Performance Comparison of PI and MFFN Based IPFC on Damping of Power System Oscillations

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Abstract: - Neural network learning is a type of supervised learning, meaning that we provide the network with example inputs and the correct answer for that input. This paper discusses a new approach for determining the effective control signals for damping of oscillations by using MFFN (Multilayer feed forward network) based Interline Power Flow Controller [IPFC]. The IPFC performance is tested with PI controllers in comparison with MFFN based controller on Modified Phllips-Heffron Model of Single Machine Infinite Bus system to achieve improved damping performance by selecting effective control signals such as deviation in pulse width modulation index of voltage series converter 1 in line 1, pulse width modulation index of voltage series converter 2 in line 2, deviation in phase angle of the injected voltage of convertor 1, injected voltage phase angle deviation of convertor 2. Investigations has been found that coordinated tuning of Interline Power Flow Controller with MFFN controller provide the robust dynamic performance. The MFFN Based Interline Power Flow Controller [IPFC] is designed with simple strategy to coordinate the additional damping signal. The proposed controllers for IPFC are able to achieve improved designed performance of the power system. Validity of effective control signals has been done by eigen value analysis.

Key-Words: - FACTS, IPFC, MFFN, Damping of oscillations

1. Introduction

The complex electric power system operated in an integrated environment. When a power system is subjected to a disturbance, the system variables undergo oscillations. Some low frequency electromechanical oscillations of small magnitude exist in the power system for long periods of time, and in some cases they might impose limitations on the transmission line functionality. With low damping, power system is subjected to prolonged large oscillations. Several devices and control methods have been developed to increase damping in power systems and improve power transfer limits. In particular, the application of multifunctional FACTS controllers based on back to back dc/ac voltage source converter has greatly meet with power demand in the recent years. The high current semiconductor device based FACTS devices with proper control strategy can improve the power system stability of power system. Many researcher presented work on various nonlinear VSC based FACTS devices like STATCOM, SSSC and UPFC for transient stability improvement of the power system under various system conditions. Amongst the other developed VSC based nonlinear FACTS devices, Interline Power Flow Controller (IPFC) is most versatile FACTS device, it consists of number of SSSC are connected in each line which are connected via common dc bus, addresses the problem of compensating a number of transmission lines. The special feature of IPFC is not only to perform an independently controllable reactive series compensation of each individual line but also to deliver real power between the compensated lines. This capability of IPFC makes it possible to: equalize both real and reactive power flow between the lines; hence avoid the burden of overloaded; making compensation for resistive line voltage drops and the associated reactive power demand and increase the efficacy of the overall compensating system for dynamic disturbances [1-22]. Shan Jiang et al [17] discusses the behaviour of two FACTS devices; the combined series-series controller and the combined series-shunt controller in a benchmark system and proved that the IPFC has more series branches than the UPFC, it provides more opportunities for network segmentation and, hence, has the potential for greater damping improvement. Gopinath et al [18] introduces the model of state estimation embedded with IPFC. A power injection model that shows the influence of IPFC on the power flow between the interconnected lines is presented. Segundo et al [15] have examined the efficacy of VSC-based FACTS controllers in contributing to system-wide damping. The strategy is tested on a practical 45-machine Mexican system that includes number of static VAR compensators.

