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Design of Ipfc to Enhance the Power System Stability and Damping of Low Frequency Oscillations

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Abstract— Interline power flow controller (IPFC) is proposed a new concept for the compensation and effective power flow management of multi-line transmission system. In addition, a supplementary controller for a novel modelling IPFC to damped out low frequency oscillations with considering four alternative damping controllers are proposed. In this project selection of effectiveness damping control signal for the design of robust IPFC damping controller to variations in system loading and faults in the power system are discussed. The presented control scheme not only performs damping oscillations but also the independent inter line power flow control can be achieved. MATLAB simulation results verify the effectiveness of IPFC and its control strategy to enhance dynamic stability.

Index Terms — FACTS controller, Phillips-Heffron model, power system dynamic stability, supplementary controllers, IPFC.

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1. Introduction

Low frequency oscillations within the frequency in range of 0.2 to3.0 Hz are in the inter connection of large power systems. To increase power system oscillations stability, power system stabilizer (PSS) is used. It is simple, effective and economically good [1]. It is necessary to improve the performance of power system to received quality power at the consumer ends. Reactive power compensation is the main measure to keep power system stability and minimum system losses. Flexible AC Transmission (FACTS) devices are found to be very effective controller to enhance the system performance. When compared with FACTS controllers, power system stabilizer may not be able to suppress oscillations resulting from severe disturbances, such as three phase faults at terminals.

Flexible AC Transmission system (FACTS) controllers, such as static VAR compensator (SVC), static synchronous compensators (STATCOM) and Unified Power Flow Controller (UPFC) can also be applied for damping oscillations and improve the signal stability of power system by adding a supplementary signal for main control loops [6].

The inter line power flow controller (IPFC) [6] is a new concept of the FACTS controller for series compensation with the unique capability of controlling power flow among multi-lines. IPFC employs two or more voltage source converters (VSCs) with a common dc link. Each VSC can provide series compensation for the selected line of transmission system (master or slave line) and it is capable of exchanging reactive power with its own transmission system.

The damping controller of low power frequency oscillations in the power system must be estimated for a non linear dynamic model of power system for its accuracy and desirable operation at damping of oscillation.

In [10],a linearized model of a system with two or more IPFC line installed, has worked but a SSSC or STATCOM can be employed in the system with a single machine and two lines, out of economic reasons. The active and reactive powers of the lines are not controlled independently. In this project, a single machine infinite bus is connected with three IPFC lines is used and linearized Phillips-Heffron model for the mentioned power system is derived for design of IPFC damping controller. In this, four alternative damping controllers are to be designed [10, 12].

2. Operation of Single Machine Infinite Bus Power System Using Power System Stabilizer

A power system stabilizer is a device that measures improvements in the stability of the system by introducing a supplementary signal to an automatic voltage regulator (AVR). The AVR is an exciter control device which means the terminal voltage of the generator at a constant level, which is one of the most common and economical method. Though generator output is decided by a turbines mechanical torque, it can be changed by transiently changing the excitation system. A power system stabilizer detects the change in generator output power, controls the excitation value and reduces the rapid power fluctuations. PSS is added to excitation system to enhance the damping of electric power system during low frequency oscillations. A dynamic modal of PSS is included to investigate the effectiveness in providing positive damping to overcome the undamped electromechanical modes. PSS have been shown to be a effective in stabilizing the modes where are different oscillation frequencies. PSS have been used as a simple, effective, and economical method to increase power system oscillation stability. To design a PSS with better performance, a several approaches have been applied to PSS design problem and many useful results have been observed. Modern power systems are highly complex and strong non-linearity and their operating conditions can vary over a wide range. Operating conditions of a power system are continuously changing due to the load patterns, electric generation variations, disturbances, transmission topology and line switching. A problem of interest in power industries in which fact controllers could play a major role is the mitigation of low frequency oscillations that often arise between areas in large interconnected power system.

