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Simultaneous Design of PSS and FACTS based Power Oscillation Damping Controller Using GA and ANFIS Techniques

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Abstract: An adaptive Neuro- Fuzzy Inference System (ANFIS) based Flexible AC Transmission System Power Oscillation Damping controller (FACTS POD) is proposed in this paper. The controller is tuned with Genetic Algorithm (GA) for coordination with Power System Stabilizer (PSS) to damp the low frequency oscillations in power systems. The work considers PSS installation on optimum machines using (sensitivity of PSS effect) SPE approach for damping the local modes of oscillation and the ANFIS based FACTS POD is considered for damping the inter-area mode of oscillation. A hybrid learning procedure is adopted to adapt the initial fuzzy parameters of the proposed POD controller for desired damping performance. The input-output data pairs for training the adaptive network is generated by using the GA based design procedure. The proposed technique is employed for simultaneous design of PSS and FACTS POD for power oscillation damping support. The effectiveness of the proposed damping controllers is examined on the modified New-England system with Unified Power Flow Controller (UPFC) FACTS device and non-linear simulation results are presented.

Keywords: ANFIS, FACTS POD, GA, low frequency oscillations, SPE approach, hybrid learning, UPFC**.**

I. Introduction

In multi-machine systems involving large number of machines and many interconnections, there are various modes of oscillations which include low frequency oscillations on account of local modes involving machines geographically near to eachother and the inter-area oscillations when power transfer among different geographically distinct areas takes place through weak tie-lines. [1-2]. The traditional approach to damp the local mode oscillations is the installation of PSS, to provide supplementary control action through the excitation system of generators [1]. Application of high power electronic devices has made the concept of FACTS feasible for power flow control, voltage control and also for enhancing the damping of low frequency electromechanical oscillations [3]. Various works have been done and published on the damping of power system low frequency oscillations with FACTS based damping controllers. Design of UPFC controllers and supplementary damping controller for stability enhancement with UPFC on a longitudinal power system is presented in [4]. Wang has proposed [5-6] modified linearized Phillips-Heffron model for low frequency oscillation study to include the various FACTS members and the model has been extended to multi-machine systems. Tambey.N and Kothari.M.L in [7] have presented designing of UPFC based damping controller using phase compensation technique. The relative effectiveness of modulating the various UPFC controller parameters for damping power system oscillations has been analyzed in the paper. In [8], the same authors have presented the design of UPFC based damping controller in multi-machine systems, in which simultaneous modulation of two UPFC control signals has been proposed. In all the above works, the controller design is done linearizing the system equations with respect to a nominal operating point. However, power networks are subjected to large variations in operating conditions due to development of real time market, emergency operating conditions as well as actions due to automatic devices. Hence the performance of the controller in damping the power system oscillations gets affected as the operating points varies from the value based on which it is designed. [9-10] discusses the issues pertaining to negative interactions between the various damping devices in multi-machine power systems and also suggests various approaches for proper coordination of these devices. The proposed design procedures relies on the full-order model of the power system and there may be the need to retune the parameter setting of damping controllers if the system configuration is significantly changed. However, in a widely interconnected power system, such changes are common and may pose frequent tuning requirements, which is undesirable.

In the application of PSS to increase the damping of poorly damped local modes in a multi-machine system, the first step is to determine the best location for the PSS. Employing each machine with PSS need not result in improved damping and thus there is a need for identifying the optimum number of machines to be equipped with PSS. This paper considers the sensitivity approach [11] for identifying the optimum PSS location in a multi-machine system. The problem of FACTS POD design in the presence of PSS is a complex exercise, as uncoordinated local control of these controllers may cause destabilizing interactions. To improve overall system performance, this paper proposes simultaneous design of PSS and FACTS POD parameters using GA technique for damping the local swing modes and the inter-area mode of oscillations. ANFIS technique is proposed to incorporate adaptivity to the POD controller. Thus, the suggested method combines the advantages offered by the heuristic search algorithm and the robust adaptive technique. These approaches are examined on a 10-machine, 39-bus system installed with UPFC to validate the improvement in damping performance of the system.

