Methodology Development for Estimation of Armature Circuit and Field Winding Parameters of Large Utility Generators

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Abstract: This paper presents a methodology to estimate armature circuit and field winding parameters of large utility generators using the synthetic data obtained by the machine natural *abc* frame of reference simulation. First, a one-machine infinite bus system including the machine and its excitation system is simulated in *abc* frame of reference by using parameters provided by the machine manufacturer. A proper data set required for estimation is collected by perturbing the field side of the machine in small amounts. The recursive maximum likelihood (RML) estimation technique is employed for the identification of armature circuit parameters. Subsequently, based on the estimates of armature circuit parameters, the field winding and some damper parameters are estimated using an Output Error Estimation (OEM) technique. For each estimation case, the estimation performance is also validated with noise corrupted measurements. Even in case of remarkable noise corruption, the agreement between estimated and actual parameters is quite satisfactory.

Keywords: Generator modeling, parameter estimation, on-line tracking, field winding degradation.

I. INTRODUCTION

The need for on-line estimation of synchronous generator parameters has arisen in recent years. On-line estimation is attractive since it does not require service interruption to identify machine parameters. Also, machine parameters can deviate substantially during on-line operation at different loading levels. This is primarily due to saturation, internal temperature, machine aging and incipient faults within the machine [1]. The motivation for on-line estimation is to detect incipient failures that slowly develop. Based on this, preventative maintenance measures can be taken into consideration before a forced outage is dictated.

The parameter identification problem of synchronous generators has been studied by many researchers [1-9]. Most of these studies are mainly conducted based on conventional *dqo* frame of reference models of synchronous generators. In spite of its simple structure, *dqo* models are not capable of simulating unbalanced and rectifier type loading conditions [10-11]. Also, due to simplifying assumptions associated with these models, it is difficult to include the higher space harmonics, which exist in the real machine. A more accurate approach to this problem is to simulate the system with direct phase quantities. By this way, various loading conditions such as sudden application and removal of balanced and unbalanced loads, rectifier loads, symmetrical and asymmetrical faults can be easily investigated.

In this study, an assumed large utility generator is simulated in the *abc* reference frame and small excitation disturbance data are generated. It is assumed that the machine model order is known (i.e. the number of differential equations). The generated data are used to estimate the machine parameters. The effects of measurement noise corruption, which is inevitable in real time data acquisition, are also investigated. For large noise corruption levels, which deteriorate estimation performance, the effect of initialization on outcome of estimation is also studied. It has been shown that the parameter estimates for both identification procedures are quite satisfactory even with noise corrupted measurements.

II. PROBLEM DEFINITION

The objective of this study is to investigate and develop a methodology to determine the armature circuit and field winding parameters of a large utility generator. For this purpose, the following problems are studied:

1. Machine modeling and simulation in direct phase quantities (*abc* frame of reference) to generate small excitation disturbance data
2. Estimation of armature circuit parameters
3. Estimation of field winding parameters along with *d*-axis damper winding parameters
4. Performance validation with noise corrupted measurement for each estimation procedure

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The small disturbance test data are generated by changing the excitation system reference voltage in such a way that the field voltage of the machine is stepped up or down by 2% to 10%. These data are later used for estimation of machine parameters by using recursive maximum likelihood (RML) and output error method (OEM) techniques. These techniques are explained in the following paragraphs.

A. Recursive Maximum Likelihood Method

Consider the system defined by the following model,

$$Y = H\theta + V \tag{1}$$

where, Y is the system output vector, H is the measurement transformation matrix, θ is the parameter vector to be estimated and V is the measurement noise (assumed to be Gaussian and independent). The RML algorithm can be used to identify the vector θ as follows: since the algorithm is recursive i.e. processing the data one sampling instant at a time, Y and H need to be represented as Y_k and H_k at the data sampling instant k. Then based on the measurement update, the unknown vector, θ, can be estimated recursively by the following steps [4]:

1. Measurement noise variance and mean update, σ_{k+1} and m_{k+1}

$$\begin{aligned} \sigma_{k+1} &= \sigma_k + \frac{1}{k+1}\left[\frac{k}{k+1}(Y_{k+1} - m_k)^2 - \sigma_k\right] \\ m_{k+1} &= m_k + \frac{1}{k+1}(Y_{k+1} - m_k) \end{aligned} \tag{2}$$

2. Error covariance update, R_{k+1}

$$R_{k+1} = R_k - R_k H_{k+1}(H_{k+1}^T R_k H_{k+1} + \sigma_{k+1})^{-1} H_{k+1}^T R_k \tag{3}$$

3. Estimation update, $\hat{\theta}_{k+1}$

$$\hat{\theta}_{k+1} = \hat{\theta}_k + R_{k+1} H_{k+1} \sigma_{k+1}{}^{-1} (Y_{k+1} - H_{k+1}^T \hat{\theta}_k) \tag{4}$$

In Eqs. (2)-(4), $\hat{\theta}_k$ and $\hat{\theta}_{k+1}$ are the estimated vectors of θ based on the measurement up to k th and $(k+1)$ th data points. In addition, the recursions by Eq. (2) to (4) are started using $\hat{\theta}_0 = 0$ and very large R_0. An assumption of a very large value of R_o specifies the absence of confidence in the initial value of $\hat{\theta}_0$ (i.e. $\hat{\theta}_0 = 0$).

