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Fuzzy control of thyristor-controlled series compensator in power system transients [1]

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Abstract

Power system transient stability is one of the most challenging technical areas in electric power industry. Thyristor-controlled series compensation (TCSC) is expected to improve transient stability and damp power oscillations. TCSC control in power system transients is a nonlinear control problem. This paper presents a T–S-model-based fuzzy control scheme and a systematic design method for the TCSC fuzzy controller. The nonlinear power system containing TCSC is modelled as a fuzzy "blending" of a set of locally linearized models. A linear optimal control is designed for each local linear model. Different control requirements at different stages during power system transients can be considered in deriving the linear control rules. The resulting fuzzy controller is then a fuzzy "blending" of these linear controllers. Quadratic stability of the overall nonlinear controlled system can be checked and ensured using H^∞ control theory. Digital simulation with NETOMAC software has verified that the fuzzy control scheme can improve power system transient stability and damp power swings very quickly.

Keywords: Fuzzy control; T–S fuzzy model; Power systems; Thyristor-controlled series Compensation; Transient stability

1. Introduction

1.1. Power system transient stability control

High reliability of power supply plays an essential part in industry, commerce, transportation, communication, domestic households, etc. A power system can generally be divided into three parts, one concerned with generation, one with transmission and one with distribution. Under normal conditions, a generator keeps synchronism with the rest of the system. Severe perturbations to the system (e.g., faults), however, may result in a large unbalance between the generation and the load, thus creating a large unbalance between the mechanical torque and the electrical torque on the generator rotor. This may drive the generator out of synchronism and cause instability. Assume that before the fault occurs, the power system is operating at some stable steady-state operating point. The *power system transient stability* problem is then

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defined as that of assessing whether or not the system will reach an acceptable steady-state operating point following the fault [2]. Power system transient stability is one of the most challenging technical areas in electric power industry.

Power system transient stability control is to minimize the net accelerating (or decelerating) torque on the generator rotor, thus ensuring that a new equilibrium state be reached before the power angle swings far enough to lose synchronism. Loss of synchronism often happens in two ways. One is that the accelerating torque pulls the generator out of synchronism during the first swing of the power angle. The other is that although the first swing has been pulled back, the generator loses synchronism after several power oscillations due to the poor damping of the system. Therefore, effective transient stability control should be able to satisfy two different requirements, keeping first-swing stability and providing good damping, at different stages during power system transients.

1.2. Flexible AC transmission systems and thyristor controlled series compensation

The power flow through a transmission line is determined by the line impedance and the magnitudes and phase angles of the line end voltages. Traditionally, control of these system parameters was achieved through mechanical devices, which was rather slow. Therefore, large margins must be applied to ensure reliable operation. With the continuing progress in power electronics, a novel concept – Flexible AC Transmission Systems (FACTS) emerged in the late 1980's [2,10]. The philosophy of FACTS is to use thyristor-based devices instead of mechanical devices to flexibly control power flows at electronic speed. Without significant change of the structure of existing power systems, FACTS allows the transmission lines to be loaded up to their thermal limits and greatly improves the controllability and reliability of the systems.

For a relatively long transmission line, the line impedance is often the dominant factor that limits the transmission capability. Since line impedance is inductive, series capacitive compensation makes the line appear shorter thus increasing the transfer capability. Conventional series compensation uses fixed or switched capacitors, which is mechanically controlled and has many disadvantages. Thyristor-controlled series compensation (TCSC, also called Advanced Series Compensation, ASC), as one of the most attractive FACTS technologies, offers fast, smooth, and flexible control of the line impedance. The first TCSC project in the world was implemented at Kayenta Substation in Northeastern Arizona in 1992 [3]. TCSC has various advantages not available with conventional compensation apparatus, including improved transient stability, effective power swing damping, Subsynchronous Resonance (SSR) mitigation, fault current reduction, etc.

1.3. Background

The background of our research is the 500 kV, 381 km Yimin–Fengtun parallel transmission lines in Northeastern China. The power flow through the lines is expected to be increased to 2000 MW in the year 2000. Due to the long transmission distance and the large power flow, the transient stability problem will be very severe. Since the transmission lines cross the Great Xing'an Mountains, it would be very expensive and cause many environmental problems to build new lines to increase the transfer capability. TCSC makes it possible to improve the system's transient stability using the existing lines. As part of the feasibility analysis of the future TCSC project, the goal of our research is to find an effective TCSC control scheme in power system transients.

