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A novel simplified approach to complexity of power system components including nonlinear controllers based model reduction

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ABSTRACT

Based on differential algebraic (DA) subsystem models of power system components including the nonlinear controllers, which are called component structural complex models, this paper presents a model reduction method (MRM). For the dynamic differential equations, based on the property that the nonlinearity of the controller compensates that of the component completely (or partially), the presented method uses the linear dynamic equations to describe the compensated dynamics. 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 static var compensators (SVC) as examples, the paper presents the basic procedure of the proposed reduction method for power system component 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.

Introduction

The power system components, such as generators and FACTS devices, are the basic cells 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 obtain the reduced global model, one can simplify the component models at local level (component model reduction), or simplify the system model as a whole at global level (system model reduction).

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, which causes above linear MRM not applicable under these situations. For the reduction methods of nonlinear models, Ref. [4] modifies the computing algorithm of Gramian controllability and observability matrices in the balanced truncation method, so as to apply this method to the nonlinear model reduction. Ref. [5] presents a method to simplify the nonlinear structure via system immersion while preserving the input–output maps. In Ref. [6], a kind of piecewise approximation method is applied to simplify the nonlinear system model.

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.

As for the power system control, there have been many literatures reporting the application of nonlinear control theory to power systems, such as Refs. [7–10]. 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. Compared with the existing linear or nonlinear model reduction problems, 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; and (2) it includes the complicated nonlinear controller. In the field

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Nomenclature

x	state variables of a component	V_t	terminal voltage amplitude of the generator (pu)
$\bar{x}$	state variables of a controller	V_t^r	reference value of the terminal voltage (pu)
u	input variables	V_q	q axis component of the terminal voltage (pu)
y	output variables	V_d	d axis component of the terminal voltage (pu)
y^r	references of output variables	E'_q	q axis transient EMF of the generator (pu)
ω	intermediate variables	E'_d	d axis transient EMF of the generator (pu)
υ	connection variables	I_q	q axis component of the stator current (pu)
$\breve{\upsilon}$	the variables denoting the impact of the external system on the component	I_d	d axis component of the stator current (pu)
$\hat{\upsilon}$	the variables denoting the impact of the component on the external system	x_q	q axis reactance (pu)
		x_d	d axis reactance (pu)
z	new defined state variables	x'_q	q axis transient reactance (pu)
δ	rotor angle (rad)	x'_d	d axis transient reactance (pu)
δ^r	rotor angle reference (rad)	T'_{q0}	q axis transient time constant (s)
ω	rotor angular frequency (rad/s)	T'_{d0}	d axis transient time constant (s)
ω_0	synchronous angular frequency (rad/s)	α	firing angle of the thyristor in SVC (rad)
H	inertia time constant of generator (s)	T_α	dead time constant of SVC (s)
C_H	high pressure cylinder distribution coefficient	B_C	compensating capacitor susceptance of SVC (pu)
C_{ML}	distribution coefficient of intermediate pressure cylinder and low pressure cylinder	B_L	reactor susceptance of SVC (pu)
		B_T	transformer susceptance of SVC (pu)
P_H	mechanical power of the high pressure cylinder (pu)	B_{svc}	total susceptance of SVC (pu)
P_e	electromagnetic power of the generator (pu)	B_{svc}^r	reference of the total susceptance of SVC (pu)
E_f	equivalent electromotive force (EMF) in the excitation coil (pu)	V_x	x axis component of the voltage (pu)
		V_y	y axis component of the voltage (pu)
u_υ	valve control signal (pu)	I_x	x axis component of the current (pu)
P_{m0}	initial mechanical power of generator (pu)	I_y	y axis component of the current (pu)

of power system component modeling and control, a kind of component structural models with DA subsystem form proposed [11,12], and discusses the decentralized nonlinear controller design method for models with this form [13,14]. The Ref. [12] 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. By the proposed MRM, 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, simulation and controller design for large-scale systems [15]. In the power system, the acceptable reduced model of a component subsystem should meet the following requirements: The reduced model should have the similar dynamic response to the original model. The connection equations in the reduced model should have the same features to the ones in the original model (the same connection variable type and number, the same connection equation number), and the connection equations in both models should be equivalent to each other. The reduced model should have simpler structure than the original model.

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 $\upsilon = (\breve{\upsilon}, \hat{\upsilon})$, where, $\breve{\upsilon}$ denotes the impact of the external system on the component, and $\hat{\upsilon}$ 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.

The component subsystem structured model consisting of differential dynamic equations and algebraic connection equations generally can be written as [13]

$$\begin{aligned} \dot{x} &= f(x, \omega, u) \\ 0 &= g(x, \omega, \upsilon) \end{aligned} \quad (1)$$

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 vector functions.

The nonlinear controller can be expressed as

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

where $\bar{x}$ 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