GLOBAL CONTROL OF POWER SYSTEM FOR TRANSIENT STABILITY ENHANCEMENT AND VOLTAGE REGULATION

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Abstract – Global control is extended to uncertain power systems to maintain the transient stability and achieve proper post-fault voltage. The power system is first decomposed into several partial models according to different control objectives and operating stages. Then the direct feedback linearization (DFL) technique is applied to linearize the partial nonlinear models and robust partial controllers are designed to consider the system uncertainties and controller interactions for different partial models. Only local variables are needed in the design of partial controllers. Finally, the global control law is obtained by aggregating the partial controllers with membership functions. The single-machine infinite-bus (SMIB) power system with the SVC is used as an example system to evaluate the effectiveness of the proposed global control approach.

Keywords: Global control, transient stability, voltage regulation

1 INTRODUCTION

The importance of power system control is highlighted due to increased utilization of the transmission system for which they are not original designed or beyond their original design limits. Several types of problems which affect controller performance are increasingly taken into account in the controller design, especially for power systems under large disturbances. Such as, the nonlinearities and uncertainties of power system models; undesirable interactions among multiple controllers; different control objectives within varying operating regions and their inherent conflicting objectives.

The use of various advanced control techniques to solve above problems in power systems seems to be one of promising applications areas. Nonlinearities and uncertainties of system models have been overcome by nonlinear feedback linearization techniques [1][2] and robust control theory [3][4]. In most practical situations, power system consists of various subsystem associated with control, which expand a vast geographical domain. Some special stability control requirements, such as the instantaneous measurement from remote phasor measurement units and remote and proper information exchanges between controllers, are so intricate that even high-capacity fiber-optical-based telecommunication network can not solve [5], decentralized control was frequently resorted to maintain a stable system with varying interconnections and coordinate versatile controllers. In additions, power systems operate in several different conditions and coordinate different control goals, which may have inherent conflicts and need to find a trade-off between these objectives. Two control systems are evidently demonstrated the conflicting control objectives during different control stages. One is the trade-off between transient stability enhancement and good voltage regulation if only excitation control used [1][6][7]. The other is revealed by analysis that the SVC voltage and damping control conflict each other [8].

Global control is a relatively new concept that has motivated by practical systems usually operates under different conditions and the ensuing controls are expected to achieve a set of goals [2][9]. Global control was first employed to large scale stressed power system by bifurcation analysis [10], and then coordinated transient stability and voltage regulation according to different operating conditions [2]. Small signal stability was taken into count in a power system with a unified power flow controller [11]. Global robust control approach was primarily proposed to uncertain systems and succeeded to apply to an example power system in our previous work [12][13].

In this work, the global control is extended to maintain the transient stability and achieve proper post-fault voltage of a power system in consideration of uncertainties and controller interactions. The power system is first decomposed into several partial models according to different control objectives and operating stages. Then the DFL technique is applied to linearize the partial nonlinear models and robust partial controllers are designed to consider the system uncertainties and controller interactions for different partial models. Finally, the global control law is obtained by aggregating the partial controllers with membership functions. The SMIB power system with the SVC is utilized as an example system to evaluate the effectiveness of the proposed global control approach.

The rest of the paper is organized as follows. Section 2 discusses the global control of the uncertain power systems. Dynamic models of SMIB system with SVC for transient stability enhancement and voltage regulation is given and global controller are designed in Section 3. The simulation results are used to demonstrate the effectiveness of global control scheme in Section 4. Conclusions are drawn in Section 5.

2 GLOBAL CONTROL OF UNCERTAIN POWER SYSTEMS

Power systems are highly nonlinear structured systems with multiple control objectives, which mainly include regulation of voltages and frequency, damping oscillations adequately and preserving synchronism in face of large disturbances. Some undesirable interactions among multiple controllers have been found and under active investigations since most traditional power system controllers are usually installed decentralized to serve single objective. Global control was proposed to realize those practically global control objectives by combining the qualitative and quantitative knowledge of power system through some hierarchy. This paper extends it to uncertain power systems with utilization of modern nonlinear control methodologies. The global control scheme applied to the uncertain power systems is shown in Figure 1.