Fuzzy control has been applied successfully to various nonlinear industrial applications. Takagi and Sugeno proposed a fuzzy model, known as the T–S model, which can be used to describe nonlinear systems [6]. In their model, local dynamics in different state space regions are represented by linear models. The overall model of the system is then a fuzzy "blending" of these linear models. The T–S fuzzy model has been employed to develop a systematic design approach to fuzzy control of nonlinear systems [8]. In this approach, a linear feedback control is designed for each local linear model. The resulting overall controller is then a fuzzy "blending" of these linear controllers. So far, there have been few reported applications of the T–S fuzzy model to power systems control.

In this paper, a T–S-model-based fuzzy control scheme for TCSC control during power system transients is presented. The motivations for adopting this control scheme are its capability of addressing the nonlinear TCSC control problem, and its potential to satisfy the different control requirements at different stages during power system transients. Traditional control methods, such as bang–bang control, linear optimal control, or PID control, have difficulties satisfying these requirements simultaneously.

The remainder of the paper is organized as follows. Some basic concepts of power systems and TCSC are discussed in Section 2. Section 3 describes the fuzzy control scheme in TCSC control. Simulation results are presented in Section 4. Some conclusions are then provided in Section 5.

2. Power system and TCSC description

2.1. Single-machine infinite-bus system

Fig. 1 shows the single-machine infinite-bus system that will be used in this analysis. An infinite-bus is a source of invariable frequency and voltage (both in magnitude and phase angle), which is often used to approximate a major bus of a power system with very large capacity. TCSC is installed at the receiving end of each line and is represented as a variable series capacitor in Fig. 1.

The fundamental equation governing the rotor dynamics is called swing equation [2], which is expressed as

$$\begin{aligned} &\dot{\delta} = \Delta\omega, \\ &\frac{H}{2\pi f_0}\Delta\dot{\omega} = P_m - P_e - P_D. \end{aligned} \tag{1}$$

Thus, a linearized model of the single-machine infinite-bus system near some operating point is given by

$$\begin{aligned} &\Delta\dot{\delta} = \Delta\omega, \\ &\frac{H}{2\pi f_0}\Delta\dot{\omega} = \Delta P_m - \Delta P_e - \Delta P_D, \end{aligned} \tag{2}$$

where $\Delta\delta$ is the deviation of the power angle from its operating point value (rad), $\Delta\omega$ the deviation of the generator angular speed (rad/s), ΔP_m the deviation of the mechanical input power from its operating point value (p.u.), ΔP_e the deviation of the electrical power from its operating point value (p.u.), ΔP_D the deviation of the damping power from its operating point value (p.u.), f_0 the rated frequency (Hz) and, H the inertia constant (s).

To highlight the impact of TCSC control on power system transient stability, we assume that the mechanical power is constant, i.e.,

$$\Delta P_m = 0, \tag{3}$$

and E'_q is constant during the transients. Then the electrical power P_e is only a function of the power angle δ and the TCSC impedance X_{TCSC}. $P_e = f(\delta, X_{TCSC})$. ΔP_e can be expressed as

$$\Delta P_e = f'_\delta \Delta\delta + f'_X \Delta X_{TCSC}, \tag{4}$$

where $f'_\delta = \partial f(\delta, X_{TCSC})/\partial\delta, f'_X = \partial f(\delta, X_{TCSC})/\partial X_{TCSC}$. In addition, ΔP_D is proportional to $\Delta\omega$, i.e.,

$$\Delta P_D = \frac{D}{2\pi f_0}\Delta\omega. \tag{5}$$

From Eq. (4), it is clear that ΔP_e can be controlled by adjusting the TCSC impedance. This provides an approach to minimize the net accelerating (decelerating) torque on the rotor and improve the transient stability.

2.2. Basic concepts of TCSC

Fig. 2 shows the basic components in a TCSC circuit: a capacitor in series with the transmission line, and a thyristor pair and an inductor in parallel with the capacitor [1]. Proper selection of the thyristor firing angle results in a loop flow I_t, which increases the capacitor current, thus increasing the voltage across the capacitor and the overall series compensation. In such cases, TCSC works in capacitive mode and acts as a variable capacitor. TCSC can also work in inductive mode, which is not of interest here. By varying the thyristor firing angle, the TCSC impedance is adjusted, and then the series compensation level and the overall impedance of the transmission line is adjusted.

