GENERATOR PARAMETER ESTIMATION: AN ALGORITHM

Celso González, Hugh Rudnick
Departamento de Ingeniería Eléctrica
Pontificia Universidad Católica de Chile, Chile

F.M. Hughes
Department of Electrical Engineering and Electronics
UMIST, Manchester, England

ABSTRACT

This paper describes a novel proposal for synchronous generator, time domain, parameter estimation. The research is oriented towards defining a generator mathematical model: structure and parameters, suitable for power systems dynamic studies. Manipulating a standard set of differential and algebraic equations for the machine, a time domain, parametric linear model is obtained for parameter estimation. Basic results, derived from digital simulation work, show a suitable linearized algorithm for on-line parameter estimation, which aside from further simulation work, needs a better handling of the estimation error model, topic very much linked with further research into real data processing.

1 INTRODUCTION

The analysis of power systems to determine design and operating limits for stability purposes, constitutes not only a major computational effort but also an important issue. The accuracy of these studies has, as one of its main factors, the quality of the models of the generators: structure and parameters [1,2]. Published studies comparing transient stability test results with simulations, have shown actual power swings damped more quickly than the simulated ones, concluding that the major factors to affect the accuracy of stability simulation, are parameters of generator, control system and load, and therefore the utilization factor of the facilities could be improved considerably [3,4]. As such, the requirement for improved stability models for synchronous machines has increased considerably in the electric power industry during the past decade. The analytical structure of synchronous machines models is well accepted and is almost always based upon d-q-0 variables obtained by transformation from a-b-c phase quantities [1,5,6]. Regarding parameters, according to standards long ago defined, design values or factory test values of generators are used for simulation and validation purposes [7]. In general, most of these values are based on the data of no load factory tests. But a generator under operation is also affected by eddy currents and magnetic saturation and due to this complex phenomena, parameters vary considerably [8,9]. Ideally, in order to validate these transient parameters, field tests must be conducted on the equipment, which until now have not been endorsed by most utilities. Things are changing nowadays and industry needs can be identified as: determining the simplest form of model that will adequately represent the machine in system dynamic studies and the development of standard methods and test procedures to determine and validate machine parameters directly from field tests (most preferably on line) [3,10,11,12]. Within these, much effort has been devoted towards the refinement of conventional methodologies or the application of new proposals like frequency-domain techniques, finite element evaluation and load-rejection tests. Of these the favorite seems to be the stand-still frequency response (SSFR) tests. The principle of SSFR tests consists of supplying the stator or the field winding with a single phase variable frequency sinusoidal source over a frequency range of 0.01-100 Hz. Thus, pertinent frequency-response curves of magnitudes and phase angles of the generator as viewed from the stator can be determined and from there parameters are estimated using curve-fitting techniques [13,14,15]. Although SSFR tests are much easier to correlate in presence of noise and drift, it places a severe demand on the excitation source to obtain a well defined input function. Also for the small magnitudes of stator currents used in these tests, the mutual inductance can be expected to be different at different levels of current. Thus in a step response test the mutual inductance would be time variant during the test interval which might make analysis more difficult. On-line FR tests are now being proposed to cope better with saturation. In this paper a new approach to generator parameter estimation is presented, while still linear, it works on the time domain and can theoretically cope better with saturation through successive linear approximations for different operational conditions.

Section 2 presents the proposal's theory, which uses a highly standardized generator model. It describes a novel digital algorithm, for estimating the machine's well known and used parameters. Section 3 shows preliminary simulation results. Remarks are also made regarding its application to on-line machines. Finally, section 4 summarizes the experience so far gained with the algorithm.

2 PROPOSED METHODOLOGY

The procedure proposed for generator parameter identification assumes a model structure, as indicated in Appendix, since it fits the physics of the whole dynamic process for which it is meant. Ideally this structure should have sufficient degrees of freedom to accommodate all significant transient, subtransient and some approximation to nonlinear effects (i.e. eddy currents and saturation). This model includes differential and algebraic equations and is well accepted within the power community. Although mechanical equations should be included for stability studies, during this research they will be omitted. The algorithm being proposed, as will be shown, considers a linear estimation model. First of all the set of electrical equations is linearized around an operating point, thus revealing an identical expression of it (i.e. same notation but incremental variables). Due to this, the model needs to be applied only to gradual changing variables, which make small excursions around a particular operating point. Considering equations as given in Appendix, they can generally be written as:

$$px(t) = A(\theta)x + B(\theta)u \qquad (1)$$

$$y(t) = C(\theta)x + D(\theta)u \qquad (2)$$

where matrices A, B and D are functions of the synchronous generator parameters (such as reactances and time constants), which are to be estimated. Vectors "x" and "y", denote the state and output variables respectively. Finally and most importantly for the estimation algorithm, vector "u" denotes the potential input variables which could be used for excitation purposes, making the parameters identifiable. This of course being a key issue in parameter estimation, since a reliable and persistent excitation signal is required for estimation feasibility.

