EXPREINCE WITH APPLICATION OF STANSSTILL FREQUENCY RESPONSE TEST FOR SYNCHRONOUS GENERATOR'S PARAMETERS IDENTIFICATION

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ABSTRACT

Accurate generator modeling allows for more precise calculation of power system control and stability limits. In this paper a procedure using a set of measured data from Standstill Frequency Response (SSFR) test on MontazerGhaem gas power plant's synchronous generator is used to obtain synchronous machine. A novel approach is used to find d-axis which is different from standard SSFR scheme which can save the time in doing SSFR tests. Hook-Jeeves method is used for optimization purpose. The test procedure and identification results are reported.

I. INTRODUCTION

Stability analysis is one of the most important tasks in power system operations and planning. Synchronous generators play a very important role in this way. A valid model for synchronous generators is essential for a reliable analysis of stability and dynamic performance. Almost three quarters of a century after the first publications in modeling synchronous generators, this subject is still a challenging and attractive research topic.

Two axis equivalent circuits are commonly used to represent the behavior of synchronous machines. The direct determination of circuit parameters from design data is very difficult due to intricate geometry and nonlinear constituent parts of machines. So several tests have been developed which indirectly obtain the parameter values of equivalent circuits.

The stand still Frequency Response (SSFR) test has been widely accepted for extraction synchronous machine parameters. The following advantages can credit to the SSFR method:

1) It is easy to implement at the factory or during outages for routine maintenance without risk to the machine, since the tests involve very little power.

2) The ready availability of powerful computer tools have eased the data logging and analysis procedures.

3) Unlike the ANSI-standardized short-circuit test, the SSFR approach can simultaneously provide the equivalent circuits for both direct and quadrate axes, and at the present time, seems the most appropriate for modeling the machine behavior for stability analysis.

Frequency response testing of electrical machines as a means of determining their parameters was introduced by [2] but the main thrust for the current work stems from the comprehensive study of the problem initiated by EPRI which culminated in the workshop in 1981 [3].

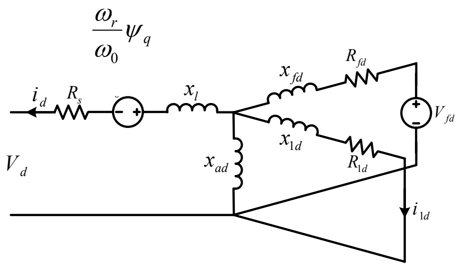
In [4] presented results of frequency response tests carried out on a 555MVA machine, with limited frequency range of 0.01 to 10 Hz but this was sufficient to identify a third order model for the machine. In [5] presented results for third order models for several machines introducing the concept of unequal mutual in the direct axis. In [6] proposed a new third order model claiming it as an improvement on the limited second order model. In [7] offered a recursive least squares algorithm with a frequency dependent weighting function to accentuate particular frequency ranges as an aid to the identification of the time constants. In [8] reported on the virtues of a "three transfer function approach" implying that such a model had not been considered before. Much of their comments related to a comparison of second and third order models, seeking to validate their extension to their new third order model. Numerical curve-fitting methods were used in all of the above papers.

In this paper an experience with SSFR test on MontazerGaem gas unit generator has been presented and used Hook and Jeeves optimization method for curve fitting purpose.

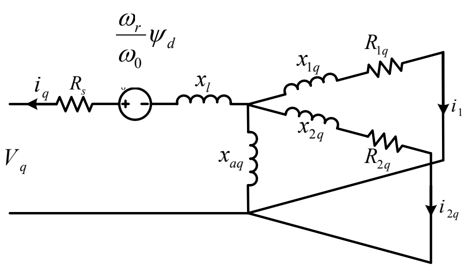
II. MACHINE MODELLING

The structure of the synchronous machine model used in this study is a standard second order model with one damper in the d-axis and two dampers in the q-axis given in Fig. 1 [9]. Degree of the applied model is selected based on synchronous generator type, rotor structure and IEEE-Std-1110 considerations. The equations of generators are as stated in [2].