TCSC control is a nonlinear control problem since the relationship between the TCSC impedance and the control output, the thyristor firing angle α, is highly nonlinear. Fig. 3 shows the TCSC impedance characteristic [3]. Another nonlinear property is that at different compensation levels, the TCSC circuit approaches its steady state at different rates, approximately 1–2 cycles at lower levels and 8–10 cycles at higher levels [1]. Therefore, approximating the TCSC impedance

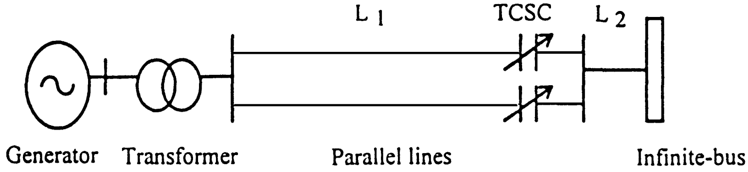

Fig. 1. Single-machine infinite-bus system.

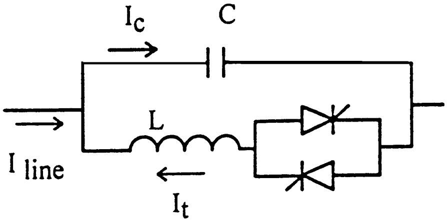

Fig. 2. TCSC circuit (capacitive mode).

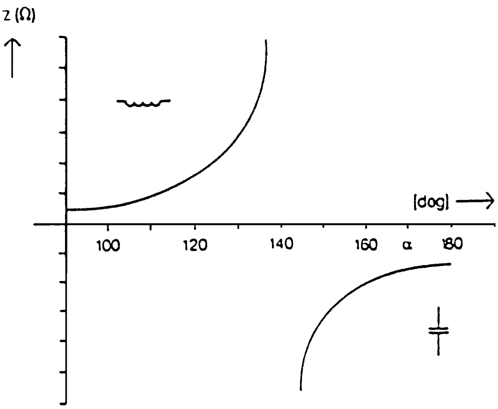

Fig. 3. TCSC impedance characteristics.

characteristic with linear relations can only be done locally at various compensation levels. The TCSC circuit can be viewed as a first-order lag element with variable time constant T_{TCSC_i} and variable gain K_i,

$$\frac{\Delta X_{\mathrm{TCSC}}}{\Delta u} = \frac{K_i}{1 + sT_{\mathrm{TCSC}_i}} \tag{6}$$

where Δu denotes the variation of the firing angle α.

3. T–S-model-based fuzzy control of TCSC

3.1. Structure of the linearized controlled subsystem

The TCSC system is locally linearized with a set of linear state equations. Linear feedback control is used for each linear sub-model. Eqs. (2)–(6) give the structure of each linearized controlled subsystem, as shown in Fig. 4.

3.2. T–S fuzzy model of the power system with TCSC

Since linear feedback will be used in each control rule, $\Delta\omega$, as an important state variable, can roughly determine the compensation level of TCSC and the local state space region of the system. $\Delta\omega$ also provides information on the system condition (in fault, large power swings, or small power swings), which is very helpful for accommodating the different control requirements during power system transients. Therefore, $\Delta\omega$ is selected as the only premise variable in the T–S fuzzy model and it is normalized to [-1 1]. Each rule of the fuzzy model has the following form:

Model Rule i:
IF $\Delta\omega$ is M_i
THEN

$$\dot{X} = A_i X + B_i \Delta u, \quad i = 1, 2, \ldots, r, \tag{7}$$

where

$$X = [\Delta P_{\mathrm{e}}, \Delta\omega, \Delta X_{\mathrm{TCSC}}]^{\mathrm{T}},$$

$$A_{\mathrm{i}} = \begin{bmatrix} 0 & f'_{\delta i} & -\dfrac{f'_{Xi}}{T_{\mathrm{TCSC}_i}} \\ -\dfrac{2\pi f_0}{H} & -\dfrac{D}{H} & 0 \\ 0 & 0 & -\dfrac{1}{T_{\mathrm{TCSC}_i}} \end{bmatrix}, \quad \text{and,}$$

$$B_i = \left[\frac{K_i f'_{Xi}}{T_{\mathrm{TCSC}_i}}, \quad 0, \quad \frac{K_i}{T_{\mathrm{TCSC}_i}}. \right]^{\mathrm{T}}$$

