

Synchronous Machine Parameter Estimation Using Orthogonal Series Expansion

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Abstract This paper presents an alternative to estimate armature circuit parameters of large utility generators using real time operating data. The alternatives consider the use of orthogonal series expansions in general and Hartley series in particular. The main idea considers the use of orthogonal series expansions for fitting operating data (voltage and currents measurements) and/or synthetic input-output data. This allows writing a set of linear algebraic equations that can be solved for the unknown parameters using the pseudoinverse. Hence, the essence of the approach is the linear state estimation and the purpose of generalizing the solution to accept orthogonal series expansion in general is indeed providing 'windows' to view the same problem. Although solutions are the same in all domains one wishes to employ the window that gives the best view and the most efficient computation. The approach may be used for static as well as dynamic problems. The approach is tested for noise corruption likely to be found in measurements. The method is found to be suitable for the processing of digital fault recorder data to identify synchronous machine parameters.

1. INTRODUCTION

The use orthogonal series expansions are well known alternatives for approximation of functions. However, they may also be used to establish algebraic methods for the solution of problems described by differential equations, such as analysis of linear time invariant and time varying systems, model reduction; optimal control and system identification. The problem of system identification using orthogonal includes linear time invariant lumped and distributed systems [23], linear time varying lumped and distributed systems [12,13] and nonlinear systems [16,17]. The utilization of this series has the common objective of representing models efficiently, and calculating intermediate parameters rapidly for the given problem. It can be said that the various domains cited are alternative 'windows' to view a problem, and one wishes to employ the window that gives the best view of the problem and the most efficient calculation. Although *solutions* are the same in all domains, the bandwidth of the problem and numerical characteristics of intermediate matrices used are different, e.g. the set of equations of a particular problem may be sparser (or fewer) in one domain than in others. Typical examples are the applications of Laguerre polynomials [10,11], Legendre polynomials [12,13], Chebyshev polynomials of the first [14] and second kind [15], Fourier series [16], Walsh series [17], block-pulse series [18], Haar series [19] and Hartley series [20].

The key point of the approach adopted in this paper for dynamic problems is the use of the operational matrix P which relates the coefficients of a given function and the coefficients of its integral. Using the operational matrix of integration overcomes the necessity to use differentiated data, a fact that is usually avoided either by integration of the data or by using discrete time models. In fact, orthogonal series expansion and their operational properties transform the original differential input-output model to a linear algebraic (or regression) model convenient for direct least squares or pseudoinverse solution.

Traditional methods of obtaining synchronous machine parameters are specified in IEEE and ICE Standards and other national electrical standards from many countries. These methods are often conducted under off-line conditions. The parameters obtained by these methods may not truly characterize the synchronous machine under various loading conditions. Many researchers have addressed the issues and problems associated with off-line parameter measurements. However, the interest and need for on-line estimation of synchronous generator parameters has arisen in recent years. On-line methods of obtaining machine parameters are most attractive due to minimal site/system impact and principally because they do not involve service interruption. On-line methods also represent a way to take into account parameter deviation due to changes in load levels, saturation, and machine aging.

In this study, the utilization of the Hartley series in a linear state estimator for synchronous generator parameters is illustrated but the approach may account for the use of different domain. The method is based on a $dq0$

model. The proposed method is verified using both synthetic data and operational data from a digital fault recorder. The effect of measurement noise corruption, always present in real time data acquisition, is also investigated.

2. ORTHOGONAL SERIES EXPANSIONS AND OPERATIONAL PROPERTIES

In this section general background on approximation using orthogonal series expansions and operational matrices that is relevant for the material that follows is presented. The notation of presentation is kept general in order to include all possible domains. With exception of some mathematical XXX‘rarezas’XXX, any function of time $f(t)$ may be approximate to arbitrary errors using orthogonal series expansions. It can be stated that all basis comprising the family of the orthogonal series expansions have same fundamental properties such as orthogonality that makes easy identifying their coefficients. Orthogonal series expansions also share other properties known as operational properties. In spite of having many common properties, orthogonal series expansions are different in their respective kernel functions or basis functions. Accordingly, while the kernel function of a complex series is $e^{-j\omega t}$, the Hartley series utilizes $\cos(\omega t) + \sin(\omega t)$, also known as the *cosine-and-sine* function or *cas*(ωt) as the base kernel. There exist also orthogonal series expansions where the kernels are step functions such as Walsh series, block-pulse series or the basic Haar wavelet kernels are not restricted to be periodic such as the trigonometric or Walsh functions, that may be in fact aperiodic such as the wavelet family or the orthogonal polynomials. The later alternatives may be in fact better suited for problems involving aperiodic phenomena such as transient responses of systems.

