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A constrained minimization approach for the estimation of parameters of transient generator models

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ABSTRACT

This paper proposes a practical method that estimates parameters of synchronous generator transient models from measurements using a constrained minimization approach. The generator is represented by a set of differential-algebraic equations (DAEs) and its solution is achieved by means of a minimization of the norm of algebraic equations subject to differential equations constraints. The proposed approach overcomes solvability problems of DAEs models. The method is robust regarding initial parameter guesses, requires no disconnection of the generator from the grid and uses measurements commonly available in power plants, such as generator terminal voltage and current, field voltage and rotor speed. Mechanical and electrical parameters of the generator are estimated separately and the load angle variable is also estimated. The method was tested with measurements obtained from both simulations and actual measurements obtained from a small power system designed in laboratory.

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1. Introduction

1.1. Motivation

The correct representation of a synchronous generator by models is an important concern for electric power system utilities. The use of specialized software packages and an accurate representation of the generator models and their parameters enable the prediction of the dynamic response of a system. In particular, the generator transient model is vital for studies on transient stability. Many methods for the identification of generator parameters have been proposed and the most traditional are sudden short-circuit [1], load rejection [2] and frequency response tests [3] which have been standardized by IEEE [4] and require disconnection of generator from the power grid.

Some methods were proposed to enable the collection of data and the parameter estimation without disconnecting the generator form the grid. Methods that intentionally inject perturbations in the machine, such as Pseudo Random Binary Sequence, to excite its dynamics can be found in [5]. Other methods that can be applied with no disconnection of the generator from the power grid ('on-line' test) are reported in [6–10]. More recently paper use synchrophasor measurements to estimate the generator parameters as refer in [11,12].

Despite the development of these methods for parameter estimation based on on-line tests, in some situations the estimation cannot be accomplished in practice because the measurement set required by the method is hard of being obtained. For example, rotor angle measurement, which is very difficult to obtain, are required in [13,14]. Usually the rotor angle is estimated by integrating rotor speed [8,7,9]; however the exact initial rotor angle must be measured which is not an easy task.

Another issue is lack of robustness with respect to initial parameter guess which produces convergence problems. In [13] convergence problems of the estimation algorithm were reported due to initial parameter guess. In [9] is shown that the parameter cannot be estimated due to the effect of the unknown of initial condition of an unobservable state. Those problems become more evidence with the increasing number of parameters to be simultaneously estimated. Few papers have been proposed to overcome this problem. One particular paper that needs to be mention is [15], wherein a classification of model parameters according to their output sensitivity is proposed as a guide to improve the parameter estimation process. In addition, in [12] a special time indicator (global discrepancy indicator) is proposed to select the parameter with higher sensitivities.

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1.2. Contribution

This paper proposes a method for the estimation of parameters of synchronous generators that satisfies practical requirements and avoids the two aforementioned problems. The method has the following features:

(i) on-line tests: measurements for the estimation are the voltages and currents of the generator's terminal bus, field voltage magnitude and rotor speed, which are obtained with no disconnection of the generator from the grid, during a perturbation;
(ii) robustness regarding initial parameter guesses;
(iii) electrical and mechanical generator parameters are separately estimated; and
(iv) generator rotor angle with respect to terminal voltage (load angle) is also estimated as a byproduct of the method.

The generator is modeled by a set of differential-algebraic equations (DAEs) for enable the estimation of parameters from commonly available measurements, avoiding in particular the measurement of rotor angle (which is not available in most power plants). In the formulation of the proposed parameter estimation algorithm, the algebraic equation of DAEs is relaxed and the problem of parameter estimation is transformed into a constrained minimization problem, in which a norm of the algebraic equations is minimized subject to differential equations constraints. This approach mitigates convergence problems due to the non solvability of the algebraic equation, which is one of the main reasons for nonconvergence in the estimation of DAE system models. The inputs and outputs of the model were carefully selected to improve the robustness of the estimation algorithm; enabling the independent estimation of mechanical and electrical parameters.

1.3. Organization of the paper

Section 2 describes the theoretical background of the proposed parameter estimation method for DAE models based on a constrained minimization approach; Section 3 addresses the generator modelling for parameter estimation; Section 4 reports the results of simulations and an experimental test; finally, Section 5 draws the conclusions.

2. Estimation of parameters of DAEs using a constrained minimization approach

Initially is presented the estimation process using traditional model of DAE systems and, after that, with the proposed approach.

