O identifikaciji parametrov sinhronskega generatorja med obratovanjem z uporabo linearnega ekvivalenta

GORAZD BONE, URBAN RUDEŽ & RAFAEL MIHALIČ

Povzetek V članku je obravnavana zmožnost identifikacije parametrov sinhronskega generatorja iz dinamičnih meritev na priključnih sponkah z uporabo linearnega ekvivalenta. Predstavljena je metoda, ki to izvede z izčrpnim pregledovanjem. Uporabljeni model generatorja ima po dve dušilni navitji na vsaki od osi rotorjev. Ker so meritve izvedene na priključnih sponkah je dinamika rotorjevega kota in vrtilne hitrosti nepoznana. Za namen študije se je simuliralo delovanje sinhronskega generatorja priključenega na togo mrežo. V simulaciji se je vzbujalna napetost stopničasto spremenila. Za iskanje parametrov sinhronskega generatorja je bilo uporabljeno izčrpno preiskovanje možnih parametrov, saj se s to metodo lahko najde vse možne kombinacije parametrov, ki zadovoljujejo kriterije identifikacije. Ob ugotovitvi, da nekateri parametri ne vplivajo na nekatere merjene signale, se je pojavila možnost uporabe razcepljene identifikacije. Brez omenjene razcepitve izčrpna metoda iskanja ne bi bila izvedljiva. Ker je bilo v študiji ugotovljeno, da zelo različni parametri dajejo zelo podobne rezultate za dinamične signale avtorji zaključijo, da parametrov modela generatorja osmega reda ne moremo identificirati z identifikacijskimi metodami, ki uporabljajo linearne ekvivalente.

Ključne besede: • identifikacija • parameter • sinhronski generator • linearni ekvivalent • meritev •

NASLOV AVTORJEV: Gorazd Bone, mladi raziskovalec, Univerza v Ljubljani, Fakulteta, za elektrotehniko, Tržaška cesta 25, 1000 Ljubljana, Slovenija, e-pošta: gorazd.bone@fe.uni-lj.si. dr. Urban Rudež, docent, Univerza v Ljubljani, Fakulteta, za elektrotehniko, Tržaška cesta 25, 1000 Ljubljana, Slovenija. dr. Rafael Mihalič, redni profesor, Univerza v Ljubljani, Fakulteta, za elektrotehniko, Tržaška cesta 25, 1000 Ljubljana, Slovenija.

https://doi.org/10.18690/978-961-286-071-4.17 ISBN 978-961-286-071-4

Dostopno na: http://press.um.si.

On-Line Identifiability of a Synchronous Generator by Linearized Equivalent

GORAZD BONE, URBAN RUDEŽ & RAFAEL MIHALIČ

Abstract In this paper the identifiability of synchronous generator's parameters from time domain measurements at the terminals using a linearized equivalent is examined and a decoupled brute force algorithm for identification is presented. The generator model has two windings on both, the quadrature and the direct axis of the rotor. Measurements are carried out at the terminals; therefore the instantaneous values for rotor's angle and rotational speed are unknown. A synchronous generator operating in a single machine infinite bus (SMIB) system was simulated. Field voltage was simulated to undergo a rectangular pulse change and the electrical quantities at the generator's terminals were measured. To search the values of generator's parameters brute force algorithm was used, since it provides an insight into all possible parameter sets which satisfy the identification criteria. After it has been established that some measured variables are insensitive to changes of certain parameters, a multistage approach was justified; without it, brute force search would not be feasible. Since the dynamics obtained with various parameter sets nearly coincides with that of the original simulation it is concluded that the synchronous generator's parameter identification using the eighth order model in a linearized set up is not generally possible.

Keywords: • identifiability • parameter • synchronous generator • linearized equivalent • measurement •

CORRESPONDENCE ADDRESS: Gorazd Bone, Researcher, University of Ljubljana, Faculty of Electrical Engineering, Tržaška cesta 25, 1000 Ljubljana, Slovenia, e-mail: gorazd.bone@fe.uni-lj.si. Urban Rudež, Ph.D., Assistant Professor, University of Ljubljana, Faculty of Electrical Engineering, Tržaška cesta 25, 1000 Ljubljana, Slovenia. Rafael Mihalič, Ph.D., Full Professor, University of Ljubljana, Faculty of Electrical Engineering, Tržaška cesta 25, 1000 Ljubljana, Slovenia.

https://doi.org/10.18690/978-961-286-071-4.17 ISBN 978-961-286-071-4

Available at: http://press.um.si.

1 Introduction

Identifying the parameters of a synchronous generator from online measurement, as an alternative to standstill testing in which the generator needs to be put offline, is a research topic that has been given much attention both in the field of research [1]–[15] and industry [16], [17]. The general approach in time domain identification is to apply a disturbance to the device, measure an input and an output and estimate the values of the model's parameters by analyzing relations between the two at different times [18], [19]. Normally, a vector made up of differences between the measured and the modeled output at matching times is constructed. Identification minimizes this error vector in some, usually second, norm sense.

The observed synchronous generator model is nonlinear. Although there are cases where the identification scheme regards nonlinearities directly [10], [11], [13], it is often the case that the model is linearized and a linear identification scheme is used. The advantage of linearization is in simplifying the identification and the justification for using a linearized identification scheme is in the fact that a synchronous machine to be identified should not be brought to disturbances large enough to forbid linearization in normal operation.

The input variables for a synchronous generator are the mechanical torque and the field voltage. In the identification process only the field voltage is normally taken as the input and the system is regarded as a SISO (Single Input Single Output) system. This is justified by the longer time constants present in the mechanical system. The disturbance applied was a field voltage perturbation. If a direct change to the field voltage was to be done in practice the excitation controller would need to be bypassed. Otherwise the field voltage controller would have to be included in the identified model.

