverters that are connected via a regulated DC link voltage. Since UPFC is flexible, it is able to affect several fundamental parameters of the power system simultaneously, a set of various purposes can be considered, and designs of control module fulfill according the purposes. In most cases, UPFC has been considered by generating or absorbing reactive power via shunt inverter to control the bus voltage and also it has considered by adjusting the amplitude and phase changes of injected voltage of series inverter for power flow controlling in the transmission lines. The control system of UPFC is consists of two shunt converter control and series converter control subsystems.

3-3-1- series converter control

There are different control modes such as direct voltage injection, angle phase shift and automatic power flow control for series voltage. In [15] injection voltage control has been used for series converter controlling that reactive voltage has been kept constant and voltage of the second port of UPFC has been controlled. There is an objection in the presented control model in [15] that the reactive voltage has not been controlled, but in [8] active and reactive power control have been used to solve the problem partially. In this study, a combination model of the two references [15] and [8] is presented for series converter control as Fig. 3.

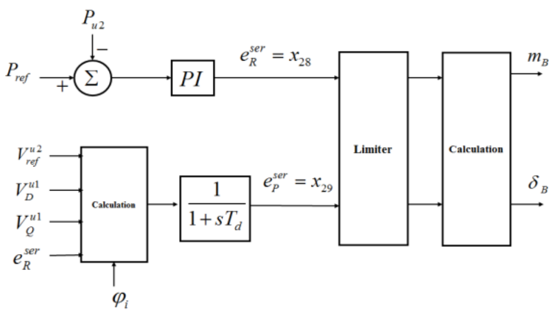

Fig. 3: Schematic of series converter control

As shown in Fig. 3, two state variables have been added to the system (x_{28}, x_{29}). On the other hand the limiters have been regulated to keep injection current and injection voltage in the specified limits for series converter control system. Also the calculation has been used to calculate $m_B$and δ_B as follows [19]:

$$\delta_B = \tan^{-1}\left[\frac{x_{28}}{x_{29}}\right] \qquad (2)$$
$$m_B = \cos^{-1}\left[\frac{\pi\sqrt{{x_{28}}^2 + {x_{29}}^2}}{2\sqrt{6}\rho_{se}x_{27}}\right]$$

where ρ_{se} is the transformation ratio of series converter transformer, x_{27} is the DC link voltage (V_{dc}) that has been created after UPFC adding to the system.

3-3-2- shunt converter control

The shunt converter absorbs controlled current from the system. One component of this current is $I^{sh}_{P\ ref}$ which is automatically determined to balance the offering real active power to series converter through the DC link. This power balance is enforced by regulating the DC capacitor voltage through feedback control. The other component of the shunt converter current is reactive current $I^{sh}_{R\ ref}$ that can be obtained by setting the first port voltage of UPFC. In [8] the shunt converter voltage controller has not been used to control the shunt converter and only currents controlling has been done. Thus, the control model shown in Fig. 4 is used to control the shunt converter.

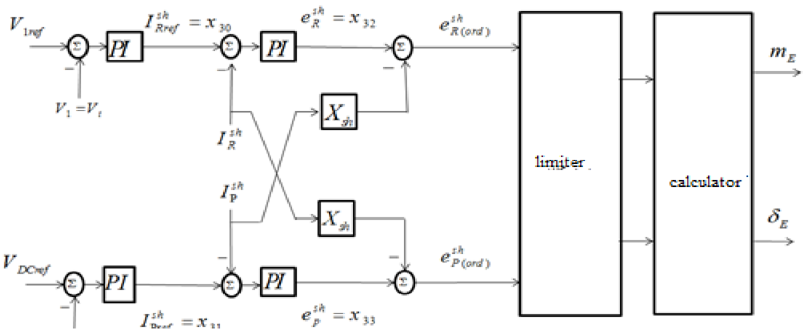

Fig. 4: Schematic of shunt converter control

As seen in Fig. 4, four new state variables have been added to the system (x_{29} to x_{33}). Also the calculation has been used to calculate m_E and δ_E as follows [15]:

$$\delta_E = \tan^{-1}\left[\frac{e^{sh}_{R(ord)}}{e^{sh}_{P(ord)}}\right]$$
$$m_E = \cos^{-1}\left[\frac{\pi\sqrt{(e^{sh}_{R(ord)})^2 + (e^{sh}_{P(ord)})^2}}{2\sqrt{6}\rho_{sh}x_{27}}\right] \qquad (3)$$

where ρ_{sh} is the transformation ratio of shunt converter transformer. Thus, in this section UPFC has been added to the system. Then, control systems for series and shunt UPFC converters have been designed such that eventually the number of system state variables reaches to 33.