If the vector of basis function $T(t)$ is used to include a particular set of basis kernels and denoted as (note that the prime notation indicates transposition),

$$T(t) = [T_{-n} \quad \cdots \quad T_{-1} \quad T_0 \quad T_1 \quad \cdots \quad T_n]'$$

Thus a function can be approximated as

$$f(t) = FT(t)$$

$$F = [F_{-n} \quad \cdots \quad F_{-1} \quad F_0 \quad F_1 \quad \cdots \quad F_n]_{(1,2n+1)}$$

Each coefficient of vector F , F_n is calculated using inner product in Equation (1),

$$F_n = k \int_0^{T_p} f(t)T(t)dt \quad (1)$$

The operational properties of the orthogonal series may be written in terms of the operational matrices of integration and differentiation. The main concept around these properties is the fact that the integral of a orthogonal series may be also expressed as a orthogonal series. The same can be stated for orthogonal series and their derivatives. In general terms the operational matrix of integration may be defined as

$$\int_0^t T(\tau)d\tau = PT(t)$$

(2)

where P is the operational matrix of integration. It becomes apparent from Equation (2) that operational matrices provide a way to transform dynamic equations into algebraic equations as it was mention before and the concept may be in fact readily related to similar property observed in Laplace transform. Similarly, a operational matrix of differentiation may be defined to hold Equation (3).

$$\frac{dT(t)}{dt} = DT(t)$$

(3)

were D is the operational matrix of integration. Higher order derivatives and integrals may be found by using equation (2) and (3) recursively. Thus the nth derivative and integral of an orthogonal series may be written as

$$\int_0^t \cdots \int_0^t T(\tau)d\tau = P^n T(t)$$

and

$$\frac{d^n T(t)}{dt^n} = D^n T(t)$$

In general algebraic methods obtained from operational matrices may be stated as one approach. The particularities of each domain are reflected in the numerical characteristics of matrices P and D and vector of coefficients F but do not modified the qualitative characteristic of the method. As an example of this, the operational matrices of integration and differentiation for the Hartley and Walsh domain are shown in Figure (1). It can be seen from Figure (1) that structures of P and D of different domains varies and also the sparsity of the matrices is different which make some of them more efficient than others for applications such as optimal control and system analysis. In terms of approximations the use of different domains is also relevant. For instance it may be enough a single term Walsh series to represent the switching function in a power converter but the signal may required a long Hartley series to achieved the same approximation.

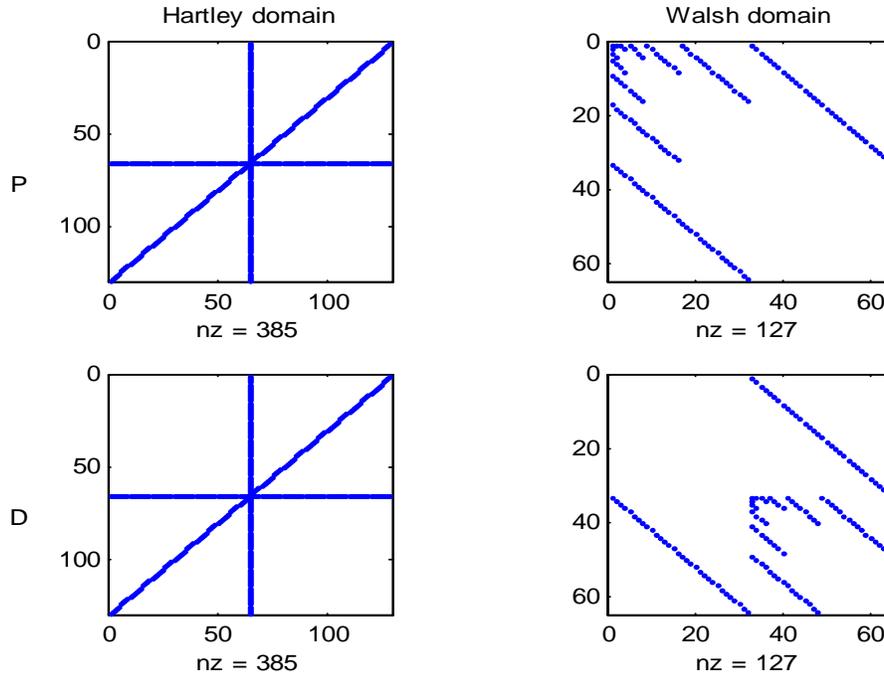


Figure (1) Operational matrices of integration, P , and differentiation, D , in Hartley and Walsh domains

Open literature also shows some other matrices related to orthogonal series expansions that are relevant especially for the analysis of time varying systems such as the product matrix and matrix of coefficients [16] but they are not addressed in this paper. In recent years many papers have written to define the operational matrices in several domains. Appendix A shows how matrix P and D may be found for the orthogonal series of Hartley used to obtained the reported here.