A generator operating in a SMIB system was considered. A series of linear simulations with various parameters sets was performed and the responses were compared to the response of the original nonlinear simulation. Although it might be better to apply white noise as the input disturbance and operate with a long duration of the dynamics observed, the disturbance considered in this work was a rectangular pulse; which we believe to be more easily reproduced in reality, and the duration of dynamics observed was 6 seconds; which must be short enough to suppose there were no changes in the power system which would affect the dynamical response. The amplitude of the field voltage pulse is 0.1 percent of initial value, which is so small it might be impossible to achieve in reality and its effects on the active power dynamics difficult to measure. The small size of the perturbation was to minimize the linearization error and to analyze identifiability with regards to modeling error alone. With larger perturbations linearization would provide additional error which would further hinder identifiability. Having observed that different sets of parameters produce similar results the brute force search was decided upon since it enables finding the parameter sets which correspond to the dynamics. The brute force search feasibility was eased noting that all parameters do not influence all measurements which enabled a multistage approach.

2 Technical work preparation

2.1 Synchronous Generator Model

The generator's parameters were taken from [20] with a small resistance added to the stator's coils. The inertia constant was 2.89 *s* and the electrical parameters were as shown in Table 17.1.

In [20] the equivalent circuit parameters are directly provided, the inertia constant H however was obtained by summing all the inertias present on the shaft. The generator was connected directly to an infinite bus, loaded with 0.2 pu active and 0.1 pu reactive power load. The synchronous generator model used has two coils in each of the two, the direct and the quadrature, axis of the rotor's equivalent circuit. This model has been chosen because it is most commonly used in power system simulation studies since sub-synchronous resonance effect was first documented [21]. Saturation effects were neglected and the inductance matrix was constant. Upon transforming it into the d-q rotating system and neglecting the zero component, the voltage equation, with time dependence not indicated, is as in [22]:

$$\mathbf{U}_{\mathrm{dq}} = \dot{\mathbf{\Psi}}_{\mathrm{dq}} / \omega_{\mathrm{s}} + \mathbf{R}_{\mathrm{dq}} \cdot \left(\mathbf{L}_{\mathrm{dq}}\right)^{-1} \cdot \mathbf{\Psi}_{\mathrm{dq}} - \mathbf{S} \cdot \omega_{\mathrm{r}} \cdot \mathbf{\Psi}_{\mathrm{dq}}, \tag{1}$$

where $\mathbf{S}$ is a square matrix containing mostly zero inputs with the values +1 and –1 being present at only two places corresponding to the ordering of vectors $\mathbf{\Psi}_{\mathrm{dq}}$ and $\mathbf{U}_{\mathrm{dq}}$. In (1) all variables are taken in pu apart from time, which is in seconds. If time were taken in pu [22] with base equal to $1/\omega_{\mathrm{s}}$, the equation would simplify into

$$\mathbf{U}_{\mathrm{dq}} = \dot{\mathbf{\Psi}}_{\mathrm{dq}} + \mathbf{R}_{\mathrm{dq}} \cdot \left(\mathbf{L}_{\mathrm{dq}}\right)^{-1} \cdot \mathbf{\Psi}_{\mathrm{dq}} - \mathbf{S} \cdot \omega_{\mathrm{r}} \cdot \mathbf{\Psi}_{\mathrm{dq}}. \tag{2}$$

Despite this possible simplification (1) was used in this work considering time is more informative if taken in seconds than in a more abstract pu value. From (1) follows

$$\dot{\mathbf{\Psi}}_{\mathrm{dq}} = \left[\mathbf{S} \cdot \omega_{\mathrm{r}}(\mathrm{t}) - \mathbf{R}_{\mathrm{dq}} \cdot \left(\mathbf{L}_{\mathrm{dq}}\right)^{-1}\right] \cdot \omega_{\mathrm{s}} \cdot \mathbf{\Psi}_{\mathrm{dq}} + \mathbf{U}_{\mathrm{dq}} \cdot \omega_{\mathrm{s}}. \tag{3}$$

Eq. (3) is a state space representation in the sense

$$\dot{\mathbf{\Psi}}_{\mathrm{dq}} = \mathbf{A} \cdot \mathbf{\Psi}_{\mathrm{dq}} + \mathbf{B} \cdot \mathbf{U}_{\mathrm{dq}}. \tag{4}$$

The matrix $\mathbf{A}$ in (4) is not constant as can be seen from (3) and so, the system is nonlinear. Equation (4) describes the electrical states. Two additional equations are needed to obtain a full description, the time derivatives of the speed and the angle. The speed of rotation has the derivative

$$\dot{\omega}_{\mathrm{r}} = \frac{\left(T_{\mathrm{m}} - T_{\mathrm{e}}\right)}{2H}, \tag{5}$$

where T_{e} follows the equation:

$$T_{\mathrm{e}} = I_{\mathrm{q}} \Psi_{\mathrm{d}} - I_{\mathrm{d}} \Psi_{\mathrm{q}}, \tag{6}$$

where I_{d}, I_{q}, Ψ_{d} and Ψ_{q} are currents and fluxes in d and q axis respectively. The rotor angle has the following derivative

$$\dot{\delta} = (\omega_{\mathrm{r}} - 1) \cdot \omega_{\mathrm{s}}. \tag{7}$$

The final relations required in above equations are (8) and (9)

$$\mathbf{I}_{\mathrm{dq}} = \left(\mathbf{L}_{\mathrm{dq}}\right)^{-1} \cdot \mathbf{\Psi}_{\mathrm{dq}} \tag{8}$$

$$\mathbf{U}_{\mathrm{dq}} = U_{\mathrm{T}} \cdot \sqrt{\frac{3}{2}} \cdot \begin{bmatrix} -\sin(\delta) \\ \cos(\delta) \end{bmatrix}, \tag{9}$$

where U_{T} stands for the amplitude of voltages of a symmetric three-phase infinite source.

