UPFC Based Damping Controller on A Single Machine Infinite Bus System (SMIB)

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Abstract—**Effectiveness and robustness of the damping function of the UPFC among which the selection of effective and robust input control signals of the UPFC to superimpose its damping function are the basic issues which are discussed. The investigations reveal that the damping controllers based on UPFC control parameters □E and □B provide robust performance to variations in system loading and equivalent reactance Xe.**

I. INTRODUCTION

The control of AC power system in real time is involved because power flow is a function of the transmission line impedance, the magnitude of the sending end & receiving end voltage, and the phase angle between these voltages. Years ago, electric power systems were relatively simple & were designed to be self sufficient, power exportation & importation were rare. Furthermore, it was generally understood that AC transmission systems could not be controlled fast enough to handle dynamic system conditions. Transmission system designed with fixed or mechanically switched series & shunt reactive compensations, together with voltage regulating & phase shifting transformer tap changer, to optimize line impendence, minimize voltage variations, the control power flow under steady state or slowly changing load condition.

UPFC is the most comprehensive multivariable flexible ac transmission system(FACTS)controller. Simultaneous control of multiple power system variables with UPFC posses Enormous difficulties. In addition, the complexity of the UPFC control increases due to the fact that the controlled and the control variables interact with each other. The Unified Power Flow Controller (UPFC) is a novel power transmission controller. The UPFC provides a full dynamic control of transmission parameters, voltage, line impedance and phase angle.

This paper gives sets of equations for a system including the UPFC and an equivalent two bus power network. Moving through the project, it was found that a Matlab tool would be very useful step between rule of thumb and the comprehensive modeling. This paper presents UPFC analysis technique, Matlab codes, examples of application and validation. The Matlab code given in the paper allows to perform fast parametric studies for the application of the UPFC

We design the linearised Phillips-Heffron model of a power system installed with an UPFC, which is of the same configuration as that of the unified model for static VAr compensator (SVS), thyristor-controlled series compensator (TCSC) and thyristor-controlled phase shifter (TCPS). selection of robust operating condition for designing damping controller; and the choice of parameters of UPFC (such as m_B ,m_E ,δ_E ,δ_B) are to be modulated for achieving desired damping are the basic issues pertaining to the design of UPFC damping controller,.

II. UNIFIED POWER FLOW CONTROLLER

In recent years. Advances in the high power solid-state switches. e.g. Gate Turn Off (GTO) thyristor, have led to the development of transmission controllers that provide controllability and flexibility for power transmission. A new technology program is known as Flexible AC Transmission System (FACTS) is currently sponsored by (EPRI) .This technological program has resulted in successful demonstration of a couple of FACTS Controllers: **208** Mvar,**500** kV Thyristor Controlled Series Capacitor (TCSC) at BPA's power system and + **100** Mvar. **161** kV Static Synchronous Compensator (STATCOM) at TVA's power system **.** The Unified Power Flow Controller (UPFC) is the latest FACTS controller **.** UPFC provides a dynamic control of transmission parameters, voltage, line impedance and phase angle..American Electric Power (AEP). in a collaborative **R&D** project with EPRI and Westinghouse is implementing a **+160** MVA Unified Power Flow Controller (UPFC).

The Unified Power Flow Controller (UPFC) is one of the FACTS devices, which can control power system Parameters such as terminal voltage, line impedance and phase angle. Therefore, it can be used not only for power flow control, but also for power system stabilizing Control.

Unified Power Flow Controller (UPFC) is a combination of static synchronous compensator (STATCOM) and a Static source.