3. Operation and Analysis of Single Machine Infinite Power System Installed With Ipfc

In the introduction part, a brief introduction of the Interline Power Flow Controller (IPFC) Operation characteristics [6] [15] is presented. General form of the Interline power flow controller employs a number of DC to AC inverters each providing series compensation for a different line. The IPFC can potentially provide a highly effective scheme for power transmission management at multiline substations. However within the general concept of the IPFC, the compensating inverters are linked together at there DC terminals, as illustrated in figure 1. With this, in addition to provide series reactive compensation, any inverter can be controlled to supply real power to common DC link from its own transmission line. Thus, an overall surplus power can be made available from the underutilised lines which can be used by other lines for real power compensations. In the same manner, some of the inverters compensating overloaded lines or lines with heavy burden of reactive power flow can be equipped with full two dimensional, reactive and real power flows, control capability, similar to that offered by UPFC [11]. This arrangement mandates the rigorous maintenance of the overall power balance at the common DC terminal between the two terminals by appropriate control action, using the general principle that the under loaded lines are providing appropriate real power transfer for overloaded lines.

In this IPFC which consisting of a master voltage source converter (VSC-M) and a slave voltage source converter (VSC-S) and its two transformers and common DC link capacitor (C_{dc}). V_{inj1} , V_{inj2} are voltages of transformers of the lines 1 and 2 respectively. While the system is utilised only with two lines, SSSC or STATCOM is installed for the purpose of control functions. In fig .1 $m_1, m_2, \delta_1, \delta_2$ are the amplitude modulation ratio and phase angle of the control signal of each VSC respectively, which are input signals for IPFC and $V_B, V_S, V_{inj1}, V_{inj2}$ are the voltages of infinite bus , terminal voltages of the generated and the injected voltages of the master and slave voltage source converters respectively.

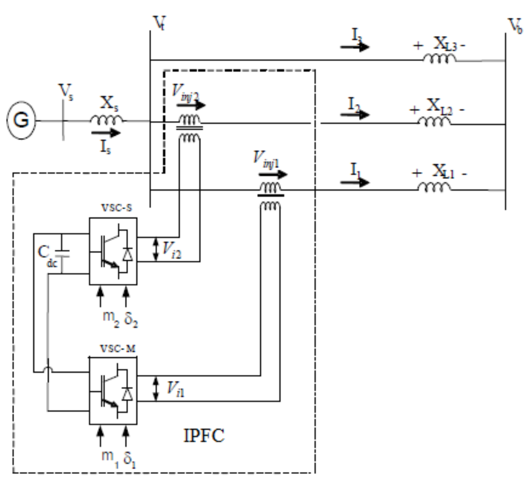

Fig.1 A single machine infinite-Bus power system installed with IPFC.

The general pulse width modulation (PWM) is adopted for the IGBT based VSC. By ignoring the resistance of the transformers of the IPFC and by applying Park's transformation, the per unit values of three-phase dynamic differential equations of IPFC as the three-phase dynamic differential equations of UPFC are obtained.

$$\begin{bmatrix} V_{inj1d} \\ V_{inj\,1q} \end{bmatrix} = \begin{bmatrix} 0 & X_{t1} \\ -X_{t1} & 0 \end{bmatrix} \begin{bmatrix} I_{1d} \\ I_{1q} \end{bmatrix} + \begin{bmatrix} V_{i1d} \\ V_{i1q} \end{bmatrix}$$

$$V_{i1d} = \frac{m_1 V_{dc} cos\,\delta_1}{2}$$

$$V_{i1q} = \frac{m_1 V_{dc} Sin\,\delta_1}{2}$$

$$\begin{bmatrix} V_{inj2d} \\ V_{inj\,2q} \end{bmatrix} = \begin{bmatrix} 0 & X_{t2} \\ -X_{t2} & 0 \end{bmatrix} \begin{bmatrix} I_{2d} \\ I_{2q} \end{bmatrix} + \begin{bmatrix} V_{i2d} \\ V_{i2q} \end{bmatrix}$$

$$V_{i2d} = \frac{m_2 V_{dc} cos\,\delta_2}{2}$$

$$V_{i2q} = \frac{m_2 V_{dc} Sin\,\delta_2}{2}$$

$$\frac{dv_{dc}}{dt} = \frac{m_1}{2C_{dc}} [Cos\delta_1 \;\; Sin\delta_1] \begin{bmatrix} I_{1d} \\ I_{1q} \end{bmatrix} + \frac{m_2}{2C_{dc}} [Cos\delta_2 \;\; Sin\delta_2] \begin{bmatrix} I_{2d} \\ I_{2q} \end{bmatrix}$$

