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ANFIS UPFC Damping Controller for Multi machines Power Systems Oscillations

***Abstract**. The main purpose of this paper is to investigate an Adaptive Neuron- Fuzzy Inference System (ANFIS) based supplementary Unified Power Flow Controller (UPFC) in superimposing a damping function on the control signal of UPFC who's incorporated in multi-machines power system. This control scheme designed to produce supplementary signal for damping oscillations in the interconnected power systems. The improved damping performance was studied and it is validated on a benchmark power system example taken from literature.The control actions are formulated as a set of local controllers, which are coordinated to maintain transient angle stability, transient voltage stability and damping of inter-area and local oscillations following a disturbance.*

***Streszczenie.** W artykule przedstawiono wyniki badania sterownika przepływu mocy UPFC wykorzystującego system ANFIS zastosowanego w systemie wielogeneratorowym. Celem było tłumienie oscylacji na połączeniach. (**Sterownik ANFIS UPFC tłumiący oscylacje w systemie złożonym z wielu generatorów**)*

Keywords: Power system stability, unified power flow controller (UPFC), frequency oscillations, ANFIS.
Słowa kluczowe: stabilność system energetycznego, przepływ mocy, system wielogeneratorowy

Introduction

Low frequency oscillations are a problem of major concern in power systems, as they place limits on power transfers, restricting the full utilization of transmission capacity. In [2] a power frequency model for UPFC is derived with its dc link capacitor dynamics included to study the UPFC effects on power system stability and a novel UPFC-network interface as suggested in [3] in order to participate the UPFC model into the conventional transient stability analysis program with good convergence and accuracy in time simulation. The application of the UPFC to the modern power system can therefore lead to more flexible, secure and economic operation. Investigations on the UPFC main control effects show that the UPFC can improve system transient stability and enhance the system transfer limit as well. The UPFC-network interface method work very well in the study of system dynamic behaviour.

Transient stability control (large-disturbance rotor angle stability) considers the problem of loss of synchronism among synchronous machines when subjected to a large disturbance, such as a short circuit on a transmission line [4]. Voltage regulation is the maintenance of required voltages at all buses during normal operation or after a disturbance. The unified power flow controller (UPFC) is the most versatile device in the flexible ac transmission systems (FACTS) which can provide superior power flow and voltage control through its main control. It can also improve power system dynamic performance through its supplementary control. During the past decade, many researches on the principles and simulation of UPFC have been made. In digital simulation, electromagnetic transient programs are widely used for UPFC analysis [4]. However in the study of power system transient and steady-state stability, a dynamic model for UPFC is required to interface UPFC to the quasi-static model of ac transmission network and to analyze its effects on large-scale power systems. Some papers suggest UPFC power frequency models which were limited to be used in one machine to infinite bus system [5], [6].

The basic structure of the type of fuzzy inference system is a model that maps input characteristics to input membership functions, input membership function to rules, rules to a set of output characteristics, output characteristics to output membership functions, and the output membership function to a single-valued output or a decision associated with the output. The adaptive neuro-fuzzy inference system (ANFIS) is learning method whose works similarly to that of neural networks. The adaptive fuzzy controller is obtained by embedding the fuzzy inference system into the framework of adaptive networks. The proposed ANFIS based damping controller performance is examined for the four choices of UPFC control signals based on modulating index and voltage phase angle of UPFC. series and shunt converters by nonlinear simulations.

In this paper, a power frequency model for UPFC is used with its dc link capacitor dynamics included and is suitable to be used in the study of UPFC effects on the real power system dynamic behaviour. A novel UPFC-network interface as in [4] is also developed. In this model the UPFC shunt element control is to keep the UPFC terminal ac bus voltage and the dc link capacitor voltage constant. The supplementary control of UPFC is added to damp power oscillation along the tie lines after disturbances.

UPFC Mathematical Model

The basic UPFC structure is depicted in Fig. 1; were all the variables used in UPFC model are denoted. We first consider the UPFC dc link capacitor charging dynamics.