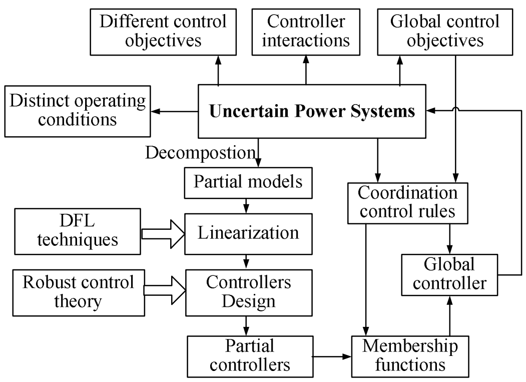


Figure 1: Global control of uncertain power systems

The uncertain power system is first decomposed into several partial models with coordination rules according to different control objectives, operating stages, controller interactions and global control objectives. Then the direct feedback linearization (DFL) technique is applied to linearize the partial nonlinear models and robust partial controllers are designed to consider the system uncertainties and controller interactions for different partial models. Finally, the global control law is obtained by aggregating the partial controllers with membership functions.

3 GLOBAL CONTROL OF SMIB SYSTEM WITH SVC

In this paper, we focus on the global control design of an SMIB system with the SVC at the midpoint of the transmission line shown in Figure 2. The global control objective is to maintain the transient stability and achieve proper post-fault voltage. Decentralized partial controllers are respectively designed for generator excitation and SVC to realize corresponding control objectives, the global control is the weighted average of partial controllers. In the design of global controller, the counteractions between two different control objectives, transient stability and voltage regulation, are tackled by coordinated control rules and membership functions. Moreover, power system uncertainties and partial controller interactions are taken into account in the design of robust partial controllers.

3.1 Dynamic model of SMIB system with SVC

The classical third-order generator models used in this paper are referred to [2][4]. The steady state equations for power system shown in Figure 2 with SVC can be found in [4]. (The notation for the system model is given in Appendix A.)

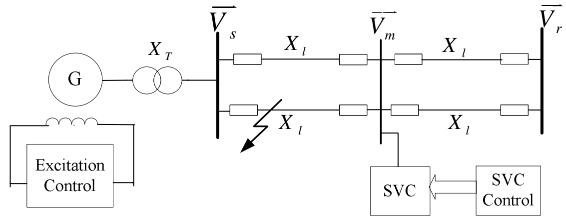


Figure 2: An SMIB system with SVC

The SVC dynamic model can be described by [4].

$$\dot{B}_L(t) = \frac{1}{T_R}(-B_L(t) + B_{L0} + k_B u_B(t)) \tag{1}$$

A three-bus SVC system in [3] is used to derive the general relation between SVC and power system. It can resemble any case where power is transmitted through a transmission line and SVC is located in the middle of the line.

3.2 Global control of generator excitation

Since the global control objective of generation excitation is to maintain the transient stability and achieve proper post-fault voltage, two different partial models are used to describe those two operating stages. In this Section 3.2, global control of generator excitation was extended to the uncertain system models based on the results of [2].

3.2.1 Transient controller of generator excitation

The characteristic of generator in the SMIB system after linearized by DFL technique is given by the following equations [2].

$$\begin{cases} \Delta\dot{\delta}(t) = \Delta\omega(t) \\ \Delta\dot{\omega} = -\dfrac{D}{2H}\Delta\omega(t) - \dfrac{\omega_0}{2H}(P_e(t) - P_m) \\ \Delta\dot{P}_e(t) = -\dfrac{1}{T'}\Delta P_e(t) + \dfrac{1}{T'}\overline{v}_{ft}(t) \end{cases} \tag{2}$$

where $T' = T'_{do}X'_{ds}/X_{ds}$, $B(t) = 1/X_{ds}$, $\Delta P_e(t) = P_e(t) - P_m$,

$$\overline{v}_{ft}(t) = \frac{P_e(t)}{X_{ad}I_f(t)}k_c u_{ft}(t) + T'_{do}(X_d - X'_d)[\frac{P_e(t)}{X_{ad}I_f(t)}]^2\Delta\omega(t) + T'[Q_e(t) + V_s^2 B(t)]\Delta\omega(t) - P_m \tag{3}$$

