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DERIVATION OF SYNCHRONOUS MACHINE PARAMETERS FROM TESTS

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ABSTRACT

This paper describes a test procedure for derivation of synchronous machine parameters. The tests can be conducted with ease and without hazard on generators in utility systems. Unlike textbook methods involving short circuit and slip tests which are inconvenient and hazardous, the proposed method involves simple procedures, which can be implemented in normal operation of the machine.

INTRODUCTION

Dynamic performance of power systems can be significantly affected by machine characteristics. Indeed in systems where designs are governed by stability, machine parameters are often specified and their economic worth can be measured against the incremental cost of alternate means of providing stability (1,2).

As the need develops for increasing use of simulation in the design of expansions to utility systems,the parallel need arises for access to reliable data on machine constants and characteristics.

A test procedure is suggested to measure machine parameters and examples are given from simulations. The procedure involves measurement of voltage and field current transient deviations caused by staged generator breaker trips starting from loaded conditions.

MACHINE MODELS

Machine representations used in modern simulation programs include field and amortisseur effects (3).

For salient pole machines the d-axis is represented with field and damper winding effects, and saturation. The q-axis is represented with one damper winding and saturation is assumed not to occur in the q-axis.

Fig. 1 shows the block diagram of a salient pole synchronous machine relating the variables in d-q axes.

This block diagram is derived from the familiar Park's equations (4,5) and expressed in terms of the constants normally used to characterize machines (Xd, Xq, Xd', Xd", Xq", etc.).

Fig. 2 shows the block diagram for a round rotor machine where the solid iron effects are approximated by field and damper winding in the d-axis and by two equivalent amortisseur circuits in the q-axis. Saturation is represented approximately to include effects in both axes.

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The problem to be addressed in this paper is the derivation of constants in the block diagrams of Figs. 1 & 2 from staged tests.

Inspection of Figs. 1 & 2 reveals that the parameters in question can be grouped as d-axis parameters and q-axis parameters and any test procedure to determine these separately would be advantageous.

D-AXIS PARAMETERS

By having the machine at zero active power but drawing or supplying reactive power, one ensures that flux exists only in the d-axis.

The test procedure is to have the machine connected to the system at zero power and, through manual control of the excitation system, to establish underexcited or overexcited initial conditions. The test would consist of opening the circuit breaker connecting the machine to the system and recording deviations in terminal voltage and field current.

With the generator underexcited, saturation effects would not be present and the test results upon opening of the circuit breaker can be used to determine the basic unsaturated values of machine parameters Xd, Xd', Xd", T'do and T"do.

Fig. 3 shows the vector diagram for an underexcited loading condition. Fig. 4 shows the voltage transients that would occur following opening of the generator breaker. Fig. 5 shows the field current transient for the same disturbance.

Considering the vector diagram of Fig. 3, parameter values can be derived from Fig. 5, given that the value of interrupted current was i_o, as follows:

$$Xd = \frac{C}{i_o} \tag{1}$$

$$X'd = \frac{B}{i_o} \tag{2}$$

$$X''d = \frac{A}{i_o} \tag{3}$$

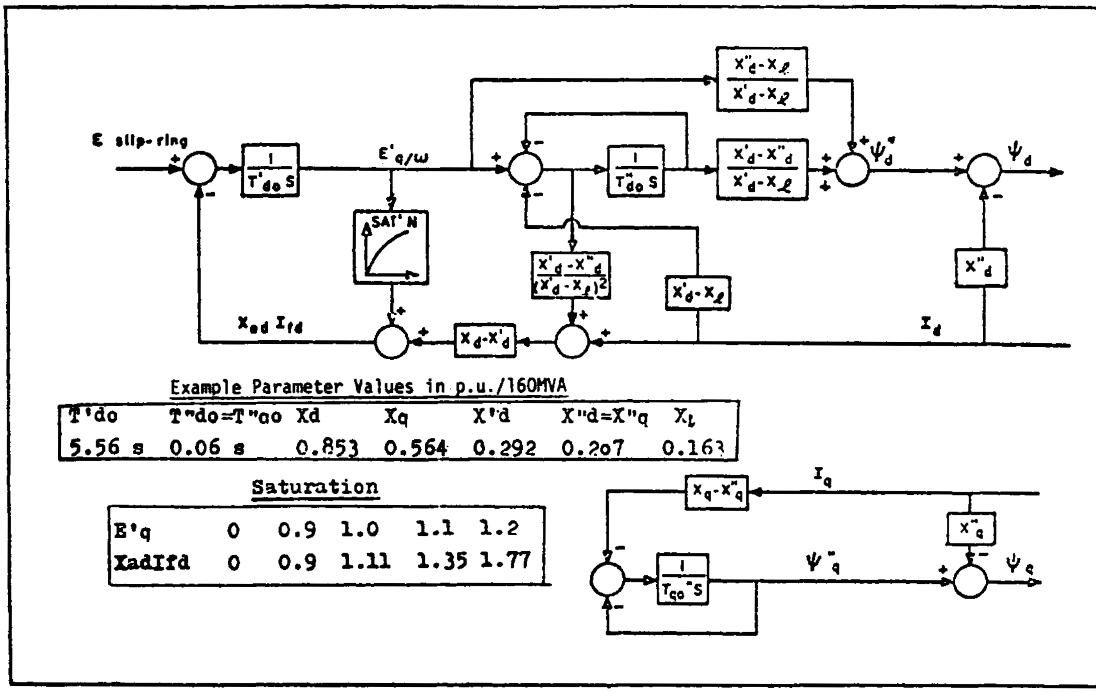
Where A, B, C are indicated in Figs. 4 and 5.