II. Power System Model With UPFC

Fig.1 shows an *n*-machine power system with UPFC installed between nodes 1 and 2. The UPFC consists of an excitation transformer (ET), a boosting transformer (BT), two three phase GTO based voltage source converters (VSCs) and a DC link capacitor. In Fig.1 m_E, m_B, δ_E, δ_B denote the input control signal of each VSC namely the amplitude modulation ratios and phase angles of control signal of each VSC.

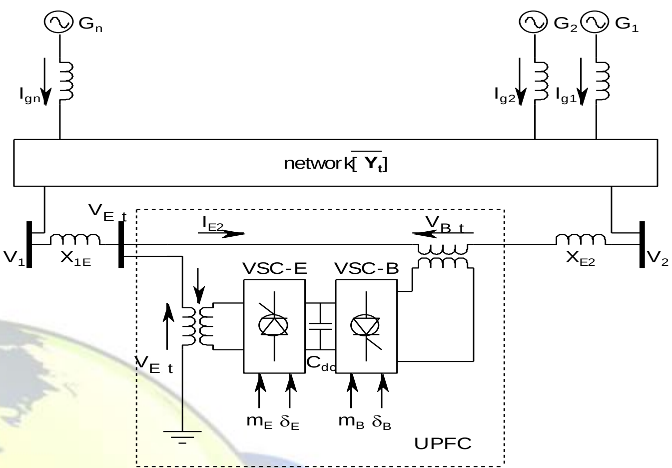

Fig.1.An n-machine power system installed with UPFC

III. Simultaneous Design Of PSS And POD Parameters

The PSS is designed targeting at damping the local mode of oscillations. It acts through the excitation system to import a component of additional damping torque proportional to speed change. The input *I* for each PSS is $\Delta\omega M_i$ where *M* is the machine identified for damping of the mode *i*. The output control signal *U* is imported through the excitation system of the machine. For the design of POD for UPFC, the controller parameters are designed targeting at damping of the inter-area mode of oscillation. The feedback signal *I* for the POD is chosen as deviation in power flow in the line ΔP_{eline} at which UPFC is connected which can be locally measured and the output control signal modulates the phase angles of series converter voltage (δ_B), the signal identified as the most significant UPFC control signal for power oscillation damping support. The structures of PSS and FACTS POD are shown in Fig. 2. It involves a transfer function consisting of an amplification block K_{PSS}/K_{POD}, a wash out block and one or more stages of lag-lead blocks to produce the required compensation.

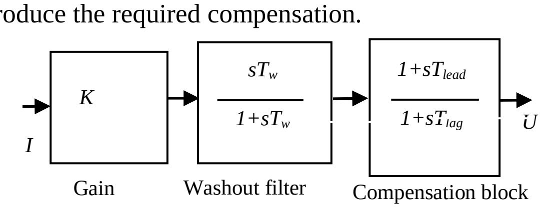

Fig. 2 PSS/POD structure

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The structure of Power System with proposed PSS and FACTS POD is shown in Fig. 3. As shown in the Fig., the PSS and POD parameters are identified using GA technique based on the algorithm shown in Fig.4 and further, the data obtained from GA tuned data base is used for training the ANFIS for FACTS POD.

