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ANALYSIS AND PERFORMANCE OF INTER LINE POWER FLOW CONTROLLER (IPFC) FOR DAMPING LOW FREQUENCY OSCILLATIONS

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Abstract — *Modeling and simulation of power system equipped with FACTS type Inter Line Power Flow Controller (IPFC) based damping controller introduced in this paper. The investigated system was a Single Machine Infinite Bus (SMIB) for assessing the performance of IPFC based stabilizer in improvement the system stability. Particle Swarm Optimization (PSO) is employed to determine the optimal settings of stabilizing controller using different modulating signals. The candidate signals is selected based on the controllability indices concept. Eigenvalues and nonlinear time domain simulation of power system is then, used to verify the effectiveness of IPFC based damping controller in mitigating the low frequency oscillations (LFO)*

Keywords- *SMIB, IPFC, PSO, LFO, EM.*

I. INTRODUCTION

Nowadays, modern power systems became more stressed and operate closer to their stability limits due to continuous changing of electric power systems operating conditions in addition to unpredicted loading condition. On another hand, usually the Electromechanical Oscillation modes (EM) in powers system follow a disturbance within frequency ranged from 0.2-3 Hz. Mitigating this sustained oscillation is playing key role in increasing the efficiency of power system operation in addition to ideal utilizing of existed facilities. This oscillations can be divided into two major types based on the frequency range: local mode which frequency ranged from 0.9-3.0 Hz while from 0.1-0.8 Hz called inter-area mode. If no sufficient damping available, these oscillations may gradually increase causing instability of power system [1-3].
Recently, Flexile AC Transmission System (FACTS) technology has appeared as a preferred option to assist in fixing many operating difficulties in power system, such as inter-area oscillations, control of voltages magnitude at critical buses and phase angles between the ends of transmission lines in addition to regulate the active transferred lines power and reactive power compensation. [6, 7]. One of emerged FACTS device called Inter Line Power Flow Controller (IPFC), it was proposed by Gyugyi in 1998 that capable of series compensation and power flow management between multi-lines of substation. The IPFC consists of two Voltage Source Converter (VSC) linked together by DC capacitor that help in real power exchanged between two lines. Each one of VSC's can provide controlled series reactive power compensation through controlling magnitude and phase angle of converter. Moreover, it can control in transferred real power between lines through dc terminal. A new function IPFC can performed such like improvement of power system stability and robust control of power flow in transmission network. [4, 5]
A new method based on heuristic algorithm developed in this paper to design and analysis the performance of IPFC to damp the low frequency oscillations of electromechanical modes.

II. POWER SYSTEM MODELLING WITH IPFC

Fig.1 shows a Single Machine Infinite Bus (SMIB) installed with IPFC. It composed of two Boosting Transformers (BT) and two VSC's linked together by DC capacitor. The two VSC's inserted in series with transmission lines through BT's that are controlled by modulation index (m_1, m_2) and phase angle (δ_1, δ_2). Equations from (1-8) represent the SMIB plus IPFC as following:

$$\dot{\delta} = \omega - \omega_s \tag{1}$$

$$\dot{\omega} = \frac{1}{2H}[P_m - P_e - D(\omega - \omega_b)] \tag{2}$$

$$\dot{\acute{E}}_q = \frac{1}{\acute{T}_{d0}}[E_{fd} - (x_d - \acute{x}_d)i_d - \acute{E}_q] \tag{3}$$

$$\dot{E}_{fd} = \frac{1}{T_A}[-E_{fd} + K_A(V_{ref} - V_t + V_S)] \tag{4}$$

$$\dot{V}_{dc} = \frac{3m_1}{4C_{dc}}[\cos\delta_1 \quad \sin\delta_1]\begin{bmatrix} i_{1d} \\ i_{1q} \end{bmatrix} + \frac{3m_2}{4C_{dc}}[\cos\delta_2 \quad \sin\delta_2]\begin{bmatrix} i_{2d} \\ i_{2q} \end{bmatrix} \tag{5}$$