Time constants T'do and T"do can also be derived as shown in Figs. 4 and 5.

The effect of saturation on all these parameters can be measured by repeating the tests for overexcited conditions.

Q-AXIS PARAMETERS

Ideally, to determine q-axis parameters, it would be desirable to have a loading condition where the armature current is composed only of a quadrature axis component.



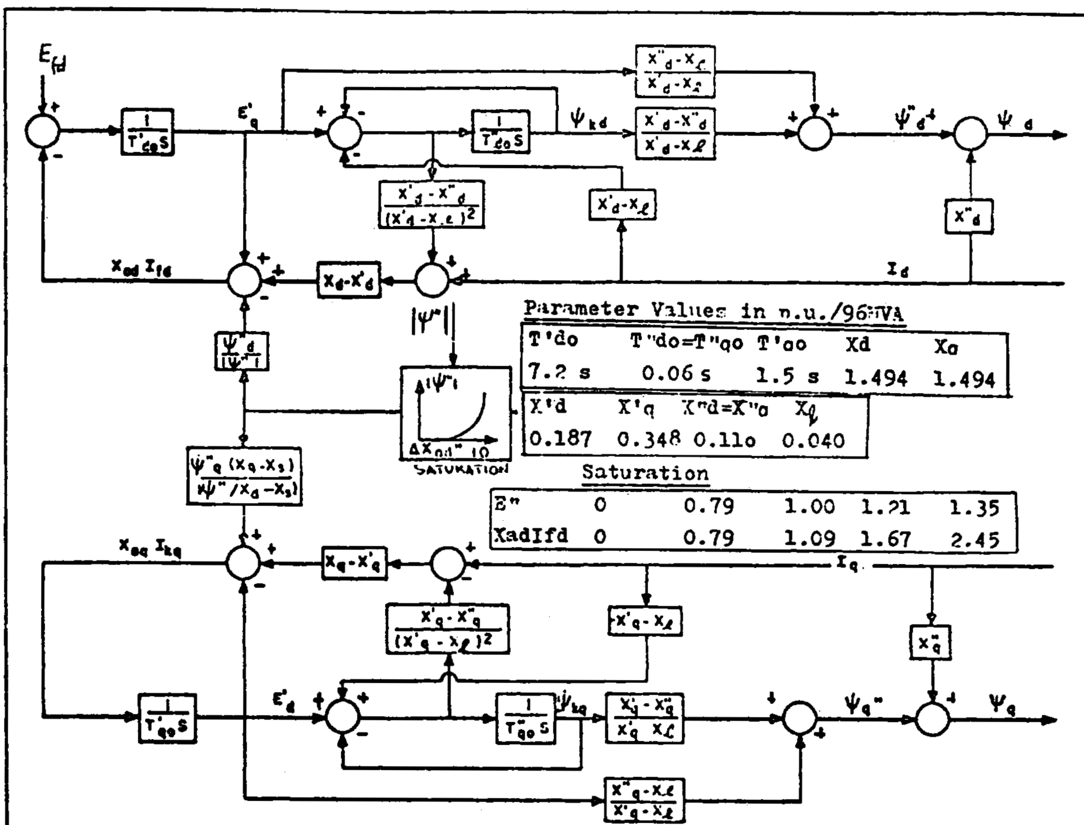
Example Parameter Values in p.u./160MVA

T'do	T"do=T"qo	Xd	Xq	X'd	X"d=X"q	X_l
5.56 s	0.06 s	0.853	0.564	0.292	0.207	0.163

Saturation

E'q	0	0.9	1.0	1.1	1.2
XadIfd	0	0.9	1.11	1.35	1.77

Figure 1. Block Diagram of Salient Pole Generator.



Parameter Values in p.u./96MVA

T'do	T"do=T"qo	T'qo	Xd	Xq
7.2 s	0.06 s	1.5 s	1.494	1.494

X'd	X'q	X"d=X"q	X_l
0.187	0.348	0.110	0.040

Saturation

E"	0	0.79	1.00	1.21	1.35
XadIfd	0	0.79	1.09	1.67	2.45

Figure 2. Round Rotor Generator Model.

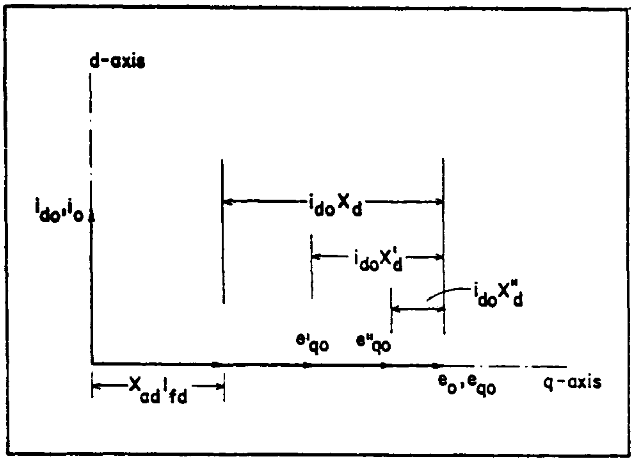


Fig. 3 Vector diagram for an underexcited loading condition. Real power is assumed to be zero.