Definition of the parameters is listed in table (1) and some relations between parameters are listed in Appendix.



a) d Axis



b) q Axis

Fig.1) Synchronous Machine Equivalent Circuits According to 2-2 Model of IEEE Std 1110

Table (1) synchronous generator parameters definition

Parameters	Parameters definition
X_l	Armature leakage inductance
X_{ad},X_{aq}	Armature to rotor mutual inductance
X_{cd}	d- axis differential leakage inductance
X_{fd}	Field winding leakage inductance
X_{1d},X_{1q},X_{2q}	Damper winding leakage inductance
R_a	AC Armature resistance
R_f	Field winding resistance
R_{1d},R_{1q},R_{2q}	Damper winding resistance
Z_d	d- axis operational impedance
Z_q	q- axis operational impedance
G(s)	standstill armature to field transfer function
Z_{afo}(s)	standstill armature to field transfer impeda
Vd	direct axis armature voltage
Vfd	field voltage
Vq	quadrate axis armature voltage
Na	effective number of turns on one phase on armature wining
Nfd	effective number of turns on field winding

III. TEST PROCEDURE

The SSFR test is categorized in off-line tests so machine shall be shut down, disconnected from its turning gear and electrically isolated. Also all connection to the field should be taken off, this can be done by removing the brush gear or, in the case of a brushless exciter, electrically disconnecting the complete exciter from the generator field winding.

This test consists of two steps, one for d-axis and another for q-axis. For each step, by positioning the rotor align with d or q axis and temporarily connecting the power amplifier as in table (2) the tests are performed.

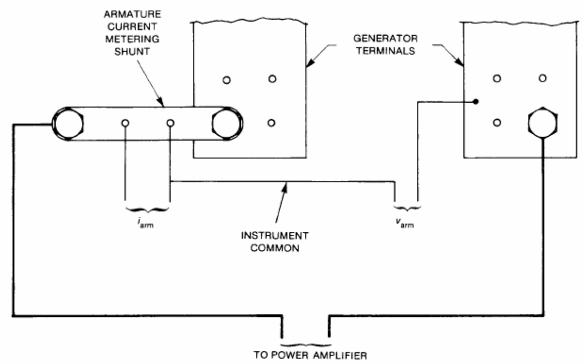


Fig.2) Connection for single ended input

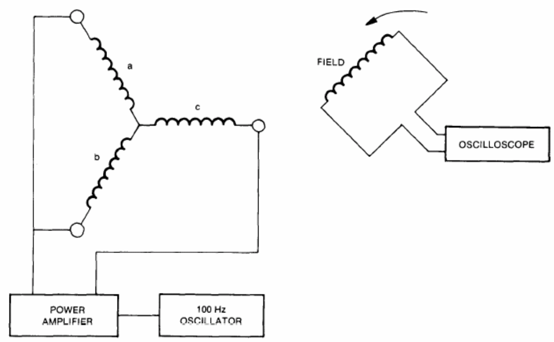


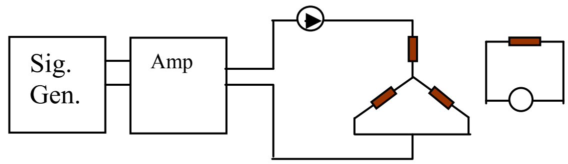
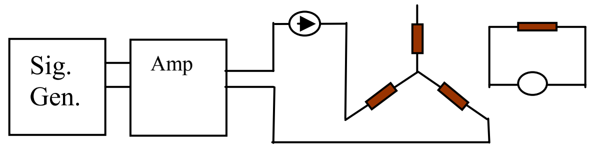
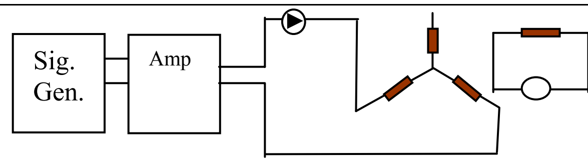
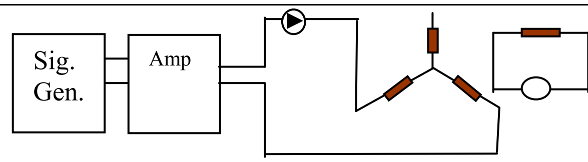
Fig.3) Positioning rotor align with q- axis tests