Dhurvey et al[20] have examined the relative effectiveness of UPFC control signals on linearized power system model of single machine infinite bus system (SMIB) system for analyzing performance comparison of IPFC in coordination with Power Oscillation Damping Controller [POD] and Power System Stabilizer [PSS]. However, results has been not presented with the consideration of various damping factor D and Kp and Ki is not properly tuned. Hence, the aim of this paper is to present the modified version of reference with unique MFFN technique. Kazemi et al [9] proved the effective damping control function of an IPFC. Parimi, et al [4] implement the Fuzzy logic control for IPFC for damping low frequency oscillations. Alivelu M. Parimi [6] develop the nonlinear model of power system incorporated with Interline Power Flow Controller (IPFC). The oscillation modes with low damping ratio are obtained from the eigen value analysis of the linearized Phillips-Heffron model Parimi [11] has proved that IPFC control signal m2 is the most effective. M.R.Banaei et al [13] has proved that signals m1, m2 based controllers have more effect on damping of oscillation and signal δ_1, δ_2 based controllers have less effect on damping of oscillation. Veeramalla, J. et al [14] investigated the effectiveness of the IPFC based damping controller. Dynamic simulations results have stressed out that damping controller which modulates the control signal *m2* provides satisfactory dynamic performance. under wide variations in loading condition and system parameters.

With the advent of Artificial Intelligence in modern era, expert system techniques are keyed out for contingency screening and ranking. Artificial neural networks (ANNs) are networks of neurons, operating on their local data and communicating with other elements. The main advantage of neural networks is the fact, that they are able to predict information hidden in data (but they are not able to extract it). Learning of neural network is the capturing of the unknown information or 'training of neural network'. These efficient networks are used for modelling complex input-output relationships.

Dash et al [22] presented the combination of both fuzzy scheme and RBFN is adopted for nonlinear control of TCSC and IPFC for improving the transient stability performance of power systems. However they have not discuss the linear model of the power system.

Chandrakar et al[19] analyzed the performance of MFFN based SSSC for the improvement in transient stability. and However, they have not presented an method for obtaining the simultaneous coordination of IPFC with each control signal and Multilayer feed forward network (MFFN).

In view of the available work presented by the researchers, the main objective of this paper is to study effectiveness of various control signals [m_{i1},m_{i2},α_1,α_2]of IPFC for damping of power system oscillations. The comparative performance of PI based and Multilayer feed forward network (MFFN) based IPFC for improved power system performance is demonstrated. The results are validated in MATLAB environment.

2. System Model

Interline Power Flow Controller is applied in SMIB system as shown in Fig.1. Δm_{i1} is the deviation in pulse width modulation index m_{i1} of voltage series converter 1 in line 1. By controlling m_{i1}, the magnitude of series injected voltage in line 1 can be controlled. Δm_{i2} is the deviation in modulation index m_{i2} 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 phase angle deviation of the injected voltage Vse_1. $\Delta\alpha_2$ is the deviation in phase angle of the injected voltage Vse_2. The numerical values of system parameters are given in Appendix-A.

3. Interline Power Flow Controller

Interline Power Flow Controller (IPFC) is VSC based FACTS controller, consists of two voltage-sourced converters (VSCs) inserted in series with transmission lines, whose DC capacitors are linked such that active power can be transferred between the two VSCs. Each VSC provides series compensation for the elected transmission line and is capable of exchanging reactive power with its own transmission system. Basic function is to control power flow among transmission lines and damping of oscillations. A non-linear dynamic model of the system is obtained by neglecting the resistances of all the components of the system and the transients of the transmission lines and transformers of the IPFC.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\Delta\dot{V}_{dc} = K_7\Delta\delta + K_8\Delta E_q^1 - K_9\Delta V_{dc} + K_{cm i1}\Delta m_{i1} + K_{c\alpha 1}\Delta\alpha_1 + K_{cmi2}\Delta m_{i2} + K_{c\alpha 2}\Delta\alpha_2 \quad (15)$$

Where,

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E_q^1 + K_{pv}\Delta V_{dc} + K_{pm1}\Delta m_{i1} + K_{p\alpha 1}\Delta\alpha_1 + K_{pm2}\Delta m_{i2} + K_{p\alpha 2}\Delta\alpha_2 \quad (16)$$

$$\Delta E_q = K_4\Delta\delta + K_3\Delta E_q^1 + K_{qm1}\Delta m_{i1} + K_{q\alpha 1}\Delta\alpha_1 + K_{qm2}\Delta m_{i2} + K_{q\alpha 2}\Delta\alpha_2 + K_{qv}\Delta V_{dc} \quad (17)$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E_q^1 + K_{vv}\Delta V_{dc} + K_{vm1}\Delta m_{i1} + K_{v\alpha 1}\Delta\alpha_1 + K_{vm2}\Delta m_{i2} + K_{v\alpha 2}\Delta\alpha_2 \quad (18)$$

