

Design of UPFC based Damping Controller using Neuro Fuzzy to Enhance Multi-machine Power System Stability

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Abstract

Objectives: Inter-area frequency oscillations are one of the major problems in the present power systems for smooth operation to transfer power from one area to another area through weak tie-lines. **Methods/Statistical Analysis:** If oscillations are not damped out quickly, problem like system instability, cascade failure and even blackouts may occur. Local mode of oscillations can be damped out by using Power System Stabilizers (PSS) but damping inter-area mode of oscillations using PSS may not be possible always. The major concerns in power system operation were damping power system oscillations. Flexible Alternating Current Transmission System (FACTS) technology has been used extensively for power control, voltage regulation, increasing the transient stability, and decreasing system oscillations. Among all FACTS devices, Unified Power Flow Controller (UPFC) is most efficient which has the potential to increase the power flow and stability of the transmission line. Due to the constantly changing nature of power system Conventional PI controller is not applicable. To overcome the drawback Artificial Intelligent (AI) techniques like Fuzzy Logic and Neural Network are combined as Neuro-Fuzzy based Controller. In this paper an Adaptive Neuro-Fuzzy Interface System (ANFIS) based UPFC is designed to enhance system stability. **Findings:** The main idea of FACTS technology is to improve controllability and optimizing the utilization of existing power system capacities using the high speed and reliable power electronic devices instead of mechanical controllers. FACTS controllers like UPFC provides set of interesting capabilities such as reactive power compensation, power flow control, voltage regulation, damping of oscillations. This paper has focused on the investigation of performance and the comparison of UPFC on power flow with ANFIS and Proportional Integral (PI) controllers. The comparative results of Eigen value and damping ratio with PI and ANFIS controllers have been shown. The comprehensive simulation cases are examined and the result shows that the proposed model are both effective and reliable in damping the inter-area oscillations of two area system. **Applications/Improvements:** The simulation studies are carried out in MATLAB/SIMULINK to analyze the performance and comparison of designed ANFIS and PI Controller.

Keywords: Adaptive Neuro-Fuzzy Interface System (ANFIS), Proportional Integral (PI) Controller, System Stability, Inter-area Oscillation, Unified Power Flow Controller (UPFC)

1. Introduction

The electric power demand has been imposed upon a high voltage transmission networks in the worldwide in recent years. Also, constructing a new generation units and transmission circuits become more difficult because of economic and environmental reasons. Because of these reasons, power utilities are compelled to benefit from existing generating units to bring closer to existing

transmission lines to their thermal limits. However, the power system stability¹ has to be maintained permanently even in the case of contingency conditions, such as loss of transmission lines or generating units, which occur frequently.

In²⁻⁶ the past few decades damping power system oscillation has been identified as one of the main issue for a smooth and stable operation of power systems. Operation of power systems are always driven close to

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power system limits, because of a continuous increase in the power demand, which in turn deals with the transmission capacity of power system. The major goal of power system operator is to boost up power transfer capability and maintaining system stability. The problem of small signal oscillation occurs, when we transfer a huge amount of power to a long distance via relatively weak tie lines and high exciters gain, Thus the power system oscillations turned power system into instability and blackouts. Hence, it is needed to implement the new control strategies in order to operate power system effectively without the reduction in system security and quality of supply. In the late 1980s, a new technology known as FACTS device was presented by Electric Power Research Institute (EPRI). The main idea of FACTS technology is to improve controllability and optimizing the utilization of existing power system capacities using the high speed and reliable power electronic devices instead of mechanical controllers. FACTS controllers like UPFC provides set of interesting capabilities such as reactive power compensation, power flow control, voltage regulation, damping of oscillations.

2. Power System Modelling

The purpose of power system modeling is to provide a means with which the performance of the system can be evaluated and to provide a starting point for the investigation of problem imposed by the damping⁷ process as well as the design of the controllers. For the modeling purpose, the power system can be divided into an umber of sub systems like generators, excitation systems, dynamic loads, FACTS devices, power system stabilizer, prime-movers, etc. that was shown in Figure 1.

