Performance Evaluation of Optimized PI Based IPFC with POD

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Abstract: - This paper displays a new access for determining the powerful firing signals for suppression of oscillations by using Optimized PI Based Interline Power Flow Controller [IPFC] through Nonlinear Control Design Block set. The IPFC performance is tested with Proportional Integral Gain [PI] controllers in comparison with Power Oscillation Damping controller [POD] on Modified Phllips-Heffron Model of Single Machine Infinite Bus system for upgraded damping performance by selecting effective signals such as deviation in pulse width modulation switching of voltage series converter 1 in line 1, converter 2 in line 2 and change in phase angle of the injected voltage of convertor 1, convertor 2. Investigations reveal that optimized PI Based Interline Power Flow Controller exhibits the robust dynamic performance. Eigen value analysis has been done for checking potency of powerful firing signals.

Key-Words: - FACTS, IPFC, PI,POD, NCD, PWM, Damping of oscillations

1 Introduction

In today's scenario, numerous electrical energy sources and load components, connected over long distances mainly through alternating current (AC) transmission and distribution grids. The increasing complexity and interconnectedness of large network set new difficulties for their secure operation, therefore, they call for new and efficient forms of controlling power. Because of low damping, power system is subjected to prolonged large oscillations and in some cases they might limit the transmission line efficiency. The FACTS technology helps us to alleviate these obstacles by providing utilities to have better service form their transmission facilities and enhance grid reliability.

Many scientist published the material on nonlinear VSC based FACTS devices like STATCOM, SSSC [19-22] and UPFC for short term stability enhancement of the power system for variation of system conditions. As compared to the other developed VSC based nonlinear FACTS devices, series-series FACTS device is most accepted FACTS device, it consists more than one SSSC are connected in each line which are connected by the route of common dc bus, providing the compensation of number of transmission lines. Speciality of IPFC is only to provide an independently reactive series compensation of each individual line but also to distribute active power among compensated lines. This typical ability of IPFC of balancing real and reactive power flow between the lines; so reducing the load on overloaded lines; making compensation for resistive line voltage drops and related reactive power demand and increase the efficacy of the overall compensating system for dynamic disturbances [1-18]. Shan Jiang et al [17] discusses the behaviour of two FACTS devices in a benchmark system and proved that the IPFC avails greater opportunities for network distribution. Gopinath et al [18] launches model of state estimation embedded with IPFC. A power injection model exhibiting the impact of IPFC between the interconnected lines is presented. Segundo et al [15] have scrutinized the strength of VSC-based FACTS controllers in contributing to system-wide damping.

Dhurvey et al [20] have investigated the potency of IPFC firing signals on linearized power system model for evaluating attainment of IPFC in coordination with Fuzzy Logic Controller and Power Oscillation Damping Controller. Still, output has been not presented with the consideration of properly tuned proportional and integral gain controller. As a deduction, target is to update reference [20]. Kazemi et al [9] proved the powerful damping control function of an IPFC installed in a power system. Parimi, et al [4] have applied the Fuzzy logic control for suppression of low frequency oscillations. Oscillation modes with low damping ratio are obtained by Alivelu M. Parimi [6]. Parimi [11] states that IPFC control signal m2 is the most effective. M.R.Banaei et al [13] has proved that modulation index have more effect as compared to phase angle deviation. Veeramalla, J. et al [14] scrutinize the speciality of the IPFC damping strategies which emphasized that the damping controller which modulates the modulation index shoes fair performance under wide variations in loading condition and system parameters. However, they have not discussed the method for obtaining the optimized PI based IPFC.

With the accessible work presented by the researchers, the main objective is to study strength of signals [m_{i1} ,m_{i2} ,α_1, α_2]of IPFC for damping of power system oscillations. The comparative performance of optimized PI based controller and Power Oscillation Damping controller [POD] for improved power system performance is demonstrated. The results are validated in MATLAB environment.

