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A Study of Fuzzy Logic Based Damping Controller for The UPFC

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ABSTRACTS

The supplementary control of the UPFC can significantly enhance the damping of interconnect power systems. However, the conventional controller designed based on a linearized model cannot provide adequate damping signal over a wide range of operation points. In this paper, a fuzzy controller is designed as the substitute of the conventional controller. The parameters of the fuzzy controller are optimized through gradient descent training. Transient stability simulation and small signal analysis are conducted to test the performance of the controller. Computer results show that the fuzzy controller is very effective in damping the oscillation and has a better robustness.

1. INTRODUCTION

The unified power flow controller (UPFC) is regarded as one of the most versatile FACTS devices [1-3]. It can operate as a shunt or/and series compensator, a power flow controller, a voltage regulator or a phase shifter depending on its main control strategy.

A power frequency model for the UPFC is derived in [4] with its dc link capacitor dynamics included to study the effects of the UPFC on power system stability. A novel UPFC-network interface is also suggested in order to participate the UPFC model into the conventional transient stability analysis program with good convergence and accuracy in time simulation. Investigations on the UPFC main control effects show that the UPFC can improve system transient stability and enhance system transfer limit. The application of the UPFC to the modern power system can therefore lead to more flexible, secure and economic operation.

Modern power systems tend to be interconnected to yield the most economic benefits. However low frequency oscillation will occur on heavily loaded tie lines especially after a large or small disturbance. Sometimes the Power System Stabilizer (PSS) installed on a specific generator cannot provide effective damping for that kind of oscillation. In [4] it is shown that the addition of PSS-like supplementary controller to the UPFC main control can provide effective damping to the low frequency oscillation on heavily loaded tie lines of interconnected system. However, the conventional controller designed based on a linearized model cannot provide satisfactory performance over a wide range of operation points and under large disturbances.

Recently, applications of the fuzzy logic theory to the engineering issues have drawn tremendous attention from researchers [5, 6]. The fuzzy controller has a number of distinct advantages over the conventional one. It is not so sensitive to the variation of system structure, parameters and operation points and can be easily implemented in a large-scale nonlinear system. The most attractive feature is its capability of incorporating human knowledge to the controller with ease.

In this paper, a fuzzy logic based supplementary controller is designed to act as the substitute of the conventional one. The fuzzy damping controller (FDC) takes the power flow of the controlled line as the input signal. The output of the FDC is sent to the main control of the UPFC as the modulation signal for improving system damping. Scaling factors are inserted to the membership functions of both inputs and output for easy design of fuzzifier and defuzzifier. The gradient descent training method [5] is used to optimize the key parameters of the FDC. The related formulas and optimizing FDC parameters is presented. The performance of the designed FDC is evaluated through transient stability simulation and small signal analysis. A 4-machine interconnected power system with a UPFC installed in one of the tie lines is used as the test system. Computer test results show that the FDC is very effective in damping the inter-area power oscillation. In the meantime, it has a better robustness as compared with its conventional counterpart.

2. THE UPFC MATHEMATICAL MODEL

A. UPFC Power Frequency Model

The power frequency model for the UPFC suggested in [4] is used in this study and is outlined as follow. Fig. 1 shows the schematic diagram for the UPFC, where n_1, X_{t1} and n_2, X_{t2} are the voltage ratio and the reactance of the shunt and series transformers respectively. All the variables used in the UPFC model are denoted in Fig. 1 with bold fonts representing phasors. The ac system uses per unit system with its variables calculated based on the system-side S_B and V_B, while the dc variables are expressed in SI units.