Table 17.1
Parameters of synchronous generator

Param.	L_{ad}	L_{aq}	L_{σ}	R_{S}	$L_{\mathrm{F\sigma}}$	$L_{\mathrm{D\sigma}}$	$L_{\mathrm{Q\sigma}}$	$L_{\mathrm{G\sigma}}$	R_{D}	R_{F}	R_{Q}	R_{G}
Value [pu]	1.66	1.58	0.13	10^{-3}	0.062	$55 \cdot 10^{-4}$	0.326	0.095	$\frac{1.54}{120\pi}$	$\frac{0.53}{120\pi}$	$\frac{5.3}{120\pi}$	$\frac{3.1}{120\pi}$

2.2 Synchronous Generator's SMIB Simulation Scheme

Equations (3) and (5) through (9) define the dynamics of the machine. As they form a nonlinear system, a nonlinear integration scheme must be used. A predictor-corrector approach was used for simulation in our study [23], with Euler's explicit method being the predictor and trapezoidal rule the corrector. The integration step was constant. Although it would be possible to compose a single matrix equation for the model and then use the predictor-corrector scheme over it, it is recommended that a separate variable, with a slower dynamics, is taken as the predictor and the corrector is then iterated with that value taken in its first run [24], [25], [26]. With a numerical integration setup it is possible to obtain the values of generator's state variables in the next time step ($t + \Delta t$), provided the values at current time (t) are known. The setup used in our work is described below:

1. Predict ω_{r} at time $t + \Delta t$ from (5) by explicit Euler.
2. Store calculated speed into a designated variable.
3. Calculate δ at $t + \Delta t$ from (7) by Trapezoidal rule.
4. Calculate $\mathbf{\Psi}_{\mathrm{dq}}$ at $t + \Delta t$ from (3) by Trapezoidal rule.
5. Calculate electrical torque at $t + \Delta t$ from (6).
6. Use (5) to obtain a corrected value for speed by trapezoidal rule considering new value of torque found in step 4 (torque value present at time $t + \Delta t$).
7. Compare values of speed from step 6 with that of step 2; if they coincide within a predetermined tolerance proceed to the next time step of simulation and restart this setup, otherwise return to step 2 of this setup.

It usually requires two iterations at each time step of the simulation, which is the case found also in [25]. By solving the differential equations for their steady states [22] one obtains the initial conditions of the generator, which provide the necessities to start the simulation.

2.3 Synchronous Generator Linearization

Obtaining linear block diagrams has been regarded as useful when analyzing power system dynamics with automatic voltage regulator (AVR) and power-system stabilizer (PSS) included. Some research papers on the topic are available [27]–[30], however, the references found model the machine using nameplate parameters. As the equivalent circuit model was used in this work, the equations of the equivalent circuit model had to be linearized.

Linearization required the equations to be put into a single matrix equation of which only first order sensitivity was considered [22], [31]. For this purpose, a software package capable of symbolic derivation was used and an expression of the following form was obtained

$$\Delta\dot{\mathbf{V}} = \mathbf{A}_{\text{Total}} \cdot \Delta\mathbf{V} + \mathbf{B}_{\text{Total}} \cdot \Delta v_{\text{F}}, \tag{10}$$

where **V** contains all the variables; magnetic fluxes, speed and angle. The Laplace' transfer function for every state variable [32] can be obtained from

$$\Delta\mathbf{V}(s) = \left(s \cdot \mathbf{I} - \mathbf{A}_{Total}\right)^{-1} \cdot \mathbf{B}_{\text{Total}} \cdot \Delta v_{\text{F}}(s). \tag{11}$$

To solve (11), Matlab's backslash operator was used. Upon having linearized the state variables the transfer functions of measured quantities must be obtained. The identification process then focuses on finding the values of parameters present in this transfer function that mimic the behavior of measurements for given input dynamics. Having supposed the measurement be carried out only at the terminals of the machine the only measurable quantities were the voltages and currents in the "abc" (three phase) frame. The synchronous machine however is modeled in the "dq" frame. The quantity used for identification must have an analytical expression obtainable in both frames. Two such commonly used quantities are the active and reactive powers as seen in Table 17.2, although any other quantity could be used provided its analytical expression can be obtained in both frames.

Table 17.2
PARAMETERS OF SYNCHRONOUS GENERATOR

Quantity	Frame "abc"	Frame "dq"
Active power	$u_a \cdot i_a + u_b \cdot i_b + u_c \cdot i_c$	$u_d \cdot i_d + u_q \cdot i_q$
Reactive power	$(u_a - u_b) \cdot i_c + (u_c - u_a) \cdot i_b + (u_b - u_c) \cdot i_a$	$u_d \cdot i_q - u_q \cdot i_d$

The linearized active and reactive powers are obtained from

$$\begin{aligned} \Delta P_{\text{e}} &= \Delta U_{\text{d}} I_{\text{d0}} + U_{\text{d0}} \Delta I_{\text{d}} + \Delta U_{\text{q}} I_{\text{q0}} + U_{\text{q0}} \Delta I_{\text{q}} \\ \Delta Q_{\text{e}} &= \Delta U_{\text{d}} I_{\text{q0}} + U_{\text{d0}} \Delta I_{\text{q}} - \Delta U_{\text{q}} I_{\text{d0}} - U_{\text{q0}} \Delta I_{\text{d}} \end{aligned}, \tag{12}$$

where a zero in the subindex indicates initial value.

The right hand side in (12) must be expressed in terms of state variables. For this it is necessary to obtain linearized equivalents of voltages and currents from (8) and (9) and insert them into (12). The equation thus obtained must then have the transfer functions of the state variables in (11) inserted. The resulting equation is in the form of

$$\begin{aligned} \Delta P_{\text{e}}(s) &= f_1(s) \cdot \Delta v_{\text{F}}(s) \\ \Delta Q_{\text{e}}(s) &= f_2(s) \cdot \Delta v_{\text{F}}(s) \end{aligned}. \tag{13}$$

Functions f_1(s) and f_2(s) from (13) can be written in the form:

$$f_1(s) = \frac{num_{\text{P}}(s)}{den(s)} \quad , \quad f_2(s) = \frac{num_{\text{Q}}(s)}{den(s)}, \tag{14}$$

The numerators and the denominators of f_1(s) and f_2(s) are polynomials in *s*. For the brute force search their evaluation was sped up by replacing parts of expression more commonly recurring with newly defined variables. Even with the mentioned introduction of variables the expressions required for their evaluation are very extensive and will therefore be omitted from the paper.