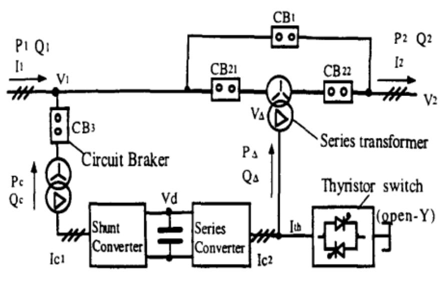

Fig 1.System configuration of the UPFC model

Flexible Alternating Current Transmission Systems (FACTS) devices,namelySTATic Synchronous COMpensator (STATCOM), Static Synchronous Series Compensator (SSSC) .Unified Power Flow Controller (UPFC), are used to control the power flow through an electrical transrnission line connecting various generators and loads at its sending and receiving ends. The UPFC, in this paper and existing references, consists of two solid-state voltage source inverters which are connected through a common DC link capacitor. Each inverter is coupled with a transformer at its output. The first inverter, known as STATic Synchronous COMpensator (STATCOM), injects an almost sinusoidal current, of variable magnitude, at the point of connection. The second inverter, known as Static Synchronous Series Compensator (SSSC) injects an almost sinusoidal voltage, of variable magnitude, in series with the transmission line . When the STATCOM and the SSSC operate as stand-alone: devices, they exchange almost exclusively reactive power at their terminals. While operating both the inverters together as a UPFC, the exchanged power at the terminals of each inverter can be reactive as well as real. The exchanged real power at the terminals of one inverter with the line flows to the terminals of the other inverter through the common DC link capacitor.

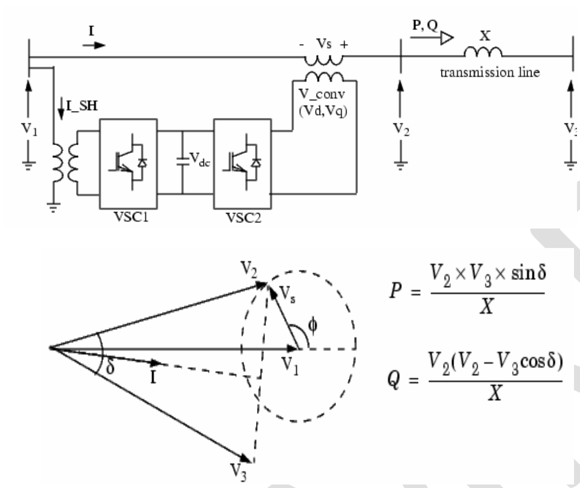

Fig:2 Implementation of the unified power flow controller

Two voltage source inverters (VSI) sharing a common DC storage capacitor. It is connected to the system through two coupling transformers [10]. One voltage source inverter is connected in shunt to the system via a shunt transformer. The other one is connected in series through a series transformer.

The UPFC has several operating modes. Two control modes are possible for the shunt control.

1. Automatic voltage control mode: The aim is to maintain the transmission line voltage at the connection point to a reference value.
2. VAR control mode: The reference input is an inductive or capacitive VAr request.

Four control modes are possible for the shunt control

1. Direct voltage injection mode: The reference inputs are directly the magnitude and phase angle of the series voltage.

2. Phase angle shifter emulation mode: The reference input is phase displacement between the sending end voltage and the receiving end voltage.

3. Line impedance emulation mode: The reference input is an impedance value to insert in series with the line impedance.

4. Automatic power flow control mode: The reference inputs are values of P and Q to maintain on the transmission line despite system changes.

Generally, for damping of power system oscillations, UPFC will be operated in the direct voltage injection mode.

The UPFC control system comprises two controllers.\

1. Power-flow controller
2. Power-system oscillation-damping controller.

III. UPFC MODELLING AND ANALYSIS

Two types of dynamic modelling of UPFC are:

A. Non linear Dynamic Model

Disregarding the resistance of all the components of the system (generator, transformer, transmission lines, and shunt and series converter transformers) and the transients of the transmission lines and transformers of the UPFC ,a non linear dynamic model of the system is derived .The non-linear dynamic model of the system using UPFC is given below.

$$\omega = \frac{(Pm - Pe - D\Delta\omega)}{M} \quad ; \quad \delta = \omega_0(\omega - 1)$$

$$E_q' = \frac{(-E_q + E_{fd})}{T_{do}'} \quad ; \quad E_{fd} = \frac{-E_{fd} + K_a(V_{ref} - V_t)}{T_a}$$

$$V_{dc} = \frac{3m_E}{4C_{dc}}(\sin(\delta_E)\, I_{ED} + \cos(\delta_E) I_{Eq}) + \frac{3m_B}{4C_{dc}}(\sin(\delta_B)\, I_{Bd} + \cos(\delta_B) I_{Bq})$$

