

# Estimation of synchronous generator parameters using an observer for damper currents and a graphical user interface

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## Abstract

This paper presents a method to identify synchronous generator parameters from on-line data. An observer for estimation of synchronous machine damper currents is designed. The observer-estimator is used in a graphical user interface (GUI) application. Possible internal machine fault conditions can be detected and remedial action can be undertaken. It is desired that an algorithm be developed such that it will enable bad measurement detection and rejection so as to increase the reliability of the results. Secondary objectives include calculation of the error characteristics of the estimation; development of an index of confidence; study of which machine parameters can be estimated, and which cannot; and evaluation of alternative GUI features.

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## 1. Introduction

Synchronous generator parameter identification is a problem that has attracted the attention of many researchers since the late sixties. Knowledge of the operational parameters of generators is necessary for performing stability studies and post mortem analysis of power systems. Traditionally, synchronous machine parameters are obtained by off-line tests as described in IEEE Standards [1]. Several researchers between 1969 and 1971 developed methods to find additional parameter values based on the existing classic synchronous machine models [2–5]. Off-line methods may not be practical and parameters obtained by these methods may not be accurate. Decommitting a machine for parameter measurement may not be convenient especially if the machine is a base loaded unit. The parameters of a synchronous machine vary under different loading conditions because of changes of the machine internal temperature, magnetic saturation,

aging, and coupling between the machine and external systems.

Researchers have attempted to tackle the parameter estimation problem using various methods: one of the methods used by Keyhani was the estimation of parameters from standstill frequency response (SSFR) test data [6,7]. In this approach, curve fitting techniques are used to derive the transfer functions of the d-axis and q-axis using available test data. The parameters of the model are then calculated from nonlinear equations. Other methods for parameter identification are presented in [8–11].

Various estimation techniques have been proposed in the literature. Least squares, infinite-norm and one-norm are some of these methods. Reference [12] offers an overview and some examples of these methods. In [13], a new approach is presented, where the authors use a Park's transformation model and synthetic data to estimate synchronous machine parameters by employing least squares minimization techniques. The paper also demonstrates a graphical user interface (GUI) that enables fast and user friendly estimation. The method suffers from the fact that measurements for the damper currents are unavailable. Therefore,

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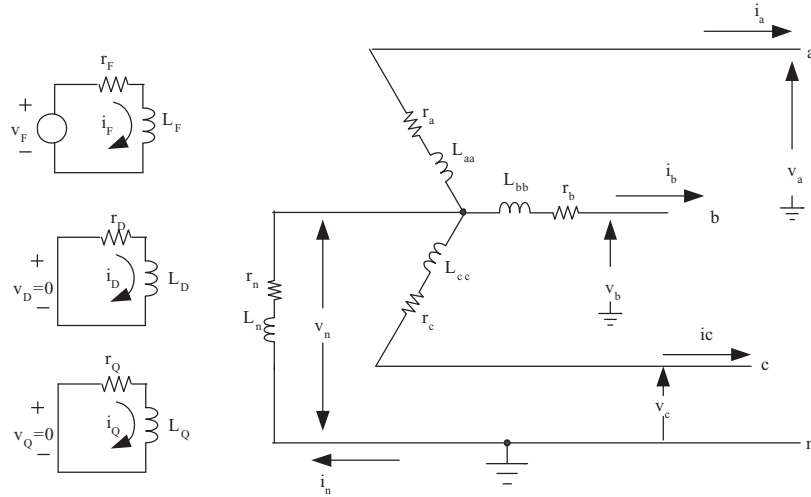


Fig. 1. Schematic diagram of a synchronous machine.

in order to use this technique, it is necessary to develop a method to estimate the unmeasurable states using known information.

## 2. Modeling of synchronous machines

In order to formulate the state estimation equation for a synchronous generator, it is necessary to employ a mathematical model which represents the synchronous generator in the conditions under study. This model will comprise three stator windings, one field winding and two damper windings as shown in Fig. 1. Magnetic coupling is a function of the rotor position and therefore, the flux linking each winding is also a function of the rotor position [14]. The instantaneous terminal voltage of any winding takes the form,

$$v = -ri - \dot{\lambda} \quad (1)$$

where  $r$  is the winding resistance,  $i$  the current and  $\lambda$  the flux linkage. It should be noted that in this notation it is assumed that the direction of positive stator currents is out of the terminals, since the synchronous machine under consideration is a generator.

