A Novel Model Reduction Approach to Power System Components Complexity Including SVC

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Abstract

This paper presents a model reduction method (MRM) for simplified the complexity of power system components. Power system components including the nonlinear controllers such as static var compensator (SVC) and generators are usually modeled based on differential algebraic. For the algebraic connection equations, the new defined state variables are used to substitute the original state variables for keeping the connection relation invariable. By selecting generators and SVC as examples, the paper presents the basic procedure of the proposed reduction method for power system components complex models in detail. The numerical simulation indicates that the derived simplified models matches the original one very well in both dynamic response behaviors and the connection relation with the external system.

Keywords— Model Reduction; Nonlinear Controller; SVC; Power System Component

1. Introduction

Generators and flexible AC transmission devices (FACTS) are the basic components to constitute the complicated power systems. When performing the simulation, the stability analysis, or area controller design, the global model of the power system is needed to be formed through establishing the local component models. However, the global model is very complicated since the power system is composed of numerous components with controllers. Without simplification, the global model cannot meet the actual requirements [1].

In order to simplify the approximate linearization models of power systems, one can use the linear model reduction methods (MRM) to reduce their orders, such as the balanced truncation method [2] and the Krylov subspace method [3]. In large disturbance cases the approximate linearization model becomes inaccurate. For the reduction methods of nonlinear models, reference [4] modifies the computing algorithm of Gramian controllability and observability matrices in the balanced truncation method. Reference [5] presents a method to simplify the nonlinear structure via system immersion while preserving the input-output maps.

These simplification methods are utilized to handle the nonlinear ordinary differential model of the power system components, but it is difficult for them to deal with models with nonlinear differential-algebraic (DA) form.

If the local components adopt the nonlinear controllers, the reduction problem of component complex models with nonlinear controllers will be encountered during the process of modeling the complicated power system. However, at present, the relevant research on this problem has not been reported.

The component complex model reduction has its particularities: 1) it has the DA structure because a component serves as a subsystem of the whole power system; 2) it includes the complicated nonlinear controller. Reference [6] focuses on the reduction method of the component complex models with DA structure. Firstly, in order to simplify the differential dynamic equation, this paper uses the linear dynamic equations to describe the original nonlinear dynamics completely or partially (corresponding to the complete or partial linearization, if completely linearized, all the nonlinear dynamics can be described by the linear dynamic equations; otherwise, only those linearized dynamics can be described by them). Based on the fact that the component complex model has the linear dynamic equations in the external input-output relation after the nonlinearities in the nonlinear controller and the component offset each other. Secondly, the original state variables in the algebraic connection equations are substituted by the new defined ones in the above linear dynamic equations, since the new state variables have already represented the original ones equivalently, so the equivalent algebraic connection equations of the reduced model are obtained. Through the above two steps, the reduced model of the complex component with DA structure is obtained. The paper selects two power system components (generator and SVC) as examples to derive their reduced models. In order to validate the method, simulation tests are performed on a typical two-area four-machine power system. The results show that the derived reduced components to satisfy the demands of theoretical analysis.

2. Power system Component Complex Models

The nonlinear control configuration of a local component is shown in Fig.1. The component model includes differential dynamic equations and algebraic connection equations. Here, the differential equations are used to describe the dynamic behaviors of the component; the connection equations are used to express the interrelation between the component and the external power system. The algebraic variables υ of the connection equations are decomposed into the $\upsilon=(\Omega,\Delta)$, where, Ω denotes the impact of the external system on the component, and Δ denotes the impact of the component on the external system. The nonlinear controller consists of a nonlinear compensator and a linear closed-loop controller. The compensator is used to offset the nonlinearities of the component, and the closed-loop controller guarantees the whole system stable or the controlled variables traceable.

