Electrical Power and Energy Systems 81 (2016) 222–231

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Development and application of a standstill parameter identification technique for the synchronous generator

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ARTICLE INFO

Article history:
Received 29 October 2015
Received in revised form 27 January 2016
Accepted 27 February 2016
Available online 9 March 2016

Keywords:
Algebraic elimination theory
Offline parameter identification
Standstill tests
Synchronous generators

ABSTRACT

This work presents the development of an offline standstill estimation technique, where the synchronous machine is locked at an arbitrary (but known) angle and is excited over a short period of time. The proposed time domain method requires few seconds of captured data in contrast to the well-known standard Standstill Frequency Response (SSFR) technique that could take more than 6 h to conduct. This is based on nonlinear least squares estimation and algebraic elimination theory. The resulting algorithm is non-iterative where the data is used to construct polynomials that are solved for a finite number of roots which determine the electrical parameter values. Experimental results are presented showing the efficacy of the technique in furnishing the parameters of a salient pole synchronous machine.

1. Introduction

The field of parameter estimation is an important area of research because it is applicable to many practical engineering problems. Here, we specifically look at the problem of identifying the electrical parameters of large synchronous machines (whether operated as generators or motors). This is motivated by the fact that power system stability analyses (voltage stability, large angle stability, small angle stability, etc.) require accurate parameter values as documented in standards IEEE 1110-2002 [1], IEEE 115-1995 [2], and by supervisory committees such as the Western Electricity Coordinating Council (WECC) in the USA [3]. These analyses are important for real-time monitoring software that alerts system operators to imminent power failures. See Ref. [4] for a major blackout caused in part by failing to respond to these software tools. Also, accurate knowledge of machine parameters improves the operation of large generators. For example, representing the field circuit dynamics significantly influences the effectiveness of excitation systems as they respond to large rotor angle disturbances (see p. 5 of [1]). Moreover, accurate representations of the field and rotor damper circuits are important for the excitation system to stabilize the machine after small rotor angle disturbances [1].

The synchronous machine model used here represents the rotor with a field winding in the *d*-axis, and a damper winding in each of the *d*-axis and *q*-axis. This is equivalent to Model 2.1 in IEEE 1110-2002 [1]. The parameters of the model can be obtained using standstill *offline* tests, i.e., with the generator disconnected from the grid. These tests, like the standstill frequency response (SSFR) [2], typically use low test voltages to obtain the resistances and unsaturated induction parameters. Other techniques are then used to account for variations due to the operating point temperature and magnetic saturation.

The SSFR is a standard test [1,2] where a low voltage test signal is applied over a range of frequencies to the stator terminals, with the rotor locked at specific angles/alignments. At each frequency, the stator voltages and currents are measured in steady state. These are used to determine a set of transfer functions representing the synchronous machine [5]. The test is carried out in two parts by aligning the rotor's *d*-axis with the stator's *a*-axis and then aligning the rotor's *q*-axis with the stator's *a*-axis [6]. By considering the breakpoints in the frequency response, the SSFR test has the capability of identifying the model structure of the machine, specifically, the number of damper windings to be modeled in the *d* and *q* axes. The breakpoints, which represent time constants and operational impedances, are related back to the resistors and unsaturated inductances of the appropriate model. Instead, the multitime scale approach by Touhami et al. [7] can reduce the model to several simpler transfer functions. As such, the slower dynamics are separated from the faster dynamics and the parameters are obtained from separate tests. Aliprantis et al. [8] developed a model of the damper windings as a general transfer function matrix using data collected by the SSFR test. Moreover, their work

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http://dx.doi.org/10.1016/j.ijepes.2016.02.030
0142-0615/

considers magnetic saturation by lumping its effect into the magnetizing branches. On the other hand, the alignment required by the SSFR test for large generators requires gantry cranes for large adjustments and hand cranks to make minor adjustments in the position, see p. 161 [2]. Bortoni and Jardini in [9] have extended the SSFR technique to allow for the test to be conducted at an arbitrary rotor angle. Their approach was an extension to the earlier work by Dalton and Cameron in [10].

In addition, time domain techniques exist including tests with higher voltage and current levels than the SSFR test, such as the standard short circuit and open circuit tests, see [2,11]. An example, is the rotating time domain response (RTDR) test by de Mello and Hannett in [12]. There, two of the machine terminals are shorted (b and c) and a field-excitation voltage is applied for a short period of time at lower than rated speeds. The RTDR and SSFR tests were compared in [13] on four generators, and the SSFR tests were found to be less expensive to implement and easier to schedule than RTDR tests. Kamwa et al. [14] use a PWM excitation with a randomly variable duty ratio applied to the field winding in standstill. The approach obtains the parameter estimates over two stages, first an initial set of operational parameters is found and then the direct parameters are found using the damped Gauss–Newton iterative search algorithm. Also, Tumageanian et al. [15,16] use a step input voltage with the machine in standstill. A maximum likelihood estimation iterative algorithm is used that requires good initial parameter values to ensure convergence. An alternative excitation is the chirp signal which is a sinusoid with linearly increasing frequency. This was used by Cisneros-Gonzalez et al. [17] with a hybrid optimization identification technique relying on Genetic algorithms and a Quasi-Newton method.