2.4 The Identification Scheme

The identification process consists of three stages. At each stage the parameters are varied, the transfer function for these parameters is evaluated, and the response of the transfer function is compared to the original dynamics. If the responses are similar the parameter set is saved for the next stage. After finishing all three stages, the obtained parameter sets corresponded to all considered measurement criteria. The mentioned stages are described below individually.

At the first stage, steady state reactive power amplification caused by field voltage step change was observed. According to the final value theorem [33] the amplification equals the ratio of the terms with zero power of *s*. To confirm that the derived expression is correct one might consider ensuring that any dynamical parameter (resistances and scattering inductances of damping coils or inertia) are absent from it. The parameter sets that best corresponded to the steady state amplification of reactive power, with regards to relative error, were saved.

At second stage, parameters sets to match reactive power dynamics were saved. The second stage of identification rests on the fact that the dynamics of reactive power is virtually unaffected by any changes done to either the damping coil scattering inductances or to the inertia. This is displayed in Figure 17.1 which compares the dynamic responses of the original generator with two other cases, where the generator inertia and damping coil scattering inductances had been greatly changed.

At the third stage of identification the active power dynamics was matched and the corresponding parameters were found. After the third and final stage the parameter combinations that correspond to all three stages of identification procedure were saved.

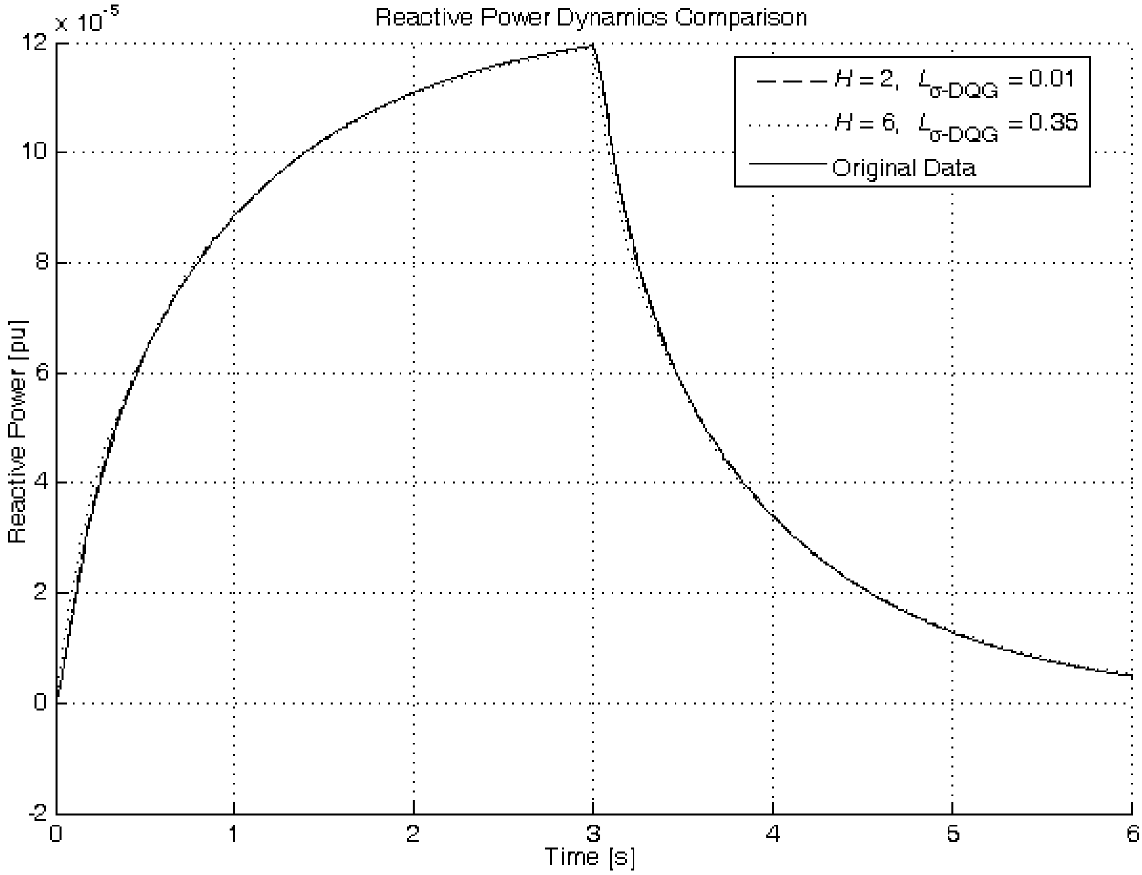

Figure 17.1. Reactive power dynamics comparison with varied inertia constant and damping scattering.

Before the linear simulation at stages 2 and 3 the transfer functions had their orders reduced. The order reduction was carried out by truncation, so that two elements, with highest powers of *s*, of the numerators and denominators in (14) were removed. The denominator's order thus became 6 and the numerator's 5. This truncation caused no visible deviation of dynamical behavior. For the linear simulation, analytical solution (matrix exponential), was used; the transfer functions in (14) were written in observable canonical state space form, the state space matrix was then diagonalized by multiplication with the eigenvector matrices and the matrix exponential was calculated for the diagonalized matrix, which simplifies into a diagonal matrix of exponentials.

2.5 The Parameter Span and Resolution

While the possible values of nameplate parameters are commonly provided in the literature, the same is not true for equivalent circuit parameters. Those parameter spans that can be found in the literature were used while the spans for all other parameters, as well as the resolution, were developed as described below.

The spans for inertia constant, for the stator's resistance and the leakage, as well as the total inductance in both the *d* and the *q* axis of the stator are provided in [22]. From the span of leakage inductance and the span of total inductance the mutual inductance span in both axes was obtained. The field coil resistance was assumed to be known. For this to be possible the field coil current and voltage can be measured directly; the ratio of the two is the field coil resistance. The rest of the parameters spans were decided by briefly reviewing some datasets found in the literature [20],[21], [22].