To overcome the uncertainty problem, such as the parameter changes in T' and $B(t)$, the structure change of transmission parameters X_{ds} and X'_{ds} under the faults, the varying reactance of SVC, the uncertainties result of modeling errors, the generator model with uncertainty is established. The compensating law (3) can be rewritten as follows:

$$u_{ft}(t) = \frac{X_{ad}I_f(t)}{k_c P_e(t)}\{\overline{v}_f(t) + P_m - \overline{T}[Q_e(t) + V_s^2\overline{B}(t)]\Delta\omega(t)\}$$

$$-\frac{(X_d - X_d^{'})P_e(t)}{k_c X_{ad} I_f(t)} T_{do}^{'} \Delta\omega(t) \qquad (4)$$

The difference between (3) and (4) is that the uncertain parameters $T^{'}$ and $B(t)$ in (3) are replaced respectively by the known parameters $\overline{T^{'}}$ and $\overline{B}(t)$ in (4). $\overline{T^{'}}$ and $\overline{B}(t)$ are the average value of $T^{'}$ and $B(t)$ respectively. The equation (2) can be rewritten as follows:

$$\Delta \dot{P}_e(t) = -[\frac{1}{\overline{T^{'}}} + \mu(t)]\Delta P_e(t) + [\frac{1}{\overline{T^{'}}} + \mu(t)]\overline{v_f}(t) + \psi(t)\Delta\omega(t) \qquad (5)$$

where $\psi(t) = [\frac{1}{\overline{T^{'}}} + \mu(t)]\{\Delta T^{'} Q_e(t) + \frac{1}{X_{ds} + \Delta X}\Delta T^{'} V_s^2\}$;

$$\mu(t) = \frac{1}{\overline{T^{'}} + \Delta T^{'}} - \frac{1}{\overline{T^{'}}}; \quad \Delta T^{'} = T_{do}^{'}\frac{X_{ds}^{'} + \Delta X}{X_{ds} + \Delta X} - \overline{T^{'}}.$$

ΔX denotes the uncertainty in reactance X_{ds} and $X_{ds}^{'}$. $\psi(t)$, $\mu(t)$ and $\Delta T^{'}$ are bounded.

Choosing $X^T(t) = [\Delta\delta(t) \quad \Delta\omega(t) \quad \Delta P_e(t)]$ as the states, the linearized uncertainties generator models can be represented in the following compact form [4]:

$$\dot{X}(t) = (A + \Delta A(t))X(t) + (B + \Delta B(t))\overline{v_{ft}}(t) \qquad (6)$$

To solve DFL compensated generator model with uncertainties (6) involves solving the algebraic Riccati equation in [4] , where details to decompose the uncertainties and obtain the robust feedback control law can be found. Therefore, the partial controller to guarantee transient stability of uncertain generator models can be obtained as

$$\overline{v_{ft}}(t) = -K_\delta \Delta\delta - K_\omega \Delta\omega - K_P \Delta P_e \qquad (7)$$

Since $[\Delta\delta(t) \quad \Delta\omega(t) \quad \Delta P_e(t)]^T$ are chosen as states in transient controller, transient stability of the SMIB system with SVC can be guaranteed. However, the generator terminal voltage $V_t(t)$ may stay at a different post-fault state if the system structure changed after the fault.

3.2.2 Voltage controller of generator excitation

To avoid the undesirable $V_t(t)$ variations with the change of power system structures, the nonlinear voltage controller choosing $[\Delta V_t(t) \quad \Delta\omega(t) \quad \Delta P_e(t)]^T$ as the states have been proposed in [14]

Since $V_t(t)$ is a nonlinear function of $\delta(t)$, $\omega(t)$ and $P_e(t)$, differential equation is given in [14]

$$V_t(t) = f_1(t)\omega(t) - \frac{f_2(t)}{T^{'}}\Delta P_e(t) + \frac{f_2(t)}{T^{'}} v_{fv}(t) \qquad (8)$$

where $f_1(t)$ and $f_2(t)$ are highly nonlinear functions of $\delta(t)$, $P_e(t)$ and $V_t(t)$. Since they are dependent on the operating region, their bounds are regarded as the uncertainties in the controller design. The uncertainties of $T^{'}$ and $B(t)$ can be considered same as in the partial model of transient controller.