Where,

$$P_e = V_{td} I_{td} + V_{tq} I_{tq} \;;\; E_q = E_q' + (X_d - X_d') I_{td}$$

$$V_t = V_{td} + jV_{tq};\; V_{td} = X_q I_{tq};\; V_{tq} = E_q' - X_d' I_{td}$$

$$I_{td} = I_{t1d} + I_{Ed} + I_{Bd};\; I_{tq} = I_{t1q} + I_{Eq} + I_{Bq};$$

$$I_{t1d} = \frac{X_E}{X_T} I_{Ed} + \frac{1}{X_T}\frac{m_E V_{dc}}{2}\cos(\delta_E) - \frac{1}{X_T} V_b \cos(\delta);$$

$$I_{t1q} = \frac{X_E}{X_T} I_{Eq} + \frac{1}{X_T}\frac{m_E V_{dc}}{2}\sin(\delta_E) - \frac{1}{X_T} V_b \sin(\delta);$$

$$I_{Ed} = \frac{(x_{dT} + x_{BB} x_{b3})}{x_{dE}} V_b \cos(\delta) - \frac{(x_{dT} + x_{BB} x_{b2})}{x_{dE}}\frac{m_B V_{dc}}{2}\cos(\delta_E) + \frac{x_{BB}}{x_{dE}} E_q' - \frac{x_{dT}}{x_{dE}}\frac{m_B V_{dc}}{2}\cos(\delta_B);$$

$$I_{Eq} = \frac{(x_{qT} + x_{BB}x_{a3})}{x_{qE}} V_b \sin(\delta) - \frac{(x_{qT} + x_{BB}x_{a2})}{x_{qE}} \frac{m_E V_{dc}}{2} \sin(\delta_E) + \frac{x_{BB}}{x_{dE}} E_q' - \frac{x_{qT}}{x_{qE}} \frac{m_B V_{dc}}{2} \sin(\delta_B);$$

$$I_{Bd} = \frac{1}{x_{dE}} \left(X_E E_q' + (x_{b1} - X_E x_{b2}) \frac{m_E V_{dc}}{2} \cos(\delta_E) + (x_{b3} X_E - x_{b1}) V_b \cos(\delta) + x_{b1} \frac{m_B V_{dc}}{2} \cos(\delta_B) \right);$$

$$I_{Bq} = \frac{1}{x_{qE}} \left((x_{a1} - X_E x_{a2}) \frac{m_E V_{dc}}{2} \sin(\delta_E) + (x_{a3} X_E - x_{a1}) V_b \sin(\delta) + x_{a1} \frac{m_B V_{dc}}{2} \sin(\delta_B) \right);$$

$$x_{dT} = X_{tE} + X_d'; \; x_{qT} = X_q + X_{tE}; \; x_{ds} = X_{tE} + X_d' + X_E; \;\; x_{qs} = X_q + X_{tE} + X_E;$$

$$x_{a1} = \frac{(x_{qs} X_T + x_{qt} X_E)}{X_T}; \; x_{a2} = 1 + \frac{x_{qT}}{X_T}; \; x_{a3} = -\frac{x_{qT}}{X_T};$$

$$x_{b1} = \frac{(x_{ds} X_T + x_{dT} X_E)}{X_T}; \; x_{b2} = 1 + \frac{x_{dT}}{X_T}; \; x_{b3} = \frac{x_{dT}}{X_T};$$

$$\text{Re}\,(V_B I_B^* - V_E I_E^*) = 0$$

This is the equation for the real power balance between the series and shunt converters.

