Experience with SSFR Test for Synchronous Generator Model Identification Using Hook-Jeeves Optimization Method

M.R. Aghamohammadi , M. Pourgholi

***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 dynamic parameters of the machine. A novel approach is used to find d-axis which is different from standard SSFR scheme which can save the time in performing SSFR tests. Hook-Jeeves optimization method is used for parameter estimation purpose. The test procedure and identification results are reported.**

***Keywords*—SSFR, Synchronous generator, Parameter identification, Hook-Jeeves optimization method.**

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. 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 Modeling

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 [8]. 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]. Some relations between parameters are listed in Appendix 1.

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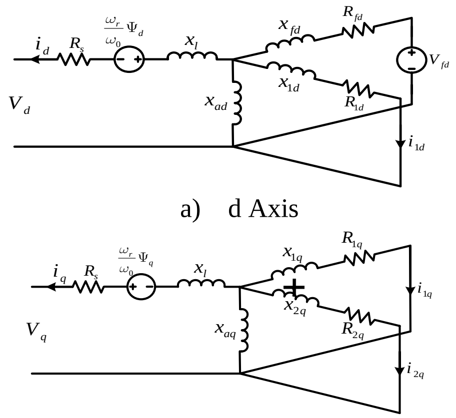


a) d Axis

b) q Axis

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

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 I the tests are performed. 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. 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.

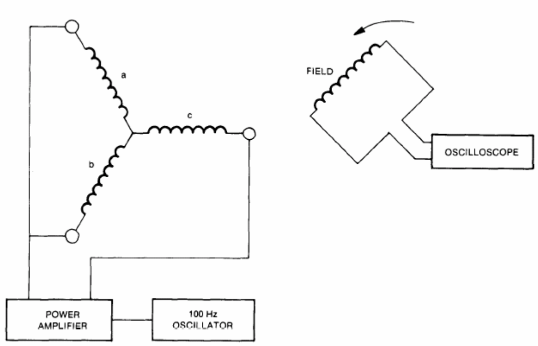


Fig. 2 Positioning rotor align with q- axis tests

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(1). 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. For performing SSFR tests, considering the test circuits illustrated in table I, the following tests are carried out.

One test for q-axis corresponding to the test circuit no.1, and two tests for d-axis corresponding to test circuits no. 2 & 3. No test has been done with respect to test circuit no.4.

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 Procedures

The procedure for extracting d and q-axes parameters from SSFR tests can be summarized as follows [10]:

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 tableI 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

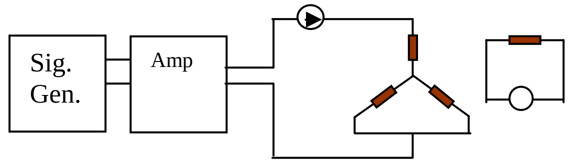
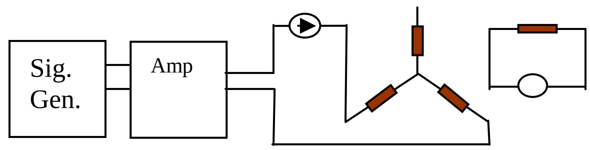
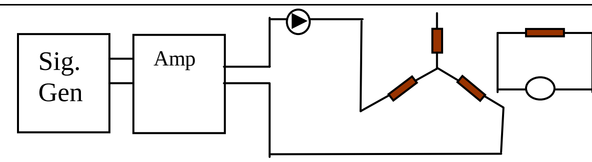
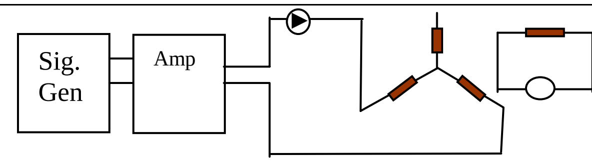
$$L_{ad}(0) = L_d(0) - L_l \tag{1}$$

$$L_{aq}(0) = L_q(0) - L_l \tag{2}$$

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

$$N_{af}(0) = \frac{1}{sL_{ad}(0)} = \lim_{s \to 0}\left[\frac{\Delta e_{fd}(s)}{\Delta i_d(s)}\right] \tag{3}$$

Table I. 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)	$_o(s) = -\frac{\Delta e_{fd}(s)}{\Delta i_d(s)}\Big\|_{\Delta i_{fd}=0}$

6) Calculate the field resistance referred to armature winding.

$$R_{fd} = \frac{sL_{ad}(0)}{\lim\limits_{s\to 0}\left[\frac{\Delta i_{fd}(s)}{\Delta i_d(s)}\frac{2}{3}N_{af}(0)\right]} \tag{4}$$

7) Define an equivalent circuit structure for 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.

$$R_{fd-\theta} = \left[\frac{234.5+\theta}{234.5+T_f}\right]r_{fd} \times \frac{3}{2}\left[\frac{1}{N_{af}(0)}\right]^2 \tag{5}$$

Where r_{fd} is the field resistance measured at field terminal and T_f is average field winding temperature during the measurement. Substitute this value for Rfd in the equivalent circuit. For the field windingmaterials other than copper, appropriate value of temperature coefficient should be used (234.4 for copper).