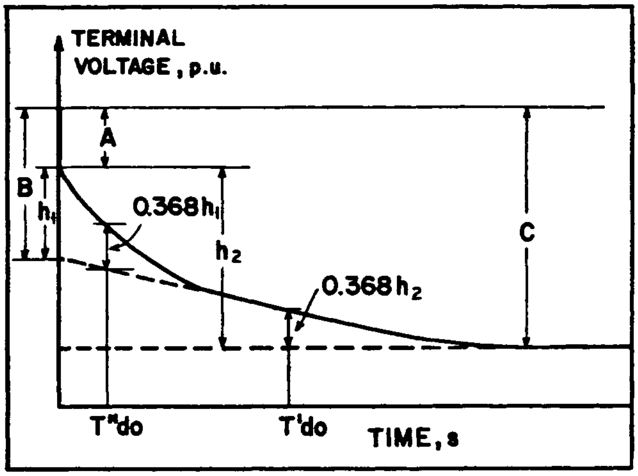


Fig. 4 Terminal voltage variation after rejection of a purely reactive load. Machine initially underexcited.

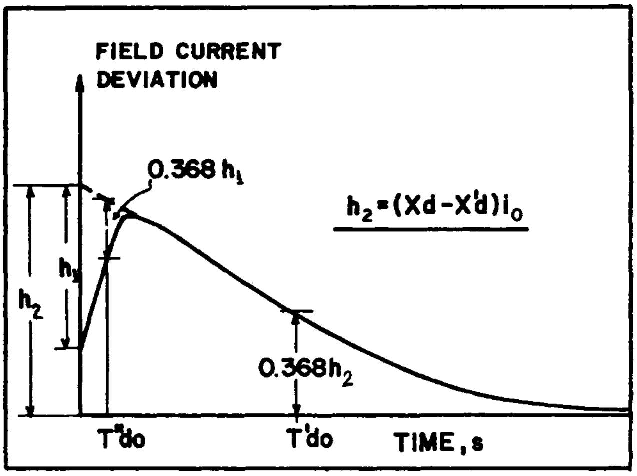


Fig. 5 Field current deviation after rejection of a purely reactive load. Machine initially underexcited.

The vector diagram of Fig. 6 and geometric relationships that can be derived from it show that if the condition can be found for which the armature current phasor lines up with the quadrature axis, then, by similarity of triangles:

$$\frac{i_P X_q}{e_t - i_Q X_q} = \frac{i_Q}{i_P} \tag{4}$$

or, solving for Xq,

$$X_q = \frac{i_Q e_t}{i_P^2 + i_Q^2} = \frac{\text{Reactive Power Output}}{|i|^2} \tag{5}$$

The desired loading condition can be arrived at by successive load rejection runs where the field current deviation is monitored, with the object of reaching the desired loading condition for which there would be no noticeable transient deviation in field current.

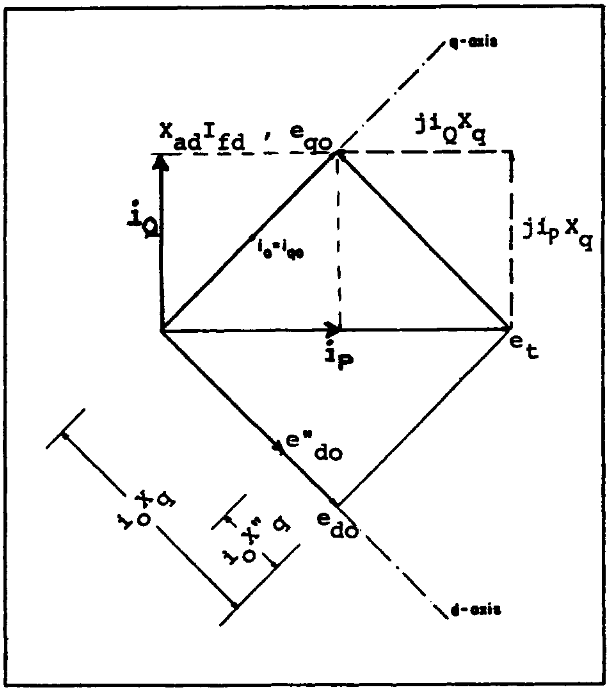


Fig. 6 Vector diagram for a condition where the d-axis component of armature current is null.

Since the objective is to derive the value of the expression $\frac{\text{KVAR (p.u.)}}{i^2 \text{ (p.u.)}}$ applying to machine loading conditions for which no field current transient deviation occurs, it is really not essential to actually establish the exact loading condition where this happens but merely to record the value of field current peak deviations and establish at least two loading conditions for which the deviations are in opposite directions. A plot of ΔIfd versus $\frac{\text{KVAR}}{i^2}$ will locate the point where ΔIfd is zero. The value of $\frac{\text{KVAR}}{i^2}$ at this point gives the value of Xq.

Fig. 7 illustrates the method.

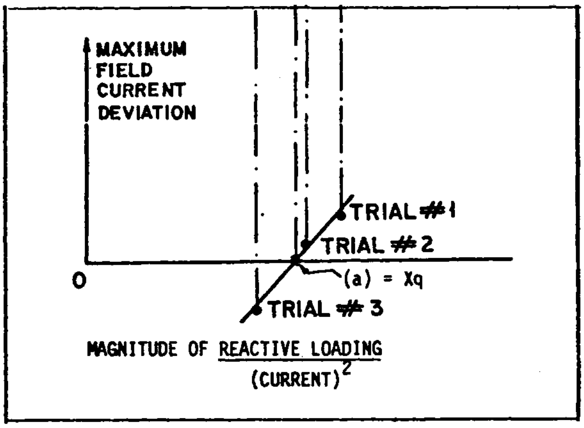


Fig. 7 Suggested scheme for determining loading such that there is no d-axis component of armature current.