Choosing $X^T(t) = [\Delta V_t(t) \quad \Delta\omega(t) \quad \Delta P_e(t)]$ as the states, the linearized uncertainties generator models can be represented in the following compact form:

$$\dot{X}(t) = (A + \Delta A(t))X(t) + (B + \Delta B(t))v_{fv}(t) \qquad (9)$$

To solve DFL compensated generator model with uncertainties (9) involves solving the algebraic Riccati equation in [14], where details to decompose the uncertainties and obtain the robust feedback control law can be found. Therefore, the partial controller to regulate voltage of uncertain generator model can be obtained as

$$v_{fv}(t) = -K_v V_t(t) - K_\omega \omega(t) - K_p \Delta P_e(t) \qquad (10)$$

Since $[\Delta V_t(t) \quad \Delta\omega(t) \quad \Delta P_e(t)]^T$ are chosen as states in partial controller, the generator terminal voltage $V_t(t)$ can be regulated around certain operating conditions. However, rotor angle of generator may not maintain its nominal value in post-fault state if the system structure changed. It has been observed that the operating changes caused by the voltage regulation will degrade the transient stability of the system [2].

3.2.3 Global control of generator excitation

To solve the inherent conflicting between transient stability enhancement and voltage regulation, the membership functions have been successfully applied to characterize the operating regions and realize the global control objective. The membership functions [2] shown in Figure 3 are used in this work:

$$\mu_V(z_G) = (1 - \frac{1}{1 + \exp(-120(z_G - 1))}) \bullet \frac{1}{\exp(-120(z_G + 1))}$$

$$\mu_\delta(z_G) = 1 - \mu_V \qquad (11)$$

where $z_G = \sqrt{\alpha_1(\Delta\omega)^2 + \alpha_2(\Delta V_t)^2} \qquad (12)$

and α_1 and α_2 are positive design constants providing appropriate scaling according to the sensitive requirement of power frequency and voltage. Since voltage controller is effective while z_G is smaller than 1, the parameter α_2 should be small enough to reach this requirement. On the other side, the parameter α_1 is expected to be large enough to make z_G larger than 1.

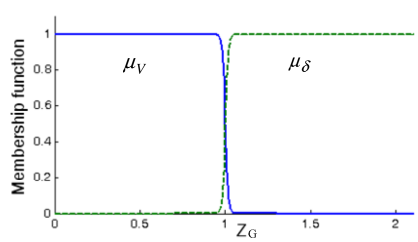


Figure 3: Membership functions

In the global control of generator excitation, membership functions (11) dynamically partition the whole operating region into two subspaces, where partial controllers for transient stability enhancement and voltage regulation function respectively. In operating region of transient stability, the real excitation control of generator is $u_{ft}(t)$ obtained from the feed back control law

(7) through compensating law (4). On the other hand, the real excitation control in operating region of voltage regulation is $u_{fv}(t)$ obtained from the feed back control law (10) through compensating law. Therefore, the global controller is weighted average of the partial controllers and the excitation control input v_f takes the form:

$$v_f = \mu_V(z_G)u_{fv}(t) + \mu_\delta(z_G)u_{ft}(t) \tag{13}$$

The most appealing ability of membership functions is that they automatically and smoothly interpolate the two partial controllers irrespective of fault sequences and locations. It is quite suitable for the practical requirements of global control objectives.

3.3 Global control of SVC

The control of SVC for voltage regulation and damping is a similar conflict happened in the controller design of the generator excitation. We applied the global control approach to the SVC to improve transient stability and achieve proper voltage level in the post-fault state.

3.3.1 SVC transient controller

Since the dynamic model of SVC (1) is a first order linear equation, the following feedback control law in [4] is chosen to maintain stability:

$$u_{Bt}(t) = -K_{BL}\Delta B_L(t) - K_{B\omega}\Delta\omega_L(t) \tag{14}$$

where $\Delta\omega_L$ is the relative speed at the SVC bus. K_{BL} and $K_{B\omega}$ can be designed by pole placement method.