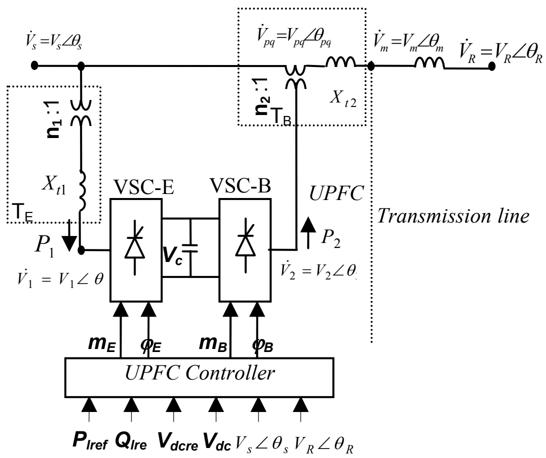


Fig. 1. Transmission line with UPFC installed.

The UPFC consists of one shunt converter and one series converter connected together through a common dc capacitor. It is capable of controlling real and reactive power flow, local voltage magnitude and damping power oscillations. The shunt converter is primarily used to provide the real power demand of the series converter at the common dc link terminal from the ac power system. It can also generate or absorb reactive power at its ac terminal, which is independent of the active power transfer to (or from) the dc terminal. Therefore, with proper control, it can also fulfil the function of an independent advanced static VAR compensator providing reactive power compensation for the transmission line and thus executing indirect voltage regulation at the input terminal of the UPFC. The main equations are listed below:

(1) $$CV_{dc}\frac{dV_{dc}}{dt} = (P_1 - P_2)S_B$$

where

(2) $$P_1 = \Re e\left(\dot{V}_1\dot{I}_1^*\right) = \Re e\left(\dot{V}_1\left(\frac{n_1\dot{V}_s - \dot{V}_1}{jX_{t1}}\right)^*\right)$$

(3) $$P_2 = \Re e\left(\dot{V}_{pq}\dot{I}_L^*\right) = \Re e\left(\dot{V}_{pq}\left(\frac{\dot{V}_s + \dot{V}_{pq} - \dot{V}_R}{jX_{t2}}\right)^*\right)$$

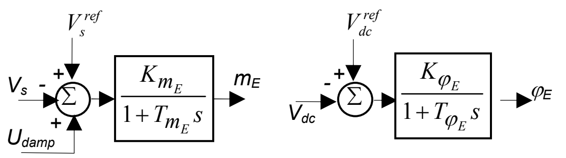
(4) $$V_1 = \frac{m_E V_{dc}}{V_B} \qquad \theta_1 = \theta_s - \varphi_E$$

(5) $$V_{pq} = \frac{m_B V_{dc}}{V_B n_2} \qquad \theta_{pq} = \theta_s - \varphi_B$$

The desired coefficients representing the PWM control m_E, m_B and the firing angles φ_E and φ_B of the two converters can be obtained from UPFC main control system.
V_S, V_R, are the sending and receiving end phasor voltages; S_B, V_B, are the system MVA and voltage base; and * denotes complex conjugate.

UPFC main control

The shunt and series VSC control strategies adopted in this paper are shown in Fig. 3 and Fig. 4 respectively. In Fig. 3, the constant ac terminal bus voltage control is achieved by controlling mE of the PWM controller of VSC-E, and the constant dc link capacitor voltage control realized by controlling the firing angle φ_E of VSC-E. The controller is modelled as a simplified 1st order inertia block. There is no difficulty to consider complex control strategies.



(a) UPFC ac terminal bus voltage control

(b) dc link capacitor Voltage control

Fig. 2. The UPFC shunt controller

In Fig. 3(a), the constant real and reactive power flow control is achieved by controlling mB and φB. It is clear that, the UPFC output series compensation voltage Vpq can be decomposed as Vp and Vq. And the former is perpendicular to VS and has strong impacts on real power flow, while the latter is in phase with Vs and has significant effects on reactive power flow.

