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# FUZZY LOGIC DAMPING CONTROLLER FOR FACTS DEVICES IN INTERCONNECTED POWER SYSTEMS

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## ABSTRACT

In this paper fuzzy controllers are designed for FACTS devices in interconnected power systems. Two typical FACTS devices, STATCOM and UPFC, are used as examples to show that FACTS devices with well designed fuzzy controllers can improve interconnected power system dynamic behavior significantly.

## 1. INTRODUCTION

The FACTS (flexible ac transmission systems) technology [1] is a new research area in power engineering. It introduces the modern power electronic technology into traditional ac power systems and significantly enhances power system controllability and transfer limit. In this paper, two typical FACTS devices, static synchronous compensator (STATCOM) and unified power flow controller (UPFC), are studied and used as examples to demo the FACTS device effects on power systems. The STATCOM resembles in many respects a rotating condenser used for reactive power compensation. Its operation principles and power frequency model can be found in [2,3,4]. The UPFC is a comprehensive FACTS device with very attractive features. It consists of two back-to-back voltage source inverters. By proper connecting UPFC into the power system and using effective control strategies, the UPFC can realize various functions, e.g. constant power flow control, series compensation, voltage regulation and phase shifting etc. The UPFC operation principles and its power frequency model for stability analysis can be found in [5, 6].

Modern power systems tend to be interconnected to yield the best benefit. Sometimes the tie lines between two interconnected power systems are heavily loaded, especially in the deregulation environment. Very often the low frequency power oscillation will occur on a heavily loaded tie line following a large or small disturbance, which is sometimes difficult to be damped by the PSS (power system stabilizer) of a certain machine. Application of FACTS devices is a promising approach to increase transfer limit and in the meantime to get desired damping. However the conventional controllers is based on the linear control theory. The entire system model should be built first and the system is then linearized at a dominant operating point. The linear controller is designed based on the linearized system

and then checked under large disturbances in the original nonlinear system. It is clear that the designed linear controller can't provide appropriate stabilization signal over a wide range of operating conditions and under large disturbances for the original nonlinear system.

In recent years increasing interest has been seen in applying fuzzy theory [7] to controller design in many engineering fields. The fuzzy controller has very attractive features over conventional controllers. It is easy to be implemented in a large-scale nonlinear dynamic system and not so sensitive to the system models, parameters and operation conditions. In particular human knowledge can be included in control rules with ease. Therefore investigation of fuzzy theory applications in power system control grows rapidly [8].

In this paper, fuzzy controller is incorporated into the two types of FACTS devices for damping interarea power oscillation. Its effects are tested in a 4-generator test power system. In section 2 the math model and the controller block diagram for STATCOM and UPFC are presented. Section 3 is the computer test results. Conclusions are made in section 4.

## 2. MATHEMATIC MODEL

### 2.1 Mathematic model for STATCOM

A STATCOM schematic circuit diagram and the corresponding block diagram for constant voltage control are shown in Figure 1. Based on ideal STATCOM assumption, its converter power frequency model can be expressed as

$$[4]: \quad \frac{dV_s}{dt} = K_v V \sin \phi \quad (1)$$

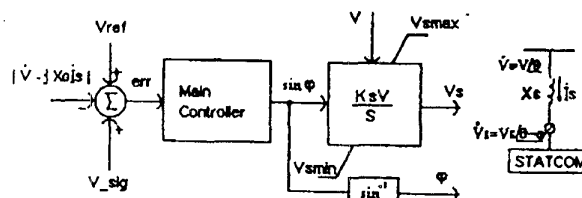


Figure 1 STATCOM schematic diagram

In the block diagram, main controller can be simplified as an inertial block with proper gain and time constant.  $X_G$  is for desired voltage regulation.  $V\_sig$  is the output of supplementary control designed for damping power

oscillation on the tie line. If we take tie line real power  $P_L$  as the input signal of supplementary controller and utilize conventional PSS-like transfer function,  $V\_sig$  will be [9]:

$$V\_sig = K_A \frac{T_w s}{1 + T_w s} \cdot \frac{1 + T_1 s}{1 + T_2 s} \cdot \frac{1 + T_3 s}{1 + T_4 s} \cdot P_L$$

The fuzzy supplementary controller math model will be presented after UPFC model description.