A load rejection test with the generator initially loaded under conditions to produce zero d-axis armature current component (as calculated by the scheme of the previous paragraph), would result in a voltage transient as sketched in Fig. 8. From this figure and geometric relations derived from the vector diagram of Fig. 6 the value of X"q and Xq can be calculated as follows:

$$X''_q = \frac{\sqrt{A^2 - C^2} - \sqrt{B^2 - C^2}}{I_0} \qquad (6)$$

$$X_q = \frac{\sqrt{A^2 - C^2}}{I_0} \qquad (7)$$

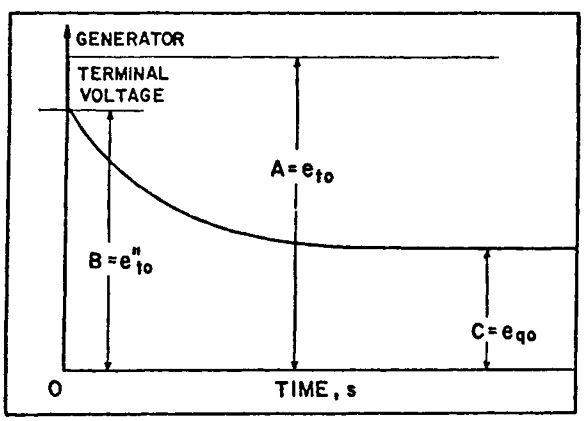


Fig. 8 Terminal voltage variation after load rejection. Machine initially loaded in such a way that there is no d-axis component of armature current.

RESULTS OF SIMULATION RUNS

Table 1 contains a list of the simulation runs performed to illustrate the proposed method, showing the relevant initial conditions for each run.

The values derived for the d-axis and q-axis parameters are indicated in the figures and summarized in Table 2 (salient pole generator) and Table 3 (round rotor generator). These tables also indicate the actual value of the parameter for ease of comparison with the derived values.

TABLE 1 - LIST OF RUNS

RUN Nº	GENERATOR MODEL	LOAD REJECTED P.U./100 MVA	INITIAL CONDITIONS P.U. e_{t_o}	E_{FD_o}	i_o	FIGURE
1	Salient pole	0-j0.8	1.03	0.616	0.777	9a-9d
2		0.8-j0.1	1.03	1.182	0.783	10a-10b
3		0.8-j0.3	1.03	1.041	0.830	10a-10b
4		0.8-j0.5	1.03	0.905	0.916	10a-10b
5		0.8-j0.23	1.03	1.089	0.808	10c
6	Round Rotor	0-j0.1	0.75	0.543	0.133	11a-11d
7		0.1-j0.05	0.75	0.679	0.149	12a-12b
8		0.1-j0.035	0.75	0.708	0.141	12a-12b
9		0.1-j0.02	0.75	0.738	0.136	12a-12b
10		0.1-j0.03	0.75	0.718	0.139	12c

TABLE 2 - SALIENT POLE GENERATOR PARAMETERS DERIVED VERSUS INPUT VALUES

Parameters	Derived	Input	% Deviation
T"do	0.057	0.06	5.0
T'do	5.53*	5.56	0.6
Xd	0.532	0.533	0.2
X'd	0.177	0.183	3.3
X"d	0.128	0.129	0.7
Xq	0.352	0.353	0.3
X"q	0.130	0.129	0.8

* Average value from figures 9-a and 9-c

TABLE 3 - ROUND ROTOR GENERATOR PARAMETERS DERIVED VERSUS INPUT VALUES

Parameters	Derived	Input	% Deviation
T"do	0.057	0.06	-5.0
T'do	7.59	7.20	+5.4
Xd	1.553	1.556	-0.2
X'd	0.183	0.195	-6.1
X"d	0.116	0.115	+0.9
Xq	1.552	1.556	-0.3
X"q	0.114	0.115	-0.9

Figs. 9-a through 9-d show results of run 1 used for determination of the d-axis parameter values for a salient pole generator. Figs. 10-a through 10-c refer to the determination of the q-axis parameter values for the same generator. The figures are self-explanatory and the procedure used for the determination of the different parameters is in accordance with the methods previously discussed.

DETERMINATION OF D-AXIS PARAMETER VALUES FOR A SALIENT POLE GENERATOR RESULTS OF SIMULATION RUN 6 - REJECTION OF A PURELY REACTIVE LOAD

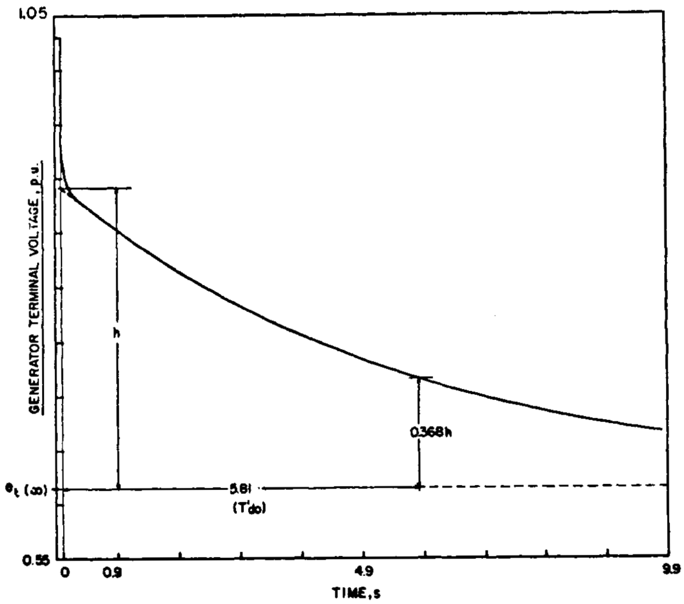


Fig. 9-a Terminal voltage variation.