The proposal here made, is to develop a discrete model (from equations (1) and (2)), suitable for use with efficient digital estimation algorithms. There are several ways to represent a discrete version of the generator equations, depending upon the assumptions on the continuous model. In this paper, v'_{fd} (equivalent field voltage) is assumed as the "controlled" input and as "uncontrolled" input i_d and i_q (direct and quadrature axis currents), which are kept constant over the sampling period T (i.e. equal to Δt). Analytically this means:

$$u(t) = u_k = u(kT) \text{ when } kT \le t < (k+1)T \qquad (4)$$

Considering such input, it can be shown that an exact discrete form, for this model turns out to be:

$$x(k+1) = Fx(k)+Gu(k) \qquad y(k+1) = Ix(k) + Du(k) \qquad (5)$$

where $F = e^{AT}$ and $G = A^{-1}(e^{AT} - I)B$. It can be demonstrated that, in this case matrices F and G are given through the following elements (the rest being null):

$$F_{11} = e^{-\frac{T}{T'_{d0}}} \qquad F_{22} = e^{-\frac{T}{T''_{q0}}}$$

$$F_{31} = \frac{T'_{d0}}{(T'_{d0} - T''_{d0})}\left(e^{-\frac{T}{T'_{d0}}} - e^{-\frac{T}{T''_{d0}}}\right) \qquad (6)$$

$$F_{33} = e^{-\frac{T}{T''_{d0}}}$$

$$G_{11} = \left(1 - e^{-\frac{T}{T'_{d0}}}\right)$$

$$G_{12} = (x'_d - x_d)\left(1 - e^{-\frac{T}{T'_{d0}}}\right) \qquad G_{23} = (x_q - x''_q)\left(1 - e^{-\frac{T}{T''_{q0}}}\right)$$

$$G_{31} = \left(1 - e^{-\frac{T}{T'_{d0}}}\right) + \frac{T''_{d0}}{(T'_{d0} - T''_{d0})}\left(e^{-\frac{T}{T''_{d0}}} - e^{-\frac{T}{T'_{d0}}}\right) \qquad (7)$$

$$G_{32} = \frac{T''_{d0}}{(T'_{d0} - T''_{d0})}\left(e^{-\frac{T}{T''_{d0}}} - e^{-\frac{T}{T'_{d0}}}\right)) + (x''_d - x'_d)\left(1 - e^{-\frac{T}{T''_{d0}}}\right) + (x'_d - x_d)(\left(1 - e^{-\frac{T}{T'_{d0}}}\right)$$

Therefore as long as v'_{fd} (as well as other input variables) holds constant through each sampling period, no approximation is involved in this representation, and the discrete model so-obtained is theoretically exact.

Although there is no difficulty in calculating these matrices, the expressions they hold are rather complicated functions of the parameters, at least for estimating purposes. In order to work with a more simple and flexible discrete structure, a second order approximation of these equations will be considered from now on. The reason to adopt this second order approximation, comes from replacing these matrices with typical synchronous machine reactances and time constants, and evaluating the matrix coefficients as more terms are included in the series expansion of each exponential term. At the end of the process, a trade off between accuracy and complexity must be reached in order to obtain a simple but hopefully reliable model structure. In any case this has to be tested, both in a simulated and a real-life environment.

