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Identification of synchronous machine parameters from field flashing and load rejection tests with field voltage variations

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ABSTRACT

In this paper, a method for the identification of the synchronous machine parameters using data from field flashing (FF) and load rejection (LR) tests performed during commissioning, is proposed. The identification using data acquired during field flashing, a commissioning standard procedure, allows an initial estimation of the *d*-axis open-circuit transient time constant. A model dependent on that time constant, which relates the applied field voltage and the field current, the model inputs, and the generator terminal voltage, the model output, is derived. In the conventional load rejection, the applied field voltage is constant. This poses a practical restriction, since a constant voltage source must be available. In the load rejection identification method proposed in this paper, a model is derived which relates variable field voltage and field current, the model inputs to the generator terminal voltage, the model output, following load rejection. From the field flashing and load rejection models, the synchronous machine parameters are determined solving an optimization problem, formulated as a nonlinear least-squares problem or as an orthogonal distance regression. The orthogonal distance regression is suited to take into account noise in the model input. The proposed method is applied to synthetic data generated by simulation of a generator with known parameters. Statistical analysis shows a maximum error with relation to the true values of 35.8% for the nonlinear least-squares problem and 5.8% for the orthogonal distance regression. The method is also tested using real data acquired during commissioning of a 140 MVA hydro powerplant. The Normalized Sum of Squared Errors (NSSE), a metric to evaluate the deviation of the simulated response with relation to the measurements, gives a value less than 1% in most of the cases and a maximum of 2.3%, corroborating the accuracy of the proposed method.

1. Introduction

Modeling and parameter identification of synchronous generators and other power system components ensure correct computer models on which operation and planning studies are based [1,2]. Methods based on the time or frequency response are well-established as standard procedures for the synchronous generator identification [3–7]. Other methods with potential for application have been reported such as trajectory sensitivities [8–10], observers [11], Kalman filtering [12,13], maximum-likelihood estimation [14], nonlinear techniques [15,16], genetic algorithms [17] and neural networks [18,19]. Recently, the wider use of synchronized phasor measurements led to development of new methods for the identification of the synchronous generator using data acquired after system disturbances [20–24].

During generator commissioning, which consists of a set of tests to ensure that all components have been installed and tested properly according to international standards, the generator parameters are identified or the ones provided by the manufacturer are validated. The determination of the generator parameters allows a first tuning of the generator control loops in the field and a promptly updated database for the system operator, ensuring the computing model reliability for operation studies.

A time domain method, the load rejection (LR) test, is widely used in the commissioning [3]. It allows the determination of the direct axis (*d*-axis) and quadrature axis (*q*-axis) parameters. This method, as initially proposed, requires specific operating conditions. For the direct axis parameters, the generator must be dispatched with zero active power and absorbing reactive power as much as possible without losing synchronism, ensuring that the only current component is in the *d*-axis. For the *q*-axis parameters, in order to eliminate the current component from the *d*-axis,

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it is necessary to ensure that the absolute value of the power factor angle (ϕ) is equal to the power angle (δ). In practice this is achieved by successive load rejections in order to minimize the field current variation.

In [25,26], methods based on LR on an arbitrary axis (*arb*-axis), dispensing with the need to align the armature with the *q*-axis, were presented. In these methods, a load rejection is first performed in the *d*-axis to find the parameters associated with this axis and then a LR on an *arb*-axis is performed to determine the *q*-axis parameters considering the previously known *d*-axis parameters.

LR methods are based on the assumption that the applied field voltage is constant. An independent and variable direct current source is required to supply the power to set the operating condition, which is not practical for medium and large-sized synchronous machines. Usually, the test is performed with the Automatic Voltage Regulator (AVR) in field current control mode and neither the field voltage nor the field current are constants. For the identification or validation of the generator parameters, it is desirable that these practical restrictions associated to the equipment used in these tests be taken into account. Commissioning procedures such as field flashing can be also used to generate data for the identification method.

In this paper an identification method of the generator parameters, using data from commissioning procedures and tests, is proposed. An analytical model, having as inputs the field voltage and current and as output the terminal voltage, describing the LR tests in an *arb*-axis is derived. The model inputs, the field voltage and the field current, can be recorded during commissioning. Therefore, the dynamics of the field current control, during the LR tests, can be considered without the need to know the control structure and its parameters. A simplified model, describing the FF procedure during commissioning, can be used to perform an initial identification of the open-circuit transient time constant. The identification is formulated as an ordinary ordinary least-squares and as an orthogonal distance regression. Physical constraints on the parameters are included in the identification method. The interior point method is used to solve the optimization problem.

The proposed method is applied to synthetic data generated by simulation of a test system and to real data obtained from the commissioning of a hydraulic unit.