B. Output Error Estimation Method

The output error estimation method is based on the minimization of the cost function of estimation error. This cost function can be stated as follows:

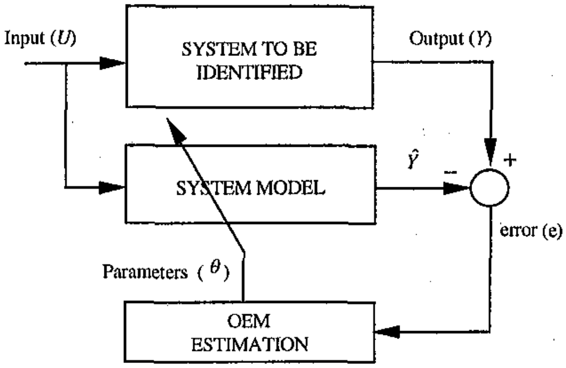

Fig. 1 OEM identification scheme

$$V(\hat{\theta}) = \frac{1}{N}\sum_{k=0}^{N}[e^T(k,\hat{\theta})e(k,\hat{\theta})] \tag{5}$$

where V is the value of the cost function, $\hat{\theta}$ is the parameter vector to be estimated, N is the number of samples required for estimation and e is the error between estimated and measured output.

The cost function V can be minimized by using the iterative Gauss Newton method [5]. The iterative identification scheme for OEM estimation is shown in Fig. 1. The algorithm steps can be found in Appendix 2.

C. Validation with Noise Corrupted Measurements

Measurement data acquired from testing of a synchronous machine is generally noise corrupted. The excitation system AC to DC conversion process, quantization errors in sensors and the surrounding electromagnetic interference are some of the contributing factors. To be able to analyze the effect of noise on the outcome of estimation, measurements obtained from the simulation of the one-machine infinite-bus system are corrupted by adding zero mean independent white noise to the synthetic data. The noise corruption equation is given by,

$$s_n(k) = s(k) + \alpha(k)\, v(k) \tag{6}$$

where s_n and s represent noise corrupted and noise free measurements, respectively, and $v(k)$ is the white noise signal with normal distribution $n(0,1)$. The $\alpha(k)$ term is defined as

$$\alpha(k) = \left|\frac{s(k)}{SNR}\right| \qquad SNR = \left[\frac{\sum_{k=1}^{N} s^2(k)}{\sum_{k=1}^{N}(\alpha(k)v(k))^2}\right]^{1/2}$$

where SNR is the signal to noise ratio.

Noise corruption is performed for different levels of *SNR* from which RML and OEM estimation performance is determined.

III. MACHINE MODEL IN DIRECT PHASE QUANTITIES

The structure of the machine model in natural *abc* axis can be obtained by simply using the following basic electromagnetic circuit equations for stator and rotor side [12-13],

$$\boldsymbol{v}_{abcs} = -\boldsymbol{R}_s \boldsymbol{i}_{abcs} + p\boldsymbol{\lambda}_{abcs} \tag{7}$$

$$\boldsymbol{v}_{qdr} = -\boldsymbol{R}_r \boldsymbol{i}_{qdr} + p\boldsymbol{\lambda}_{qdr} \tag{8}$$

where p denotes time derivative, also, flux linkages,

$$\boldsymbol{\lambda}_{abcs} = -\boldsymbol{L}_s \boldsymbol{i}_{abcs} + \boldsymbol{L}_{sr} \boldsymbol{i}_{qdr} \tag{9}$$

$$\boldsymbol{\lambda}_{qdr} = -(\boldsymbol{L}_{sr})^T \boldsymbol{i}_{abcs} + \boldsymbol{L}_r \boldsymbol{i}_{qdr}\,. \tag{10}$$

A detailed discussion of these equations can be found in reference [12]. Since inductance matrices for this model are functions of rotor angle θ_r (except rotor self inductance matrix $\boldsymbol{L}_r$), their time derivative should be taken into account for simulation. Then, in general form (7), (8), (9) and (10) can be combined as follows by defining currents as system states and voltages as inputs,

$$\boldsymbol{v} = \{-\boldsymbol{R} + \omega_r p\boldsymbol{L}(\theta_r)\}\, \boldsymbol{i} + \boldsymbol{L}(\theta_r)\, p\boldsymbol{i}. \tag{11}$$