Thus, considering this second order expansion for each exponential function of equations (6) and (7), leads to eqs. (8) and (9). Notice that neglecting the quadratic terms in $F^{(2)}$ and $G^{(2)}$ gives a first order approximation (i.e. $F^{(1)}$ and $G^{(1)}$). Let the sample time be denoted by "k", then the 2nd order discrete model of equations, turns out to be as expressed in eqs. (10) and (11). For the sake of notation simplicity, the "dash" sign of the equivalent field voltage and current has been dropped, it is implicitly meant.

$$\left[F^{(2)}\right] = \begin{bmatrix} 1 - \frac{T}{T'_{d0}} + \frac{T^2}{2T'^2_{d0}} & 0 & 0 \\ 0 & 1 - \frac{T}{T''_{q0}} + \frac{T^2}{2T''^2_{q0}} & 0 \\ \frac{T}{T''_{d0}} - \frac{T^2}{2T'_{d0}T''_{d0}} - \frac{T^2}{2T''^2_{d0}} & 0 & 1 - \frac{T}{T''_{d0}} + \frac{T^2}{2T''^2_{d0}} \end{bmatrix} \tag{8}$$

$$\left[G^{(2)}\right] = \begin{bmatrix} \frac{T}{T'_{d0}} - \frac{T^2}{2T'^2_{d0}} & (x'_d - x_d)\left(\frac{T}{T'_{d0}} - \frac{T^2}{2T'^2_{d0}}\right) & 0 \\ 0 & 0 & (x_q - x''_q)\left(\frac{T}{T''_{q0}} - \frac{T^2}{2T''^2_{q0}}\right) \\ \frac{T^2}{2T'_{d0}T''_{d0}} & \begin{array}{c} (x'_d - x_d)\frac{T^2}{2T'_{d0}T''_{d0}} \\ (x''_d - x'_d)\left(\frac{T}{T''_{d0}} - \frac{T^2}{2T''^2_{d0}}\right) \end{array} & 0 \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} E'^{k+1}_q \\ E''^{k+1}_d \\ E''^{k+1}_q \end{bmatrix} = \left[F(\theta)^{(2)}\right] \begin{bmatrix} E'^{k}_q \\ E''^{k}_d \\ E''^{k}_q \end{bmatrix} + \left[G(\theta)^{(2)}\right] \begin{bmatrix} v^k_{fd} \\ i^k_d \\ i^k_q \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} i^k_{fd} \\ v^k_d \\ v^k_q \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} E'^{k}_q \\ E''^{k}_d \\ E''^{k}_q \end{bmatrix} + \begin{bmatrix} 0 & (x_d - x'_d) & 0 \\ 0 & -r_a & x''_q \\ 0 & -x''_d & -r_a \end{bmatrix} \begin{bmatrix} v^k_{fd} \\ i^k_d \\ i^k_q \end{bmatrix} \tag{11}$$

$$\Delta i_{fd}^{k} = (x_d - x'_d)\Delta i_d^{k} + \left(\frac{T}{T'_{d0}} - \frac{T^2}{2T'^2_{d0}}\right)(v_{fd}^{k} - i_{fd}^{k}) \tag{12}$$

$$\Delta v_d^{k} = -r_a \Delta i_d^{k} + x''_q \Delta i_q^{k} + \left[x_q\left(\frac{T}{T''_{q0}} - \frac{T^2}{2T''^2_{q0}}\right)\right] i_q^{k} + \left(\frac{T^2}{2T''^2_{q0}} - \frac{T}{T''_{q0}}\right) v_d^{k} + r_a\left(\frac{T^2}{2T''^2_{q0}} - \frac{T}{T''_{q0}}\right) i_d^{k} \tag{13}$$

$$\Delta v_q^{k} = -r_a \Delta i_q^{k} - x''_d \Delta i_d^{k} + \left[x_d\left(\frac{T^2}{2T''^2_{d0}} - \frac{T}{T''_{d0}}\right)\right] i_d^{k} + \left(\frac{T}{T''_{d0}} - \frac{T^2}{2T''^2_{d0}}\right)(i_{fd}^{k} - v_q^{k}) - r_a\left(\frac{T}{T''_{d0}} - \frac{T^2}{2T''^2_{d0}}\right) i_q^{k} + \frac{T^2}{2T'_{d0}T''_{d0}}(v_{fd}^{k} - i_{fd}^{k}) \tag{14}$$

The latter two equations, although approximated, constitute a solid discrete-time state space model for the synchronous generator. These expressions, although adequate to study discrete time-evolution of variables, are not suitable for the purpose of this research, mainly because they are not in the form of an easily or directly measurable input-output model (i.e. data). Therefore they will be manipulated in order to obtain an output-input model, suitable for synchronous machine parameter estimation.