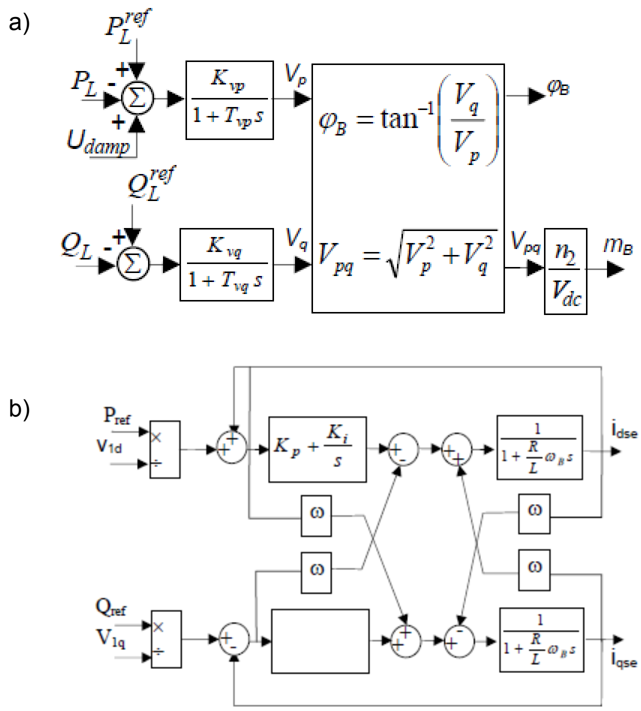


Fig.3. The UPFC series controllers : (a) constant active and reactive power flow control, (b) active and reactive power flow control

Damping Controller Design

The UPFC is installed for the purpose of multiple control functions, one of which will be the suppression of low-frequency oscillations occurring in the system. In literature [2-5] the effectiveness of improving the oscillation damping by a FACTS supplementary damping controller has been explored. Various feedback signals namely, deviation in generator rotor angle, deviations in real power flow through the transmission line, accelerating power, have been identified as capable of contributing direct electric damping torque to the electromechanical oscillation loop of the generator.

The supplementary control can be applied to the shunt element control via voltage modulation or to the series element via power modulation, voltage modulation, phase-shift-angle modulation or series compensation degree modulation depending on the control strategy currently used. In order to avoid unnecessary switching of control strategy, right after the first swing the control returns to the constant real and reactive power control. Therefore two different damping schemes are tested in this paper. One is the voltage modulation in voltage control of the shunt element (see U_{damp} in Fig. 2(a)). The other is power modulation in constant power control of the series element (see U_{damp} in Fig. 3(a)). In our paper the input signal used for supplementary control is the tie line real power flow or its terminal voltage phase angle difference. The supplementary control has a PSS-like transfer function which is given in Fig. 4.

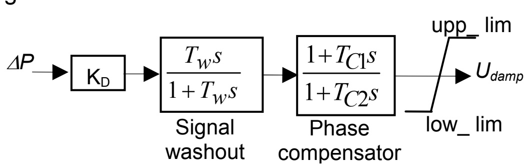


Fig. 4. Supplementary control block diagram.

Multi-machine system modelling

A 3-machines 9-bus system as shown in Fig.4 is considered [8] by incorporating a UPFC in the line 7-8. The power system is represented by the non-linear equations (6). Excitation system Type-1 IEEE is considered for all machines and they are assumed to be provided with power system stabilizers. The system data are given in reference [8].The UPFC ratings are so chosen to enhance the power flow through the line 7-8 by 10% along with sufficient transient and design margin [3]. The steady state values for the UPFC series and shunt voltages are computed by modifying the load flow programme with UPFC embedded line.