Reducing or eliminating the effect of contact resistances is very important to the accuracy of the measurements, particularly for the armature winding. The armature current metering shunt should be bolted directly to the conductor in the isolated phase bus, as close to the generator terminals as possible, also conducting grease should be used to enhance the contact. Fig. 2 shows the proper connection of the test leads for such devices.

For aligning the rotor with the q-axis, a power amplifier is temporarily connected as in Fig 3. A signal generator tuned on 100 Hz and 10 amps drives the amplifier. Then the induced field voltage is measured with an oscilloscope. The generator rotor is slowly turned until a null induced field voltage is achieved. This situation indicates quadrate-axis of the synchronous machine.

In this paper a novel approach is used to obtain d-axis which is different from standard SSFR scheme [1]. For this purpose, after finding q-axis, by keeping rotor position the armature phase winding connection is changed as illustrated in table(2). In this situation the rotor is aligned with d-axis. With using this novel method, the d-axis could be found as precisely as q-axis without additional work.

Table (2) Standstill Frequency Response Test

|No.	Measurement	Test Diagram	Measured Value	Relationships
1	q-Axis operational Impedance $Z_q(s)$		U_{stator} I_{stator} $U_{rotor(about\ 0)}$	$Z_q(s) = -\frac{\Delta e_q(s)}{\Delta i_q(s)}\Big\|_{\Delta e_{fd}=0}$
2	d-Axis operational Impedance $Z_d(s)$		U_{stator} I_{stator} $U_{rotor(max)}$	$Z_d(s) = -\frac{\Delta e_d(s)}{\Delta i_d(s)}\Big\|_{\Delta e_{fd}=0}$
3	Standstill armature to field transfer function $sG(s)$		U_{stator} I_{stator} I_{rotor}	$sG(s) = -\frac{\Delta i_{fd}(s)}{\Delta i_d(s)}\Big\|_{\Delta e_{fd}=0}$
4	Standstill armature to field transfer impedance Z_{afo}		U_{rotor} I_{stator} Irotor(about-0)	$(s) = -\frac{\Delta e_{fd}(s)}{\Delta i_d(s)}\Big\|_{\Delta i_{fd}=0}$

For each test, the frequency of the provided sin wave signal by the signal generator is changed over the range of .01Hz to 1000 Hz. Then for each frequency, the magnitude and phase of $\Delta e_q, \Delta i_q, \Delta e_d, \Delta i_d, \Delta e_{fd}$ and Δi_{fd} are measured.

Approximately 10 test points, logarithmically spaced per decade of frequency, is a satisfactory measurement density.

IV. IDENTIFICATION PROCEDURE

The procedure for extracting d and q-axes parameters from SSFR tests can be summarized as follows [12]:

1) Use the best available estimation for armature leakage inductance L_l; it could be valued supplied by manufacturer.
2) Using the measured values, by means of Fourier transform the RMS value of the main wave associated with each measured quantities and corresponding to each frequency are obtained.
3) Based on the equations for Zd and Zq mentioned in table(2) and using RMS values for the measured quantities, the value for Zd, Zq and $G(s)$ are obtained corresponding to each frequency.
4) Obtain $L_d(0)$ and $L_q(0)$ which are low- frequency limit of $L_d(s)$ and $L_q(s)$ and then determine

$$L_{ad}(0) = L_d(0) - L_l$$
$$L_{aq}(0) = L_q(0) - L_l$$

5) find the field to armature turns ratio Nfd/Na using the armature to field transfer impedance $Z_{afo}(s)$

$$N_{af}(0) = \frac{1}{sL_{ad}(0)} = \lim_{s\to 0}\left[\frac{\Delta e_{fd}(s)}{\Delta i_d(s)}\right]$$

