Application of Interline Power Flow Controller (IPFC) for Damping Low Frequency Oscillations in Power Systems

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***Abstract*—In this paper, the application of Interline Power Flow Controller (IPFC) in damping of low frequency oscillations is investigated. An extended Heffron-Phillips model of a single machine infinite bus (SMIB) system is used to analyze the damping torque contribution of the IPFC in power systems. The potential of various IPFC control signals upon the power system oscillation stability is investigated under various loading conditions. Simulation results demonstrate the effectiveness of IPFC controllers on damping low frequency oscillations.**

***Index Terms*— IPFC, PID controller, lead-lag controller, power Oscillation damping, genetic algorithm.**

I. Introduction

Present day interconnected power systems consist of a large number of generators 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 low frequency oscillations constrain the capability of power transmission, threaten system security and affect the efficient system 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 importance.

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 [7-14].

Interline power flow controller (IPFC) [15] is a 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 [16], its basic function to control power flow among transmission lines [17] and oscillation damping [18]. Kazemi and Karimi proposed a PI supplementary damping controller for the IPFC for damping inter-area oscillations [18]. However, Further, no effort had been made to identify the most suitable control parameter. A supplementary PID damping controller was proposed in [19], but the performance degraded due to the system nonlinearity and complexity.

Conventional fixed structure power system stabilizers (CPSS) are widely used by power system utilities to damp out small oscillations. CPSS gives optimum performance around a nominal operating point. The tuned parameters of PSS are determined at this point only. However, the performance becomes sub-optimal following the variations in loading conditions and system parameters. The parameters of the power system stabilizer (PSS) must be re-tuned so that it can provide the desired performance. A self –tuning PSSs have been proposed to overcome such problem [20]. However, they are designed on the basis of parameter identification of the system model in real time, feedback gain computation and state observation, which are time consuming and results in computational burden.

Recently, the advanced numerical computation methods such as Artificial Neural Network (ANN), Fuzzy Logic systems (FLS) and Genetic Algorithms (GA) have been applied to various power system problems including PSS design [21-23]. Genetic algorithms are global search techniques which can solve anoptimization problem by miming the mechanism of natural selection and genetics.

In this paper, an SMIB system is utilized to investigate the effectiveness of the IPFC with GA based Lead-lag supplementary damping controller is proposed and simulated.

This is organized as follows; In Section II, the model of the power system including IPFC is explained. The proposed GA based lead- lag controller is explained in Section III. The results of the simulation are finally given in Section IV.

II. SYSTEM MODELING

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. A simple IPFC consisting of two, three phase GTO based voltage source converters (VSC's), each providing a series compensation for the two lines is incorporated in the system. 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.

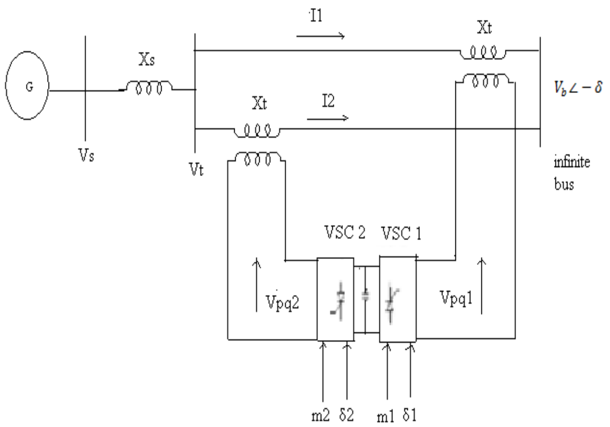


Fig. 1 Single machine connected to infinite bus with IPFC

The equations describing the dynamic performance of the IPFC are[18]

$$\begin{bmatrix} V_{se1d} \\ V_{se1q} \end{bmatrix} = \begin{bmatrix} 0 & -X_T \\ X_T & 0 \end{bmatrix} \begin{bmatrix} i_{1d} \\ i_{1q} \end{bmatrix} + \begin{bmatrix} \dfrac{m_1 \cos(\delta_1) V_{dc}}{2} \\ \dfrac{m_1 \sin(\delta_1) V_{dc}}{2} \end{bmatrix}$$