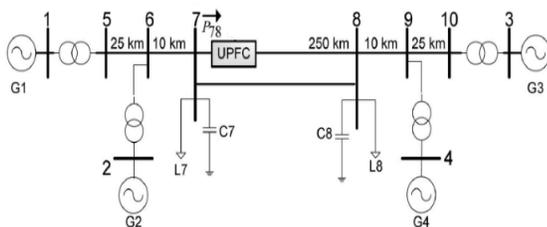


Figure 1. Overview of test system.

2.1 Stator Equations

All the generators of the test system (G1 to G4) are represented by a subtransient model, with four equivalent coils on the rotor. The rotor coils are; field coil, one equivalent dampercoil in the direct axis and two in the quadrature axis. The differential equations governing the sub-transient behavior of the ith generator is given by

$$\frac{d\psi_{2di}}{dt} = -\frac{1}{T_{doi}'' [\psi_{2di} + E_{qi}' + (X_{di}' - X_{lsi})I_{qi}]} \quad (1)$$

$$\frac{d\psi_{2qi}}{dt} = -\frac{1}{T_{doi}'' [\psi_{2qi} + E_{di}' + (X_{qi}' - X_{lsi})I_{di}]} \quad (2)$$

The stator transients are generally much faster compared to the swing dynamics. Hence, for stability studies, assume that the stator quantities are to be related to the terminal bus quantities through algebraic equations rather than state equations. The stator algebraic equations are given by

$$V_i \sin(\delta_i - \theta_i) + \frac{(X_{qi}'' - X_{lsi})}{(X_{qi}' - X_{lsi})} E_{di}' - \frac{(X_{di}' - X_{qi}'')}{(X_{qi}' - X_{lsi})} \psi_{2qi} + R_{si} I_{di} - X_{qi}'' I_{di} = 0 \quad (3)$$

$$V_i \cos(\delta_i - \theta_i) - \frac{(X_{di}'' - X_{lsi})}{(X_{di}' - X_{lsi})} E_{qi}' - \frac{(X_{di}' - X_{di}'')}{(X_{di}' - X_{lsi})} \psi_{1di} + R_{si} I_{qi} - X_{di}'' I_{di} = 0 \quad (4)$$

2.2 Network Power Flow Model

The network equations are put in the power balance forms as follows

For the generator buses are given by

$$V_i \cos(\delta_i - \theta_i) I_{qi} - V_i \sin(\delta_i - \theta_i) I_{di} - \sum_{k=1}^{k=n} V_i V_k [G_{ik} \cos(\theta_i - \theta_k) + B_{ik} \sin(\theta_i - \theta_k)] = 0 \quad (5)$$

$$-V_i \sin(\delta_i - \theta_i) I_{qi} - V_i \cos(\delta_i - \theta_i) I_{di} - \sum_{k=1}^{k=n} V_i V_k [G_{ik} \sin(\theta_i - \theta_k) - B_{ik} \cos(\theta_i - \theta_k)] = 0 \quad (6)$$

2.3 Damping Ratio

For a complex pair of Eigenvalues,

$$\lambda_{1,2} = \alpha \pm j\omega \quad (7)$$

The real component α of the Eigen values gives the damping, and the imaginary component ω gives the frequency of oscillations in rad/s. The damped frequency of oscillation in Hz is given by:

$$f = \frac{\omega}{2\pi} \tag{8}$$

The damping ratio is given by:

$$\zeta = \frac{-\alpha}{\sqrt{\alpha^2 + \omega^2}} \tag{9}$$

The damping ratio ζ determines the rate of decay of the amplitude of the oscillation. The time constant of amplitude decay is $1/|\alpha|$. It is known that if:

- $\zeta > 0.25$, the system is well damped
- $\zeta = 0.1$, the system is damped
- $\zeta < 0.03$, the system is weakly damped
- $\zeta < 0.0$, the system is unstable

2.4 Participation Factor Analysis

In order to design effective damping controllers, it is necessary to identify the EM modes. The PF analysis on open loop 2A4M power system shows three EM modes, one in inter-area and two in local frequency ranges, as depicted⁹⁻¹⁰ in Table 1. It is obvious that the power system is unstable for inter-area mode because of negative damping ratio.

