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A Robust approach for the identification of synchronous machine parameters and dynamic states based on PMU data

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ABSTRACT

In this paper an approach for on-line identification of parameters and dynamic states of synchronous generator, is proposed. Synchrophasors data and Hybrid Dynamic Simulation provide the trajectories deviations caused by parameters errors. Simulated variables are combined with measurements to obtain Hybrid Trajectory Sensibility Functions (HTSF), which are used in the identification process based on Nonlinear Least Squares. This approach simplifies the calculation of HTSF. Constraints on the parameters range are enforced and the resulting constrained optimization problems is solved by a Primal-Dual Interior Points method. This solution is discussed in the paper. The method is applied to synthetic data and to a large generator of the Itaipu power plant.

1. Introduction

Simulation models are crucial for power systems operation. Model inaccuracies may lead to incorrect evaluation of the system conditions and inadequate control actions by operators. Discrepancies between measurements and dynamic simulations have been identified as the cause of blackouts [1,2].

The synchronous machines, which generates a large share of energy in current power systems, are strongly associated to many of the dynamic phenomena. Therefore, correct synchronous generator parameters are required for the correct simulation of power system dynamics.

As part of commissioning, tests are performed in order to identify unknown synchronous generator parameters or to validate the values provided by the manufacturer. However, periodic validation of generating units models is required, not only to detect errors in data bases [3,4], but also to keep updated models as the parameters may suffer substantial changes during operation caused by factors such as magnetic saturation, internal temperature, aging, effects of centrifugal force on the windings contacts and incipient faults in the machine [5].

Standard procedures for parameter identification requires specific tests. These tests need special operating conditions, the application of disturbances or, in some cases, the disconnection or shutdown of the machine, with the consequent negative economic impact [6].

Therefore, on-line parameters identification, based on measurements of disturbances that occur naturally in the system, is advantageous leading to a growing utilization of Phasor Measurement Unit (PMU) by utilities in order to ensure the quality of models [7].

For on-line parameter identification, existing methods can be included into two sets: those which use synchronized measurements and those which do not. The main advantage of synchronized measurements is the use of hybrid simulation in order to reproduce large disturbances by simulation and compare with measurements in the identification.

Most of the methods proposed for the on-line identification of synchronous generator parameters can be classified according to: the type of machine model used, classical model used in [8], transient model used in [9–11], subtransient model [12–14] and in saturated conditions [5,15–17]; the type of estimation method employed: based on recursive methods such as the Kalman Filter [11,18,19] and batch methods based on Nonlinear Least Squares [9,10,12], heuristic methods [14], or methods based on artificial intelligence [20–23].

The optimization of a quadratic performance index using trajectory sensitivities, is a simple and reliable approach for the identification of synchronous generator parameters [9,10,12]. This approach has been used for parameter calibration, validation and sensitivity evaluation.

The use of PMUs for the application of natural disturbances is still in development. Recent work has focused on the validation of the generating power plant, that is, the parameters validation of the machine, turbine, Automatic Voltage Regulator (AVR), Governor (GOV) and Power System Stabilizer (PSS) [14,18,19]. In these references the parameter calibration is performed in two steps. Initially, a sensitivity analysis determines the sensitive parameters that can be calibrated. Then, the sensitive parameters are calibrated. However, these approaches can be affected by identifiability problems which result in

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correlated parameters, where, for example, a machine parameter affects an AVR parameter identification, as reported in [14].

Therefore, this work is focused on the identification of synchronous machine parameters, with the advantage of using phasor and non-phasor synchronized measurements and adding other contributions. The proposed method in this paper is also based on the optimization of a quadratic index, using Hybrid Dynamic Simulation (HDS) but improves that approach. The main contributions are:

- The initial conditions for differential states in the HDS are considered as parameters to be identified together with the synchronous generator parameters.
- The Hybrid Trajectory Sensitivity Functions (HTSF) are calculated directly, using the derivatives of the differential algebraic model functions. This approach uses measured and simulated (hybrid) variables in their evolution over time.
- Constraints on the parameters are considered in the optimization problem. The Primal-Dual Interior Point method is used to solve the constrained optimization problem. The method is improved by using a damping factor similar to the Levenberg-Marquardt algorithm. Results are compared with unconstrained optimization.
- The method is applied to a real generator in a large power plant using data acquired from phasor and non-phasor synchronized measurements.

The paper is organized as follows. In Section 2 the machine model, the parameter identification problem, the use of synchrophasors and the HTSF are presented. The identification method is presented in Section 3. In Section 4, characteristics and difficulties of parameter identification are discussed. The results are presented in Section 5, for synthetic data, and in Section 6, for real data. The conclusions are presented in Section 7.

2. System identification model

In this section, the identification model is presented. Although a specific model is assumed for the generator, generic equations are used in the analysis so that the extension to other generator models is straightforward.