In Eq. (1), the voltage is expressed in terms of both currents and flux linkages. This is not desirable and therefore one of the two variables has to be replaced. The flux linkage equations for the synchronous generator are given by,

$$\begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \\ \lambda_F \\ \lambda_D \\ \lambda_Q \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} & L_{aF} & L_{aD} & L_{aQ} \\ L_{ba} & L_{bb} & L_{bc} & L_{bF} & L_{bD} & L_{bQ} \\ L_{ca} & L_{cb} & L_{cc} & L_{cF} & L_{cD} & L_{cQ} \\ L_{Fa} & L_{Fb} & L_{Fc} & L_{FF} & L_{FD} & L_{FQ} \\ L_{Da} & L_{Db} & L_{Dc} & L_{DF} & L_{DD} & L_{DQ} \\ L_{Qa} & L_{Qb} & L_{Qc} & L_{QF} & L_{QD} & L_{QQ} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_F \\ i_D \\ i_Q \end{bmatrix} \quad (2)$$

where  $L_{jk}$  is a self-inductance when  $j = k$  and a mutual inductance when  $j \neq k$ . The inductances in the above matrix are given by well known expressions [14].

It is observed that (2) has time-varying terms which will cause complication when their derivatives are taken. Thus, it is convenient to refer all quantities to a rotor frame of reference through a Park's transformation [15,16],

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

The angle  $\theta$  is given by,

$$\theta = \omega_R t + \delta + \frac{\pi}{2} \quad (4)$$

where  $\omega_R$  is the rated (synchronous) angular frequency in rad/s and  $\delta$  is the synchronous torque angle in electrical radians. The transformed currents are,

$$\mathbf{i}_{0dq} = \mathbf{P} \mathbf{i}_{abc} \quad (5)$$

where the current vectors are defined as,

$$\mathbf{i}_{0dq} = \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} \quad \text{and} \quad \mathbf{i}_{abc} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (6)$$

Similarly, to transform the voltages and flux linkages,

$$\mathbf{v}_{0dq} = \mathbf{P} \mathbf{v}_{abc} \quad \text{and} \quad \boldsymbol{\lambda}_{0dq} = \mathbf{P} \boldsymbol{\lambda}_{abc} \quad (7)$$

Park's transformation leads to

$$\begin{bmatrix} v_0 \\ v_d \\ v_q \\ -v_F \\ 0 \\ 0 \end{bmatrix} = - \begin{bmatrix} r + 3r_n & 0 & 0 & 0 & 0 & 0 \\ 0 & r & \omega L_q & 0 & 0 & \omega kM_Q \\ 0 & -\omega L_d & r & -\omega kM_F & -\omega kM_D & 0 \\ 0 & 0 & 0 & r_F & 0 & 0 \\ 0 & 0 & 0 & 0 & r_D & 0 \\ 0 & 0 & 0 & 0 & 0 & r_Q \end{bmatrix} \begin{bmatrix} i_0 \\ i_d \\ i_q \\ i_F \\ i_D \\ i_Q \end{bmatrix} - \begin{bmatrix} L_0 + 3L_n & 0 & 0 & 0 & 0 & 0 \\ 0 & L_d & 0 & kM_F & kM_D & 0 \\ 0 & 0 & L_q & 0 & 0 & kM_Q \\ 0 & kM_F & 0 & L_F & M_R & 0 \\ 0 & kM_D & 0 & M_R & L_D & 0 \\ 0 & 0 & kM_Q & 0 & 0 & L_Q \end{bmatrix} \begin{bmatrix} i_0 \\ i_d \\ i_q \\ i_F \\ i_D \\ i_Q \end{bmatrix} \quad (8)$$

where all parameters in the coefficient matrices are constant [13,17]. Further, since the synchronous speed is constant if small time periods are studied, then Eq. (8) can be considered as a linear time invariant equation.

### 3. Development of an observer for the damper winding currents

Usually, available data for synchronous generators are the stator phase currents and voltages at the terminals of the machine, and the field voltage and current. Often, it is possible to measure the rotor torque angle  $\delta$ , using commercially available instruments. The torque angle enables the transformation of abc quantities to 0dq quantities as they appear in Eq. (8). In order to set up the parameter estimation problem, it is necessary to have measurements for the damper currents  $i_D$  and  $i_Q$ . Otherwise, it is not possible to transform the system into the form  $\mathbf{H} \cdot \mathbf{x} = \mathbf{z}$ . An alternative approach would have been the transformation of Eq. (8) in the form  $\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u$  and the use of adaptive observers to estimate both the unavailable states and the unknown parameters [18,19]. This is not very practical in this case, since transformation of the system into observer canonical form leads to a system that is nonlinear in the parameters and thus makes the estimation process more involved. Furthermore, the parameters of the system are not exactly constant due to inductance saturation and changes of parameters according to the operating point. It is also desired to keep the estimation method as simple as possible so as to enable a development of a graphical user interface that will perform the estimation in a fast and reliable manner.