Where X_{t1} , X_{t2} , are the reactance of master and slave injection transformers and V_{dc} is the dc link voltage and

$$\bar{I}_1 = I_{1d} + jI_{1q} \;, \bar{I}_2 = I_{2d} + jI_{2q}$$

The complete dynamic model of the single machine infinite bus power system equipped with an IPFC can be developed by above equations.

$$\dot{\delta} = \omega_0 \omega \qquad (1)$$

$$\dot{\omega} = \frac{P_m - P_e - D\omega}{2H}$$

$$\dot{E}'_q = \frac{-E_q + E_{fd}}{T'_{do}}$$

$$\dot{E}_{fd} = -\frac{1}{T_A} E_{fd} + \frac{K_A}{T_A}(V_{s0} - V_s) \qquad (2)$$

Where V_s ,V_{s0} are the terminal voltage and the reference of terminal voltage respectively and also ,

$$T_e = P_e = V_{sq} I_q + V_{sd} I_d \,,$$

$$E_q = E'_q + (X_d - X'_d) I_d, V_s = \sqrt{V_{sd}^2 + V_{sq}^2}, V_{sd} = X_q I_q$$

$$V_{sq} = E'_q - X'_d, I_d = I_{1d} + I_{2d} + I_{3d}, I_q = I_{1q} + I_{2q} + I_{3q} \qquad (3)$$

From figure 1 we can have

$$V_{sd} + jV_{sq} = X_q + (I_{1q} + I_{2q} + I_{3q}) + j[E'_q - X'_d(I_{1d} + I_{2d} + I_{3d})]$$

$$\mathrm{j}(X_{L3})(I_{3d} + jI_{3q}) = j(X_{L1} + X_{t1})(I_{1d} + jI_{1q}) - V_{i1d} - jV_{i1q} \quad (4)$$

From above equations [1-4]

$$I_{1q} = V_{i1d}\,X_{q11} + V_{i2d}\,X_{q21} + V_b X_{qb1}\,\sin\delta \quad (5)$$

$$I_{1d} = V_{i1q}\,X_{d11} + V_{i2d}\,X_{d21} + V_b\,X_{db1}\cos\delta + E'_q\,X_{de1} (6)$$

$$I_{2q} = V_{i1d}\,X_{q12} + V_{i2d}\,X_{q22} + v_b\,X_{qb2}\sin\delta \;(7)$$

$$I_{2d} = V_{i1q}\,X_{d12} + V_{i2d}\,X_{d22} + V_b\,X_{db2}\cos\delta + E'_q\,X_{de2} \quad (8)$$

$$I_{3q} = V_{i1d}\,X_{q13} + V_{i2d}\,X_{q23} + v_b\,X_{qb3}\sin\delta \;(9)$$

$$I_{3d} = V_{i1q}\,X_{d13} + V_{i2d}\,X_{d23} + V_b\,X_{db3}\cos\delta + E'_q\,X_{de3} \quad (10)$$