6) Calculate the field resistance referred to armature winding.

$$R_{fd} = \frac{sL_{ad}(0)}{\lim_{s\to 0}\left[\frac{\Delta i_{fd}(s)}{\Delta i_d(s)}\frac{2}{3}N_{af}(0)\right]}$$

7) Define an equivalent circuit structure for the d and q axes.
8) Use the Hook-Jeeves optimization technique to find the best value for generator parameters which provide the best fits for $L_d(s)$ and $L_q(s)$ and $sG(s)$
9) Measure the fields winding resistance , convert it to the desired operating temperature, and refer it to the stator

$$R_{fd-\theta} = [\frac{234.5+\theta}{234.5+T_f}]r_{fd} \times \frac{3}{2}[\frac{1}{N_{af}(0)}]^2$$

V. HOOK-JEEVES OPTIMIZATION METHOD

The pattern search method of Hook and Jeeves is a sequential technique in which each step consists of two kinds of moves, one called exploratory move and another called as pattern move. The first move is to explore the local behavior of the objective function and the second move is to take advantage of the pattern direction. The general procedure can be described by the following steps [13].

1- Start with an arbitrarily initial point $X_1=[x_1\ x_2\ \dots\ x_n]^T$, called the starting base point and prescribed step lengths Δx_i in each of the coordinate directions u_i, $i=1,2,....,n$. set k=1.

2- Compute $f_k = f(X_k)$. Set $i=1$ and define new variable with initial value set as, $Y_{k0} = X_k$ and start the exploratory move as stated in step 3.

3- The variable x_i is perturbed about the current temporary base point $Y_{k,i-1}$ to obtain the new temporary base point as follows:

$$Y_{k,i}\begin{cases} Y_{k,i-1}+\Delta x_i u_i & \text{if} \quad f^{+}=f(Y_{K,i-1}+\Delta x_i u_i) \\ & \quad < f=f(Y_{k,i-1}) \\ Y_{k,i-1}-\Delta x_i u_i & \text{if} \quad f^{-}=f(Y_{K,i-1}-\Delta x_i u_i) \\ & \quad < f=f(Y_{k,i-1}) \\ & \quad < f^{+}=f(Y_{k,i-1}+\Delta x_i u_i) \\ Y_{k,i-1} & \text{if} \quad f=f(Y_{K,i-1})<\min(f^{+},f^{-}) \end{cases}$$

This process of finding the new temporary base point is continued for i=1,2, …. Until x_n is perturbed to find $Y_{k,n}$.

4- If the point $Y_{k,n}$ remains same as the X_k , reduce the step lengths Δx_i (say by a factor of two), set i=1 and go to step 3.

If $Y_{k,n}$ is different from X_k, obtain the new base point as

$$X_{k+1} = Y_{k,n}$$

and go to step 5.

5- With the help of the base points X_k and X_{k+1} establish a pattern direction S as

$$S = X_{k+1} - X_k$$

and find a point $Y_{k+1,0}$ as

$$Y_{k+1,0} = X_{k+1} + \lambda S$$

The point Y_{kj} indicates the temporary base point obtained from the base point X_k by perturbing the j^{th} component of X_k.

Where λ is the step length which can be taken as 1 for simplicity.

6- set k=k+1 , $f_k = f(Y_{k0}), i=1$ and repeat step 3, if at the end of step 3 , $f(Y_{k,n}) < f(X_k)$, we take the new base point as $X_{K+1} = Y_{k,n}$, and go to step 5. On the other hand if $f(Y_{k,n}) \geq f(X_k)$, set $X_{k+1} = X_k$, reduce the step length Δxi, set $k = k+1$ and go to step 2.