Observation of the synchronous generator model as was derived in Eq. (8), shows that it is possible to use the last two equations and rearrange them so as to obtain expressions for the damper winding currents. The parameters that are involved in this process are not operational parameters of the machine, but parameters of the damper windings. These are constant and well known from manufacturers' data. Further, there is no interest in estimating those parameters, and hence one can separate the two equations from the rest of the model. Rewriting the last two equations of Eq. (8),

$$0 = \begin{cases} -r_D i_D - kM_D i'_d - M_R i'_F - L_D i'_D \\ -r_Q i_Q - kM_Q i'_q - L_Q i'_Q \end{cases} \quad (9)$$

In general, the current derivatives can be approximated by the forward difference formula,

$$i'(t) \approx \frac{i(t + \Delta t) - i(t)}{\Delta t}. \quad (10)$$

Therefore, Eq. (9) can be rearranged in discrete form as,

$$\begin{aligned} i_D(n+1) &= \left[ 1 - \frac{r_D}{L_D} \Delta t \right] i_D(n) - \frac{kM_D}{L_D} \Delta t i'_d(n) \\ &\quad - \frac{M_R}{L_D} \Delta t i'_F(n), \quad i_Q(n+1) \\ &= \left[ 1 - \frac{r_Q}{L_Q} \Delta t \right] i_Q(n) - \frac{kM_Q}{L_Q} \Delta t i'_q(n) \end{aligned} \quad (11)$$

Eq. (11) enables the calculation of the damper currents. All parameters can be accurately calculated using manufacturer's data, while the time varying quantities are available measurements. The only ambiguity in Eq. (11) is the value of  $i_D(0)$  and  $i_Q(0)$ . These are needed to initiate the observation process. Nevertheless, the initial conditions can be assumed to be 0 without loss of accuracy as will be shown in the two case studies in the next section.

### 4. Case studies for damper winding currents observer

In order to ascertain the validity of the proposed method, it is desired to perform a number of case studies comparing the estimated damper currents to damper currents generated using the Electromagnetic Transients Program (EMTP). Two of the conducted case studies are presented.

A synchronous generator was simulated in EMTP both in steady state and in transient mode. The machine under consideration is a cross-compound generator located in the southwest USA. The generator contains a high pressure unit rated at 483 MVA and a low pressure generator rated at 426 MVA. Table 1 shows the parameters for this generator as calculated by manufacturer's data. These parameters are used in the EMTP program for generation of the required measurements.

In the first case study, the machine is operating nearly in steady state. The starting point for the simulation is not exactly in the steady state, and there is a small transient that results in a small damper current. Observation of the damper current for a longer period of time shows that it damps out to

Table 1  
Synchronous generator parameters

Parameter	Value (p.u.)	Parameter name
$r$	0.0027	Stator phase resistance
$r_n$	100	Equivalent neutral resistance
$L_q$	1.72	Equivalent quadrature-axis reactance
$L_d$	1.80	Equivalent direct-axis reactance
$M_F$	1.339	Stator to field mutual inductance
$M_D$	1.339	Stator to damper winding D mutual inductance
$M_Q$	1.2737	Stator to damper winding Q mutual inductance
$r_F$	$9.722 \times 10^{-4}$	Equivalent field resistance
$r_D$	$8.823 \times 10^{-3}$	Equivalent resistance of damper winding D
$r_Q$	0.07151	Equivalent resistance of damper winding Q
$L_0$	0.15	Equivalent zero-sequence inductance
$L_n$	100	Equivalent neutral inductance
$L_F$	1.7579	Field winding self inductance
$M_R$	1.64	Rotor mutual inductance
$L_D$	1.68124	Self inductance of damper winding D
$L_Q$	1.59059	Self inductance of damper winding Q

0 as expected. The damper currents are observed according to Eq. (11) with the initial conditions assumed to be 0. The general concept of an observer is as follows: certain states of a physical system may be difficult to measure or calculate. These unobserved states may nonetheless be needed to calculate an estimate of the machine parameters. An ‘observer’ is a dynamic system that is constructed so that the unobserved states may be estimated. The observer is adaptive: parameters of the observer are adjusted methodically so that the output of the machine simulation agrees with the actual measured machine output. Fig. 2 shows the concept of an observer.