The whole system can be illustrated as follows:

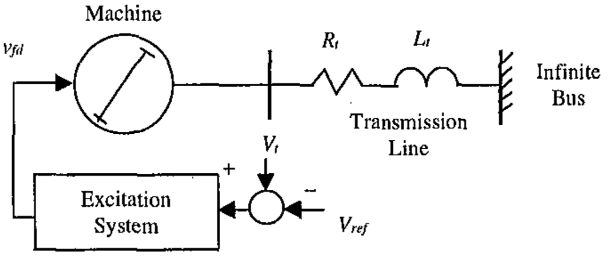

Fig.2 One-machine infinite-bus system

The excitation system (with 2nd order linear structure) controls the terminal voltage V_t based on reference voltage V_{ref} by adjusting the field voltage v_{fd}.

This simulation provides measurable synchronous generator quantities, v_{as}, v_{bs}, v_{cs}, i_{as}, i_{bs}, i_{cs}, δ and i_{fd} which are then transformed in *dq* axis and used for estimation of machine parameters. In addition, measurable generator quantities are noise corrupted and then the effect of noise on the estimation process is evaluated.

The system parameters can be found in Appendix 1.

IV. ESTIMATION OF ARMATURE CIRCUIT PARAMETERS

After the one-machine infinite bus system is simulated for a specific steady state operating point defined by rotor angle and field current, only measurable states and inputs are collected for estimation. Note that, the machine field is disturbed in this stage of estimation for proper identification of armature circuit parameters [4]. The quantities needed to be used for the estimation procedure are v_{as}, v_{bs}, v_{cs}, i_{as}, i_{bs}, i_{cs}, δ, i_{fd}.

The following model which is used for estimation of armature circuit parameters can be established in terms of *dq* axis variables assuming the damper winding currents and the rate of change of stator flux linkages are zero,

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} -i_d & 0 & \omega_e i_q & 0 \\ -i_q & \frac{2}{3}\omega_e i_{fd} & 0 & -\omega_e i_d \end{bmatrix} \begin{bmatrix} R_a \\ aL_{ad} \\ L_q \\ L_d \end{bmatrix} + \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}. \tag{12}$$

The above equation is in the form of $Y = H\theta + V$ that was described in Equation (1), where, $a = N_{fd}/N_s$ is the field to stator turns ratio, v_1 and v_2 represent the measurement noise. Measurement noise elements v_1 and v_2 are varied to examine their effect on the estimation procedure.

These are the well known steady state equations of a synchronous machine for the armature side in rotor reference frame [12]. In order to be able to use this model, measurable quantities are needed to be converted to *dq* axis equivalents as follows [4]:

1) Find the terminal voltage peak value V_t

$$V_t = \sqrt{(v_{as}^{\;2} + v_{bs}^{\;2} + v_{cs}^{\;2})/1.5} \tag{13}$$

2) Find d and q axis voltages v_d and v_q

$$\begin{aligned} v_d &= V_t \;\sin\delta \\ v_q &= V_t \;\cos\delta \end{aligned} \tag{14}$$

3) Compute active and reactive powers P and Q

$$\begin{aligned} P &= i_{as}v_{as} + i_{bs}v_{bs} + i_{cs}v_{cs} \\ Q &= (\, v_{ab}i_{cs} + v_{bc}i_{as} + v_{ca}i_{bs})/\sqrt{3} \end{aligned} \tag{15}$$

where, $v_{ab}=v_{as}-v_{bs}$, $v_{bc}=v_{bs}-v_{cs}$, $v_{ca}=v_{cs}-v_{as}$.

4) Find d and q axis voltages i_d and i_q

$$\begin{aligned} i_d &= (\,P\,\sin\delta \;+\; Q\,\cos\delta\,)\,/\,1.5V_t \\ i_q &= (\,P\,\cos\delta \;-\; Q\,\sin\delta\,)\,/\,1.5V_t \end{aligned} \tag{16}$$