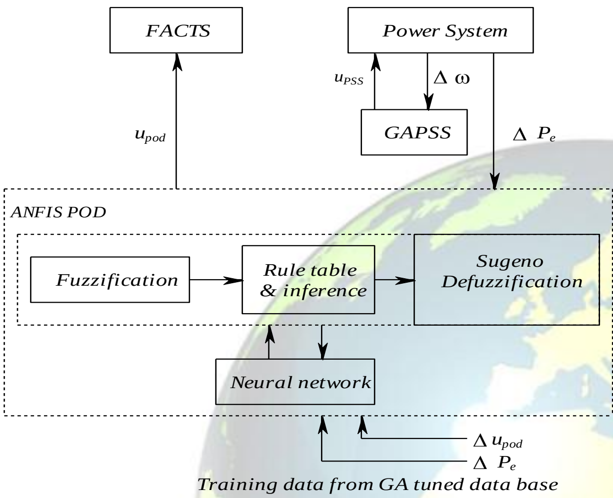

Fig. 3.Structure of Power System with proposed PSS and FACTS POD

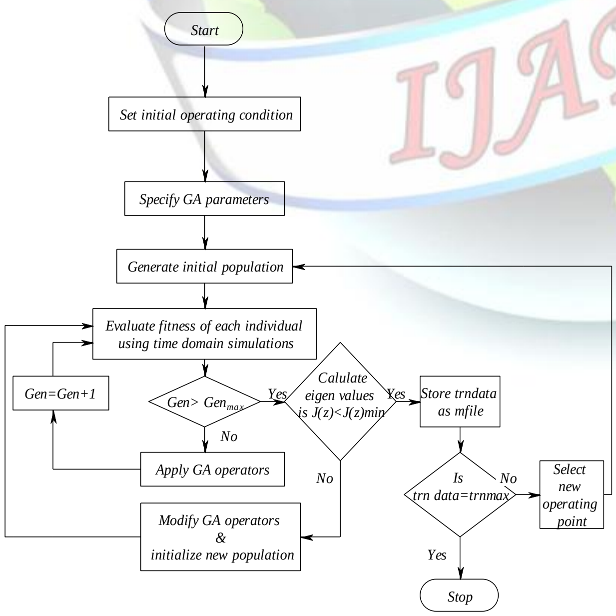

Fig. 4. Flow chart for the proposed Genetic Algorithm

The objective of the algorithm is to optimize the parameters of the gain and time constants of the PSS ($K_{PSS/}$,T_{lead} &T_{lag})and FACTSPOD(K_{POD}, T_{lead} &T_{lag}) for improved overall damping performance. The time domain simulations of the non-linear dynamic model of the system provide the fitness function chosen for optimization.

To provide robustness and adaptivity for the FACTS damping controller, neuro fuzzy based adaptive FACTS POD is proposed in this paper. The adaptive fuzzy controller is obtained by embedding the fuzzy inference system into the framework of artificial neural networks.

The design procedure for the proposed ANFIS POD consists of

(a) Determination of initial fuzzy structure.

(b) ANFIS training of the initial fuzzy structure for updating the fuzzy parameters to meet the desired control performance.

a) Determination of initial fuzzy structure

For the proposed fuzzy structure, the input is taken as the deviation in the active power flow in the line installed with UPFC, ΔP_{eline} and the output is the damping control signal, ΔU_{POD} same as in the case of constant gain controller. The linguistic rules, considering the dependence of the plant output on the controlling signal, are used to build the initial fuzzy inference structure

This work considers the generalized bell-shaped function as the initial fuzzy membership function for the premise parameters [14]. The seven *MFs* with the spacing [-1 1] and with degree of membership maximum equal to 1 and minimum equal to 0 and is given by

$$\mu A_i(X) = \frac{1}{1+\left|\frac{x-c_i}{a_i}\right|^{2b_i}}, i = 1to7 \quad (4)$$

The rule base with seven fuzzy if-then rules of (TS) Takagi and Sugeno's type [15] given by

$$If\ \Delta P_{elinei}\ is\ A_i\ then\ \Delta u_i\ is\ p_i x + r_i\ ; i = 1to7 \quad (5)$$

The output ΔU, the output control signal of the damping controller is calculated by the linear combination of the inputs and $\{p_i, r_i\}$ denote the consequent parameter set. These parameters are updated by ANFIS training process

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presented in section (b). However the seven rules of the initial fuzzy structure remain unchanged during the adaptation process

b) ANFIS training

The steps for ANFIS training to adapt the initial fuzzy premise parameters for construction of the proposed optimum input- output pattern are:

i) Selection of the network architecture

A four layer feed forward network architecture is selected for the ANFIS based damping controller. The node functions of the various layers of ANFIS for the adjustments of premise parameter set $\{a_i,b_i,c_i\}$ are as follows.