B. Linear Dynamic Model (modified Heffron-Phillips model of an single machine infinite bus system including UPFC)

A linear dynamic model is obtained by linearising the non-linear model around an operating condition. The linearised model is given below:

$$\Delta\omega = \frac{(\Delta P_m - \Delta P_e - D\Delta\omega)}{M} \quad ; \quad \Delta\delta = \omega_o \Delta\omega$$

$$\Delta E_q' = \frac{(-\Delta E_q + \Delta E_{fd})}{T_{do}'}$$

$$\Delta E_{fd} = \frac{-\Delta E_{fd} + K_a(\Delta V_{ref} - \Delta V_t)}{T_a}$$

The modified Heffron-Phillips model has 28 constants as opposed to 6 constants in the Heffron-Phillips model. These constants are functions of the system parameters and the initial operating condition. Fig.2 shows the modified Heffron-Phillips transfer function model of the system including UPFC. The equations for computing the constant of the model are given below. The control vector u is defined as follows:

$$\Delta V_{dc} = K_7\Delta\delta + K_8\Delta E_q' - K_9\Delta V_{dc} + K_{ce}\Delta m_E + K_{c\delta e}\Delta\delta_E + K_{cb}\Delta m_B + K_{c\delta b}\Delta\delta_B$$

Where,

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E_q' + K_{p\delta b}\Delta\delta_B + K_{pe}\Delta m_E + K_{p\delta e}\Delta\delta_E + K_{pb}\Delta m_B + K_{pd}\Delta V_{dc}$$

$$\Delta E_q = K_4\Delta\delta + K_3\Delta E_q' + K_{qe}\Delta m_E + K_{q\delta e}\Delta\delta_E + K_{qb}\Delta m_B + K_{q\delta b}\Delta\delta_B + K_{qd}\Delta V_{dc}$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E_Q' + K_{ve}\Delta m_E + K_{v\delta e}\Delta\delta_E + K_{vb}\Delta m_B + K_{v\delta b}\Delta\delta_B + K_{vd}\Delta V_{dc}$$

$$u = [\Delta m_B \quad \Delta m_E \quad \Delta\delta_E \quad \Delta\delta_B]^T$$

Where,

Δm_B = Deviation in pulse width modulation index m_B of series inverter. By controlling m_B, the magnitude of series-injected voltage can be controlled.

$\Delta\delta_B$ = Deviation in phase angle of the injected voltage

Δm_E = Deviation in pulse-width modulation index m_E of the shunt inverter. By controlling m_E the output, voltage of the shunt converter is controlled.

$\Delta\delta_E$ = Deviation in phase angle of the shunt-inverter voltage.

The series and shunt converters are controlled in a coordinated manner to ensure that the real power input to the series converter. The fact that the DC voltage remains constant ensures that this equality is maintained.

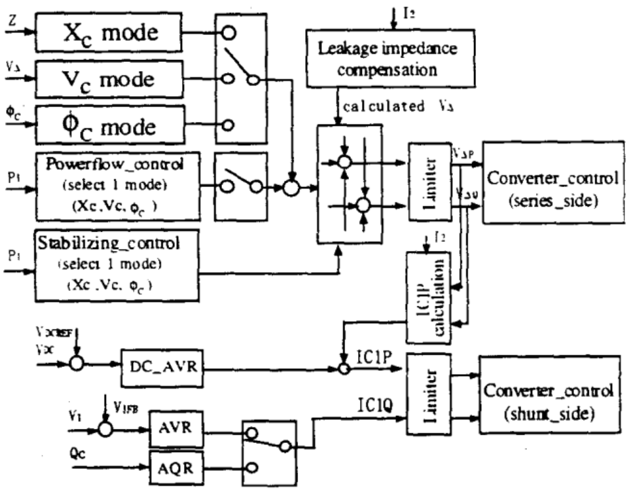

Fig 3.Control scheme of UPFC Model

It may be noted that K_{pu}, K_{qu}, K_{vu} and K_{cu} in Fig.3 are the row vectors defied below:

$$K_{pu} = [K_{pe} \;\; K_{p\delta e} \;\; K_{pb} \;\; K_{p\delta b}];$$
$$K_{qu} = [K_{qe} \;\; K_{q\delta e} \;\; K_{qb} \;\; K_{q\delta b}];$$
$$K_{vu} = [K_{ve} \;\; K_{v\delta e} \;\; K_{vb} \;\; K_{v\delta b}];$$
$$K_{cu} = [K_{ce} \;\; K_{c\delta e} \;\; K_{cb} \;\; K_{c\delta b}];$$