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

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

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

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

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

$$B=\begin{bmatrix} 0 & 0 & 0 & 0 \\ \frac{-K_{pmi1}}{M} & \frac{-K_{p\alpha 1}}{M} & \frac{-K_{pmi2}}{M} & \frac{-K_{p\alpha 2}}{M} \\ \frac{-K_{qmi1}}{M} & \frac{-K_{q\alpha 1}}{M} & \frac{-K_{qmi2}}{M} & \frac{-K_{q\alpha 2}}{M} \\ \frac{-K_a K_{vmi1}}{T_a} & \frac{-K_a K_{v\alpha 1}}{T_a} & \frac{-K_a K_{vmi2}}{T_a} & \frac{-K_a K_{v\alpha 2}}{T_a} \\ K_{cmi1} & K_{c\alpha 1} & K_{cmi2} & K_{c\alpha 2} \end{bmatrix} \quad (23)$$

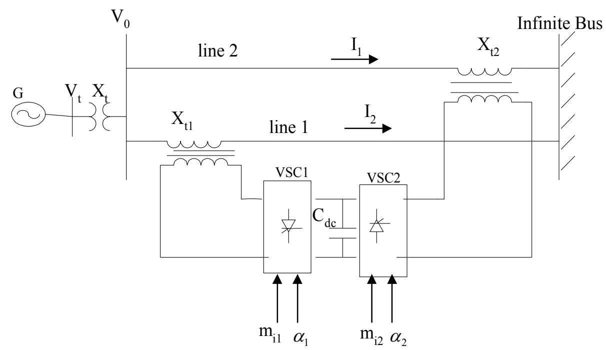


Fig. 1: A single machine infinite bus power system installed with an IPFC in one of the lines

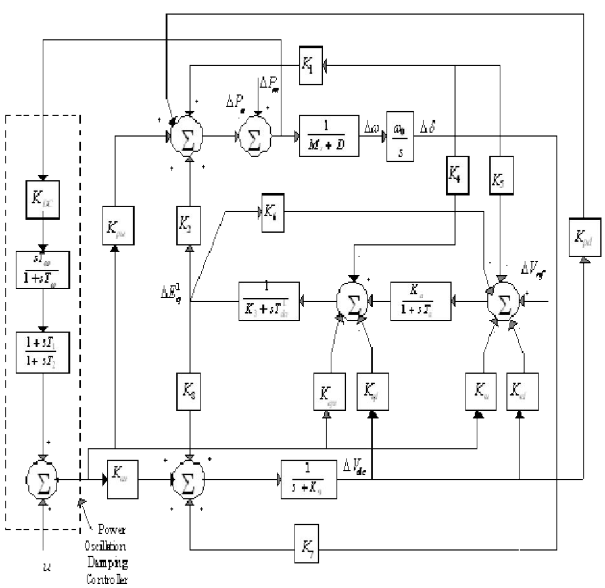


Fig. 2: Phillips Heffron Model of IPFC

4. Proportional Integral (PI) Based IPFC

In this section, PI Based IPFC[20],[21] is suggested for damping 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 [20] may be considered as comprising gain K_{DC}, wash out block and lag-lead compensator. The values of parameters of the lead-lag compensator are chosen so as to obtain best damping performance. Optimum parameters for the damping controllers are given in Appendix-A. The IPFC controllable signals (m_{i1}, α_1, m_{i2} and α_2) can be modulated in order to produce a damping torque. Controllability indices for the different Interline Power Flow Controller controllable parameters are given in Appendix-A. The washout circuit as shown in Fig 3 is provided to elimi.nate steady-state bias in the output of POD Controller. The Tω must be chosen in the range of 10 to 20.