Layer1: This layer has adaptive nodes denoted by squares with node function

$$O_i^1 = \mu A_i(X); \quad i = 1 \; to \; 7 \tag{6}$$

where X is the input to node i, A_i the linguistic label associated with this node. Oi specify the degree to which the given X satisfies the quantifier A_i. Parameters in this layer are referred to as premise parameters is denoted by the parameter set $\{a_i,b_i,c_i\}$

Layer 2: Every node in this layer is fixed, denoted by circle, which calculates the ratio of the i^{th} rule's firing strength to the sum of all rules' firing strengths

$$\varpi_i = \omega_i \Big/ \sum_{i=1}^{7} \omega_i \tag{7}$$

Where ω_i represent the firing strengths of each rule and ϖ_i the normalized firing strengths for the output function.

Layer 3: This adaptive node layer represented by squares has a node function

$$O_i^3 = \varpi_i f_i = \varpi_i (p_i X + r_i), \quad i = 1 to 7 \tag{8}$$

$\{p_i,r_i\}$is the parameter set of this adaptive layer and is referred to as consequent parameters

Layer 4: The single node in this layer represented by a circle labeled Σ computes the overall output as the summations of all incoming signals

$$O_i^4 = \sum_{i=1}^{7} \varpi_i f_i = \sum_{i=1}^{7} (p_i X + r_i) \tag{9}$$

ii). *Learning Algorithm*

The learning method adopted in this paper is the hybrid learning rule combining the learning rule based on the gradient descent method and the Least Square Error (LSE) method [16].

IV. Test System And Controller Parameters

The proposed controller performance is examined on a 10-machine, 39-bus system with a UPFC connected between buses 14 and 34 as shown in Fig.5. The UPFC is proposed to be installed in the system to modulate the power flow through the line 14-34 by 10% and accordingly, the UPFC ratings are chosen [17-18].

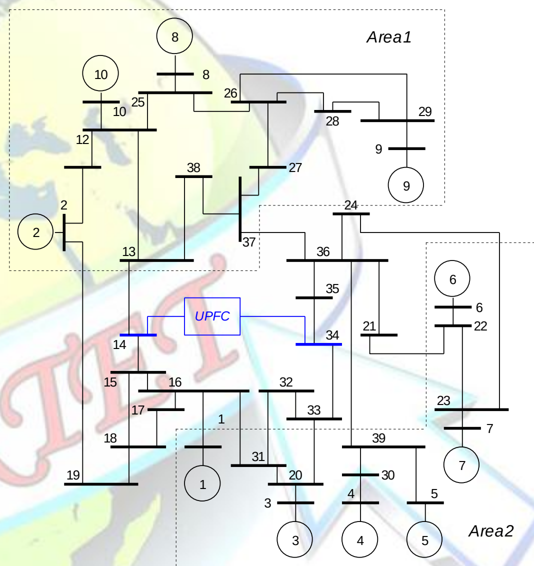

Fig.5.New England System modified with UPFC

The various steps involved in the method adopted for identifying PSS locations and proposed design of PSS and POD parameters are:

i. Identification of optimum PSS location using sensitivity of PSS effect (SPE)
ii. Sequential design of PSS and POD parameters using conventional method
iii. Simultaneous design of PSS and POD parameters using GA
iv. ANFIS training of POD using GA tuned training

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A. *Optimum PSS location for the test system*

For the system shown in Fig.5, the eigen values are computed and the swing modes are listed in the Table1. From the Table, it is observed that swing modes λ_2, λ_3 , λ_5, λ_7 are poorly damped and are needed to be compensated. Among these λ_7 with a low frequency of nearly 0.8Hz is an inter-area mode and the remaining are local modes.