The UPFC dc link capacitor dynamics can be expressed as follows with harmonics and UPFC losses neglected:

$$CV_d \frac{dV_d}{dt} = (P_1 - P_2)S_B \tag{1}$$

where

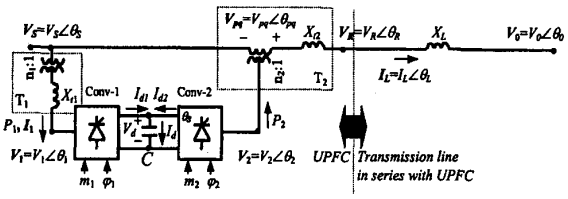


Fig. 1 Transmission line with the UPFC installed

$$P_1 = \mathrm{Re}(\dot{V}_1 \dot{I}_1^*) = \mathrm{Re}(\dot{V}_1 (\frac{n_1 \dot{V}_S - \dot{V}_1}{jX_{t1}})^*) \tag{2}$$

$$P_2 = \mathrm{Re}(\dot{V}_{pq} \dot{I}_L^*) = \mathrm{Re}(\dot{V}_{pq} (\frac{\dot{V}_S + \dot{V}_{pq} - \dot{V}_R}{jX_{t2}})^*)$$

PWM control technique is applied to both of the voltage source converters so that the relations between the inverter dc- and ac-side voltages are:

$$\begin{cases} V_1 = m_1 V_d / V_B \\ V_{pq} = m_2 V_d / (V_B n_2) \end{cases} \tag{3}$$

where coefficients m_1 and m_2 represent the PWM control effects in order to maintain desired inverter ac-side voltage V_1 and V_2 respectively. The phase angles of V_1 and V_2 can be controlled through firing angles φ_1 and φ_2 of the converters, i.e.

$$\begin{cases} \theta_1 = \theta_S - \varphi_1 \\ \theta_{pq} = \theta_S - \varphi_2 \end{cases} \tag{4}$$

The preferred m_1, m_2, φ_1 and φ_2 are outputs from the UPFC main control which are assumed to be realized without time delay. Equations (1) to (4) constitute the UPFC power frequency model for power system stability study.

B. UPFC Conventional Main and Supplementary control

The UPFC shunt and series element conventional main control and supplementary control are shown in Fig. 2 - 4 respectively. The shunt element control is the constant dc link capacitor voltage control realized by controlling the firing angle φ_1 of inverter 1 (Fig. 2(a)); and the constant ac bus voltage control achieved by controlling m_1 of the PWM controller of inverter 1 (Fig. 2(b)). Although a simple transfer function is used for the main control, there is no difficulty to include more complicated transfer functions. As for the series element, the inserting voltage $\dot{V}_{pq}$ in Fig. 1 can be decomposed to V_p and V_q. The former is perpendicular to $\dot{V}_S$, and the latter is in phase with $\dot{V}_S$ (see Fig. 3(a)). Obviously, these two components have strong impacts on active and reactive power flow respectively. Based on this decomposition, Fig. 3(b) shows the constant active and reactive power flow control for the series element main control.

In order to improve system damping, a PSS-like supplementary control [7] (see Fig. 4) is added with its output *dmp_sig* used to modulate the terminal bus voltage (Fig. 2(b)) in order to provide the damping effect.

C. Mathematical model for other elements and the interface of the UPFC to ac network

The subtransient model is used for the generators with the third-order excitation control [7]. The mechanical power of each generator is approximately constant. Loads are expressed as constant impedance and the ac network is linear. The sequential solution method, which has been successfully used in ac/dc power system load flow and transient stability analysis for ac-dc interface, is extended for the UPFC interface to ac network. The detail can be found in [8].

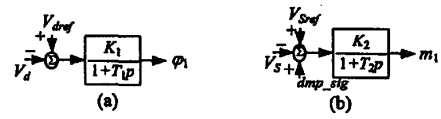


Fig. 2 The UPFC shunt element main control diagram

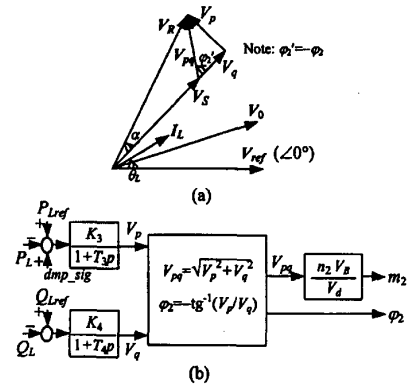


Fig. 3 The UPFC series element main control and the phasor diagram

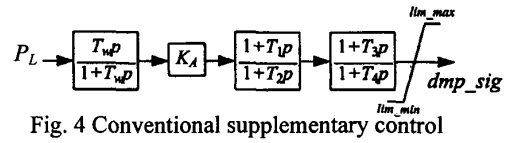


Fig. 4 Conventional supplementary control

3. The UPFC fuzzy damping controller

Fig. 5 shows the structure of the proposed Fuzzy Damping Controller (FDC). The FDC input signal is the same as its conventional counterpart; i.e., the tie line real power P_L. The FDC output is still the damping signal *dmp_sig*, which will be sent to the main controller for damping power oscillation.

