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Dual Damping Controller using Interline Power Flow Controller

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***Abstract*— The Interline Power Flow Controller (IPFC) is a voltage-source-converter (VSC)-based flexible ac transmission system (FACTS) controller which can inject a voltage with controllable magnitude and phase angle at the line-frequency thereby providing compensation among multiple transmission lines. In this paper, the use of the IPFC based controller in damping of low frequency oscillations is investigated. An extended Heffron-Phillips model of a single machine infinite bus (SMIB) system installed with IPFC is established and used to analyze the damping torque contribution of the DUAL IPFC damp- ing control to the power system. In dual damping controller provide more damping The potential of various IPFC control signals upon the power system oscillation stability is investigated a using controllability index. Simulation results using Matlab Simulink demonstrate the effectiveness of IPFC damping controllers on damping low frequency oscillations.**

I. INTRODUCTION

The present day interconnected power system consists of a great number of generators being connected together through a high-voltage long transmission network, supplying power to loads through lower-voltage distribution systems. The phenomenon that is of great concern in the planning and Operation of interconnected power systems is the low Frequency electromechanical oscillations. These oscillations are the consequence of the dynamical interactions between the generator groups. The oscillations associated with groups of generators when oscillating against each other are called inter-area modes and having frequencies in the range 0.1 to
0.8 Hz, whereas the oscillations, associated with a single generator oscillating against the rest of the system, are called local modes and normally have frequencies in the range of 0.7 to 2.0 Hz[1] . These
the capability of power transmission, threaten system
low frequency oscillations constrain security and damage the efficient operation of the power system [2-3]. For this reason, the use of controllers to provide better damping to the power system oscillations is of utmost importance to maintain power stability. In the last decade, the flexible ac transmission systems (FACTS) devices have been progressively developed to deal with the above control objectives [4]. A stream of voltage source converter (VSC) based FACTS devices, [5], and [6]
such as Static Compensator (STATCOM), Static Synchronous Series Compensators (SSSC), and Unified Power Flow Controller (UPFC) have been successfully applied in damping power system oscillations [7-11].

Interline power flow controller (IPFC) is the latest generation of FACTS controllers [12]. It is the combination of two or more SSSCs which are coupled via a common DC link. With this scheme, IPFC has the capability to provide an independently controllable reactive series compensation for each individual line and also to transfer real power between the compensated lines. There has been growing interest recently in studying the IPFC modeling [12], its basic function to control power flow among transmission lines [13] and oscillation damping [15]. Kazemi and Karimi proposed a PI supplementary damping controller for the IPFC for damping inter-area oscillations. However, the controller parameters are not optimized. Further, no effort had been made to identify the most suitable control parameter. A supplementary PID damping controller was proposed, but the performance degraded due to the system nonlinearity and complexity. Therefore, in this paper, the linearised Heffron-Phillips model of a single machine infinite bus (SMIB) power system installed with an IPFC is first established. It is of same form as that of the unified model presented in [16-17] for UPFC. Phase compensation method is applied for the design of IPFC damping controllers based on the established
linearzed model. The relative effectiveness of modulating alternative IPFC control parameters for damping power system oscillations at the nominal point of the system is examined. The controllability index is used to determine the most effective output control signal among ($m1$,$\theta1$,$m2$, and $\theta2$) from the damping controller.

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II. MODEL OF THE SYSTEM STUDIED

A single machine infinite bus (SMIB) system installed with IPFC is considered for the analysis of stability. Fig. 1. shows the generator connected to the infinite bus through the two parallel transmission lines. The static excitation system, model type IEEE-ST1A, has been considered. PSS is not taken into account in the power system. A simple IPFC is incorporated into the system, which consists of two, three phase GTO based voltage source converters (VSC's), each providing a series compensation for the two lines. The converters are linked together at their dc terminals and connected to the transmission lines through their series coupling transformers. This configuration allows the control of real and reactive power flow in line 1. For the series converter in line 2, it is assumed that active power flow constraint is used while reactive power flow is relaxed. The system data and the initial operating conditions of the

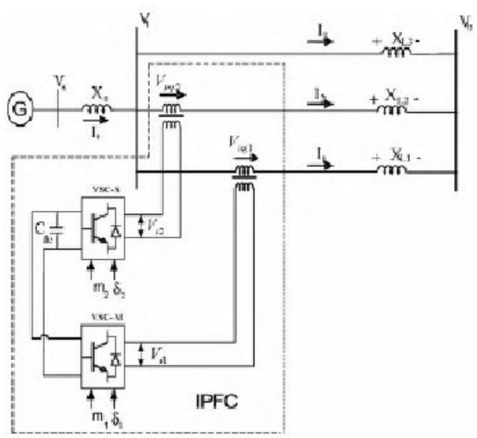

Fig.1 A single-machine infinite-bus power system installed with an IPFC.