Where $u = [\Delta m_B \quad \Delta m_E \quad \Delta\delta_E \quad \Delta\delta_B]^T$ is a column vector

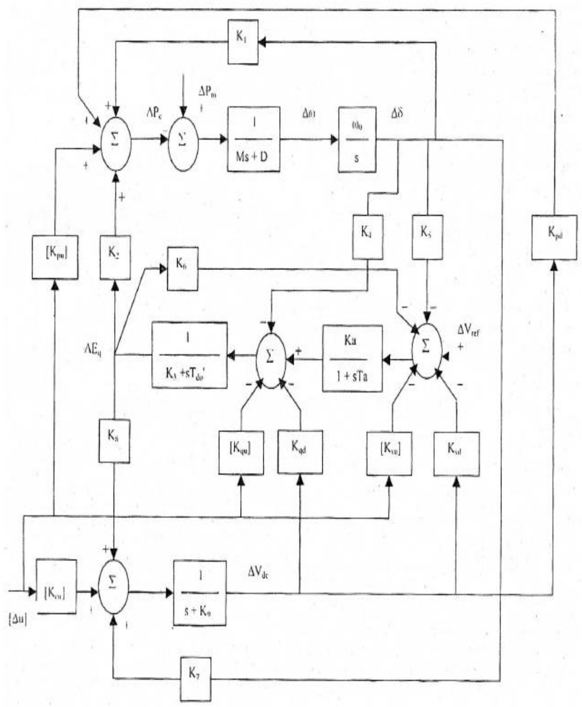

Fig. 4 UPFC Based Modified Heffron-Phillips model of SMIB system

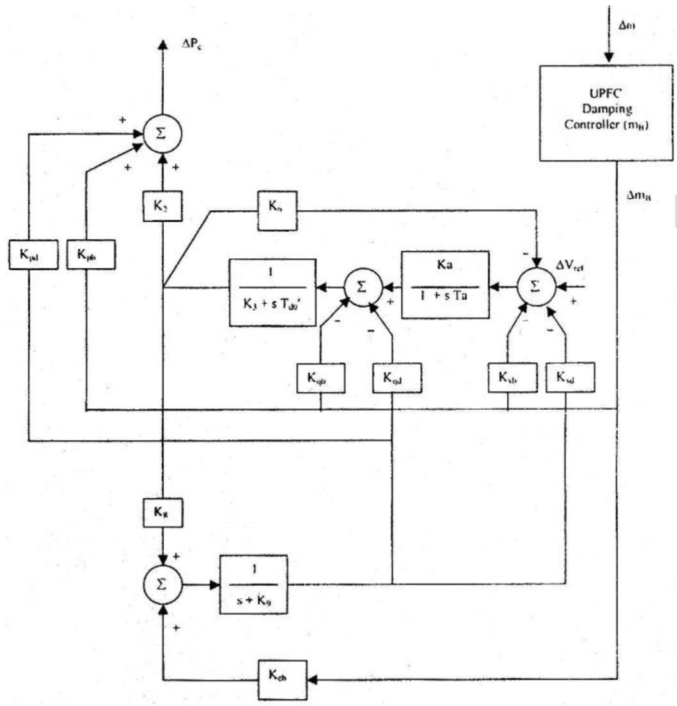

Fig 5. Transfer function of the system relating component of electrical power (ΔPe) produced by damping controller (m_B).

IV. DAMPING CONTROLLERS DESIGNING

Designing of damping controllers is done to produce an electrical torque in phase with the speed deviation. The four control parameters of the UPFC are there (i.e, m_B, m_E, δ_B and δ_E) which can be modulated in order to produce the damping torque. The four alternative UPFC based damping controllers are examined in the present work The speed deviation Δω is considered as the input to the damping controllers. Damping controller based on UPFC control parameter m_B shall henceforth by denoted controller (m_B). Similarly damping controllers based on m_E, δ_B and δ_E shall henceforth be denoted as damping controller (m_E), damping controller (δ_B), and damping controller (δ_E), respectively. The parameters of the damping controller are obtained using the phase compensation technique.The block diagram of UPFC based damping controller is shown in Fig.6. It consists of gain, signal washout and phase compensator blocks..

