TCSC Controller Design Considering Torsional Vibration Suppression in Turbine-Generator System

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Abstract

In this paper, TCSC controller using linear feedback control law is proposed to suppress the torsional vibration. We use TCSC as a speedy feedback control actuator. We investigate the characteristic of TCSC and design feedback controller. By numerical simulation, the control performance is validated

Key words: TCSC, 2-mass system, PD controller, CDM, nonlinear control, SMIB system.

1 Introduction

New power electric control devices, called FACTS (Flexible AC Transmission Systems) can change some parameters of power system which have not been controllable. To use this new controllability, many researches for FACTS have been done[1]. As one of these FACTS, there is TCSC which is mainly proposed for power flow control[2]. In this paper, we propose this TCSC can suppress torsional vibration in turbine-generator system. This proposal is a new control application of TCSC.

Torsional vibration between turbines and generator can cause extensive damage to turbine-generator shafts. In the case of nuclear generation system, this torsional vibration can be fatal for the shaft tends to be long. In 1970s there are two power breakdowns arising from this torsional vibration in United States. To suppress it, some controllers using PSS have been proposed[5],[6]. But, we propose TCSC can be a better controller for suppression of this torsional vibration

In section 2, the general figures and conventionally proposed usage of TCSC are explained, and we show the difference of our proposal from these conventional TCSC controllers. In section 3, some vibration problems in power system are explained. After these explanations, we analyze control characteristics of TCSC in section 4, then design two controllers and validate these controllers by numerical simulations in section 5.

2 General Figures of TCSC

Fig.1 is a simplified structure of TCSC. The impedance of transmission line can be varied arbitrarily by TCSC, choosing the fire angle of thyristor properly.

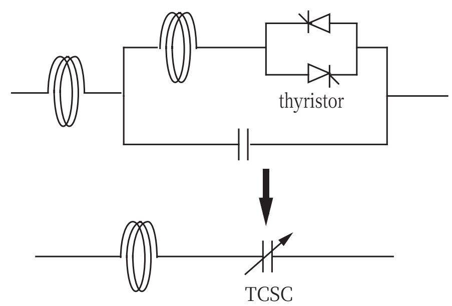

Figure 1. Structure of TCSC

2.1 TCSC in Power Flow Control

By inserting the TCSC into a transmission line, the impedance X of the line can be adjusted freely, and consequently the maximum value of power flow, formulated in Eq.1, becomes controllable. This is a conventionally proposed usage of TCSC.

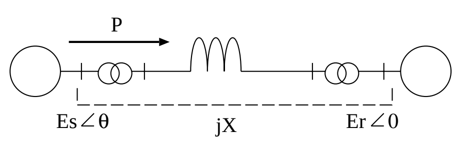

Figure 2. Power Transmission

$$P = \frac{E_s E_r}{X}\sin\theta = P_{max}\sin\theta \quad (1)$$

2.2 TCSC in SSR(Subsynchronous Resonance)

TCSC is considered to be effective for mitigation of subsynchoronous resonance(SSR). Some researches

[3], [4] explore the SSR mitigation using impedance frequency domain characteristics of TCSC. But, these mitigation performance is obtained by only installing TCSC. It does not consider any feedback control.

We need to notice the characteristic of TCSC. By changing the fire angle, we can get speedy electric torque response. This characteristic can be a good control capability. Using this capability, we can suppress high frequency vibrations.

In this paper, TCSC feedback control for vibration suppression is proposed. We are interesting in electric torque as controller output not in frequency response of TCSC.And, this point is explained in section4.

3 Vibrations in Power System

Vibrations of some specified frequencies rise in power system when disturbances break down[7]. In this section, 2 types of these vibrations are analyzed.

We explore these vibrations using the single machine infinite bus (SMIB) system model [7]. The single machine infinite bus system model is the most frequently used model for generator analysis. In this model, a generator is supposed to be connected toa infinite bus by a transmission line which has the impedance of $R_e + jX_e$(Fig. 3).