TABLE I
SWING MODES OF THE TEST SYSTEM

Swing Modes	$-\sigma \pm \omega_d i$	f(Hz)	ξ
λ_1	-0.3885 ± 12.4347i	1.9790	0.0312
λ_2	-0.0874 ± 8.6397i	1.3751	0.0101
λ_3	-0.0841 ± 7.9244i	1.2612	0.0106
λ_4	-0.3846 ± 7.3530i	0.8738	0.0699
λ_5	-0.1397 ± 5.4902i	0.8738	0.0254
λ_6	-0.3750 ±10.3184i	1.6422	0.0363
λ_7	-0.0300 ± 5.2830i	0.8408	0.0057
λ_8	-0.4310 ± 6.0658i	0.9654	0.0709
λ_9	-0.5682 ± 8.6110i	1.3705	0.0658

Participation of each machine into these modes is shown in Table 2 (magnitude only).

From the machine participation listed in Table 2, it is observed that the machines M_1, M_3, M_4, M_5, M_6 and M_7 are participating in the local modes λ_2, λ_3 and have negligible participation in the local mode λ_5. The remaining machines M_2, M_8, M_9 and M_{10} are involved in the local mode λ_5 and they are found to have negligible participation in λ_2 and λ_3.

However with respect to the inter-area mode λ_7, all machines are found to have considerable participation. Based on this information, the system is considered to be operating as two areas, *Area 1* comprising of M_1, M_3, M_4, M_5, M_6 andM_7 and *Area 2* of M_2, M_8, M_9 and M_{10} machines. The low frequency inter-area mode represents the swinging of *Area1* with respect to *Area 2*.

TABLE III
PARTICIPATION FACTOR OF MACHINES IN SWING MODES

Swing Mode / Machine	λ_2	λ_3	λ_5	λ_7
1	0.5000	0.0874	0.0012	0.5013
2	0.0001	0.0015	0.5002	0.0270
3	0.4011	0.5007	0.0010	0.1448
4	0.5013	0.3282	0.0006	0.5001
5	0.5011	0.4176	0.000	0.5003
6	0.3240	0.4451	0.0003	0.2290
7	0.1530	0.5002	0.0007	0.1987
8	0.0004	0.0011	0.1617	0.5011
9	0.0003	0.000	0.4060	0.1624
10	0.0003	0.0010	0.5011	0.5003

For identification of machine for PSS location, the machines with major participation with respect to each local mode are selected from the participation table and the most significant machine location is identified using the SPE approach. With respect toλ_2, M_1, M_4 and M_5 with nearly equal participation are chosen for finding the SPE and M_3, and M_7, are chosen for finding SPE with respect to λ_3. Similarly for λ_5, M_2 and M_{10} are considered.

The SPE computed for the machines [11] with the corresponding eigen modes are given in table 3

Based on the SPE computations, the PSS locations are suggested on

M_5 for damping of local mode λ_2
M_7 for damping of local mode λ_3
M_{10} for damping of local mode λ_5

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TABLE IIIII
SPE OF SELECTED MACHINES W.R.T. LOCAL MODES

 # Not applicable

Local mode → / Machine ↓	λ_2	λ_3	λ_5
M₁	0.2330	#	#
M₂	#	#	0.0498
M₃	#	0.0117	#
M₄	0.0027	#	#
M₅	0.3936	#	#
M₇	#	1.000	#
M₁₀	#	#	0.1632

B. Sequential design of PSS and POD parameters

The PSS parameters for the identified machines are designed targeting damping the local modes λ_2, λ_3, λ_5 and POD parameters are designed for damping of the low frequency inter-area mode λ. The design of these controller parameters is done sequentially using the conventional residue approach and phase compensation technique [19]. The controller parameters obtained for the system at nominal operating condition is shown in Table 4.To achieve the required compensation angle, the number of stages of compensation blocks is 1 for PSS and 2 for FACTS POD.