A. Operation Principle of the FDC

The input signal after passing through a washout block (or reset filter) forms the first signal x_1 which is corresponding to the line power increment ΔP_L. The signal x^*_2 is the integration of ΔP_L with dc component filtered out. For a sinusoidal power oscillation of a certain frequency, we all know the signals x^*_2 and x_1 can span into a phasor plane. After proper scaling of the two

signals a phasor can be worked out with desired phase angle on the phasor plane. In real application we take $x_2 = -x^*_2$ as the second input signal of fuzzy damping control and consider that it is approximately in phase to the time derivative of ΔP_L from the phasor point of view based on the conventional frequency domain controller design widely used in PSS design. This signal has the advantages of having less noise and being smoother as compared with the time derivative of ΔP_L. Two gains (or scaling factors) K_1 and K_2 are inserted to make $x'_1 = K_1x_1$ and $x'_2 = K_2x_2$ usually at a proper range of [-1, 1] for easy design of the fuzzifier. The gain K_3 at the output path plays a similar role for easy design of the defuzzifier. It is clear that K_1, K_2 and K_3 should be optimized in order to get satisfied FDC performance.

The differentiable Gaussian membership function is used to fuzzifying the two input signals which is required by the GDT method. The triangular function is used to defuzzify the output fuzzy sets for its easy calculation. Seven fuzzy sets are defined for each of the input and output signals. They are NB, NM, NS, ZR, PS, PM and PB which stand for negative big, negative medium, negative small, zero, positive small, positive medium and positive big respectively. In the implementation, PB and NB are extended to reach ±2 respectively so as to fit the input signals of excessive range. Based on the human experience, the fuzzy rule base is formed. Table 1 shows the fuzzy rules which take the form:

IF K_1x_1 is A_i and K_2x_2 is B_i THEN output y/K_3 is C_i

where A_i and B_i are the input fuzzy sets with Gaussian membership functions, while C_i is the output fuzzy set with triangular membership function.

In the FDC, singleton fuzzifier, centre average defuzzifier, and product inference engine are used for fuzzifying, defuzzifying and inference process respectively. If the rules in Table 1 are numbered from 1 to 49 row by row, the fuzzy rule implementation can then be expressed as the following nonlinear relation where the extended parts of the fuzzy sets PB and NB are ignored:

$$y = f(x) = K_3 \frac{\sum_{r=1}^{M} \bar{y}'^r \left[\prod_{i=1}^{n} exp\left(-\left(\frac{K_i x_i - \bar{x}'^r_i}{\sigma_i^r} \right)^2 \right) \right]}{\sum_{r=1}^{M} \left[\prod_{i=1}^{n} exp\left(-\left(\frac{K_i x_i - \bar{x}'^r_i}{\sigma_i^r} \right)^2 \right) \right]} \quad (5)$$

where $\bar{x}'^r_i$ and σ_i: centre and standard deviation of the Gaussian membership functions corresponding to the rth rule input fuzzy set of variable x_i $(i=1, 2)$; $\bar{y}'^r$: centre of the Gaussian membership function corresponding to the rth rule output fuzzy set of variable y'; M: total number of the rules, M=49; n: total number of the input signals, n=2; $x = [x_1, x_2]$ and $x_i' = K_i x_i$;

Table 1 Fuzzy rule base

K_1x_1 / K_2x_2	NB	NM	NS	ZR	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	ZR
NM	PB	PB	PM	PM	PS	ZR	NS
NS	PB	PM	PM	PS	ZR	NS	NM
ZR	PM	PM	PS	ZR	NS	NM	NM
PS	PM	PS	ZR	NS	NM	NM	NB
PM	PS	ZR	NS	NM	NM	NB	NB
PB	ZR	NS	NM	NM	NB	NB	NB