$$\begin{bmatrix} V_{se2d} \\ V_{se2q} \end{bmatrix} = \begin{bmatrix} 0 & -X_T \\ X_T & 0 \end{bmatrix} \begin{bmatrix} i_{2d} \\ i_{2q} \end{bmatrix} + \begin{bmatrix} \dfrac{m_2 \cos(\delta_2) V_{dc}}{2} \\ \dfrac{m_2 \sin(\delta_2) V_{dc}}{2} \end{bmatrix} \qquad (1)$$

$$\frac{dV_{dc}}{dt} = \frac{3m_1}{4c_{dc}} \begin{bmatrix} \cos\delta_1 & \sin\delta_1 \end{bmatrix} \begin{bmatrix} i_{1d} \\ i_{1q} \end{bmatrix} + \frac{3m_2}{4c_{dc}} \begin{bmatrix} \cos\delta_2 & \sin\delta_2 \end{bmatrix} \begin{bmatrix} i_{2d} \\ i_{2q} \end{bmatrix}$$

The nonlinear dynamic model of the power system of Fig. 1 is

$$\begin{aligned} \dot{\delta} &= \omega_o(\omega - 1) \\ \dot{\omega} &= \frac{1}{M}(P_m - P_e - P_d) \\ \dot{E}_q^{'} &= \frac{1}{T_{do}^{'}}\left(E_{fd} - (X_d - X_d^{'})I_d - E_q^{'}\right) \qquad (2) \\ \dot{E}_{fd} &= \frac{1}{T_A}\left[K_A(V_{ref} - V_s) - E_{fd}\right] \end{aligned}$$

By combining and linearizing equations (1) and (2), the state variable equations of the power system equipped with the IPFC can be represented as

$$\dot{X} = AX + BU$$

where the state and control vectors are as follows:

$$X = [\Delta\delta \quad \Delta\omega \quad \Delta E_q^{'} \quad \Delta E_{fd} \quad \Delta V_{dc}]^T$$
$$U = [\Delta m_1 \quad \Delta\delta_1 \quad \Delta m_2 \quad \Delta\delta_2]^T$$

The system and control matrices are

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & -\frac{K_{pv}}{M} \\ -\frac{K_4}{T_{do}^{'}} & 0 & -\frac{K_3}{T_{do}^{'}} & \frac{1}{T_{do}^{'}} & -\frac{K_{qv}}{T_{do}^{'}} \\ -\frac{K_a K_5}{T_a} & 0 & -\frac{K_a K_6}{T_a} & -\frac{1}{T_a} & -\frac{K_a K_{vv}}{T_a} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\frac{K_{pm_1}}{M} & -\frac{K_{p\delta_1}}{M} & -\frac{K_{pm_2}}{M} & -\frac{K_{p\delta_2}}{M} \\ -\frac{K_{qm_1}}{T_{do}^{'}} & -\frac{K_{q\delta_1}}{T_{do}^{'}} & -\frac{K_{qm_2}}{T_{do}^{'}} & -\frac{K_{q\delta_2}}{T_{do}^{'}} \\ -\frac{K_a K_{vm_1}}{T_a} & -\frac{K_a K_{v\delta_1}}{T_a} & -\frac{K_a K_{vm_2}}{T_a} & -\frac{K_a K_{v\delta_2}}{T_a} \\ K_{cm_1} & K_{c\delta_1} & K_{cm_2} & K_{c\delta_2} \end{bmatrix}$$

where Δm_1, $\Delta\delta_1$, Δm_2 and $\Delta\delta_2$ are the deviation of input control signals of the IPFC.

III. GA BASED TUNING OF IPFC SUPPLEMENTARY CONTROLLER

GA based lead-lag supplementary controllers are designed so as to control the inputs m_1, δ_1, m_2 and δ_2 of the IPFC for effective damping of low frequency oscillations in order to improve the damping of low frequency oscillations.

The controllers have to produce additional damping torque. The speed deviation Δω is taken as the input to the damping controllers.

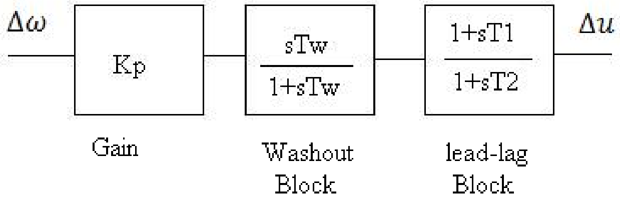


Fig.2 Structure of the supplementary damping controller

A widely used conventional lead-lag block is considered in this study. Its structure is shown in Fig. 2.It consists of a gain block with gain K_P , a signal washout block, and phase compensation block with time constants T_1 and T_2 .In this structure, T_W is the washout time constant Δω is the speed deviation and Δu is the stabilizing signal output of the supplementary damping controller.