MACHINE MODEL

A state space mathematical model for synchronous machine is used in stability studies is used to validate the approach presented in this paper. There are two models that have been developed, one using currents as state variables and another using flux linkages. The flux linkage models have nonlinear characteristics due to saturation and are very difficult to measure. Continuous measurements of stator and field voltage and current are available and will be used as state variables in the current model. The synchronous machine model considered here is applicable to a round rotor. It has three stator windings, one field winding and two damper or amortisseur windings. Applying Park's transformation and with the appropriate simplifications, the state space equations for a synchronous machine can be written as given by Equation (4). Derivation of Equation (4) can be found in references [21] and [22],

$$\begin{bmatrix} v_0 \\ v_d \\ v_q \\ -v_f \\ v_D = 0 \\ v_Q = 0 \\ v_G = 0 \end{bmatrix} = A \begin{bmatrix} i_0 \\ i_d \\ i_q \\ i_f \\ i_D \\ i_Q \\ i_Q \end{bmatrix} + B \begin{bmatrix} \dot{i}_0 \\ \dot{i}_d \\ \dot{i}_q \\ \dot{i}_f \\ \dot{i}_D \\ \dot{i}_Q \\ \dot{i}_Q \end{bmatrix} \quad (A1)$$

$$A = \begin{bmatrix} r + 3r_n & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & r & \omega L_q & 0 & 0 & \omega kM_Q & \omega kM_G \\ 0 & -\omega L_d & r & -\omega kM_F & -\omega kM_D & 0 & 0 \\ 0 & 0 & 0 & r_F & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & r_D & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & r_Q & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & r_G \end{bmatrix}$$

$$B = \begin{bmatrix} L_0 + 3L_n & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & L_d & 0 & kM_F & kM_D & 0 & 0 \\ 0 & 0 & L_q & 0 & 0 & kM_Q & kM_G \\ 0 & kM_F & 0 & L_F & M_R & 0 & 0 \\ 0 & kM_D & 0 & M_R & L_D & 0 & 0 \\ 0 & 0 & kM_Q & 0 & 0 & L_Q & M_s \\ 0 & 0 & kM_G & 0 & 0 & M_s & L_G \end{bmatrix}$$

In practice, constants used in Equation (4) are obtained directly with help of the manufacturer's stability study data sheets, curve saturation and the equivalent circuit of a synchronous generator. The derivation and calculation of the parameters for the generator under study are given in reference [22].

2. PARAMETER IDENTIFICATION PROBLEM IN SYNCHRONOUS MACHINES

There are numerous applications for which the parameters of a synchronous generator need to be measured or estimated. For example, transient stability studies are routinely done within reliability areas in order to study the consequences of line switching and unit outages. In many cases, 'post mortem' studies are done to determine why the system responded the way it did – perhaps during a fault, unit outage, or component failure. For these studies, accurate models are needed. In most cases, manufacturers data are used to satisfy the parameter needs of synchronous generator models. However, saturation, nonlinearities, and machine aging may result in inaccuracies when manufacturers' data are used. In addition, there is an increasing need to use parameter identification to determine either incipient or existent failures: for example, a turn-to-turn short in a field winding of a large generator may be determined through the use of an on-line parameter estimator. When values of field resistance and inductance, and mutual inductances relating to the field winding are estimated as 'out of range', an alarm may be issued to indicate the failure.

Traditional methods of obtaining synchronous machine parameters are specified in IEEE and ICE standards and other national electric standards from many countries. A major drawback of these methods is that they are often conducted under off-line conditions. The parameters obtained by these methods may not truly characterize the synchronous machine under various loading conditions. Owing to this, on-line estimation of synchronous machines has arisen in recent years. On-line methods are most attractive due to minimal site/system impact and principally because they do not involve service interruption. However this 'nice' feature is obtained at the expenses of having to estimate the parameter under more constrained scenarios.