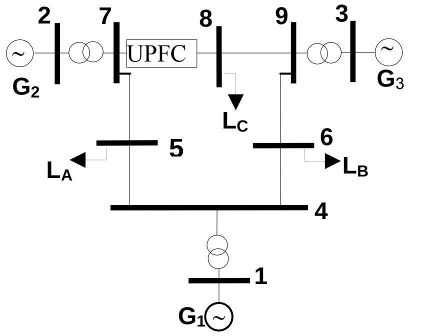


Fig. 5. 3-Machines, 9-Bus system installed with UPFC [8]

Interface of UPFC to the AC Network

The interface calculation of UPFC to ac network will have significant impacts on transient stability analysis speed and accuracy [9,10]. The sequential solution method, which has been successfully used for ac-dc interface in ac/dc power system load flow and transient stability analysis, has been extended here for UPFC interface to ac network (Fig. 7).
In the interface calculation we assume that the bus admittance matrix has been reduced to generator internal buses with UPFC ac terminal buses remained.

$$(6)\qquad \begin{cases} \dfrac{dE'_{qi}}{dt} = \dfrac{1}{\tau'_{d0i}}\left[E_{fdi} - E'_{qi} + \left(x_{di} - x'_{di}\right)i_{di}\right] \\ \dfrac{dE'_{di}}{dt} = \dfrac{1}{\tau'_{q0i}}\left[E'_{di} - \left(x_{qi} - x'_{qi}\right)i_{qi}\right] \\ \dfrac{d\omega_i}{dt} = \dfrac{\omega_{ir}}{2.H_i}\left[P_{mi} - P_{ei} - D_i\left(\omega_i - \omega_r\right)\right] \\ \dfrac{d\delta_i}{dt} = \omega_i - \omega_r \\ \dfrac{dVdc}{dt} = \dfrac{3m_E}{4C_{dc}}\left(i_{Ed}\cos(\delta_E) + i_{Eq}\sin(\delta_E)\right) - \\ \qquad \dfrac{3m_B}{4C_{dc}}\left(i_{Bd}\cos(\delta_B) + i_{Bq}\sin(\delta_B)\right) \end{cases}$$

With $P_{ei} = E'_{di} i_{di} + E'_{qi} i_{qi} \qquad i = 1,2,3,...m$

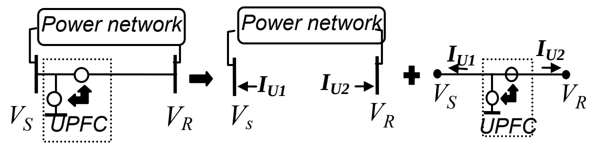


Fig. 7. The interface of the UPFC to the network

The corresponding reduced bus admittance matrix equation takes the form:

$$(7)\qquad \begin{bmatrix} Y_{GG} & Y_{GU} \\ Y_{UG} & Y_{UU} \end{bmatrix} \begin{bmatrix} \dot{E}_G \\ \dot{V}_U \end{bmatrix} = \begin{bmatrix} \dot{I}_G \\ \dot{I}_U \end{bmatrix}$$

where $\dot{E}_G$: generator internal voltage behind the sub transient X'_d reactance. $\dot{V}_U = [V_S \quad V_R]^t$: ac terminal bus voltages of the UPFC (see Fig. 7). $\dot{I}_G$: Generator currents injecting to the network.

$i_U = [i_{U1} \quad i_{U2}]^t$: UPFC currents injecting to the network at buses *S* and *R* respectively.

The UPFC currents injecting to the ac network can be expressed by (see Figs. 1 and 7):

$$(8)\qquad \dot{I}_{U1} = \frac{n_1 V_S - V_1}{jX_{t1}} n_1 - \dot{I}_{U2}$$

$$(9)\qquad \dot{I}_{U2} = \frac{\dot{V}_S + \dot{V}_{pq} - \dot{V}_R}{jX_{t2}}$$