Fig. 3 shows the actual and estimated damper current in the direct-axis winding. The estimated current is in good agreement with the actual current. The mean square error (MSE) of the two signals is  $8.7 \times 10^{-13}$  p.u. Fig. 4 depicts the

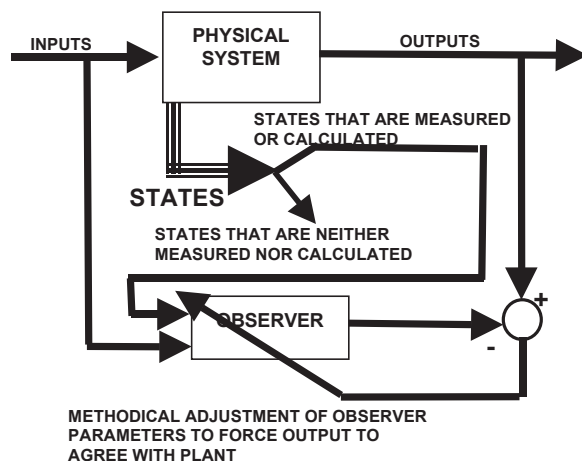


Fig. 2. Concept of an observer for a dynamic system.

actual and estimated currents for the quadrature-axis damper winding. The observed state is in phase with the actual value for the damper current. There is some difference between the two states, but this is insignificant since the MSE was calculated to be  $2.4 \times 10^{-10}$  p.u. As it will be shown later, this difference does not affect the accuracy of the estimated parameters.

In the second case study, transient data were considered. A permanent line to line fault was applied at 0.25 s between phases b and c. The observed damper currents as compared to the actual damper currents for each axis can be seen in Figs. 5 and 6. The same trend appears in each case. The direct-axis damper model seems to offer an exact observed state. The MSE is calculated to be 0.0147 p.u. On the other hand, the quadrature-axis damper current has a more significant error. The MSE is calculated to be 0.705 p.u., but still the observed current is in phase with the actual current.

## 5. Configuration of the state estimator

State estimation is a process during which a number of unknown system state variables or parameters are assigned a value based on measurements from that system [18]. Typically, the number of measurements (or number of equations) is greater than the parameters to be estimated. In this case the system is overdetermined and the solution is found in a least squares sense. That is, it is desired that the sum of the squares of the differences between the estimated and the measured parameters to be minimized.

It is desired to rearrange Eq. (8) into the form  $\mathbf{H} \cdot \mathbf{x} = \mathbf{z}$  and obtain the estimated parameters by  $\hat{\mathbf{x}} = \mathbf{H}^+ \mathbf{z}$ , where  $\mathbf{H}^+$  is the pseudoinverse of  $\mathbf{H}$  [13,20].  $\mathbf{H}$  is a matrix of dimension  $m \times n$  and contains the coefficients of the unknowns, which are either obtained by direct measurements of current and voltages, or via the observer in the case of the damper currents, or via calculation in the case of the derivatives. The formula for the derivatives is the forward difference formula (10). The vector  $\mathbf{z}$  has dimension  $m$  and it contains known parameters, or measurements or a combination of the two. Fig. 7 illustrates in block diagram form the idea of the observer, the data manipulation and the parameter estimation algorithm.

## 6. Estimation of machine parameters and testing of the algorithm

The machine parameter estimation algorithm was tested using the available steady state EMTF data where the exact parameters are those listed in Table 1.

It is desired to estimate each one of the parameters in Eq. (8) and to verify the validity of the program, as well as to ascertain which parameters are possible to be estimated. In case that a parameter is not estimated within an acceptable error using noise free data, then its estimation using noise

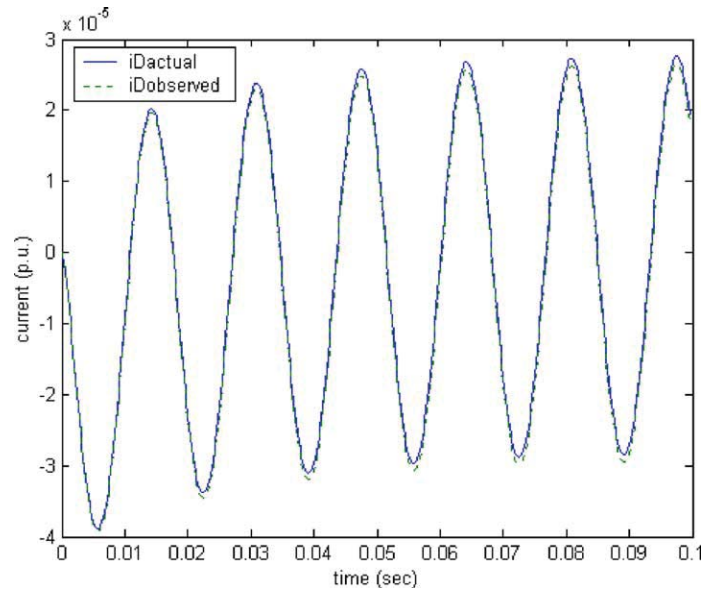


Fig. 3. Actual and estimated d-axis damper current using steady state data.

corrupted data will not be feasible. There are six parameters that are desired to be estimated in the two matrices of Eq. (8). Most of these parameters appear two or three times in the two matrices.