Table 1. Analysis without controller

EM Oscillation frequency	EM Real Value	Damping Ratio
0.4734	0.0232	-0.0077
1.8852	-0.7704	0.1087
1.3195	-0.6789	0.0982

3. Principle of Unified Power Flow Controller

The Unified Power Flow Controller (UPFC) is a special arrangement of two VSCs, one of which is connected with the AC system in series and the other is connected in shunt with the AC system with common dc terminal. UPFC is a combination of STATCOM and SSSC, which is coupled via a common DC link as shown in Figure 2. This link allows a bi-directional real power flow from the shunt output terminals of the STATCOM to the series output terminals of the SSSC^{11,12}. The two VSCs, which

operate from a common link with a DC storage capacitor, use the technique of power switches.

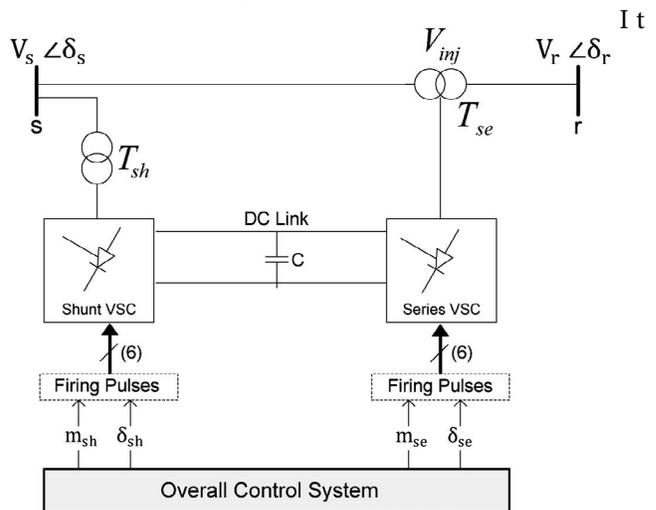


Figure 2. Schematic of UPFC.

It functions as an ideal AC to AC power converter, where the real power can freely flow in either direction between the AC terminals of two converters and also each converter can independently generate or absorb the reactive power at its own AC output terminal. UPFC is able to control selectively or concurrently the transmission line voltage and line impedance, angle or alternatively the real and reactive power flow in the line by means of angularly unconstrained series voltage injection.

The additional storage such as DC capacitor connected to the dc link via electronic interface would provide the means of enhancing further the effectiveness of UPFC. The controlled exchange of real power with an external source, such as storage is very much effective in controlling system dynamics than modulation of the power transfer within a power system. UPFC performs not only the functions of the STATCOM, SSSC and the phase angle regulator but also provides additional function as flexibility by combining some of the functions of these controllers. In general, the control strategy of UPFC have preferably the following attributes:

- The steady state objectives such as real and reactive power flows are achieved by the references of the controllers.
- The dynamic and transient stability improvement by using appropriate controller.

4. Adaptive Neuro-Fuzzy Interface System (ANFIS)

ANFIS was first introduced by Takagi and Sugeno in 1985 and further developed by Jang^{13,14}. The network is built to have a capability of ANNs in learning and adapting together with a merit of approximate reasoning offered by fuzzy logic. Unlike neural networks, the weights of the connections between nodes located in one layer and the nodes in the subsequent layer are constant and have values of one combined. The basic idea of a neuro-fuzzy system is to model a fuzzy logic system by a neural network and then applying the learning algorithms developed in the field of neural networks to adapt the parameters of the fuzzy system. An NFC can be defined as a multi-layer network that has the elements and functions of typical fuzzy logic control systems, with additional capability to adjust its parameters via learning techniques. The motive of combining fuzzy logic with neural networks is to take advantage of their strengths and overcome shortcomings.