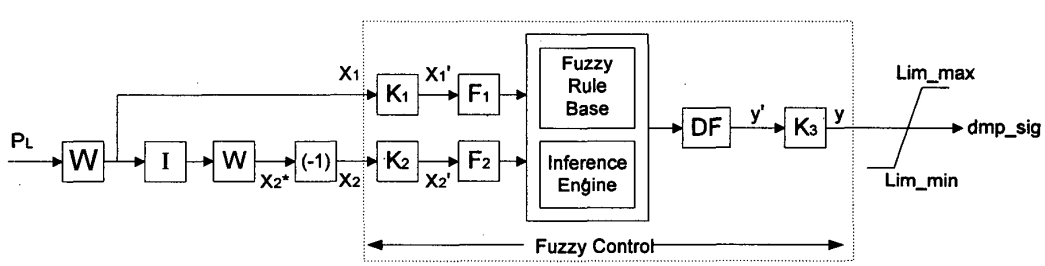
B. Gradient Descent Training (GDT) for FDC Coefficient Optimization

The GDT method [5] is used as a deterministic approach to optimize K_i. This method is to make the designed FDC performance close to a desired characteristic. We assume that the desired input-output characteristic of the FDC is available and defined by a collection of input-output data, say from a well-designed conventional controller.

Suppose that we are given the following input-output pairs: $(x_0^{(j)}, y_0^{(j)}) = (x_{10}^{(j)}, x_{20}^{(j)}, y_0^{(j)})$, $j=1,2,\ldots,p$. p is the total number of the input-output pairs available. The task is to design a fuzzy system with its input-output relation as (5) which can imitate the characteristic of the given input-output pairs, that is, to determine an optimal set of $\{K_i\}$, such that the matching error

$$e = \sum_{j=1}^{p} e^{(j)} = \sum_{j=1}^{p} \frac{1}{2}\left[f(x_0^{(j)}) - y_0^{(j)} \right]^2 \quad (6)$$

is minimized.



W: washout block, I: integration block, F: fuzzifier, DF: Defuzzifier

Fig. 5 Fuzzy damping controller for the UPFC

The gradient descent algorithm is used to solve the problem through the following iteration:

$$K_{q+1} = K_q - \alpha \left.\frac{\partial e}{\partial K}\right|_{Kq} \tag{7}$$

where q: the current iteration number; $-\frac{\partial e}{\partial K} = -\nabla_K e$, the optimal search direction; α: the optimal step length; $K=(K_1, K_2, K_3)^T$.

According to (6), we have (l=1, 2, 3)

$$\frac{\partial e}{\partial K_l} = \sum_{j=1}^{p} \left[\left(f(x_0^{(j)}) - y_0^{(j)} \right) \frac{\partial f(x_0^{(j)})}{\partial K_l} \right] \tag{8}$$

Let

$$a^r = \prod_{i=1}^{n} \exp\left(-\left(\frac{K_i x_i - \bar{x}_i^r}{\sigma_i^r} \right)^2 \right) \tag{9}$$

we have

$$f(x) = K_3 \frac{\sum_{r=1}^{M} \bar{y}^r a^r}{\sum_{r=1}^{M} a^r} \tag{10}$$

From (5) and (6) - (9), for l=1, 2, we can derive

$$\frac{\partial f(x)}{\partial K_l} = K_3 \frac{\sum_{r=1}^{M} \bar{y}^r \frac{\partial a^r}{\partial K_l}}{\sum_{r=1}^{M} a^r} - K_3 \frac{\sum_{r=1}^{M} \bar{y}^r a^r}{\left(\sum_{r=1}^{M} a^r \right)^2} \cdot \sum_{r=1}^{M} \frac{\partial a^r}{\partial K_l} \tag{12}$$

$$\frac{\partial a^r}{\partial K_l} = -2a^r \cdot \left(\frac{K_l x_l - \bar{x}_l^r}{\sigma_l^r} \right) \frac{x_l}{\sigma_l^r} \tag{13}$$