Table 2 depicts the actual and estimated parameters and the percent error for each parameter. The estimation was performed using EMTP steady state data. Two of the parameters in Eq. (8),  $r + 3r_n$  and  $L_0 + 3L_n$ , cannot be estimated with good accuracy in the steady state. This is expected since these quantities are located in the first equation of (8), which is decoupled from the others. All the voltage

Table 2  
Estimated parameters using EMTP data

Parameter	Actual value (p.u.)	Estimated value (p.u.)	% error
$r$	0.0027	0.00261	3.3
$L_d$	1.80	1.7999	$5.6 \times 10^{-3}$
$L_q$	1.72	1.72009	$5.2 \times 10^{-3}$
$r_F$	$9.722 \times 10^{-4}$	$9.7994 \times 10^{-4}$	0.8
$L_F$	1.75791	1.746998	0.62
$M_F$	1.33905	1.33908	$2.2 \times 10^{-3}$

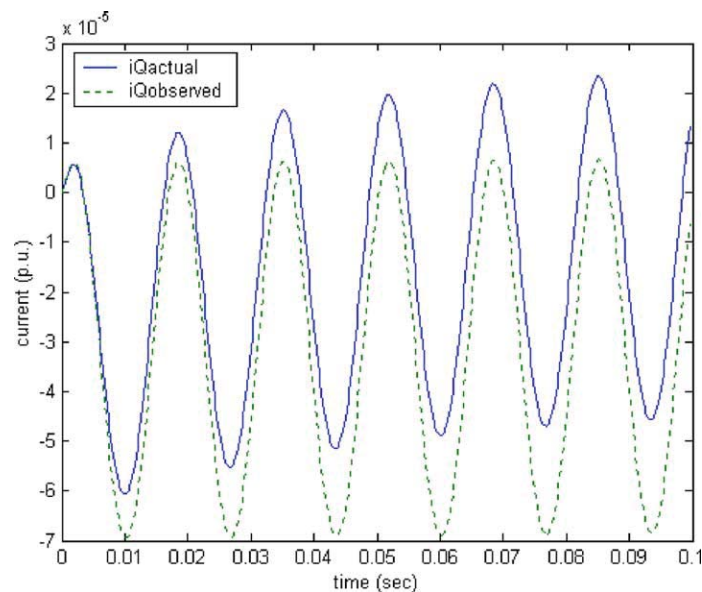


Fig. 4. Actual and estimated q-axis damper current using steady state data.



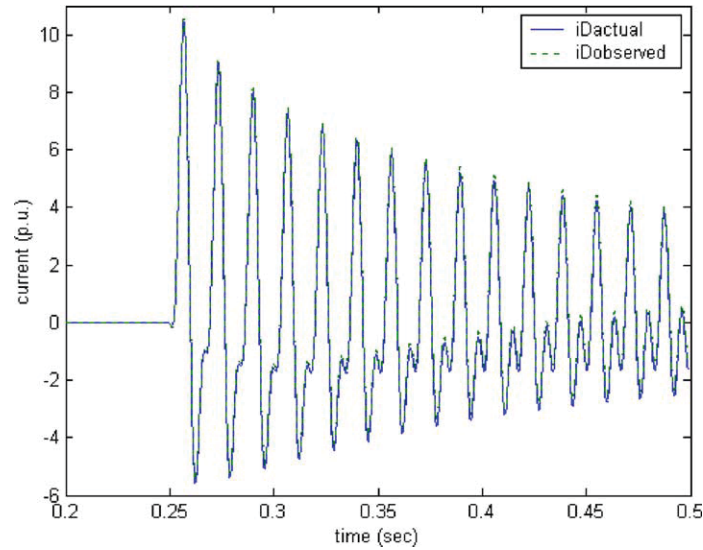


Fig. 5. Actual and estimated d-axis damper current using transient data.

and current states in this equation are 0 in the steady state and it is not possible to calculate these parameters. These two quantities are possible to be estimated in the transient case, as the zero-axis quantities will not be 0. Observation of the other parameters in Table 2 shows that it is possible to estimate all parameters with satisfactory results. The maximum error observed was 3.3% and it occurred for the stator resistance  $r$ . The field resistance  $r_F$ , which is significant for studies performed by utilities, was estimated with an accuracy of 0.8% which is considered satisfactory.