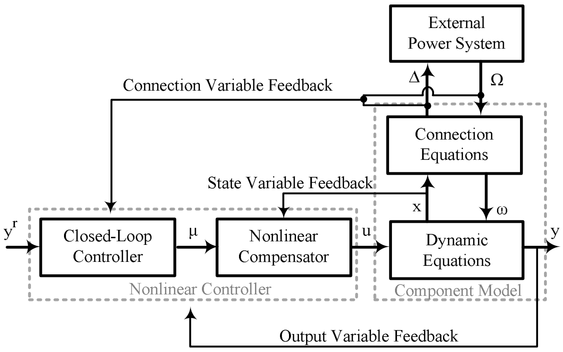

Fig. 1. Configuration of component complex model

The component subsystem structured model consisting of differential dynamic equations and algebraic connection equations generally can be written as [7]

$$\begin{cases} \dot{x} = f(x, \omega, u) \\ 0 = g(x, \omega, \upsilon) \end{cases} \tag{1}$$

Where, x are the state variables; u are the input variables; ω are the intermediate variables; υ are the connection variables; *f* and *g* are the vectors functions. The nonlinear controller can be expressed as

$$\begin{cases} \dot{\bar{x}} = f^{\bar{x}}(x,\bar{x},\omega,\upsilon,y,y^r) \\ u = \varphi(x,\bar{x},\omega,\upsilon,y,y^r) \end{cases} \tag{2}$$

Where, $\dot{\bar{x}}$ are the state variables of the controller; y and y^r are the output variables and the reference values respectively; $f^{\bar{x}}$ and φ are the vector functions. It is notable that there is no dynamic equation in (2) if the controller is static.

$$\begin{cases} \dot{x} = f(x,\omega,u) \\ \dot{\bar{x}} = f^{\bar{x}}(x,\bar{x},\omega,\upsilon,y,y^r) \\ u = \varphi(x,\bar{x},\omega,\upsilon,y,y^r) \\ 0 = g(x,\omega,\upsilon) \end{cases} \tag{3}$$

The variables and equations in the complex model (3) have the clear physical meaning and specific function. However, this model is not applicable under many situations because it has complicated structure (too many equations and variables, strong nonlinearity and coupling). Therefore, it is necessary to simplify the complex model to benefit the research.

3. Proposed Model Reduction Method

3.1. Generator Complex Model Reduction

3.1.1 Establish Generator Complex Model

To establish the generator complex model which is suitable for excitation controller and valve controller design, this paper ignores some factors of the generator, including the damping coefficient D, the resistance R_a of stator windings, the electromagnetic transient process of stator windings, and the dynamic process of excitation system. The state equations of the generator are expressed as [8]:

$$\begin{cases} \dot{\delta} = \omega - \omega_0 \\ \dot{\omega} = \dfrac{\omega_0}{2H}[P_H + C_{ML}P_{m0} - (E'_q I_q + E'_d I_d \\ \qquad - (x'_d - x'_q)I_d I_q)] \\ \dot{E}'_q = \dfrac{1}{T'_{d0}}[E_f - E'_q - (x_d - x'_d)I_d] \\ \dot{E}'_d = \dfrac{1}{T'_{d0}}[-E'_d + (x_q - x'_q)I_q] \\ \dot{P}_H = \dfrac{1}{T_\Sigma}(-P_H + C_H P_{m0} + C_H u_\upsilon) \end{cases} \tag{4}$$

The first two equations denote the dynamic behaviors of rotor angle δ and rotating speed ω, the following two equations represent q and d axis transient EMF of the generator, respectively and the last equation means the valve control of the generator. In the public coordinate system, the algebraic connection equations are;

$$\begin{cases} \begin{bmatrix} V_x \\ V_y \end{bmatrix} = T(\delta)\begin{bmatrix} E'_q \\ E'_d \end{bmatrix} + T(\delta)\begin{bmatrix} 0 & -x'_d \\ x'_q & 0 \end{bmatrix}\begin{bmatrix} I_q \\ I_d \end{bmatrix} \\ \begin{bmatrix} I_q \\ I_d \end{bmatrix} = T(\delta)\begin{bmatrix} I_x \\ I_y \end{bmatrix} \\ T(\delta) = \begin{bmatrix} \cos(\delta) & \sin(\delta) \\ \sin(\delta) & -\cos(\delta) \end{bmatrix} \end{cases} \tag{5}$$