The main contributions of this paper are:

1. Development of a model for field flashing, a standard commissioning procedure, and its use for an initial identification of the *d*-axis open-circuit transient time constant T'_{do}.
2. Development of a load rejection model considering field voltage variations, dispensing with the need of a constant voltage source required by the conventional load rejection tests.
3. Application of the orthogonal distance regression which is suited to take into account noise in the recordings that correspond to the model input.
4. Incorporation in the optimization problem of physical constraints on the generator parameters and its solution by the interior point method.

2. Synchronous machine model

The equations of the synchronous machine in operational form, neglecting the rotor resistance, speed variations ($\omega = 1$) and the variational voltage terms $d\psi_d/dt$ and $d\psi_q/dt$, where the variables and parameters follow the standard notation used in [27], are given by [27,28]:

- *Incremental armature voltage*

$$\Delta e_d(s) = s\Delta\psi_d(s) - \Delta\psi_q(s) \quad (1)$$

$$\Delta e_q(s) = s\Delta\psi_q(s) + \Delta\psi_d(s) \quad (2)$$

- *Incremental armature flux*

$$\Delta\psi_d(s) = -L_d\,\Delta i_d(s) + L_{ad}\,\Delta i_{fd}(s) + L_{ad}\,\Delta i_{1d}(s) \quad (3)$$

$$\Delta\psi_q(s) = -L_q\,\Delta i_q(s) + L_{aq}\,\Delta i_{1q}(s) \quad (4)$$

- *Incremental field voltage*

$$\Delta e_{fd}(s) = s\,\Delta\psi_{fd}(s) + R_{fd}\,\Delta i_{fd}(s) \quad (5)$$

$$0 = s\,\Delta\psi_{1d}(s) + R_{1d}\,\Delta i_{1d}(s) \quad (6)$$

$$0 = s\,\Delta\psi_{1q}(s) + R_{1q}\,\Delta i_{1q}(s) \quad (7)$$

- *Incremental Field Flux*

$$\Delta\psi_{fd}(s) = L_{ffd}\,\Delta i_{fd}(s) + L_{ad}\,\Delta i_{1d}(s) - L_{ad}\,\Delta i_d(s) \quad (8)$$

$$\Delta\psi_{1d}(s) = L_{ad}\,\Delta i_{fd}(s) + L_{11d}\,\Delta i_{1d}(s) - L_{ad}\,\Delta i_d(s) \quad (9)$$

$$\Delta\psi_{1q}(s) = L_{11q}\,\Delta i_{1q}(s) - L_{aq}\,\Delta i_q(s) \quad (10)$$

The above equations can also be presented as:

$$\Delta\psi_d(s) = \Delta\psi''_d(s) - L''_d\,\Delta i_d(s) \quad (11)$$

$$E'_q(s) = \frac{1}{sT'_{do}}\left[E_{fd}(s) - I_{fd}(s)\right] \quad (12)$$

$$\Delta\psi''_d(s) = \left[\frac{L'_d - L''_d}{L'_d - L_l}\right]\Delta\psi_{1d}(s) + \left[\frac{L''_d - L_l}{L'_d - L_l}\right]E'_q(s) \quad (13)$$

$$\Delta\psi_{1d}(s) = \left[\frac{1}{sT''_{do} + 1}\right]\left(E'_q(s) - (L'_d - L_l)\,\Delta i_d(s)\right) \quad (14)$$

$$\Delta\psi_q(s) = -L_q\frac{\left(1 + sT''_q\right)}{\left(1 + sT''_{qo}\right)}\Delta i_q(s) \quad (15)$$

where

$$E'_q(s) = \frac{L_{ad}}{L_{ffd}}\Delta\psi_{fd}(s) \quad (16)$$

$$E_{fd}(s) = \frac{L_{ad}}{R_{fd}}\Delta e_{fd}(s) \quad (17)$$

$$I_{fd}(s) = L_{ad}\Delta i_{fd}(s) \quad (18)$$

$$T''_q = \frac{L''_q}{L_q}T''_{qo} \quad (19)$$

In (17) and (18); $E_{fd}(t)$ and $I_{fd}(t)$ represent the field voltage and the field current in the air gap line, respectively.

From (1) and (2), changes of voltage and flux linkage are related by:

$$\Delta e_d(t) = -\Delta\psi_q(t) \quad (20)$$

$$\Delta e_q(t) = \Delta\psi_d(t) \quad (21)$$

Voltage changes around the initial operating condition are given by:

$$e_d(t) = e_{do} + \Delta e_d(t) \quad (22)$$

$$e_q(t) = e_{qo} + \Delta e_q(t) \quad (23)$$

where e_{do} and e_{qo} are the *d*–*q*-axes stator voltages of the steady state before FF or LR, respectively.

The magnitude of the terminal voltage V_t can be calculated as:

$$V_t(t) = \sqrt{e_d(t)^2 + e_q(t)^2} \quad (24)$$