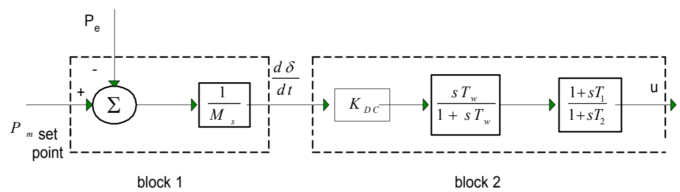


Fig. 3: Structure of Power Oscillation Damping [POD] controller

5. MFFN Based IPFC

There exist two main types of training process: supervised and unsupervised training. Supervised training means, that neural network knows the desired output and weight coefficients are adjusted in such way, that the calculated and desired outputs are similar to some extent. Each neuron in the network is able to receive input signals, and after processing send an output signal. Each neuron is connected at least with one neuron, and each connection is evaluated weight coefficient.

In the multilayer feedforward neural network [19], number of layers in a neural network are the number of layers of perceptrons. The neural network consists of one single input layer and an output layer of perceptrons. The network in

Fig. 4 describes the structure which consists of one-layer feedforward network with two outputs as the output layer is the only layer with an activation calculation.

To save execution time, by avoiding the more number of perceptrons in the hidden layers, it is sometimes better to add a hidden layers to improve the performance of the ANN. However, in practice, it is uncommon to see neural networks with more than two or three hidden layers

More specifically, back-propagation is the method which is used during training for calculating the gradient of the network.

The important objective of network training is to estimate weights. Sum-of-squared errors is the the most commonly used error function in forecasting.

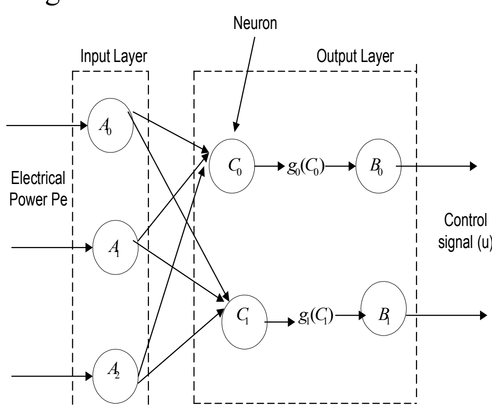


Fig. 4: Structure of MFFN Controller

Fig. 5 illustrates the flowchart which gives the complete sequence of initialisation, training, input-output mapping and error calculations.

In error calculations, N is the total number of training cases, C is the number of network outputs, t_{ij} is the observed output for the i^{th} training and the j^{th} network output, and $\hat{t}_{ij}$ is the network's forecast for that case.