7- The process is assumed to be converged whenever the step lengths fall below a small quantity ε . thus the process is terminated if

$$\max_i(\Delta x_i) < \varepsilon$$

VI. CARRY OUT SSFR TEST AND PARAMETER EXTRACTION

SSFR tests were performed on MontazaerGhaem rated 147.8 MVA gas Generator. The nominal values of the generator are shown in table (3). Leakage reactance is extracted from design data and equals to 0.095 p.u. Armature and field resistances are taken as R = 0.00141 Ω R_f =0.1015 Ω from generator technical document. Temperature during tests was measured as 27 ˚C, while operating temperature is supposed to be 100 ˚C.

The rotor position was changed by means of rotor lifting pump which made it easy to rotate the rotor with the use of proper pulling tools. During positioning of the rotor, zero voltage on the field winding could not be precisely achieved, so the final position was decided by achieving the minimum induced field voltage. During measurements, signals became noisier as the frequency was decreased below 0. 1 Hz.

Table(3) Nominal Values for MantazerGhaem gas unit synchronous generator

Rated Power (MVA)	Rated Voltage (KV)	Air Gap Field Current to Produce Rated Terminal Voltage (A)	Rated Frequency (Hz)
147.775	13.8	491	50

The extracted test result is shown in table (5).

During the test instantaneous value of measured current and voltage are recorded by transient recorder in each scanning frequency. Using Fourier transform, from the instantaneous measured values, RMS values are extracted by which operational impedances Z_d , Z_q and G(s) (both magnitudes and angles) are calculated for the whole range of scanning frequency. The magnitudes and phase angles of Z_d and Z_q are illustrated in fig (4), (5) respectively.

Table(4) calculated base parameter

Armature Base Current	6182.46	A
Armature Base Inductance	0.0041	H
Field Base Current	1076.763	A
Field Base Inductance	0.4057	H

R_d , R_q are obtained by extrapolating operational impedances Z_d , Z_q at zero frequency as illustrated in Fig.6. Using operational impedances Z_d , Z_q and R_d , R_q , the d and q axes impedances are calculated and depicted as Fig. for finding $L_d(0)$ and $L_q(0)$ is used from a fictitious quadrate rational function.(Fig.7)

Table(5) the extracted test result

Armature Resistance in d-axes Test	0.0014	Ω
Armature Resistance in q-axes Test	0.0017	Ω
Field Resistance in Test	0.0020	Ω
Ld(0)	0.0095	H
Lq(0)	0.0090	H
Nfd/Na	12.18	

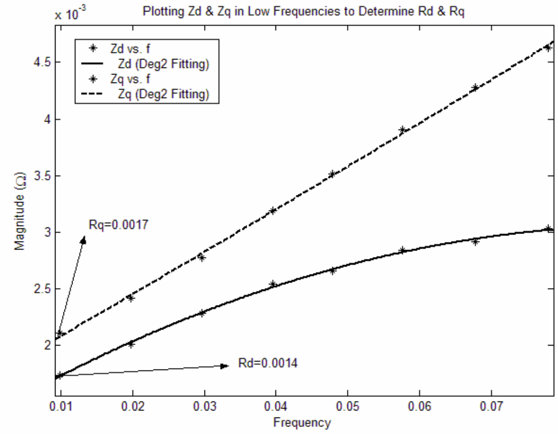


Fig.6) Extended window for Low frequency magnitudes of Z_d and Z_q to obtain R_d and R_q