2.1. Parameter estimation using traditional model of DAE systems

Consider the following class of nonlinear constrained systems

$$\begin{aligned} \dot{x} &= f(x, z, p, u) \\ 0 &= g(x, z, p, u) \\ y &= h(x, z, p, u) \end{aligned} \tag{1}$$

where $x \epsilon R^m$ is the state vector, $z \epsilon R^q$ is the algebraic vector, $y \epsilon R^r$ is the output vector, $u \epsilon R^l$ is the input vector and $p \epsilon R^p$ is the parameter vector. Let p_i be the ith component of p. Functions f, g and h are assumed differentiable with respect to each component p_i of p. The parameter estimation is formulated as an optimization problem for the minimization of the cost function that measures the mismatch between the Real System output, y_r, and the Mathematical Model output, y (Auxilary System):

$$J(p) = \frac{1}{2}\int_0^{T_0} (y_r - y)^T (y_r - y) dt \tag{2}$$

Optimality condition $\partial J(p)/\partial p = 0$ is given by

$$G(p) := \frac{\partial J(p)}{\partial p} = -\int_0^{T_0} \left(\frac{\partial y}{\partial p}\right)^T (y_r - y) dt = 0 \tag{3}$$

Newton's method can solve nonlinear equation (3). Starting from an initial parameter guess $p^{(0)} = p_0$, the parameter fitting at the kth iteration is given by

$$p^{(k+1)} = p^{(k)} - h_{opt}\Gamma^{-1} G(p)\Big|_{p=p^{(k)}} \tag{4}$$

where h_{opt} is an optimal step size that can be calculated by a quadratic search line method [16] and Γ is the Jacobian matrix of $G(p)$, which can be approximated (neglecting the second-order term) by

$$\Gamma \approx \int_0^{T_0} \left(\frac{\partial y}{\partial p}\right)^T \left(\frac{\partial y}{\partial p}\right) dt\Big|_{p=p^{(k)}} \tag{5}$$

where $\partial y/\partial p_i$ are called sensitivity functions and obtained differentiating (1) with respect to each parameter p_i and solving the resulting system

$$\begin{aligned} \frac{d}{dt}\frac{\partial x}{\partial p_i} &= \frac{\partial f(x,z,p,u)}{\partial x} \cdot \frac{\partial x}{\partial p_i} + \frac{\partial f(x,z,p,u)}{\partial z} \cdot \frac{\partial z}{\partial p_i} + \frac{\partial f(x,z,p,u)}{\partial p_i} \\ 0 &= \frac{\partial g(x,z,p,u)}{\partial x} \cdot \frac{\partial x}{\partial p_i} + \frac{\partial g(x,z,p,u)}{\partial z} \cdot \frac{\partial z}{\partial p_i} + \frac{\partial g(x,z,p,u)}{\partial p_i} \\ \frac{\partial y}{\partial p_i} &= \frac{\partial h(x,z,p,u)}{\partial x} \cdot \frac{\partial x}{\partial p_i} + \frac{\partial h(x,z,p,u)}{\partial z} \cdot \frac{\partial z}{\partial p_i} + \frac{\partial h(x,z,p,u)}{\partial p_i} \end{aligned} \tag{6}$$

A difficulty detected in the estimation of parameters using the traditional model (1) is the possibility of the algebraic equation $0 = g(x, z, p, u)$ having no solution for a certain guess of parameter vector p, which leads to nonconvergence problems in numerical algorithms.

2.2. Parameter estimation using a constrained minimization approach

This section proposes a method for the estimation of parameters of differential algebraic equations (DAEs) based on trajectory sensitivity functions using a especial model for DAE systems. Its main feature, in comparison with other nonlinear methods [17] is the fact that parameters can be estimated even when the iterative parameter estimation algorithm reaches an intermediate parameter value for which the algebraic equation of the DAEs have no solution. Before present this propose, an important definition of 'Convergence Region' of an estimation method is introduced.

Definition 2.1. Convergence Region It is a subset of the parameter space composed of initial conditions that lead the estimation method to converge to the correct parameter vector, p^*.

The parameter space is composed of feasible and unfeasible regions and the convergence region is usually a small subset of such regions, as shown in Fig. 1. If the estimation method starts from p^o, the parameter will converge to the true vector p^* because p^o is inside the convergence region. However, if it starts from p^{oa}, the parameter will diverge or converge to an incorrect parameter vector because p^{oa} is outside the convergence region. According to experiences in the estimation of nonlinear systems, the convergence region depends mainly on the information contained in

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