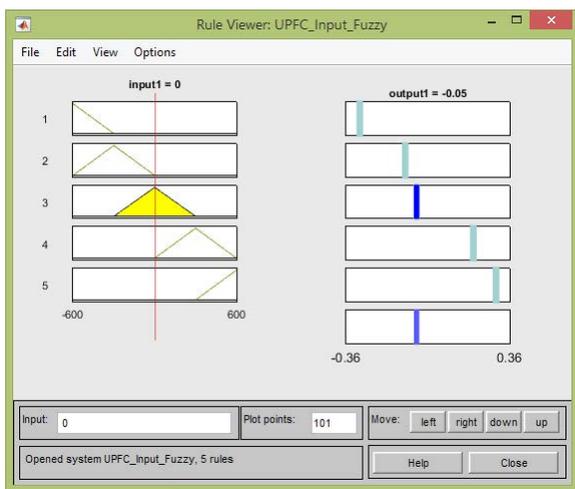


Figure 3. Fuzzy rule viewer.

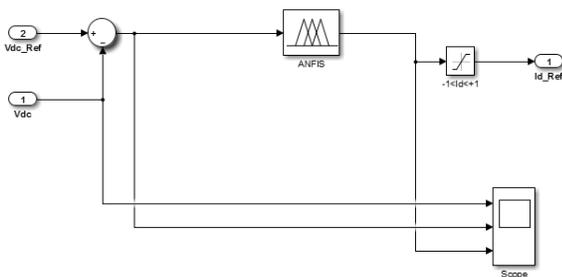


Figure 4. ANFIS controller.

It includes one input and one output, input consists of 5 set of Gaussian membership functions and output consists of 5 set triangular membership function and 5 rules are framed based on low, medium and high. The rule viewer shown in Figure 3 and surface viewer shown in Figure 4 are observed from MATLAB.

4.1 Fuzzy Controller

Figure 5 consists of ANFIS controller is replaced by conventional PI controller mainly focused on regulating dc voltage provided between series and shunt converter.

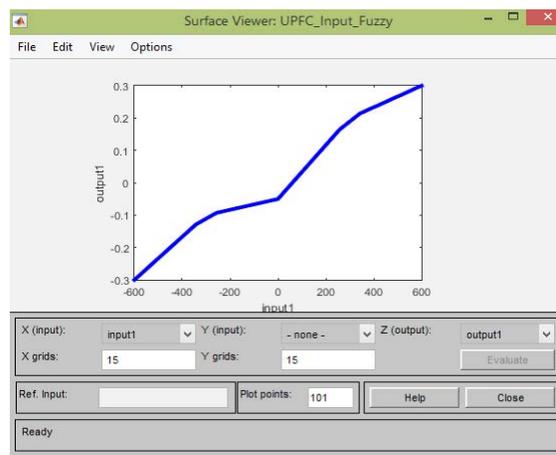


Figure 5. Fuzzy surface viewer.

4.2 Adaptive Neuro-Fuzzy Interface System Architecture

The ANFIS¹⁴⁻¹⁶ represents Sugeno first order fuzzy model and it can be trained by a hybrid learning algorithm presented by Jang shown in Figure 6, and its architecture is shown in Figure 7.