If l=3, we have:

$$\frac{\partial f(x)}{\partial K_l} = \frac{\sum_{r=1}^{M} \bar{y}^r a^r}{\sum_{r=1}^{M} a^r} \tag{14}$$

The GDT process can be conducted as follows based on an initial guess of K_l (l=1, 2, 3):

1) Use equations (12) to (14) to calculate $\frac{\partial f(x)}{\partial K_l}$ (l=1, 2, 3).
2) Substitute these derivatives into equation (8) to calculate $-\nabla_K e = -\left[\frac{\partial e}{\partial K_1} \quad \frac{\partial e}{\partial K_2} \quad \frac{\partial e}{\partial K_3} \right]^T$ (15)
3) In the opposite direction of the gradient ($-\nabla_K e$), search an optimal step length α (see (11)) to minimize the mismatch e. A new set of $\{K\}$ can be obtained.
4) Repeat steps 1 to 3 till $\left| \frac{\partial e}{\partial K_l} \right|$ is smaller than the given tolerance. The final set of $\{K\}$ is taken as the solution.

4. COMPUTER SIMULATION RESULTS

A two-area 4-machine interconnected power system [7] shown in Fig. 6 is used as the test system with a UPFC installed in one of the tie line 101-13. At steady state, about 700 MW power is generated from each of the generators. The loads on buses 3 and 13 are 967 MW and 1767 MW respectively. About 400 MW power is transferred from area 1 to area 2 through the parallel tie lines. The parameters of the UPFC system and its main control can be found in the appendix.

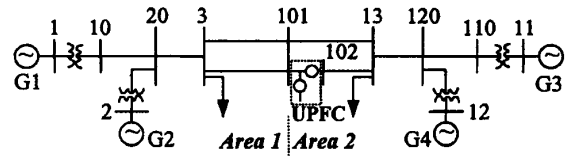


Fig. 6 Two-area 4-machine test system

A. GDT - sample data acquisition and result

In order to get a set of training sample data for the FDC and compare the controller performance, a PSS-like conventional supplementary controller (CSC) is well designed based on the linear control theory with its dynamic response to a certain disturbance served as the FDC training sample data. The disturbance considered is a stub three-phase fault on tie line 3-101 close to the terminal bus 3, which is cleared in 0.05sec. without line tripping. Because of the high non-linearity of the system transients right after the fault, the training data exceeds the FDC output limit [-0.2, 0.2] will have negative impacts on training results. Therefore, 250 samples in the time period of 4sec. ~ 9sec. are collected for FDC training.

The selection of initial value is very important for gradient descent training. The preferred K_i is roughly selected through trail and error as K = (0.5, 1.5, 0.5). Applying the gradient descent algorithm formulated previously, K converges very fast to the value:

K_{GDT} = (0.43, 1.82, 0.75)

B. Time simulation results

The performance of the FDC is tested using time simulation. The disturbance used is still the three-phase fault on tie line 3-101 close to the terminal bus 3. Two cases are studied:

Case 1: Fault occurs at t = 0.5 sec. and cleared in 0.1 sec. without line tripping.
Case 2: Fault occurs at t = 0.5 sec. and cleared in 0.075 sec. by tripping line 3-101.

From Fig. 7 & 8, we can see that when there is no supplementary controller installed to the UPFC, the damping of the system is very poor even though the system is stable. The addition of either the CSC or the FDC can increase the system damping significantly and reduce the first swing peak angle slightly. The computer results show that the FDC is more effective in damping the rotor-angle oscillation. Also, as the system topology and operation point has changed, the FDC still performs very well. This indicates that the FDC has a better robustness as compared with its conventional counterpart.