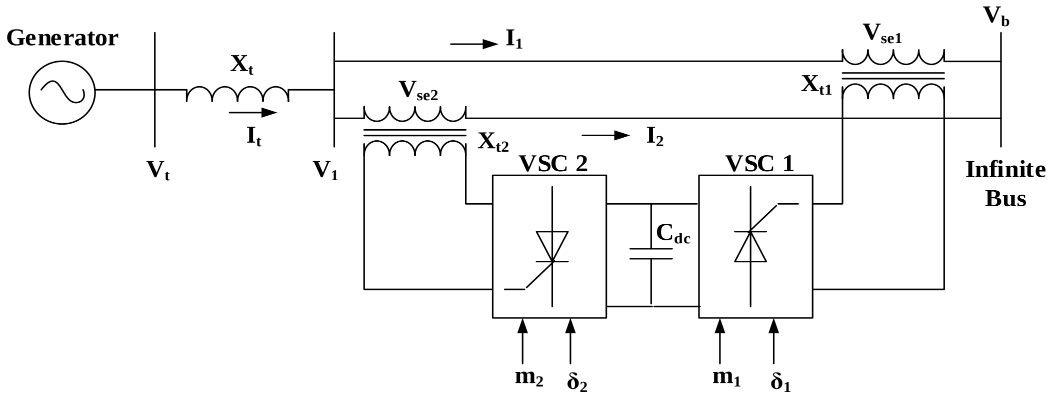

Fig.1: SMIB power system equipped with IPFC.

Equations (10-11) represent the linear model of system, in addition to Heffron Philips model shown in fig.2:

$$[\Delta\dot{X}] = [A][\Delta X] + [B][\Delta U] \tag{10}$$

Where the state and control vectors are as following:

$$[\Delta X] = \left[\Delta \acute{E}_q \quad \Delta\delta \quad \Delta\omega \quad \Delta E_{fd} \quad V_{dc}\right]^T$$
$$[\Delta U] = [\Delta m_1 \quad \Delta\delta_1 \quad \Delta m_2 \quad \Delta\delta_2]^T \tag{11}$$

$$[A] = \begin{bmatrix} \frac{-K_3}{\acute{T}_{do}} & \frac{-K_4}{\acute{T}_{do}} & 0 & \frac{1}{\acute{T}_{do}} & \frac{-K_{qV}}{\acute{T}_{do}} \\ 0 & 0 & \omega_s & 0 & 0 \\ \frac{-K_2}{M} & \frac{-K_1}{M} & \frac{-D\omega_s}{M} & 0 & \frac{-K_{PV}}{M} \\ \frac{-K_A K_6}{T_A} & \frac{-K_A K_5}{T_A} & 0 & \frac{-1}{T_A} & \frac{-K_A K_{VV}}{T_A} \\ K_8 & K_7 & 0 & 0 & -K_9 \end{bmatrix} \qquad [B] = \begin{bmatrix} \frac{-K_{qm1}}{\acute{T}_{do}} & \frac{-K_{q\delta1}}{\acute{T}_{do}} & \frac{-K_{qm2}}{\acute{T}_{do}} & \frac{-K_{q\delta2}}{\acute{T}_{do}} \\ 0 & 0 & 0 & 0 \\ \frac{-K_{Pm1}}{M} & \frac{-K_{P\delta1}}{M} & \frac{-K_{Pm2}}{M} & \frac{-K_{P\delta2}}{M} \\ \frac{-K_A K_{Vm1}}{T_A} & \frac{-K_A K_{V\delta1}}{T_A} & \frac{-K_A K_{Vm2}}{T_A} & \frac{-K_A K_{V\delta2}}{T_A} \\ K_{cm1} & K_{c\delta1} & K_{cm2} & K_{c\delta2} \end{bmatrix}$$

The K-factors calculated at system operates in normal condition.