4. SSR Controller Damping (SSRDC) design

4.1 Description of the proposed controller

The UPFC control system does not provide the essential damping of oscillations by itself, because its primary mission is the regulation of the bus voltage and controlling the power flow in transmission line. However, the UPFC control signals including m_E،δ_B ،m_B and δ_E can be modulated to provide some other ancillary duties such as Sub-Synchronous Damping (SSD), power oscillation damping etc. In order to achieve an effective damping of SSR, it is necessary to apply synchronized regulation of UPFC with auxiliary SSD controllers. Fig. 5 presents two controllers which are granted to shunt and series branch control systems respectively.

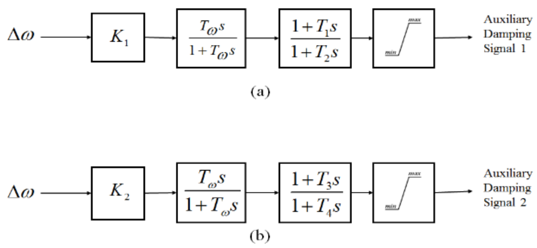

Fig. 5: damping controller related to the shunt branch (a) and series branch (b) [8]

The controllers generate auxiliary signals for main control circuits of shunt and series converters. To achieve the effective damping of oscillations, the output of SSD controller is utilized to modulate δ_E in shunt converter. In contrast, the output of SSD controller related to the series branch is devised to regulate m_B with the aim of providing the proper damping. As shown in Fig. 5, a SSD controller consists of a gain block, a washout filter and a lead-lag compensator. Δω signifies the angular frequency difference and is considered as a feedback input signal. The addition of auxiliary signals to the main control system has been shown in Fig. 6.

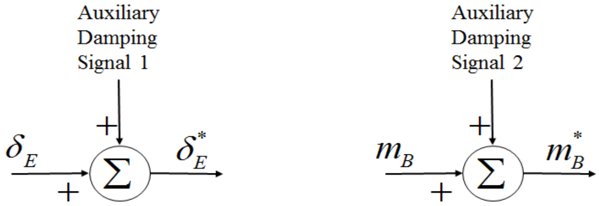

Fig. 6: auxiliary control signals to control signals of UPFC

In [8] a trial and error approach has been applied to adjust various parameters of the proposed controller that cannot be reliable and optimal. In this study, the eigenvalues sensitivity algorithm has been used to obtain the controller parameters.

4.2 eigenvalues sensitivity algorithm

4-2-1- description the eigenvalues sensitivity

Eigenvalues sensitivity of power system is a perfect tool for designing the power systems damping controllers. The eigenvalues sensitivity shows the size and direction of transfer of the eigenvalues when a parameter changes. Many approaches have been proposed for eigenvalues sensitivity calculating. A perfect approach is based on a hybrid representation of system linear model as shown in Fig. 7. This representation assumes that the system is divided into two parts, a section shows the state space of system and the other one is transfer function F(s, q) that is related to the controller design.

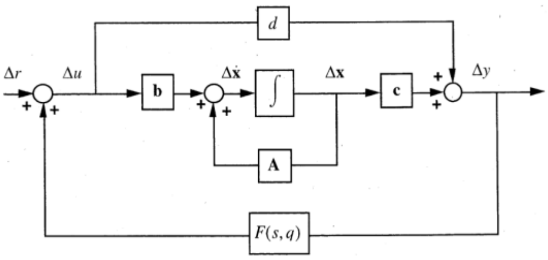

Fig. 7: hybrid representation of system model

Closed-loop eigenvalues sensitivity related to a q parameter from the transfer function F (s,q) are as follows:

$$\frac{\partial \lambda_i}{\partial q} = R_i \frac{\partial F(s,q)}{\partial q}\Bigg|_{s=\lambda_i} \quad (4)$$

where R_i is the residue of closed loop transfer function $\frac{\Delta y}{\Delta r}$:
where v_i and w_i are right and left eigenvectors related to eigenvalue λ_i respectively [20].

4.2.2 Controller design by eigenvalues sensitivity algorithm

Now according to the described algorithm, the damping controller design consists of two stages: phase compensator design of the lead- lag Controller and calculating gain of controller. Phase compensation controller is in a way that phase of eigenvalues sensitivity approaches as much as possible to 180 degrees and gain of the controller is obtained such that all damping eigenvalues be bigger than their determined ratio.

