KIEE International Transactions on PE, Vol. 4-A No. 3, pp. 109~114, 2004 **109**

A Study on Power System Stability Enhancement by Robust Control of SPFC and Generators

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Abstract - In this paper, the H_∞ control method is applied in the control of SPFC and generators in order to obtain the robust stability performance of the power system. Moreover, a SPFC H_∞ controller based on loop shaping is designed to achieve first-rate tracking properties in addition to the robust stability. This robust control method is applied to a Ward and Hale 6-bus power system and the effects are analyzed. The MATLAB program is used for simulation of the robust controller.

Keywords: generator, H_∞ control, loop shaping, power system, robust control, SPFC

1. Introduction

Environmental, regulatory and economic constraints have restricted the growth of electric power transmission facilities, and the technologies to enlarge the levels of power transmission and enhance stability through existing transmission lines have become greatly needed. The recent availability of solid-state power switching devices with controlled turn off capability has made possible further advances in power conversion and control, leading to the development of a new generation of FACTS devices such as STATCOM (Static Synchronous Compensator), UPFC (Unified Power Flow Controller) and SPFC (Series Power Flow Controller) [1-6]. SPFC uses self commutating devices like GTOs and is a voltage-source inverter-based series device. The SPFC is connected to the transmission system via a series of inserted transformers with the ability to interchange actual power with the line. It can be used for enhancement of small-signal stability and mitigation of system oscillation [5-6].

PID is the most commonly used control algorithm in the practical industry and it has also been used to control FACTS devices. However, the uncertainties that exist in FACTS devices as well as the nonlinear characteristics of power systems make it difficult to design an effective controller for the FACTS and other power system devices under all operating conditions. A major source of difficulty is that the model of an open-loop plant may be inaccurate or may change with time. This problem has led to a body of studies during the past decade that are focused on robust control design such as the H_∞ control method. Several important requirements such as internal stability, disturbance rejection and tracking properties should be considered in control system design in addition to the robust control property. Chung presented to design a robust turbo-generator control system using H_∞ control synthesis for improving small-signal stability [7]. [8] shows that the inter-area low frequency oscillation in large power systems was damped effectively by H_∞ control of the TCSC (Thyristor controlled series capacitor). In this case the H_∞ control method is considerably conservative even though it is robust for modelling error and disturbances. The characteristics of this controller depend on the shaping function added to the plant, and in general it doesn't demonstrate good tracking property.

In this paper, the H_∞ robust control method is applied to controlling the SPFC and generator in order to enhance the robust stability performance of the power system. The H_∞ controller based on loop shaping that is easy to use is designed in order to obtain robust stabilization and good tracking performance. This robust control method is applied to a Ward and Hale 6 bus power system with a SPFC. The SPFC is considered as a voltage source inverter and applied for enhancement of power system stability. The generators are represented by a two-axis model. The MATLAB program is employed for simulation of the robust controller. The cases where the H_∞ controllers are applied to the SPFC or generator are analyzed and compared with each other from the standpoint of robust stability and tracking properties of the SPFC.

2. Power System Modeling for Robust Control

One of the most important stability problems arising from power system interconnections is low frequency oscillation. The frequency is of the order of a fraction of 1 Hz to a few Hz. The oscillations may be sustained for minutes and grow to cause system separation if no

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Received March 23, 2004 ; Accepted Auguest 5, 2004

adequate damping at the system oscillating frequency is available. Additional damping can be provided by supplementary excitation control. The power system stabilizer (PSS) is commonly used in order to provide desired additional damping via supplementary excitation control and the SPFC can also be used for improving transient stability by dynamically interchanging real power at key points.

The model of generators for the stability analysis includes the machine model with a 2-axis representation of the generator and the first order linear approximation of the excitation system. The dynamic stability model is obtained as follows:

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s, \qquad i = 1, \cdots, m \tag{1}$$

$$M_i \frac{d\omega_i}{dt} = P_{Mi} - (E'_{qi} - X'_{di} I_{di}) I_{qi} - (E'_{di} - X'_{qi} I_{qi}) I_{di} - D_i(\omega_i - \omega_s), \qquad i = 1, \cdots, m \tag{2}$$

$$T'_{di} \frac{dE'_{qi}}{dt} = -E'_{qi} - (X_{di} - X'_{di}) I_{di} + E_{fdi}, \quad i = 1, \cdots, m \tag{3}$$

$$T'_{qi} \frac{dE'_{di}}{dt} = -E'_{di} - (X_{qi} - X'_{qi}) I_{qi}, \quad i = 1, \cdots, m \tag{4}$$

$$T'_{Ai} \frac{dE'_{fdi}}{dt} = -E_{fdi} + K_{Ai}(u_E + V_{refi} - V_i\ ), \quad i = 1, \cdots, m \tag{5}$$

Here, power system stabilizers are installed at the generators to damp the oscillations of their rotors and are controlled by H_∞ controllers that have the speed deviation of the rotor ($\Delta\omega$) as the input and the supplementary excitation control signal (u_E) as the output. The definitions of the variables and parameters in the above equations can be referred to in [9] and [10].