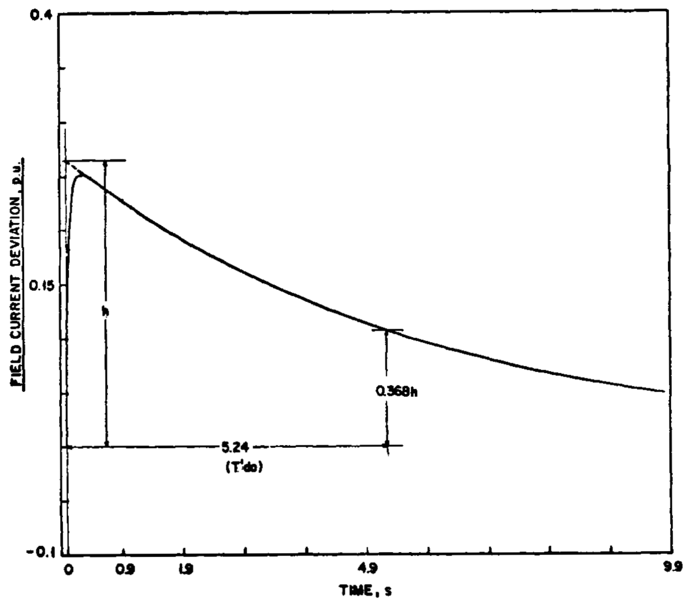


Fig. 9-c Field current deviation.

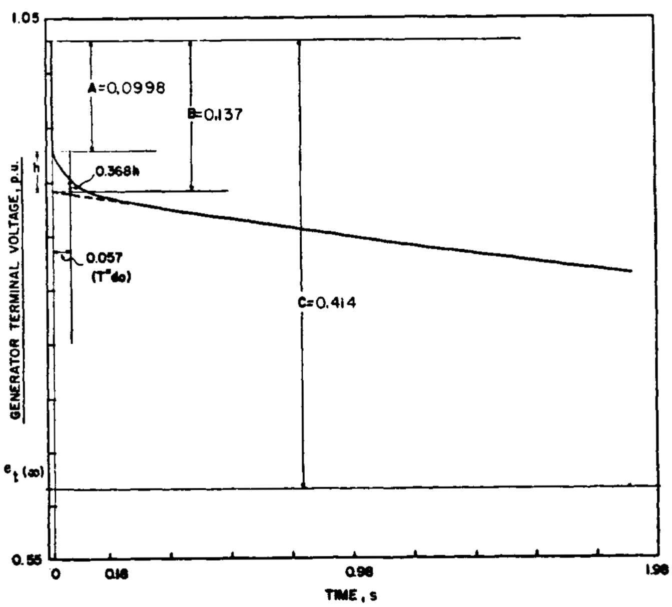


Fig. 9-b Terminal voltage variation, expanded time scale.

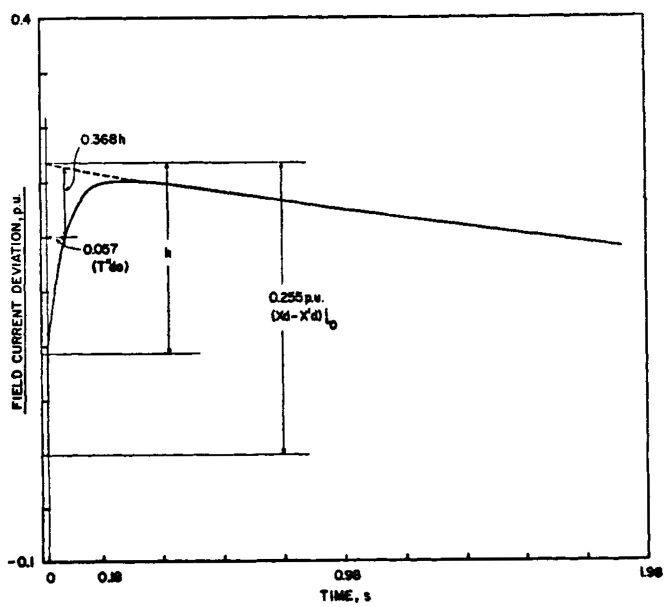


Fig. 9-d Field current deviation, expanded time scale.

DETERMINATION OF Q-AXIS PARAMETER VALUES FOR A SALIENT POLE GENERATOR

RESULTS OF SIMULATION RUNS # 2 THROUGH # 5

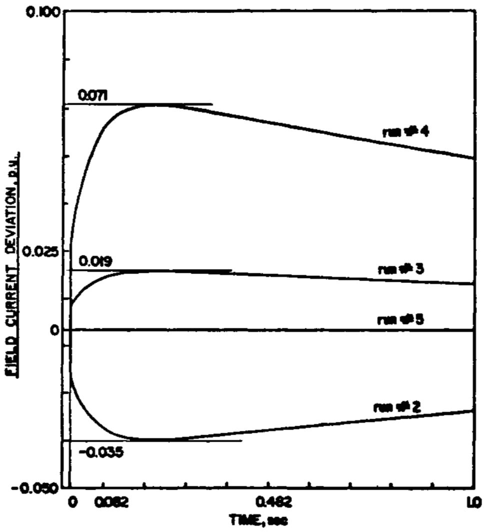


Fig. 10-a Field current deviation following load rejection (see Table 1 for detail on runs).

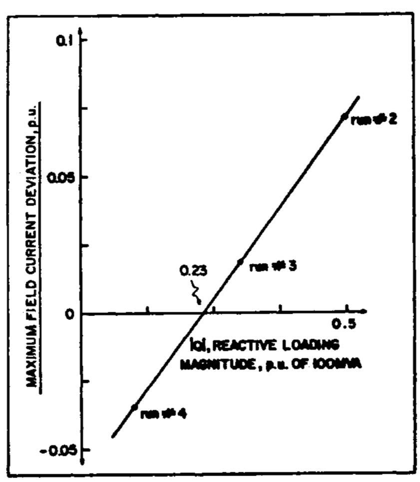


Fig. 10-b Max. value of field current deviation versus magnitude of the reactive loading. Interpolation gives the value of Q_o required for zero d-axis component of armature current.