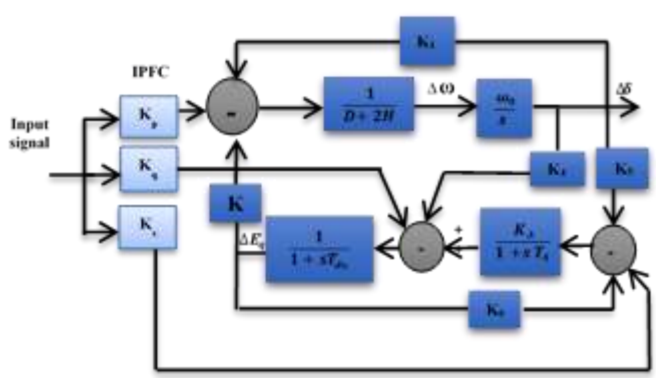

Fig. 2: Linear model representation of SMIB system with IPFC.

III. Damping Controller Structure and Design

The function of damping controller is providing adequate positive damping component to enhance the system stability and overall performance of the system. Fig.3 illustrates the structure of IPFC damping controller, which comprise of three blocks connected in cascade form. Therefore, to design IPFC damping controller whose transfer function given by eq. (12), speed deviation ($\Delta\omega$) is selected as input signal to stabilizing controller while the candidate control signals (Δu) of VSC's are selected based on the controllability indices of each one.

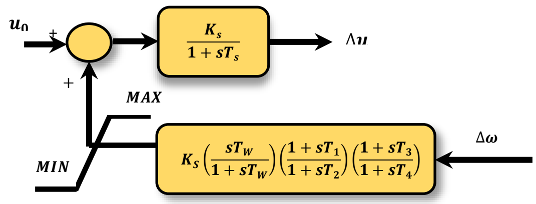

Fig. 3: IPFC Stabilizing Controller Structure.

$$u_{IPFC} = K_s \frac{sT_W}{1+sT_W}\left[\frac{1+sT_1}{1+sT_2}\right]\left[\frac{1+sT_3}{1+sT_4}\right]\Delta\omega \quad (12)$$

The best signal that has the highest controllability index while the worst signal that has the lowest index. Table I illustrates the controllability indices of four choice of input control signals. Obviously the modulation index (Δm_1, Δm_2) for each converter consider as best signal compared with the phase angle of each one. [8]

TABLE I: Controllability Indices of controlled signals

Control Signal	Index
Δm_1	5.8332
$\Delta\delta_1$	0.1649
Δm_2	6.8054
$\Delta\delta_2$	0.2308

IV. PROBLEM FORMULATION.

To determine the optimal setting of controller parameters that, contribute in enhancement of power system stability, an optimization techniques based on POS is proposed. Fitness function (*J*) based on inequality constraint is formulated. The objective of optimization is to maximize to damping ratio above predetermined value. Constraints are defined by gain K_s and time constants T_1-T_4, which are the limits of each controller. To remedy the stabilizing controller problem, two different objective functions are proposed. First objective function is formulated based on eigenvalue that can represented by:

$$J_1 = Max\left({-\sigma}/{\sqrt{\sigma^2+\omega^2}}\right) \quad (13)$$

It's objective to maximize this fitness function to improve the power system stability through increase the damping ratio, while the second one is formulated based on time domain which can represented by:

$$J_2 = Min\left(\int_{t=0}^{t_{sim}} |\Delta\omega|.t \ \ dt\right) \quad (14)$$

It's objective to minimize this fitness function to improve the power system stability through decrease the speed deviation multiplied in selected time. Therefore, design problem can be formulated as:

Optimize J_1 and J_2 Subject to:

$$K_S^{min} \le K_s \le K_S^{max}$$
$$T_1^{min} \le T_1 \le T_1^{max}$$
$$T_2^{min} \le T_2 \le T_2^{max}$$
$$T_3^{min} \le T_3 \le T_3^{max}$$
$$T_4^{min} \le T_4 \le T_4^{max}$$