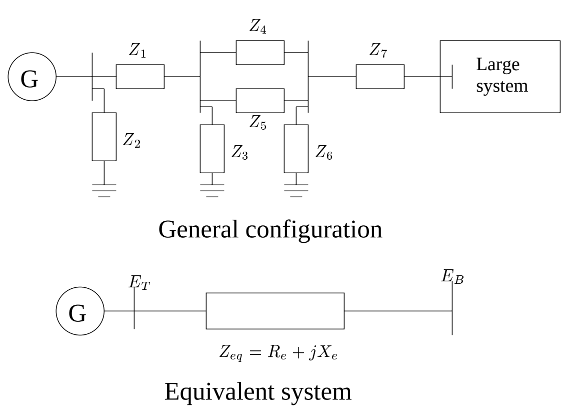

Figure 3. Single Machine Infinite Bus (SMIB) System

3.1 Local Mode Vibration

A vibration called local mode can be analyzed based on this SMIB model. Fig. 4 is the block diagram of this model. The dynamics surrounded by dotted rectangle shows that there is a synchronous torque. This torque intends to synchronize the phase of the generator rotor angle with that of the infinite bus. If the system is perturbed, this torque makes a vibration.

Power System Stabilizer (PSS) is used to suppress this vibration.

3.2 Torsional Mode Vibration

There are a generator and several turbines in a generator system. This turbine-generator system can be modeled as a multi-mass system, and therefore it has torsional vibrations which are attributed to the multi-mass system. To confirm this torsional vibration, a frequency response of power system from mechanical torque input to terminal voltage of generator is shown in Fig. 5.

Thick line describes the response of turbine-generator system, and dotted line describes the response of the system connected with the infinite bus. By this diagram, we can say that the local mode vibration appears at 1Hz and the torsional mode one at 7.5Hz.

4 Analysis of New Control Capability Obtained by Using TCSC

4.1 The Characteristic of TCSC

Eqs. from (2) to (4) show the dynamics of SMIB system.

$$\dot{\delta} = \omega_0 \Delta\omega \tag{2}$$

$$\begin{aligned}\Delta\dot{\omega} &= \frac{1}{2H}(T_m - T_e) \qquad (3)\\ &= \frac{1}{2H}T_m - \frac{1}{2H}\Bigg(\frac{1}{(X'_d + X_e)}E'_q E_B \sin\delta \\ &\quad + \frac{L_{aq} - L'_{ad}}{2(X'_d + X_e)(X_q + X_e)}E_B^2 \sin 2\delta\Bigg)\end{aligned}$$

$$\begin{aligned}\dot{E}'_q &= e_{fd} - \frac{1}{T'_{d0s}}\frac{X_q + X_e}{X'_d + X_e}E'_q \\ &\quad - \frac{L_{ads} - L'_{ads}}{T'_{d0s}(X'_d + X_e)}E_B \cos\delta \qquad (4)\end{aligned}$$

Conventional vibration suppressing controllers which use PSS, control the excitation voltage e_{fd}[5],[6]. While, TCSC can directly affect the electric torque

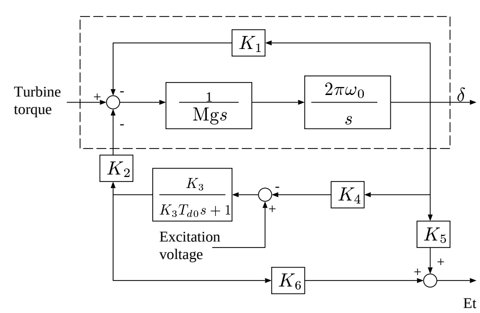

Figure 4. Block Diagram of SMIB

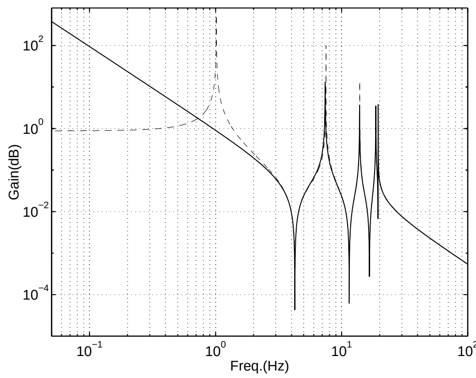

Figure 5. Frequency Response of Five-mass System (From Torque Input To Angular Velocity of Generator)

by contolling the impedance X_e. But X_e is a complex nonlinear input. This nonlinearity must be considered when designing the controller.