It is clear that in equation (11), though the UPFC output voltage magnitudes V1 and Vpq can be known from control output and equation (4), (5), and (9). The phase angles of V1 and Vpq are unknown since they depend on the phase angle of Vs. the phase angle of Vs is unknown that should be obtained from the network solution. Therefore an iteration approach is required to obtain the network solution. Substituting equation (8) into equation (7), and rearranging the second equation of equation (7), we finally have:

$$(10)\qquad \frac{n_1}{jX_{t1}}\dot{V}_1 = \dot{I}_{1G} + \dot{I}_{2G} + \left(Y_{SS} + Y_{RS} + \frac{n_1^2}{jX_{t1}}\right)\dot{V}_S + \\ + \left(Y_{SR} + Y_{RR}\right)\dot{V}_{R1}$$

$$(11)\qquad \frac{1}{jX_{t2}}\dot{V}_{pq} = \dot{I}_{2G} + \left(Y_{RS} - \frac{1}{jX_{t2}}\right)\dot{V}_S + \\ + \left(Y_{RR} + \frac{1}{jX_{t2}}\right)\dot{V}_R$$

Where $\begin{bmatrix} Y_{SS} & Y_{SR} \\ Y_{RS} & Y_{RR} \end{bmatrix} = Y_{UU}$ and $\begin{bmatrix} \dot{I}_{1G} \\ \dot{I}_{2G} \end{bmatrix} = Y_{UG}\dot{E}_G$ which can be calculated according to generator state variables. If we define a constant matrix:

$$(12)\qquad \widetilde{Y}_{UU} = \begin{bmatrix} \left(Y_{SS} + Y_{SR} + \dfrac{n_1^2}{jX_{t1}}\right) & \left(Y_{SR} + Y_{RR}\right) \\ \left(Y_{RS} - \dfrac{1}{jX_{t2}}\right) & \left(Y_{RR} + \dfrac{1}{jX_{t2}}\right) \end{bmatrix}$$

and a fictitious time varying current vector:

$$(13)\qquad \widetilde{I}_U = \begin{bmatrix} \dfrac{n_1}{jX_{t1}}\dot{V}_1 - \left(\dot{I}_{1G} + \dot{I}_{2G}\right) \\ \dfrac{1}{jX_{t2}}\dot{V}_{pq} - \dot{I}_{2G} \end{bmatrix}$$

we have: $\widetilde{Y}_{UU}\dot{V}_U = \widetilde{I}_U$

The equations (10) to (13) are used for the iteration steps of UPFC network interface as depicted in follows three steps;

Step 1: Estimate the initial voltages of $\dot{V}_S^{(0)}$ and $\dot{V}_R^{(0)}$ (e. g. according to the last step) and calculate $\widetilde{I}_U$ based on equations (11) and (7).

Step 2: Solve equation (7) for $\widetilde{V}_U$. If the difference of V_U and $\widetilde{V}_U$ is less than the given tolerance then $\dot{V}_S^{(0)}$ and

$\dot{V}_R^{(0)}$ are considered as the solution of equations (10) and (11). Otherwise go to step 3

Step 3: Update by and repeat steps 1 and 2 till convergence is reached.

Adaptive Neural Fuzzy Damping Controller For UPFC

The steps involving the passage from classical fuzzy logic to the neuron-adaptive learning approach are elaborated with reference to UPFC installed in multi-machines system fig.4, and are briefly presented below[12],[14].

• Determination of initial fuzzy structure.

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

• Evaluation of the performance of the ANFIS controller under different operating situations.

Determination of initial fuzzy structure

The linguistic rules, considering the dependence of the plant output on the controlling signal, are used to build the initial fuzzy inference structure. The input signal (line power PL) is fuzzified using seven fuzzy sets A_i; $i=1$ to 7. Any continuous and piecewise differentiable functions are qualified candidates for node functions of premise parameters of the ANFIS structure. However to satisfy the Stone-Weierstrass theorem [7] it is desirable that the class of membership function is invariant under multiplication. This work considers the generalized bell-shaped function as the initial fuzzy membership function, with maximum equal to 1 and minimum equal to 0. The initial values of premise parameters are set in such a way that the MF's are equally spaced in the range [-1 1]. The rule base with seven fuzzy if-then rules of Takagi and Sugeno's type [14] given by

