Dynamic State Estimation Based Synchronous Generator Model Calibration Using PMU Data

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***Abstract*— a method for synchronous generator parameter estimation by dynamic state estimation is presented using PMU data. A three phase physically based two-axis generator model with two damper windings is utilized for the dynamic state estimation. Eleven independent parameters are estimated: ten self and mutual inductances of the various windings and the inertia constant. These parameters can be either used for the three phase physically based model or be converted to the usual dq0 synchronous generator model. The proposed method requires time domain three phase sampled data for better estimation accuracy. In the paper, the PMU phasor data with disturbance provided by NERC was converted to three phase sampled data first and then they were fed into the dynamic state estimation. The comparison between the calibrated parameters and the actual parameters provided by NERC is shown to prove the effectiveness of the proposed method. The accuracy of the proposed method can be greatly improved if the three phase sampled value data are provided at the generator three phase terminals, the exciter and the governor.**

***Index Terms*- Generator parameter estimation, dynamic state estimation, PMU data, synchronous generator modeling**

I. INTRODUCTION

AS one of the most expensive and important power apparatus in the power system, the performance of synchronous generators needs to be analyzed and studied very carefully under normal and faulty conditions. An accurate synchronous generator model is essential to achieve this goal. In addition, a high fidelity generator model can also bring huge benefits to any model based generator protection function. However, obtaining the accurate synchronous generator model is always challenging because of the fact that the generator parameters are not exactly the same as the manufacturer provided data. Aging, saturation or temperature may also change the parameters slightly.

Many studies have been done to seek the best way to estimate the generator parameters. IEEE released Standard Procedures and Guide to obtain the synchronous generator parameters in [1], [2]. However, these methods can only be applied for the generator during offline status. When the generator is put into operation, the parameters may change again. Some other online approaches have been proposed by researchers in [3]-[6]. In [3], operational data from both steady state and disturbance operation are utilized to estimate the generator parameters. Reference [4] uses the least square algorithm to perform the parameter estimation from experimental data. In [5], measurements from a hydro unit are used to extract the generator and exciter parameters. Reference [6] uses a simplified discrete auto-regression with an exogenous input model. Since it is a simplified model, it cannot represent the electromagnetic.

Among all the generator parameter estimation literatures (including [3]-[5]), most of them use the common synchronous generator dq0 model. The widely-used dq0 model is derived from the actual three phase model after applying Park's transformation. The application of Park's transformation reduces the three AC quantities to three DC quantities. In addition, it decouples the equations. Thus, the calculation can be simplified. However, the Park's transformation is carried out based on the assumption that the reference frame rotates at synchronous speed. So when frequency changes and there are imbalances, the dq0 model loses accuracy which is also amplified under asymmetrical or unbalanced generator conditions (which is quite normal when internal faults occur in the generator). The three phase physically based model is leveraged in this paper. This model is derived based on the circuits of self and mutual inductance of the stator and rotor windings. The advantage of this model is huge including the capability of simulating unbalanced loads or asymmetrical faults. The model is more complicated than the dq0 model, thus the computation burden is heavier. But present computer hardware is powerful enough to handle this kind of calculation.

In this paper, the dynamic state estimation method is utilized to estimate the synchronous generator parameters. Dynamic state estimation computes the unknown states based on the measurements and the model. Eleven independent generator parameters are treated as unknown states in the generator model so that accurate parameters can be provided by the dynamic state estimation. To increase the estimation accuracy, sampled value measurements are preferred. With more and more merging units deployed in the power system, measurements with sampling rate of 4800 samples/second (IEC-61850 standard) can be expected. Recently, Georgia Tech was invited to participate in a synchronous generator model calibration workshop organized by NERC. The provided data is PMU phasor data with the sampling rate of 90 samples/second. The conversion from PMU data to sampled value data is shown in the paper.