4.2 Comparison Controllability

In this section, the merit of TCSC as actuator is explained.

First, we model the power system to compare TCSC with PSS. When focusing on the torsional vibration, the dynamics of turbines and generator can be modeled as two-mass system(Fig.6). This modeling will be explained in detail in Session 5.2.

In PSS controller design, the plant is nominalized like 'Plant 1' in Fig.6, while in the case of TCSC controller, the plant is nominalized like 'Plant 2' in Fig.6, because TCSC uses the electric torque as plant input.

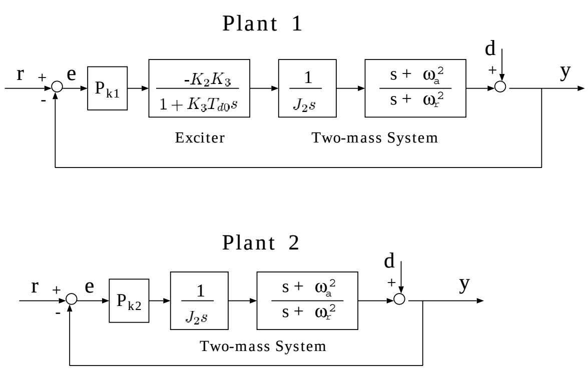

Figure 6. Comparison of Two Plants

Plant 1 has an exciter system which plays the role of low pass filter. Because of this low pass filter, larger controller output is needed to affect the 2-mass system in plant 1. Comparing with this, in plant 2, we can control the 2-mass system with smaller controller output.

5 Design of TCSC Controller

5.1 Proposal of New Control Law for TCSC

There are two remarkable points in the control strategy which we will state in this section. Firstly, the whole system (single machine infinite bus system) will be nominalized as a two mass system. Then, we will apply a linear control law to this system, in spite of the nonlinear characteristic of TCSC. It can be realized by using a conversion.

The control strategy proposed in this paper is shown in Fig. 7 and Eq. 5. Electric torque T_e changes when the value of X_e is adjusted by TCSC control. We can handle this T_e as a new virtual input. Using this virtual linear input, we can easily apply some linear control law. For convenience, u_1 that is equal to $-\frac{1}{2H}\Delta T_e$ is used as new virtual input in this paper.

$$
\begin{aligned}
\Delta\dot{\omega} &= \frac{1}{2H}\{T_m - T_e(X_e)\} \\
&= \frac{1}{2H}\{T_m - (T_{e0}(X_{e0}) + \Delta T_e(\Delta X_e))\} \\
&= \frac{1}{2H}(T_m - T_{e0}(X_{e0})) + u_1(\Delta X_e) \qquad (5)
\end{aligned}
$$

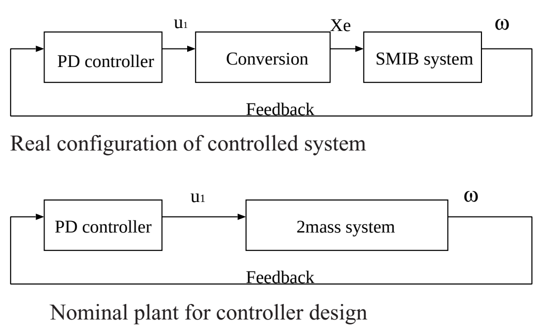

Figure 7. Control Strategy

Proportional and Differential (PD) controller is often used for the vibration suppression[9]. In this paper, this PD controller is applied. For calculating PD gain, CDM (Coefficient Diagram Method) is employed.

5.2 Nominal Model

Two-mass system is a simple analytical model of torsional system. We use this two-mass model as the

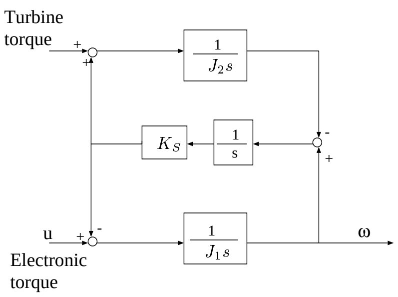

Figure 8. Two-mass model

nominal model of the plant system(SMIB system). This is reasonable, because the purpose of this TCSC control is to suppress the vibration. Thus the vibration information of system is only needed for the control. And if the designed controller is robust enough, the stability of system does not matter.