3.3.2 SVC voltage controller

The dynamic behavior of the simple three-bus SVC system can be linearized by the DFL technique in a state space form [3]:

$$\begin{bmatrix}\Delta\dot{V}_B \\ \Delta\ddot{V}_B\end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{1}{B_C}\left(\frac{1}{X_S}+\frac{1}{X_R}\right) & 0\end{bmatrix}\begin{bmatrix}\Delta V_B \\ \Delta\dot{V}_B\end{bmatrix} + \begin{bmatrix}0\\1\end{bmatrix}v_L(t) + \begin{bmatrix}0\\1\end{bmatrix}d(t) \tag{15}$$

where X_S and X_R represent the reactance of the transmission lines, V_B is the SVC bus voltage, $v_L(t)$ is the new control input. The nonlinear feedback control law can be obtained:

$$u_B(t) = -\frac{B_C B_L(t) T_R}{k_B i_L(t)} v_L(t) + \frac{1}{k_B}(B_L(t) - B_{L0}) - \frac{B_L^2(t) T_R}{k_B i_L(t)}\Delta V_B(t) \tag{16}$$

Considering the parameter changes in T_R, X_{ds} and $X_{ds}^{'}$, the SVC model (15) becomes as follow:

$$\dot{X}(t) = (A + \Delta A)X(t) + (B + \Delta B)v_L(t) \tag{17}$$

To solve DFL compensated SVC model with uncertainties (17) involves solving the algebraic Riccati equation in [3] , where details to decompose the uncertainties and obtain the robust feedback control law can be found. Therefore, the partial controller to regulate voltage of uncertain SVC model can be obtained as

$$v_L(t) = -K_{v1}\Delta V_B(t) - K_{v2}\Delta\dot{V}_B(t) \tag{18}$$

Only the SVC parameters and the bounds of system parameters have to be known in the design of the nonlinear SVC voltage controller. Exact parameters of transmission lines are not required. System parameters and system operating points are treated as the uncertainties and handled by the robust control approach.

3.3.3 Global control of SVC

Similar with the global control of generator excitation, the membership functions (11) are used to partition the whole operating regions of SVC into two parts. The voltage V_B and the relative speed $\Delta\omega_L$ at the SVC bus are chosen as the input of membership functions and

$$z_{SVC} = \sqrt{\alpha_1(\Delta\omega_L)^2 + \alpha_2(\Delta V_B)^2} \tag{19}$$

In operating region of transient stability, the control input of is $u_{Bt}(t)$ obtained from the feed back control law (14). On the other hand, the control input in operating region of voltage regulation is $u_B(t)$ obtained from the feed back control law (18) through compensating law (16). Therefore, the global controller is weighted average of the partial controllers and the control input u_{SVC} takes the form:

$$u_{SVC} = \mu_V(z_{SVC})u_B(t) + \mu_\delta(z_{SVC})u_{Bt}(t) \tag{20}$$

Membership functions will automatically and smoothly interpolate the two partial controllers for transient stability enhancement and voltage regulation irrespective of fault sequences and locations. Thus, it is convenient for global control scheme to realize the two practical functions of SVC, damping oscillation in face of large disturbances and providing the voltage support.

3.4 Global control of the SMIB system with SVC

To this point, four partial controllers for different control objectives have been designed separately. Only local measurements are used for each partial controller. From above design procedures, the partial controllers for generator and the SVC are independent of each other since the interconnections between them are treated as the parameter uncertainties by the robust control approach. Therefore, the global control of the SMIB system with SVC for transient stability enhancement and voltage regulation can be demonstrated in Figure 4, where four parts in dash rectangle represented four partial controllers.