The organization of this paper is as follows: In Section II, the derivation of synchronous generator model with parameters is described. In Section III, dynamic state estimation based parameter estimation algorithm is introduced. In Section IV, the estimated parameters for the NERC provided case are presented and the comparison with the corrupt parameters as well as the actual parameters is shown as well. Section V draws the conclusions.

II. Derivation of Synchronous Generator Model with Parameters

This section presents the three phase physically based synchronous generator model. It is capable of simulating unbalanced conditions or internal faults of the generator.

A. *Synchronous Generator Quadratized Model*

The physical circuit of the two-axis synchronous generator with two damper windings is shown in Figure 1.

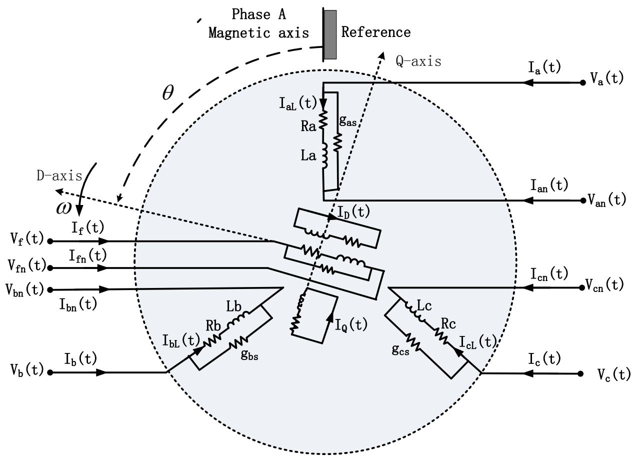

Figure 1. Circuit model of two-axis synchronous generator

The synchronous generator dynamic mathematical model is derived from the above physical circuit. It consists of a set of algebraic and differential equations. The model is as follows:

$$i_{abc}(t) = i_{aL\ bL\ cL}(t) + g_{as,bs,cs}\cdot(v_{abc}(t) - v_{an\ bn\ cn}(t))$$
$$i_{an\ bn\ cn}(t) = -i_{aL\ bL\ cL}(t) + g_{as,bs,cs}\cdot(v_{an\ bn\ cn}(t) - v_{abc}(t))$$
$$i_f(t) = i_{fL}(t) + g_{fs}\cdot(v_f(t) - v_{fn}(t))$$
$$i_{fn}(t) = -i_{fL}(t) + g_{fs}\cdot(v_{fn}(t) - v_f(t))$$
$$T_m(t) = J d\omega_m(t)/dt + T_e(t) + T_{wf}(t)$$
$$0 = v_{abc,f}(t) - v_{an\ bn\ cn,fn}(t) - R_{abc,f}\, i_{aL\ bL\ cL,fL}(t) + e_{abc,f}(t)$$
$$0 = R_{DQ} i_{DQ}(t) + e_{DQ}(t)$$
$$0 = d\theta_m(t)/dt - \omega_m(t)$$
$$0 = d\lambda_{abc,fDQ}(t)/dt - e_{abc,fDQ}(t)$$
$$0 = T_{wf}(t) - \left(D_{fw} + D'_{fw}\cdot\omega_m(t) + D''_{fw}\cdot\omega_m(t)^2\right)$$
$$0 = P_{em}(t) - e_{abc}(t)^T i_{aL\ bL\ cL}(t)$$
$$0 = P_{em}(t) - T_e(t)\cdot\omega_m(t)$$
$$0 = -\begin{bmatrix}\lambda_{abc}(t)\\ \lambda_{fDQ}(t)\end{bmatrix} + \begin{bmatrix}L_{ss}(\theta(t)) & L_{sr}(\theta(t))\\ L_{rs}(\theta(t)) & L_{rr}\end{bmatrix}\cdot\begin{bmatrix}-i_{aL\ bL\ cL}(t)\\ i_{fL\ DQ}(t)\end{bmatrix}$$