In order to attain such an objective, equations (10) and (11) are worked through in such a way to get rid off the internal, unmeasurable, voltages (i.e. E'_q, E''_q and E''_d). Therefore considering only measured variables (whether directly or indirectly), the proposed model of eqs. (12), (13) and (14) can be obtained, where it has been defined $\Delta x^k = x^{k+1} - x^k$ for any stator or rotor variable.

As can be seen, although the model is not linear in terms of single "isolated" parameters (reactances, time constants and resistances), it can be grouped forming three independent linear estimation models of the type: $[Z]^t = [\delta(\mu)]*[U]^t$. In this case:

$$Z_1^t = (\Delta i_{fd})^t \text{ and } U_1^t = (\Delta i_d,\ v_{fd} - i_{fd})^t$$
$$Z_2^t = (\Delta v_d)^t \text{ and } U_2^t = (\Delta i_d,\ \Delta i_q,\ i_q,\ v_d,\ i_d)^t \tag{15}$$
$$Z_3^t = (\Delta v_q)^t \text{ and } U_3^t = (\Delta i_q,\ \Delta i_d,\ i_d,\ i_{fd} - v_q,\ i_q,\ v_{fd} - i_{fd})^t$$

and $[\delta(\mu)]$ represents a matrix, whose elements are function of the machine original parameters "μ", which are also independent of each other (i.e. a diagonal matrix). Theoretically, $[\delta(\mu)]$ expressions are easily related to the original parameters, thus imposing no great restriction upon their solution. As such, this overall expression can be taken as a linear relationship between output $[Z]^t$ values and input $[U]^t$ values, that is $[Z]^t = [\theta]*[U]^t$. Whereby for simplicity "θ" represents the parameters to be estimated. This makes it possible to use very simple but powerful algorithms for parameter estimation.

It can be noticed from equation (15) that only variable v_{fd} (i.e. v'_{fd}), can be taken or considered as a truly (i.e. in practice) controllable input, through the real field voltage. This research assumes this fact, and this excitation signal "v_{fd}" is considered to be a Pseudo Random Binary Sequence (PRBS) signal, externally applied to the model as an input variable (i.e. v_{fd}). In a real-life on-line environment, the PRBS can be considered to be injected to the field voltage reference set point, which in turn will affect the field voltage or equivalently the simulated value of v_{fd}. In other words, in a real size power station, this can be done at the summation junction, usually available for other signals (i.e. power system stabilizer) to be added to the field reference set point.

From a complementary point of view, it is worth mentioning that another truly controllable excitation signal, can be the mechanical power reference set point (i.e. "P_m"). This can be considered through a similar discrete version of equations (1) and (2), which would additionally include the mechanical equations. This signal would theoretically help to excite other dynamic modes of the synchronous machine for estimation purposes, in case "v_{fd}" is not sufficiently persistent by itself.

3 DIGITAL SIMULATION: COMMENTS & RESULTS

The simulated algorithm is assumed to start from d-q axes, thus there is no need to apply Park's transformation (i.e. from a-b-c to d-q). Nevertheless, this is a problem which must be dealt with when making real life generator parameter estimation, which for this proposal requires the load angle, besides measuring time phase voltages and currents, field voltage and current. With available equipment this is already being done for other purposes.

Initially data is generated to obtain equations (12), (13) and (14). To do this, the continuous model described in section 2 (linear expression of the Appendix equations) was implemented and evaluated using Matlab's software simulation facilities. This actually means solving a linearized version (i.e. around a steady-state operational value) of the Appendix equations, which includes the set of differential equations with (assumed) zero starting conditions (i.e. subtracting D.C. steady-state values). During the simulation, as previously described, the only input variable is the field equivalent voltage "v_{fd}" (i.e. v'_{fd}), considered to be a 6th order maximal length PRBS sequence of magnitude 0.5 p.u. A reasonable sampling time for d-q variables, considering standard parameter values, was set to 0.01 seconds (i.e. T = 0.01 seconds). Although this is adequate for the transformed direct-quadrature variables, it is too large to be used in real time phase variables, since A.C. variations require a much higher sampling frequency (i.e. greater than 2 kHz).