Conversely, there are *online* estimation methods, i.e., with the machine connected to the grid. An early work by Dandeno et al. in [18] applies a supplementary sinusoidal signal to the reference of the automatic voltage regulator (AVR) that results in changes in the field voltage and current. This test is performed while the machine is at 80% of its full load. The data is used to tune the parameters that were previously obtained from an offline SSFR test. Another technique by Tsai et al. in [19] injects excitation disturbance voltages into the field winding. Also, in [20] a disturbance in the field excitation reference voltage during online operation is used for their parameter estimation technique. The work in [21] employs a gradient based simulation optimization technique that updates the parameter values based on how closely their simulated response matches recorded data. In [22–25] the authors formulate their online estimation method as a nonlinear least-squares problem and solve it through iterative methods. The work of [20,26] use maximum likelihood methods, which are also iterative, and assume the process and measurement noise are white for which a Kalman filter type formulation can be used. However, iterative methods have concerns whether they converge or not and, if they do, whether it is to a local or a global minimum.

An approach that does not explicitly inject disturbance signals into the system is presented in [27]; the machine parameters are assumed to be known (using nominal values) and a Luenberger observer is used to estimate the rotor damper winding currents. Using these estimates of the currents, a linear least-squares formulation is then employed to estimate the parameters. The system, including the Luenberger observer, is then updated with the estimated parameter values. However, as the parameters are assumed to be known in order to estimate their values, there is no guarantee that the determined parameters will converge (e.g., in the sense of minimizing a least-squares criterion or some other criteria).

This work presents a standstill test where the stator windings are excited by a balanced three-phase chirp waveform, which sufficiently excites the dynamics of the machine and is continuously differentiable. The stator voltages and currents, and field current are collected over a short period. Using the theory of resultants, an identification model is developed that is directly (non-iteratively) solved for the parameter set that globally minimizes a least-squares criterion. Experimental results are compared with simulation. The methodology was previously applied to develop an identification model for the induction machine in [28–35]. The paper expounds on an earlier one [36] by presenting the detailed derivation along with the application of the algorithm. The organization is as follows: Section 2 gives the machine model and the parameters to be estimated. Section 3 presents the derivation of the nonlinear parameter identification model. Sections 4 and 5 give the experimental results and the conclusions, respectively.

2. DQ model of the synchronous machine

The nonlinear model of the synchronous machine presented here uses the reference frame adopted by Bergen [37] and Anderson and Fouad [38]. Also, following the approach of Krause [5], the rotor quantities of the machine are scaled using equivalent scaling factors (turn-ratios), but without per-unitization. For more on this model see Ch. 2 of [39]. The synchronous machine reference frame is depicted in Fig. 1.

The $0dq$ electrical model is given by

$$v_0 = -r_S i_0 - L_{lS}\frac{di_0}{dt} \tag{1}$$

$$v_{Sd} = -r_S i_{Sd} - \omega L_{Sq} i_{Sq} - \omega L_{AQ} i'_{Rq} - L_{Sd}\frac{di_{Sd}}{dt} - L_{AD}\frac{di'_F}{dt} - L_{AD}\frac{di'_{Rd}}{dt} \tag{2}$$

$$v_{Sq} = -r_S i_{Sq} + \omega L_{Sd} i_{Sd} + \omega L_{AD} i'_{Rd} + \omega L_{AD} i'_F - L_{Sq}\frac{di_{Sq}}{dt} - L_{AQ}\frac{di'_{Rq}}{dt} \tag{3}$$

$$-v'_F = -r'_F i'_F - L_{AD}\frac{di_{Sd}}{dt} - L'_F\frac{di'_F}{dt} - L_{AD}\frac{di'_{Rd}}{dt} \tag{4}$$

$$0 = -r'_{Rd} i'_{Rd} - L_{AD}\frac{di_{Sd}}{dt} - L_{AD}\frac{di'_F}{dt} - L'_{Rd}\frac{di'_{Rd}}{dt} \tag{5}$$

$$0 = -r'_{Rq} i'_{Rq} - L_{AQ}\frac{di_{Sq}}{dt} - L'_{Rq}\frac{di'_{Rq}}{dt} \tag{6}$$

The variables of the model are the $0dq$ stator voltages v_0, v_{Sd}, v_{Sq}, the scaled field voltage v'_F, the $0dq$ stator currents i_0, i_{Sd}, i_{Sq}, and the scaled field current i'_F. Other variables include the angle of the rotor θ (in electrical radians) and the angular velocity of the rotor $\omega = d\theta/dt$.

The parameters of the model are the dq stator self inductances L_{Sd}, L_{Sq}, leakage inductance L_{lS} and resistance r_S, the mutual inductances L_{AD}, L_{AQ}, the scaled damper winding self inductances L'_{Rd}, L'_{Rq} and resistances r'_{Rd}, r'_{Rq}, and the scaled field self inductance L'_F, and resistance r'_F.

The stator variables of the model in the $0dq$ coordinate system are related to their measurable counterparts in the abc coordinate system by a power invariant transformation (in Fig. 1 $v_a = v_{aa'}$, $v_F = v_{FF'}$) as follows

$$\begin{bmatrix} v_0 \\ v_{Sd} \\ v_{Sq} \end{bmatrix} \triangleq P \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}, \quad \begin{bmatrix} i_0 \\ i_{Sd} \\ i_{Sq} \end{bmatrix} \triangleq P \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{7}$$

with the transformation matrix P defined as

$$P \triangleq \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}.$$