The state variables in the above model are: $v_{abc}(t)$, stator terminal phase voltage; $v_{an\ bn\ cn}(t)$, stator neutral point voltage; $v_f(t)$, rotor field winding terminal voltage; $v_{fn}(t)$, rotor field winding neutral voltage; $\omega_m(t)$, mechanical speed; $i_{aL\ bL\ cL}(t)$, inductance current of stator; $i_{fL}(t)$, inductance current of rotor field winding; $i_{DQ}(t)$, rotor d,q axis damper winding current; $i_{DQ}(t)$, rotor d,q axis damper winding current; $\theta(t)$, electrical rotor position angle; $\omega(t)$, electrical speed; $e_{abc}(t)$, electromotive force of stator winding; $e_{fDQ}(t)$, electromotive force of field & damper winding; $T_{wf}(t)$, windage and friction torque; $P_{em}(t)$, electrical power; $T_e(t)$, electrical torque; $\lambda_{abc}(t)$, flux linkage through stator winding; $\lambda_{fDQ}(t)$, flux linkage through field & damper winding.

B. *Synchronous Generator Independent Parameters*

The independent parameters of the synchronous generator are summarized in Table 1.

Table 1. Generator Independent Parameters

Parameters	Description
L_s	Stator self-inductance constant part
L_m	Stator self-inductance varying part
L_f	Field self-inductance
L_D	D damper self-inductance
L_Q	Q damper self-inductance
M_S	Stator mutual inductance
M_F	Field D damper mutual inductance
M_R	Stator field mutual inductance
M_D	Stator D damper mutual inductance
M_Q	Stator Q damper mutual inductance
H	Generator inertia constant

The above parameters are treated as states for the synchronous generator model when performing the parameter estimation. The related coefficients and matrices appearing in the generator model, which are J, $L_{ss}(\theta(t))$, $L_{sr}(\theta(t))$ and L_{rr}, are expressed as functions of the eleven independent parameters.

$$L_{ss} = \begin{pmatrix} L_{aa} & L_{ab} & L_{ac}\\ L_{ba} & L_{bb} & L_{bc}\\ L_{ca} & L_{cb} & L_{cc}\end{pmatrix},\ L_{rr} = \begin{pmatrix} L_{ff} & L_{fD} & L_{fQ}\\ L_{Df} & L_{DD} & L_{DQ}\\ L_{Qf} & L_{QD} & L_{QQ}\end{pmatrix}$$

$$L_{sr} = -L_{rs} = \begin{pmatrix} L_{af} & L_{aD} & L_{aQ}\\ L_{bf} & L_{bD} & L_{bQ}\\ L_{cf} & L_{cD} & L_{cQ}\end{pmatrix},\ 0 = J(t) - \frac{2H(t)\cdot S_{base}}{\omega_s}$$

where, $L_{aa} = L_s(t) + L_m(t)\cos\left(2\theta(t)\right)$

$L_{ab} = L_{ba} = -M_S(t) - L_m(t)\cos 2\left(\theta(t) + \pi/6\right)$

$L_{af} = L_{fa} = M_F(t)\cos\theta(t)$,

$L_{aD} = L_{Da} = M_D(t)\cos\theta(t)$

$L_{aQ} = L_{Qa} = M_Q(t)\cos\left(\theta(t) - \pi/2\right)$,

$L_{ff} = L_f(t),\ L_{DD} = L_D(t),\ L_{QQ} = L_Q(t)$,

$L_{fD} = L_{Df} = M_R(t),\ L_{DQ} = L_{QD} = 0,\ L_{Qf} = L_{fQ} = 0$

Phase B and phase C are 120° and 240° apart (spatially) from phase A. Their expressions are not listed here due to the space limitation.