It is also useful to study the effect of estimating more than one parameter at a time. This will indicate whether multiple parameter estimation is feasible and it will enable the user to avoid multiple program executions. For this purpose it was

Table 3  
Multiple simultaneous parameter estimation using EMTP data

Parameter	Actual value (p.u.)	Estimated value (p.u.)	% error
$L_d$	1.80	1.7999	$5.6 \times 10^{-3}$
$L_q$	1.72	1.72009	$5.2 \times 10^{-3}$
$r_F$	$9.722 \times 10^{-4}$	$9.7994 \times 10^{-4}$	0.8

decided to estimate three parameters simultaneously. These parameters are  $L_d$ ,  $L_q$  and  $r_F$ . Table 3 shows the estimated quantities and the percent error for each of the parameters. It can be seen that the estimated parameters and the percent error are identical to the previous case study (Table 2),

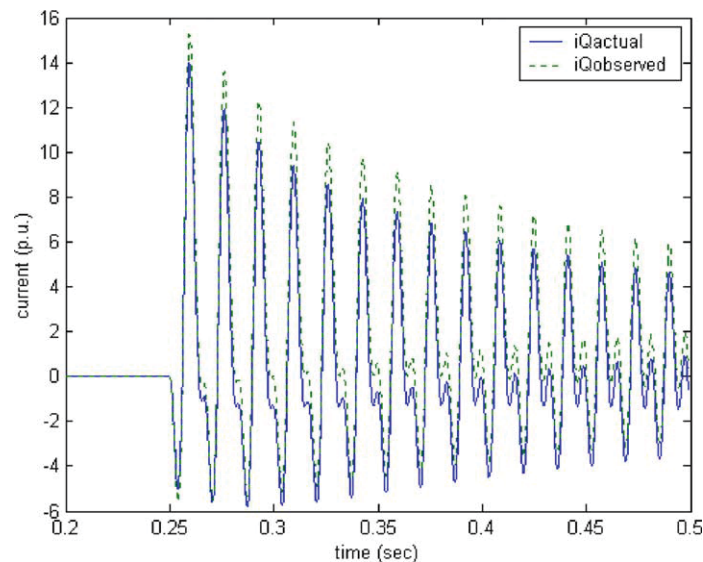


Fig. 6. Actual and estimated q-axis damper current using transient data.

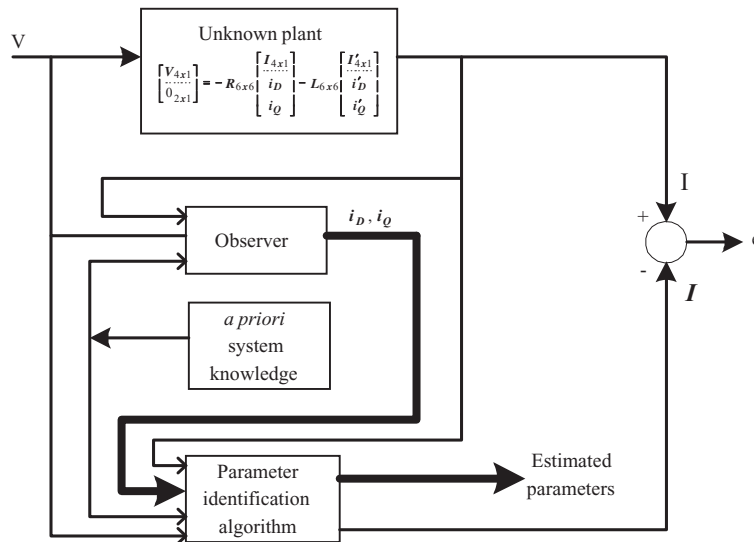


Fig. 7. Block diagram for observer implementation and parameter identification algorithm.

where these parameters were estimated individually. This shows that more than one generator parameters can be estimated at the same time, and it will be particularly useful in case that there is uncertainty about two or more parameters.

## 7. Graphical user interface implementation using Visual C++

One of the major objectives of this research work is to develop a visual graphical user interface in the form of a Windows application for a synchronous machine state estimator. This application will enable the practicing engineer and interested utilities to estimate the parameters of a synchronous machine without having to decommit the unit or get involved in time consuming methods of estimation. The application developed during this research work is unique due to three main characteristics: on-line operation, portability and user friendly interaction.

