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A methodology for equivalent modeling of distribution system based on nonlinear model reduction

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ABSTRACT

This paper presents a new method to construct the low-order equivalent model for distribution system, which is very essential in large power system simulations. The distribution system connected to a substation is seen from the transmission power system as a nonlinear input–output system. In order to cope with the computation complexity, nonlinear model reduction technique based on covariance matrix is employed to obtain a new low-order dynamic system, which can closely represent the dynamic characteristics of the detailed system. The absence of drastic simplifications, direct consideration of the distribution network and the proper preservation of the input–output behavior of the detailed distribution system allow the equivalent model to attain good accuracy. Simulations and analysis are carried out on WSCC system to verify the validity of the proposed method. The simulation results show that this new method could attain high accuracy of simulation of distribution system under various operating conditions, thus improving the precision of power system stability analysis.

Introduction

Nowadays, dynamic simulation has been becoming the main tool for electric power system analysis. Thus, accurate modeling of the elements that compose the power system is of vital importance. It has been proved that, among all the elements, load model is least accurate. More importantly, the dynamic characteristics of power system loads have significant influence on the power system stability [1–4]. Although the importance of load modeling has been well recognized, load is still one of the most difficult components to model in power system due to its complexity.

Generally, load modeling is to find a mathematical model which can describe relationship between bus voltage and power that consumed by the load. Recent studies have addressed mainly two ways of constructing load model: component-based load modeling method [5–9] and measurement-based load modeling method [10–12]. The component-based method collects the information on load class mix, on load composition, and on characteristics of load connected to a particular bus. Then, equivalent load model is acquired by aggregating the dynamic part and static part separately. The measurement-based method, on the other hand, records the load dynamics by field test. Then the parameters of load model are identified from the recorded data. Using these two methods, the load supplied by a bus is represented by an equivalent induction motor and some static load component, such as ZIP and parallel connected to the bus. However, there are two important drawbacks of these methods. The first problem is that the loads are often supplied through large-scale distribution network, as noted in [13]. A common solution to this problem is to use a fictitious impedance to represent the distribution network [14]. Unfortunately, this simplification could introduce significant inaccuracies [13]. The second problem is that, in the modeling process of these methods, one induction motor is used to represent the dynamic behavior of the all the loads connected to a bus. Therefore, it is necessary to introduce the model reduction techniques originated from system theory to equivalent modeling for distribution systems.

The idea of model reduction is to replace a given mathematical model of a system with a model, which is much smaller than the original one, yet still attains satisfactory accuracy of describing the input–output characteristics of the system. A large number of works on model reduction have been published, such as balanced truncation [15], singular perturbation approximation [16] and proper orthogonal decomposition [17]. Among them, the balanced truncation method is well established and probably the most popular method. Based on Moore's work [15], Scherpen [18] proposed the balancing for nonlinear systems. However, the balancing procedure presents computational difficulties so that it is hard to obtain a closed form solution for the energy functions. In order to address this point, the empirical gramians for nonlinear systems

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is proposed by Lall [19]. These empirical gramians, which are extension to the gramians of linear systems, can be obtained based on system trajectories under typical inputs and initial conditions. However, the empirical gramians are restricted to nonlinear control-affine system [20]. Meanwhile, the model reduction of DAE system has received little attention. From our necessarily limited survey on this subject, the only approach is the reduction technique proposed by Marquardt [21]. The reduced-order system is obtained based on the principal component of system trajectories. The main drawback of this method is that it does not consider the state-to-output characteristics.

In this paper, a new approach for equivalent modeling of distribution system using nonlinear model reduction techniques is proposed and tested. From the view of transmission power system, the distribution system connected to a substation can be regarded as a nonlinear differential-algebraic equations (DAE) system. In order to cope with the computation complexity of the high-order distribution system model, covariance matrices based nonlinear model reduction technique is introduced. Covariance matrices, put forward by Hahn [22], is an extension to the empirical gramians of nonlinear systems. These covariance matrices are calculated using simulation trajectories and can server as a quantitative indicator of the importance of state variables to the input-state and state-output behavior of the system. Then, based on the idea for nonlinear balancing, the order of the differential equations can be reduced by Galerkin projection. In addition, the artificial neural network is adopted to replace algebraic equations. Thus, a low-order ordinary-differential equations model, which can closely represent the dynamic characteristics of the detailed distribution system, is obtained. Simulation results under different operating conditions are shown to illustrate the efficiency of the proposed method.