V. PARTICLE SWARM OPTIMZER (PSO)

Getting the best solutions is one of the goals of using the heuristic algorithms. PSO is deemed one of these algorithms, which, introduced for first time in 1995 by Edward and Kennedy. Representation the social behavior of animals such as bird flocking or fish schooling is main thought behind create this algorithm. This algorithm features by simplicity, flexibility and easy coded in few lines. It starts with a random population (particles) in multi-dimension space. This particles represented by $X_i=(x_{i1}, x_{i2}, \dots x_{in})$ and moves about cost surface with a velocity. Updating the positions and velocities of particles based on the local and global solutions as following: [9]

$$v_i^{new} = wv_i^{old} + c_1 r_1 * \left(P_i^{Local\ best} - P_i^{old}\right) + c_2 r_{2*}(P_i^{global\ best} - P_i^{old}) \quad (15)$$
$$P_i^{new} = P_i^{old} + v_i^{new} \quad (16)$$

Where: c, r are learning factor and independent random uniform numbers respectively. Reference [9] have more details about PSO algorithm and its steps have been implemented in this paper.

VI. SIMULATION AND RESULTS

Proposed PSO algorithm has been implemented to compute the best parameter settings of damping controllers based on m_1 and m_2 as candidate control signals, so that the fitness function is optimized. Table II contains the optimal parameter settings of damping controllers and the corresponding objective function values and, figures (4-5) shows the fitness function curves. Moreover, eigenvalues of system under different loading conditions (*Normal*, *Heavy*, *Light*) which described in Table III have been calculated to verify the validity of proposed method that employed for controller design. Only Electromechanical Modes (EM) are indicated by their frequency and damping ratio with bold line. In addition, nonlinear time domain simulation of system has been carried out when the system subjected to 3-phase short circuit for 5 cycle to prove the effectiveness and robustness of proposed controller. From all that, it is clear of Table IV the damping ratio of system has been increased and the EM eigenvalues shifted to the left s-plane for three different modes of operating conditions. Moreover, the power system became more stable post insertion the damping controller when subjected to unexpected 3-phase fault and the figures (6-11) shows the power system responses at normal loading condition.

TABLE II: Optimal Parameters settings of damping controller

	m₁		***m₂***	
	J₁	***J₂***	***J₁***	***J₂***
K_s	18	300	18	100
T_1	1.5	1.5	1.5	1.1108
T_2	0.5472	1.5	0.5430	0.6620
T_3	1.5	1.5	1.5	1.4980
T_4	0.5326	0.5072	0.5959	1.2820
J	**0.7624**	**0.0014**	**0.7745**	**0.0013**

TABLE III: Power system loading conditions.