A typical model of SPFC is provided in Fig. 1. The SPFC considered is a voltage-sourced inverter-based series device. The inverter that is connected in series with the ac power system via a series inserted transformer can modulate the inserted voltage and can also interchange real power with the line. Therefore it can adjust real power dynamically within the desired range, leading to the enhancement of small-signal stability. The SPFC is modeled as an inserted voltage source and the desired output values of the series inserted voltage source are adjusted by control of the firing angle to cause some time delay. The dynamics of the inserted voltage source can be simply represented as the model in Fig. 2.

Here, V_{ins} is the magnitude of inserted voltage source, P_f is the actual power flow, P_{fref} is the reference power flow, and P_s is the supplementary signal. K_p and K_i are constants and T_r is the time constant considering the time delay. The SPFC is controlled by the H_∞ controller based on loop shaping.

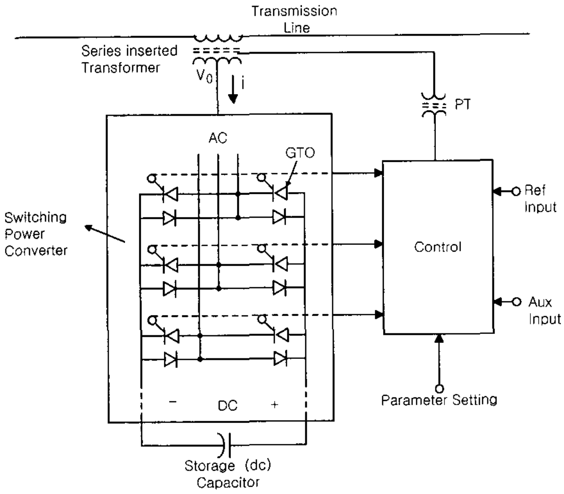

Fig. 1 The structure of a SPFC

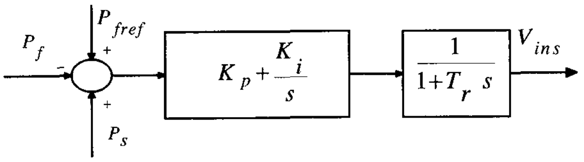

Fig. 2 The block diagram of a SPFC model

3. A Design of the Controller Based on H_∞ Technique

3.1 LFT framework for disturbance rejection

There are differences between the behaviors of the nominal plant and actual plant and these errors are called uncertainty or perturbation. Classical control objectives such as disturbance attenuation, noise insensitivity and robust stabilization of uncertain systems can be expressed in terms of H_∞ performance and tackled by the H_∞ control technique. The LFT (Linear fractional transformation) framework for disturbance rejection is shown in Fig. 3, where w1 and w2 are external disturbances indicating measurement noise and torque disturbance, respectively; z1 and z2 are error signals that should be kept minimal; u is the output vector of the controller, which includes the supplementary excitation control signal of PSS and the supplementary signal of SPFC; x is the state vector of the plant; and y is the measurement vector available to the controller, which includes the angular velocity of the rotor and the actual power flow of the line. W_d and W_n are torque disturbance weighting function and noise disturbance weighting function, respectively.

o selection of W_d

The weighting function W_d reflects the gain characteristics from the torque to the angular velocity and it is selected to diminish the oscillation of the rotor around the frequencies where its oscillation contains a large amount of energy. W_d can be expressed as follows:

$$W_d = r_d \frac{s}{(s+w_{d1})(s+w_{d2})} \tag{6}$$

o selection of W_n

The weighting function W_n is used to model the frequency contents of the sensor noise.