The paper is organized as follows: In Section 'Dynamic model of distribution system', the detailed dynamic model of distribution system is developed. In Sections 'Model reduction for nonlinear system via covariance matrices' and 'Load modeling of distribution system via nonlinear model reduction approach', a method for reducing the order of nonlinear system based on covariance matrix and how it is applied to the dynamic model of distribution system is presented. Validation of the proposed method and conclusion are presented in Sections 'Numerical results' and 'Conclusion', respectively.

Dynamic model of distribution system

Dynamic model of load buses in the distribution system

Generally, most distribution systems have radical configurations, as shown in Fig. 1. At the tip of the system are multiple motors (or other kind of load) supplied by the same bus.

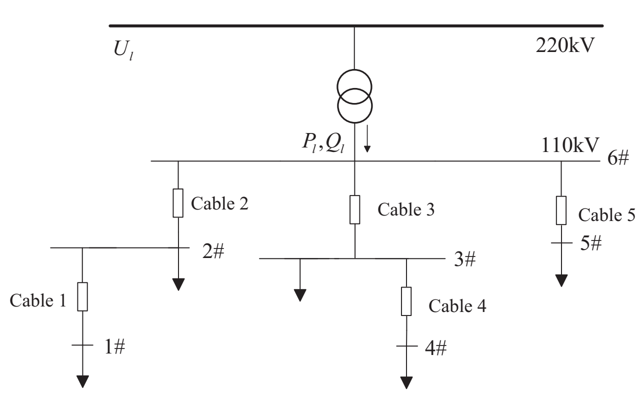

Fig. 1. Structure of a typical distribution system.

In this paper, the composite load model (CLM), which consist of an induction motor paralleled with a ZIP, is adopted to represents the load supplied by each bus in the distribution system. The structure of CLM is shown in Fig. 2.

In Fig. 2, Z represents the constant impedance load, I the constant current load, P the constant power load. R_1, R_2 are stator and rotor resistance, respectively; X_1, X_2 are stator and rotor reactance, respectively, X_m is magnetizing reactance; and s is the slip speed of the rotor.

The first-order slip model based on the rotor speed is used to describe the dynamics of induction motors. The model of induction motor is given by

$$T_J \dot{s} = T_m - T_e \tag{1}$$

where T_J is the inertia moment, T_e is the electro-magnetic torque and is given by

$$T_e = \frac{2T_{e\max}}{\frac{s}{s_{cr}} + \frac{s_{cr}}{s}} \left(\frac{U}{U_0}\right)^2 \tag{2}$$

and T_m is the applied mechanical torque given by

$$T_m = T_{m0}\left(A\left(\frac{1-s}{1-s_0}\right)^2 + B\left(\frac{1-s}{1-s_0}\right) + C + D\left(\frac{1-s}{1-s_0}\right)^{\gamma}\right) \tag{3}$$

where A, B, C and D are the mechanical torque characteristic coefficients which satisfy

$$A + B + C + D = 1 \tag{4}$$

In the above equations, s_0 is the rated slip speed, T_{m0} is the initial mechanical torque, U and U_0 are the actual and rated terminal voltages of the motor, $T_{e\max}$ is the max electro-magnetic torque under rated terminal voltage, and s_{cr} is the critical slip.

The equivalent impedance of the induction motor is

$$Z = R_1 + jX_1 + jX_m//(R_2/s + jX_2) \tag{5}$$

The power drawn by the motor at any given time can be calculated by

$$S = \dot{U}^2/Z^* \tag{6}$$

Detailed dynamic model of distribution system

Assume that the information on composition and characteristics of the load supplied by each bus of the distribution system has been collected. According to Ref. [1], the detailed dynamic model of the distribution system can be obtained as Eq. (7). The concrete procedure for the modeling of distribution system is derived in Appendix A.

$$\begin{cases} \dot{\boldsymbol{s}} = \boldsymbol{f}(\boldsymbol{s}, \boldsymbol{U}) \\ \boldsymbol{0} = \boldsymbol{g}(\boldsymbol{s}, \boldsymbol{U}, \boldsymbol{U}_l) \\ \boldsymbol{y} = \boldsymbol{h}(\boldsymbol{s}) \end{cases} \tag{7}$$

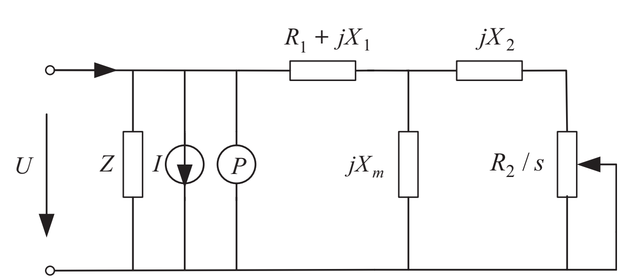

Fig. 2. Structure of composite load model.