C. Synchronous Generator Quadratized Model with Parameters

By combining the generator model in Section A and the equations in Section B, the synchronous generator quadratized model with parameters can be obtained. A generalized format is used here to represent the model:

$$i(t) = Y_{eqx1}\mathbf{x}(t) + D_{eqxd1}\frac{d\mathbf{x}(t)}{dt} + C_{eqc1}$$

$$0 = Y_{eqx2}\mathbf{x}(t) + D_{eqxd2}\frac{d\mathbf{x}(t)}{dt} + C_{eqc2}$$

$$0 = Y_{eqx3}\mathbf{x}(t) + \begin{Bmatrix} \vdots \\ \mathbf{x}(t)^T \left\langle F^i_{eqxx3} \right\rangle \mathbf{x}(t) \\ \vdots \end{Bmatrix} + C_{eqc3}$$

where, matrices *Y* are linear term coefficients, matrices *D* are linear differential term coefficients, matrices *F* are quadratic term coefficients, vectors *C* are constants, vector $\mathbf{x}$ is the state variables, vector *i* is terminal currents and *(t)* stands for time stamp *t* (other time stamps will be introduced later).

The generalized model has three sets of equations. The first set is the equations for the interface current. The second and third sets are linear and nonlinear internal equations, respectively. The synchronous generator model is easy to be written in the above format by introducing additional states. The final states of the generator include both the generator internal electrical states and independent parameters.

D. Synchronous Generator AQCF Model with Parameters

Quadratic integration method is applied to eliminate the differential terms in the quadratized model. Quadratic integration is based on a numerical integration scheme that assumes the model states vary quadratically within a time step h [7]. The state values at time stamp *t-h* and t_m (intermediate time stamp of *t* and *t-h*) are introduced by this integration method. The model after the quadratic integration is referred as algebraic quadratic companion form (AQCF) [8] and it is shown below:

$$\begin{Bmatrix} i(t) \\ 0 \\ 0 \\ i(t_m) \\ 0 \\ 0 \end{Bmatrix} = Y_{eqx}\mathbf{x}(t,t_m) + \begin{Bmatrix} \vdots \\ \mathbf{x}(t,t_m)^T \left\langle F^i_{eqx} \right\rangle \mathbf{x}(t,t_m) \\ \vdots \end{Bmatrix} + C_{eq}$$

$$C_{eq} = N_{eqx}\mathbf{x}(t-h) + M_{eq} i(t-h) + K_{eq}$$

where: $i(t),\ i(t_m)$ are currents that flow into the device at two adjacent time instances *t* and time t_m; $x(t),\ x(t_m)$ are state variables of the AQCF model at time *t* and time t_m; Y_{eqx} is linear term coefficients; F_{eqx} is quadratic term coefficients; C_{eq} is past history part; N_{eqx} is past history linear term coefficients; M_{eq} is past history current term coefficients; K_{eq} is past history constants. The coefficient matrices can be derived from the quadratized model.

$$Y_{eqx} = \begin{bmatrix} \frac{4}{h}D_{eqxd1} + Y_{eqx1} & -\frac{8}{h}D_{eqxd1} \\ \frac{4}{h}D_{eqxd2} + Y_{eqx2} & -\frac{8}{h}D_{eqxd2} \\ Y_{eqx3} & 0 \\ \frac{1}{2h}D_{eqxd1} & \frac{2}{h}D_{eqxd1} + Y_{eqx1} \\ \frac{1}{2h}D_{eqxd2} & \frac{2}{h}D_{eqxd2} + Y_{eqx2} \\ 0 & Y_{eqx3} \end{bmatrix} \quad N_{eqx} = \begin{bmatrix} -Y_{eqx1} + \frac{4}{h}D_{eqxd1} \\ -Y_{eqx2} + \frac{4}{h}D_{eqxd2} \\ 0 \\ \frac{1}{2}Y_{eqx1} - \frac{5}{2h}D_{eqxd1} \\ \frac{1}{2}Y_{eqx2} - \frac{5}{2h}D_{eqxd2} \\ 0 \end{bmatrix}$$

$$F_{eqx} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ F_{eqxx3} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & F_{eqxx3} \end{bmatrix} \quad M_{eq} = \begin{bmatrix} I_{size(i(t))} \\ 0 \\ 0 \\ \frac{1}{2}I_{size(i(t))} \\ 0 \\ 0 \end{bmatrix} \quad K_{eq} = \begin{bmatrix} 0 \\ 0 \\ C_{eqc3} \\ \frac{3}{2}C_{eqc1} \\ \frac{3}{2}C_{eqc2} \\ C_{eqc3} \end{bmatrix}$$