This W_n is selected to have high pass filter characteristics so as to reduce the noise effect around high frequency range. W_n can be expressed as follows:

$$W_n = r_n \frac{(s+w_{n1})}{(s+w_{n2})} \tag{7}$$

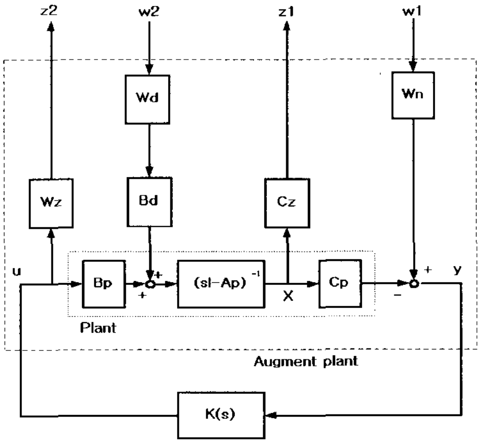

Fig. 3 LFT framework for disturbance rejection

3.2 Design of H∞ controller of SPFC based on loop shaping

H_∞ design technique provides effective robust control, but the method is considerably conservative though it is robust for modelling error and disturbances. The characteristics of this controller depend on the shaping function added to the plant and in general it doesn't demonstrate good tracking property. A H_∞ loop shaping design that is easy to use is applied in order to obtain robust stabilization and superior tracking performance of SPFC. The rejection of noises and disturbances, good tracking characteristics and robustness to the modeling errors are all required when designing the controller. The addition of a stable weighting function doesn't cause stability problems because the weighting function is not part of the feedback loop. However, the open loop plant with a shaping function can result in stability problems because the plant is a component of the feedback loop. Let the transfer function of the open loop plant including the shaping function be $T(s)$. Then, $T(s)$ should satisfy following conditions:

i) $\sigma_{\max}\left[\frac{T(j\omega)}{1+T(j\omega)}\right] < E_{\max}^{-1}(\omega), \quad \mathit{for}\ \omega \geq 0$

ii) $\sigma_{\min}[T(j\omega)] >> 1, \quad \mathit{for}\ \omega \in \Omega_r$

iii) $\sigma_{\max}[T(j\omega)] << 1, \quad \mathit{for}\ \omega \in \Omega_n$,

where ω represents frequency; $E_{\max}(\omega)$ is the maximum modelling error at the frequency ω; $\sigma_{\max}$ and $\sigma_{\min}$ are the maximum and minimum singular values, respectively; Ω_r and Ω_n are the frequency ranges corresponding to the frequencies of the control signal and the noise, respectively. The above inequality *i*) signifies the condition for robustness against any modelling error. The above inequalities *ii*) and *iii*) signify the conditions for good tracking and noise rejection, respectively.

In order to consider these significant requirements, the following shaping function can be utilized.

$$L_S(s) = \frac{1}{s+\varepsilon} \cdot \left\{ \frac{T_1 s+1}{\alpha_1 T_1 s+1} \cdot \frac{T_2 s+1}{\beta_2 T_2 s+1} \right\}^n \cdot \frac{1}{T_c s+1} \cdot K_g \tag{8}$$

The first term in the right side of the shaping function represents an integral function to decrease the steady state error and increase the gain for low frequency signal. ε is zero in general. The addition of an integral part can result in a negative effect on stability. If the increase of low frequency gain is required and the addition of an integral part creates stability problems, an appropriate small positive value can be given to ε . The term in the large parenthesis on the right portion of the shaping function is introduced for providing good tracking property around frequencies of key signals. The first term in the large parenthesis represents a phase lead compensation and the second term in the large parenthesis represents phase lag compensation. Here, $\frac{1}{\alpha_1 T_1}$ and $\frac{1}{T_2}$ are the low frequency and high frequency of the signal to be emphasized.

$\alpha_1 < 1$, and $\beta_2 > 1$. The value of β_2 can be selected as the reciprocal of α_1. An exponential index n is a positive integer equal to or more than 1 according to the degree of compensation. Only one of these terms in the large parenthesis can be considered corresponding to the requirements of the controller. On the contrary, this term can also be used to decrease the effect of the signal arround the considered frequencies. In this case, $\alpha_1 > 1$ and $\beta_2 < 1$.

The third term in the right side of the shaping function reflects the cut-off property used to reject the effect of noise. In the SPFC model, $\frac{1}{1+T_r s}$ is the term to approximate a time delay $e^{-Tr\,s}$. The phase of the time delay term is very sensitive to high frequency signals. It is necessary to reject the high frequency noise in order to design the controller that is insensitive to the noise. $\frac{1}{T_c}$ is the cut-off frequency to refuse the effect of the noise with high frequencies. The last term K_g represents a constant gain to satisfy the above condition i).