Any experimental design must take account of the constraints on the allowable experimental conditions. Typical constraints that might be met in practice are:

- amplitude on inputs and outputs or internal variables
- power constraints on inputs, outputs or internal variables
- total time available for the experiment

- total number of samples that can be take or analyzed
- maximum sampling rate
- availability of transducers and filters; and
- availability of hardware and software for analysis

Which of the above mentioned constraints are important in a particular experiment will depend upon the situation. On-line experiments designed for parameters of large utility synchronous generator, for instance, must be conducted bearing in mind that the impact on the power quality delivered must be minimized. In particular industrial loads allow only small percents voltage sags during few cycles. However, in most cases this constraint also reduces the information provided by the experiment because small disturbances will excite only some modes of the synchronous machine making impossible to observe estates and parameters related to modes that have not been excited by the particular inputs in case. Availability of the transducers is also an important restriction in parameter estimation of electric machines in general since there are not methods for measuring damping currents or field measurements are not easily instrumented. Based on all this concepts a three stage identification procedure is proposed for the linear machine model identification

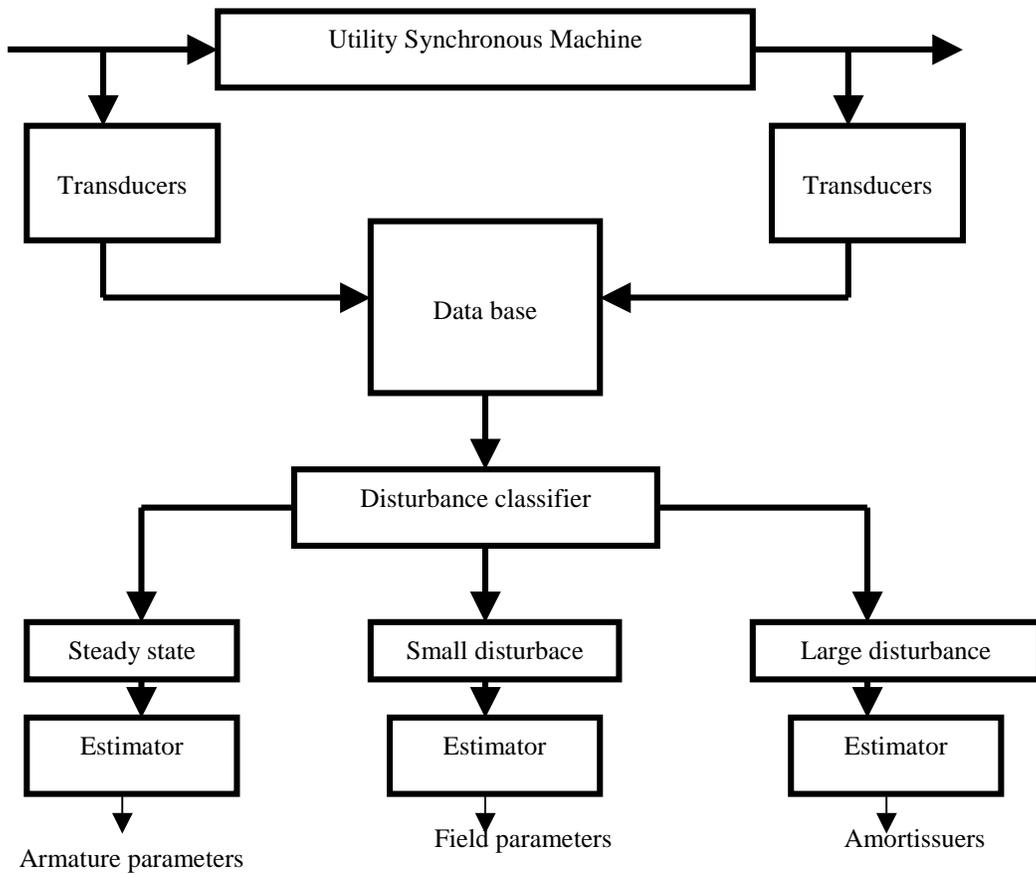


Figure (2) Estimation procedure.

In the first stage steady state data is used to identified parameters of synchronous machine armature, this include M_f , L_d , L_q and R_{fd} . In the second stage parameters identified in the first stage plus small disturbance recorded data are used to identified excitation field parameter, L_{fd} . The dynamic response generated during stage two is generated by 2% to 5% changes in the excitation field system reference. Such experimental testing may be conducted repeatedly under different operating conditions without any serious effect on the overall operating status system and loads. Stage three requires recording large disturbances and experimental design of this stage is restricted to record dynamics caused

by faults and other large transients caused by other than experimental design for identification purposes. The stages are illustrated in Figure (2).