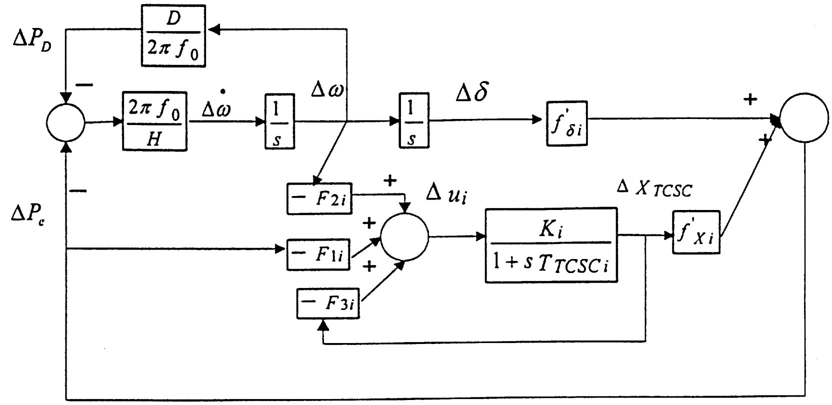

Fig. 4. Block diagram of the linearized controlled subsystem.

3.3. Fuzzy controller of TCSC

The fuzzy controller of TCSC has r rules:
Controller Rule i:
IF $\Delta\omega$ is M_i
THEN

$$\Delta u_i = -F_i X, \quad i = 1, 2, \ldots, r. \tag{8}$$

F_i is obtained using linear optimal control theory. In deriving F_i, we need to select an appropriate weight matrix Q_i for the state variables and an appropriate weight coefficient R_i for the control variable, to deal with the different control requirements under different system conditions. Let R_i be constant, then Q_i can be chosen as follows. When the power system is under fault condition, Q_i should be relatively large to increase the feedback gains, enhance the influence of the feedback signals, provide prompt compensation and hold back the power angle's first swing. When the system is in power swings, Q_i should be relatively small to decrease the feedback gains, reduce the impact of noise and provide effective damping.

The final control Δu is inferred using the Sum–Product reasoning method:

$$\Delta u = \frac{-\sum_{i=1}^{r} w_i F_i X}{\sum_{i=1}^{r} w_i}, \tag{9}$$

where w_i is the activating degree of the i-th rule. The overall controlled system is

$$\dot{X} = \frac{\sum_{i=1}^{r} w_i (A_i X + B_i \Delta u)}{\sum_{i=1}^{r} w_i}. \tag{10}$$

System (10) is not always stable even if all its subsystems are stable. Some recent significant stability analysis results have provided methodologies for ensuring the stability of system (10) [4,5,7,9]. One solution is to recast the control problem as an linear matrix inequality (LMI) problem [9]. Another solution is to use H^∞ control theory [4].

3.4. Design example

The parameters used here were obtained from the actual Yimin–Fengtun transmission system. Table 1 indicates the generator and transformer constants. Table 2 indicates the line and TCSC parameters (Note: the compensation scheme employed in the system combines both TCSC and fixed compensation). The power flow is 2000 MW.

$\Delta\omega$ is divided into five fuzzy sets: PL, PS, Z, NS and NL. Therefore, there are five rules in both the T–S fuzzy model and the fuzzy controller. Membership functions of the fuzzy sets are shown in Fig. 5. Table 3 lists A_i, B_i in Eq. (7) and F_i in Eq. (8) for each rule.

Quadratic stability of the controlled system is checked using Theorem 4.1 (C14) in [4]. The final matrix

$$\boldsymbol{H} = \begin{bmatrix} -7.22 & 0.474 & -21.7 & -29.9 & 0 & -57.2 \\ -51.5 & 0 & 0 & 0 & 0 & 0 \\ -12.0 & -2.63 & -37.8 & -57.2 & 0 & -111.7 \\ 15 & 0 & 0 & 7.22 & 51.5 & 12.0 \\ 0 & 15 & 0 & -0.474 & 0 & 2.63 \\ 0 & 0 & 15 & 21.7 & 0 & 37.8 \end{bmatrix}.$$

Table 1
Generator and transformer constants

f_0(Hz)	50
H(s)	6.1
D(p.u.)	0.0
X_T (p.u.)	0.05
X_d (p.u.)	1.15
X'_d (p.u.)	0.141
X''_d (p.u.)	0.109
X_q (p.u.)	1.15
X''_q (p.u.)	0.109
T'_{d0} (s)	15.5
T''_{d0} (s)	0.084
T''_{q0} (s)	0.129

Table 2
Lines and TCSC parameters

X_{L1} (p.u.)	Line L_1 reactance	0.972
X_{L2} (p.u.)	Line L_2 reactance	0.53
X_{FC} (p.u.)	Fixed compensation	−0.23
X_{TCSC1} (p.u.)	Minimum TCSC compensation	−0.117
X_{TCSC2} (p.u.)	Maximum TCSC compensation	−0.23