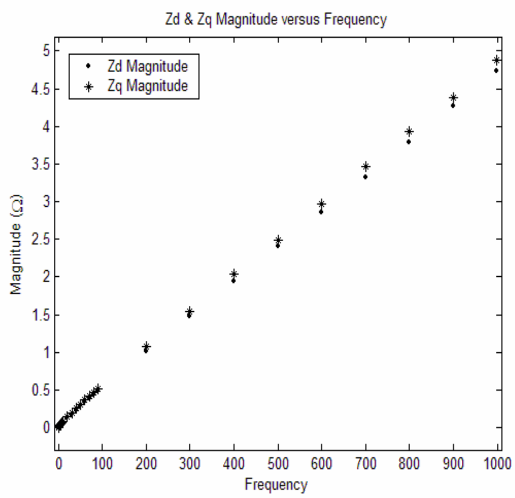


Fig.4) Z_d and Z_q magnitudes obtained by SSFR test

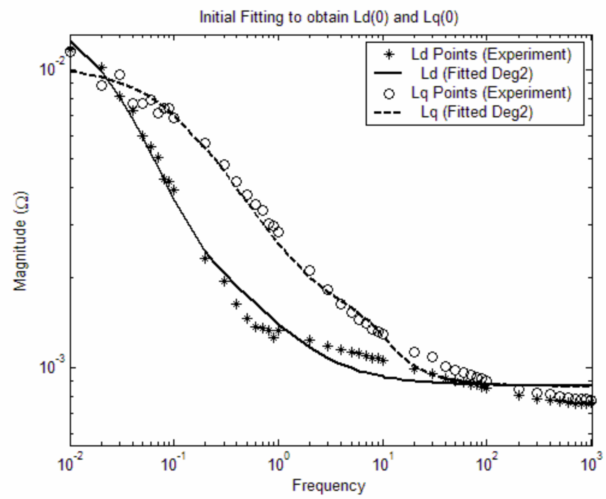


Fig.7) Finding $L_d(0)$ and $L_q(0)$ using a fictitious quadrate rational function