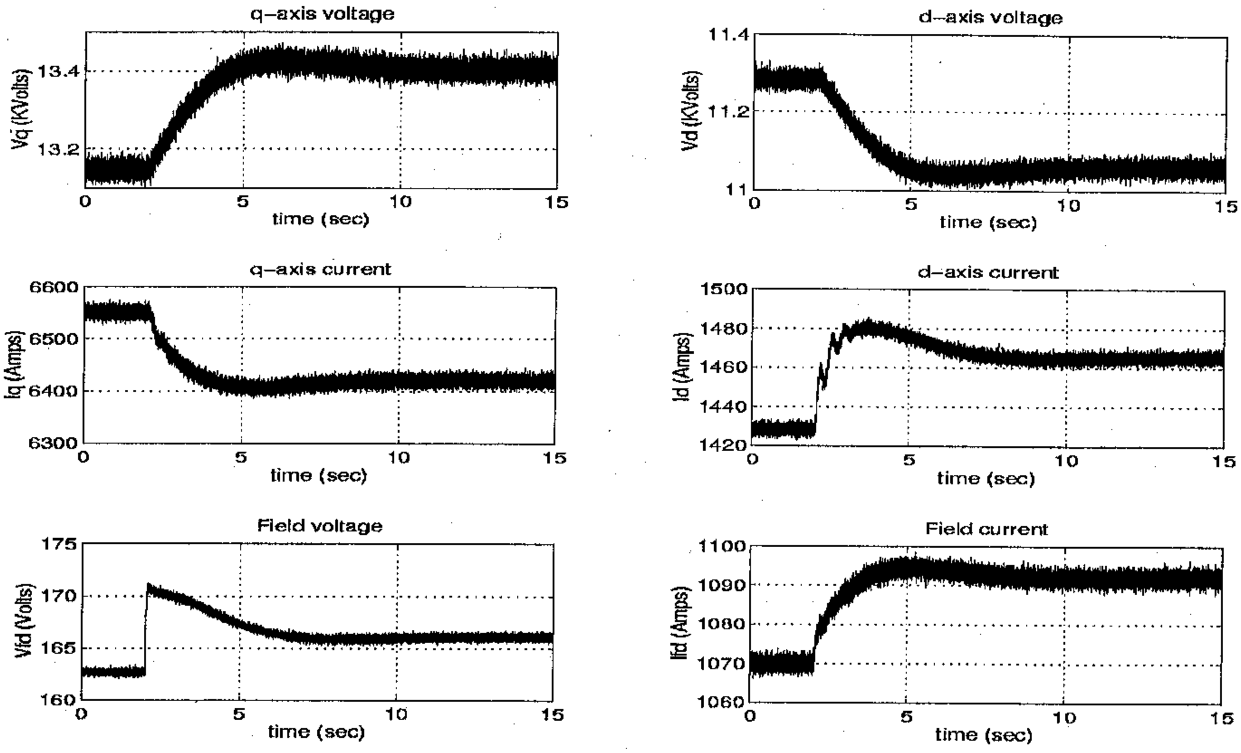

Fig. 3 Simulated small disturbance responses with noise corruption for which parameter estimates converge

Having calculated v_d, i_d, v_q, i_q and i_{fd} quantities, estimation procedure can be initialized. The parameter vector to be estimated is $\theta = [\ R_a \quad aL_{ad} \quad L_q \quad L_d\ ]$. The RML method is employed to estimate θ from measurable quantities. All parameters are initialized at zero.

Table 1: The estimates of armature circuit parameters from one machine infinite bus simulation (steady state parts used)

Case		R_a (Ω)	aL_{ad} (mH)	L_q (mH)	L_d (mH)
Initial Values		0	0	0	0
Actual Values		.0046	58.5838	4.5719	4.7845
Noise Free	Estimates	.0046	58.5822	4.5719	4.7838
	% Errors	0.00	0.00	0.00	0.01
SNR= 10000:1	Estimates	.0046	58.5872	4.5719	4.7860
	% Errors	0.00	0.01	0.00	0.03
SNR= 1000:1	Estimates	.0047	58.6131	4.5720	4.7934
	% Errors	2.17	0.05	0.00	0.19
SNR= 500:1	Estimates	x	59.2250	4.5726	5.0872
	% Errors	x	1.09	0.02	6.32
SNR= 100:1	Estimates	x	60.1955	4.5824	5.3847
	% Errors	x	2.75	0.23	12.5

x: did not converge

The measurement data obtained from the one machine infinite bus simulation is manipulated in such a way that the contribution of damper winding currents and the rate of change of stator flux linkages can be neglected. To do this, only the steady state pieces of the data (given in Fig.3) before and after the disturbance are utilized for estimation. The estimation results given in Table 1 for 2% v_{fd} disturbance shows the perfect agreement between estimated and actual values in case of no noise corruption. Also, the algorithm is tested for different levels of *SNR* as explained in Section II.*C*. As can be seen from Table 1, for randomly initialized values, parameter estimates are reasonably reliable up to *SNR* = 500:1 except for R_a which can not be recovered beyond the *SNR* = 1000:1 level. Noise corrupted measurements and estimated parameter trajectories for *SNR* = 1000:1 are given in Fig. 3 and Fig. 4, respectively.