V. Hook and 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 [11].

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

$$Y_{k,i}\begin{cases} Y_{k,i-1}+\Delta x_i u_i & if \quad f^+ = f(Y_{K,i-1}+\Delta x_i u_i) \\ & \qquad < f = f(Y_{k,i-1}) \\ Y_{k,i-1}-\Delta x_i u_i & if \quad f^- = f(Y_{K,i-1}-\Delta x_i u_i) \\ & \qquad < f = f(Y_{k,i-1}) \\ & \qquad < f^+ = f(Y_{k,i-1}+\Delta x_i u_i) \\ Y_{k,i-1} & if \quad f = f(Y_{K,i-1}) < \min(f^+, f^-) \end{cases} \tag{6}$$

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 the 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

$$X_{k+1} = Y_{k,n} \tag{7}$$

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

$$S = X_{k+1} - X_k \tag{8}$$

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

$$Y_{k+1,0} = X_{k+1} + \lambda S \tag{9}$$

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

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

$$\max\left\{\Delta x_i\right\} < \varepsilon \tag{10}$$

VI. CARRY OUT SSFR TEST AND PARAMETER EXTRACTION

SSFR tests were performed on gas Generator of MontazaerGhaem power plant rated 147.8 MVA, 13.8KV, 50 Hz,. 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 by means of proper pulling tools. During positioning 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.

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 figures (3) and (4) respectively.

R_d, R_q are obtained by extrapolating operational impedances Z_d , Z_q at zero frequency as illustrated in Fig.5. Using operational impedances Z_d , Z_q and R_d, R_q , the d and q axes impedances are calculated by equation (11) which are depicted in Figures 7-10:

$$\begin{aligned} L_d(s) &= \frac{Z_d(s) - R_d}{s} \\ L_q(s) &= \frac{Z_q(s) - R_q}{s} \end{aligned} \tag{11}$$

A fictitious quadrate rational function as shown in Fig.6 is used for finding $L_d(0)$ and $L_q(0)$.

For fitting L_d and L_q to obtain equivalent circuit parameters we used the Hook-Jeeves optimization technique [11]. 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.7 – Fig. 10.

Field resistance is modified according to operating temperature and actual value obtained from manufacturer. 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 II and table III respectively. The manufacturer parameter for d-axis and q-axis is shown in table IV.

VII. CONCLUSION

In this paper, it has been demonstrated that the problem of parameters identification of synchronous machine from the measured data obtained by frequency response tests can be essentially carried out by an analytical process. In this paper, the machine parameters are estimated using Hook-Jeeves pattern search method using frequency response data. Also a novel approach is used to find d-axis which is different from standard SSFR scheme which can save the time in performing SSFR tests

Simulation and experimental results show that the parameters of an adopted model for a synchronous generator can be identified successfully and have good accuracy compared to the parameters presented by manufacturer. The estimated model can then be used for studying stability and low frequency oscillations ad design and tuning power system stabilizers of the generator.