Combining the differential state equations (4) and the algebraic connection equations (5) we gain the structured model of the generator subsystem, where, the state variables are $x = [\delta, \omega, E'_q, E'_d, P_H]^T$, input variables are $u = [E_f, u_\upsilon]^T$, the intermediate variable are $\omega = [I_d, I_q]^T$, and the connection variables are $\upsilon = [V_x, V_y, I_x, I_y]^T$. Here, $\Delta = [V_x, V_y]^T$ denote the impact of the generator on the external system, and $\Omega = [I_x, I_y]^T$ denotes the impact of the external system on the generator. Here, if the terminal voltage and the rotor angle are selected as the controlled variables, then the output equations are

$$\begin{cases} y_1 = V_t = \sqrt{[(E'_d + x_q I_q)^2 + (E'_q + x'_d I_d)^2]} \\ y_2 = \delta \end{cases} \tag{6}$$

The linear closed-loop controller by the static feedback method can be obtained as follows:

$$\begin{cases} E_f = \dfrac{T'_{do}}{V_q}[\kappa_1(V_t^r - V_t)V_t - \gamma_1 - \gamma_2] \\ \qquad = \varphi_E(V_q, V_d, I_q, I_d, \dot{I}_q, \dot{I}_d, V_t, V_t^r) \\ u_\upsilon = \dfrac{2HT_\Sigma}{C_H \omega_0}[-\kappa_2(\delta - \delta^r) - \kappa_3(\omega - \omega_0) - \kappa_4\dot{\omega}] \\ \qquad - P_{m0} + \dfrac{1}{C_H}P_H + \dfrac{T_\Sigma}{C_H}\dot{P}_e \quad = \varphi_\upsilon(\delta, \omega, P_H, \dot{\omega}, \dot{P}_e, \delta^r) \end{cases} \tag{7}$$

Combining the differential state equations (4), the algebraic connection equations (5), and the nonlinear controller (7), one gains the generator complex model as

$$\begin{cases} \dot{\delta} = \omega - \omega_0 \\ \dot{\omega} = \dfrac{\omega_0}{2H}[P_H + C_{ML}P_{m0} - (E'_q I_q + E'_d I_d - (x'_d - x'_q)I_d I_q)] \\ \dot{E}'_q = \dfrac{1}{T'_{d0}}[E_f - E'_q - (x_d - x'_d)I_d] \\ \dot{E}'_d = \dfrac{1}{T'_{d0}}[-E'_d + (x_q - x'_q)I_q] \\ \dot{P}_H = \dfrac{1}{T_\Sigma}(-P_H + C_H P_{m0} + C_H u_\upsilon) \\ \begin{bmatrix} V_x \\ V_y \end{bmatrix} = T(\delta)\begin{bmatrix} E'_q \\ E'_d \end{bmatrix} + T(\delta)\begin{bmatrix} 0 & -x'_d \\ x'_q & 0 \end{bmatrix}\begin{bmatrix} I_q \\ I_d \end{bmatrix} \\ \begin{bmatrix} I_q \\ I_d \end{bmatrix} = T(\delta)\begin{bmatrix} I_x \\ I_y \end{bmatrix} \\ E_f = \varphi_E(V_q, V_d, I_q, I_d, \dot{I}_q, \dot{I}_d, V_t, V_t^r) \\ u_\upsilon = \varphi_\upsilon(\delta, \omega, P_H, \dot{\omega}, \dot{P}_e, \delta^r) \end{cases} \tag{8}$$