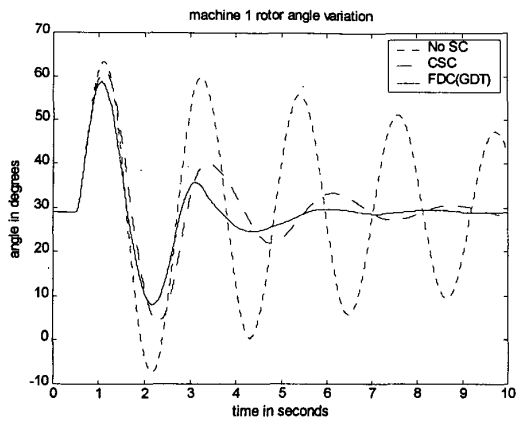


Fig. 7 System response for case 1

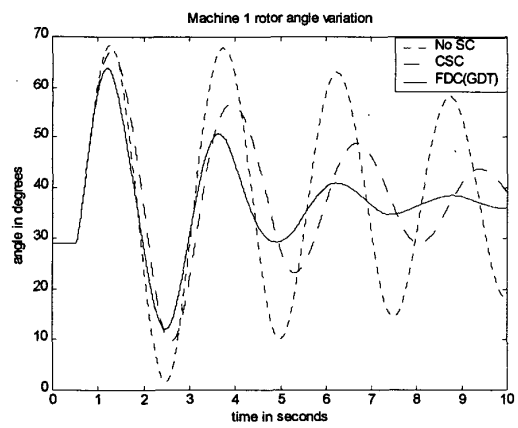


Fig. 8 System response for case 2

C. Small signal analysis

The eigenvalue analysis is carried out in order to have a clearer insight of the FDC performance. Perturbation method is used in forming the system matrix in FDC case.

Table 2 System Eigenvalue (interarea mode)

	No SC	CSC	FDC
Eigenvalue	*-0.081±j2.89*	*-0.431±2.48*	*0.490±j2.92*

We can see from Table 2 that the interarea mode of oscillation is improved by the addition of the supplementary controller. In addition, the FSC can result in a larger negative shift of the eigenvalues which means the system is more stable under small disturbances.

5. CONCLUSIONS

The application of fuzzy logic theory to the design of the supplementary controller for the UPFC is investigated. Gradient descent training is applied to optimise the parameters of the FDC. Transient stability simulation and small signal analysis are conducted to examine the performance of the FDC as compare with the conventional counterpart. The computer results show that the designed FDC has a superior performance over the CSC in improving damping of the system and has better robustness.

6. ACKNOWLEDGEMENT

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7. REFERENCE

[1] IEEE FACTS Application Task Force, "FACTS Applications", Publication of IEEE PES S.M., 1996.
[2] L. Gyugyi, "Unified Power-Flow Control Concept for Flexible AC Transmission Systems", IEE Proceedings-C, Vol. 139, No.4, July 1992. pp: 323-331.
[3] M. P. Bottino, B. Delfino, G. B. Denegri, FACTS for More Effective Networks: Unified Power Flow Controller Using PSCAD/EMTDC Code, EPRI-the Future of Power delivery Conference, Washington DC, 1996.
[4] Zhenyu Huang, Yixin Ni, et al. "Application of Unified Power Flow Controller in Interconnected Power Systems - Modeling, Interface, Control Strategy and Case Study", to be appeared on IEEE Trans. on Power Systems.
[5] Li-Xin Wang, "A Course in Fuzzy Systems and Control", Prentice Hall, 1997.
[6] J. A. Momoh, and X. W. Ma, et al. "Overview and Literature Survey of Fuzzy Set Theory in Power Systems", IEEE Trans. on Power Systems, Vol. 10, No. 3, Aug. 1995. pp: 1676-1690.
[7] P. Kundur, "Power System Stability and Control", McGraw Hill, 1993.
[8] Lai On Mak, Zhenyu Huang, Yixin Ni, et al, " A versatile interface between FACTS devices and ac power systems", Proceedings of 13th Power System Computation Conference, Norway, 1999. pp: 533-538.

8. APPENDIX

Parameters of the UPFC and its control system

The UPFC model:
V_B=220 kV, S_B=100 MVA, n_1=0.05, n_2=0.25, X_{t1}=0.00025, X_{t2}=0.05 (all in p. u.)
UPFC main control:
K_1=0.05, T_1=0.01, K_2=1.0, T_2=0.05, K_3=5.0, T_3=0.1, K_4=5.0, T_4=0.1, $V_{d,ref}$≈44 kV
The parameters of the CSC:
K_A=0.83, T_w=3.0s, T_1=T_3=0.02s, T_2=T_4=0.33s, *lim_max*=0.2, *lim_min*= −0.2