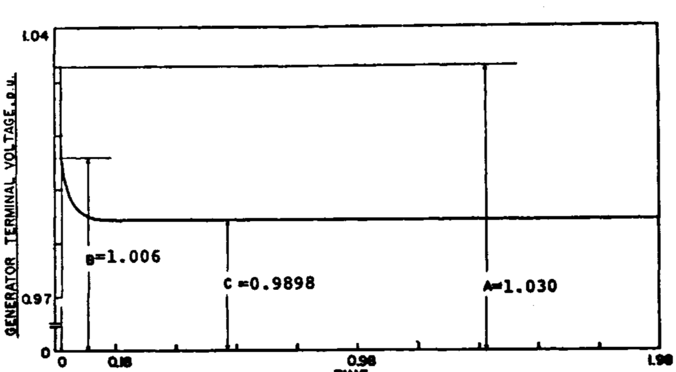


Fig. 10-c Run # 5 - Terminal voltage, variation after load rejection.

Figures 11-a through 12-c similarly refer to the determination of parameter values for a round rotor generator.

DETERMINATION OF D-AXIS PARAMETER VALUES FOR A ROUND ROTOR GENERATOR — RESULTS OF SIMULATION RUN # 10 - REJECTION OF A PURELY REACTIVE LOAD

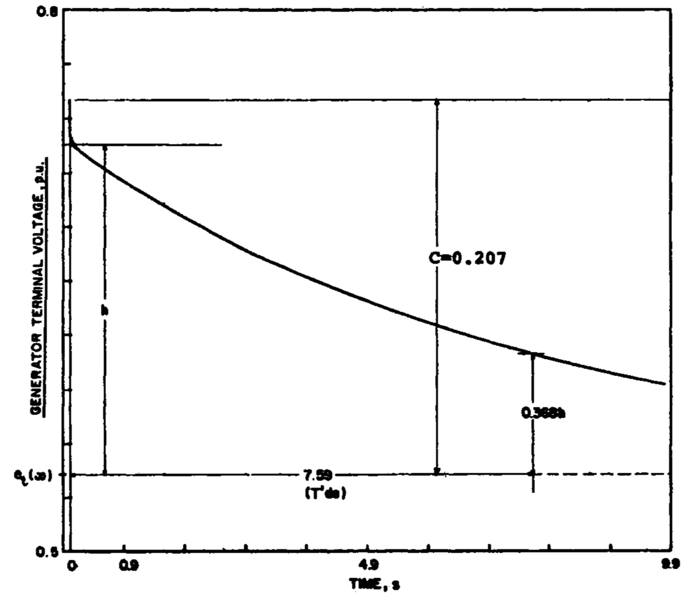


Fig. 11-a Terminal voltage variation.

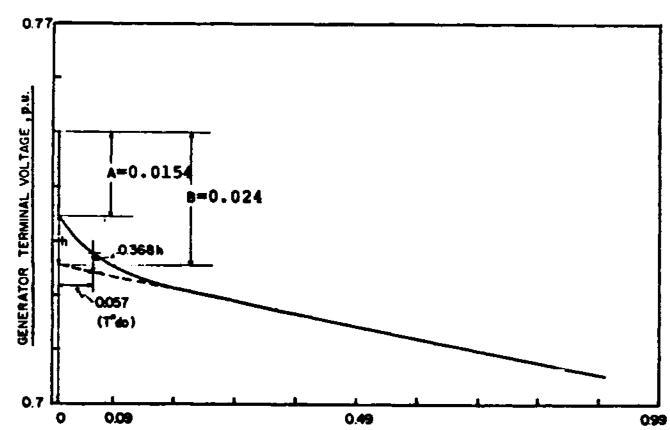


Fig. 11-b Terminal voltage variation, expanded scales.

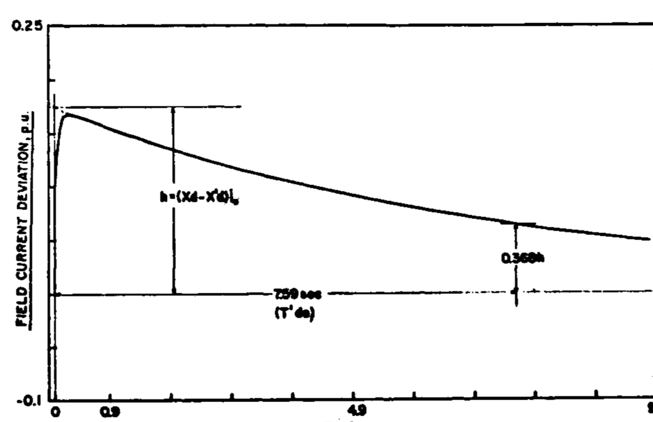


Fig. 11-c Field current deviation.

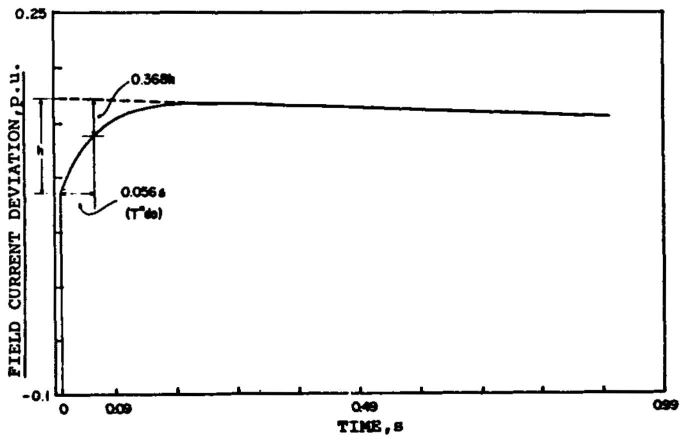


Fig. 11-d Field current deviation, expanded time scale.