The values of inertia considered ranged from 2.5 to 6 s with the step of 0.1, the values of leakage inductance ranged from 0.1 to 0.2 pu with the step of 0.01 pu and the values of mutual inductance in the *d* axis ranged from 1 to 2.2 pu with the step of 0.01 pu. The abovementioned steps were decided upon since they correspond to the least significant digit provided in the data while the span is found in [2]. The span of the *q* axis mutual inductance was varied from 80 % to 99% of the mutual inductance in the *d* axis with the step of 1%. The span of the *q* axis mutual inductance was decided by assuming knowledge of rotor's nonsaliency, while the step size was decided upon due to the fact that the dynamics changed only slightly if the parameter changed by that step.

The values considered for the stator's resistance were 0.001, 0.01 and 0.1 pu. The span encompasses that reported in [22] and the step size, a factor of 10, ensured that the dynamics still did not change severely.

The field leakage inductance was varied in the range from 0.035 to 0.49 pu, with the step of 0.035 pu. The damping coil resistances were varied according to the below definition, which pertains to all three damping coils

$$R_{\mathrm{D,Q,G}} = (0.5 \cdot 1.3^{\mathrm{K}}) / \omega_{\mathrm{s}} \ , \ K \in [0,1,...,9] . \tag{15}$$

The damping coils' scattering inductances assumed the following values which again pertain to all three coils

$$\begin{aligned} L_{\sigma-\mathrm{D,G,Q}} = [&.001\ .02\ .04\ .06\ .09\ .12\ .15\ .19... \\ &.23\ .27\ .32\ .37\ .42\ .48\ .54] \end{aligned} . \tag{16}$$

The span of the damping coils' resistances and scattering inductances as well as the field scattering inductance was chosen so that the datasets found are well within the limits considered here and the resolution was decided upon so that the dynamics of the machine of two consecutive parameter values did not differ severely.

3 Results

The number of parameter sets that passed the identification process was over 10'000. The obtained parameter sets ranged very broadly as can be seen in Table 17.3. Figures 17.2 and 17.3 compare the simulated dynamical response of the original generator to the simulation with the parameter sets that had undergone the three identification phases. In Figures 17.2 and 17.3 only the responses of every seventh of the parameter sets were plotted, as the authors had noticed that plotting more responses will not increase the broadness of deviation between compared dynamics, it would however increase computer memory consumption. The two figures show over 1600 curves each. Identifiability can be defined as uniqueness of measured response with regards to a parameter set [34]; in case of system identifiability, if two dynamical responses are identical they have to have been made by the same parameters. In case of a deterministic set up or some known noise this might be accomplishable; however, the difficulty with identifiability becomes clear when possible noise present in a synchronous machine is taken into consideration.

In [35] the authors reviewed the modeling fidelity of a synchronous machine by comparing the rotor angle dynamics of a physical synchronous machine to a simulated equivalent. The authors found some noticeable discrepancy between the two as can be seen from figure 17.4 taken from [35].

Table 17.3
SPAN OF PARAMETERS OBTAINED AFTER PROCEDURE

Parameter	From	To	Correct	Error from, to [%]
L_{ad}	1.61 pu	1.9 pu	1.66 pu	-3.0 , 14.5
L_{aq}	1.41 pu	1.67 pu	1.58 pu	-10.7 , 5.7
L_{σ}	0.12pu	0.18 pu	0.13 pu	-7.7 , 38.5
R_s	10^{-3} pu	10^{-3} pu	10^{-3} pu	0
$L_{F\sigma}$	0.035 pu	0.105 pu	0.062 pu	-43.5 , 69.4
$L_{D\sigma}$	0.001 pu	0.02 pu	0.0055 pu	-81.8 , 263.6
$L_{Q\sigma}$	0.001 pu	0.54 pu	0.326 pu	-99.7 , 65.5
$L_{G\sigma}$	0.001 pu	0.54 pu	0.095 pu	-98.9 , 468.4
R_D	0.0029 pu	0.011 pu	0.0041 pu	-29.0 , 169.3
R_Q	0.0064 pu	0.014 pu	0.0141 pu	-54.5 , 0
R_G	0.0064 pu	0.014 pu	0.0082 pu	-22.2 , 71.5
H	2.7 s	3.1 s	2.8941 s	-6.7 , 10.6

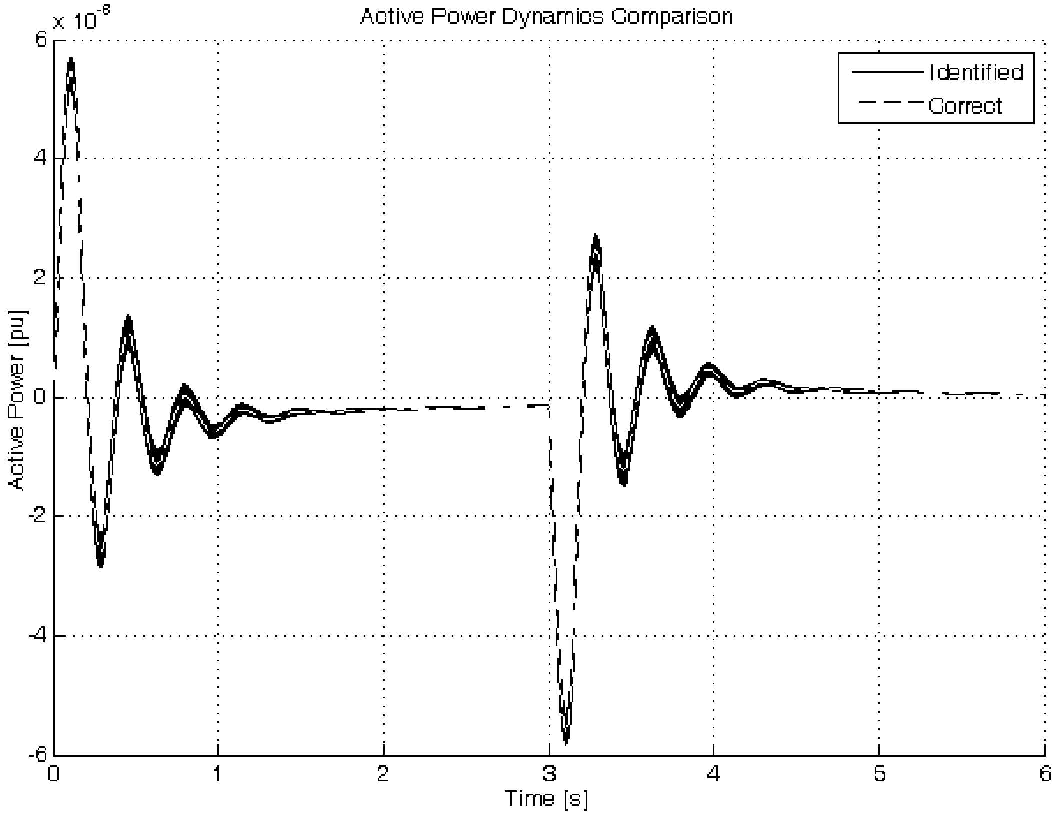

Figure 17.2. Active power dynamics for parameters obtained.