2. Case Study

Interline Power Flow Controller in one of the two transmission lines for SMIB system is examined which consists of an excitation transformer, a boosting transformer, a pair of voltage source converters and a DC link capacitor is shown in Fig.1. Δm_{i1} is the PWM switching of voltage series converter 1 in line 1. By controlling m_{i1}, the amount of series injected voltage in line 1 can be controlled. Δm_{i2} is the PWM switching of series converter 2 in line 2. By controlling m_{i2}, the magnitude of series injected voltage in line 2 can be controlled. $\Delta\alpha_1$ is the change in phase angle of the injected voltage Vse_1. $\Delta\alpha_2$ is the change in phase angle of the injected voltage Vse_2 displayed in Appendix-A.

3. Interline Power Flow Controller

Interline consists of VSCs inserted in series with transmission lines in which active power can be transferred through DC link. Basic function is to control power flow among transmission lines and damping of oscillations. A non-linear model of the system is formulated by cancelling the resistances of all parameters and the transients of the transmission lines and transformers of the IPFC.

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

$$\dot{\omega} = \frac{P_m - P_e - P_D}{M} \tag{2}$$

$$\dot{E}_q^1 = \frac{(-E_q + E_{fd})}{T_{do}^1} \tag{3}$$

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

$$\dot{V}_{dc} = \frac{3m_{i1}}{4C_{dc}}(\cos\alpha_1 I_{1d} + \sin\alpha_1 I_{1q}) + \frac{3m_{i2}}{4C_{dc}}(\cos\alpha_2 I_{2d} + \sin\alpha_2 I_{2q}) \tag{5}$$

$$V_{se1d} = -x_{t1}I_{1q} + \frac{V_{dc}}{2}m_{i1}\cos\alpha_1 \tag{6}$$

$$V_{se1q} = -x_{t1}I_{1d} + \frac{V_{dc}}{2}m_{i1}\sin\alpha_1 \tag{7}$$

$$V_{se2d} = -x_{t2}I_{2q} + \frac{V_{dc}}{2}m_{i2}\cos\alpha_2 \tag{8}$$

$$V_{se2q} = -x_{t2}I_{2d} + \frac{V_{dc}}{2}m_{i2}\sin\alpha_2 \tag{9}$$

$$V_{sei} = V_{seid} + jV_{seiq} = V_{seie}{}^{j\alpha 1} \tag{10}$$

A linear dynamic model of IPFC is obtained by linearizing at operating point [13].

$$\dot{\Delta\omega} = \frac{(\Delta P_m - \Delta P_e - D\Delta\omega)}{M} \qquad (11)$$

$$\dot{\Delta\delta} = \omega_0 \Delta\omega \qquad (12)$$

$$\Delta \dot{E}_q^1 = \frac{\left(-\Delta E_q + \Delta E_{fd}\right)}{T_{do}^1} \qquad (13)$$

$$\Delta\dot{E}_{fd} = \frac{-\Delta E_{fd} + K_a\left(\Delta V_{ref} - \Delta V_t\right)}{T_a} \qquad (14)$$

$$\dot{\Delta V}_{dc} = K_7\Delta\delta + K_8\Delta E_q^1 - K_9\Delta V_{dc} + K_{cmi1}\Delta m_{i1} + K_{c\alpha1}\Delta\alpha_1 + K_{cmi2}\Delta m_{i2} + K_{c\alpha2}\Delta\alpha_2 \qquad (15)$$

Where,

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E_q^1 + K_{pv}\Delta V_{dc} + K_{pmi1}\Delta m_{i1} + K_{p\alpha1}\Delta\alpha_1 + K_{pmi2}\Delta m_{i2} + K_{p\alpha2}\Delta\alpha_2 \qquad (16)$$

$$\Delta E_q = K_4\Delta\delta + K_3\Delta E_q^1 + K_{qmi1}\Delta m_{i1} + K_{q\alpha1}\Delta\alpha_1 + K_{qmi2}\Delta m_{i2} + K_{q\alpha2}\Delta\alpha_2 + K_{qv}\Delta V_{dc} \qquad (17)$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E_q^1 + K_{vv}\Delta V_{dc} + K_{vmi1}\Delta m_{i1} + K_{v\alpha1}\Delta\alpha_1 + K_{vmi2}\Delta m_{i2} + K_{v\alpha2}\Delta\alpha_2 \qquad (18)$$