II. Dynamic State Estimation Based Parameter Estimation Algorithm

This section presents the parameter estimation algorithm using dynamic state estimation. The dynamic state estimation computes the states based on the measurements and the model. From the above generator AQCF model, any measurement can be written as follows [9]:

$$z = h(x) + \eta = \sum_i a_{i,x} \cdot x_i + \sum_{i,j} b_{i,j,x} \cdot x_i \cdot x_j + c + \eta$$

In the paper, the weighted least square (WLS) method is used to perform the dynamic state estimation. WLS method tries to find the best estimate for the states that generate the minimum weighted squared error. The optimization problem is as follows:

$$Minimize \quad J = \sum_i \left(\frac{h_i(\mathbf{x}) - z_i}{\sigma_i} \right)^2 = \sum_i s_i^2 = \boldsymbol{\eta}^T W \boldsymbol{\eta}$$

where, $s_i = \eta_i / \sigma_i$, $W = diag\{..., 1/\sigma_i^2, ...\}$, z_i is the measurement value. σ_i is standard deviation of each measurement, which is the noise of the meter and *W* is the diagonal matrix whose diagonal non-zero entries are the inverse of the measurement variance.

The solution is given with the Newton's iterative algorithm:

$$\mathbf{x}^{\nu+1} = \mathbf{x}^{\nu} - (H^T W H)^{-1} H^T W (\mathbf{h}(\mathbf{x}^{\nu}) - \mathbf{z})$$

where *H* is the Jacobean matrix: $H = \partial \mathbf{h}(\mathbf{x}) / \partial \mathbf{x}$

Once the solution is calculated, chi-square value is computed. The chi-square test quantifies the goodness of fit between the model and measurements by providing the probability that the measurements are consistent with the dynamic model. The chi-square value is computed with the equation below:

$$\xi = \sum_{i=1}^{n} \left(\frac{h_i(\mathbf{x}) - z_i}{\sigma_i} \right)^2$$

It is obvious that a low chi-square value indicates the measurements highly fit the model and the states including the parameters are estimated accurately. A high chi-square value means the measurements and model are not aligned, thus the states in this condition may not be accurate.

IV. Demonstration Case Provided By NERC

Recently Georgia Tech was invited to participate in a generator model calibration workshop launched by NERC. The purpose of this workshop is to find a good way to estimate the generator parameters. NERC provided the PMU phasor measurements and the corrupt model parameters. This section shows the tuned parameters by applying the proposed algorithm.

A. *Test System*

The test system consists of a synchronous generator, a transformer and an equivalent external system. The PMU measurements are taken at the high side of the step-up transformer side as shown in Figure 2.

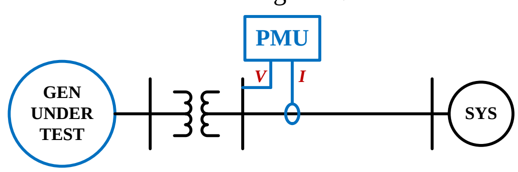

Figure 2. Test system and measurement location

The measurements are bus voltage magnitude, voltage angle, bus frequency, active power and reactive power with sampling rate of 90 samples/second. The case is 90 seconds long and Figure 3 is a graphical presentation of all measurements.