The first stage for the phase compensation design is that assumes α_j is filter coefficient and n_{sj} is the number of phase compensation steps of the controller j. The designing includes the determination of time constant T_{s1j} of the following lead - lag compensation transfer function (in a way that the phase of eigenvalues sensitivity related to the controller j approachs as much as possible to 180 degrees).

$$\left(\frac{1 + sT_{s1j}}{1 + s\dfrac{T_{s1j}}{\alpha_j}} \right)^{n_{sj}} \tag{6}$$

In other words:

$$\underset{T_{s1j}}{Min}\, G(T_{s1j}) = Min \sum_{i=1}^{N_E} \beta_{ij} \cos\left\{ \arg\left[s_i\left(T_{s1j}\right) \right] \right\} \tag{7}$$

where N_E is the number of eigenvalues and:

$$\beta_{ij} = \frac{\left|R_{ij}\right|}{\sum_{k=1}^{N_E} \left|R_{ij}\right|} \tag{8}$$

$$S_i\left(T_{s1j}\right) = R_{ij} \frac{\partial F(s,q)}{q} \tag{9}$$

where F (s,q) is based on the controller that must be considered and the controller of Fig. 5 is considered for this system.

Filter coefficients are achieved from the average phases of sensitivities. If compensation is considered lag or lead [20]:

$$\alpha_j = \frac{1-\sin\phi_j}{1+\sin\phi_j} \tag{10}$$

where:

$$\phi_j = \frac{\pi - \varphi_j}{n_{sj}} \tag{11}$$

$$\varphi_j = \arg\left\{ \sum_{i=1}^{N_E} \frac{S_{ij}}{((1+sT_{s1j})\big/(1+s^{T_{s1j}}\big/\alpha_j))^{n_{sj}}} \right\} \tag{12}$$

The gains of the controllers are selected to transfer eigenvalues after approaching the sensitivity phase to 180 degrees. Control operation is expressed based on the total gains computed by sensitivities:

$$Min \sum_{j=1}^{N_C} \gamma_j \Delta K_j \tag{13}$$

$$\Delta K_j = K_j - K_j^0 \tag{14}$$

$$\gamma_j = \sum_{i=1}^{N_E} \left| \frac{\partial \lambda_i}{\partial K_j} \right| \tag{15}$$

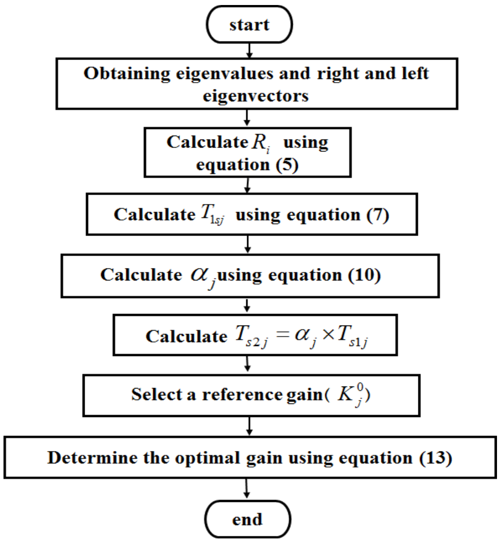

Fig. 8: eigenvalues sensitivity algorithm

The considered limits include the lowest real part of eigenvalues, the upper and lower limitation of the gains.

$$\sum_{j=1}^{N_C} \mathrm{Re}\left(\frac{\partial \lambda_i}{\partial K_j}\right) \Delta K_j \leq \mathrm{Re}\left(\lambda_i^d - \lambda_i^0\right)$$
$$i = 1, \ldots, N_E \tag{16}$$

λ_i^d and λ_i^0 are the estimated and original eigenvalues, respectively. If the sensitivity phase of the eigenvalues is 180 degrees, then the imaginary part of eigenvalues remains constant and the real part of eigenvalues is determined by the damping of eigenvalues [20]. The proposed algorithm has been shown in Fig. 8. In figure the equation 13 from solved in 13 until 15. By obtaining eigenvalues and left and right eigenvectors of system and applying eigenvalues sensitivity algorithms, controller coefficients were earned for 55% series compensation ($\frac{X_C}{X_L}$) as Table 2.