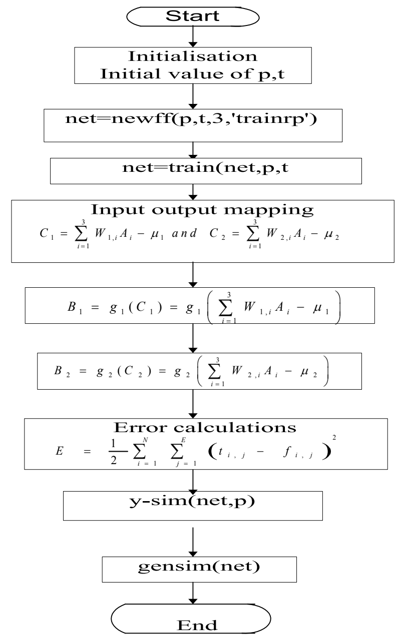


Fig. 5: Flowchart of MFFN

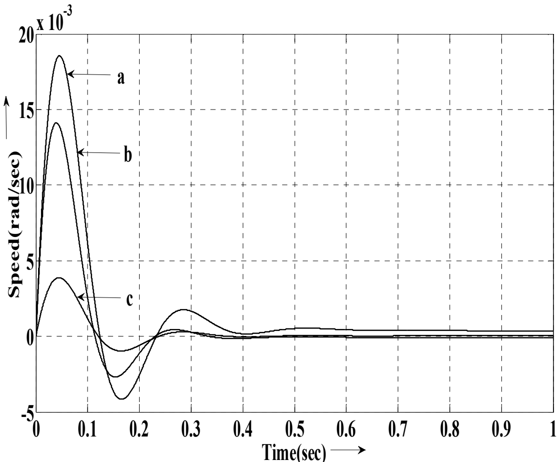
6. Simulation Results

Digital Simulation has been carried out with Modified Phillips Heffron model in MATLAB environment. Independent damping signals and MFFN with IPFC has been demonstrated. In small signal analysis, the simulation result of the linearized model with four different input control signals under 10% of variation in mechanical power input is considered. The proposed PI and MFFN controllers performances are tested in Single Machine Infinite Bus system.

6.1 Dynamic performance of the system with control signal m_{i1}

Fig. 6 depicts the comparative analysis of PI based IPFC, IPFC with POD as additional damping controller and MFFN based IPFC for control signal m_{i1}. Simulation result depicts the performance of IPFC with POD as additional damping controller for control signal m_{i1}, first peak of speed deviation is reduced from 0.018rad/sec. to 0.014rad/sec. and settling time is reduced upto 0.43 sec. However, MFFN based IPFC reduces first swing from 0.018rad/sec to 0.004rad/sec with settling time 0.4 sec. Hence fuzzy based IPFC with damping controller m_{i1} shows robust performance.

The eigen values as shown in Table 1 lying on negative half of the s-plane shows the stablility of system.



a.Control signal m_{i1} b. Control signal $m_{i1}$and POD c. Control signal $m_{i1}$with MFFN

Fig.6 Time Domain Simulation of the signal m_{i1}

Table 1**:** Eigen value **c**omparison with POD controller and MFFN controller for control signal m_{i1}

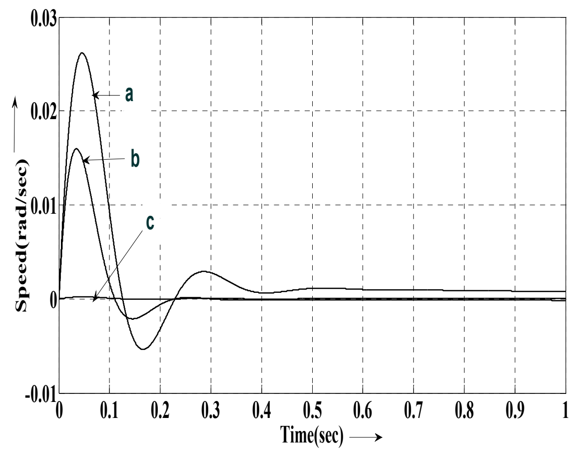
Control signal mi_1	With POD	With MFFN
-11.1052 ± 26.1203i	-14.6918 ±27.3709i	1.0e+002 *
0.0000	-19.4661	
-0.0022	-0.7128 ± 3.7544i	-5.7917
-0.7128 ± 3.7544i	-0.0721	-0.2382
		-0.1945
		-0.0071 ± 0.0375i
		0.0005

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

Fig.7 shows the satisfied performance of PI based IPFC, IPFC with POD as additional damping controller and MFFN based IPFC for control signal m_{i2}. Result indicates that with coordinated action of IPFC and POD Controller, first peak of speed deviation is reduced from 0.025 to 0.015 rad/sec with settling time 0.4 sec. and steady state error has been significantly.

Also, system is more amenable with MFFN which suppress the oscillations well and hence gives the best result. Hence, MFFN based IPFC significantly improves small signal stability of Single Machine Infinite Bus system.