Where,

$$\Delta P_e = k_1\Delta\delta + K_2\Delta E'_q + K_{pd}\Delta V_{dc} + K_{p1}\Delta m_1 + K_{p\delta 1}\Delta\delta_1 + K_{p2}\Delta m_2 + K_{p\delta 2}\Delta\delta_2 \quad (11)$$

$$\Delta E'_q = k_4\Delta\delta + K_3\Delta E'_q + K_{qd}\Delta V_{dc} + K_{q1}\Delta m_1 + K_{q\delta 1}\Delta\delta_1 + K_{q2}\Delta m_2 + K_{q\delta 2}\Delta\delta_2 \quad (12)$$

$$\Delta V_s = k_5\Delta\delta + K_6\Delta E'_q + K_{vd}\Delta V_{dc} + K_{v1}\Delta m_1 + K_{v\delta 1}\Delta\delta_1 + K_{v2}\Delta m_2 + K_{v\delta 2}\Delta\delta_2 \quad (13)$$

$$\Delta V_{dc} = k_7\Delta\delta + K_8\Delta E'_q - K_9\Delta V_{dc} + K_{c1}\Delta m_1 + K_{c\delta 1}\Delta\delta_1 + K_{c2}\Delta m_2 + K_{c\delta 2}\Delta\delta_2 \quad (14)$$

From the above equations we arrange in metrics form as

$$\dot{X} = AX + BU$$
$$\mathrm{U} = [\Delta m_1\ \Delta m_2\ \Delta\delta_1\ \Delta\delta_2]^{\mathrm{T}}$$

Where $\Delta m_1, \Delta m_2, \Delta\delta_1, \Delta\delta_2$ represents the linearization of the input control signals of the IPFC. The linearized dynamic model of can be shown by figure 2.This explanation applies to the both an elementary IPFC shown in fig.1 and a multi converter IPFC arrangement. The injection of V_{inj1} on system 1 usually results in an exchange of P_{s1} and Q_{s1}between converter VSC_1 and the line. Commonly the $V_{inj1,2}$ voltage is split into its d-q components which eases the analysis of this system as a whole. The V_{inj1q} component has predominant effect on the line real power, while the in phase component (V_{inj1d}) has over the lines reactive power. The reactive power exchange Q_{s1} is supplied by the converter itself. However, the active power (P_{S1}) imposes a demand to be fulfilled at the dc terminals. Converter VSC-2 is in charge of fulfilling this demand through the PS1+PS2 =0 constraint.

Since the problem of LFOs can be analyzed from a small-signal stability standpoint, the power system is described by a set of state equations that are linearized. For this particular study, a search is performed for unstable or poorly-damped inter-area modes of oscillation. A PSS controller is constructed to stabilize and damp these modes together with any local rotor-angle oscillatory modes. To this end, a model that is representative of the entire power system, yet which allows the identification of the modes of interest, must be employed. Specifically, the generator and excitation system state equations are linearized and their time derivatives are put into matrix form.

4. Controller Design of PSS AND IPFC

Phillips-Heffron model of a synchronous machine is commonly used in small signal stability analysis and for off-line design of PSS. A cost efficient and satisfactory solution to the problem of oscillatory instability is to provide damping for generator rotor oscillations. The objective of designing PSS is to provide additional damping torque without affecting the synchronising torque at critical oscillation frequencies.