4. THE FREQUENCY DOMAIN ESTIMATOR FORMULA

Consider a deterministic time-invariant single-input single-output (SISO) system with zero initial conditions of the type

$$A_n(\rho)y(t) = B_n(\rho)u(t) \quad (5)$$

where

$$\begin{aligned} A_n(\rho) &= \frac{d^n}{dt^n} + a_{n-1} \frac{d^{n-1}}{dt^{n-1}} + \dots + a_1 \frac{d}{dt} + a_0 \\ B_n(\rho) &= \frac{d^n}{dt^n} + b_{n-1} \frac{d^{n-1}}{dt^{n-1}} + \dots + b_1 \frac{d}{dt} + b_0 \end{aligned} \quad (6)$$

The problem is to determine (compute or estimate) the $2n$ parameters $a_0, a_1, \dots, a_{n-1}, b_0, b_1, \dots, b_{n-1}$ by using a record of input-output measurements $\{u(t), y(t)\}$ over an interval T . Without loss of generality, assume that

$$T = \{t; 0 \leq t \leq l\}.$$

If

$$T = \{t; 0 \leq t \leq t_f\}$$

the time interval is normalized by $\sigma = t / t_f$ to obtain the normalized interval ,

$$T = \{\sigma; 0 \leq \sigma \leq 1\}.$$

At this point, the synchronous machine model (Park's equations) is introduced in form by referring to one of many references, e.g., [21],

$$FF = -AZ - B\dot{Z}.$$

To solve the problem of parameter identification, the differential which involves the derivatives of the available input output data must first be converted to an algebraic model. Functions $y(t)$ and $u(t)$ are expanded in a Hartley series and the operational matrix of differentiation is successively employed to yield,

$$\begin{aligned} \frac{d^n}{dt^n} y(t) &= D^n Y T(t) & \frac{d^n}{dt^n} u(t) &= D^n U T(t), \\ \frac{d^{n-1}}{dt^{n-1}} y(t) &= D^{n-1} Y & \frac{d^{n-1}}{dt^{n-1}} u(t) &= D^{n-1} U T(t), \\ &\dots & \dots & \\ \frac{d}{dt} y(t) &= D Y T(t) & \frac{d}{dt} u(t) &= D U T(t). \end{aligned} \quad (7)$$

In these expressions, Y and U are the Hartley series coefficients of $y(t)$ and $u(t)$ respectively, i.e.,

$$U = [U_{-n} \quad \dots \quad U_0 \quad \dots \quad U_1] \quad (8)$$

$$Y = [Y_{-n} \quad \dots \quad Y_0 \quad \dots \quad Y_1]$$

Using Equations (5)- (7), the machine model becomes,

$$A_n(D)YT(t) = B_n(D)UT(t). \quad (9)$$

Defining the vectors

$$\begin{aligned} \theta_a &= [a_{n-1} \quad a_{n-1} \quad \dots \quad a_0] \\ \theta_b &= [b_{n-1} \quad b_{n-1} \quad \dots \quad b_0] \\ \theta &= [\theta_a \quad \theta_b] \end{aligned}$$

yields a model appropriate for the pseudoinverse solution,

$$\theta [D^{n-1}Y \quad D^{n-2}Y \quad \dots \quad Y \quad D^n U \quad D^{n-1}U \quad \dots \quad U]^T = D^n Y.$$

Or in compact form,

$$\theta Q = q. \quad (10)$$

Finally, solving for the parameters,

$$\theta = qQ^+ \quad (11)$$

where the '+' superscript means the pseudoinverse. Similar equations may be derived using the operational matrix of integration and the basic formula can be readily extended to account for multiple input multiple output (MIMO) systems as well as for accounting for noise effects without knowing its stochastic nature [23]

5. ESTIMATION OF ARMATURE CIRCUIT PARAMETERS

To illustrate the identification approach a one machine infinite bus is simulated for a specific steady state operating point. The constants in Park's state voltage equation [21-22] are obtained directly (or by simple calculation) from the manufacturers' stability study data sheet and saturation curves. The detailed derivation of these constants for the example shown here can be found in [22]. Table (1) lists the final per unit quantities that are used in exemplar studies to follow.

Table (1) Example machine parameters

Parameter	Value (per unit)	Description
$r_a = r_b$	.0027	Stator phase resistance
R_n	.00	Equivalent neutral resistance
$L_q =$	.72	Equivalent quadrature axis inductance
$M_Q =$	.27	Mutual inductance between phase and damper winding Q
$L_d =$	.80	Equivalent direct axis inductance
M_F	.339	Mutual inductance between phase winding and field winding
M_D	.339	Mutual inductance between phase winding and damper winding D
r_F	$.722 \cdot 10^{-4}$	Field resistance
r_D	.01254	Direct axis resistance
r_Q	.01632	Quadrature axis resistance
$L_0 =$ x_0	.150	Zero sequence inductance of stator
L_n	.00	Neutral inductance
$L_F =$	.1353	Field inductance
$M_R =$ L_{AD}	.64	Mutual inductance between field windings and damper winding D
$L_D =$ l_D	.1321	Rotor direct axis inductance
$L_Q =$ l_Q	.03059	Rotor quadrature axis inductance

The estimation of the armature parameters employs the Moore-Penrose pseudoinverse. This method is identical to the least squares estimation for linear systems.