Fig. 2 shows the modified Phillips-Heffron model of the SMIB system with IPFC installed [3] whose constants are dependent on the value of system parameters and the initial operating condition given in Appendix –A. The power system can be modelled in terms of state-space representation as-

$$\dot{X} = AX + BU \qquad (19)$$

$$x = \left[\Delta\delta \quad \Delta\omega \quad \Delta E_q^1 \quad \Delta E_{fd} \quad \Delta V_{dc}\right]^T \qquad (20)$$

$$u = [\Delta m_{i1} \quad \Delta m_{i2} \quad \Delta\alpha_1 \quad \Delta\alpha_2] \qquad (21)$$

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & \frac{-D}{M} & -\frac{K_2}{M} & 0 & -\frac{K_{pv}}{M} \\ -\frac{K_4}{T_{do}^1} & 0 & -\frac{K_3}{T_{d0}^1} & \frac{1}{T_{do}^1} & -\frac{K_{qv}}{T_{do}^1} \\ -\frac{K_aK_5}{T_a} & 0 & -\frac{K_aK_6}{T_a} & -\frac{1}{T_a} & -\frac{K_aK_{vv}}{T_a} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \qquad (22)$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \frac{-K_{pmi1}}{M} & \frac{-K_{p\alpha1}}{M} & \frac{-K_{pmi2}}{M} & \frac{-K_{p\alpha2}}{M} \\ \frac{-K_{qmi1}}{M} & \frac{-K_{q\alpha1}}{M} & \frac{-K_{qmi2}}{M} & \frac{-K_{q\alpha2}}{M} \\ \frac{-K_aK_{vmi1}}{T_a} & \frac{-K_aK_{v\alpha1}}{T_a} & \frac{-K_aK_{vmi2}}{T_a} & \frac{-K_aK_{v\alpha2}}{T_a} \\ K_{cmi1} & K_{c\alpha1} & K_{cmi2} & K_{c\alpha2} \end{bmatrix} \qquad (23)$$

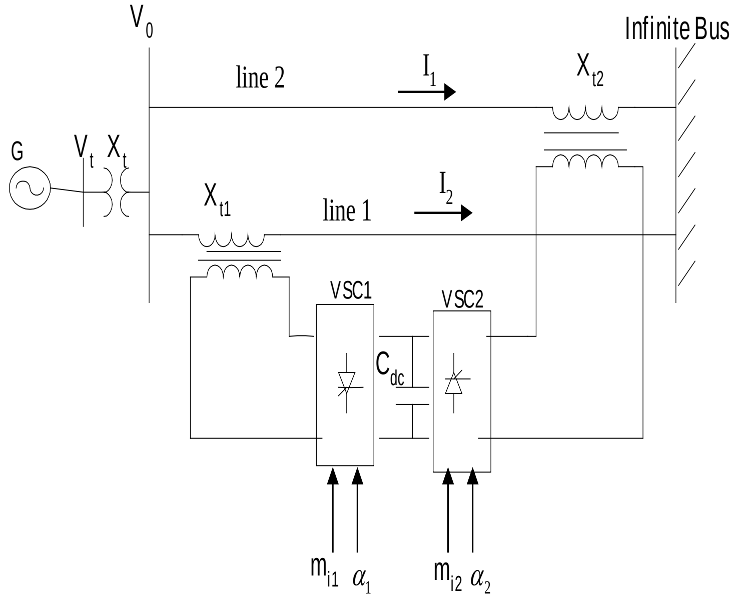

Fig. 1: A single machine infinite bus power system installed with an IPFC in one of the lines

Fig. 2: Phillips Heffron Model of IPFC

4. Coordinated Tuning of POD and IPFC

In this section, PI Based IPFC [20] is suggested for suppression of oscillations. The PI constants Kp and Ki are chosen by trial and error method.