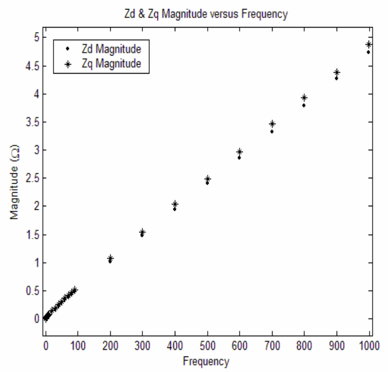


Fig. 3 Z_d and Z_q magnitudes obtained by SSFR test

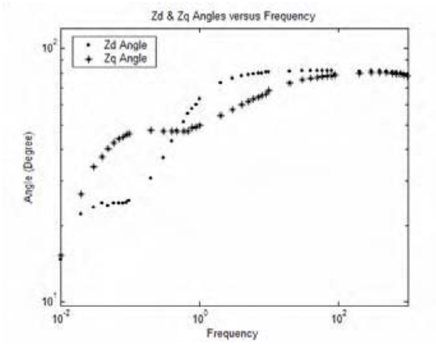


Fig. 4 Z_d and Z_q pahse angles obtained by SSFR test

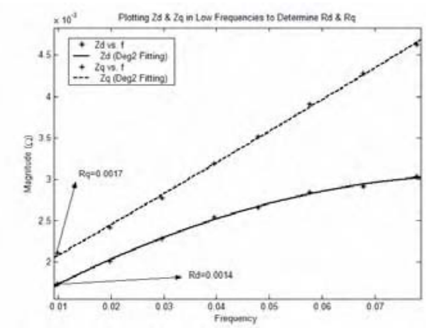


Fig. 5 Extended window for Low frequency magnitudes of Z_d and Z_q to obtain R_d and R_q

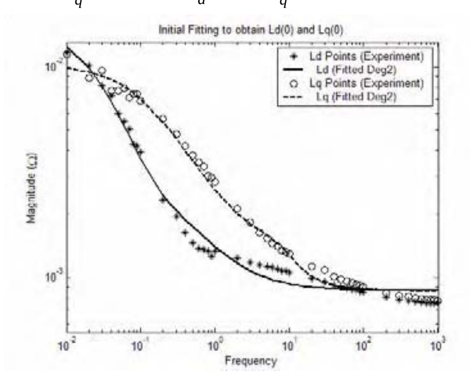


Fig. 6 Finding $L_d(0)$ and $L_q(0)$ using a fictitious quadrate rational function

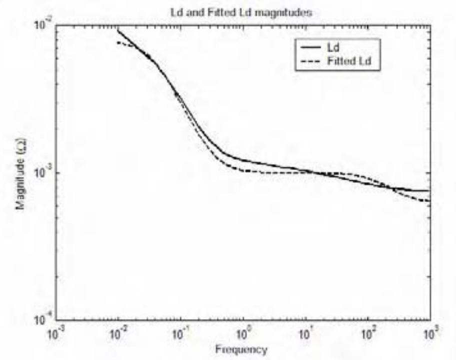


Fig. 7 L_d magnitude fitting to obtain parameters, a second order model

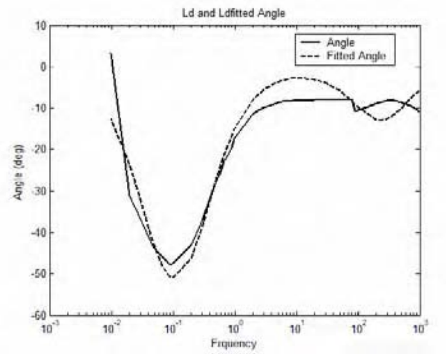


Fig. 8 Angle of L_d and fitted quad rational function, second order model

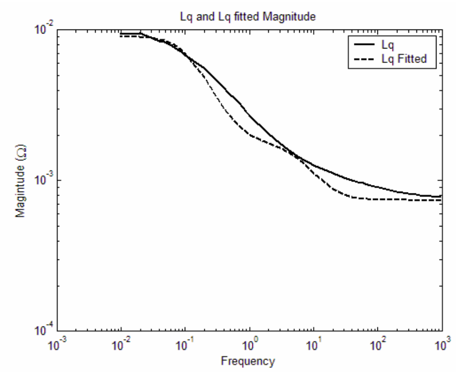


Fig. 9 L_q magnitude fitting to obtain parameters, a second order model

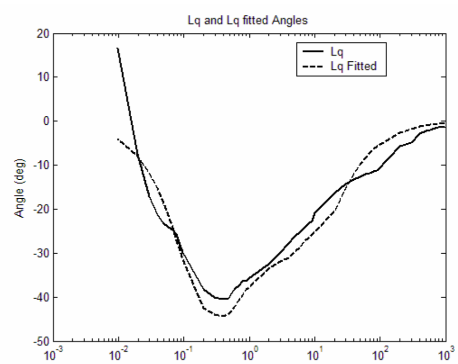


Fig. 10 Angle of L_q and fitted quad rational function, second order model

Table II. 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 III. 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

TableIV. 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.

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

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

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

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

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

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

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

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

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

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

Mohammad Reza Aghamohammadi he was born in Iran on August 5, 1955. He received his BSC degree from sharif University of Technology 1989, MSc degree from Manchester University (UMIST) in 1985 and his PhD from.Tohoku University, Japan in 1994. He is head of Iran Dynamic Research Center (IDRC) and his research interest includes application of Neural Networks for power system security assessment and operation