3.1.2 Reduce Generator Complex Model

According to the inverse system method, it is known that the sum of the relative degree $r = [1,3]$ is equal to 4, and it is less than the order of the dynamic equations of generator. In this situation, there is one hidden dynamic in the linearized state equations. By analyzing the solving process of the nonlinear compensator, we find that the state equations corresponding to the variables δ, E'_q, ω and P_H have been replaced by the linear state equations corresponding to the new state variables z_1, z_2, z_3, and z_4. The E'_d state equation is the hidden one, since it neither includes the input variable (E_f, u_υ) nor appears as the derivative variable during the solving process of the compensator. Considering that the hidden dynamic equation does not contain the state variables $(\delta, E'_q, \omega, P_H)$ and input variables (E_f,u_υ), we can preserve this equation in the reduction model directly. Thus the linear state equations and the hidden state equation can be obtained as

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \\ \dot{z}_4 \end{bmatrix} = \begin{bmatrix} -\kappa_1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -\kappa_2 & -\kappa_3 & -\kappa_4 \end{bmatrix}\begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} + \begin{bmatrix} \kappa_1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \kappa_2 \end{bmatrix}\begin{bmatrix} y_1^r \\ y_2^r \end{bmatrix} \tag{9}$$

$$\dot{E}'_d = \frac{1}{T'_{d0}}[-E'_d + (x_q - x'_q)I_q]$$

Considering that the algebraic connection equations (5) include the linearized state variables E'_q and δ, which have been replaced by the new defined ones z_1 and z_2, we need to make the equivalent transformation for E'_q and δ in (5). According to the stator voltage equations,

$$\begin{aligned} E'_q &= V_q + x'_d I_d = \sqrt{V_t^2 - V_d^2} + x'_d I_d \\ &= \sqrt{V_t^2 - (E'_d + x'_q I_q)^2} + x'_d I_d \\ &= \sqrt{z_1^2 - (E'_d + x'_q I_q)^2} + x'_d I_d \end{aligned} \tag{10}$$

Substituting (10) and δ=z_2 into (5), then the equivalent algebraic connection equations obtained as follow:

$$\begin{cases} \begin{bmatrix} V_x \\ V_y \end{bmatrix} = T(z_2)\begin{bmatrix} \sqrt{z_1^2 - (E'_d + x'_q I_q)^2} + x'_d I_d \\ E'_d \end{bmatrix} + T(z_2)\begin{bmatrix} 0 & -x'_d \\ x'_q & 0 \end{bmatrix}\begin{bmatrix} I_q \\ I_d \end{bmatrix} \\ \begin{bmatrix} I_q \\ I_d \end{bmatrix} = T(z_2)\begin{bmatrix} I_x \\ I_y \end{bmatrix} \end{cases} \tag{11}$$

By the proposed reduction method, the differential equation (9) and the algebraic connection equations (11) are combined to describe the generator complex model (8) equivalently. Thus the reduced model of the generator component can be obtained as

$$\begin{cases} \dot{z} = Az + By^r \\ \dot{E}'_d = \dfrac{1}{T'_{d0}}[-E'_d + (x_q - x'_q)I_q] \\ \begin{bmatrix} V_x \\ V_y \end{bmatrix} = T(z_2)\begin{bmatrix} \sqrt{z_1^2 - (E'_d + x'_q I_q)^2} + x'_d I_d \\ E'_d \end{bmatrix} \\ \qquad + T(z_2)\begin{bmatrix} 0 & -x'_d \\ x'_q & 0 \end{bmatrix}\begin{bmatrix} I_q \\ I_d \end{bmatrix} \\ \begin{bmatrix} I_q \\ I_d \end{bmatrix} = T(z_2)\begin{bmatrix} I_x \\ I_y \end{bmatrix} \end{cases} \tag{12}$$

where,

$$A = \begin{bmatrix} -\kappa_1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -\kappa_2 & -\kappa_3 & -\kappa_4 \end{bmatrix}, \quad B = \begin{bmatrix} \kappa_1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \kappa_2 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}.$$

Compared with the complex generator model (8), the reduced model (12) has been simplified to a great extent in two aspects, firstly, the state equations are linear except one hidden dynamic equation; secondly, the reduced model includes no algebraic equation of the complicated nonlinear controller.