If ΔPLi is Ai then Δu_i is $p_i x + r_i$; $i=1$ to 7

In the ANFIS 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 {ai,bi,ci } are as follows. *Layer1:* This layer has adaptive nodes denoted by squares with node function

(14) $$O_i^1 = \mu_{A_i}(x) \quad i = 1\ldots7$$

where x is the input to node i, A_i the linguistic label associated with this node. O_i specify the degree to which the given input 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

(15) $$\varpi = \frac{\omega_i}{\sum \omega_i}; \qquad i = 1\ldots7$$

where ω_i represents 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

(16) $$O_i^3 = \overline{\omega}_i(p_i x + r_i); \qquad i = 1\ldots7$$

$\{ p_i , r_i\}$ 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 labelled Σ computes the overall output as the summations of all incoming signals

(17) $$O_i^4 = \sum \overline{\omega}_i(p_i x + r_i); \qquad i = 1\ldots7$$

The ANFIS networks need to be trained with the collected data. The data base is generated as follows: for the various choices of UPFC control signals namely m_E, m_B ,δ_E , δ_B the constant gain damping controller, using phase compensation technique is design and from the constant gain controller so designed, the training pairs (ΔP_L, U_{damp}) is generated. The training phase is a process that determines the optimum value of parameters so that ANFIS successfully fits the training data.

Simulation Results

The system shown in Fig.4 is assumed to be operating at the nominal load condition at which the supplementary controller design with the chosen control signal, namely δ_B is done. The loading and system conditions are as in [5]. Tow cases are considered:

Case1: Change of 10% in power transfer from bus 7 to bus8 at 1.0 second of the simulation.

Case2: oscillation is triggered by a three-phase short circuit occurring at the line 5-7 near bus 7 at 4.0 second of the simulation and cleared after 100 ms. Fig.8 show the comparison of the variation of relative rotor angle of G2 with respect to G1 when the system is equipped with the constant gain controller and the proposed UPFC damping controller whose gains have been adapted. It is observed that the performance of both the controllers are almost similar except for the lesser settling time in the case of ANFIS based controller. The simulation is repeated by changing damping signal and the results are presented in Fig.9, 13, 14 and 15. It is evident that with the series angle δse signal to show damping oscillation in machines speed and rotors deviation. With the proposed controller the machines are swinging together.

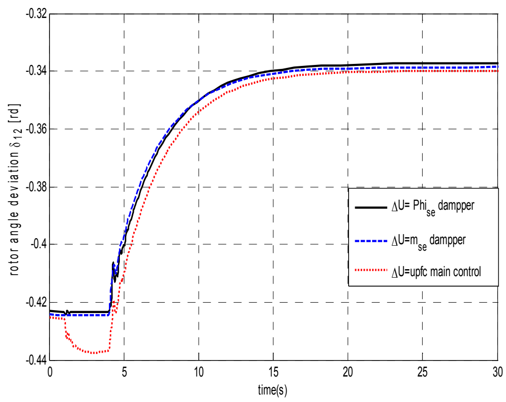


Fig.8. Variation of δ_{12} for *case1* and *case2*; UPFC main control, δ_{se} and m_{se} signal

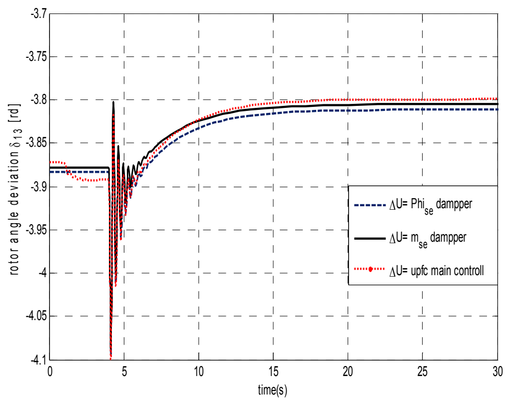


Fig. 9 Variation of δ_{13} for *case1* and *case2*; UPFC main control, δse and m_{se} signal