Table 2: Noise corrupted estimates of armature circuit parameters for fixed R_a=.0046 (steady state parts used)

Case		aL_{ad} (mH)	L_q (mH)	L_d (mH)
Initial Values		0	0	0
Actual Values		58.5838	4.5719	4.7845
SNR= 500:1	Estimates	58.5748	4.5719	4.7800
	% Errors	0.02	0.00	0.09
SNR= 100:1	Estimates	59.1658	4.5726	5.0767
	% Errors	0.99	0.02	6.11
SNR= 50:1	Estimates	59.5369	4.5716	5.2596
	% Errors	1.63	0.01	9.93

In order to improve estimates of aL_{ad}, L_q and L_d beyond *SNR*=500:1, R_a is fixed to its actual value and estimations are repeated. As seen from Table 2, the estimates are reasonably corrected by fixing R_a=.0046. However, beyond *SNR*=50:1, it is still impossible to recover some parameters.

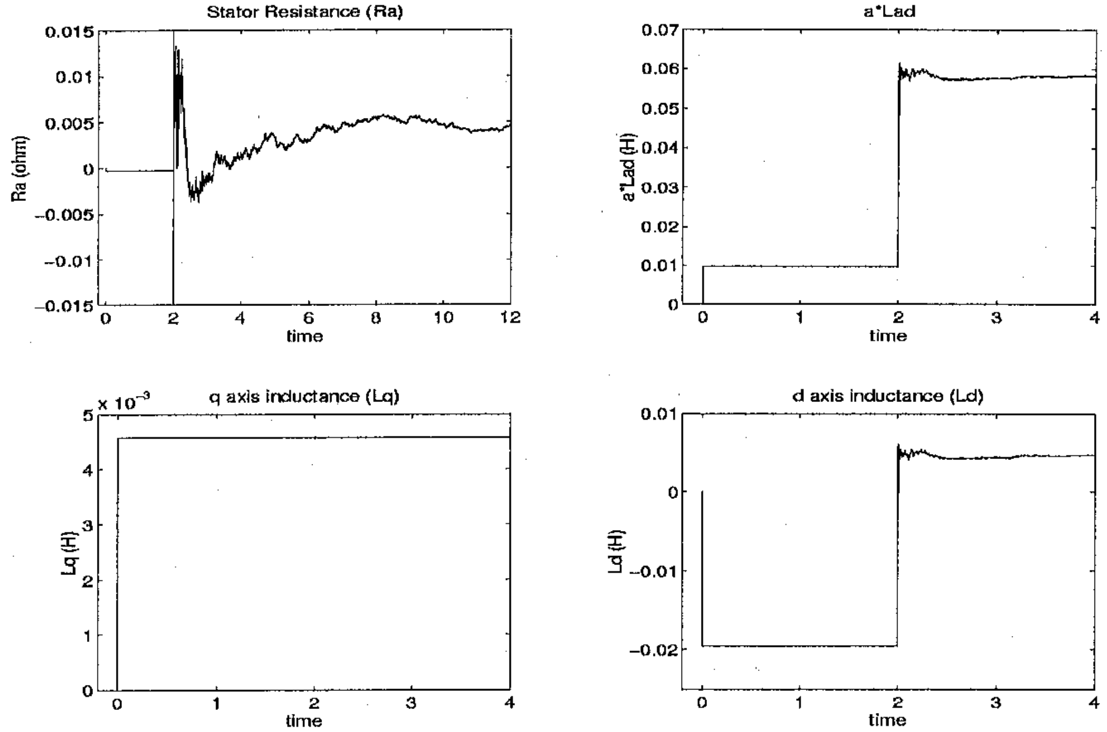

Fig. 4 Trajectories of recursively estimated armature circuit parameters for *SNR*=1000:1

VI. ESTIMATION OF FIELD WINDING AND DIRECT AXIS DAMPER WINDING PARAMETERS

A model which also includes damper winding contributions is presented in this section. To establish this model, the synchronous machine standard d-axis circuit [13] (Fig. 5) should be taken into consideration.

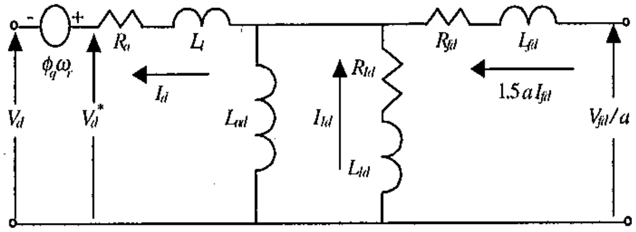

Fig. 5 Synchronous machine standard d-axis model

Normally, d- and q-axis models are coupled due to the speed voltages, $\phi_q\omega_r$ and $\phi_d\omega_r$. In order to decouple the model, the voltages V_d^* and V_q^* should be computed as follows. The stator voltages in rotor reference frame are,

$$v_d = -R_a i_d - \phi_q\omega_r + p\phi_d \tag{17}$$

$$v_q = -R_a i_q + \phi_d\omega_r + p\phi_q. \tag{18}$$

From (17) and (18), flux dynamics are established as,

$$p\begin{bmatrix}\phi_d \\ \phi_q\end{bmatrix} = \begin{bmatrix} 0 & \omega_r \\ -\omega_r & 0\end{bmatrix}\begin{bmatrix}\phi_d \\ \phi_q\end{bmatrix} + \begin{bmatrix} v_d + R_a i_d \\ v_q + R_a i_q\end{bmatrix} \tag{19}$$