3.2. Reduction for SVC Complex Model

3.2.1. Establish SVC Complex Model

The SVC consisting of thyristor controlled reactors (TCR) and fixed capacitors is shown in Fig.2. First-order inertial process to describe the dynamic of the TCR obtained as follows:

$$\dot{\alpha} = \frac{1}{T_\alpha}(u - \alpha) \tag{13}$$

Where, α denotes firing angle; u denotes firing order; T_α is total dead time. The algebraic connection equations are

$$\begin{cases} V_x = \dfrac{1}{B_{svc}(\alpha)}I_y \\ V_y = -\dfrac{1}{B_{svc}(\alpha)}I_x \end{cases} \tag{14}$$

where, V_x and V_y are the x axis and y axis components of voltage on the SVC; I_x and I_y are the x axis and y axis components of current passing through the SVC; $B_{svc}(\alpha)$, the total susceptance of the SVC, is function of the firing angle α [9], that is

$$B_{svc}(\alpha) = \frac{\varphi_1(\alpha)}{\varphi_2(\alpha)} = \frac{B_T[\pi B_C + B_L(2\pi - 2\alpha + \sin 2\alpha)]}{\pi B_T + \pi B_C + B_L(2\pi - 2\alpha + \sin 2\alpha)]} \quad (15)$$

B_C, B_L and B_T are the susceptance of the compensating capacitors, the reactors and transformers, respectively.

Combining the differential equation (13) and the algebraic connection equations (14), we gain the SVC subsystem structured model. Here, α is the state variable, u is the input variable, $\Delta = [V_x, V_y]^T$ and $\Omega = [I_x, I_y]^T$ are the connection variables, and $B_{svc}(\alpha)$ are the output variable. It is worth noting that there is no intermediate variable ω in the SVC structured model. Here we choose the SVC susceptance as the controlled variable, thus the output equation is

$$y = B_{svc}(\alpha) \quad (16)$$

Finally, the nonlinear controller is expressed as follows:

$$u = -\frac{T_\alpha \varphi_2^2 \kappa_{svc}[B_{svc}^r - B_{svc}(\alpha)]}{4B_L \sin^2 \alpha (B_T \varphi_2 - \varphi_1)} + \alpha \quad (17)$$

Combining the differential equation (13), algebraic connection equation (14), and the nonlinear controller equation (17), the SVC complex model is obtained as

$$\begin{cases} \dot{\alpha} = \frac{1}{T_\alpha}(u - \alpha) \\ \begin{cases} V_x = \frac{1}{B_{svc}(\alpha)} I_y \\ V_y = -\frac{1}{B_{svc}(\alpha)} I_x \end{cases} \\ u = -\frac{T_\alpha \varphi_2^2 \kappa_{svc}[B_{svc}^r - B_{svc}(\alpha)]}{4B_L \sin^2 \alpha (B_T \varphi_2 - \varphi_1)} + \alpha \end{cases} \quad (18)$$

3.2.2. Reduce SVC Complex Model

According to the inverse system method, it is known that the relative degree r=1 is equal to the order of the SVC subsystem, which means the SVC subsystem does not include hidden dynamic in the linearized state equation. Under this situation, the input-output linearization of the SVC subsystem can be realized, and the original state variable α is replaced by the new defined one z_{svc} . Here the new state dynamic equation of the SVC complex model can be obtained as

$$\dot{z}_{SVC} = -\kappa_{svc} z_{svc} + \kappa_{svc} B_{svc}^r \quad (19)$$

Since the algebraic connection equations (14) include the original state variable α, which has been replaced by the new defined state variable z_{svc}, so we substitute $z_{svc} = B_{svc}(\alpha)$ into (14) to eliminate α, and gain

$$\begin{cases} V_x = \frac{1}{z_{svc}} I_y \\ V_y = -\frac{1}{z_{svc}} I_x \end{cases} \quad (20)$$