Time domain result has been verified by obtaining eigen value analysis of PI based IPFC, IPFC with POD as additional damping controller and based IPFC for control signal m_{i2} as shown in Table 2 in which the negative real part of eigen values proves that the system is stable.



a.Control signal m_{i2} b. Control signal $m_{i2}$and POD c. Control signal m_{i2} with MFFN

Fig.7 Time Domain Analysis of the signal m_{i2}

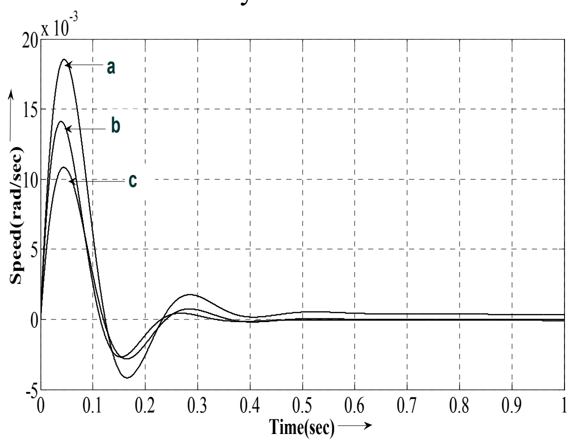
Table 2**:** Comparison with POD controller and MFFN controller for control signal $\mathbf{m_{i2}}$

Control signal mi_2	With POD	With MFFN
-11.0063 ±26.0774i	-18.6719 ±28.1777i	-11.0429 ±26.0939i
0.0000	-19.4655	-19.4666
-0.0022	-0.7128 ± 3.7544i	-0.7128 ± 3.7544i
-0.7128 ± 3.7544i	-0.0605	-0.1011

6.3 Dynamic performance of the system with control signal α_1

The MATLAB result as shown in Fig.8 demonstrates the satisfactory performance of PI based IPFC, IPFC with POD as additional damping controller and MFFN based IPFC for control signal α_1. Result indicates with MFFN based IPFC, first peak of speed deviation is reduced from 0.018 to 0.012 rad/sec, settling time is reduced. Also, system is more suitable with MFFN based controller which suppress the oscillations well and hence give the best result.

Time domain result has been verified by obtaining eigen value analysis which are tabulated in Table 3 in which all the eigen values regarding PI based IPFC, IPFC with POD as additional damping controller and MFFN based IPFC for control signal α_1 respectively lies on negative part of real axis which ensures that the system is stable.



a.Control signal α_1 b. Control signal α_1 and POD c. Control signal α_1 with MFFN
Fig.8 Time Domain Analysis of the signal α_1

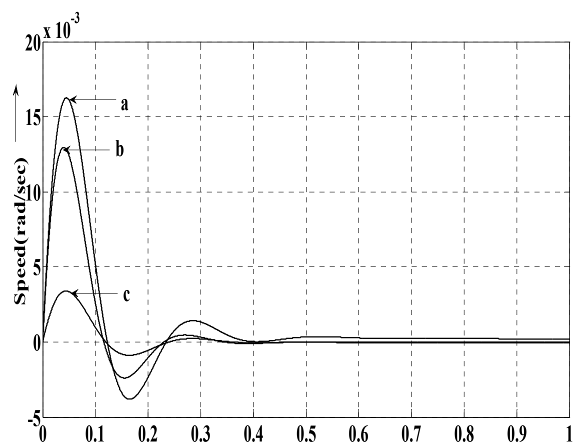
6.4. Dynamic performance of the system with control signal α_2

With coordinated action of IPFC and POD as additional damping controller, reduction in peak amplitude, settling time and steady error are delineated in Fig. 9. However, MFFN based IPFC shows the improvement in the response of the system for control signal α_2 in which first peak of speed deviation is reduced from 0.016 to 0.003 rad/sec with settling time 0.4 sec. This again highlights the efficacy of the MFFN based IPFC.