Once flux terms are computed using (19), the voltages v_d^* and v_q^* can be found as,

$$v_d^* = v_d + \phi_q\omega_r \tag{20}$$

$$v_q^* = v_q - \phi_d\omega_r. \tag{21}$$

Finally, based on v_d^*, the decoupled d-axis dynamic is,

$$\begin{bmatrix} v_d^* \\ v_{fd} \\ 0\end{bmatrix} = \begin{bmatrix} -R_a & 0 & 0 \\ 0 & R_{fd} & 0 \\ 0 & 0 & R_{1d}\end{bmatrix}\begin{bmatrix} i_d \\ i_{fd} \\ i_{1d}\end{bmatrix} + \begin{bmatrix} -(L_l + L_{ad}) & aL_{ad}/1.5 & L_{ad} \\ -aL_{ad} & a^2(L_{fd} + L_{ad})/1.5 & aL_{ad} \\ -L_{ad} & aL_{ad}/1.5 & L_{1d} + L_{ad}\end{bmatrix} p\begin{bmatrix} i_d \\ i_{fd} \\ i_{1d}\end{bmatrix} \tag{22}$$

The model (22) is not in proper form for estimation. To render it amenable for state space representation, it should be rearranged. This is accomplished by taking current vector i as outputs and voltage vector v as inputs of the system, then the state space form is,

$$pi = -L^{-1} R\, i + L^{-1} v. \tag{23}$$

Armature circuit parameters obtained from the first test are fixed in model (22). Then the parameter vector to be estimated is $\Theta = [\, R_{fd}\ L_{fd}\ R_{1d}\ L_{1d}\,]$. Note that the parameters to be estimated are not only field side parameters but also *d*-axis damper winding parameters.

By using model (23) with OEM estimation, the parameter vector Θ can be estimated. The estimation results for noise free and noise corrupted measurements for 2%, 7% and 11% excitation disturbances are given in Tables 3, 4 and 5, respectively. All parameters are initialized to 20% of the actual values.

Table 3: The estimates of field winding and *d*-axis damper winding parameters for 2% excitation disturbance

Case		R_{fd} (Ω)	L_{fd} (mH)	R_{1d} (Ω)	L_{1d} (mH)
Initial Values		0.0304	0.0607	0.0025	0.0219
Actual Values		0.1521	0.3134	0.0126	0.1096
Noise Free	Estimates	0.1521	0.3126	0.0126	0.1135
	% Errors	0.00	0.26	0.00	3.56
SNR= 10000:1	Estimates	0.1521	0.3151	0.0127	0.1175
	% Errors	0.00	0.57	0.79	7.21
SNR= 5000:1	Estimates	0.1521	0.3153	0.0127	0.1196
	% Errors	0.00	0.61	0.79	7.21
SNR= 3000:1	Estimates	0.1520	0.3546	0.0155	0.1796
	% Errors	0.07	13.1	23.0	63.9
SNR= 1000:1	Estimates	0.1522	0.2275	0.0083	x
	% Errors	0.07	27.4	34.1	x

x: did not converge

Table 4: The estimates of field winding and *d*-axis damper winding parameters for 7% excitation disturbance

Case		R_{fd} (Ω)	L_{fd} (mH)	R_{1d} (Ω)	L_{1d} (mH)
Initial Values		0.0304	0.0607	0.0025	0.0219
Actual Values		0.1521	0.3134	0.0126	0.1096
Noise Free	Estimates	0.1521	0.3126	0.0126	0.1136
	% Errors	0.00	0.26	0.00	3.65
SNR= 10000:1	Estimates	0.1521	0.3116	0.0125	0.1121
	% Errors	0.00	0.57	0.79	2.28
SNR= 5000:1	Estimates	0.1521	0.3141	0.0127	0.1159
	% Errors	0.00	0.22	0.79	5.75
SNR= 3000:1	Estimates	0.1520	0.3243	0.0133	0.1317
	% Errors	0.07	3.48	5.56	20.2
SNR= 1000:1	Estimates	0.1521	0.3246	0.0134	0.1361
	% Errors	0.00	3.57	6.35	24.2

It is clear that the OEM estimation with larger excitation disturbance has a better noise rejection feature compared to the results in Tables 3, 4 and 5.