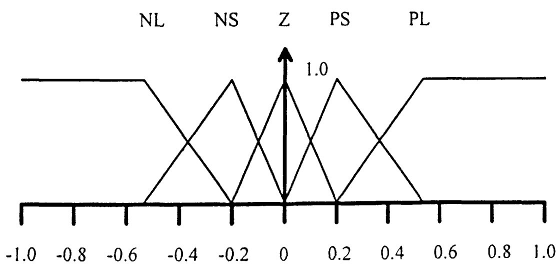

Fig. 5. Membership functions of $\Delta\omega$.

The eigenvalues of $\boldsymbol{H}$ are $-46.0\pm 28.3i$, $20.7\pm 55.8i$, 48.8 and 1.67. Therefore, $\mathrm{Re}\,\lambda_j(\boldsymbol{H}) \neq 0$ for $j = 1, 2, \ldots, 6$ and the fuzzy controller quadratically stabilize the nonlinear system.

4. Simulation results

Digital simulation results with NETOMAC software are given in Figs. 6 and 7. Each figure contains curves of the electric power, the power angle and the TCSC impedance. NETOMAC is a large power system simulation program developed by Siemens. It can simulate both electromagnetic transients and electromechanical transients of power system. The fuzzy controller was tested for two different faults. The action sequence of breakers under each fault is described below. Parallel lines are both in service before the fault occurs.

Table 3
Fuzzy model and controller rules

i	M_i	A_i	B_i	F_i^t
1	PL	$\begin{bmatrix} 0 & 0.304 & -122 \\ -51.5 & 0 & 0 \\ 0 & 0 & -18.9 \end{bmatrix}$	$\begin{bmatrix} -12.7 \\ 0 \\ -19.6 \end{bmatrix}$	$\begin{bmatrix} -1.73 \\ 0.994 \\ -0.206 \end{bmatrix}$
2	PS	$\begin{bmatrix} 0 & 0.281 & -23.5 \\ -51.5 & 0 & 0 \\ 0 & 0 & -40.0 \end{bmatrix}$	$\begin{bmatrix} -12.2 \\ 0 \\ -20.8 \end{bmatrix}$	$\begin{bmatrix} -0.839 \\ 0.706 \\ -0.119 \end{bmatrix}$
3	Z	$\begin{bmatrix} 0 & 0.269 & -25.3 \\ -51.5 & 0 & 0 \\ 0 & 0 & -45.5 \end{bmatrix}$	$\begin{bmatrix} -9.35 \\ 0 \\ -16.8 \end{bmatrix}$	$\begin{bmatrix} -0.359 \\ 0.317 \\ -0.021 \end{bmatrix}$
4	NS	$\begin{bmatrix} 0 & 0.26 & -26.8 \\ -51.5 & 0 & 0 \\ 0 & 0 & -50. \end{bmatrix}$	$\begin{bmatrix} -5.57 \\ 0 \\ -10.4 \end{bmatrix}$	$\begin{bmatrix} -0.638 \\ 0.707 \\ -0.095 \end{bmatrix}$
5	NL	$\begin{bmatrix} 0 & 0.252 & -51.5 \\ -51.5 & 0 & 0 \\ 0 & 0 & -100 \end{bmatrix}$	$\begin{bmatrix} -2.31 \\ 0 \\ -4.49 \end{bmatrix}$	$\begin{bmatrix} -0.487 \\ 1.0 \\ -0.031 \end{bmatrix}$

(1) *Single-phase-to-ground fault*:
- At $t = 0.1$ s: A single-phase-to-ground fault is applied to one line at the sending end;
- At $t = 0.2$ s: Breakers of the phase in fault are opened;
- At $t = 1.0$ s: Breakers of the phase in fault are closed again to check whether the fault has been cleared;
- At $t = 1.1$ s: The fault still exists, therefore breakers of all three phases of the line in fault are opened, and there is only one line left in service.

(2) *Three-phase-to-ground fault*:
- At $t = 0.1$ s: A three-phase-to-ground fault is applied to one line at the sending end;
- At $t = 0.2$ s: The breakers of all three phases of the line in fault are opened and there is only one line left in service.