## 2.2 Mathematic model for UPFC

A UPFC circuit diagram is shown in Figure 2 where the  $n_1$ ,  $X_{l1}$  and  $n_2$ ,  $X_{l2}$  are the voltage ratio and the impedance of the shunt and series transformers respectively. Per unit (p. u.) system and SI units are used for ac and dc circuits respectively. The p. u. values of ac system are calculated based on system-side  $S_B$  and  $V_B$ . All the variables used in UPFC model are denoted in figure 2 with bold fonts representing phasors. The corresponding power frequency model can be derived as [6]:

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

$$P_1 = \text{Re}(\dot{V}_1 (\frac{n_1 \dot{V}_s - \dot{V}_1}{jX_{l1}})^*) \quad (2a)$$

$$P_2 = \text{Re}(\dot{V}_{pq} (\frac{\dot{V}_s + \dot{V}_{pq} - \dot{V}_R}{jX_{l2}})^*)$$

$$\begin{aligned} V_1 &= m_1 V_d / V_B \\ V_2 &= m_2 V_d / V_B \\ \theta_1 &= \theta_s - \varphi_1 \\ \theta_2 &= \theta_s - \varphi_2 \\ V_{pq} &= V_2 / n_2 \\ \theta_{pq} &= \theta_2 \end{aligned} \quad (2b)$$

The UPFC control system block diagram is shown in Figure 3. Figure 3(a) is the constant  $V_d$  control through controlling the firing angle  $\varphi_1$  of converter 1. Figure 3(b) is the constant ac bus voltage control of sending end through controlling coefficient  $m_1$  of the PWM controller of converter 1. Figures 3(c) to 3(f) are the control of  $m_2$  and  $\varphi_2$  of inverter 2 to be explained below.

The series voltage provided by UPFC

$$\dot{V}_{pq} = V_{pq} \angle \theta_{pq} \quad (\theta_{pq} = \theta_2 = \theta_s - \varphi_2)$$

can be decomposed as  $V_p$  and  $V_q$  (see phasor diagram of figure 3(f)). The former is perpendicular with  $\dot{V}_s$ ; and the latter is in phase with  $\dot{V}_s$ . In figure 3(c), the desired  $V_p$  and  $V_q$  are obtained from the constant line P and Q Control; and in figure 3(d), the desired  $V_p$  and  $V_q$  are obtained from the constant series compensation control. The selected pair of  $V_p$  and  $V_q$  then enters figure 3(e) to calculate corresponding desired  $m_2$  and  $\varphi_2$  for using in PWM and firing angle

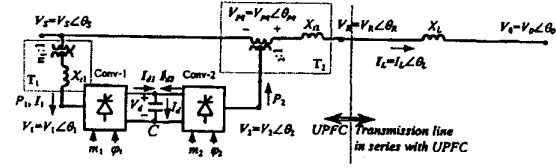


Figure 2 UPFC circuit diagram

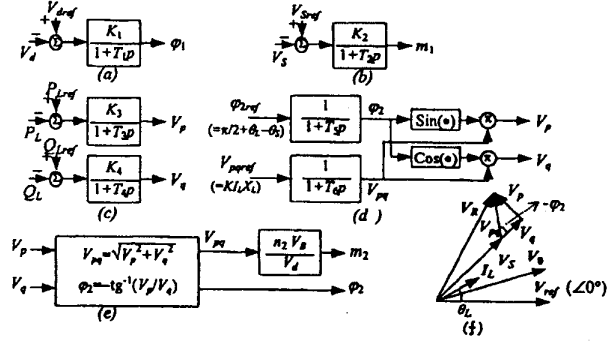


Figure 3 UPFC control block diagram

controllers of converter 2 respectively. In figure 3(d), T5 and T6 represent control delay.  $\varphi_{2,ref} = \pi/2 + \theta_L - \theta_s$ ,  $V_{pq,ref} = KI_L X_L$ , where  $K$  is the series compensation degree. In figure 3(e), the block of  $\frac{n_2 V_B}{V_d}$  is based on the relation of  $V_2 = m_2 V_d / V_B = n_2 V_{pq}$ . According to the UPFC control model, its outputs  $m_2$ ,  $\varphi_2$  can be obtained. Figure 3 and equation (2) constitute the UPFC power frequency model for power system stability analysis.