The transfer function of the PSS controller is obtained as

$$H_{PSS}(s) = K_{PSS}\frac{sT_w}{1+sT_w}\left[\frac{1+sT_{lead}}{1+sT_{lag}}\right] \quad (10)$$

The transfer function of the FACTS POD is obtained as

$$H_{POD}(s) = K_{POD}\frac{sT_w}{1+sT_w}\left[\frac{1+sT_{lead}}{1+sT_{lag}}\right]^2 \quad (11)$$

C. Simultaneous design of PSS and POD parameters

The simultaneous design PSS and POD parameters is done using GA technique and further, the data obtained from GA tuned data base is used for training the ANFIS for FACTS POD. The time domain simulations of the non-linear dynamic model of the system provide the fitness function chosen for optimization. The fault sequence for the simulation of fitness function is

Triggering of a 3φ SC on the line 14-34, the line on which the UPFC is installed which is cleared at 5 cycles. The fitness function chosen is the Integral absolute error given by

TABLE IVV
CONTROLLER PARAMETERS FOR NOMINAL OPERATING CONDITION

Eigen mode		***Controller Type***	***Feedback signal***	***Gain***	T_w **(s)**	T_{lead}**(s)**	T_{lag}**(s)**
local mode	λ_2	PSS	$\Delta\omega_{M5}$	11.4	10	0.0980	0.1095
	λ_3	PSS	$\Delta\omega_{M7}$	22.55	10	0.1227	0.1250
	λ_5	PSS	$\Delta\omega_{M10}$	28.19	10	0.0023	0.0427
Inter-area mode	λ_7	FACTS POD	$\Delta P_{e(14\text{-}34)}$	27.89	10	0.0025	0.0448

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$$F = ITAE = \int_{t=0}^{t_{sim}} t\left|\delta_{Area1}(t) - \delta_{Area2}(t)\right| dt \qquad (12)$$

$$s.t.\ J(z) \le \varepsilon$$

$$\delta_{Area1}(t) = COA_1 = \frac{\sum_{k \in Area_1} S_k H_k \delta_k(t)}{\sum_{k \in Area_1} S_k H_k}$$

$$\delta_{Area2}(t) = COA_2 = \frac{\sum_{k \in Area_2} S_k H_k \delta_k(t)}{\sum_{k \in Area_2} S_k H_k} \qquad (13)$$

$$J(z) = CDI = \sum_{i=1}^{n} (1 - \varsigma_i)$$

COA1& COA2 denote the center of power angle [20-21] of the corresponding area, tsim is the simulation period considered and CDI [20] denote the comprehensive damping index. S_k is the base MVA of k^{th} machine and H_k denote the concerned machine inertia.

The algorithm adopted for GA tuning given in Fig.4, is used for the searching of the best individuals based on fitness function given by eqn. (12). The fitness function comes from the time domain simulation of the dynamic model for the fault sequence considered. The inequality constrain given by eqn. (13) ensures minimum damping for all dominant eigen modes of the system

D. .ANFIS training of POD using GA tuned training data

The optimization procedure is repeated for various fault sequences to obtain training data for the ANFIS structure. The fault sequences considered are,

- *Initiating 3φ SC at each machine terminal and clearing the fault at various clearing times.*
- *Triggering 3φ SC on major lines in Area1 and Area 2 and clearing the fault at various clearing times*

The relevant ANFIS training details for the test system are:

- *Number of nodes: 32, Number of linear parameters: 14,*
- *Number of nonlinear parameters: 21, Total number of parameters: 35*
- *Number of GA tuned training data pairs: 1652*
- *ANFIS training terminated at epoch 40, Training Error 0.0441*

V. SIMULATION RESULTS

To examine the performance of the proposed controllers, system is subjected to non-linear disturbances with the conventional PSS& POD (CPSS&CPOD) and also with the GA tuned PSS & ANFIS based POD (GAPSS & ANFISPOD) with various types of fault conditions. Significant cases are presented here.