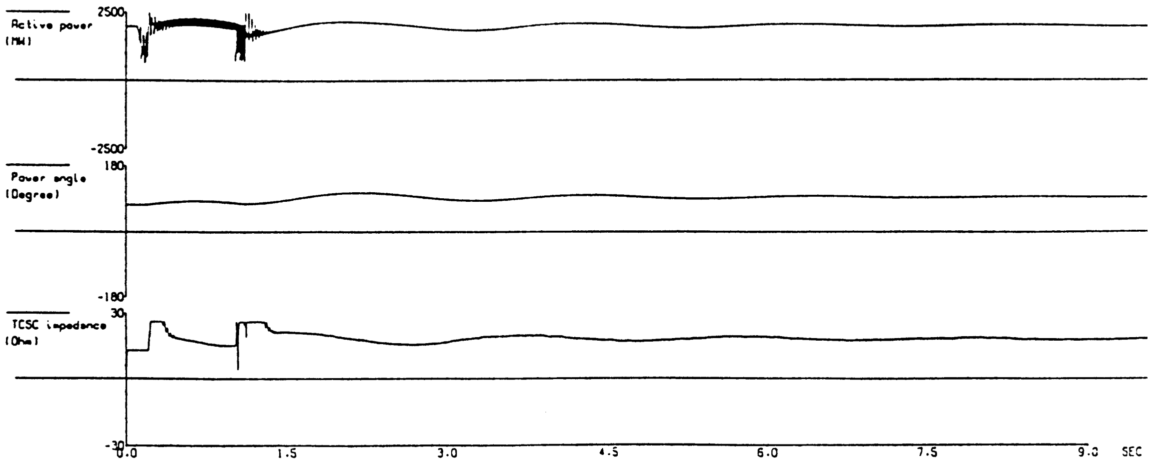

Fig. 6. Result of single-phase-to-ground fault case.

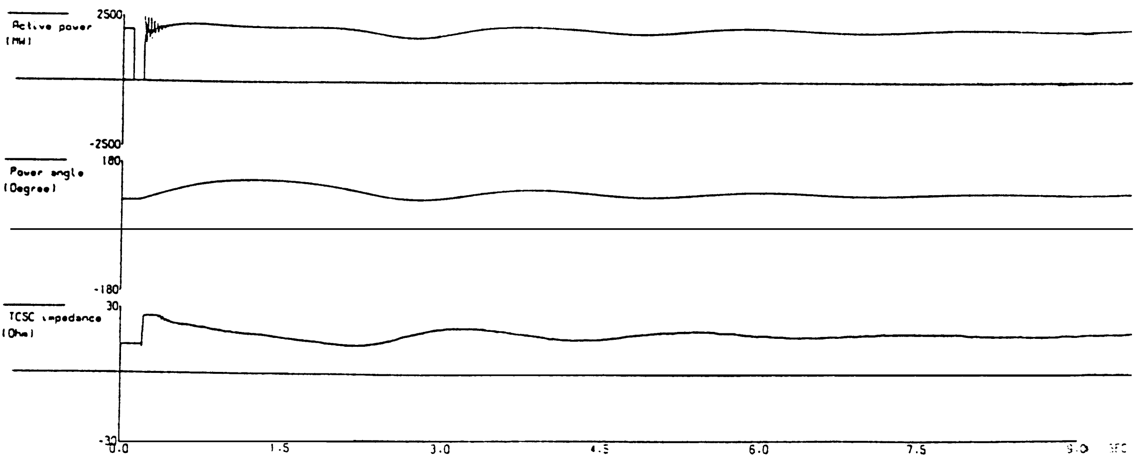

Fig. 7. Result of three-phase-to-ground fault case.

In both Figs. 6 and 7, the first swing of power angle is pulled back after the fault, and the subsequent power oscillations are effectively damped.

5. Conclusion

A T–S-model-based fuzzy control scheme is developed as an effective solution to the nonlinear TCSC control problem in power system transients. The nonlinear system is a fuzzy "blending" of a set of locally linear models. A systematic design approach for TCSC control is provided. Linear optimal control theory is utilized and extended in deriving the control rules so that different control requirements can be simultaneously satisfied in power system transients. Quadratic stability of the overall controlled nonlinear system can be checked and ensured using H^{∞} control theory. The fuzzy control scheme works well over a wide range and is robust under different fault conditions. The successful application of the fuzzy control scheme to TCSC control reveals that the approach is very promising in control of other FACTS devices and other complex nonlinear industrial plants.

To further check the effectiveness of the fuzzy control scheme, current work includes simulation in a multi-machine system and physically dynamic experiments. Preliminary results are satisfactory and will be reported later.

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