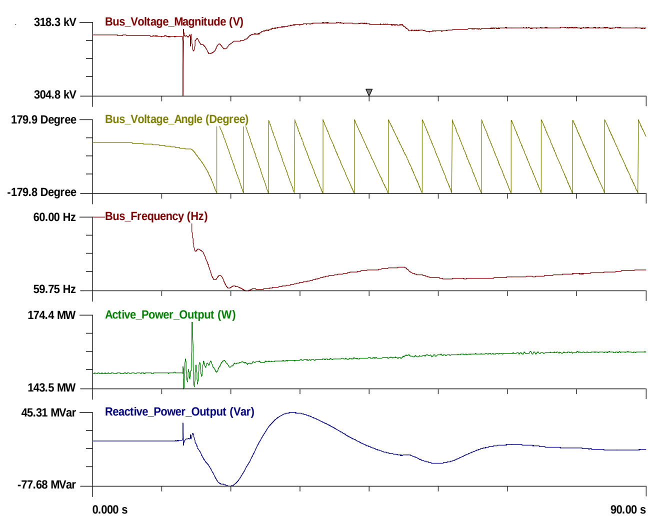

Figure 3. Graphical presentation of the provided measurements

B. *Measurements Conversion*

Since our method requires three phase sampled value data at the generator side, the provided phasor measurements at the step-up transformer side are converted to three phase data at the generator terminal first (via the model of the step-up transformer) and then the three phase measurements are converted to sampled values at 4800 samples per second. This calculation is straightforward according to the basic power system analysis, so the final results from time 10.0 second to 10.1 second are illustrated in Figure 4.

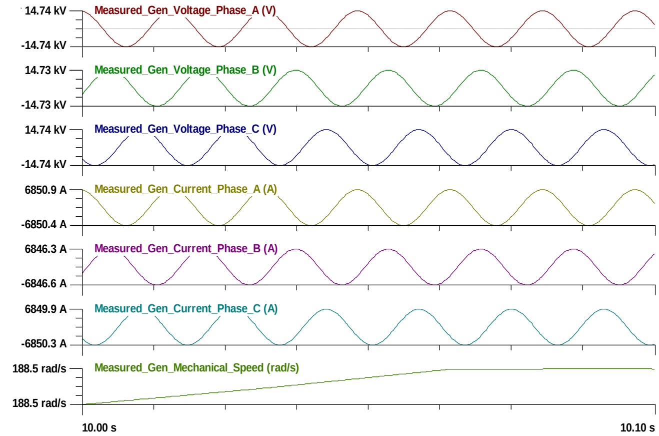

Figure 4. Sampled value data of the generator terminal measurements from time 10.0s to 10.1s

C. *Dynamic State Estimation with Provided Parameters*

NERC provided some corrupt parameters and these parameters are used for the dynamic state estimation in this section. The results are shown in Figure 5.

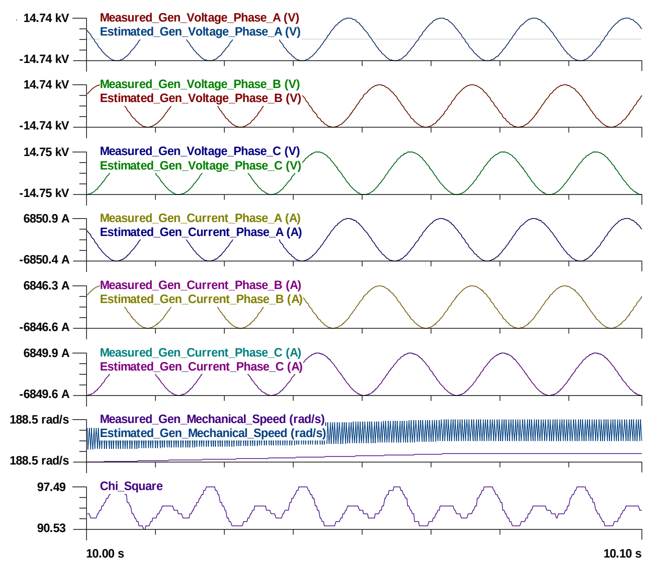

Figure 5. Dynamic state estimation results using provided parameter from time 10.0s to 10.1s

The figure shows the estimated and measured measurements at generator terminals and the chi-square value. It can been seen that using the provided parameters, the chi-square value is very large, which means the model does not fit the measurements well.