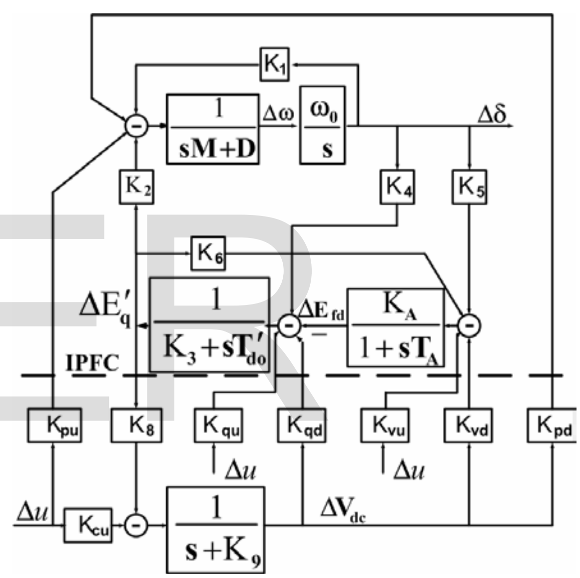

Fig.2.Phillips Heffron Model of power system installed with IPFC

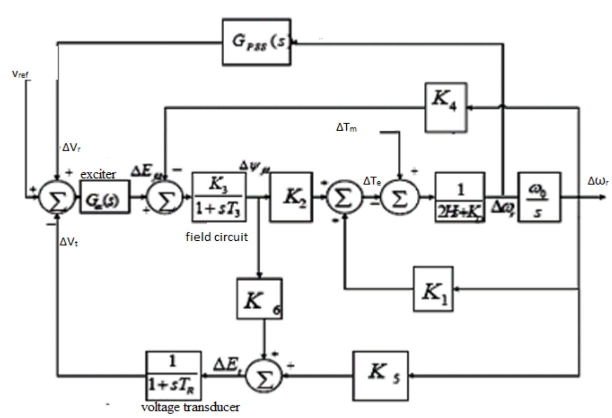

Fig. 3.control block diagram for power system stabilizer

The theoretical basis for power system stabilizer may be illustrated with the aid of block diagram as shown in figure.3, the pur-

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pose of PSS is to introduce a damping torque component. A logical signal to be used for controlling generator excitation is the speed deviation $\Delta\omega_r$. The PSS transfer function, $G_{pss}(s)$, should have appropriate phase compensation circuits to compensate for the phase lag between exciter input and electrical torque.

5. Design of Damping Controller

The damping controllers are designed to produce an electric torque in phase with the speed deviation. The four control parameters of the IPFC (m_1,m_2, δ_1,δ_2) can be modulated in order to produce the damping torque. The speed deviation Δw is considered as the input to the damping controllers. The four alternative IPFC based damping controllers are examined in the present work. Damping controller based on IPFC control parameter m_1 shall henceforth by denoted as damping controller (m_1). Similarly damping controllers based on m_2, δ_1, δ_2 .

The detailed step-by-step procedure for computing the parameters of the damping controllers using phase compensation technique is given below.

1. Computation of natural frequency of oscillation ω_n from the mechanical loop.

$$\omega_n = \sqrt{\frac{K_1\omega_0}{M}}$$

2. Computation of $\angle GEPA$ (phase lag between Δu and ΔP_e) at $S=j\omega_n$. Let it be γ.

3. design of phase lead /lag compensator G_c :

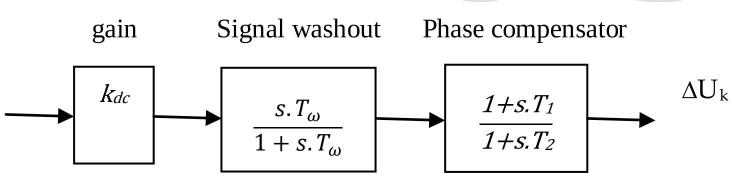

Fig. 4 structure of IPFC based damping controller

The phase lead/lag compensator G_c is designed to provide the required degree of phase compensation. For 100% phase compensation.

$$\angle G_c (j\omega_n) + \angle GEPA (j\omega_n) = 0$$

Assuming one lead-lag network, $T_1 = aT_2$, the transfer function of the phase compensator becomes,

$$G_c (s) = \frac{1+s.aT_2}{1+s.T_2}$$

Since the phase angel compensated by lead-lag network is equal to γ , the parameters and T_2 are computed as,

$$a = \frac{1+\sin(\gamma)}{1-\sin(\gamma)}$$

$$T_2 = \frac{1}{\omega_n}$$

4. Computation of optimum gain K_{dc} .

The value K_{dc} is setting to achieve the required amount damping torque can be provided by IPFC damping controller.

The signal washout is the high pass filter that prevents steady changes in the speed from modifying the IPFC input parameter. The value of the washout time constant should be high enough to allow signals associated with oscillations in rotor speed to pass unchanged. From the viewpoint of the washout function, the value of is not critical and may be in the range of 1s to 20s. In this paper T_w equal to10s is chosen References.