In Fig.3, additional damping signal Power Oscillation Damping Controller [POD] can be applied for improvement in PI controller performance. The POD controller [19] may be considered as comprising gain K_{DC}, wash out block and lag-lead compensator. To obtain best damping performance, best values of parameters of the lead-lag compensator are chosen. The IPFC controllable signals (m_{i1}, α_1, m_{i2} and α_2) can be modulated in order to produce a damping torque. The washout circuit as shown in Fig 3 is provided to eliminate steady-state bias in the output of POD Controller. The Tω should be in the range of 10 to 20.

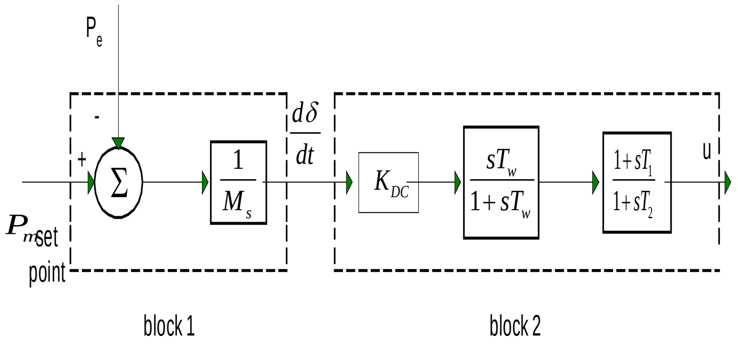

Fig. 3: Structure of Power Oscillation Damping [POD] controller

5. Optimization of Parameters using Nonlinear Control Design (NCD) Block Set

Various optimization techniques are available in literature for parameter optimization. However, trial and error method for parameters selection is very time consuming and less accurate whereas available optimization tool offers better result. The nonlinear control design block set [23] in MATLAB uses the optimization tool box and it provides the simple approach to optimize model for given target output under define constraints and the define time intervals. The aim of the parameter optimization is to achieve optimal performance. This objective can be formulated as follows:

$$Min\,f(x) \qquad (24)$$

$$s.t. A(x) = 0 \qquad (25)$$

$$B(x) \geq 0 \qquad (26)$$

where f(x) is objective function, x are the parameters of the controllers. A(x) are the equality functions and B(x) are the inequality functions. Particularly B(x) indicates the restriction of the parameters (i.e K_p, K_i etc.) The objective function in the simulation is defined as:

$$f(x) = \int_0^{t1} \omega(t, x)dt \qquad (27)$$

where, ω (t, x) is the speed and the time range of the simulation . ω(t, x) changes by changing the parameters of x. The M file programme is employed to initialize NCD Block [23], to evaluate the performance of various parameters used in controllers. In the place of speed, rotor angle variation can be also used. The optimization starts with the pre-selected initial values of the feedback gains. Then the nonlinear algorithm is used iteratively to adjust the parameters, until the objective function equation (27) is minimized . These parameters so determined are the optimal setting of the parameters used as feedback gains.

The flow chart of the parameter optimization is shown in Fig.4. The proposed optimization algorithm is realized in a single machine infinite bus system.

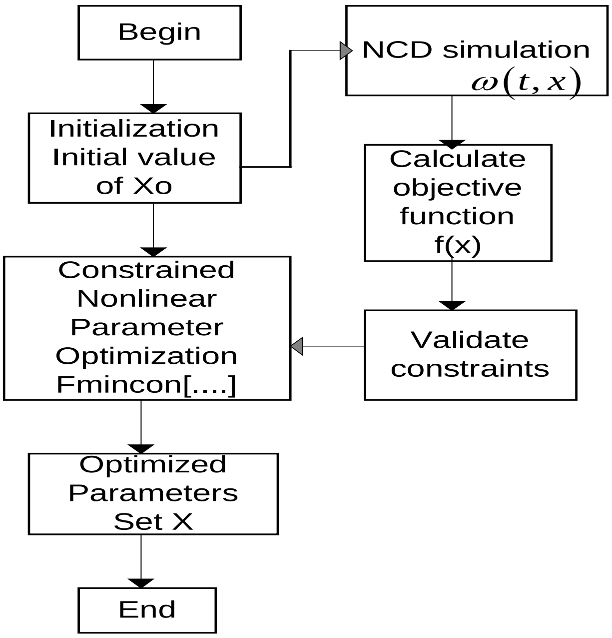

Fig.4: Flow chart of the parameters optimization

Fig.5 shows the functional diagram of NCD for SMIB system with IPFC in which optimization of proportional & integral gain controller (K_p & K_i) has been done by NCD Block set.