system are as follows:
Generator: M=2H=8.0 MJ/MVA D=0 *Td′o* =5.044s
xd =1.0pu *xq* = 0.6pu *x′d* = 0.3pu
Excitation system: *Ka* = 50 *Ta* = 0.05s
Transmission line : *xL*1 = *xL*2 = *xL* =0.5 pu
Transformers: *xt* = 0.15pu *xt*1 *xt*2 =□0.1pu
Operating condition:
P=0.8 *Q*=0.1958 *Vt* =1.0 pu *Vb* =1.0pu *f* = 60 Hz
IPFC parameters :
*m*1 = 0.15, *m*2 = 0.1. *Vdc* =2 pu, *Cdc* = 1 pu

A. Power system Non Linear Dynamic Model

A non-linear dynamic model of the system is derived by neglecting the resistances of all the components of the system (generator, transformer, transmission lines and series converter transformers) and the transients of the transmission lines and transformers of the IPFC. The IPFC considered is based on pulse width modulation. The nonlinear dynamic model of the power system in Fig. 1 is

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

$$\dot{\omega} = \frac{P_m - P_e - P_D}{M} \quad (2)$$

$$\dot{E}'_q - \frac{(-E_q + E_{fd})}{T'_{do}} \quad (3)$$

$$\dot{E}_{fd} - \frac{-E_{fd} + K_a(V_{ref} - V_t)}{T_a} \quad (4)$$

$$\dot{V}_{dc} = \frac{3m_1}{4C_{dc}}(\cos\theta_1 I_{1d} + \sin\theta_1 I_{1q}) + \frac{3m_2}{4C_{dc}}(\cos\theta_2 I_{2d} + \sin\theta_2 I_{2q}) \quad (5)$$

Where δ, is the rotor angle of synchronous generator in radians, $\omega$is rotor speed in rad/sec, *Vt* is the terminal voltage of the generator, *Eq′*is generator internal voltage, *E fd* is the generator field voltage, *Vdc* is the voltage at DC link. The voltages injected by the IPFC converters in d-q coordinates are obtained as follows:

$$V_{se1d} = -x_{t1}I_{1q} + \frac{v_{dc}}{2}m_1\cos\theta_1$$

$$V_{se1q} = x_{t1}I_{1d} - \frac{v_{dc}}{2}m_1\sin\theta_1$$

$$V_{se2d} = -x_{t2}I_{2q} + \frac{v_{dc}}{2}m_2\cos\theta_2,$$

$$V_{se2q} = x_{t2}I_{2d} + \frac{v_{dc}}{2}m_2\sin\theta_2$$

$$V_{sei} = V_{seid} + jV_{seiq} = V_{sei}e^{j\theta} \quad (5)$$

Where *Vse i* , *i1*, 2 is the complex controllable series injected voltage, *xt*1 and *xt*2 are the reactance's of the trans- formers in line 1 and 2.

B. Power System Linear Model

The linear Heffron-Phillips model of SMIB system installed with IPFC is obtained by linearizing the non linear model around an operating condition, which is obtained from power flow analysis [19]. The linearized model obtained is given as:

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$$\Delta\dot{\omega} = \frac{(\Delta P_m - \Delta P_e - D\Delta\omega)}{M} \tag{7}$$

$$\Delta\dot{\delta} = \omega_o \Delta\omega \tag{8}$$

$$\Delta\dot{E}'_q = \frac{-\Delta E_q + \Delta E_{fd}}{T'_{do}} \tag{9}$$

$$\Delta\dot{E}_{fd} = \frac{-\Delta E_{fd} + K_a(\Delta V_{ref} - \Delta V_t)}{T_a} \tag{10}$$

$$\Delta\dot{V}_{dc} = K_7\,\Delta\delta + K_8\,\Delta E'_q - K_9\,\Delta V_{dc} + K_{cm1}\,\Delta m_1 + K_{c\theta 1}\,\Delta\theta_1 + K_{cm2}\,\Delta m_2 + K_{c\theta 2}\,\Delta\theta_2 \tag{11}$$