2.1. Generator model

The generator model used in this paper is a fifth order model, also known as subtransient model [24], suited for hydro-generators.

$$\dot{\omega} = \ddot{\delta} = \frac{\omega_0}{2H}(P_m - P_e - D(\omega - \omega_0)) \tag{1a}$$

$$\dot{\delta} = \omega - \omega_0 \tag{1b}$$

$$\dot{E}'_q = \frac{1}{T'_{do}}[E_{fd} - E'_q + (x_d - x'_d)I_d] \tag{1c}$$

$$\dot{E}''_q = \frac{1}{T''_{do}}[E'_q - E''_q + (x'_d - x''_d)I_d] \tag{1d}$$

$$\dot{E}''_d = \frac{1}{T''_{qo}}[-E''_d - (x_q - x''_q)I_q] \tag{1e}$$

$$V_q = E''_q - r_a I_q + x''_d I_d \tag{1f}$$

$$V_d = E''_d - r_a I_d - x''_q I_q \tag{1g}$$

$$P_e = E''_d I_d + E''_q I_q + (x''_d - x''_q)I_d I_q - r_a|I|^2 \tag{1h}$$

$$Q_e = E''_d I_q + E''_q I_d + x''_d I_d^2 - x''_q I_q^2 \tag{1i}$$

where ω is the rotor speed (rad/s), δ is the rotor angle (rad), H is the inertia constant (s), D is the damping factor (pu), ω_0 is the nominal synchronous rotor speed (rad/s), P_m is the mechanical power in machine axis (pu), P_e and Q_e are terminal active and reactive powers (pu), E'_q is the quadrature-axis transient internal voltage (pu), E''_d and E''_q are direct and quadrature-axes subtransient internal voltages (pu), V_d and V_q are the direct and quadrature-axes terminal voltages (pu), I_d and I_q are the direct and quadrature-axes stator current (pu), I is the terminal current magnitude (pu), E_{fd} is the field voltage observed in the armature winding (pu), x_d and x_q are the direct and quadrature-axes sustained reactances (pu), x'_d is the direct axis transient reactance (pu), x''_d and x''_q are the direct and quadrature-axes subtransient reactances (pu), r_a is the armature resistence (pu), T'_{do} is the direct-axis transient open-circuit time constant (s), and and T''_{qo} are the direct and quadrature-axes subtransient open-circuit time constants (s).

The model of the synchronous machine can be represented as a differential algebraic system:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{z}, \mathbf{p}, t) \tag{2a}$$

$$0 = \mathbf{g}(\mathbf{x}, \mathbf{z}, \mathbf{p}, t) \tag{2b}$$

$$\mathbf{y} = \mathbf{h}(\mathbf{x}, \mathbf{z}, \mathbf{p}, t) \tag{2c}$$

where $\mathbf{x}$ is the differential state variables vector, $\mathbf{z}$ is a vector of algebraic variables, $\mathbf{p}$ is the parameters vector and $\mathbf{y}$ is the output variables vector, give by

$$\mathbf{x} = [\omega \quad \delta \quad E'_q \quad E''_q \quad E''_d] \tag{3}$$

$$\mathbf{z} = [P_e \quad I_d \quad I_q \quad V_d \quad V_q \quad E_{fd} \quad P_m] \tag{4}$$

$$\mathbf{p} = [r_a \quad D \quad H \quad x_d \quad x_q \quad x'_d \quad x''_d \quad x''_q \quad T'_{do} \quad T''_{do} \quad T''_{qo}] \tag{5}$$

$$\mathbf{y} = [P_e \quad Q_e] \tag{6}$$

Functions $\mathbf{f}$, $\mathbf{g}$ and $\mathbf{h}$ are non-linear, continuous and satisfy the *Lipschitz* condition. The set ((2a), (2b)), together with initial conditions constitute an Initial Value Problem (IVP). The IVP solution is obtained by numerical integration methods. The system performance can be evaluated by the time solution of the system variables, for a given initial condition following system disturbances.

2.2. Use of PMU and hybrid dynamic simulation

PMUs provide synchronized phasors in time through the use of satellites signals (GPS). The synchronization uses the concept of *absolute phasor* which depends on the nominal system frequency (50 or 60 Hz) [25]. One advantage of PMU data is the continuous monitoring of natural disturbances, avoiding the need to perform tests under specific operating conditions. However, the measurements are subjected to noise and phasor estimation errors. Consequently, these errors affect the applications that employ the measurements.

2.2.1. Hybrid dynamic simulation

The HDS consists in the injection of measurements in simulation programs. Therefore, in the solution of the problem (2a) by HDS, outputs, differential states and algebraic variables vectors (x,y,z) are functions of simulated and measured variables [26].

The validation of dynamic models is based on the comparison between simulated and measured variables. The use of HDS decouples the identified subsystem from the rest of the system, since all the variables at the connection point are measured, reducing the dependence on the system operating conditions and event sequence and improving the simulation accuracy [26].

The terminal voltage magnitude and angle are measured and therefore the direct and quadrature axes components of the terminal voltage are given by

$$V_d = V_t \sin(\delta - \theta_t) \tag{7a}$$

$$V_q = V_t \cos(\delta - \theta_t) \tag{7b}$$