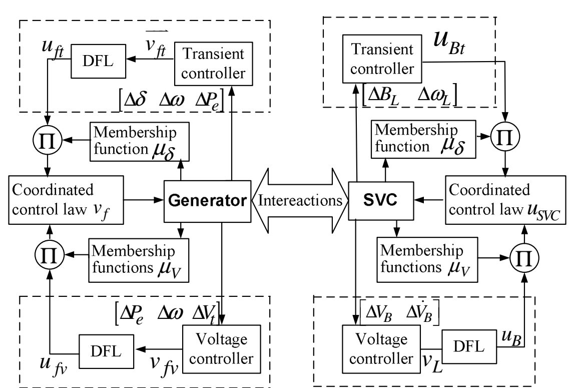


Figure 4: Global control of the SMIB system with SVC

4 SIMULATION RESULTS

To evaluate the above global control schemes for transient stability enhancement and voltage regulation, the example SMIB system in Figure 2 is utilized in the simulation study. Since the global control of generator excitation for transient stability and voltage regulation has been elaborated in [2], we only present the simulation results relative with the global control of SVC and the global control of the SMIB system with SVC in this paper.

4.1 Parameters in SMIB system with SVC

The system parameters and physical limits of generator and linear excitation system are given as follow:

Synchronous machine:

ω_0= 314.159 rad/sec.; D= 5.0 p.u.; H= 4.0 sec.; $T^{'}_{d0}$= 6.9 sec.; $T^{''}_{d0}$= 0.03 p.u.; $T^{'}_{q0}$= 0.06 sec.; k_c= 1; X_d= 1.863 p.u.; $X^{'}_d$= 0.657 p.u.; X_{ad}=1.712 p.u.; $X^{''}_d$= 0.245 p.u.; X_q= 0.657 p.u.; $X^{''}_q$= 0.27 p.u.; The physical limits of the excitation voltage is max $|k_c u_f|$= 6.0 p.u.

Transmission lines: X_l= 0.2426 p.u.; R_l= 0.03 p.u. $f_0 = 50Hz$; X_T= 0.127 p.u; V_s= $1\angle 0$ p.u.

The parameters and physical limits of SVC are as follow:

$0.02 \le T_R \le 0.1$ sec.; B_{L0}= 1.0 p.u.; B_{C0}= 1.0 p.u.; k_B= 1; $0.2 \le B_L(t) \le 1.2$ p.u.

The operating point of the system considered in the simulation is $\delta_0 = 72.0^0$, $P_{e0} = 1.0$ p.u.; $V_{t0} = 1.05$ p.u.

A symmetrical three-phase short circuit fault occurs at the terminal of generator bus. Two fault sequences in the simulation are described as follow:

Case 1. Temporary Fault:

- Stage 1: The system is in a pre-fault steady state.
- Stage 2: A fault occurs at t = 0.1 second.
- Stage 3: The fault is removed by opening the breaker of the fault line at 0.22 second.
- Stage 4: The transmission line is restored with the fault clear at t= 1.4 second.
- Stage 5: The system is in a post-fault state.

Case 2. Permanent Fault:

- Stage 1: The system is in a pre-fault steady state.
- Stage 2: A fault occurs at t = 0.1 second.
- Stage 3: The fault is removed by opening the breakers of the fault lines at t= 0.22 sec.
- Stage 4: the system is in the post-fault state.

Using the system parameters stated above, four partial controllers can be obtained.

The transient controller of generator excitation:

$$\overline{v_{ft}}(t) = 33.48\,\Delta\delta + 10.65\,\Delta\omega - 84.16\,\Delta P_e$$

The voltage controller of generator excitation:

$$v_{fv}(t) = -29.76\,V_t(t) + 6.66\,\omega(t) - 11.96\,\Delta P_e(t)$$

The SVC transient controller:

$$u_{Bt}(t) = -10\,\Delta B_L(t) - 4.5\,\Delta\omega_L(t)$$

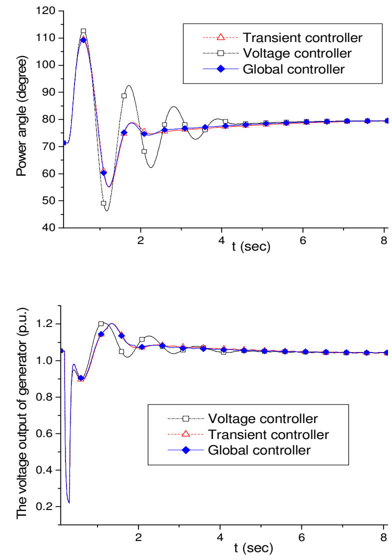
The SVC voltage controller:

$$v_L = -13.75\,\Delta V_B - 6.56\,\Delta\dot{V}_B$$

The constant α_1 and α_2 are chosen 10 and 0.5 respectively in the simulation.