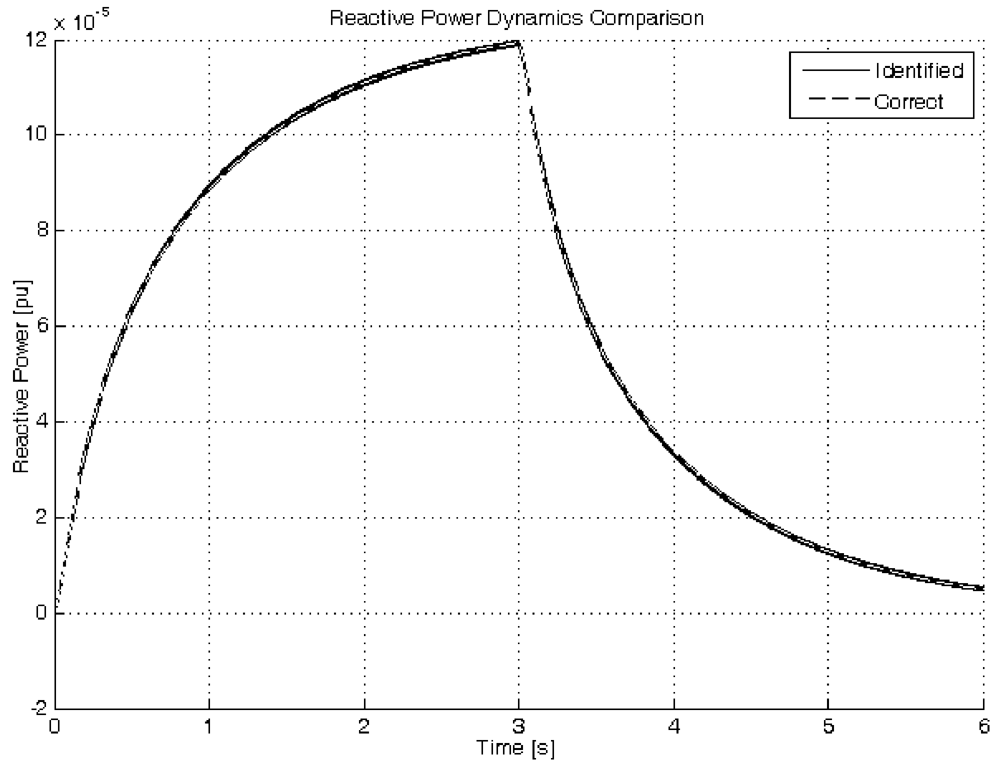

Figure 17.3. Reactive power dynamics for parameters obtained.

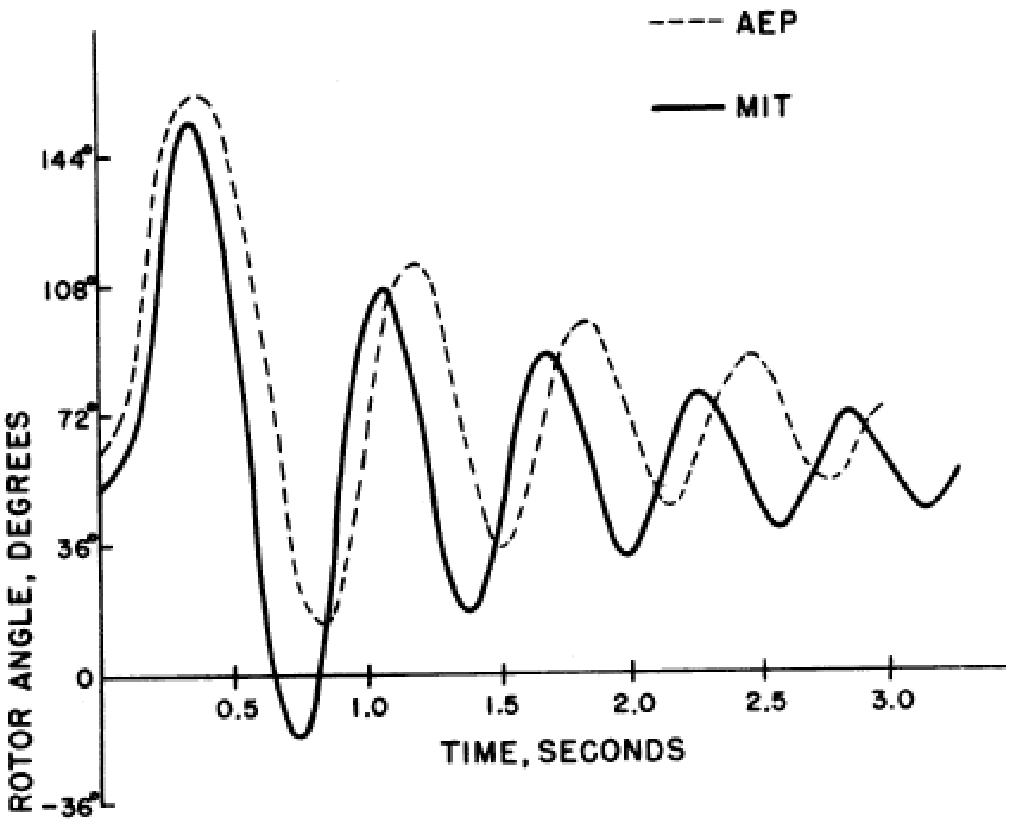

Figure 17. 4. Comparison of rotor's angle dynamics, simulated by the American Electric Power (AEP)Transient Stability Program – actual model at Massachusetts Institute of Technology (MIT) [35].

