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SYNCHRONOUS MACHINE PARAMETER ESTIMATION BY STANDSTILL FREQUENCY RESPONSE TESTS

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This paper presents the steps of the approach to identify the linear parameters of a salient-pole synchronous machine at standstill and by frequency response tests data (SSFR). It is currently established and demonstrated that stability parameters for synchronous machines can be obtained by performing frequency response tests with the machine at standstill. The objective of this study is to use several input-output signals, according to a setup test recommended by the standard IEEE Std 115, to identify the model structure and parameters of a salient-pole synchronous machine from frequency response tests data. This procedure consists of defining and conducting the frequency response tests, identifying the model structure, estimating the corresponding parameters, and making valid the resulting model. We estimate the parameters of operational impedances, or in other terms, the reactances and the time constants. The results are presented from tests on the synchronous machine of 1.5 kVA/380V/1500 rpm.

K e y w o r d s: synchronous machine, parameter estimation, modeling, standstill tests, frequency response

1 INTRODUCTION

Accurate identification of the field circuit is a desirable feature for present day stability analyses where excitation controls play an important role. This is not possible with the standard tests described in IEEE Std 115 (1995). Another difficulty with these tests lies in defining adequate tests for quadrature-axis parameters, there are not practical or acceptable procedures for obtaining quadrature-axis transient or subtransient reactances or time constants. Present day studies require quadrature-axis as well as direct-axis values for an accurate and adequate synchronous machine stability simulation [1].

A new approach has demonstrated that stability parameters for synchronous machines can be obtained by performing frequency response tests with the machine at standstill.

Many papers have been published on the modelling and parameter estimation of synchronous machines [2–8] using the standstill frequency response test data and the time-domain response data. In reference [4–10], the standstill frequency response test data method is used to estimate machine parameters. The results given in [10–14] indicate that when two-rotor winding or three rotor winding models are used, a good estimate of machine parameters can be obtained

In reference [11] methods are described for obtaining synchronous machine parameters in the form of reactances and time constants.

Frequency response data describe the response of machine fluxes to stator current and field voltage changes in both the direct and quadrature axes of a synchronous machine. Some advantages of the method can be done either in the factory or on site, it poses a low of risk to the machine being tested, and it provides complete data in both direct and quadrature axes. Resistances and reactances for the associated models can be calculated using the methods in the Paragraph 3.

2 SYNCHRONOUS MACHINE MODELLING

Today a synchronous machine is normally modelled in the two axes with transient and subtransient quantities (2^{nd} order) [11]. For synchronous machine studies, the two-axis equivalent circuits with two or three damping windings are usually assumed at the proper structures [6]. In this work, and using the Park's d and q-axis reference frame, the synchronous machine is supposed to be modelled with one damper winding for the d-axis and two windings for the q-axis (2×2 model) as shown in Fig. 1 [2–6].

Voltage equations

$$V_d(p) = r_a i_d(p) + p\varphi_d(p) - \omega_r \varphi_q(p)\,, \tag{1a}$$

$$V_q(p) = r_a i_q(p) + p\varphi_q(p) + \omega_r \varphi_d(p)\,, \tag{1b}$$

$$V_f(p) = r_f i_f(p) + p\varphi_f(p)\,, \tag{1c}$$

$$0 = r_D i_D(p) + p\varphi_D(p)\,, \tag{1d}$$

$$0 = r_Q i_Q(p) + p\varphi_Q(p)\,. \tag{1e}$$

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While eliminating φ_f, i_f, φ_D, i_D, φ_Q, i_Q we obtain the following equations:

$$V_d(p) = r_a i_d(p) + p\varphi_d(p) - \omega_r \varphi_q(p)\,, \qquad (2a)$$

$$V_q(p) = r_a i_q(p) + p\varphi_q(p) - \omega_r \varphi_d(p)\,, \qquad (2b)$$

$$\varphi_d(p) = X_d(p) i_d(p) + G(p) V_f(p)\,, \qquad (2c)$$

$$\varphi_q(p) = X_q(p) i_q(p)\,. \qquad (2d)$$

This form of writing of the equations of the machine has the advantage of being independent of the number of dampers considered on each axis.