This shaping function is added to the open-loop plant and the characteristic function of the closed loop to govern the final stability is changed. The several terms given in the function can be selected optionally according to the characteristics of the plant. The procedures of the controller design based on loop shaping are as follows:

1) Obtain the transfer function of the open loop plant and check the singular values and phase characteristics.
2) Determine if the integral term is needed or the increase of low frequency gain is required, and if the phase compensation is needed.
3) Select the frequencies of the signal to be emphasized or deemphasized and determine the quantities of the gain and phase compensations. If necessary, also select the cut-off frequency.
4) Design the H_∞ controller. In the case in which the integral part is added, check for problems of stability. If instabllity is found, proceed to step 2, and modify the value of ε or remove the integral part.
5) Check the performance of the controller. If it is unsatisfactory, proceed to step 3 and modify the related parameters. If it is satisfactory, discontinue the design procedures.

The H_∞ loop shaping design presented here can be used very easily in order to obtain robust stabilization and good tracking performance of the controller.

4. Simulation and Results

The system used for simulation is a Ward and Hale 6-bus power system as shown in Fig. 4. Buses 1 and 2 are generator buses and others are load buses. The SPFC is installed at the bus 6 side of the line between bus 6 and bus 5, which is not connected directly with generator buses and has large line power flow. Power system stabilizers are also installed at the generators to damp the oscillations of their rotors. The H_∞ controller design based on loop shaping is applied to this 6-bus power system.

The line data and the initial data for generation and load of the power system are provided in Tables 1 and 2, respectively. The values of the parameters in weighting functions are as follows:

$$r_d = 20,\ w_{d1} = 1,\ w_{d2} = 10,\ r_n = 30,$$
$$w_{n1} = 200,\ w_{n2} = 200{,}000,\ w_z = 10^{-6}.$$

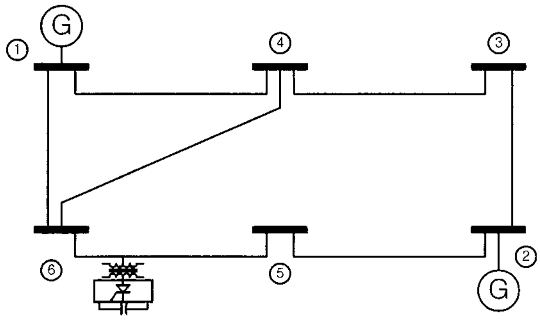

Fig. 4 A 6 bus power system with SPFC

The values of the parameters in the generators are presented in Table 3.

Table 1 Line data for the 6-bus power system

Line number	From bus number	To bus number	Line impedance (p.u)	
			R	X
1	1	6	0.0135	0.0962
2	1	4	0.010	0.0756
3	4	6	0.012	0.0795
4	5	6	0.011	0.0873
5	2	5	0.0142	0.0983
6	2	3	0.0181	0.121
7	3	4	0.005	0.041

Table 2 Initial data of generation and load of the system

Bus number	Voltage Magnitude	Voltage angle	P	Q
1	1.02	0.0		
2	1.02		0.52	
3			-0.37	-0.09
4			0.0	0.0
5			-0.59	-0.15
6			-0.48	-0.13

Table 3 Data of generator

Variable	Value	Variable	Value
X_d	0.973 pu	T_A	0.05 s
X_q	0.90 pu	K_A	3.0
X'_d	0.19 pu	T'_d	4.0 s
X'_q	0.35 pu	T'_q	0.5 s
M	10.6 s	D	0.0

Investigating the model of SPFC in Fig. 2, it already includes an integral term and so it is unnecessary to introduce another integral term. Subsequently, it is required to track the control signals around frequencies of 0.6 ~ 12 [rad/sec] effectively and to reduce the noise signals above frequencies 1,000[rad/sec].

Here, the following shaping function is selected for the SPFC.

$$L_{SPFC}(s)=\left\{\frac{T_1 s+1}{\alpha_1 T_1 s+1}\cdot\frac{T_2 s+1}{\beta_2 T_2 s+1}\right\}\cdot\frac{K_g}{T_c s+1}. \qquad (9)$$

The values of the parameters related to the SPFC are as follows:

$T_1 = 16.7$, $T_2 = 0.0083$, $\alpha_1 = 0.1$, $\beta_2 = 10.0$

$K_g = 10$, $T_c = 0.001$, $K_p = 0.5$, $K_i = 0.1$, $T_r = 0.05$

The dB magnitude plot of the open loop transfer function from torque disturbance to rotor speed is shown in Fig. 5 and the dB magnitude plot of the open loop transfer function of SPFC with loop shaping is shown in Fig. 6. It is observed that the open loop transfer function of SPFC has a fine form for robust stabilization and tracking performance.