6. Simulation Results

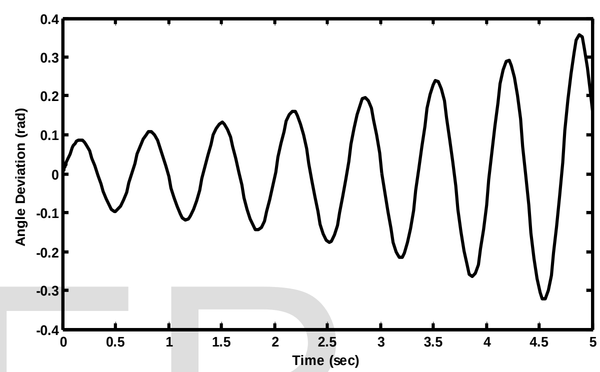

Fig. 5. Angle deviation without using PSS and IPFC

Generally the power system is not in stable condition, when loads are changing and those are effecting on the transmission system. For the different load variations torque angle and speed deviations are occurred in power system and therefore power changes may exists in the power system. Without using any controllers the low frequency oscillations and angle deviation are increased with respect to time , which is shown in Fig (5). Due to these low frequencies oscillations system losses its stability.

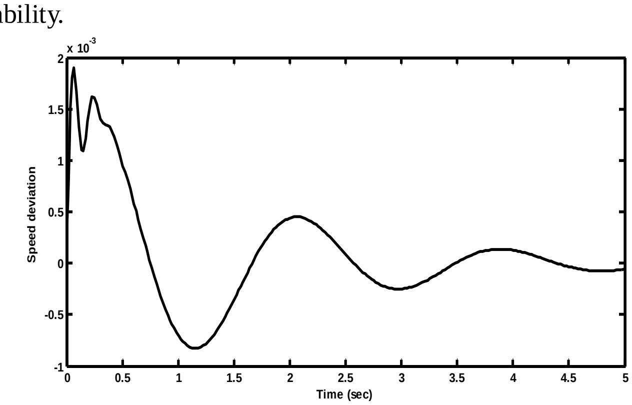

Fig. 6. Speed change with time when PSS is in operating condition

For decreasing of these low frequency oscillations, consider a power system stabilizer which is shown in previous and it is in operating condition, the speed deviation in generator side we can control and the waveforms show in Fig (6).

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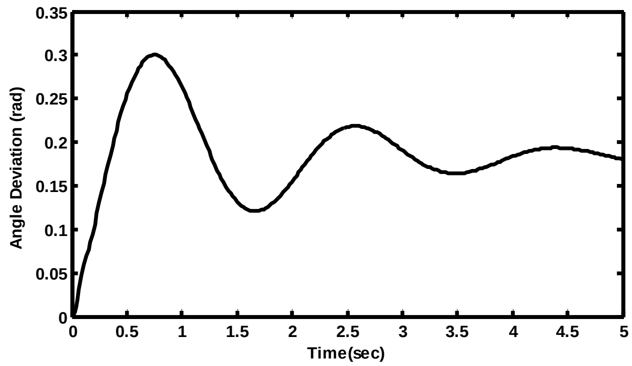

Fig. 7. Angle deviation with PSS

Similarly, with the installation of power system stabilizer we can also control the angle deviations shown in above Fig (7) and controls low frequency oscillations in transmission system. By controlling of these low frequency oscillations we will try to stabilize the system stability.

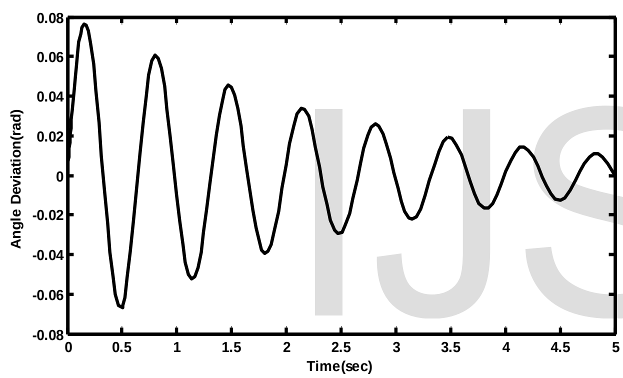

Fig. 8. Phase angle deviation when IPFC in operating condition

In Fig (5), the low frequency oscillations are increased with different loads in power system which is installed with interline power flow controller in series with transmission system and it controls phase angle and then speed deviations in system which is shown in Fig (8).