Preliminary simulations tests carried out, showed that the estimation of the stator resistance r_a, caused a lot of numerical instability to the estimation algorithm, based on off-line, recursive least square and instrumental variables estimation methods [16]. This problem stems primarily from the low value which r_a has, this in turn even lowers the estimated "θ_i" values, when multiplied by the output vectors (i.e. $[\theta]*[U]^t$). On the other hand, contrary to the reactances and time constants, in practice resistances can be measured with relatively high accuracy, and even more they are usually neglected during dynamic power system studies. Ultimately, most of the new algorithms being proposed in the literature (including the earlier proposals), considered this value given or at least an easily measurable constant. Strictly speaking, the resistance really depends on the load point (i.e. due to temperature). Finally, from a theoretical point of view, using fewer parameters has some positive effects on the estimation procedure: the variance of the parameter estimates will decrease.

For these reasons and until further refinements can be made, to the proposed algorithm, r_a will be assumed known. Some minor modifications to the original model (equation (15)), establishes a new input-output set of equations:

$$\Delta i_{fd}^{k} = (x_d - x'_d)\Delta i_d^{k} + \left(\frac{T}{T'_{d0}} - \frac{T^2}{2T'^{2}_{d0}}\right)(v_{fd}^{k} - i_{fd}^{k}) \qquad (16)$$

$$\Delta v_d^{k} + r_a \Delta i_d^{k} = x''_q \Delta i_q^{k} + \left[x_q\left(\frac{T}{T''_{q0}} - \frac{T^2}{2T''^{2}_{q0}}\right)\right] i_q^{k} + \left(\frac{T^2}{2T''^{2}_{q0}} - \frac{T}{T''_{q0}}\right)(v_d^{k} + r_a i_d^{k}) \qquad (17)$$

$$\Delta v_q^{k} + r_a \Delta i_q^{k} = -x''_d \Delta i_d^{k} + \left[x_d\left(\frac{T^2}{2T''^{2}_{d0}} - \frac{T}{T''_{d0}}\right)\right] i_d^{k} + \left(\frac{T}{T''_{d0}} - \frac{T^2}{2T''^{2}_{d0}}\right)(i_{fd}^{k} - v_q^{k} - r_a i_q^{k}) + \frac{T^2}{2T'_{d0}T''_{d0}}(v_{fd}^{k} - i_{fd}^{k}) \qquad (18)$$

Or otherwise written as:

$$Z_1^t = (\Delta i_{fd})^t \quad \text{and} \quad U_1^t = (\Delta i_d, v_{fd} - i_{fd})^t$$
$$Z_2^t = (\Delta v_d + r_a \Delta i_d)^t \quad \text{and} \quad U_2^t = (\Delta i_q, i_q, v_d + r_a i_d)^t \qquad (19)$$
$$Z_3^t = (\Delta v_q + r_a \Delta i_q)^t \quad \text{and} \quad U_3^t = (\Delta i_d, i_d, i_{fd} - v_q - r_a i_q, v_{fd} - i_{fd})^t$$

Worthy of mentioning at this stage, is that initially a first order approximation of equations (6) and (7) was simulated. Results were not encouraging and as a consequence a second order model was developed as shown above. Table 1 summarizes the results obtained up to date. They represent average values obtained using either off-line or recursive algorithms. It can be seen that this 2nd order expansion, provides reasonable results. Besides, it makes the whole procedure more robust (numerically), since reliable values can be obtained from all input-output sets (contrary to 1st order). Still and only for theoretical purposes, a third-order expansion was developed for certain elements, but their complexity discouraged further research in this area.

Table 2 shows the parameters obtained when using a least square recursive algorithm, with different starting points but the same covariance matrix. From these results it can be seen that, except for the third vector, the estimated parameters are almost the same, revealing numerical robustness of these vectors. On the other hand the third one, particularly parameter T''_{d0}, seems to be very sensible to the SP's, maybe because the corresponding output vector is not sufficiently excited. More precisely an answer to this seems to lie in the structural error behind the model, therefore a logical next step would be to consider this fact not only within the model itself but most important, in the estimation procedure. That is with sufficient excitation signal, or maybe through the use of robust estimation techniques like the Unknown But Bounded methodology [17], which could overcome this numerical problems.

On the other hand, the PRBS signal was widely varied in magnitude and length to analyze its influence on the algorithm. No radical conclusions were reached. The reason for this may be found in the fact that no explicit noise was ever considered, and any inaccuracies detected in the model are thought to come from the approximated model developed. This is now being studied.