As can be observed from the tables, the field winding parameter estimates are less sensitive to noise, compared to *d*-axis damper winding parameters. R_{fd} estimates are reasonably accurate and consistent. The estimates of parameters R_{1d} and L_{fd} stay somewhat reasonable as noise contribution increases, however estimation error for L_{1d} becomes significant beyond *SNR*=5000:1.

Table 5: The estimates of field winding and *d*-axis damper winding parameters for 11% excitation disturbance

Case		R_{fd} (Ω)	L_{fd} (mH)	R_{1d} (Ω)	L_{1d} (mH)
Initial Values		0.0304	0.0607	0.0025	0.0219
Actual Values		0.1521	0.3134	0.0126	0.1096
Noise Free	Estimates	0.1521	0.3127	0.0126	0.1137
	% Errors	0.00	0.22	0.00	3.74
SNR= 10000:1	Estimates	0.1521	0.3132	0.0126	0.1145
	% Errors	0.00	0.06	0.00	4.47
SNR= 5000:1	Estimates	0.1521	0.3124	0.0125	0.1134
	% Errors	0.00	0.32	0.79	3.47
SNR= 3000:1	Estimates	0.1520	0.3206	0.0131	0.1254
	% Errors	0.07	2.30	3.97	14.4
SNR= 1000:1	Estimates	0.1521	0.2986	0.0117	0.0946
	% Errors	0.00	4.72	7.14	13.7

VII. CONCLUSION

A new methodology for estimation of armature circuit and field winding parameters of large utility generators is presented. The machine is simulated in the natural *abc* frame of reference to accommodate unbalanced operation modes. This simulation provides measurable synchronous generator quantities which are then used for estimation of machine parameters. In the first stage, armature circuit parameters are estimated from small excitation disturbance data using the RML estimation method. In the second stage, field winding parameters along with direct axis damper winding parameters are estimated for different levels of excitation disturbance. Estimation results reveal that good estimates of the actual parameters can be obtained with proper initialization. Also, estimation procedures are repeated with noise corrupted measurements to investigate noise effects on the estimation process. The study shows that noise corruption problems can be effectively handled with the RML algorithm for estimation of armature circuit parameters up to a certain point. Although excitation disturbance increase improves OEM estimation performance, below a certain *SNR*, estimation of certain machine parameters is not possible. Future work is required to improve the noise rejection feature of estimation of field winding parameters and implement this methodology on a data set acquired from the real machine.

VIII. ACKNOWLEDGEMENTS

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IX. REFERENCES

[1]. El-Serafi A.M., Abdallah A.S., El-Sherbiny M.K., Badawy E.H., "Experimental Study of the Saturation and the Cross-Magnetizing Phenomenon in Saturated Synchronous Machines," *IEEE Trans. On Energy Conversion*, Vol.EC-3, Dec. 1988, pp.815-823.

[2]. Chiang-Tsung Huang, Yung-Tien Chen, Chung-Liang Chang, Chung-Yi Huang, Hsiao-Dong Chiang and Jin-Cheng Wang, "On-line Measurement-Based Model Parameter Estimation for Synchronous Generators: Model Development & Identification Schemes," IEEE Transactions on Energy Conversion v. 9 (June '94) pp.330-6.

[3]. Jintao Ma, B.W. Hogg, Nan Zhiyuan and Yang Yihan, "On-line Decoupled Identification of Transient and Sub-Transient Generator Parameters," *IEEE Transactions on Power Systems*, Vol. 9, No.4, November 1994.

[4]. H. Tsai, A. Keyhani, J.A. Demcko, and R.G. Farmer, "On-line synchronous machine parameter estimation from small disturbance operating data," *IEEE Transactions on Energy Conversion* v 10 n 1 Mar 1995. Pp.25-36.

[5]. A. Keyhani, S. Hao, and R. P. Schulz, "Maximum likelihood estimation of generator stability constants using SSFR test data," *IEEE Trans. Energy Conversion*, vol. 6, pp. 140-154, Mar. 1991.

[6]. I.M Canay, "Determination of Model Parameters of Machines from Reactance Operators $x_d(p)$, $x_q(p)$: Evaluation of Standstill Frequency Response Test)," *IEEE Transactions on Energy Conversion*, vol. 8, June 1993. Pp.272-279.

[7]. James L. Kirtley Jr., "On Turbine-Generator Rotor Equivalent Circuit Structures for Empirical Modeling of Turbine Generators," *IEEE Trans. PWRS*-9(1), 1994, pp. 269-271.