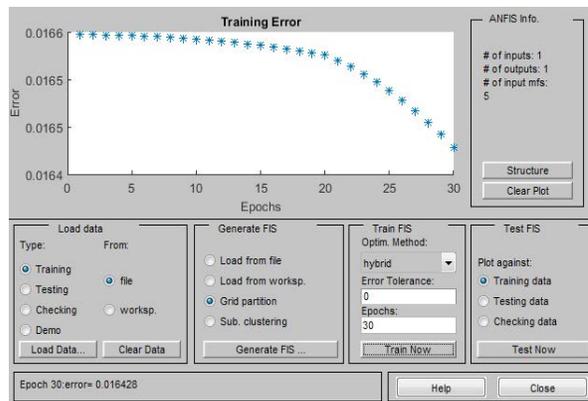


Figure 6. Training error in ANFIS.

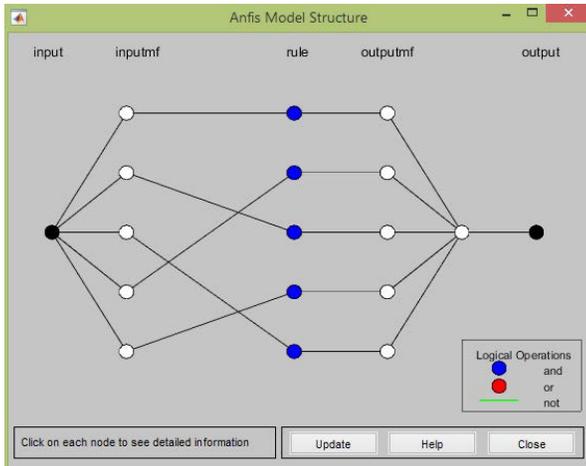


Figure 7. Architecture of ANFIS.

- In the forward pass, algorithm uses the least-squares method to identify consequent parameters on layer 4.
- In the backward pass, errors are being propagated backward and the premise parameters are updated by gradient descent. It includes five layer and are as follows
- Input Membership Layer
- Firing Strength Layer
- Normalized Firing Strength Layer
- Consequent Layer
- Defuzzification Layer

5. Simulation and Results

For simulation of proposed method Fuzzy Logic Toolbox present in the MATLAB is used. The test system consists of two coherent areas linked together by two lines of 230 kV which is 220 km length. Each area is being equipped with two identical round rotor synchronous generators rated 20kV/900 MVA. This is due to three phase fault applied in one of the tie line at 0.12 secs for duration of 0.12 secs. Figure 8 shows the reference dc voltage, obtained dc voltage, error in dc voltage and output from PI controller is shown in magenta and output from ANFIS controller¹⁷ is shown in blue.

When three phase fault is applied in one of the tie line at 1 sec for duration of 0.12sec the voltage at Bus 1 and Bus 2 and active power from Area 1 and Area 2 are obtained as shown in the Figure 9. Machines power and voltages are also obtained during faulty condition as

shown in Figure 10. We could infer that the Real part of Eigen value and the Damping ratio for local and inter area mode of oscillations due to ANFIS controller¹⁸ are greatly improved compared to conventional PI controller from Table 2. Figures 11 and 12 shows the comparative results of Eigen value and damping ratio with PI and ANFIS controllers.



Figure 8. Comparison of DC voltage.

Table 2. Comparison of various controllers

Various controller	EM Oscillation frequency	EM Real Value	Damping Ratio
Without controller	0.4734	0.0232	-0.0077
	1.8852	-0.7704	0.1087
	1.3195	-0.6789	0.0982
PI controller	0.4734	-0.9543	0.3054
	1.8852	-6.5617	0.6734
	1.3195	-5.1999	0.4019
ANFIS controller	0.4734	-1.0020	0.3359
	1.8852	-6.8899	0.6826
	1.3195	-5.4599	0.4422