Similar to STATCOM, supplementary control should be added in order to damp the interarea power oscillation. The same transfer function and input signal used for STATCOM can be used for UPFC as well. The supplementary control output signal  $V\_sig$  can be superposed onto  $V_{sref}$  (see Figure 3(b)) of UPFC shunt element control for damping power oscillation through sending end bus voltage modulation.  $V\_sig$  can also be superposed onto  $P_{L,ref}$  (in constant power control, see Figure 3(c)) or  $V_{pq,ref}$  (in constant series compensation control, see Figure 3(d)) of UPFC series element control for damping power oscillation.

## 2.3 Fuzzy supplementary controller for damping power oscillation

Figure 4 shows the proposed fuzzy logic damping controller block diagram. The input signal of the damping controller is the real power of the tie-line, which is filtered by washout blocks to eliminate the dc component. In fact, this is a nonlinear PI-type fuzzy damping controller. The output of the controller is the damping signal ( $dmp\_sig = V\_sig$ ) which will be sent to the main controller (see Figures 1 and 3) to modulate certain reference value for damping power

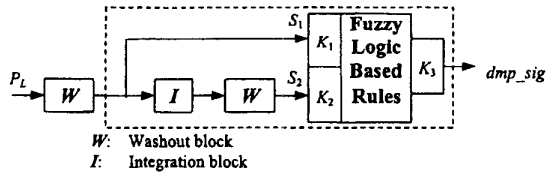


Figure 4 Fuzzy damping controller block diagram

oscillation. In this paper, The bus voltage modulation is used for STATCOM, and the line real power modulation for UPFC.

For the fuzzy control implementation[7], we use singleton fuzzifier, center average defuzzifier with seven linguistic variables for the fuzzy controller input signal ( $S_1K_1+S_2K_2$ ) (see figure 4) and output signal *dmp\_sig* respectively. They are PB(positive large), PM(positive medium), PS(positive small), Z(zero), NS(negative small), NM(negative medium) and NB(negative large). The corresponding fuzzy rules are taken as:

( $S_1K_1+S_2K_2$ ) NB NM NS Z PS PM PB  
*dmp\_sig* PB PM PS Z NS NM NB

The two parameters,  $K_1$  and  $K_2$ , are used to scale the input signals. Similarly,  $K_3$  is applied to the output signal *dmp\_sig* to get appropriate value for the signal modulation of the basic controller. Fuzzy Toolbox of MATLAB is used in computer programming.

### 3. COMPUTER TEST RESULTS

#### 3.1 Computer test results for STATCOM

A 4-generator 2-area interconnected power system is used for computer test (see figure 5). The output power of generators 1 to 4 is 350 MW, 350 MW, 267 MW, and 350 MW respectively. The loads on the buses 9 and 11 are 500 MW and 800 MW respectively. About 200 MW power are transferred from area 1 to area 2 through a long transmission corridor with a 100MW STATCOM installed on the bus at the center of the transmission lines. The disturbance used is a three-phase fault on the bus 9 at  $t=0.10$  second, and cleared in 0.09 second at  $t=0.19$  second by tripping line 9-10.

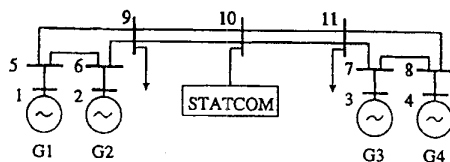


Figure 5 STATCOM test system

Figure 6 shows that the system is unstable when there is no STATCOM (case 1). Figure 7 shows the system is stable

when there is a STATCOM in the system (case 2). However the damping is poor when there is no supplementary control. Figure 8 shows that damping effect has been improved significantly after the installation of fuzzy supplementary controller (case 3). Some other computer tests are conducted which show that fuzzy supplementary controller has almost the same damping effect at the design point as and better robustness than the well-designed conventional controller.