5. Simulation results

5.1. Eigenvalues analysis

In this part, the system state equations are implemented in different conditions in MATLAB/SIMULINK software and then eigenvalues of the system in different modes are earned after linearization of them around their operating point. At first system without UPFC is considered that includes 26 state equations; so in this case, 26 eigenvalues are obtained that only torsional and electrical modes of system have been shown in Table 3. These values have been achieved for different levels of series compensation ($\frac{X_C}{X_L}$). As can be seen from the table, the eigenvalues of the generator turbine shaft ($\lambda_{11,12}$) have a positive real part and unstable. The eigenvalues of 1 to 12 represent the torsional dynamic of multi mass system turbo-generators; eigenvalues of 13 and 14 represent super-synchronous mode and eigenvalues of 15 and 16 show the sub-synchronous mode of the electrical network. In the next step, a UPFC is placed in the system for damping the sub-synchronous resonance. This mode brings the number of new state variables to 33 that eigenvalues of the system have been earned as Table 4. As it was predicted, the system still has sub-synchronous resonance and eigenvalues have the positive real part; so in the third stage, the system has been simulated with UPFC and SSR damping controller that its coefficients were obtained by using eigenvalues sensitivity algorithms and the results of this simulation have been shown in Table 5. All obtained eigenvalues in this step have negative real part and can be said that the effects of sub-synchronous resonance is damped by using UPFC and the SSR damping controller. UPFC has four different operating modes, including SSSC, STATCOM, SSSC + STATCOM (without DC link) and UPFCthe eigenvalues analysis and has been shown in Table 6..

5.2 The non-linear simulation in the time domain

The non-linear simulation has been used to show the effect of UPFC for the sub-synchronous oscillations damping with more exactitude. A disturbance such as a fault or a small perturbation could crate SSR when 55% series compensation is applied. This is shown through a simulation in MATLAB/SIMULINK. A three-phase fault was introduced at 0.01 s and was released after 0.0169 s. Fig. 9 shows rotor speed oscillations before and after using UPFC and SSRDC.

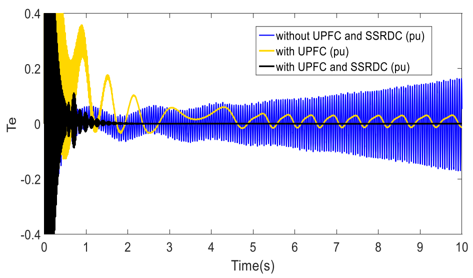

Fig. 9: rotor speed oscillations

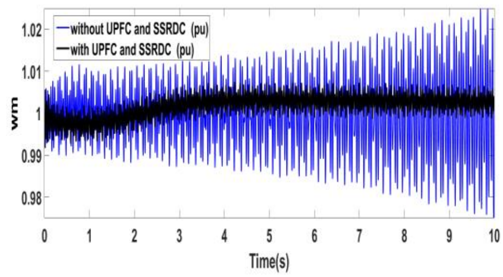

Fig. 10: electromagnetic torque oscillations

As it is inferred from Fig. 9, oscillations have been decreased. Fig. 10 shows the electromagnetic torque before and after using UPFC and also simultaneous using UPFC and SSRDC. The oscillations damping is seen in this figure again. On the other hand, dynamic response and torque between different parts of the generator turbine before and after simultaneous using UPFC and SSRDC have been shown in Figs. 11 and 12 respectively.

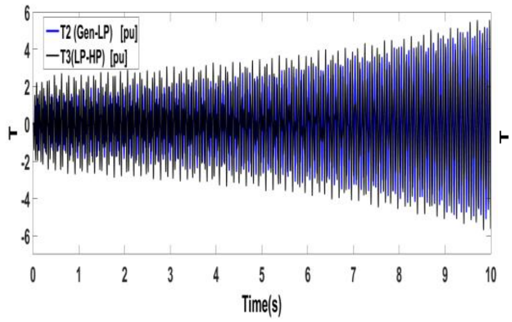

Fig. 11: torque between different parts of the turbine before simultaneous using UPFC and SSRDC

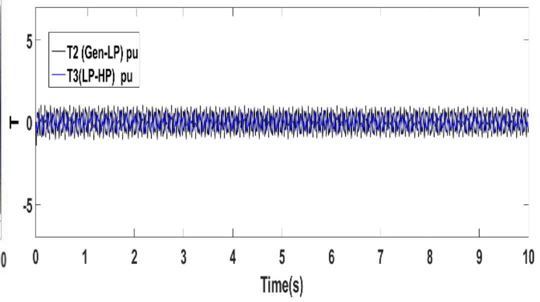

Fig. 12: torque between different parts of the turbine after simultaneous using UPFC and SSRDC

Also output active and reactive power of the generator before and after using UPFC and their simultaneous using UPFC and SSRDC have been shown in Fig. 13 and 14 respectively.