Case.1. Three phase SC on machine terminal

To validate the controller performance of PSS installed on identified machine to improve the poorly damped local mode of oscillations, each of these machine terminal is subjected to 3φ SC initiated at t=1 sec of simulation period and cleared at 5 cycles and 6.5 cycles. Fig. 6 to 8 show the time response of rotor angle of the concerned machine with respect to M_3 for *Area1* machines and M_2 for *Area2* machines.

From the simulation results it is observed that the system damping is improving with the proposed controller parameters when subjected to large disturbances. On increasing the clearing time to 6.5 cycles, the system is becoming unstable with drift in rotor angle, when performing with CPSS &CPOD controllers. However, when operating with the proposed GAPSS and ANFIS POD controllers, the system is quite stable as shown in Fig. 6 to Fig.8. From the simulation results it is also observed that the first swing magnitude has improved significantly with the proposed controllers.

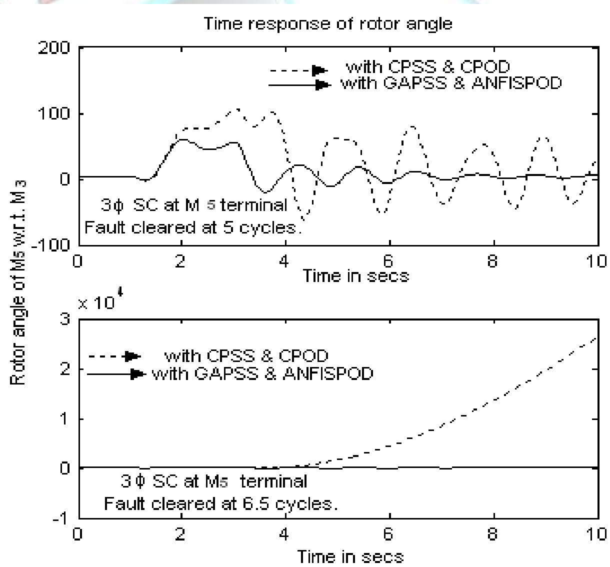

Fig.6.Relative rotor angle of M_5 w.r.t M_3

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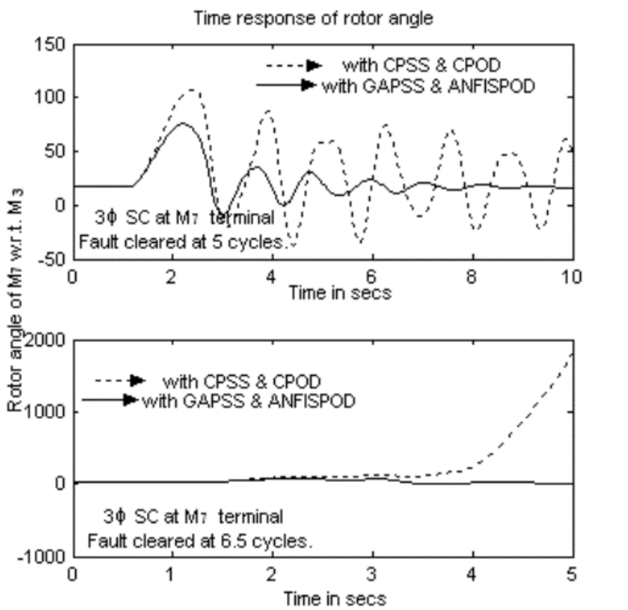