where

$$\Delta P_e = K_1\,\Delta\delta + K_2\,\Delta E'_q + K_{pv}\,\Delta V_{dc} + K_{pm1}\,\Delta m_1 + K_{p\theta 1}\,\Delta\theta_1 + K_{pm2}\,\Delta m_2 + K_{p\theta 2}\,\Delta\theta_2 \tag{12}$$

$$\Delta E_q = K_4\,\Delta\delta + K_3\,\Delta E'_q + K_{qv}\,\Delta V_{dc} + K_{qm1}\,\Delta m_1 + K_{q\theta 1}\,\Delta\theta_1 + K_{qm2}\,\Delta m_2 + K_{q\theta 2}\,\Delta\theta_2 \tag{13}$$

$$\Delta V_t = K_5\,\Delta\delta + K_6\,\Delta E'_q + K_{vv}\,\Delta V_{dc} + K_{vm1}\,\Delta m_1 + K_{v\theta 1}\,\Delta\theta_1 + K_{vm2}\,\Delta m_2 + K_{v\theta 2}\,\Delta\theta_2 \tag{14}$$

The model has 28 K-constants. These constants are functions of system parameters and the initial operating condition.

C. State space Model

In state-space representation, the power system can be modeled as

$$X = AX + BU \tag{15}$$

where the state vector and control vector are as follows:

$$X = [\Delta\delta \quad \Delta\omega \quad \Delta E'_q \quad \Delta E_{fd} \quad \Delta V_{dc}]^T$$

$$U = [\Delta m_1 \;\; \Delta\theta_1 \;\; \Delta m_2 \;\; \Delta\theta_2]^T \tag{16}$$

The system matrix and control matrix are:

$$A = \begin{bmatrix} 0 & \omega_o & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & -\frac{K_{pv}}{M} \\ -\frac{K_4}{T'_{do}} & 0 & -\frac{K_3}{T'_{do}} & \frac{1}{T'_{do}} & -\frac{K_{qv}}{T'_{do}} \\ -\frac{K_a K_5}{T_a} & 0 & -\frac{K_a K_6}{T_a} & -\frac{1}{T_a} & -\frac{K_a K_{vv}}{T_a} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \frac{K_{pm1}}{M} & \frac{K_{p\theta 1}}{M} & \frac{K_{pm2}}{M} & \frac{K_{p\theta 2}}{M} \\ -\frac{K_{qm1}}{T'_{do}} & -\frac{K_{q\theta 1}}{T'_{do}} & -\frac{K_{qm2}}{T'_{do}} & -\frac{K_{q\theta 2}}{T'_{do}} \\ -\frac{K_a K_{vm1}}{T_a} & -\frac{K_a K_{v\theta 1}}{T_a} & -\frac{K_a K_{vm2}}{T_a} & -\frac{K_a K_{v\theta 2}}{T_a} \\ K_{cm1} & K_{c\theta 1} & K_{cm2} & K_{c\theta 2} \end{bmatrix}$$

and $\Delta m1$ is the deviation in pulse width modulation index $m1$ of voltage series converter 1 in line 1. By controlling $m1$, the magnitude of series injected voltage in line 1 can be controlled. $\Delta m2$ is the deviation in pulse width modulation index $m2$ of voltage series converter 2 in line 2. By controlling $m2$, the magnitude of series injected voltage in line 2 can be controlled. $\Delta m1$ is the deviation in phase angle of the injected voltage $Vse1$. $\Delta m2$ is the deviation in phase angle of the injected voltage $Vse\ 2$. Fig. 2 shows the modified Phillips-Heffron transfer function model of the system incorporating IPFC. The model has 28 constants similar to SMIB model with UPFC [5]. These constants are functions of system parameters and the initial operating condition. It should be noted that $K\,p$,Kq ,Kv and Kc in Fig. 2 are the row vectors defined as

$K\,p = [K\,pm1\ K\,p\theta 1\ K\,pm2\ K\,p\theta 2]$
$K\,q = [Kqm1\ K\,q\theta 1\ Kqm2\ K\,q\theta 2]$
$K\,v = [Kvm1\ K\,v\theta 1\ Kvm2\ K\,v\theta 2]$
$K\,c = [Kcm1\ K\,c\theta 1\ Kcm2\ K\,c\theta 2]$