4.2 Global control of SVC

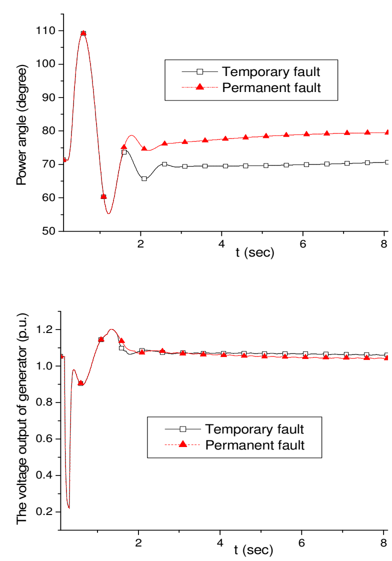
In order to demonstrate the effectiveness of the global control of the SVC clearly, the conventional linear excitation controller is used with the global controller of SVC. The parameters of linear excitation controller can be found in Appendix B.



(a)

(b)

Figure 5: Responses with different SVC controllers (Case 2)



(a)

(b)

Figure 6: Responses with global SVC controller (Cases 1 and Case 2)

The power system responses with different SVC controller subjected to different faults are shown in Figure 5 and 6. It can be observed that global SVC controller can achieve satisfied performance compared with the controllers design for single objective. The global SVC controller can help restore the steady pre-fault voltage value and damp the oscillation when the system is subjected to the temporary or permanently faults.

4.3 Global control of the SMIB with SVC

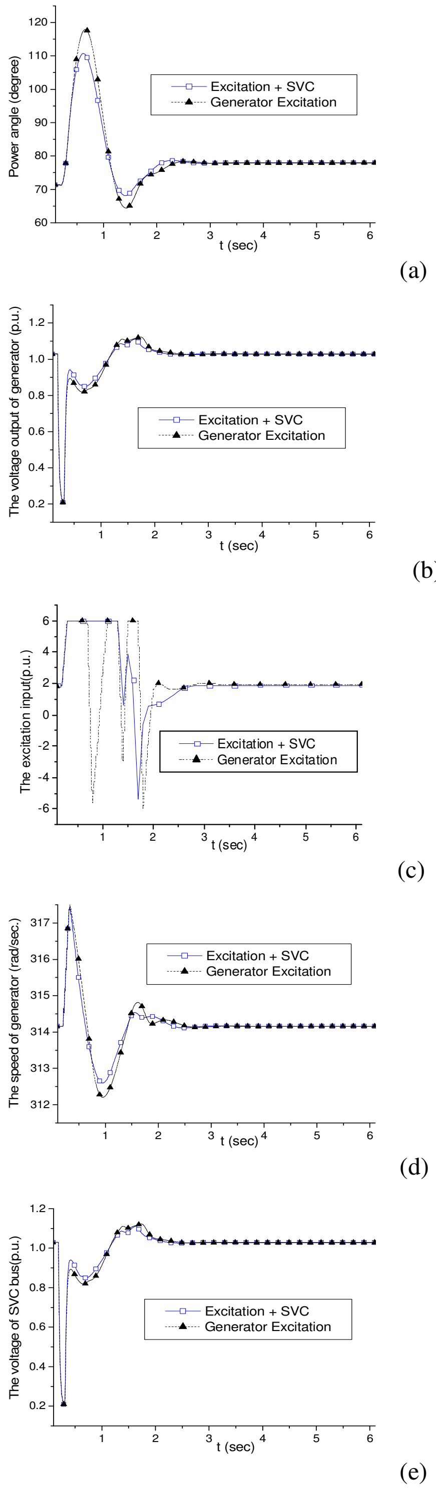


Figure 7: Responses with global control scheme (Case 2)

In this subsection, the performances of global control scheme shown in Figure 3 are illustrated in Figure 7 and 8. Figure 7 exhibits good transient performance and restoration voltage of global control scheme compared with the system with only global control of generator excitation. The power system responses shown in Figure 8 demonstrate that the global control objectives can be realized in the presence of different fault cases by the proposed global control scheme. Thus, the trade-off problems can be successfully solved by this control scheme.