#### 3.2 Computer test results for UPFC

The two area interconnected power system in [9] is used for UPFC test (see figure 9).

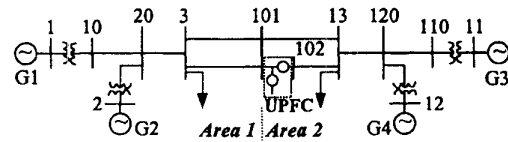


Figure 9 UPFC test system

The electric power output of generators 1 to 4 is 700 MW, 700 MW, 716 MW, and 700 MW respectively. The loads on the buses 3 and 13 are 967 MW and 1767 MW. About 390 MW power is transferred from area 1 to area 2 with a UPFC installed on one of the tie lines. The disturbance used is a three-phase stub fault on bus 3 at  $t=0.50$  second, and cleared in 0.10 second.

Figure 10 shows that the system is unstable when there is no UPFC (case 4). Figure 11 shows the system is stable when there is a UPFC in the system (case 5). However the damping is poor when there is no supplementary control. Figure 12 shows that damping effect has been improved significantly after the installation of fuzzy supplementary controller (case 6). Some other computer tests are conducted which show that fuzzy supplementary controller has almost the same damping effect at the design point as and better robustness than the well-designed conventional controller.

### 4. CONCLUSION

In this paper fuzzy controllers are designed for FACTS devices in interconnected power systems. Two typical FACTS devices, STATCOM and UPFC, are used as examples to show that FACTS devices with well designed fuzzy controllers can improve interconnected power system dynamic behavior significantly.

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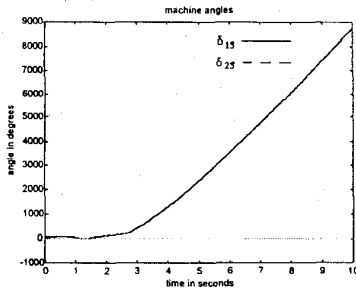


Figure 6 Rotor angle plot for case 1

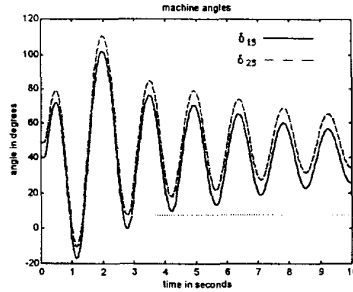


Figure 7 Rotor angle plot for case 2

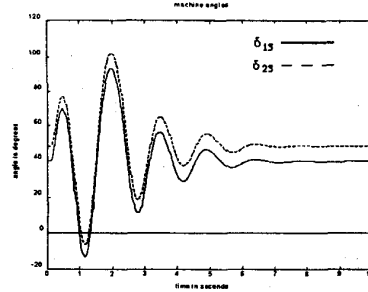


Figure 8 Rotor angle plot for case 3

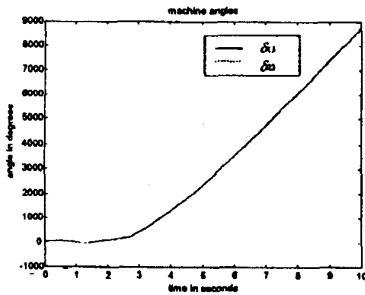


Figure 10 Rotor angle plot for case 4

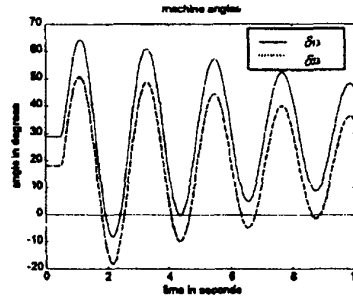


Figure 11 Rotor angle plot for case 5

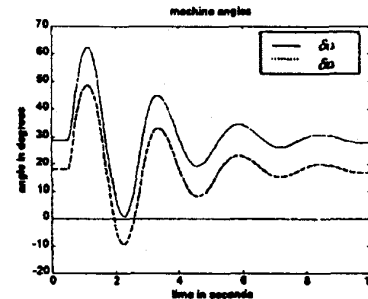


Figure 12 Rotor angle plot for case 6

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