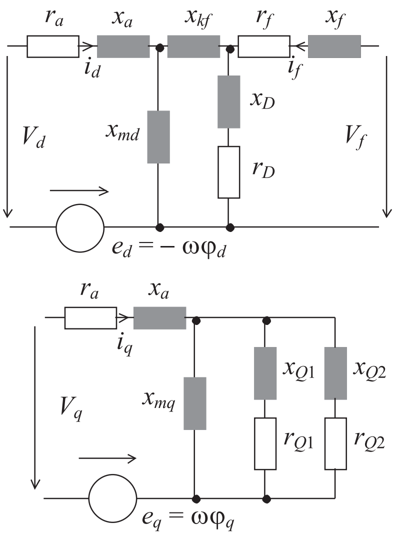


Fig. 1. Standard d-q axis circuit models.

In fact, it is the order of the functions $X_d(p)$, $X_q(p)$ and $G(p)$, which depend on the number of dampers. In theory we can represent a synchronous machine by an unlimited stator and rotor circuits. However, the experience show, in modelling and identification there is seven models structures which can be used. The complex model is the 3×3 model which have a field winding, two damper windings on the direct axis, and three on the quadrature axis.

The more common representation is the one deduced from the second order characteristic equation which describes the 2×2 model [8–10]

Damper circuits, especially those in the quadrature axis provide much of the damper torque. This particularity is important in studies of small signal stability, where conditions are examined about some operating point [10]. The second order direct axis models includes a differential leakage reactance. In certain situations for second order models, the identity of the transients field winding. Alternatively, the field circuit topology can alter by the presence of an excitation system, with its associated nonlinear features.

For machine at standstill, the rotor speed is zero ($\omega = 0$) and using the p Laplace's operator, the voltage equations are:

– For the d-axis

$$V_d = \Big[r_a + \frac{p}{\omega_0} X_d(p)\Big] i_d + pG(p) v_f\,, \qquad (3a)$$

$$V_f = \Big[r_f + \frac{p}{\omega_0} X_f(p)\Big] i_f + \frac{p}{\omega_0} X_{md} i_d\,. \qquad (3b)$$

– For the q-axis

$$V_q = \Big[r_a + \frac{p}{\omega_0} X_q(p)\Big] i_q\,. \qquad (3c)$$

With the operational reactances:

$$X_{d,q,f}(p) = X_{d,q,f} \frac{\big(1 + pT'_{d,q,f}\big)\big(1 + pT''_{d,q,f}\big)}{\big(1 + pT'_{d0,q0,f0}\big)\big(1 + pT''_{d0,q0,f0}\big)} \qquad (4a)$$

and the operational function $G(p)$:

$$G(p) = \frac{X_{md}}{r_f} \frac{1}{1 + pT'_{d0}}\,. \qquad (4b)$$

d, q, f denote the d-axis, q-axis and field respectively. From these equations it follows that only the three functions $X_d(p)$, $X_q(p)$ and $G(p)$ are necessary to identify a synchronous machine. In the original theory, the quadrature axis has no transient quantities. However, the DC measurements at standstill recommended by IEC, and also the short-circuit tests in the quadrature axis show that the real machine also has transient values $X'_q(p)$, T'_q in addition to the sub transient values $X''_q(p)$, T''_q.

3 TEST PROCEDURE

The procedure for determining the values of synchronous machine parameters, using the frequency response tests data, follows several steps:

- Step 1 is the standstill frequency response process; it determines the data of operational impedances and transfer functions, which punitively describe the interactions of voltages and currents as functions of frequency.
- Step 2 is the determination of transfer functions to quantize the current-flux-voltage relations in simple, standard forms, such as $Xd(P)$. Step 2 is a conventional curve fitting process.
- Step 3 is the determination of equivalent circuit data $(r_i, X_i, T_i, \dots)$ that are used in simulations from the transfer functions of step 2.

These are various steps that we follow to identify our machine.

The tests are described in ANSI-IEEE Std.115A publications [1]. It is very easy to perform in practice.. The rotor is placed so that the magnetic field axis due to DC stator current, be along the direct axis (d-axis test) and then along the quadrature axis (q-axis test).