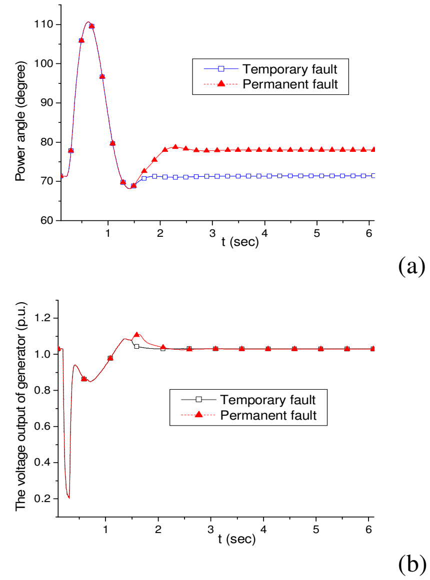


Figure 8: Responses with different fault cases.

5 CONCLUSION

In this paper, the global control is extended to uncertain power systems to maintain the transient stability and achieve proper post-fault voltage. The power system is first decomposed into several partial models according to different control objectives, operating stages, controller interactions and global control objectives. Then the DFL technique is applied to linearize the partial nonlinear models and robust partial controllers are designed to consider the system uncertainties and controller interactions for different partial models. Only local variables are needed in the design of partial controllers. Finally, the global control law is obtained by aggregating the partial controllers with membership functions.

The SMIB power system with the SVC at the midpoint of the transmission line is utilized as an example system to evaluate the effectiveness of the proposed global control approach. Both the SVC global control and the global control scheme for generator excitation and SVC have achieved good transient performance and restored the steady pre-fault voltage value. Therefore, the proposed global control scheme can successfully solve the trade-off problems in the practice. This global control scheme is expected to extend to the multimachine systems by combined with the decentralized control techniques.

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APPENDIX

A. Notation for the SMIB system with SVC

$\delta(t)$: the power angle the generator; $\omega(t)$: rotor speed of the generator; ω_0: synchronous machine speed; $P_e(t)$: the active electrical power delivered by the generator; P_m: the mechanical input power of the generator; $Q_e(t)$: the reactive power of the generator; D: the damping constant of the generator; H: the inertia constant of the generator; $T_{do}^{'}$: the direct axis transient open circuit time constant; $u_f(t)$: the input of the SCR amplifier of the generator; k_c: the gain of the excitation amplifier of the generator; $I_f(t)$: the excitation current of the generator; V_s: infinite bus voltage; X_d: direct axis reactance of the generator; $X_d^{'}$: direct axis transient reactance of the generator; X_{ad}: mutual reactance between the excitation coil and the stator coil; X_l: reactance of the transmission line; R_l: resistance of the transmission line; X_T: reactance of the transformer; X_E :the Thevenin's equivalent reactance of the network to the right of generator terminal bus as shown in Fig. 2; $X_{ds} = X_d + X_T + X_E$; $X_{ds}^{'} = X_d^{'} + X_T + X_E$; $B_L(t)$: susceptance of the TCR of the SVC; T_R: time constant of the control system of the TCR of the SVC; k_B: gain of the control system of the TCR of the SVC; u_B: input of the control system of the TCR of the SVC.

B. Parameters of the linear excitation controller

AVR: IEEE STA1excitation system, K_A= 60; T_A= 0.05sec.; K_f = 0.05; T_f = 1.0sec.; I_{LR} = 4.4 p.u.; K_{LR}= 4.54 p.u.; $|V_A|$< 999.0 p.u.; $|E_f|$< 6.0 p.u.

PSS: the transfer function of PSS can be represented as: $G_{PSS} = K_{PSS} \frac{T_r s}{1+T_r s} \frac{(1+T_1 s)^2}{(1+T_2 s)^2}$

where K_{PSS}=15; T_r=3 sec.; T_1=0.25 sec.; T_2=0.05sec.; $|V_{PSS}|$<0.05 p.u.