The detailed systematic procedure for computing technique is given below:

1. Calculation of natural frequency of oscillation ωn from the mechanical loop.

$$\omega n = -\sqrt{\frac{\text{K1}\omega 0}{\text{M}}}$$

2. Calculation of Phase lag between Δ u and ΔPe at s = j ωn i.e ∠GEPA. Let it be γ .
3. Design of phase lead/lag compensator Gc.
4. For 100% phase compensation the phase lead/lag compensator Gc is designed to provide the required degree of phase compensation. ∠Gc(j ωn) + ∠GEPA(j ωn) =0 Assuming T1 =aT2 in one lead-lag network,, the transfer function of the phase compensator becomes,

$$G_c\,(s) = \frac{1+saT2}{1+sT2}$$

Since the phase angle compensated by the lead-lag network is equal to – γ, the parameters a and T2 are computed as,

$$a = \frac{1+\sin\gamma}{1-\sin\gamma}; \qquad T2 = \frac{1}{\omega n\,\sqrt{a}}$$

5. Computation of optimum gain K_d: The required gain setting Kdc for the desired value of damping ratio $\zeta = 0.5$ is obtained as,

$$\text{Kdc} = \frac{2\zeta\omega\,\text{nM}}{|\text{Gc (s)}||\text{GEPA (s)}|}$$

Where $|\text{Gc(s)}|$and$|\text{GEPA(s)}|$ are evaluated at s = j ωn.

The value of the washout time constant Tω should be high enough to allow signals associated with oscillations in rotor speed to pass unchanged. The single washout is the high pass filter that prevents steady changes in the speed from modifying the UPFC input parameter. The value of Tω is not critical and may be in the range of 1s to 20s . Tω equal to 10s is chosen in the present studies.

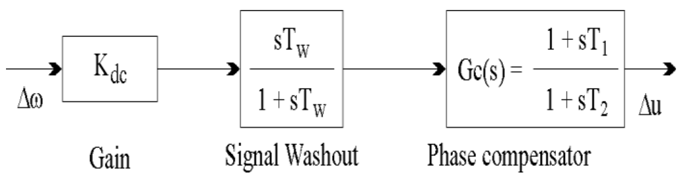

Fig 6 Structure of UPFC based damping controller

V. SIMULATION RESULT

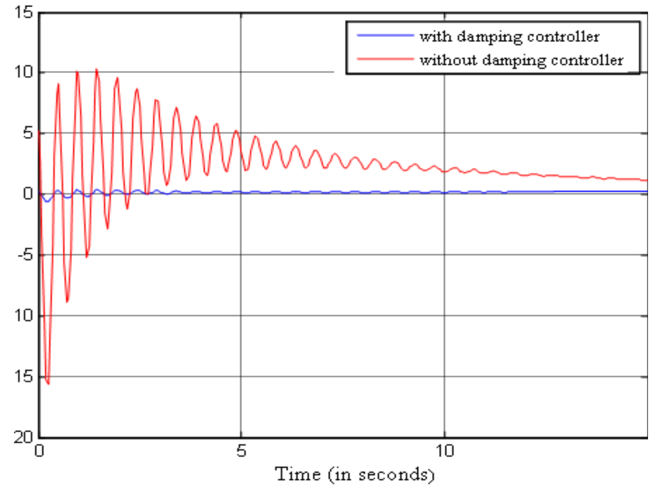

Fig.7 The UPFC controller having load Pe=1 with and without damping controller m_E