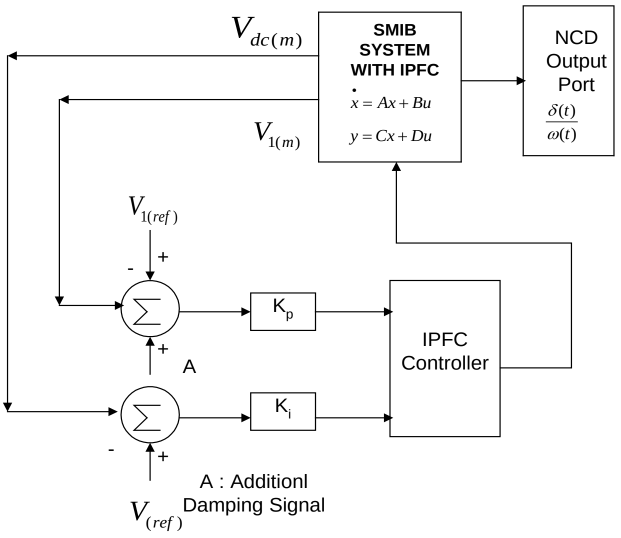

Fig.5: Functional diagram of IPFC parameters optimization

6. Small Signal Stability Analysis

Independent damping signals with IPFC during 10% of variation in mechanical power input has been demonstrated by using digital simulation with Modified Phillips Heffron model in MATLAB environment.

6.1 Effective performance of the system with firing signal m_{i1}

Result shown in Fig.6 indicates that PI based IPFC exhibit relatively high peak, whereas POD performance is improved with less settling time. Also, in case of PI based IPFC for control signal m_{i1}, when the value proportional and integral setting is optimized, transient response is significantly improved.
Eigen value analysis of system confirms Time domain analysis as shown in Table 1**.**

6.2. Dynamic performance of the system with firing signal m_{i2}

From Fig.**7** it is clear that with system is amenable with POD Controller with settling time 0.2 sec. Also, in PI based IPFC with control signal m_{i2}, when the value proportional and integral setting is optimized, transient response is significantly improved and hence gives the better result.
This observation is validated by PI based IPFC and coordinated action of IPFC with POD in which all the Eigen values are driven into the negative real part of axis as shown in Table 2.

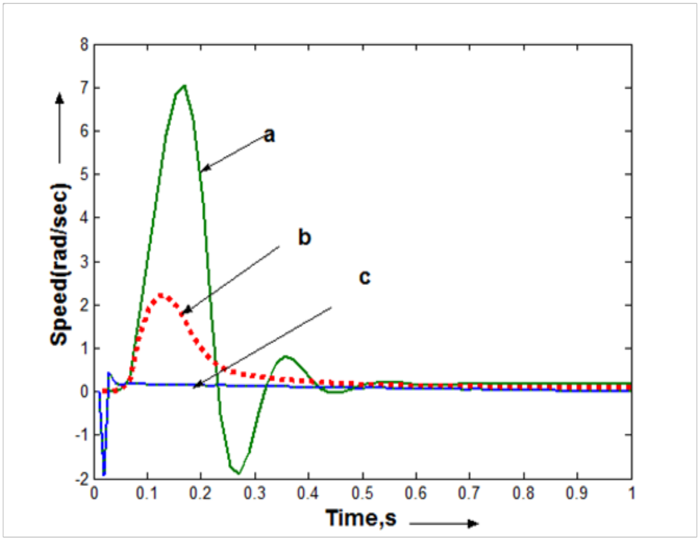

Fig.6: Dynamic response of linearized SMIB system
a. control signal m_{i1} b. m_{i1} with POD c. m_{i1} with optimized PI

Table 1: Eigen value analysis of linearized SMIB system with control signal m_{i1}

