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Low-order dynamic equivalent estimation of power systems using data of phasor measurement units

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ABSTRACT

This paper utilizes data measured by phasor measurement units (PMUs) to extract a low-order dynamic equivalent model for power system stability studies. The estimated model is a 2-order model for synchronous machines. This model has the advantage of simplicity of classical model and considerably reduces the oversimplifying error of classical model. This method offers an alternative approach to analytical model reduction techniques based on the detailed system models. The proposed method uses the synchronized bus voltage and current phasors measured by PMUs. Using post disturbance data, electrical and mechanical parameters of the equivalent generator are estimated sequentially. Furthermore, a new approach for estimation of two-machine and single machine infinite bus (SMIB) equivalent systems are presented for analysis of electromechanical oscillations. To evaluate the performance of the proposed approach, simulations are performed on a two area 13-bus test system and real measured PMU data. Simulation results show that the estimated model can represent the dynamic behavior of the studied system with good approximation.

Introduction

With the development of electrical industry, the scales of power systems have become larger than ever. Owing to the dimension of interconnected power systems, it is often impractical to represent the entire system model in detail. Therefore, reduced order dynamic equivalents are used to represent groups of generators or external systems [1].

Many efforts are devoted to reduce power system model using analytical approach [1–4]. Analytical approaches based on the concept of coherency have the benefit of saving power system structure. However, these approaches need detailed parameters of all power system machines and elements. Due to continuous variation of system parameters and changing environment of nowadays power system, analytical approach may not be a good choice for model reduction. To overcome this shortcoming and take system structure and parameters changes into account, measurement based approaches have been proposed [5,6].

Measurement-based methods use dynamic responses of system disturbance to estimate dynamic equivalent parameters. The unknown parameters of the dynamic equivalent model can be determined using identification and parameter estimation methods [7]. The main drawback of measurement based approach is their need for fast dynamic response of power system. Fortunately, modern power systems use wide area measurement system (WAMS) [8,9] that utilize phasor measurement unit (PMU) as a basis for data gathering system. PMUs measure phasors of voltage, current and frequency with a time stamp in the time interval down to 20 ms. A review of application of PMUs to power system operation and PMU placement methods has been provided in [10]. Therefore from organization point of view, there would be no concern about gathering fast dynamic response of power system. In [5,11], a new method for parameter estimation using neural network has been presented. Wavelet transform is used in [12] for identification of inter-area oscillations using measured data by PMU. Third-order synchronous generator model estimation is presented in [13,14]. In these methods, transfer function of the machine is calculated by linearizing its equations about the operating point and estimating the parameters. These methods have limited accuracy because of linearization error. Power system Thevenin model estimation for use in voltage stability evaluation is performed in [6]. This method uses continuously changing operating data in power system for parameter estimation. Reference [15] equivalences two sides of a tie line by two classical machines and estimates their parameters by neglecting the damping effect. This approach uses the inter-area oscillation components in the bus voltages resulting from disturbances. The main attributes of measurement based methods are the ability to aggregate several

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coherent or non-coherent groups of generators without requiring a large data set.

In this paper, a new measurement based method using synchronized phasor measurements is presented. Dynamic equivalent of the external system viewed from the measured bus is identified in the form of classical or second-order model of synchronous generator. Estimation of the model parameters is done in two simple steps. At the first step, electrical parameters of equivalent machine are estimated. Mechanical parameters are estimated in the next step. Estimation of electrical parameters is carried out by two methods. In one method, using non-linear least square, electrical parameters of the machine and its internal voltage angle are estimated together. In the other method, electrical parameters are estimated without estimation of the internal angle, which is calculated after estimation of the transient reactance. The latter method is faster, while the former yields more accurate results. Machine modelling is then extended to model the prevailing tie-line oscillations using SMIB and two-area equivalent.

The remainder of the paper is organized as follows. In Section 'The equivalent machine parameter estimation', estimation of the classical model is formulated and presented with two methods. Section 'Illustration using the SMIB system' and Section 'Estimation of external power system dynamics for a two-area system' provide simulation results of these methods on the SMIB and two-area systems. In Section 'Estimation of external power system dynamics for a two-area system', it is also shown how to identify a two-machine or SMIB equivalent model to investigate tie-line inter-area oscillations. The application of estimation approach on the real data is presented in Section 'Application on the real PMU data'. Conclusions are given in Section 'Conclusion'.