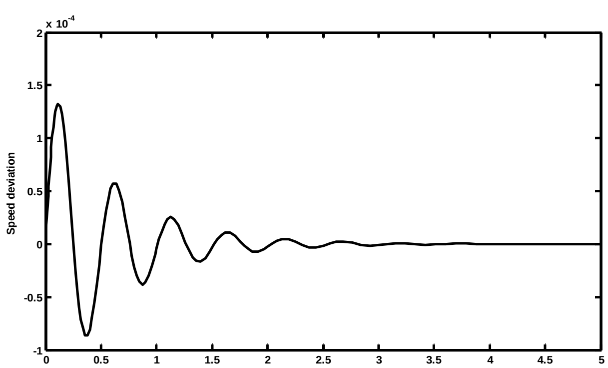

Fig. 9. Speed changes with IPFC is used

The interline power flow controller will control the speed deviations with in minimum time when compared to power system stabilizer, and it will control system stability which is shown in fig.9.

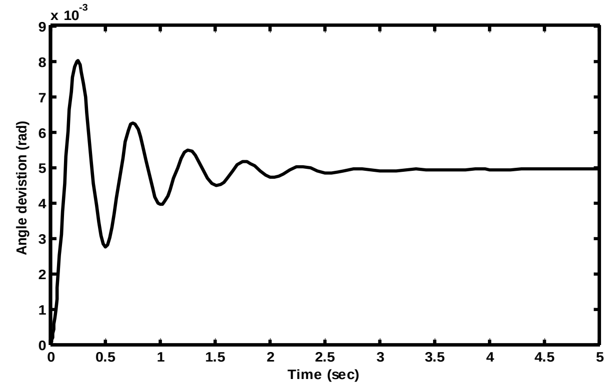

fig. 10. Angle deviation with IPFC in operating condition

Especially, by the controlling of angle deviation in interline powerflow controller with respect to time as shown in fig.10 and which are to be controlled in minimum time compared to PSS.

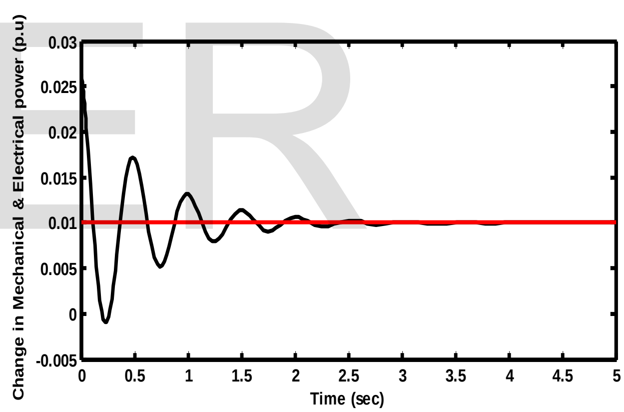

Fig. 11. Mechanical and electrical power flow response with IPFC

Both controlling of speed deviation and angle deviation in power system with IPFC, the transmission system stability will be increased. And also the power flow to be controlled as shown in fig.11. In the waveform mechanical power and electrical power of Power system will be controlled in transmission system.

7. Conclusion

In this project, considering a single machine infinite bus power system which is operated in stable condition, for the sudden changes in the loads the changes occurred in speed, torque angle due to low frequency oscillations. Due to this, the power transfer capability is decreased and the system loses its stability. To avoid these low frequency oscillations power systems stabilizer and Interline Power Flow controller controllers are employed in power system, which is discussed in simulation results. Also better performance and stability is achieved by these controllers with less time ellapse, which are shown in resultant waveforms. Power system stabilizer can control the lows frequency oscillations and speed deviations consisting of large time to stabilize the system when compared to Interline power flow controller which is decreased in this project. IPFC is controlled the power flow within the less time to reach system stability point.

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