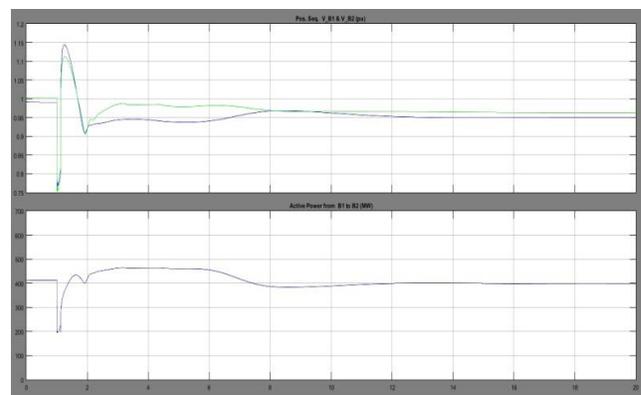


Figure 9. Under fault condition.

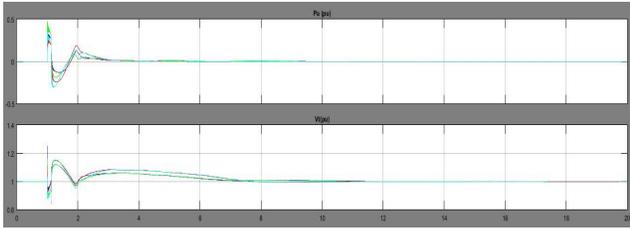


Figure 10. Machines power and voltages.

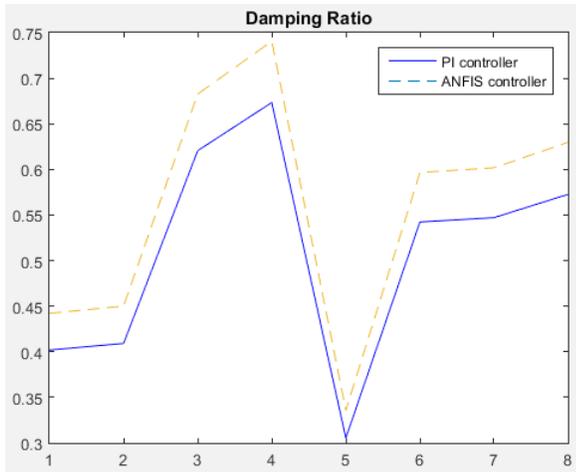


Figure 11. Damping ratio.

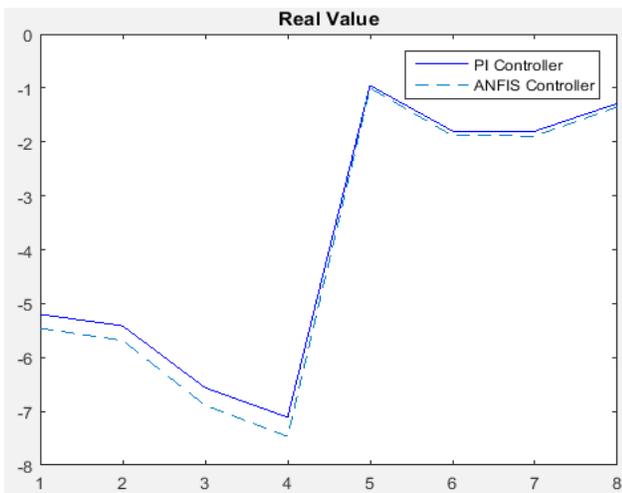


Figure 12. Real part of Eigen value.

6. Conclusion

Unified Power Flow Controller (UPFC) is one of the FACTS device which is used to maintain and improve the power system stability and voltage regulation. This paper has focused on the investigation of performance

and the comparison of UPFC on power flow with Adaptive Neuro Fuzzy Interface System (ANFIS) and Proportional Integral (PI) controllers. The comparative results of Eigen value and damping ratio with PI and ANFIS controllers have been shown. The comprehensive simulation cases are examined and the results show that the proposed model are both effective and reliable in damping the inter area oscillations of two area system. The detailed observation has been made on power system parameters, such as real and reactive power flows as well as the bus voltage control in this study.

7. References

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