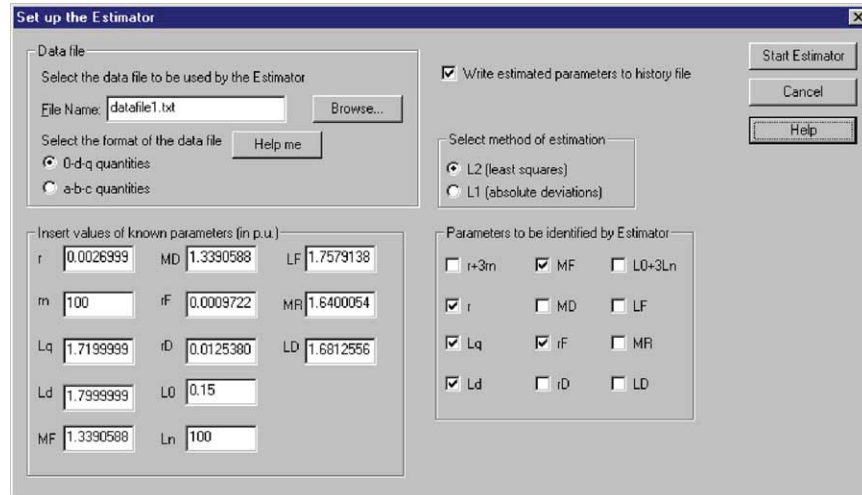
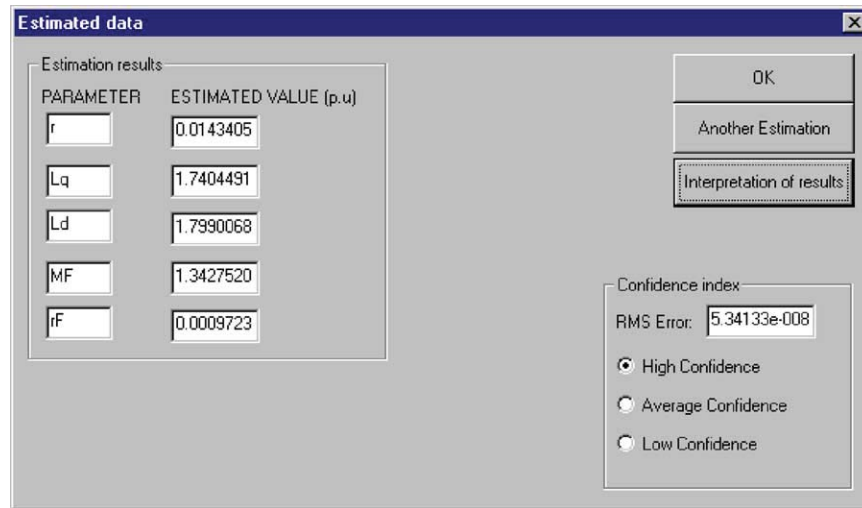
On-line operation is the distinguishing characteristic of this application. It enables on-line and expeditious estimation of any given synchronous machine based on measurements of the field and stator voltages and currents. Such measurements are readily available and in large quantities in every utility. Moreover, the application developed is portable, since it can be installed in any personal computer operating under Windows. The application does not require a Visual C++ environment, since it is a stand-alone application, able to operate without the support of external C++ libraries. User friendly interaction is achieved by means of the dialogs and context-sensitive help provided on request. The input and output dialogs are self explanatory and will be described in Section 8.

## 8. Input/output dialog and estimator configuration

The main window of the program offers a variety of options on its toolbar, like any other Windows program. To begin the process of estimating machine parameters, the user must open the input screen as shown in Fig. 8. This is achieved by selecting the option *Estimator* on the toolbar of the main window, and then selecting the *Set up Estimator* option.

The user can set up the *Estimator* and calculate the parameters of the synchronous machine that is to be studied, in three steps. The first step is to enter the name of the data file in the edit box as shown in Fig. 8. This can be done by clicking on the *Browse* button and navigating through the hard disk of the computer until the desired file is located. The file should be of type .txt to be eligible for usage by the application. Text files can be created either by using the Windows Notepad or any other software with similar capabilities. Another option is to create text files using Microsoft Excel and save the file as a text—tab delimited—format.

The second step on behalf of the user is to input the known parameters of the synchronous machine. These parameters may be known either from previous off-line tests or from manufacturer's data. Sample values are shown in Fig. 8 and these are the default values for the generator that is being studied for this application. The existence of default values does not require the user to enter the values anew every time it is desired to execute the application. The fact that all values are set to default values should not be confusing to the user. If the user desires the estimation of a certain parameter, then the default value of that specific parameter does not interfere in any way in the estimation. The third and final step of this process is to select the parameters that are desired to be estimated. The user has the opportunity to

Fig. 8. Input window of the *Estimator*.Fig. 9. Output window of the *Estimator*.

select up to five parameters for estimation. This selection can be done by simply clicking on the check box corresponding to the parameter to be estimated as shown in Fig. 8.

Finally, the software offers a number of options to the user, such as the estimation method (least squares or least absolute deviation), the data type (abc or 0dq quantities) and whether the output should be written in a history data file or not.