By the proposed method, the differential state equation (19) and the algebraic connection equation (20) are combined to replace the SVC complex model (18). Thus the reduced form of the SVC complex model can be gained as below;

$$\begin{cases} \dot{z}_{SVC} = -\kappa_{svc} z_{svc} + \kappa_{svc} y^r \\ V_x = \frac{1}{z_{svc}} I_y \\ V_y = -\frac{1}{z_{svc}} I_x \end{cases} \quad (21)$$

Compared with the SVC complex model (18), the reduced model (21) has simpler structure than the complex model. Though the dynamic equations in both of them are linear, the reduced model removes the complicated algebraic equation of the nonlinear controller, and clearly indicates the response relation between the reference input and the actual output.

4. Simulations

In order to verify the proposed MRM of power system complex components, this paper selects a typical two-area four-machine system for simulation tests on MATLAB/Simulink [10]. The single-line diagram of the system is shown in Fig.2. For testing the simplified model of complex SVC component, the compensating capacitors on the bus 9 are replaced by the SVC. In the test, the nonlinear controllers are adopted in generator 1 (G1), generator 2 (G2), and the SVC, while the conventional linear controllers are used in generator 3 (G3) and generator 4 (G4). For the comparative analysis, we set up two simulation systems, the reduced system and the original system. Here, the two systems explain as follows:

- In both of the systems, the models of G3 and G4 are not simplified since the two generators adopt the linear controllers.
- In the reduced system, the reduced models of G1, G2, and SVC are used, given as model (12) and model (21), respectively.
- In the original system, the complex models of G1, G2, and SVC are adopted, given as model (8) and model (18), respectively.
- In the following simulation results, the blue dash lines denote the curves of the reduced system, and the red solid lines denote the curves of the original system.

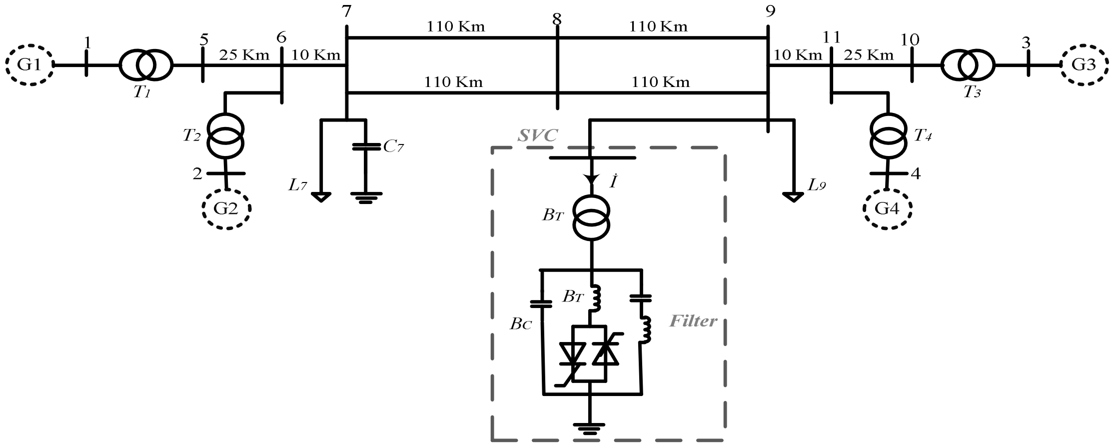

Fig. 2. Single-line diagram of two-area four-machine system

4.1. Tests on the reduced models of generators

The simulation sequences for the step change of the rotor angle references as: during 0<t<2s, the system operates on the equilibrium point; at t=2s , the rotor angle references of G1 and G2 step to $\delta_1^r = 1.20$ rad and $\delta_2^r = 1.00$ rad from $\delta_{10} = 1.11$ rad and $\delta_{20} = 0.92$ rad, respectively.