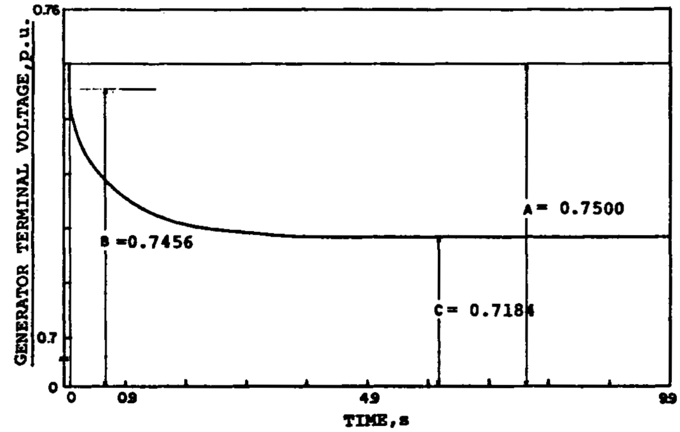


Fig. 12-c Run # 10 - Terminal voltage variation after load rejection.

DETERMINATION OF Q-AXIS PARAMETER VALUES FOR A ROUND ROTOR GENERATOR

RESULTS OF SIMULATION RUNS # 6 THROUGH 10

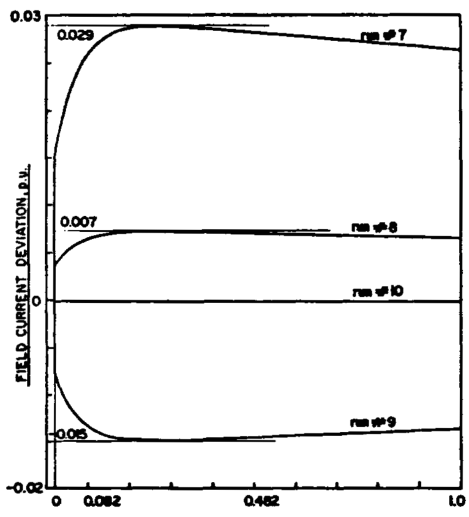


Fig. 12-a Field current deviation following load rejection.

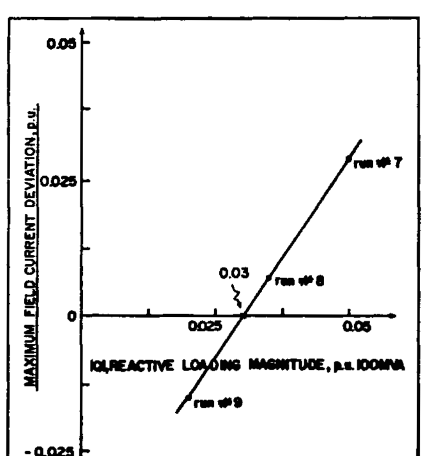


Fig. 12-b Max. value of field current deviation versus magnitude of the reactive loading. Interpolation gives the value of Q_o required for zero d-axis component of armature current.

DISCUSSION

Tables 2 and 3 show that the derived values are within a few percent of the actual values (input data). Deviations can be attributed to reading errors, since values were read off the plots. Although digital output was available, results were read off the plots to keep conditions as close to reality as possible. Results from field tests are usually obtained in the form of recordings.

The determination of unsaturated values of the parameters requires establishing underexcited loading conditions, including operation at low terminal voltage. Once the basic unsaturated parameters are obtained the effects of saturation can be evaluated by similar tests in the overexcited region. These would serve to validate the method of representing saturation and should be the subject of further research.

It should be noted that the loading conditions for which only the q-axis component of armature current is present can be estimated from approximate knowledge of Xq. The locus of operating points can be deduced from equation (4) and is given by the equation:

$$P^2 = \frac{Qet^2}{X_q} - Q^2 \qquad (6)$$

where

P = Power

Q = Underexcited Reactive Power

et = Terminal Voltage

This relationship shows that feasible reactive loading conditions should be in the region were

$$P < \frac{et^2}{2Xq} \qquad (7)$$

CONCLUSIONS

A test procedure has been illustrated for the derivation of synchronous machine parameters which are used in power system dynamic analysis studies.

The procedure is simple and can be applied in the course of normal operation of the machine as it is synchronized or taken off line.

The techniques shown, the most important of which involves a new method of determining q-axis parameters, should be of value to the industry in resolving the adequacy of machine modeling methods for system dynamic studies.

REFERENCES

(1) "Effects of Excitation, Turbine Energy Control and Transmission on Transient Stability", P. G. Brown, F. P. de Mello, E. H. Lenfest and R. J. Mills. IEEE Transactions 70-TP-203, IEEE Winter Power Meeting, 1970.

(2) "Modern Concepts of Power System Dynamics - The Effects of Control", F. P. de Mello. IEEE Tutorial Course, publication 70 M 62-PWR, 1970.

(3) Ibid. - "The Synchronous Machine" C. C. Young.

(4) "Synchronous Machines", Book, C. C. Concordia, J. Wiley & Sons, 1951.

(5) "The General Theory of Electrical Machines", Book, B. Adkins, J. Wiley & Sons, 1957.