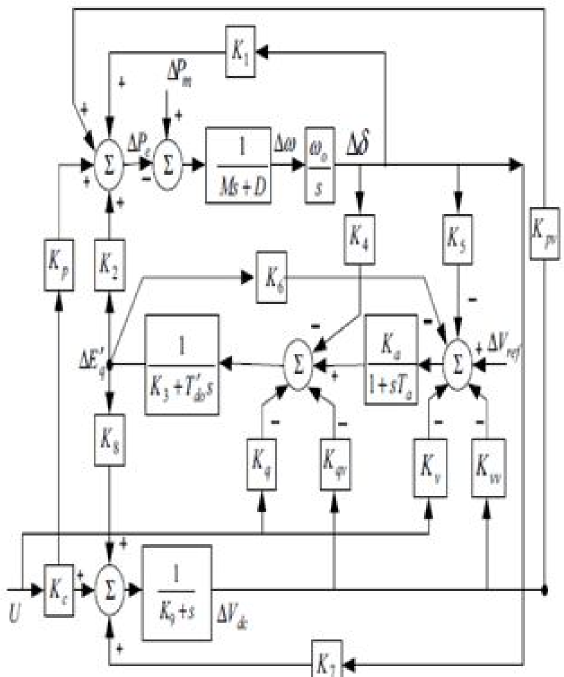

Fig:2 Modified hefron Philips model SIMB with IPFC

D. Computation of Constants of the Power System

The initial d-q axes voltage and current components computed for the nominal operating point (Pe =0.8 $p.u.$, Qe=0.4 $p.u.$, Vt=1.0, Vb=1.0 $p.u.$) are as follows:

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$$V_{do} = 0.3610 \qquad V_{qo} = 0.9326$$
$$I_{do} = 0.6618 \qquad I_{qo} = 0.6017$$
$$\delta_o = 53.1301^0 \qquad V_{se1o} = 0.1328$$
$$\theta_{1o} = 71.565^0 \qquad \theta_{2o} = 4.44^0$$

The system is linear zed about this operating point. The K-constants for the system installed with IPFC, are computed as fallows:

$$K_1 = 2.0552 \qquad K_2 = 0.0413 \qquad K_3 = 0.7333$$
$$K_4 = 0 \qquad K_5 = 0.0185 \qquad K_5 = 0.0001$$
$$K_7 = -0.0885 \qquad K_8 = -0.1088 \qquad K_9 = 7.6663\times10^{-4}$$
$$K_{pv} = 0.0672 \qquad K_{qv} = -0.0087 \qquad K_{vv} = -0.0116$$
$$K_{pm1} = 0.0552 \qquad K_{p\delta1} = 0.0376 \qquad K_{pm2} = 0.2530$$
$$K_{p\delta2} = -0.0045 \qquad K_{qm1} = -0.0326 \qquad K_{q\delta1} = 0.0010$$
$$K_{qm2} = 0.0056 \qquad K_{q\delta2} = 0.0033 \qquad K_{vm1} = -0.0350$$
$$K_{v\delta1} = -0.0029 \qquad K_{vm2} = -0.0038 \qquad K_{v\delta2} = -0.0021$$
$$K_{cm1} = 7.6663\times10^{-4} \qquad K_{c\delta1} = 0.0672 \qquad K_{cm2} = -0.0087$$
$$K_{c\delta2} = -0.0116$$

E. Design of Damping Controllers

The damping controllers are designed to provide an additional electrical torque in phase with the speed Deviation. The speed deviation isΔw considered as the input to the damping controller whose output is used to modulate the controlled parameter $m2$ which controls the series voltage injected in line 2. It is assumed that, for the series converter in line 2, the active power flow control constraint is used while the Reactive power flow constraint is relaxed. The structure of IPFC based damping controller is shown in Fig. 3. It consists of gain, signal washout and phase compensation blocks.

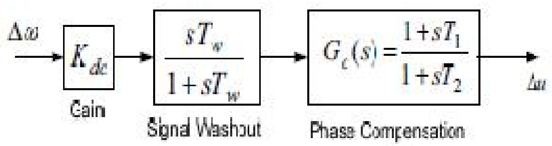

Figure 3: IPFC based damping controller

The parameters of the damping controller are determined using the phase compensation technique [13]. The magnitude and phase angle of transfer function, $\Delta Pe / \Delta m2$ is computed for $s = j\omega n$ at nominal operating condition where $\omega = \sqrt{(k1\omega 0)}/M$ The gain setting of the damping controller is chosen to achieve required damping ratio equal to 0.5. The time constants computed to compensate the phase angle of the transfer function ΔPe / $\Delta m2$ for the system at $s = 6.7314i$ are $T1 = 0.1478s$ and $T2 = 0.1493s$. The gain setting Kdc is equal to 511.0965. The value of Tw (the washout filter time constant) is chosen as 20s which should be high enough to pass low frequency oscillations unchanged. Then, the dynamic performance of the system is investigated with the designed controller while varying the loading conditions and the equivalent line reactance xe over the range of $\pm20\%$ from its nominal value considering a step perturbation $\Delta Pm = 0.01 p.u.$