Finally a comment regarding equation (19). A numerical inconsistency appears in the third estimation block Z_3^t. In it, one of the machine parameters, T''_{d0}, can be obtained from two different sources, thus giving two solutions. This situation, so far, has been tried to be solved in a rather iterative way (i.e using variations to the recursive least-square algorithm, extended like). Unfortunately the numerical sensibility is high and at the moment no (acceptable) solution has been obtained. It seems this informative set is not sufficiently persistently excited. A third order approximation for this block gave much more accurate values, but this makes the model more complex. It is suggested that this could be solved considering an average value for the parameter or including another additional parameter to be estimated (i.e. torque angle, damping coefficient), or the use of robust estimation techniques.

Parameter	Estimated Values (1)	Estimated Values (2)	Simulated Values*
r_a	not estimated	not estimated	0.001096
x_d	1.80974	1.8081	1.81
x'_d	0.30	0.2981	0.30
x''_d	0.2347	0.15-0.29#	0.217
x_q	1.7598	1.7598	1.76
x''_q	0.3494	0.3491	0.254
T'_{do}	7.8	7.8041	7.8
T''_{do}	0.02079(0.02522)**	0.019-0.026#	0.022
T''_{qo}	0.0785	0.0732	0.074

Table 1 Results of Proposed Algorithm

(1) straight least square and instrumental variable

(2) recursive least square, very much dependent upon the initial starting point in case of the third block Z_3^t. Starting points are based on standard values

\# range of results obtained   * reference [1]   ** two solutions are obtained, an average value can be used

Parameter	Estimated Values (1)	Estimated Values (2)	Simulated Values*
	SP = [0]	SP = [simul. values]	
r_a	not estimated	not estimated	0.001096
x_d	1.8101265	1.809929	1.81
x'_d	0.301226	0.301029	0.30
x''_d	0.2216	0.1915	0.217
x_q	1.759811	1.760784	1.76
x''_q	0.3488	0.3493	0.254
T'_{do}	7.806401	7.806401	7.8
T''_{do}	0.089392(0.092083)**	0.022987(0.0271398)**	0.022
T''_{qo}	0.07306407	0.07306407	0.074

Table 2 Results using recursive least square algorithm with different Starting Points (SP)

(1) Starting Point equal to zero for all values   (2) Starting Point equal to simulated values

* reference [1]   ** two solutions are obtained, an average value can be used

4 CONCLUSIONS AND FUTURE WORK

Some critical comments, conclusions and suggestions can be made regarding the proposal presented:

a) the numerical results obtained, even in this much simplified proposal, are robust only when there is sufficient excitation signal on each variable (i.e. i_d, i_q, v_d, v_q). Only in those cases can all parameters be obtained fairly accurate, no matter which estimation algorithm is used. This was experimentally proved using an additional, exaggerated non-controllable, excitation signal: the generator terminal voltage magnitude. The last statement is even true when a first order model is used. Thus, this leads the responsibility to find another controllable and usable input variable, besides v_{fd}.

b) the proposed model for generator parameter estimation behaved linearly correct during simulation. In theory, an on-line application of it seems feasible, once numerical problems are solved. Critical problems appear when rather small forced-variations in the d-q axis variables are obtained. This problem comes about in trying to estimate T''_{do}; the solution so far adopted has been to use average values of those obtained or if a further refinement is desired, a third order expansion can be used.

c) undoubtedly another excitation signal would be highly welcome, particularly for the q-axis, early simulation results have shown so. This is currently been studied through extensions to the algorithm which include the mechanical equations. Also it can be expected that,random variations, coming naturally from the system, will be of benefit to the algorithm, of course as long as they are small (i.e. linear).

d) saturation makes machine constants not truly constants. It is proposed to carry out a number of measurements, under typical load conditions and from those obtain different sets of parameters. Therefore, the idea would be to correlate the "linear" results to the most pronounced nonlinearities of the machine (i.e. saturation and eddy currents). Thus an implicit estimation of the saturation factor is obtained. In this sense, efforts devoted to saturation representation techniques offer the greatest potential for gains in model accuracy.

e) It is suggested to estimate parameters keeping the structure as close as possible to the theoretical one. This means to estimate the parameters using a non-linear optimization algorithm (i.e. Levenhardt-Marquadt), together with some restrictions on the parameters (i.e. non-negative, bigger than a certain value, bounded values, etc.). On the other hand, a complementary approach to the one used in this research, would be to use the Unknown But Bounded algorithm, selecting an appropriate bounding for the error.