Control signal m_{i1}	m_{i1} with POD
-11.0077 ±29.1683i	-78.8099
-0.7128±+ 3.7544i	-34.7446
0.0000	-19.4602
-0.0025	-4.9371
	0.0167
	-0.7128±+ 3.7544i

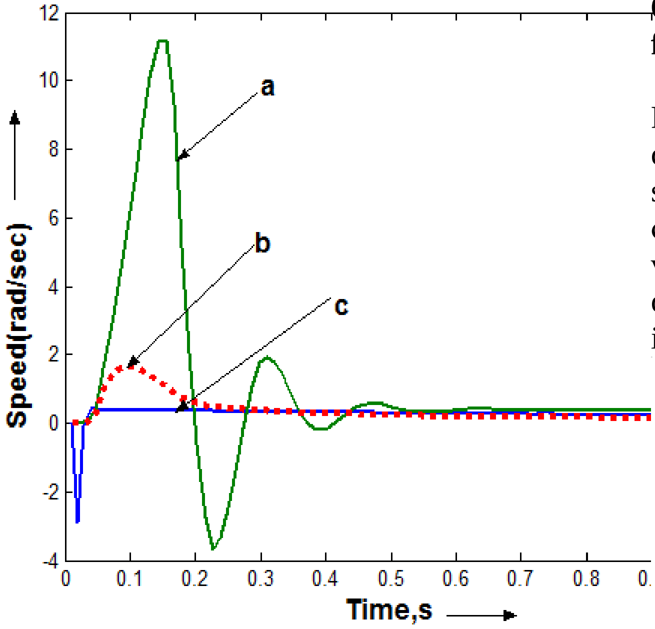

Fig.7:Dynamic response of linearized SMIB system
a. control signal m_{i2} b. m_{i2} with POD c. m_{i2} with optimized PI

Table 2: Eigen value analysis of linearized SMIB system with control signal m_{i2}

Control signal m_{i2}	mi_2 with POD
-10.6292 ±33.9215i	1.0e+002 *
-0.7128 ± 3.7544i	-2.4459
0.0000	-0.2625
-0.0025	-0.1946
	-0.0366
	0.0001
	-0.0000
	-0.0071 ± 0.0375i

6.3 Effective performance of the system with firing signal α_1

From Fig.8, it can be inferred that with coordinated tuning of IPFC and POD, system is stable, with settling time 0.5 sec. Also, in case of PI based IPFC for control signal α_1, when the value proportional and integral setting is optimized, transient response is significantly improved.

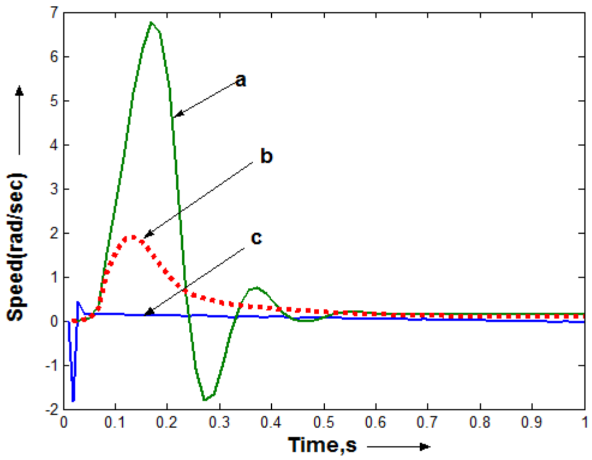

Fig.8:Dynamic response of linearized SMIB system
a. control signal α_1 b. α_1 with POD c. $\alpha_1$with optimized PI

Time domain analysis can be verified by Eigen value analysis of PI based IPFC and coordinated action of IPFC with POD as shown in Table 3.