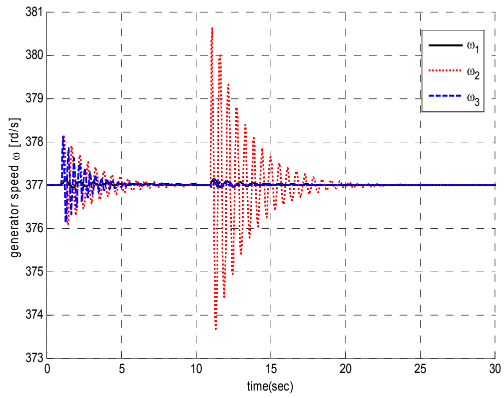


Fig 10 Generators speed at *case1* and *case2* without damping controllers.

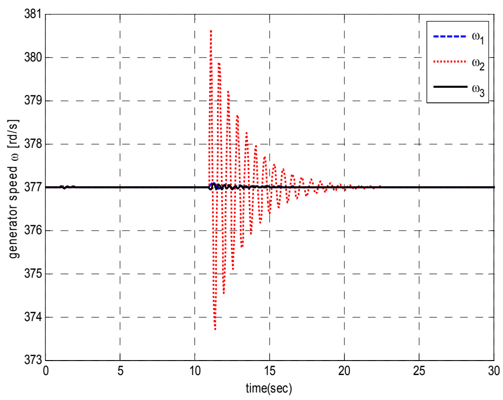


Fig.11. Generators speed at *case1* and *case2* with UPFC main control.

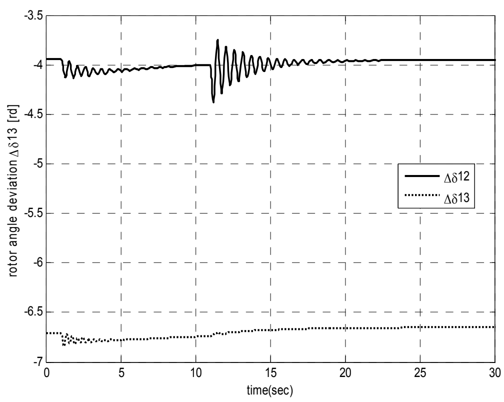


Fig.12. Rotor angle deviations at *case1* and *case2* without damping controllers

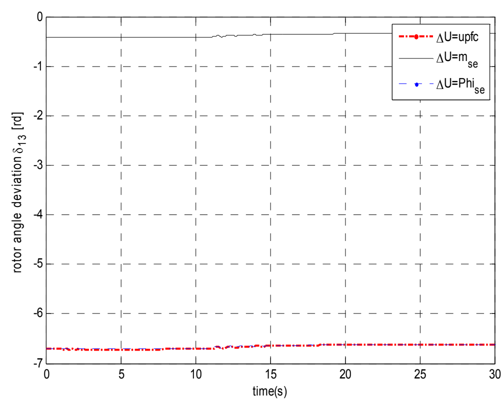


Fig. 13 Generators angle deviation at *case1* and *case2* with damping controllers; UPFC main control, δ_{se} and m_{se} signal

Conclusion

This paper investigates the capability of ANFIS based UPFC controller on the suppression of small signal oscillations in a multi-machines power system. The adaptive controller, adapted by a proper training data, is showing improved performance with the three choices of UPFC control signals compared to constant gain controller designed at a nominal operating condition. With regard to damping of low frequency oscillations of the system, it is observed that the performance of the proposed controller is improving when the UPFC is installed with control signals based on phase angle modulation of shunt and series converter voltages, which results in real power exchange with respect to the system. The novel hybrid simulation method has been introduced for the power system with a dynamic model of UPFC.

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