The dynamic performances of the system when a small torque change occurs abruptly are analyzed according to the applied controllers. It is assumed that a disturbance of torque occurs as a type of step function between 1 and 2 seconds. The MATLAB program has been used for simulation of the robust controller and the following 3 cases have been analyzed:

Case (i): No controller is installed in the system.

Case (ii): The generators are controlled by H_∞ controllers.

Case (iii): The SPFC and generators are controlled by H_∞ controllers.

The system used in this study oscillates continuously with a small signal disturbance if no controller is applied to the generator. The dotted line in Fig. 7 shows the trajectory of the power flow of the line between bus 6 and bus 5 in the power system with no controller (Case (i)). It is indicated that the system oscillates largely for a long period of time. The thin solid line in Fig. 7 shows the trajectory of the line power flow from bus 6 to bus 5 in Case (ii). When generators are controlled by H_∞ controllers, we know that the damping of the oscillation of the line power flow is improved significantly. The thick solid line in Fig. 7 illustrates the trajectory of the line power flow from bus 6 to bus 5 in the case (iii) that generators and SPFC are controlled by H_∞ controllers. It is shown that the oscillations are damped more effectively in this case. In addition to the trajectories of the line power flow, Fig. 8 indicates the simulation results of the rotor angle of generator 2. From the simulation results we are aware that SPFC has a primary effect on controlling the real power flow of the line and is able to enhance the small-signal stability of power systems effectively.

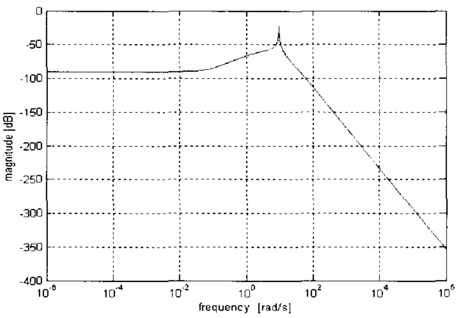

Fig. 5 The magnitude plot of the open loop transfer function from torque disturbance to rotor speed

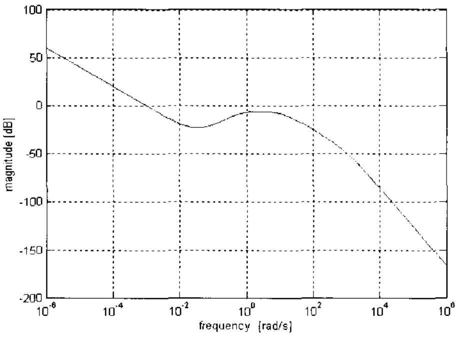

Fig. 6 The magnitude plot of the open loop transfer function of the SPFC

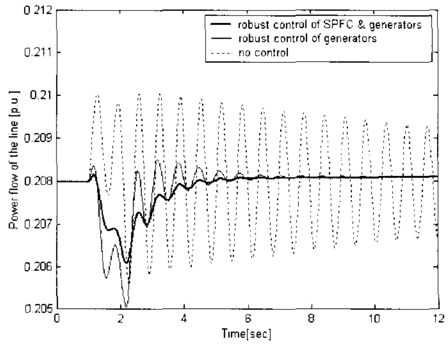

Fig. 7 The comparison of line power flow oscillations

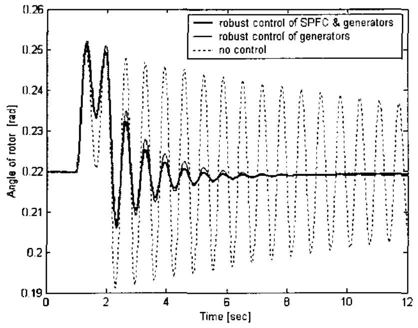

Fig. 8 The comparison of rotor angle oscillations of generator 2

5. Conclusion

A SPFC H_∞ controller based on loop shaping is designed to achieve good tracking properties in addition to robust stability. This method is applied to the 6 bus power system with SPFC. The cases where H_∞ techniques are applied to SPFC or generators are compared with each other from the standpoint of robust stability and tracking properties. It is shown that the H_∞ design based on loop shaping can be used for power system stability enhancement and SPFC can effectively improve the small-signal stability of power systems.

Acknowledgements

This work was supported in part by the Korea Electrical Engineering & Science Research Institute 99-029.

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