Table 3: Eigen value analysis of linearized SMIB system with control signal α_1

Control signal α_1	α_1 with POD
-11.0333 ±28.8257i	1.0e+002 *
-0.7128±+ 3.7544i	-1.0267
-0.0000	-0.3023
-0.0026	-0.0418 ± 0.0153i
	0.0002
	-0.0000
	-0.0071 ± 0.0375i

4.4.4 Dynamic performance of the system with control signal α_2

Result as shown in Fig.9 indicates that with the with coordinated action of IPFC and POD Controller, first peak of speed deviation, settling time and steady state error has been significantly improved. Also, the action of IPFC with Optimized PI Controller gives the best result.

Table 4 shows the Eigen value analysis of Single Machine Infinite Bus System with IPFC in coordination with POD.

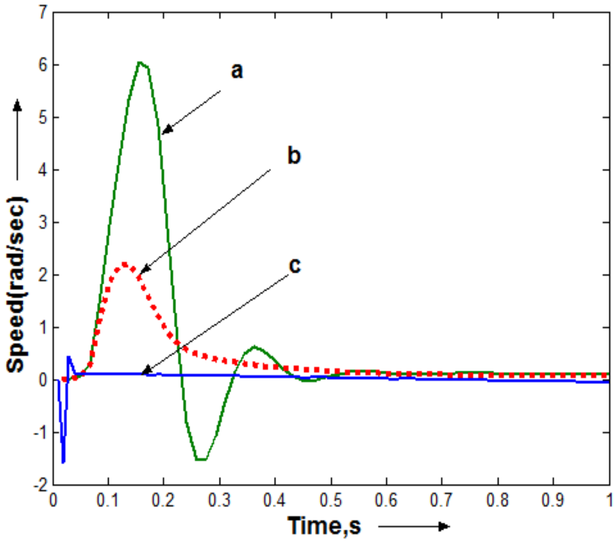

Fig.9: Dynamic response of linearized SMIB system
a. control signal α_2 b. α_2 with POD c. $\alpha_2$with optimized PI

Table 4: Eigen value analysis of linearized SMIB system with control signal α_2

Control signal α_2	$\alpha_2$with POD
-11.0887 ±28.0454i	-62.6351
-0.7128 ± 3.7544i	-37.8621
0.0000	-4.5395 ± 1.5558i
-0.0025	0.0185
	-0.0000
	-0.7128 ± 3.7544i

4.5. Conclusion

The linearized power system model of Single Machine Infinite Bus system for analyzing the performance comparison of optimized PI based IPFC in coordination with Power Oscillation Damping (POD) Controller has been considered. These control signals gives the significant improvement in performance of system for damping of power system oscillations. Investigations have revealed that IPFC control signals m_{i1} and α_2 shows robust performance over other signals. Also, POD Controller shows the improvement in transient response of the system. Optimized system parameters further improves the transient response of the system. Time domain analysis and Eigen value analysis results validated the performance of various IPFC control strategy under variation of system parameters. Optimized results of control signals m_{i1} and α_2 in coordination with POD shows that oscillations are well damped.

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REFERENCES

[1]P. Kundur(1994) Power System Stability and Control, *Mc Graw-Hill*, New York, ch. 12.

[2]N.G. Hingorami, L.Gyugyi(2001), Understanding FACTS: Concepts and Technology of Flexible AC Transmission system, *IEEE Power Engineering Society, IEEE press*, Delhi.

[3]Y.H. Song and A.T. Johns, (1999) Flexible AC Transmission systems, IEE Power and Energy series 30, London, 1999.

[4]Parimi A.M., Elamvazuthi I., Saad N.(2010), Fuzzy logic control for IPFC for damping low frequency oscillations, *Intelligent and Advanced Systems (ICIAS)*: International Conference, 1 – 5.

[5]Babu A.V.N., Sivanagaraju S.(*2010*), Mathematical modeling, analysis and effects of interline power flow controller (IPFC) parameters in power flow studies, *Power Electronics (IICPE), India International Conference*, 1 – 7.

[6] Parimi A.M., Sahoo N.C., Elamvazuthi I, Saad N.(2011) Transient stability enhancement and power flow control in a multi-machine power system using Interline Power Flow Controller, *Energy, Automation, and Signal (ICEAS)*, International Conference ,1 – 6.