GA has been used for optimizing the parameters of the control system that are complex and difficult to solve by conventional optimisation methods. GA maintains a set of candidate solutions called population and repeatedly modifies them. At each step, the GA selects individuals from the current population to be parents and uses them to produce the children for the next generation. Candidate solutions are represented as strings of fixed length, called chromosomes. A fitness function is used to reflect the goodness of each member of the population. Given a random initial population, GA operates in cycles called generations, as follows [21-23]:

- Each member of the population is evaluated using fitness function.
- The population undergoes reproduction in a number of iterations. One or more parents are chosen stochastically, but strings with higher fitness values have higher probability of contributing an offspring.
- Genetic operators, such as crossover and mutation, are applied to parents to produce offspring.
- The off-springs are inserted into the population and the process is repeated.

The choice of suitable performance index is extremely important for the design of GA based lead-Lag supplementary damping controller. In this study, the supplementary controller parameters are coded in a binary string and initial population is randomly generated. The proposed algorithm employs GA to solve this optimization problem and search for the optimum set of supplementary damping controller parameters.

A simple performance index that reflects small steady state error, small overshoots and oscillations is selected. GA search employs Integral Squared Time Square Error (ISTSE) optimization technique. *Δω* is the rotor speed deviation in p.u. following a small perturbation in the system. The performance index (objective function) is defined as

$$J = \int_0^\infty (t\Delta\omega)^2 \, dt$$

The GA parameters used are as shown in Table I.

TABLE I
GA PARAMETERS

Population size	10
Number of variables	4
Generations	10
Crossover fraction	0.8
mutation	0.001

IV. SIMULATION RESULTS

During a step change of 0.01pu in mechanical input power the performance of the designed GA based lead-lag supplementary damping controller and PID controllers have been simulated and compared. Firstly, the IPFC has no controller. For this case the rotor speed deviation response is shown in Figu.4. As this figure shows, the rotor speed deviation is poorly damped.

The optimum parameters of the supplementary damping controller at different IPFC controller inputs are shown in Table-II.

TABLE-II

PARAMETERS OF THE IPFC DAMPING CONTROLLERS

IPFC Controller input	Lead-lag controller Parameters			
	K_P	T_W (s)	T_1 (s)	T_2 (s)
m_1	308.1583	13.2799	0.198	0.0195
m_2	300.2638	9.6307	0.1993	0.0198
δ_1	312.4573	9.1681	0.1986	0.0192
δ_2	323.7909	12.2496	0.1931	0.0144

The simulation is repeated with the same step change in mechanical power input of the synchronous machine, but with the IPFC provides with supplementary damping controllers. In the first case the IPFC is equipped with the conventional PID controller and in the second case the IPFC has GA based lead-lag supplementary controller. The results of simulation for the two cases are shown in Fig. 5. In Fig. 5, the simulation is performed by controlling the input m_2 of the IPFC.

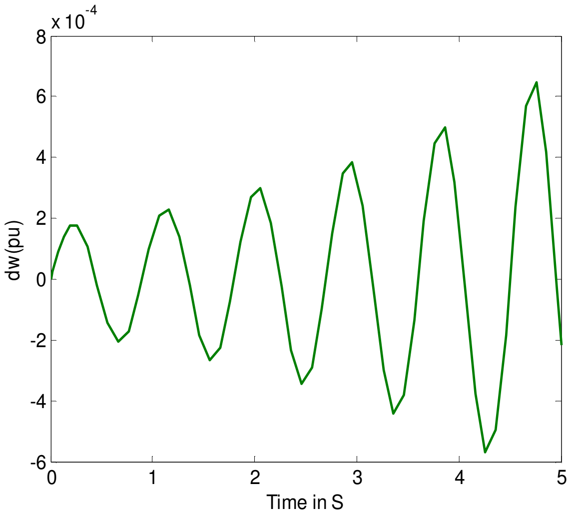


Fig. 4 Low frequency oscillations of power system without any damping controller

Fig.6 to 8 show results of the IPFC based system with IPFC inputs m_1, δ_1 and δ_2 respectively.