	Pe	***Qe***
Normal	0.9	0.1958
Heavy	1.4	0.4
Light	0.2	0.1958

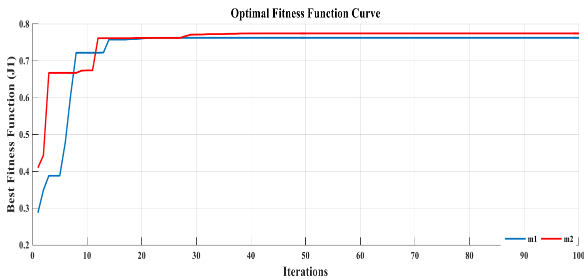

Fig.4: Optimal objective function (J_1) graph

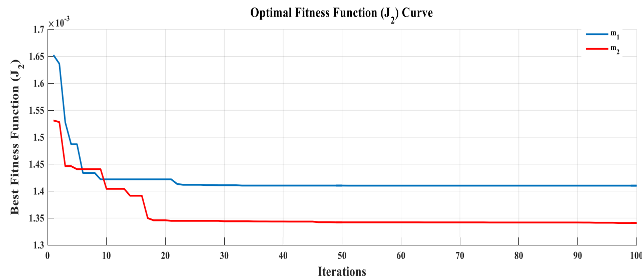

Fig.5: Optimal objective function (J_2) graph

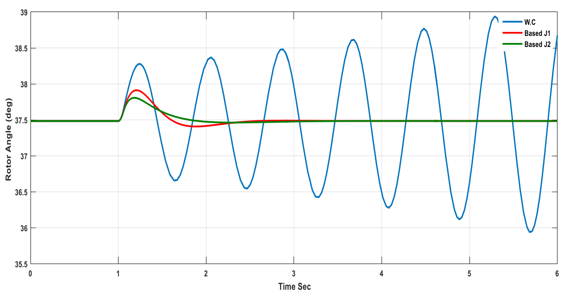

Fig.6: Rotor Angle (deg) using m_1 stabilizing Signal.

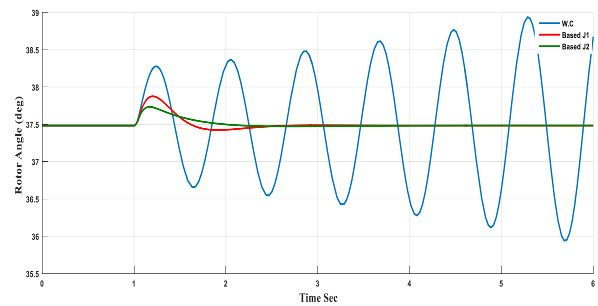

Fig.7: Rotor Angle (deg) using m_2 stabilizing Signal.

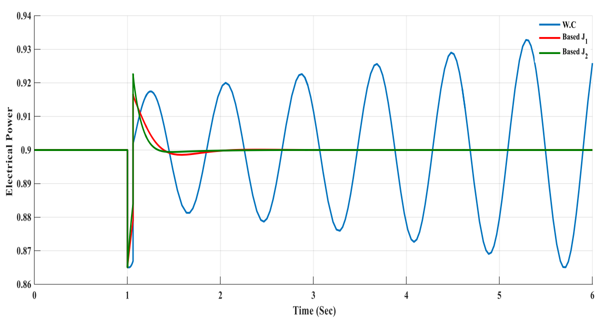

Fig.8: Electrical Power using m_1 stabilizing Signal

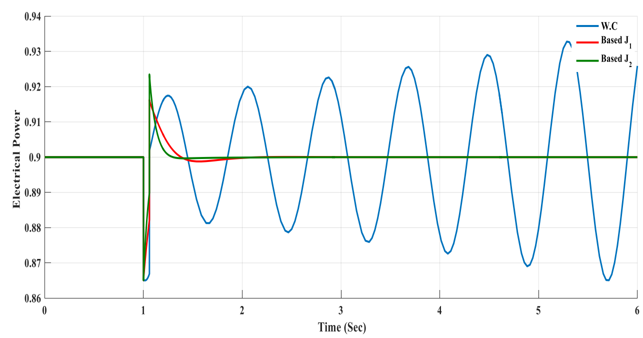

Fig.9: Electrical Power using m_2 stabilizing Signal.

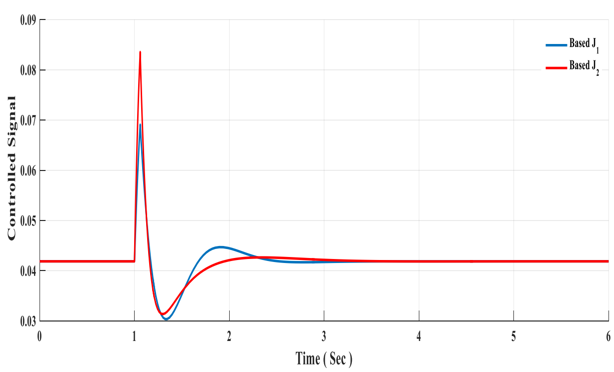

Fig.10: Stabilizing Signal using m_1.