Upon execution of the main program of the application, which contains the state estimator, the values of the estimated parameters and the rms error for this estimation are returned to the graphical user interface for output. The resulting output window can be seen in Fig. 9. On the left side of the output window, the user can see the parameters selected previously and their estimated value in per unit. The rms error on the lower right side of the estimator is a measure of confidence on the estimated parameters and is given by,

$$\text{rms error} = \sqrt{\frac{\text{residual}}{\text{number of measurements}}} \quad (12)$$

where  $(\text{residual})^2 = \{[\mathbf{H}] \cdot [\mathbf{x}] - [\mathbf{z}]\}^T \{[\mathbf{H}] \cdot [\mathbf{x}] - [\mathbf{z}]\}$ , and  $\hat{\mathbf{x}}$  is the vector of the estimated parameters.

## 9. Conclusions

In this paper, a method to identify synchronous machine parameters from on-line measurements is shown. The method is based on least squares estimation and a simple formula for the derivative operator. The method is developed to be used with a Visual C++ engine and graphical user interface, so that the practicing power engineer may link machine measurements taken in an on-line environment with the *Estimator*. An observer for identification of the unmeasurable damper winding currents is also presented. The two case studies show that the observed currents are in good agreement with the actual currents in both steady state and transient operation. Parameter estimation results show that the machine parameters are estimated accurately, with



a maximum error of 3.3% for the stator resistance, while all other errors are less than 1%. Multiple parameters at a time were also estimated accurately. This enables estimation of more than one machine parameter in the real data case, when more than one parameter is unknown. The accuracy of estimation was shown not to degrade with multiple parameter estimation.

The GUI was developed in Visual C++ and its correct operation was verified. The GUI is user friendly and self-guiding. Calculation time is in the order of a few seconds, while the results are presented on the computer screen automatically.

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### Appendix A. List of Symbols

$dq0$	stator transformation to direct, quadrature and zero-axis parameters
$abc$	stator per-phase quantities on conventional $a, b, c$ axes
$i_0$	stationary current, proportional to zero-sequence current
$i_a$	current through stator phase a
$i_b$	current through stator phase b
$i_c$	current through stator phase c
$i_d$	current through rotor axis d
$i_D$	current through damper winding D
$i_F$	current through field winding
$i_q$	current through rotor axis q
$L_0$	equivalent zero-sequence inductance ( $L_0 = x_0$ in p.u.)
$L_{aa}$	stator phase winding a self inductance
$L_{ab} = L_{ba}$	stator phase winding a to b mutual inductance
$L_{ac} = L_{ca}$	stator phase winding a to c mutual inductance
$L_{aF} = L_{Fa}$	stator phase winding a to field winding mutual inductance
$L_{aD} = L_{Da}$ $= L_{md} = L_{AD}$	stator phase winding a to damper winding mutual inductance
$L_{bb}$	stator phase winding b self inductance
$L_{bc} = L_{cb}$	stator phase winding b to c mutual inductance
$L_{bF} = L_{Fb}$	stator phase winding b to field winding mutual inductance
$L_{bD} = L_{Db}$	stator phase winding b to damper winding mutual inductance
$L_{cc}$	stator phase winding c self inductance
$L_{cF} = L_{Fc}$	stator phase winding c to field winding mutual inductance

$L_{cD} = L_{Dc}$	stator phase winding c to damper winding mutual inductance
$L_d$	equivalent direct-axis reactance
$L_{DD} = L_D$	damper winding D self inductance
$L_{DF} = L_{FD}$	damper winding to field winding mutual inductance
$L_{FF} = L_F$	field winding self inductance
$L_m$	stator phase winding magnetizing inductance
$L_n$	equivalent neutral inductance
$L_q$	equivalent quadrature-axis reactance ( $L_q = x_q$ in p.u.)
$L_{QQ} = L_Q$	damper winding Q self inductance
$L_s$	stator phase winding inductance
$M_D$	stator to damper winding D mutual inductance
$M_F$	stator to field winding mutual inductance
$M_Q$	stator to damper winding Q mutual inductance
$M_R$	rotor mutual inductance
$M_s$	stator phase winding mutual inductance
$P$	Park's transformation matrix
$r = r_a = r_b = r_c$	stator phase resistance
$r_D$	equivalent resistance of damper winding D
$r_F$	equivalent field winding resistance
$r_Q$	equivalent resistance of damper winding Q
$r_n$	equivalent neutral resistance
$v_0$	zero-axis voltage, proportional to zero-sequence voltage
$v_a$	stator phase a voltage
$v_b$	stator phase b voltage
$v_c$	stator phase c voltage
$v_d$	direct-axis voltage
$v_q$	quadrature-axis voltage
$\delta$	synchronous machine torque angle in electrical radians
$\Delta t$	time step
$\theta$	angular displacement of d axis from a axis in mechanical radians
$\lambda$	flux linkage
$\omega$	synchronous angular frequency in radians per second
$\omega_R$	rated synchronous angular frequency in radians per second

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