4 Conclusions and remarks

By comparing Figures 17.2, 17.3 and 17.4 it can be concluded that the error due to incorrect parameters might be very small with regards to the modeling error. The modeling error is inherent to the machine identified and, although not present when dealing with identifying simulated machines, is to be expected in case a physical machine is to be identified.

Apart from modeling infidelity the identification process of a real synchronous machine would have to deal with noisy measurements of both input and output variables, the distribution of which may be not be known. Linearization itself would also bring additional error if larger deviation values of the field voltage were used. Additionally the SMIB model used is also a source of error as the real identified generator will be operating in a system with no infinite bus to keep the voltage at the terminals perfectly constant. Any fluctuations of the terminal voltage will produce some additional noise for the model. Lastly the governor might also affect the dynamics.

It appears that very precise values of identified parameters are unattainable by linear SISO identification in which the field voltage was varied in the simple manner as in this work, as the accuracy with which one can measure the dynamics of a theoretical model is not perfect. It might be possible to obtain better results with longer duration of white noise input, however the realization of white noise disturbance upon field voltage might be practically difficult and the time duration necessary might be problematic since larger time scales have higher probability of having experienced some change in the system which would influence dynamics.

The works [6] and [15] may serve as indicative of the possibility parameter unambiguity, with [6] further hinting at a possibility of a multistage identification scheme. In [15], where the authors used a somewhat different set up for the identification process, a problem with generator identifiability is found and explained as insensitivity of the error norm to the change in the parameter vector in some direction, at the point of the correct solution. In [6] where the authors concentrated on a two stage set up, it is noted that a small field voltage change is a disturbance too small for larger currents in damper windings to be induced and that the damper coil parameters cannot be asserted by it. From Table III one might conclude that the damping coils' parameters were completely unidentifiable this way. This is not to be interpreted as though the dynamics were insensitive to the damping coils; the damping coils affect the dynamics of the generator, however, for every particular value of a certain damping coil's scattering it is possible to obtain the set of all other parameters so that the dynamics matches the original.
In our work the identifiability of the parameters of a synchronous generator from a linearized scheme was examined. For this purpose a new systematic method to identify the parameters of a generator by a linear equivalent using the eighth order model was developed. During the development phase of this method the authors focused on measurements on the terminals bearing in mind that some generators might not be equipped to measure a detailed dynamics of the internal variables. The decoupling mechanism which makes the brute force search feasible is provided. As the brute force search traverses all the parameters combinations the end result is a collection of parameters that correspond to the measured dynamics.

Nomenclature

$\mathbf{U}_{dq\ abc}$	Voltage vector in dq,abc frame respectively in pu
$\mathbf{\Psi}_{dq}$	Vector of coil fluxes in the dq frame in pu

$\mathbf{R}_{dq}$	Coil resistances vector in the dq frame in pu
$\mathbf{L}_{dq}$	Coil inductances vector in the dq frame in pu
ω_{sr}	Rotating speed: rated in rad/s and physical in pu
δ	Rotor angle in rad.
$T_{M,E}$	Torque in pu; mechanical and electrical respectively.
Δv_F	Field voltage step change in pu.
$R_{D,F,G,Q}$	Resistance of coil D, F, G and Q respectively in pu.
H	Inertia constant in s.
$u,i_{a,b,c}$	Phase to ground voltage and line current of phases a, b and c respectively, pu.
$u,i_{d,q}$	Stator voltage and current of the *d* and *q* axis, respectively in pu.
$L_{ad,\ aq}$	Mutual inductance in *d* and *q* axis, respectively in pu.
$L_{d,q,F,D,G,Q}$	Self-inductance of coil d, q, F, D, G, respectively in pu.

References

[1] J. T. Ma and Q. H. Wu, ‘Estimation of generator parameters using evolutionary programming’, in *International Conference on Control, 1994. Control ’94*, 1994, vol. 2, pp. 1442–1447 vol.2.

[2] B. Zaker, G. B. Gharehpetian, M. Karrari, and N. Moaddabi, ‘Simultaneous Parameter Identification of Synchronous Generator and Excitation System Using Online Measurements’, *IEEE Trans. Smart Grid*, vol. 7, no. 3, pp. 1230–1238, May 2016.

[3] G. Hutchison, B. Zahawi, K. Harmer, S. Gadoue, and D. Giaouris, ‘Non-invasive identification of turbo-generator parameters from actual transient network data’, *Transm. Distrib. IET Gener.*, vol. 9, no. 11, pp. 1129–1136, 2015.

[4] S. Guo, S. Norris, and J. Bialek, ‘Adaptive Parameter Estimation of Power System Dynamic Model Using Modal Information’, *IEEE Trans. Power Syst.*, vol. 29, no. 6, pp. 2854–2861, Nov. 2014.

[5] B. Mogharbel, L. Fan, and Z. Miao, ‘Least squares estimation-based synchronous generator parameter estimation using PMU data’, in *2015 IEEE Power Energy Society General Meeting*, 2015, pp. 1–5.

[6] H. B. Karayaka, A. Keyhani, G. T. Heydt, B. L. Agrawal, and D. A. Selin, ‘Synchronous generator model identification and parameter estimation from operating data’, *IEEE Trans. Energy Convers.*, vol. 18, no. 1, pp. 121–126, Mar. 2003.

[7] M. Karrari and O. P. Malik, ‘Identification of physical parameters of a synchronous Generator from online measurements’, *IEEE Trans. Energy Convers.*, vol. 19, no. 2, pp. 407–415, Jun. 2004.

[8] Z. Zhao, F. Zheng, J. Gao, and L. Xu, ‘A dynamic on-line parameter identification and full-scale system experimental verification for large synchronous machines’, *IEEE Trans. Energy Convers.*, vol. 10, no. 3, pp. 392–398, Sep. 1995.

[9] J. Zhang, A. Xue, T. Bi, Z. Wang, and W. Tang, ‘On-Line Synchronous Generator’s Parameters Identification with Dynamic PMU Data’, in *2012 Asia-Pacific Power and Energy Engineering Conference*, 2012, pp. 1–4.