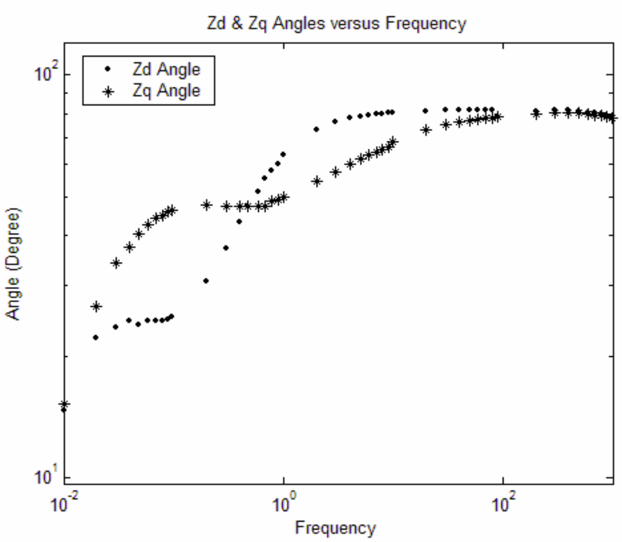


Fig.5) Z_d and Z_q pahse angles obtained by SSFR test

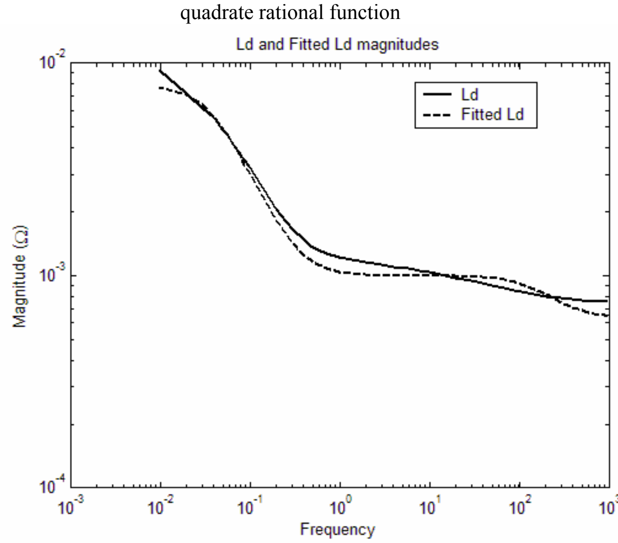


Fig.8) L_d magnitude fitting to obtain parameters, a second order model

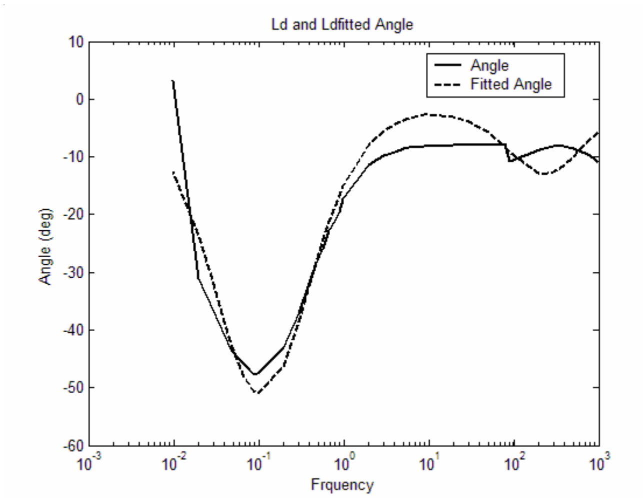


Fig.9) Angle of L_d and fitted quad rational function, second order model

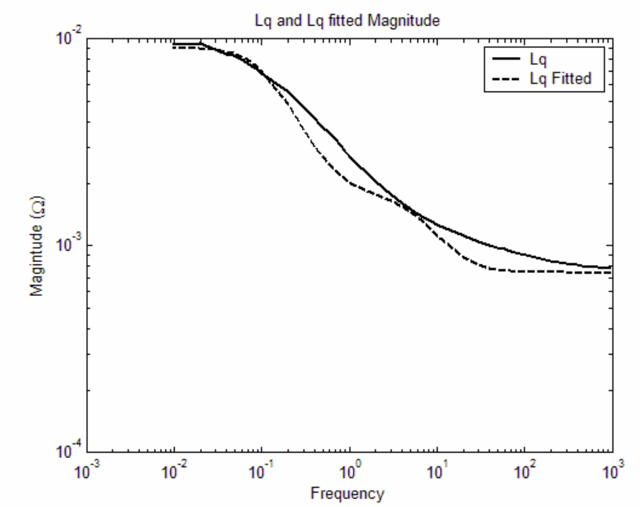


Fig.10) L_q magnitude fitting to obtain parameters, a second order model

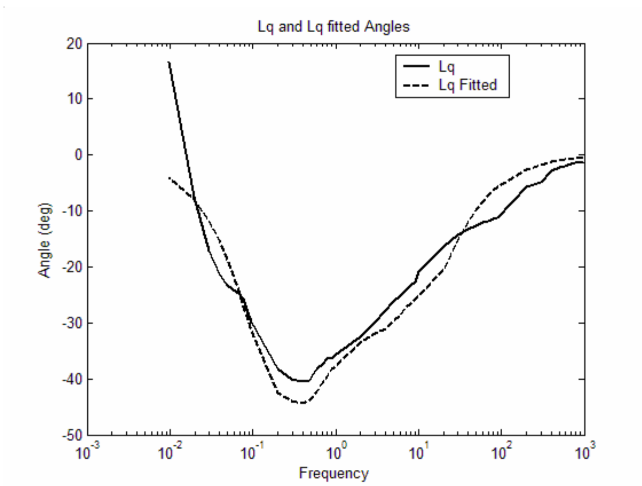


Fig.11) Angle of L_q and fitted quad rational function, second order model

For fitting L_d and L_q to obtain equivalent circuit parameters we used the Hook-Jeeves optimization technique [13]. All data processing was done in actual units and at the end p.u values was calculated relevantly. Curve fitting for finding L_d and L_q magnitude and phase using Hook-Jeeves method is illustrated in Fig.8 – Fig. 11.

Field resistance is modified according to operating temperature and actual value obtained from manufacturer. An unsaturated value for L_{ad} in Henrys can be calculated from rated speed open circuit saturation curve:

$$L_{adu} = \left(\frac{3}{2}\right)\left(\frac{N_a}{N_f}\right)\left(\frac{V_t}{\omega I_{fd}}\right)$$

Where V_t and I_{fd} define a point on the air gap lin, and ω is the rotor speed in electrical radians per second and V_t is peak voltage line to neutral. Similarly in the quadrature- axis equivalent circuit L_{aq} must be adjusted to its unsaturated value.