After the one-machine infinite bus system is simulated and steady state measurable states and inputs are collected for estimation, Park's state voltage equation are written in the compact form

$$V = -AI - B\dot{I} \quad (12)$$

where V refers to the forcing functions ($dq0$ and field voltages), I is the state vector and A and B are the matrices of machine parameters. Since the armature parameters are estimated from steady state data the following model can be established in terms of dq axis variables taking into account that in this operating point damper winding currents and the rate of change of stator flux linkages are zero,

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = - \begin{bmatrix} r & \omega L_q & 0 \\ -\omega L_d & r & -\omega k M_F \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_F \end{bmatrix} \quad (13)$$

that for estimation purposes should be rewritten as

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = - \begin{bmatrix} i_d & \omega i_q \\ i_q & -\omega k i_F & -\omega i_d \end{bmatrix} \begin{bmatrix} r \\ M_F \\ L_d \\ L_q \end{bmatrix}. \quad (14)$$

Having collected measurable variables $v_d, i_d, v_q, i_q, v_F, i_F$ and the Hartley coefficients of each variable Equation (14) in the frequency domain becomes

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = - \begin{bmatrix} I_d & \omega I_q \\ I_q & -\omega k I_F & -\omega I_d \end{bmatrix} \begin{bmatrix} r \\ M_F \\ L_d \\ L_q \end{bmatrix} \quad (15)$$

where V_d, I_d, V_q, I_q , are the vectors containing the Hartley coefficients of variables v_d, i_d, v_q, i_q . Parameters are obtained from solution of Equation (11).

In order to obtain parameters from Equation (15), the one machine infinite bus system was simulated for v_{fd} disturbances within 2% and steady state data before and after the disturbances are utilized for estimation. The estimation results obtained from this experiment are outlined in Table (2). At this point the algorithm was also tested for noise corruption that often appears in real time measurements. The algorithm is tested for different values of SNR (signal / noise ratio). It can be seen that in absence of noise the algorithm is able to recover armature parameters without error.

Table (2) Estimates of armature parameters (per unit, steady state components used in estimation process)

Case		a	F	d	q
NR	ctual Values	.0027	.64	.80	.72
	estimate	.0027	.64	.8	.72
	error				
0^5	estimate	.0027	.64	.80	.72
	Error				
0^3	estimate	.00273	.6401	.8002	.7199
	Error	.133	.006	.0125	.0017
00	estimate	.002638	.6403	.8004	.72005
	Error	.26	.0183	.026	.003
00	estimate	.00271639	.6402	.80034	.720007
	Error	.607	.0125	.0212	

00	stimate		.6426	.8030	.72144	1
	Error		.1576	.183	.0877	0
0	stimate		.63075	.7893	.7144	1
	Error		.567	.6551	.339	0

It can be also seen from Table (2) that performance is very good even for cases for high levels of noise corruption. Parameters were recovered with an error of 1% for SNR levels up to 200:1. For larger levels of noise the parameter with the smallest value is impossible to recover. However, the remainder of the parameters can be recovered within remarkably low error even for considerable levels of noise such as SNR 10:1. In this case, the largest detected error was 1.2%.

6. DATA TRANSFORMATION

The measurements provided include v_{ab} , v_{bc} , v_{ca} , i_{as} , i_{bs} , i_{cs} , v_{fd} , and i_{fd} . Since the machine is connected to a large power system with almost balanced conditions, the electric frequency, ω , varies little from the rated line frequency. This facilitates the transformation since instead of using Park's transformation matrix at each time step, the following equations can be used. to converted abc quantities to $dq0$ axis equivalents

$$\begin{aligned}
 V_t &= \sqrt{(v_{as}^2 + v_{bs}^2 + v_{cs}^2)}/1.5 \\
 v_d &= V_t \sin \delta \\
 v_q &= V_t \cos \delta \\
 P &= i_{as} v_{as} + i_{bs} v_{bs} + i_{cs} v_{cs} \\
 Q &= (v_{ab} i_{cs} + v_{bc} i_{as} + v_{ca} i_{bs})/\sqrt{3} \\
 i_d &= (P \sin \delta + Q \cos \delta)/1.5 V_t \\
 i_q &= (P \sin \delta - Q \cos \delta)/1.5 V_t \\
 E_q \angle \delta &= V_t \angle \theta + I_t \angle \phi (R_a + jX_a).
 \end{aligned}$$

Data transformed from abc axis to a $dq0$ quantities is noisy due to sensor noise, electromagnetic interference and especially due to the AC to DC rectification process at the excitation system. Typical levels of noise are shown in Figure (3). Figure (3) shows steady state operating variables in $dq0$ quantities corresponding to a real operating point recorded at terminals of a large utility company.