The testing results of the reduced models of generators are shown in Fig.3. The dynamic response curves of the four variables (rotor angle, angular speed, terminal voltage, and active power) of each generator are plotted. From the simulation curves, it is known that the responses of G1 and G2 in the reduced system are almost the same to the corresponding responses in the original system, which indicates that it is feasible to replace the original state equations of the generator complex model with the reduced ones. In addition, the dynamic behaviors of generators (G3 and G4) in the reduced system can match the ones in the original systems as well, which shows that the original connection relation between the generator and the external power system is preserved in the algebraic connection equations of the reduced model. In other words, the algebraic connection equations in both the reduced model and the original model are equivalent.

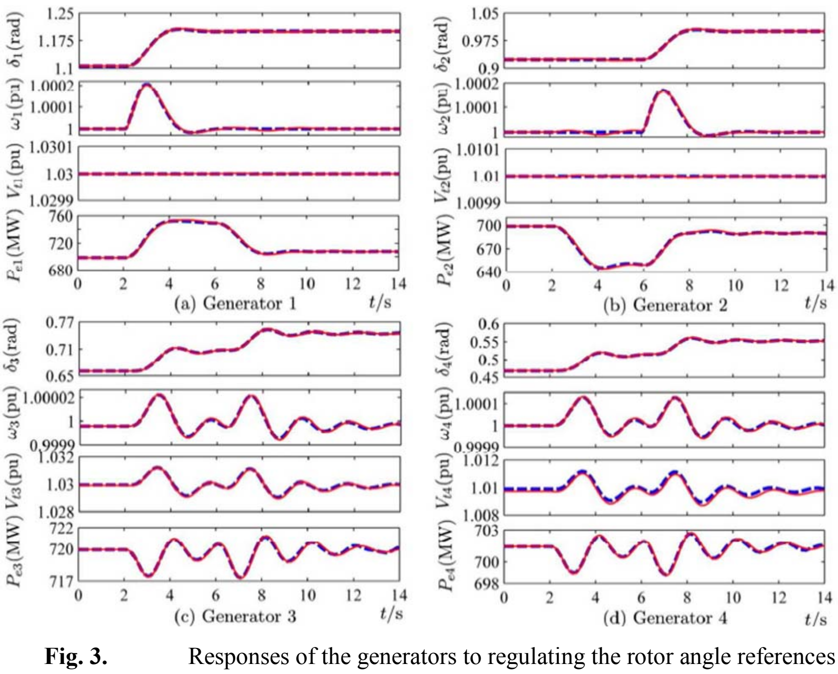

Fig. 3. Responses of the generators to regulating the rotor angle references

4.2. Tests on the reduced models of SVC

The simulation sequences for the step change of the susceptance reference of SVC as: during 0<t<1s , the system operates on the equilibrium point; at t=1s, the susceptance reference steps to B^r_{svc}=0.5 pu from B_{svc}=0.39s ; at t=3s , the susceptance reference steps to B^r_{svc}=0.25 pu . In the simulation, the reference values of the rotor angles and the terminal voltages for G1 and G2 are kept constant.

The testing results are shown in Fig.4 for the actual response of the SVC susceptance and Fig.5 for the responses of the generators. It is known from Fig.4 that the dynamic behaviors of the reduced model are the same with those of the original SVC complex model during the susceptance regulation. Fig.5 shows that the dynamic behaviors of the generators do not change when the reduced SVC model are adopted in the reduced system, which means that the algebraic connection equations of the reduced SVC model are equivalent to the ones of the original complex SVC model.