REFERENCES

1.- Anderson, P.M., Fouad, A.A. (1977). Power System Control and Stability. The Iowa State University Press, U.S.A.

2.- Dandeno, P., Kundur, P., Schulz, R. (1974). Recent trends and progress in synchronous machine modeling in the electric utility industry. Proceedings of the IEEE, vol.62, Nº7, July.

3.- The task force on definitions. (1980). Supplementary definitions & associated test methods for obtaining parameters for synchronous machine stability study simulations. IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, Nº4 July/Aug.

4.- Namba, M., Hosoda, J. Doi, S., Udo, M. (1981). Development for measurement of operating parameters of synchronous generator and control systems. IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, Nº2, February.

5.- Park, R.H. (1929). Two reaction theory of synchronous machines. Generalized Method of Analysis. Part I. A.I.E.E. Transactions, Vol. 48, July.

6.- Sarma, M.S. (1985) Electric Machines, Steady-State Theory and Dynamic Performance. West Publishing Company, U.S.A.

7.- Wright. H., Sherwin (1933). Determination of Synchronous Machine Constants by Test. Reactances, Resistances and Time Constants. A.I.E.E. Transactions.

8.- Watson, W., Manchur, G. (1973). Synchronous machine operational impedances from low voltage measurements at the stator terminals. Paper presented at the IEEE PES Summer Meeting & EHV/UHV Conference, Vancouver, July.

9.- Takeda, Y. Adkins, B. (1974). Determination of synchronous-machine parameters allowing for unequal mutual inductances. Proc. IEE, Vol, 121, Nº12, December.

10.- Shackshaft, G., Poray, T. (1977). Implementation of new approach to determination of synchronous-machine parameters from tests. Proc. IEE Vol. 124, Nº12, December.

11.- De Mello, F.P., Ribeiro, J.R. (1977). Derivation of synchronous machine parameters from tests. IEEE Transactions on Power Apparatus and Systems, Vol. PAS-96, July/August 1977.

12.- Dandeno, P.L., Kundur, P., Poray, A.T., Coultes, M.E. (1981). Validation of turbogenerator stability models by comparisons with power system tests. IEEE Transactions on Power Apparatus and Systems, Vol.PAS-100, Nº4, April.

13.- Dandeno, P.L., Poray, A.T. (1981). Development of detailed turbogenerator equivalent circuits from standstill frequency response measurements. IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, Nº4, April.

14.- Hurley, J.D., Schwenk, H.R. (1981). Standstill frequency response modeling and evaluation by field tests on a 645 MVA turbine generator. IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, Nº2, February.

15.- Dandeno, P.L., Kundur, P., Poray, A.T., Zein El-Din, H.M. (1981). Adaptation and validation of turbogenerator model parameters through on-line frequency response measurements. IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, Nº4, April.

16.- Ljung, L. (1987). System Identification: Theory for the User. Prentice-Hall Inc., New Jersey, U.S.A.

17.- Milanese, M., Tempo, R. (1985). Optimal algorithms theory for robust estimation and prediction. IEEE Transactions on Automatic Control, Vol. AC-30.

ACKNOWLEDGEMENTS

Thanks to the British Council and Fundación Andes for scholarship support, to Fondecyt (Project 91-796) and the United Nations Development Program (Project 87-030).

APPENDIX

A model based on transient-subtransient reactances and time constants is used. It is possible to express the synchronous machine equations, from the original expressions as developed through Park's transformation, into what is known as a conventional set of equations:

$$\frac{dE'_q}{dt} = -\frac{E'_q}{T'_{d0}} + \frac{(x'_d - x_d)i_d}{T'_{d0}} + \frac{v'_{fd}}{T'_{d0}}$$

$$\frac{dE''_q}{dt} = \frac{E'_q}{T''_{d0}} - \frac{E''_q}{T''_{d0}} - \frac{(x'_d - x''_d)i_d}{T''_{d0}}$$

$$\frac{dE''_d}{dt} = \frac{E''_d}{T''_{q0}} + \frac{(x_q - x''_q)i_q}{T''_{q0}}$$

$$v_d = -r_a i_d + x'' i_q + E''_d$$

$$v_q = -r_a i_q - x'' i_d + E''_q$$

$$i'_{fd} = E'_q + (x_d - x'_d)i_d$$