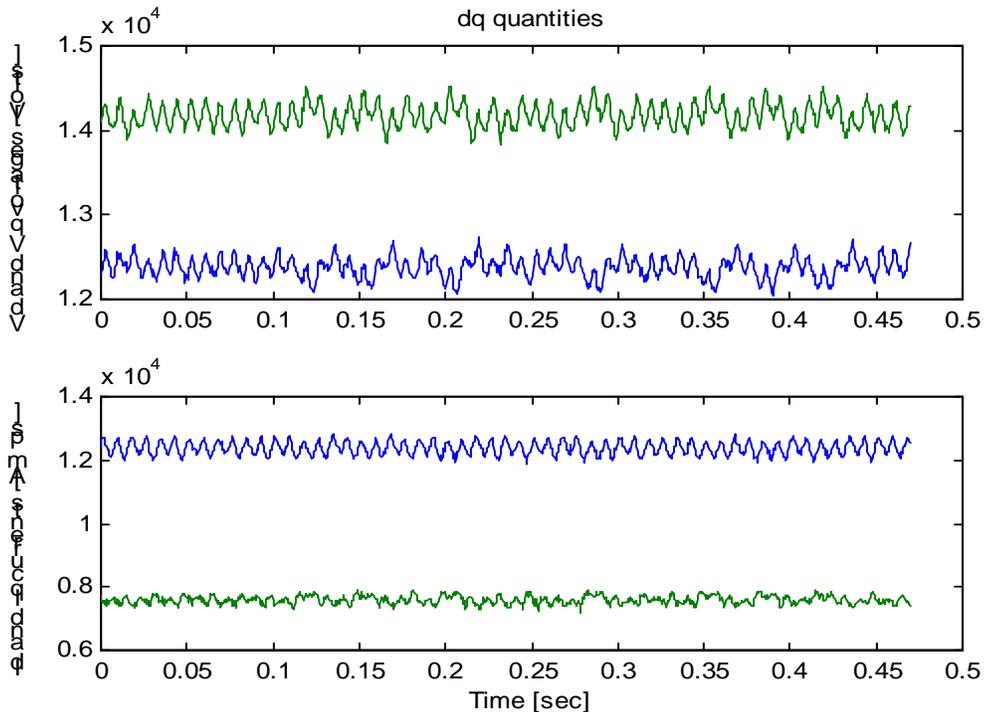


Figure (3) Steady state measurements in dq0 quantities

Additional to the transformation, some authors [5] proceed to filter measurements before parameter estimation is carried out. In the method proposed in this paper this filtering stage was not required because the truncation of the orthogonal series is playing the role of a low pass filter.

7. ESTIMATION OF ARMATURE CIRCUIT PARAMETERS FROM OPERATING DATA

In order to validate our approach two DFR data set with similar steady state operating conditions were used to estimate the armature parameters. The main variables describing the two steady state operating conditions are shown in Table (3).

Table (3) Operating point

Vd	Vq	Id	Iq	Ifd	Del	P	Q								
KV	kV	KA	KA	kA	degrees	W	Mvar								
41	16.	3	5.1	42	13.	6	8.2	7	2.9	65	72.	3.77	39	100	-
82	15.	3	7.7	58	12.	9	8.2	8	2.9	96	63.	4.78	39	50.72	-

It was impossible to recover r from the limited sets of data available but considering that the sensitivity of the parameters M_f , L_d and L_q is negligible for changes in r , this value was set constant at the manufacturer's value.

Table (4) summarizes the estimated parameters for the machine cited earlier. The manufacturer's data are shown for comparison only: there may be disagreement between estimated and manufacturer's data due to estimation error and parameter variation with operating point, saturation, and age.

Table (3) Estimated values for an actual synchronous machine (note: 'a' is the field / stator turns ratio)

Parameter	Estimate (mH)	Manufacturer's value (mH)
AL_a		61.3
L_d		8.0
L_q		5.0

The accuracy of the parameters is shown by simulating outputs using model in Equation () and the estimated parameters. Figure (4) shows both real and simulated response for one of the data sets. Similar results were obtained for the other data set.