[8]. I. Kamwa, P. Viarouge, J. Dickinson, "Identification of Generalized Models of Synchronous Machines from Time-Domain Tests," *IEE Proc. C*, 138 (6), Nov. 1991. Pp. 485-498.

[9]. Salon S. J., "Obtaining Synchronous Machine Parameters from Test," *Symposium on Synchronous Machine Modeling for Power Systems Studies*. Paper No. 83THO101-6-PWR. Available from IEEE Service Center, Piscataway, NJ,USA.

[10]. Subramaniam, P., and Malik, O.P., "Digital simulation of synchronous generator in direct-phase quantities," *Proc. IEE*, 1971, **118**, (1), pp. 153-160.

[11]. Abdel-Halim, M.A., and Manning, C.D., "Direct phase modeling of synchronous generators," *IEE Proceedings, Electric Power Applications*, Vol 137, No. 4, Pt. B., pp. 239-247, July 1990.

[12]. P.C Krause, *Analysis of Electric Machinery*, Mc-Graw Hill, New York. 1987.

[13]. P.L. Dandeno, Chair, "IEEE Guide for Synchronous Generator Modeling Practices in Stability Analysis," *IEEE Std. 1110*. 1991.

Appendix

1. Synchronous Generator Simulation Parameters

The nominal parameters of the 483 MVA, 60Hz, 22.0 KV, and 3600 RPM utility generator along with its excitation system and transmission line parameters used in the simulation are listed below.

Table 7: One machine infinite bus simulation parameters

Machine Parameters		Excitation System Parameters	
R_a	0.0046	K_a	200
R_{fd}	0.1521	T_a	0.02
R_{1d}	0.0126	T_b	13.5
R_{1q}	0.0107	T_c	1
R_{2q}	0.0164		
L_l	0.4253		
L_{ad}	4.3592	Transmission Line Parameters	
L_{1d}	0.1096		
L_{fd}	0.3134	R_t	0.02
L_{aq}	4.1466	L_t	0.5848
L_{1q}	1.1125		
L_{2q}	0.0877		

All resistances are in units of ohms and all inductances are in units of millihenries.

2. Output Error Estimation Method

The iterative OEM procedure steps to determine parameter vector θ of an unknown plant is as follows:

1. Define initial estimates for parameter vector θ.
2. Compute the estimation error of $Y(k)$ for k=1:n

$$e(k) = Y(k) - \hat{Y}(k) \tag{A.1}$$

3. Compute the cost function $V(\hat{\theta})$

$$V(\hat{\theta}) = \frac{1}{N}\sum_{k=0}^{N}[e^T(k,\hat{\theta})e(k,\hat{\theta})] \tag{A.2}$$

4. Compute hessian matrix H and gradient vector G:

$$H = \frac{\partial^2 V(\hat{\theta})}{\partial\hat{\theta}} \qquad G = \frac{\partial V(\hat{\theta})}{\partial\hat{\theta}} \tag{A.3}$$

5. Update estimate of parameter vector θ:

$$\hat{\theta}_{new} = \hat{\theta}_{old} - H^{-1}G \tag{A.4}$$

6. Repeat steps (2) through (5) till $V(\hat{\theta})$ is minimized.

BIOGRAPHIES

H. Bora Karayaka received the BSEE and MSEE degrees from Istanbul Technical University, Istanbul, Turkey, in 1987 and 1990, respectively. Since 1996, he has been a research associate at The Ohio State University. He is currently working towards his Ph.D. in the Department of Electrical Engineering, the Ohio State University, Columbus, Ohio.

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Gerald Thomas Heydt is from Las Vegas, Nevada. He holds the BEEE degree from the Cooper Union in New York, and the MSEE and Ph.D. degrees from Purdue University in West Lafayette, Indiana. He was a Professor of Electrical Engineering at Purdue for about 25 years and decided to come back to the West in January, 1996. He presently holds the position of Professor of Electrical Engineering and Center Director for the Center for the Advanced Control of Energy and Power Systems (ACEPS) at Arizona State University in Tempe. This center, focusing on electric power quality in the power industry and automatic control of electric power systems, is sponsored by the National Science Foundation and about 13 electric utility companies and EPRI. He is also the director of the EPRI sponsored ACEPS Power Quality Service Center. Jerry has industrial experience with the Commonwealth Edison Company in Chicago and E. G. & G. in Las Vegas. He also has industrial experience abroad. In 1995, he was selected by the University of Canterbury as an Erskine Fellow, an honor accorded to visiting scholars to New Zealand. He is the author of about 200 technical papers and three books, one on electric power quality. He is a registered professional engineer, a member of the National Academy of Engineering, and a Fellow of the IEEE. In 1995, he was named Power Engineering Educator of the Year by the IEEE Power Engineering Society. His interests are electric power quality and computer applications in power engineering.