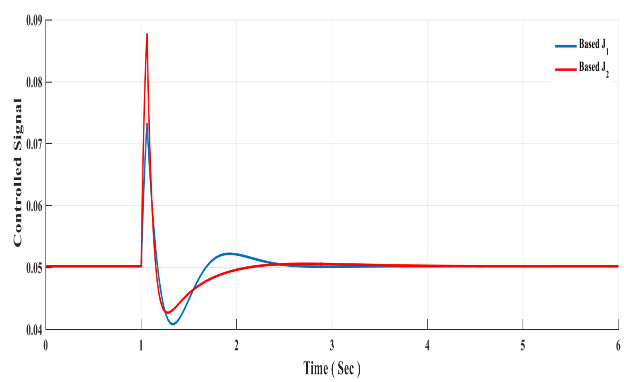

Fig.11: Stabilizing Signal using m_2.

TABLE III: Eigenvalues of power system and damping ratios at different loading condition.

Loading	*Without Control*		*m_1*		*m_2*	
	Eigenvalues	*D. Ratio*	*Eigenvalues*	*D. Ratio*	*Eigenvalues*	*D. Ratio*
Normal	**0.3405 ± j8.0605;** -94.9074; -6.1973; 0.0019	-0.0422	**-5.1467 ± j4.3674;** -3.4789 ± j2.9528; -95.0932; -1.4535; -0.1002;-0.0069	0.7625	**-5.6027 ± j4.5776;** -3.2047 ± j2.6166; -95.1033; -1.3856; -0.1002; -0.0069	0.7744
Heavy	**0.4776 + j8.8864;** -94.9017; -6.4767; 0.0024	-0.0537	**-5.3096 ± j6.4580;** -3.4469 ± j2.2919; -95.1984; -1.4626; -0.1002; -0.0082	0.6351	**-5.6953 ± j6.5178;** -3.2499 ± j2.1302; -95.2146; -1.3941; -0.1002; -0.0082	0.6580
Light	**0.0212 ± j7.3179;** -94.6849; -5.7819; -0.0001	-0.0029	**-3.1814 ± j5.3068;** -3.9605 ± j1.7636; -94.7643; -1.4731; -0.1001; -0.0030	0.5142	**-3.4876 ± j5.2657;** -3.7567 ± j1.7131; -94.7685; -1.4035; -0.1002; -0.0030	0.5522

VII. CONCLUSIONS

Nonlinear model of FACTS type IPFC equipped with SMIB has been developed in this paper in addition to Heffron Philips model. The optimal parameters of IPFC damping controller is determined using the PSO algorithm based on two fitness functions. Moreover, the candidate signal for damping low frequency oscillations of IPFC input signals are elected based on controllability indices which consider the best signal that has the high index (Δm2) while the worst signal that has the lowest one ($\Delta\delta 1$). The SIMB incorporate with IPFC damping controller is investigated under different operating conditions through the eigenvalue analysis and nonlinear simulation to prove the robustness and effectiveness of damping controller settings.

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APPENDIX

The Investigated System Parameters are:
Machine: X_d =1.0, X_d' = 0.3, X_q=0.6, M= 8, f= 60, T'_{do}= 5.044, V_b=1.0.
Transmission Line: X_{L1}=X_{L2}=0.5, R_e=0.0;
Transformer: X_{tr} = 0.15;
IPFC: X_{t1}=X_{t2}=0.1, C_{dc} =1.0, V_{dc}=2.0.
Exciter: K_a =50, T_a=0.05, T_w=10.

BIOGRAPHIES

Mohammed Osman Hassan: He received his Bachelor degree in Electrical Engineering, and his Master degree in Power System, in 1997, 2003 from Sudan University of Science and Technology (SUST) –Sudan, and his Ph.D, in 2010, from Huazhong University of science and technology (HUST) - china. Currently, he is an Assistant Professor in Sudan University of Science and Technology. He won the prize of best paper in electrical track in ICCCEEE 2018 that held in Sudan. His main research interests are power system control, economic operation of power system, power system stability analysis, FACTS devices and application of AI in power systems.

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