D. *Dynamic State Estimation with Tuned Parameters*

The dynamic state estimation is performed for the generator model with the eleven parameters added to the states of the generator. The results with the tuned parameters model are shown in Figure 6.

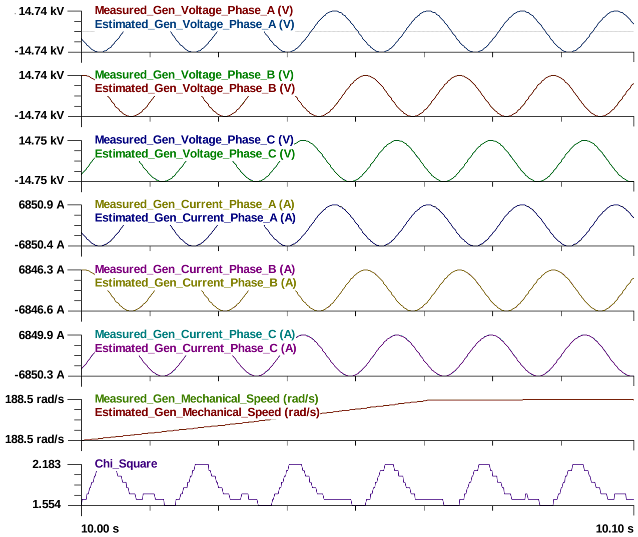

Figure 6. Dynamic state estimation results using tuned parameter from time 10.0s to 10.1s

Compared with the above case, the chi-square value is much smaller using the tuned parameters, which means the measurements fit the model well and the estimated parameters are accurate enough.

E. Model Calibration Summary

During the workshop, NERC released the actual values of the generator. Since NERC uses the dq0 model parameters, our estimated physical parameters are also converted to the dq0 parameters for easy comparison. The parameter conversion steps are not shown here and it can be found in any machine analysis book. The results are listed in Table 2.

Table 2. Summary of actual, corrupt and tuned parameters

Parameter	Actual	Corrupt	Estimated
Xd	1.85	1.85	1.75
X'd	0.21	0.21	0.21
X"d	0.15	0.15	0.15
Xq	1.8	1.3	1.7
X'q	0.45	0.7	0.6
X"q	0.15	0.15	0.2
Xl	0.15	0.15	0.15
T'd0	6.5	5	9.5
T"d0	0.05	0.25	0.12
T'q0	1	1	1
T"q0	0.05	0.05	0.08
H	6	3.1	6

From the table, it can be seen that compared to the corrupt parameters, the calibrated parameters are close to the actual parameters in the correct direction (highlighted in the table). Although some of the parameters are still not exactly the same as the actual values, the calibrated model is still more suitable to the measurements.

The reasons that cause the imperfect parameter estimation are (1) only phasor measurements are available at the high side of the step-up transformer and we had to convert the phasor measurements to three phase sampled value based on the assumption that the three phases are balanced, and (2) no measurements are available at the exciter and governor terminal sides. For best performance of the proposed method for generator parameter identification, these measurements are required. If there were three phase generator terminal measurements, exciter and governor measurements, the generator parameters can be estimated more accurately.

It should be noted that initially we understood that the generator inertia was not corrupted and it was not included in the parameters to be estimated. This resulted in slightly larger errors of the ten estimated parameters. These results are available in the NERC report.

V. Conclusions

This paper introduces a dynamic state estimation based generator parameter estimation method. It uses the three phase physically based model which is capable of simulating unbalanced conditions and asymmetrical internal faults. The three phase model can also be converted to the common dq0 model if necessary. The proposed method prefers sampled value measurements with high sampling rate. It can also work with PMU phasor data. The test case provided by NERC shows the effectiveness of the proposed method using PMU phasor data. It should be noted that the proposed method works better when more measurements and high frequency sampled value measurements are available.

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