Discussion

Yao-nan Yu and **M. D. Wvong** (University of British Columbia, Vancouver, Canada): Our congratulations to the authors for their timely contribution toward the development of test methods for synchronous machine parameters as an alternative to the IEEE Test Code [A]. We would appreciate the authors' comments upon the question: How their method compares with the frequency response method which involves rather wider frequency spectra. We would also like to refer to the following publications [B, C] which may be of interest to readers in this regard.

REFERENCES

[A] "Test Procedures for Synchronous Machines", IEEE Publication No. 115, 1965.

[B] Yao-nan Yu and H. A. M. Moussa, "Experimental Determination of Exact Equivalent Circuit Parameters of Synchronous Machines", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-90, pp. 2555-2560, Nov./Dec. 1971.

[C] Y. Takeda and B. Adkins, "Determination of Synchronous-Machine Parameters Allowing for Unequal Mutual Inductances", Proc. IEE, Vol. 121, pp. 1501-1504, December 1974.

Manuscript received February 22, 1977.

Stephen D. Umans (Massachusetts Institute of Technology, Cambridge, MA): The tests described in this paper are well defined and clearly presented. I find the procedure for obtaining q- axis data by looking for a null in transient field current deviations to be particularly ingenuous. The test procedures which the authors present are of significance due both to their ease of implementation without risk of damage to the machine under test as well as to their ability to measure both the d- and q- axis properties.

I have a number of questions and comments.

(1) These procedures are, in effect, a set of step response tests for the d- and q- axes. As a result, the "input" signals (i.e., the steps in d- and q- axis current) have frequency spectra which are relatively poor in high frequency components, the spectrum of a step being inversely proportional to frequency. Thus, it would seem that the results of these tests may be insensitive to values of the shorter rotor time constants. Would the authors care to comment?

Manuscript received February 18, 1977.

(2) Have the authors actually tested this procedure on any generators or are such tests planned?

(3) Given that the authors were undoubtably unable to present any field test results, it would seem to me that perhaps a slightly different set of simulations should have been used to demonstrate the procedure. The models being derived are of the same order (i.e., number of rotor windings) as the models being used for the simulations. Thus, it is not surprising that the derived results agree so closely with the input data.

I would think that more complex models should have formed the basis of the simulations – perhaps a 3 rotor winding d-axis and a 2-rotor winding q-axis. This corresponds to the "benchmark model" approach used in the paper by Schulz, et al. [1]. Of course, the problem with this approach is that it is more difficult to interpret the results. However, it is a much stronger test of the techniques.

I am looking forward to seeing this technique applied in the field and hope that the authors will present test results when they become available.

REFERENCE

[1] R. P. Schulz, W. D. Jones and D. N. Ewart, "Dynamic Models of Turbine Generators Derived from Solid Rotor Equivalent Circuits", IEEE Trans. PAS, Vol. 92, pp. 926-933, May/June 1973.

F. P. de Mello and **J. R. Ribeiro**: We thank Messrs. Umans, Yu, and Wvong for their comments and questions.

Addressing to Mr. Umans' questions:

1. It is correct that the procedures suggested are essentially a set of step response tests if the interruption of the phase currents are considered instantaneous and simultaneous. An ideal step would thus exhibit the entire frequency spectrum. In actual fact however, interruption occurs on successive individual phase current zeros so that the front of the step would be corrupted by the existence of equal and opposite current in two phases for about 4 millisec following extinction of the first phase current. Simulations have indicated that this effect is not significant relative to the basic rotor time constants of concern. It is appropriate at this point to note that the fidelity of the generator models in terms of frequency spectra must be consistent with the phenomena under investigation. In stability problems where the network response is simulated as instantaneous (algebraic fundamental frequency treatment) it is futile to extend the frequency bandwidth of the rotor representation without corresponding treatment of the armature and network as a dynamic versus algebraic system of equations.

2. There have been many recorded tests of rejections made through the years. A concerted program of using them for derivation of machine parameters as outlined in the paper is underway as part of an EPRI sponsored research activity.

3. The intent of the paper was tutorial, to demonstrate a simple test procedure for d- and q-axis process identification. It was entirely out of the scope of the investigation to discuss the merit of the form of the model, whether 2nd, 3rd or higher order, linear or nonlinear. Such conclusions will be possible when actually trying to derive parameters of a given postulated model structure from test results. The success with which the assumed model structure with appropriately fitted parameters duplicates test results under varying conditions will be the basis to judge the adequacy of the particular model.

With regard to Prof. Yu and Mr. Wvong's question on the merits of frequency response versus step response testing, we would comment as follows:

1. Frequency response testing while ideal as a technique for laboratory type machines is expensive and impractical on utility size machines. Power levels of the exciting source of necessity have to be a very small fraction of the machine rating and it is questionable whether representative values of permeability of the magnetic circuits are obtainable at such low excitation levels.

2. Frequency response testing is a small perturbation technique that provides the linearized characteristic about a given level of flux. It is difficult to derive the true nonlinear characteristics of machines as affected by saturation from frequency response tests. Both from the point of view of simplicity and cost as well as the ability to exercise characteristics over the meaningful nonlinear range of operation, the time response tests that were suggested provide a relatively easy means of deriving machine parameters with sufficient accuracy for use in system studies.

We thank Prof. Yu and Mr. Wvong for the very pertinent references which they cite for the benefit of readers interested in the subject. We have found these very instructive with particular reference to the problem of identifying the leakage reactance parameter through the additional test with field winding open. On-going studies in the authors' company devoted to this subject show promise of an alternate method which does not require opening of the field winding and which is, therefore, also applicable for identification of the q-axis leakage reactance.

Manuscript received March 31, 1977.