5.3 Design of PD Gains by Coefficient Diagram Method

Coefficient Diagram Method (CDM) is a control design method proposed by Prof. Shunji Manabe[10]. By this method, we can design the controller and the characteristic polynomial of the closed-loop system simultaneously, taking a good balance of stability, response, and robustness.

The closed-loop characteristic polynomial of the target system with PD controller is given by Eq.(6).

$$\begin{aligned} P(s) &= (J_2 + K_D)s^3 + K_P s^2 \\ &\quad + (J_2\omega_r^2 + K_D)s + K_P\omega_{a2}^2 \\ &= a_3 s^3 + a_2 s^2 + a_1 s + a_0 \end{aligned} \tag{6}$$

Each gain K_P, K_D is calculated by keeping the rates of coefficients as follows.

$$\tau = \frac{a_1}{a_0} = \frac{(J_2\omega_r^2 + K_D\omega_{a2}^2)}{K_P\omega_{a2}^2} \tag{7}$$

$$\begin{aligned} \gamma_1 &= \frac{a_1^2}{a_2 a_0} = \frac{(J_2\omega_r^2 + K_D\omega_{a2}^2)^2}{K_P^2\omega_{a2}^2} \\ &= 2.5 \\ \gamma_2 &= \frac{a_2^2}{a_3 a_1} = \frac{K_P^2}{(J_2\omega_r^2 + K_D\omega_{a2}^2)(J_2 + K_D)} \\ &= 2 \end{aligned} \tag{8}$$

6 Two Design Methods and Simulation Results

So far, we have designed the virtual input u_1, but our concern is the decision of the real input X_e. For this X_e design, we use two conversions. One is based on the linear approximation, and the other is on the nonlinear conversion using system state.

6.1 Linear Approximation

The relation between u_1 and X_e is complex as in shown (11), but we can obtain a simple linear relation by using the linear approximation.

$$\begin{aligned} u_1(\Delta X_e) &= -\frac{1}{2H}\Delta T_e(\Delta X_e) \\ &= -\frac{1}{2H}\{T_{e0} - T_e(\Delta X_e)\} \end{aligned} \tag{9}$$

Eq. (11) shows the linear conversion from u_1 to X_e.

$$u_1 = -\frac{1}{2H}\Delta T_e = -\frac{1}{2H}\frac{\partial T_e}{\partial X_e}\Delta X_e \tag{10}$$

$$\Delta X_e = -\frac{2H}{\frac{\partial T_e}{\partial X_e}} u_1 \tag{11}$$

The effect of this TCSC controller on SMIB system is examined by some numerical simulations. Simulation condition is as follows. After 1 second of the start of simulation, three-line-to-ground fault occurs at the terminal of generator, and 70ms later the fault recovers. Figs. 9, 10 show the suppression effect of the TCSC. With the TCSC control, the vibration of 7.5Hz is suppressed.

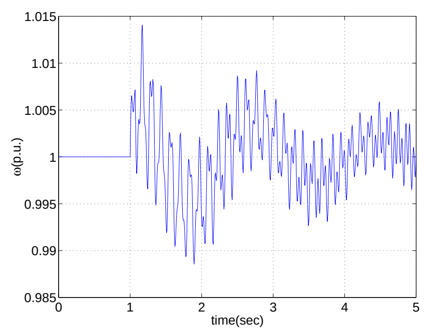

Figure 9. ω without control

6.2 Nonlinear Conversion Using System State

As we confirm above, TCSC is a nonlinear system. In this section, we design X_e using a nonlinear conversion which needs a system state. At first, some following assumptions are needed to make the conversion simple[11].