L_{ad} and L_{aq} are modified for operating flux density using linear equation of [2]. The final result for d and q axis is summarized in table (6) and table (7) respectively. The manufacturer parameter for d-axis and q-axis is shown in table (8).

VII. CONCLUSION

It has been demonstrated here that the problem of identification of the parameters of synchronous machines from the results of frequency response tests can be done by an essentially analytical process. The parameters are estimated using Hook-Jeeves pattern search method. Simulation and experimental results show that the parameters of model for a synchronous generator can be identified successfully and have good accuracy with parameters presented by manufacturer. The model can then be used for studying low frequency oscillations and design and tuning power system stabilizers.

ACKNOWLEDGEMENT

The SSFR test is supported by Iran Grid Management Company (IGMC).

Table(6) D-axes results

Rfd (pu)	Lfd (pu)	Rd1 (pu)	Ld1 (pu)	Ladu(Test) (pu)	Ladu(mod) (pu)	Ll (pu)	Ra (pu)	X"d (pu)	T"d (s)	X'd (pu)	T'd (s)	Xd (pu)
0.001018	0.18182	0.96219	0.11716	2.22088	2.19300	0.095	0.001094	0.16401	0.0190	0.2629	0.8526	2.2880

Table (7) Q-axes results

Rq2 (pu)	Lq2 (pu)	Rq1 (pu)	Lq1 (pu)	Laqu (Test) (pu)	Laqu (mod) (pu)	Ll (pu)	Ra (pu)	X"q (pu)	T"q (s)	X'q (pu)	T'q (s)	Xq (pu)
0.051411	0.098088	0.007403	0.379834	2.098992696	2.0726421	0.095	0.001094	0.17013	0.020612	0.4160	0.2023	2.16764

Table (8) Manufacturer provided data

X"d (pu)	T"d (s)	X'd (pu)	T'd (s)	Xd (pu)	X"q (pu)	T"q (s)	X'q (pu)	T'q (s)	Xq (pu)
0.19	0.021	0.28	0.88	2.29	0.19	0.021	0.39	0.15	2.12

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APPENDIX

Some relations between operational parameters and dynamical parameters are presented here.

$$X_d = x_l + x_{ad}$$

$$X_q = x_l + x_{aq}$$

$$X'_d = x_l + x_{ad} \| x_{fd} = x_l + \frac{x_{ad} x_{fd}}{x_{ad} + x_{fd}}$$

$$X'_q = x_l + x_{aq} \| x_{1q} = x_l + \frac{x_{aq} x_{1q}}{x_{aq} + x_{1q}}$$

$$X''_d = x_l + x_{ad} \| x_{fd} \| x_{1d} = x_l + \frac{x_{ad} x_{fd} x_{1d}}{x_{ad} x_{fd} + x_{ad} x_{1d} + x_{fd} x_{1d}}$$

$$X''_q = x_l + x_{aa} \| x_{1q} \| x_{2q} = x_l + \frac{x_{aq} x_{1q} x_{2q}}{x_{aq} x_{1q} + x_{aq} x_{2q} + x_{1q} x_{2q}}$$

$$T'_{do} = \frac{1}{\omega_0 R_{fd}} \left(x_{fd} + x_{ad} \right)$$

$$T'_{qo} = \frac{1}{\omega_0 R_{1q}} \left(x_{1q} + x_{aq} \right)$$

$$T''_{do} = \frac{1}{\omega_0 R_{1d}} \left(x_{1d} + x_{fd} \| x_{ad} \right) = \frac{1}{\omega_0 R_{1d}} \left(x_{1d} + \frac{x_{fd} x_{ad}}{x_{fd} + x_{ad}} \right)$$

$$T''_{qo} = \frac{1}{\omega_0 R_{2q}} \left(x_{2q} + x_{1q} \| x_{aq} \right) = \frac{1}{\omega_0 R_{2q}} \left(x_{2q} + \frac{x_{1q} x_{aq}}{x_{1q} + x_{aq}} \right)$$