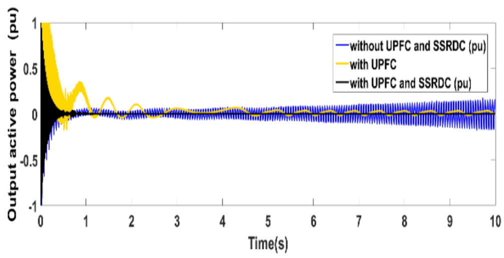

Fig. 13: output active power of generator

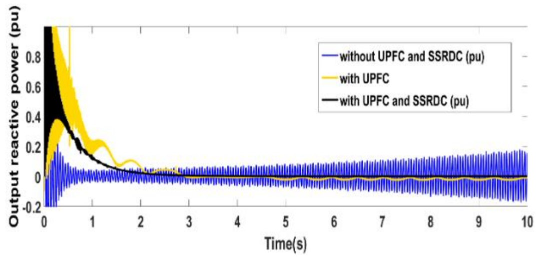

Fig. 14: output reactive power of generator

6. Conclusion

In this paper represent of, a new control method is used for UPFC eigenvalues sensitivity theorem, actually used methods are robust against the parameter changes. In other words, it has been tried to implement the UPFC control properly such that the sub-synchronous oscillations are damped without changing the transmitted power. Damping controller coefficients has been obtained using the eigenvalues sensitivity theorem. As shown in the eigenvalues analysis, the UPFC cannot provide the enough damping of oscillations by itself, because its primary mission is the regulation of the bus voltage and controlling the power flow in transmission line. However, the UPFC control signals including $m_B$can be modulated to provide some other ancillary duties such δ_E and m_E ،δ_B ، as SSD, power oscillation damping, etc. In order to achieve an effective damping of SSR, it is necessary to apply synchronized regulation of UPFC with auxiliary SSD controllers. In other studies, a trial and error approach has been applied to adjust various parameters of the proposed controller that cannot be reliable and optimal. In this paper, the eigenvalues sensitivity algorithm has been used to obtain the controller parameters. This algorithm is in a way which calculates eigenvalues sensitivity by controller parameters changing using system eigenvalues and eigenvectors. It transfers system eigenvalues to the perfect place by determining the controller optimal coefficients. Therefore, it results the system oscillations damping and the robustness of the system by system parameters changing. According to the results of the eigenvalues analysis and nonlinear simulation it can be said that the proposed control method is an appropriate and optimal approach for damping the sub-synchronous oscillations.

R E F E R E N C E S

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APPENDIX

Table 1:

Parameters of synchronous machine and generator turbine shaft

Parameter	Value	Parameter	Value	Parameter	Value
X_d	1.79	R_D	0.0037	K_{IA}	34.093
X_q	1.71	R_Q	0.0182	K_{AB}	52.04
X_D	1.666	R_S	0.053	K_{BG}	70.86
X_l	0.3	M_H	0.1857	K_{GE}	2.822
X_Q	1.695	M_I	0.3112	D_H	0.1
X_{md}	1.66	M_A	1.7173	D_I	0.1
X_{mq}	1.58	M_B	1.7684	D_A	0.1
X_f	0.1	M_G	1.737	D_B	0.1
R_a	0.0015	M_E	0.0684	D_G	0.1
R_f	0.001	K_{HI}	19.3	D_E	0.1

Table 2

Proposed controller coefficients for 55% series compensation

Parameter	Value
K_1	100
K_2	100
T_w	100
T_1	0.06
T_2	0.04
T_3	0.06
T_4	0.04

Table 3:

Eigenvalues of torsional and electrical modes without UPFC for different series compensation

Modes	Compensation level		
	%55	%40	%30
$\lambda_{11,12}$	i9 .72±09.+1	i5 .74±53.+2	i7 .75±33.+3

Table 4:

Eigenvalues of torsional and electrical modes with UPFC for different series compensation

Modes	Compensation level		
	%55	%40	%30
$\lambda_{11,12}$	i24 .+0/5±11	i75 .4±088.+0	i49 .+0/4±08

Table 5:

Eigenvalues of torsional and electrical modes with UPFC and SSRDC for different series compensation

Modes	Compensation level		
	%55	%40	%30
$\lambda_{11,12}$	i21 .5±155.-0	i74 .4±17.-0	i49 .4±18.-0

Table 6:

Eigenvalues of the system in various operating modes of UPFC and 55% series compensation

Modes	UPFC	SSSC	STATCOM	SSSC+STATCOM (without DC link)
$\lambda_{11,12}$	i21 .5±155.-0	i95 .4±091.-0	i24 .5±11.+0	i24 .5±11.+0