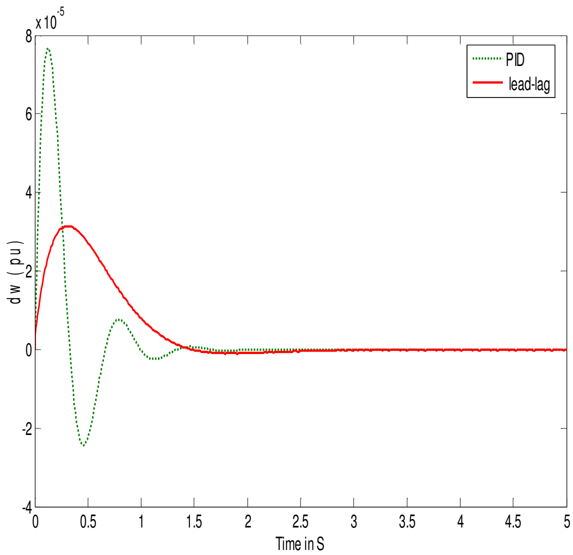


Fig.5 Rotor speed deviation during step change in mechanical input power, dashed line is PID controller response and solid line is GA based lead-lag controller response. (m_2 Controller)

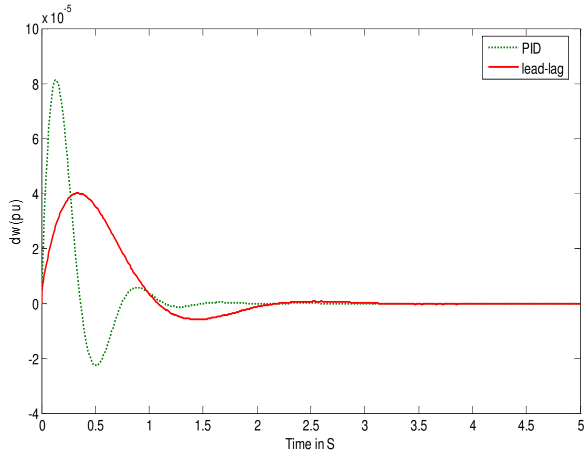


Fig.6 Rotor speed deviation during step change in mechanical input power, dashed line is PID controller response and solid line is GA based lead-lag controller response. (m_1 Controller)

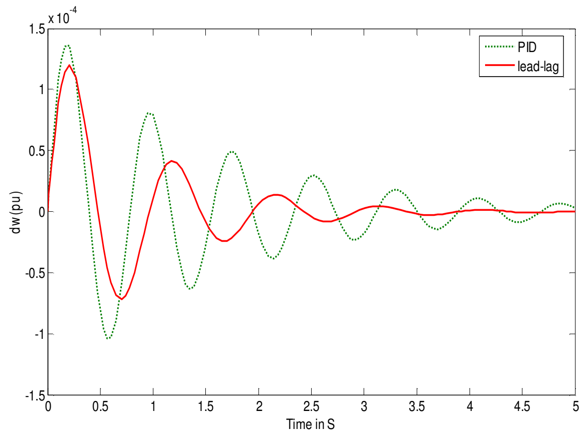


Fig.7 Rotor speed deviation during step change in mechanical input power, dashed line is PID controller response and solid line is GA based lead-lag controller response. (δ_1 Controller)

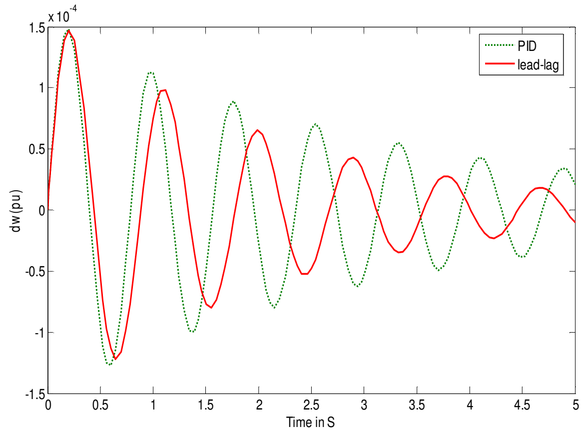


Fig.8 Rotor speed deviation during step change in mechanical input power, dashed line is PID controller response and solid line is GA based lead-lag controller response. (δ_2 Controller)