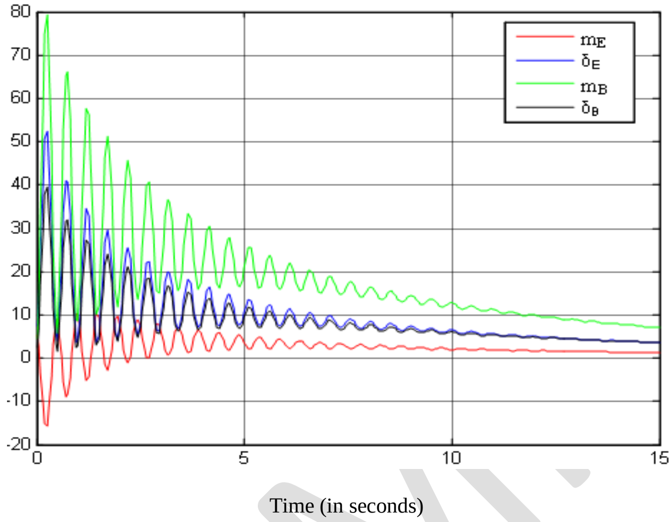

Fig.8 Dynamic responses of four UPFC damping controller with Pe =1

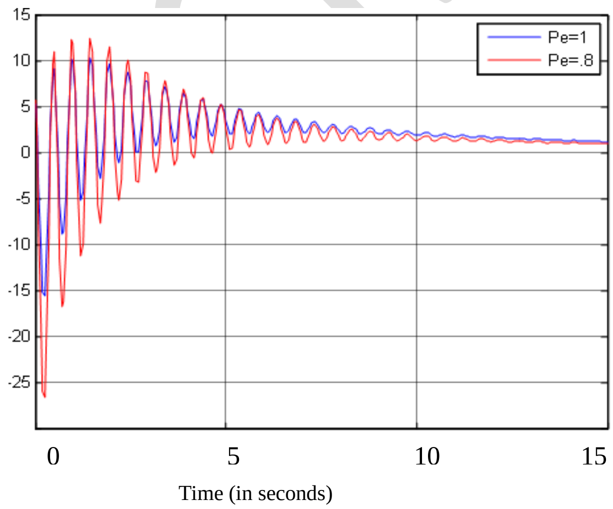

Fig.9 Dynamic response of mE damping controller with wide variation in loading

VI. EFFECT OF VARIATION OF LOADING CONDITION ON THE DYNAMIC PERFORMANCE OF THE SYSTEM

In any power system ,the operating load varies over a wide range .It is extremely impoprtatant to investigate the effect of variation of the load conditions on the dynamic performance of the system.

Loading of the system is varied for Pe=1 and Pe=0.8 and the dynamic responses are obtained for each of the loading condition considering parameters of the damping controllers computed at nominal operating condition for the step load perturbation in mechanical power (ie, $\Delta Pm = 0.01$ pu).in order to examine the robustness of the damping controllers to wide variation in the loading condition.

CONCLUSION

The significant contributions of the research work presented are as follows.A systematic and comprehensive approach to designing UPFC controllers has been presented.The relative effectiveness of UPFC control signals (m_E, m_B, δ_E ,) in damping low-frequency oscillations has been examined. Investigations have revealed that UPFC control signal δ_E and δ_B provide robust performance to wide variation in loading conditions. In near future ,the project can be extended to multi machine model.

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APPENDIX

List of symbols:

C_{dc} : dc link capacitance
D : damping constant
H : inertia constant (M=2H)
K_a :AVR gain
K_{dc} : gain of damping controller
m_B : modulation index of series converter
m_E : modulation index of shunt converter
P_e : electrical power of the generator
P_m : mechanical power input to the generator
T_a : time constant of AVR
T_{do} : d-axis open circuit time-constant of generator
T_1,T_2 : time constant of phase compensator
V_b: infinite bus voltage
V_{dc} : voltage at dc link
V_t : terminal voltage of the generator
X_B : reactance of boosting transformer
X_d : direct axis steady-state synchronous reactance of generator
X'_d : direct axis transient synchronous reactance of generator
X_E : reactance of excitation transformer
X_e : equivalent reactance of the system
X_q : quadrature axis steady-state synchronous reactance of generator
X_{tE} : reactance of transformer
δ_B : phase angle of series converter voltage
δ_E : phase angle of shunt converter voltage
ω_n : natural frequency of oscillation