[10] M. Karrari and O. P. Malik, ‘Nonlinear state space identification of a synchronous generator’, in *IEEE Power Engineering Society General Meeting, 2003*, 2003, vol. 4, p. 2404 Vol. 4.

[11] R. D. Fard, M. Karrari, and O. P. Malik, ‘Synchronous generator model identification for control application using volterra series’, *IEEE Trans. Energy Convers.*, vol. 20, no. 4, pp. 852–858, Dec. 2005.

[12] L. Sun, P. Qu, Q. Huang, and P. Ju, ‘Parameter Identification of Synchronous Generator by Using Ant Colony Optimization Algorithm’, in *2007 2nd IEEE Conference on Industrial Electronics and Applications*, 2007, pp. 2834–2838.

[13] J. C. N. Pantoja, A. Olarte, and H. Díaz, ‘Simultaneous estimation of exciter, governor and synchronous generator parameters using phasor measurements’, in *Electric Power Quality and Supply Reliability Conference (PQ), 2014*, 2014, pp. 43–49.

[14] H. Zihua, X. Ancheng, Y. Hongyu, Z. Zhaoyang, and H. Jiandong, ‘A novel online robust identification method for Xq of synchronous generator based on IGG criterion’, in *Control Conference (CCC), 2015 34th Chinese*, 2015, pp. 2883–2888.

[15] M. Burth, G. C. Verghese, and M. Velez-Reyes, ‘Subset selection for improved parameter estimation in on-line identification of a synchronous generator’, *IEEE Trans. Power Syst.*, vol. 14, no. 1, pp. 218–225, Feb. 1999.
[16] Gerald T. Heydt *et al.*, ‘Estimation of Synchronous Generator Parameters from On-line Measurements’, Power Systems Engineering Research Center, Ithaca, New York, Project report 05–36, Jun. 2005.
[17] U. Rudež, G. Bone, J. Bogovič, and R. Mihalič, *Identification of synchronous generator parameters : final report*. Ljubljana: Faculty of Electrical Engineering, Laboratory of Electric Power Supply, 2012.
[18] J. Schoukens, R. Pintelon, and Y. Rolain, *Mastering System Identification in 100 Exercises*, 1 edition. Hoboken, NJ: Wiley-IEEE Press, 2012.
[19] L. Ljung, *System Identification: Theory for the User*, 2 edition. Prentice Hall, 1998.
[20] IEEE Subsynchronous Resonance Task Force of the Dynamic System Performance Working Group Power System Engineering Camnittee, ‘First benchmark model for computer simulation of subsynchronous resonance’, *IEEE Trans. Power Appar. Syst.*, vol. 96, no. 5, pp. 1565–1572, Sep. 1977.
[21] P. M. Anderson, B. L. Agrawal, and J. E. V. Ness, *Subsynchronous Resonance in Power Systems*, 1 edition. New York: Wiley-IEEE Press, 1999.
[22] P. Kundur, *Power System Stability and Control*, 1st edition. New York: McGraw-Hill Education, 1994.
[23] B. Orel, *Osnove numerične matematike*. Ljubljana: Fakulteta za računalništvo in informatiko, 2004.
[24] Hermann W. Dommel et. al., *Electro Magnetic Transient Program (EMTP) Theory book*, 1st ed. Portland, Oregon, United States of America: Branch of System Engineering, Bonneville Power Administration, 1995.
[25] B. Kulicke, ‘Numerische Berechnung der Momentanwerte elektromechanischer Ausgleichsvorgänge von Drehfeldmaschinen im Verbundbetrieb.’, Techn. Hochsch., Darmstadt, 1975.
[26] V. Brandwajn, ‘Synchronous generator models for the simulation of electromagnetic transients’, University of British Columbia, Vancouver, B.C., 1977.
[27] I. Nagy, ‘Synchronous machine dynamics with saturation’, *Period. Polytech. Mech. Eng.*, vol. 30, no. 1, pp. 51–71, Feb. 1984.
[28] I. Nagy, ‘Block Diagrams and Torque-Angle Loop Analysis of Synchronous Machines’, *IEEE Trans. Power Appar. Syst.*, vol. PAS-90, no. 4, pp. 1528–1536, Jul. 1971.
[29] M. Saidy and F. M. Hughes, ‘Block diagram transfer function model of a generator including damper windings’, *Transm. Distrib. IEE Proc. - Gener.*, vol. 141, no. 6, pp. 599–608, Nov. 1994.
[30] M. Saidy and F. M. Hughes, ‘An extended block diagram transfer function model of a synchronous machine’, *Int. J. Electr. Power Energy Syst.*, vol. 18, no. 2, pp. 139–142, Feb. 1996.
[31] J. Machowski, J. Bialek, and D. J. Bumby, *Power System Dynamics: Stability and Control*, 2 edition. Chichester, U.K: Wiley, 2008.
[32] X. Wang, ‘Modal analysis of large interconnected power systems’, Berlin, Techn. University, Berlin, 1997.
[33] G. Doetsch, *Introduction to the Theory and Application of the Laplace Transformation*. Berlin, Heidelberg: Springer Berlin Heidelberg, 1974.
[34] M. Grewal and K. Glover, ‘Identifiability of linear and nonlinear dynamical systems’, *IEEE Trans. Autom. Control*, vol. 21, no. 6, pp. 833–837, Dec. 1976.
[35] R. D. Dunlop and A. C. Parikh, ‘Verification of Synchronous Machine Modeling in Stability Studies: Comparative Tests of Digital and Physical Scale Model Power System Simulations’, *IEEE Trans. Power Appar. Syst.*, vol. PAS-98, no. 2, pp. 369–378, Mar. 1979.
[36] Bone, Gorazd, Rudež, Urban, Bogovič, Jerneja, and Mihalič, Rafael, ‘Identification of synchronous generator parameters by a decoupled brute-force search using a linearized model’, presented at the 9th International Conference on Deregulated Electricity Market Issues in South Eastern Europe, Nicosia, Cyprus, 2014.