III. RESULTS AND DISCUSSION

To examine the effect of IPFC based damping controller on the system, simulations are performed Using Matlab simulink on the system, first without IPFC and then, with IPFC and damping controller. The K constants for the system without IPFC are computed which are given as follows:

$k1$=1744 $k2$=0.1706 $k3$=0.7182
$k4$=0.2884 $k5$=0.7385 $k6$=0.8467

Using these values the Phillips-Heffron linear model of the single machine infinite bus without IPFC is simulated in Mat lab. The response of change in speed $\Delta\omega$ for the system when there is no IPFC is given in Fig 4. Which indicates the system is unstable and requires additional damping to sustain the oscillation.

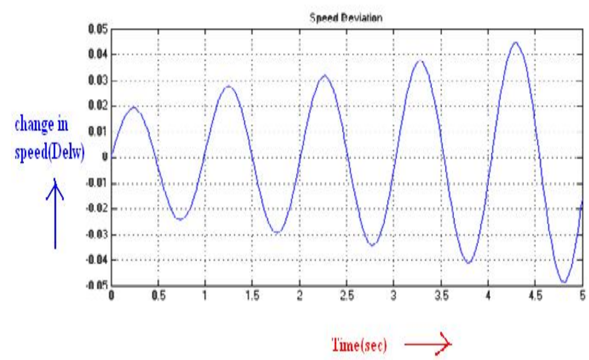

Figure 4. Dynamic response for $\Delta\omega$without IPFC

The system is incorporated with IPFC and the operating point is obtained from load flow. The K constants are computed using the system parameters and initial operating point, as given in section C and the system is simulated. The response of Δw for the system with the IPFC based damping controller included. It shows the damping controller provides satisfactory performance at the nominal operating condition. The robustness of the damping controller designed at the nominal operating point is examined by varying the loading conditions of the system. The load condition of the system is varied from Pe=0.1 to Pe=1.0. The dynamic responses of the system are obtained for each loading condition.

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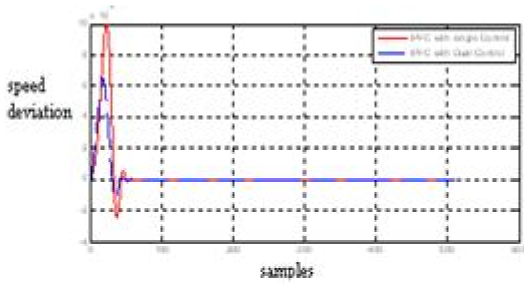
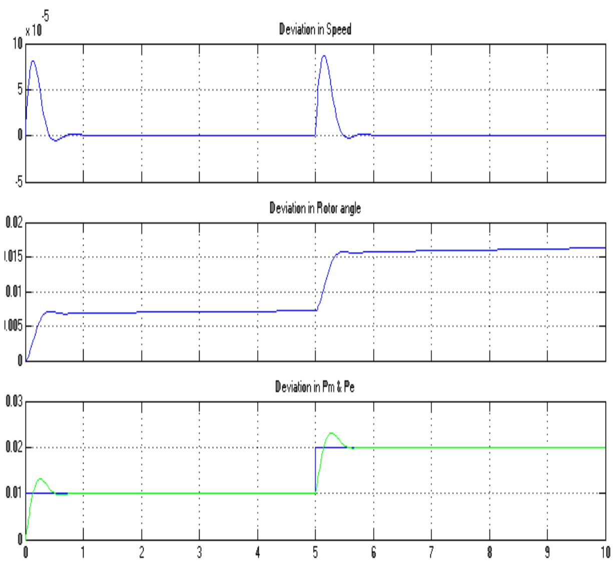
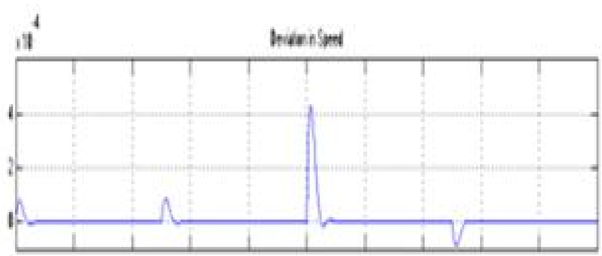