[7]Gomathi V., Ramachandran, Kumar C.V.(2010) Simulation and state estimation of power system with Interline Power flow Controller, *Universities Power Engineering Conference (UPEC)*, 45th International,1 – 6.

[8] Moghadam M.F., Gharehpetian G.B., Askarian Abyaneh H(2010) Optimized regulation of DC voltage in Interline Power Flow Controller (IPFC) using genetic algorithm**,** *Power Engineering and Optimization Conference (PEOCO)*,117 - 121

[9]Kazemi, Karimi(2006)The Effect Interline Power Flow Controller (IPFC) on Damping Inter-area Oscillations in the Interconnected Power Systems', *Industrial Electronics, IEEE International Symposium,* 3,1911 – 1915.

[10]Zhihui Yuan, de Haan S.W.H., Ferreira, Braham(2008) A new concept of exchanging active power without common DC link for Interline Power Flow Controller(S-IPFC),Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, *IEEE Conference*,1 – 7.

[11]Parimi A.M., Elamvazuthi I, Saad, N., Interline Power Flow Controller (IPFC) based damping controllers for damping low frequency oscillations in a power system(2008), *Sustainable Energy Technologies, ICSET. IEEE International Conference*,334 – 339.

[12]Xia Jiang, Xinghao Fang, Chow, J.H., Edris, A., Uzunovic, E.(2007) Regulation and Damping Control Design for Interline Power Flow Controllers**'**, *Power Engineering Society General Meeting*,1 - 8

[13]Banaei M.R. ,Kami A.(2009) Interline power flow controller based damping controllers for damping low frequency oscillations, *Telecommunications Energy Conference, INTELEC 2009*, 31st International Conference,1 – 6

[14]Veeramalla J., Sreerama Kumar R.(2010) Application of Interline Power Flow Controller (IPFC) for damping low frequency oscillations in power systems, *Modern Electric Power Systems*

(MEPS), Proceedings of the International Symposium ,1 – 6.

[15]Segundo F.R., Messina, A.R. (2009) Modeling and simulation of Interline Power Flow Controllers: Application to enhance system damping', *North American Power Symposium (NAPS),*1 – 6.

[16]Xia Jiang , Xinghao Fang, Chow J.H., Edris A., Uzunovic E., Parisi, M., Hopkins, L.(2008) A Novel Approach for Modeling Voltage-Sourced Converter-Based FACTS Controllers**,** *Power Delivery, IEEE Transactions* Vol. 23 , N0. 4, **,** pp. 2591 - 2598

[17]Shan Jiang, Gole A.M., Annakkage U.D., Jacobson D.A.(2011), Damping Performance Analysis of IPFC and UPFC Controllers Using Validated Small-Signal Models, *Power Delivery, IEEE Transactions* on Vol.26 , No.1, 446 - 454

[18]Gopinath B., SureshKumar S., Ramya M. (2013)Circuits, Power an Genetically optimized IPFC for improving transient stability performance in power system', *Computing Technologies (ICCPCT),* International Conference, 120 – 125.

[19]S.N.Dhurvey, V.K.Chandrakar(2008) Performance Comparison of UPFC In Coordination with Optimized POD and PSS On Damping of Power System Oscillations, *International Journal of WSEAS Transaction on Power System*, Vol.3,No.5, 287-299.

[20] S.N.Dhurvey, V.K.Chandrakar(2011) Performance Evaluation of IPFC By Using Fuzzy Logic Based Controller, *IEEE Fourth International Conference on Emerging Trends in Engineering & Technology*, ICETET 2011, Mauritius, 16th-18th Nov.,168-173.

[21]V.K.Chandrakar, A.G.Kothari (10-12 Sept 2007) Comparison of RBFN and Fuzzy based STATCOM Controllers for Transient Stability Improvement, *IEEE Aegean Conference on Electric Machines Powers and Electromotion*, Bodrum,Turkey, 520 – 525.

[22]Chandrakar V.K. and Kothari A.G. (2006) RBFN based Static Synchronous Series Compensator (SSSC) for Transient Stability improvement. *ICARCV*, 1-7.

[23] MATLAB User's Manual, NCD Block Set, version 5.8.