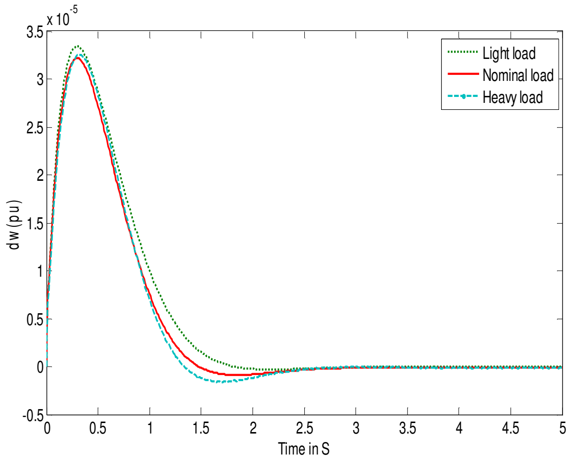


Fig.9 Rotor speed deviation during step change in mechanical input power, under different loading conditions.

Simulation results show that GA based lead-lag supplementary controller successfully increases damping rate and decreases the amplitude of low frequency oscillations. Results comparison between conventional PID controller and the proposed GA based lead-lag supplementary controller for the IPFC indicates that the proposed GA based lead-lag supplementary controller has less settling time and less overshoot and compared with the conventional PID controller. Here m_2 controller is effective then other IPFC controllers.

V. CONCLUSION

The effectiveness of the IPFC based damping controller has been investigated in damping low frequency oscillations. Dynamic simulations results have emphasized that the damping controller which modulates the control signal m_2 provides satisfactory dynamic performance under wide variations in loading condition and system parameters. Further work will be carried on applying the controller design for a multi-machine system.

APPENDIX

The values of the parameters used in the simulation are as follows:

Generator: M=2H=8.0MJ/MVA, D=0

T'_{do} = 5.044s

X_d =1.0pu, X'_d =0.3pu, X_q =0.6pu

Parameters of automatic voltage Regulator (AVR):

K_A =50, T_A =0.05s

Reactances:

X_S =0.15pu, $X_{t_1} = X_{t_2} = X_t$ =0.1pu

$X_{L_1} = X_{L_2} = X_L$ =0.5pu

Operating condition:

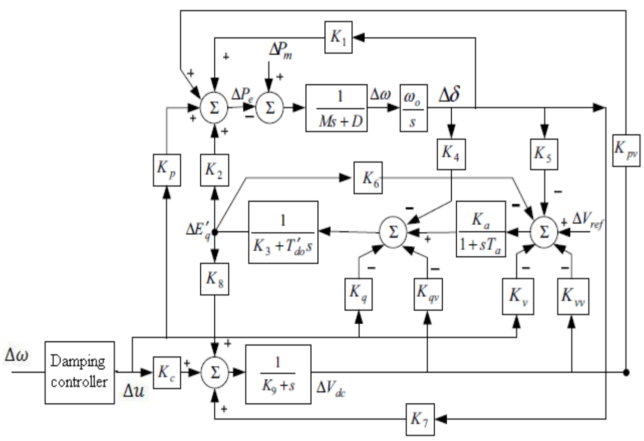
P_e = 0.8 pu (nominal load), V_t = 1 pu, V_o =1 pu
=0.2pu (light load)
=1.2pu (heavy load)

IPFC parameters: m_1 =0.15, m_2 =0.1

DC link: V_{dc} = 2 pu , C_{dc} = 1 pu

K-constants at nominal load:

K_1 = 1.0586 K_2 = 0.7930 K_3 = 1.9333 K_4 =0.6549
K_5 = -0.1210 K_6 = 0.5251 K_7 = -0.0514 K_8 = -0.1070
K_9 = 0.0007385 K_{pv} = -0.0694 K_{qv} = -0.0226 K_{vv} = -0.0013
K_{pm_1} =0.5344 $K_{p\delta_1}$ =0.0403 K_{pm_2} =0.5710 $K_{p\delta_2}$ =0.012
K_{qm_1} =-0.3035 $K_{q\delta_1}$ =0.0532 K_{qm_2} =0.0041 $K_{q\delta_2}$ =0.046
K_{vm_1} =0.044 $K_{v\delta 1}$ =-0.0288 K_{vm_2} =-0.0926 $K_{v\delta_2}$ =-0.017
K_{cm_1} =0.0327 $K_{c\delta_1}$ =0.0188 K_{cm_2} =-0.0715
$K_{c\delta_2}$ =-0.0263



Heffron-Phillips model of SMIB system with IPFC

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