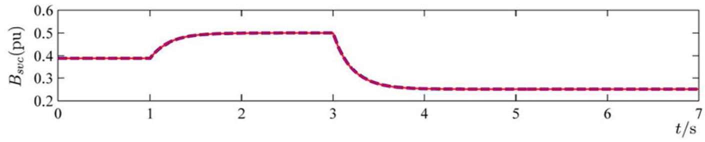

Fig. 4. Actual response to regulating the reference value of SVC susceptance

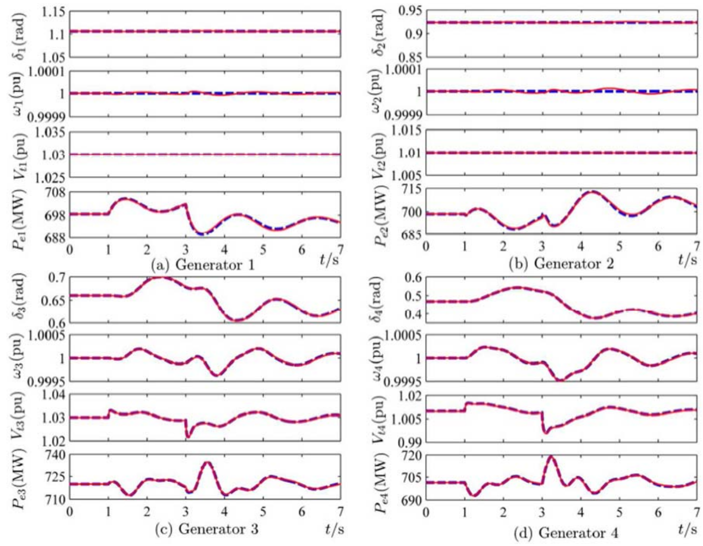

Fig. 5. Responses of the generators to regulating the reference value of SVC susceptance

5. Conclusions

According to the proposed MRM, this paper derives the reduced models of the generator and SVC respectively. The simulation tests on a typical two-area four-machine power system show that the reduced models can match the component complex models well. Thus the validity of the proposed method is confirmed. By the proposed reduction method, the simple local component model is obtained for the complicated power system modeling and analysis. Especially, the obtained reduced models of local components will contribute to the further reduction of global power system models and the global controller design under the hierarchical control framework.

6. References

[1] N. Kishor, L. Haarla, J. Seppanen, S. R. Mohanty, “Fixed-order controller for reduced-order model for damping of power oscillation in wide area network”, International Journal of Electrical Power and Energy Systems, vol 53, pp. 719–732, 2013.

[2] G. Troullinos and J. Dorsey, “Application of balanced realizations to power system equivalents”, IEEE Tran. on Automatic Control, vol. 30, no. 4, pp. 414- 416, 1985.

[3] D. Chaniotis and M. A. Pai, “Model reduction in power systems using Krylov subspace methods”, IEEE Trans. on Power Systems; vol. 20, no. 2, pp. 888-894, 2005.

[4] Juergen Hahn and Thomas F. Edgar, “An improved method for nonlinear model reduction using balancing of empirical Gramians”, Computers & Chemical Engineering, vol. 26, no. 10, pp. 1379-1397, 2002.

[5] Toshiyuki Ohtsuka, “Model structure simplification of Nonlinear Systems via immersion”, IEEE Trans. on Automatic Control; vol. 50, no.5, pp. 607- 618, 2005.

[6] K. F. Zhang and X. Z. Dai, “Structural analysis of large-scale power systems”, Mathematical Problems in Engineering, 2012.

[7] X. Z. Dai, K. F. Zhang, and Q. Zang, “Nonlinear decentralized control method of power systems based on component structural model”, Proceedings of the CSEE; vol. 28, no. 22, pp.15-22, 2008.

[8] K. F. Zhang, X. Z. Dai, and C. X. Huang, “Left-inversion soft-sensor of synchronous generator”, International Transactions on Electrical Energy Systems, vol. 21: pp. 1914–1922, 2011.

[9] Qiang Lu, Yuanzhang Sun, and Shengwei Mei, “Nonlinear control systems and power system dynamic”, Kluewer Academic Publishers, pp. 320-325, 2001.

[10] P. Kundur, “Power system stability and control”, McGraw-Hill Inc., pp. 813-814, 1994.