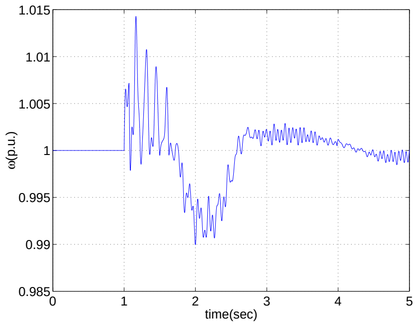

Figure 10. ω with linear approximation control

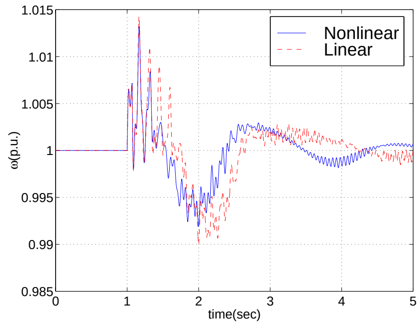

Figure 11. ω with nonlinear conversion control

1. One of the state variable $E_q^{'}$ has the constant value $E_{q0}^{'}$.

2. As $X_q > X_d^{'}$, the deviation of $\frac{1}{X_q+X_e}$ is small enough comparing with $\frac{1}{X_d^{'}+X_e}$. This means that the variable $\frac{1}{X_q+X_e}$ has the constant value of $\frac{1}{X_q+X_{e0}}$ in spite of the deviation X_e.

With these assumptions, the nonlinear conversion from u_1 to X_e is formulated like (13). There is a state variable δ in the conversion. We need to measure this state.

$$\begin{aligned} u_1(\Delta X_e) &= -\frac{1}{2H}\Delta T_e(\Delta X_e) \\ &= -\frac{1}{2H}\{T_e(\Delta X_e) - T_{e0}\} \\ &= -\frac{1}{2H}\{(E_{q0}' E_B \sin\delta - \frac{L_{aq} - L_{ad}'}{2(X_q + X_{e0})} \\ &\quad E_B^2 \sin 2\delta)\frac{1}{X_d' + X_{e0} + \Delta X_e} \\ &\quad -T_{e0}\} \qquad (12) \\ \Delta X_e &= \frac{1}{T_{e0} - 2Hu_1}(E_{q0}' E_B \sin\delta - \\ &\quad \frac{L_{aq} - L_{ad}'}{2(X_q + X_{e0})}\ E_B^2 \sin 2\delta) \\ &\quad -X_d' - X_{e0} \qquad (13) \end{aligned}$$

This conversion is essentially the same with the exact linearization which is one of the most used nonlinear control law.

The simulation result of this TCSC controller is shown on the Fig. 11, where the result of linear approximation designed controller is also reported. Comparing these curves, we can state that there is no conspicuous difference between these two control designs.

7 The Comparison of Both Designs

To see the difference between these two proposed designs, one more simulation is performed. The duration of fault time is changed from 70ms to 140ms. Under this larger fault, the difference between two controllers appears (Figs. 12, 13). The nonlinear conversion control shows better output. The system under linear approximation control is not stable with this fault. This result shows that the nonlinear conversion has wider control region.

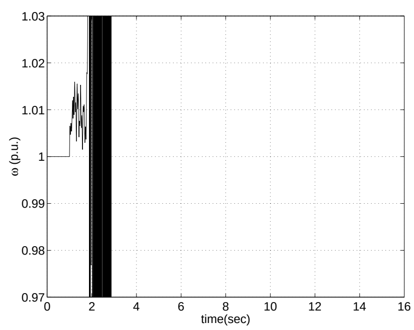

Figure 12. ω with linear approximation control

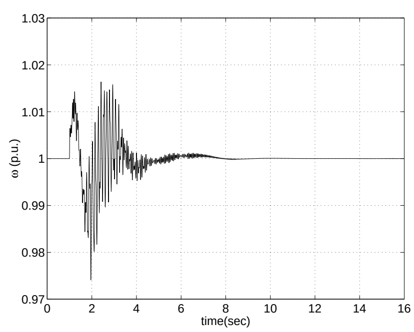

Figure 13. ω with nonlinear conversion control

8 Conclusion and Future Work

In this paper, it is shown that TCSC can suppress the torsional vibration using the proposed control design.

We ensure the control characteristic of TCSC. And considering the nonlinear input property, we use some special invention for controller design. Two control designs are proposed and simulated. The simulation results show that the nonlinear conversion control has more effective transient performance.

These proposal is showing the potential controllability of TCSC as feedback controller. To confirm the effectiveness of these proposals, the more quantitative analyses are necessary.

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