Fig.7.Relative rotor angle of M_7 w.r.t M_3

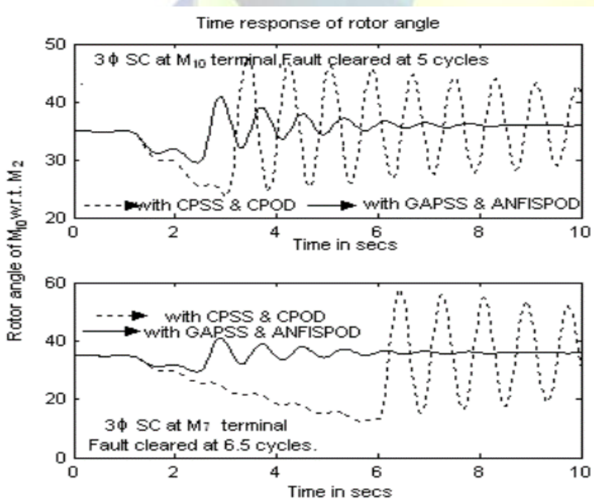

Fig.8.Relative rotor angle of M_{10} w.r.t M_2

Case.2. Three phase SC on line 14-34

To evaluate the performance of FACTS POD controller, an oscillation is triggered by initiating a 3φ SC on line 14-34 at 1 sec of simulation, which is cleared at 5 cycles. The inter- area oscillations are examined by plotting the COA of *Area 1* w.r.t COA of *Area 2* given by eqn. (14) and the simulation result is shown in Fig. 9.

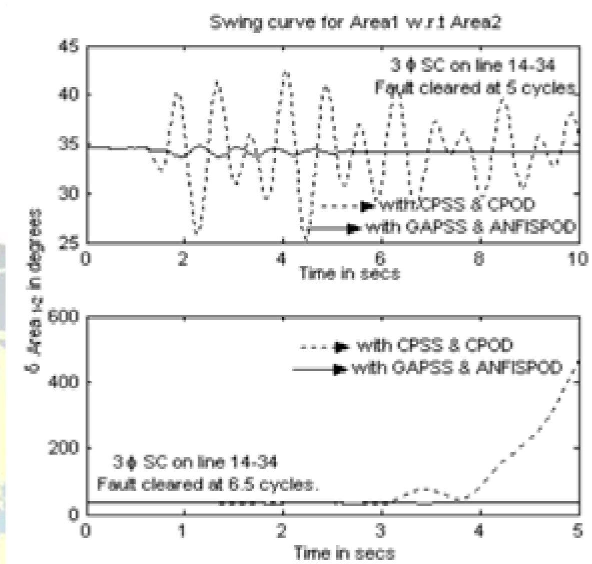

Fig.9.COA of *Area1*w.r.t *Area2*

The figure validates the improved damping behavior of the proposed controller compared to CPSS & CPOD

Figure also shows the swing curve of Area 1 w.r.t Area2 for the system when the clearing angle is increased to 6.5 cycles. The inter-area oscillations are undamped in this case making the system unstable when performing with the conventional stabilizers, but it remains stable with the proposed stabilizers.

VI. Conclusion

In this paper an adaptive approach based on ANFIS technique with GA based training data, for the design of FACTS POD to damp the low frequency oscillations in power system is proposed. The heuristic search genetic algorithm used for coordinated design of PSS and FACTS POD parameters requires minimal system knowledge. The freedom in choice of fitness function offered by the algorithm makes the fitness evaluation and parameter identification less complex and fittest population is captured from time domain simulation. To combine adaptivity offered by neural networks and robustness by fuzzy logic for damping performance, ANFIS technique is adopted to adapt the POD to various system faults. The proposed controller is examined on a 10-Machine 39- Bus system installed with UPFC. The system performance under the presence of large disturbances is examined to validate the damping function of the PSS and FACTS POD. The proposed technique is found to be improving the damping and the transient stability margin of the system under large disturbance compared to conventional approach.

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