The equivalent machine parameter estimation

The classical or the second-order model of synchronous machine is the simplest model that can be used in electromechanical dynamics analysis. This model offers considerable computational simplicity; it allows the transient electrical performance of a machine to be represented by a simple voltage source with fixed magnitude behind an effective transient reactance as shown in Fig. 1 [16]. This model has good performance in determining the first swing stability [17]. When the system is subjected to a disturbance, parameters of the classical model can be estimated using post disturbance data. The electrical parameters of the model to be estimated are the generator internal voltage (E), transient reactance (X'_d) and the variable rotor phase angle (δ). The mechanical parameters to be estimated are damping coefficient K_d and inertia constant (H). As stated above, the generator internal voltage is assumed to be constant but the rotor phase angle varies from one sample to the other.

Estimation of the classical model can be divided into two steps: estimation of the electrical parameters and estimation of the mechanical parameters.

Estimation of electrical parameters

In this work, two different formulations for estimation of electrical part of classical model are presented.

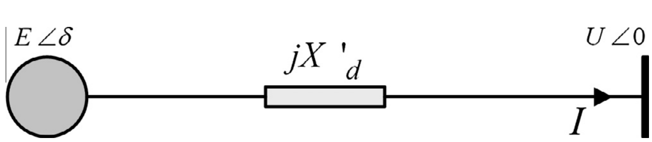

Fig. 1. Circuit diagram of a classical model of a synchronous generator.

Nonlinear Least Square-1 (NLS1)

According to Fig. 1, relationship between the internal voltage and the terminal voltage can be stated as follows:

$$E\angle\delta - jX'_d I = U \tag{1}$$

where, U and I are the generator terminal voltage and current phasors. By separating real and imaginary parts, (1) is divided into two equations as presented in the following.

$$I^r = \frac{U^j - E\sin(\delta)}{X'_d} \tag{2}$$

$$I^j = \frac{U^r - E\cos(\delta)}{X'_d} \tag{3}$$

where, U^r, U^j, I^r and I^j are real and imaginary parts of terminal voltage and current, respectively. Considering the last m samples, the above equations can be rewritten as following.

$$E\sin(\delta_i) + X'_d I^r_i - U^j_i = 0 \quad i = 1, \ldots, m \tag{4}$$

$$E\cos(\delta_i) + X'_d I^j_i - U^r_i = 0 \tag{5}$$

With $2m$ equations in (4) and (5) only $m+2$ variables, i.e. E, X_d and $\delta_i, i = 1, \ldots, m$ are unknown. If $m \succ 2$ then the set of equations will be over determined and can be calculated using the following nonlinear least square optimization:

$$\underset{E,X'_d,\delta_i}{Min} \left\| \begin{matrix} E\sin(\delta_1) + X'_d I^r_1 - U^j_1 \\ E\cos(\delta_1) + X'_d I^j_1 - U^r_1 \\ \vdots \\ E\sin(\delta_m) + X'_d I^r_m - U^j_m \\ E\cos(\delta_m) + X'_d I^j_m - U^r_m \end{matrix} \right\| \tag{6}$$

In (6) a suitable choice for initial conditions can be $E = 1, X'_d = 0.2$ and $\delta_i = \angle\tilde{U}$. In the above least square formulation, with m sets of measurements, the Jacobian matrix has the size of $(m+2)\times(m+2)$. Therefore, by increasing the number of measurement sets, computational effort will increase progressively.

Nonlinear Least Square-2 (NLS2)

In the least square formulation of (6) with m sets of measurements, m unknowns are the generator internal angle (δ) corresponding to the individual samples. The following formulation removes these variables from the optimization problem. By assuming the terminal voltage phasor as the angle reference, (1) is rewritten as:

$$E\angle\delta' = \mathrm{U} + jX'_d \mathrm{I} \tag{7}$$

By decomposing the current term (I) into real and imaginary parts, Eq. (7) can be written as follows:

$$E\angle\delta' = U + jX'_d(I^r + jI^j) = (U - X'_d I^j) + j(X'_d I^r) \tag{8}$$

where I^r and I^j are the real and imaginary part if I. By calculating squared absolute value of the two sides of above equation, the following equation can be obtained.

$$E^2 = U^2 - 2X'_d U I^j + {X'_d}^2 {I^j}^2 + {X'_d}^2 {I^r}^2 = U^2 + 2X'_d Q + {X'_d}^2 I^2 \tag{9}$$

where, Q is the generator reactive power output ($Q = -UI^j$) and I is the magnitude of generator output current $\left(I = \sqrt{({I^r}^2 + {I^j}^2)}\right)$.

With m sets of measurements, there will be m equations with only two unknown variables E and X'_d. Therefore, two measurement samples would be sufficient to solve the equations. For more