This inference has been checked by obtaining eigen value analysis of PI based IPFC, IPFC with POD as additional damping controller and MFFN based IPFC for control signal α_2 as displayed in Table 4. System is stability is shown by negative real part of eigen value .

Table 3**:** Comparison with POD controller and MFFN controller for control signal α_1

Control signal α_1	With POD	With MFFN
-11.1140 ±26.1241i	-15.6530 ±27.4281i	-10.3873 ±25.8504i
0.0000	-4.5630	-4.8569
-0.0022	-0.7128 ± 3.7544i	-0.7128 ± 3.7544i
-0.7128 ± 3.7544i	-0.0727	-0.1058
	-0.0026	-0.0018



a.Control signal α_2 b. Control signal α_2 and POD c. Control signal α_2 with MFFN
Fig.9.Time Domain Analysis of the signal α_2

Table 3**:** Comparison with POD controller and MFFN controller for control signal α_2

Control signal α_2	With POD	With MFFN
-11.1351 ± 26.1331i	-14.4546 +27.1546i	-10.3873± 25.8504i
0.0000	-4.6185	-4.8569
-0.0022	-0.7128 + 3.7544i	-0.7128 ± 3.7544i
-0.7128 ± 3.7544i	-0.0767	-0.1058

The comparative performance of Fig. 6,7,8,9 justified that MFFN based IPFC with pulse width modulation index of voltage series converter 1 and 2 (m_{i2} and α_2) are damps the oscillations more effectively. This inference has been checked by obtaining eigen value analysis which indicates that the system is stable.

5. CONCLUSION

In this paper, a systematic approach for determining relative effectiveness of Interline Power Flow Controller (IPFC) control signals (mi_1, α_1, mi_2, α_2) in damping low frequency oscillations has been presented. The linearized power system model of Single Machine Infinite Bus system for analyzing the performance of MFFN based IPFC for variation in system parameters has been studied. These control signals shows the significant improvement in damping of power system performance. Investigations have revealed that IPFC control signals m_{i2} and α_2 provide robust performance over other signals. The proposed MFFN Controller performance is comparatively better than PI based controller. The MFFN strategy have been designed to minimize transients swing, improvement in damping of oscillations. The controllers comparative performance in terms of small signal stability improvement and damping of oscillations is demonstrated. The MFFN demonstrates the robust performance and easy to coordinate with damping schemes. The proposed controller fulfills the main objective of this paper. Time domain analysis and eigen value analysis results demonstrated the IPFC performance.

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APPENDIX-A

A.1. Generator

$M=2H=0.1787, T_{do}^{1}=5.044$, $V_b=1$ p.u.

A.2. Excitation system

$K_a=50.0$, $T_a=0.05$

A.2. Constants

$K_1=0.3837$, $K_2=-0.1717$, $K_3=3.6667$, $K_4=-0.7350$, $K_5=-0.0237$, $K_6=1.0659$, $K_7=-0.0139$, $K_8=-0.6890$, $K_9=0.0023$

A.3. Interline Power Flow Controller Parameters

$K_{p\alpha 1}=0.0376$, $K_{q\alpha 1}=0.0010$, $K_{v\alpha 1}=-0.0029$, $K_{c\alpha 1}=0.0672$,

$K_{p\alpha 2}=-0.0045$, $K_{q\alpha 2}=0.0033$, $K_{v\alpha 2}=-0.0021$, $K_{c\alpha 2}=-0.01116$,

$K_{pmi1}=0.0552$, $K_{qmi1}=-0.0326$, $K_{vmi1}=-0.0360$, $K_{cmi1}=-0.000766$,

$K_{pmi2}=0.2530$, $K_{qmi2}=0.0056$, $K_{vmi2}=-0.0038$, $K_{cmi2=-0.0087}$, $K_{pp}=1$, $K_{pi}=0.5$