Figure:5 comparision of dual damping controller with single damping contoller

Compare to single controller damping of oscillations for dual controller is more efficient. Dual Damping controller is damped out oscillations less than single damping control system

If any sudden load changes present at generator rotor makes oscillations in generator. if such oscillations also cause in stability. by using IPFC damping controller reduce the oscillations with out change in stability. If change in mechanical power also does not effect the system stability. The change in speed and rotor angel with respect to change in mechanical variations as shown in fig:6





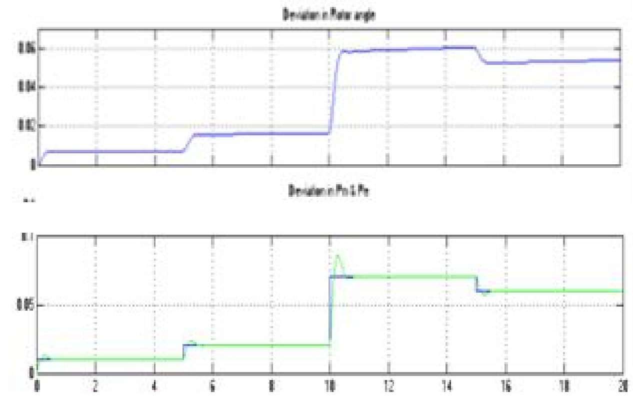
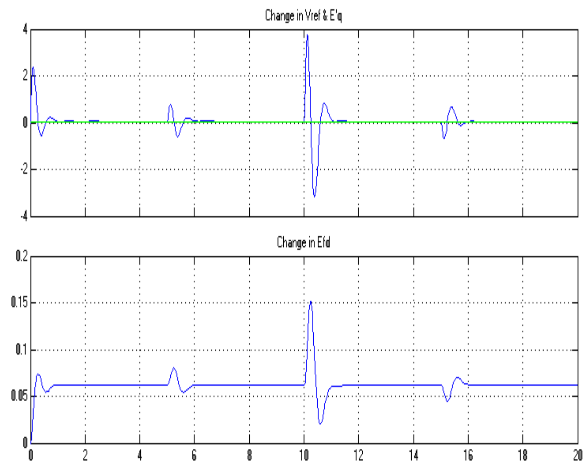


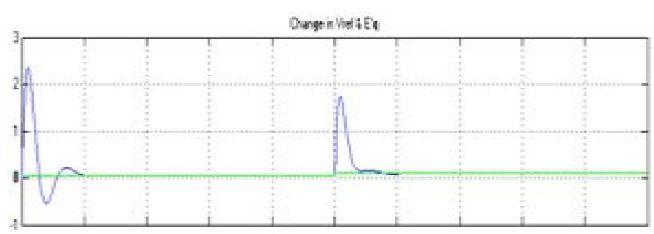
FIG:6:DYNAMIC RESPONCES OF DUAL CONTROLLER

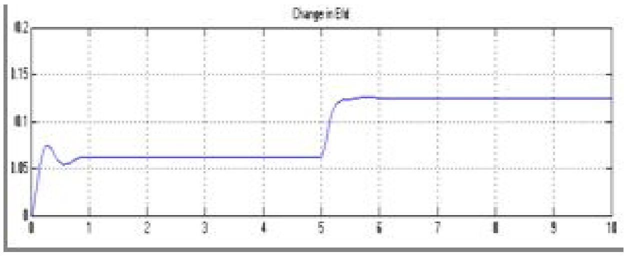
Dual response of dual controller can be seen that the responses are similar in terms of settling time which indicates that the damping provided than single controller and also shows the vide variation in variation of load power. damping controller provides satisfactory performance under wide variation in loading conditions.

Dynamic response of change in rotor angle and speed against step load power variations



Dynamic change in E'q and Efd against load power variations





Even though if change in load power variations also system regain its stability. The damping controller provides a satisfactory response even with variation of load power

IV. CONCLUSION

The effectiveness of the IPFC based damping controller has been investigated in damping low frequency oscillations. Controllability index is utilized to determine the most effective damping control signal for the design of IPFC damping controller. dual damping controller is more efficient damping provided than single controller and also shows the vide variation in variation of load power.

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