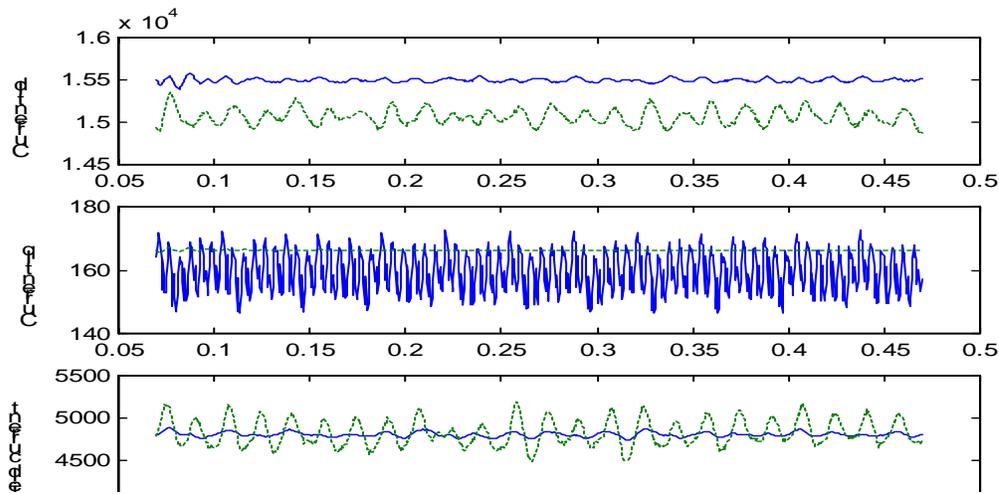


Figure (4). Real and simulated operating data

8. ESTIMATION OF FIELD RESISTANCE DEGRADATION

The parameter estimation algorithm was developed originally to detect field turns shorts for the synchronous generator under study. The basic approach was to use the algorithm for estimating the field winding parameters, mainly field winding resistance, for different time windows so that incipient changes of this parameter could be identified and accordingly corrective action taken.

A field winding failure occurred and reported to authors while this research was undertaken. Two different data sets recorded before (data set 1) and after (data set 2) the field winding failure were used for the parameter identification as listed in Table (4). As can be seen from Table (4), the estimated value of r_f has changed by 4.7 % from its estimated value during the field failure. In identifying parameter variation, the operating point of the machine needs to be taken into consideration. This generally includes temperature of the windings as well as electrical parameters. However, for simplified purposes of this paper, the change in r_f illustrated in Table (4) demonstrates the potential use of the Hartley estimation algorithm for the determination of turn-to-turn winding faults.

Table (4) Operating points for the data sets recorded for field winding failure detection

ata set	A ctive power, P (pu)	R eactive Power, Q (pu)	δ (degrees)	r_f (pu)
1	0.90372	0.07727	1.66	.00983
2	.67808	.02153	8.2479	.00943

9. CONCLUSIONS

The main conclusion of the study is that the Hartley series is useful for the estimation of synchronous machine parameters, including on-line estimation. The accuracy of typical synthetic data tests indicates that discrepancies in parameters (estimate vs. given) in the order of 1% or less are attainable through SNR 50:1. The algorithm was also evaluated using steady state operating data. The parameters obtained are in the range of the values saturated values of the machine. One potential application of the estimator is in the detection of turn-to-turn shorts in the field winding of synchronous generators.

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APPENDIX A

THE HARTLEY SERIES AND THEIR OPERATIONAL PROPERTIES

In this section a brief review of the Hartley series is given. It can be stated that the kernel function of the familiar Fourier transform and Fourier series is the complex exponential, $e^{-j\omega t}$. The Hartley transform and series utilizes a similar frequency based kernel, the function $\cos(\omega t) + \sin(\omega t)$, also known as the *cosine-and-sine* function or $cas(\omega t)$. Thus Hartley technology does not employ complex numbers. Reference [24] is a definitive work on the subject.

The Hartley series basis function $T(t)$ is denoted as (note that the prime notation indicates transposition),

$$T(t) = [T_{-n} \quad \dots \quad T_{-1} \quad T_0 \quad T_1 \quad \dots \quad T_n]'$$

$$T_n = cas(nvt) = \cos(nvt) + \sin(nvt).$$

$$\frac{dT(t)}{dt} = \begin{bmatrix} \frac{dT_{-n}(t)}{dt} \\ \vdots \\ \frac{dT_{-1}(t)}{dt} \\ 0 \\ \frac{dT_1(t)}{dt} \\ \vdots \\ \frac{dT_n(t)}{dt} \end{bmatrix} = \begin{bmatrix} -nvcas(nvt) \\ \vdots \\ -vcas(vt) \\ 0 \\ vcas(-vt) \\ \vdots \\ nvcas(-nvt) \end{bmatrix}$$

or in matrix form

$$\frac{dT(t)}{dt} = DT(t) \tag{A6}$$

where D is the operational matrix of differentiation which has the following form

$$D = \begin{bmatrix} & & & & -nv \\ & & & & \ddots \\ & & & & -v \\ & & & 0 & \\ & & & v & \\ & & \ddots & & \\ nv & & & & \end{bmatrix}$$

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