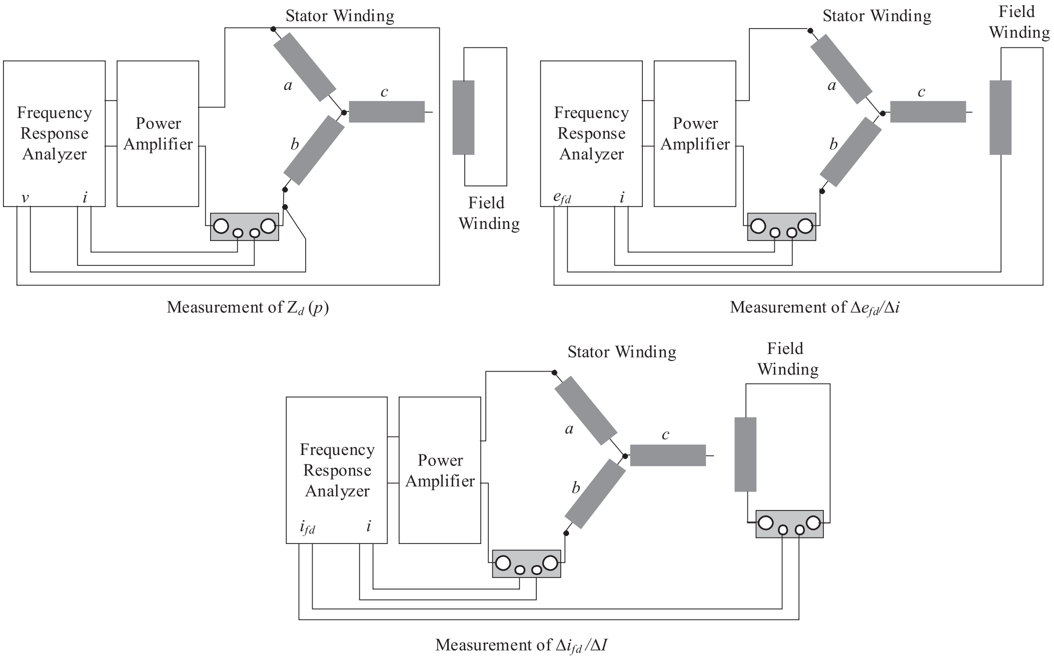


Fig. 2. Test Setup for Direct-Axis Measurements, using the current shunts according to the IEEE standard 115 A

It should be recognized that during standstill frequency response tests, the capability of the machine will be reduced with respect to its capability at normal operating conditions. Therefore, test levels of currents and voltages shall be maintained at sufficiently low levels to avoid any possible damage to either stator or rotor components. This can be achieved by limiting the maximum output of the power source to levels equal to or less than the standstill capability of the machine.

The tests cannot be performed at the rated stator voltage or current; the determination of quantities referred to the unsaturated state of the machine must be done from tests with supply voltages (1 to 2%) of the nominal values.

The acquisition of the experimental data is made by a data acquisition system connected to the computer for processing by the Software Matlab. The remainder consists of classical devices such as, ampermeter, voltmeter, wattmeter, frequency response analyzer, power amplifier, *etc*that are necessary in controlling the physical parameters of the system to be identified.

A. *Positioning the rotor for d- and q- axis tests*

In this section, the practical aspects of measurements are described and machine conditions for standstill tests are also given [1–2].

The tests are described in ANSI-IEEE Std.115 A publications [1]. It is very easy to perform in practice. The alignment of the rotor can be accomplished with shorted excitation winding. A sine wave voltage is applied between two phases of the stator. The duration of the voltage application should be limited to avoid serious overheating of solid parts. The rotor is slowly rotated to find the angular positions corresponding to the maximum value of the excitation current that gives the direct axis and zero value of the excitation winding current, and that corresponds to the quadrature axis. This procedure is used by the authors [2, 5 and 6].

B. *Typical test setup*

The power amplifier should create readily measurable signal levels for the armature and field winding voltages and currents. Tests currents should be small enough to avoid temperature changes in the armature, field, or damper circuits during the test. Voltages at the armature or field winding terminals shall not exceed rated voltage levels

The magnitude and phase of the desired quantities $Z_d(p)$, $Z_q(p)$ and $\frac{\Delta i_{fd}(p)}{\Delta i_q(p)}$ are measured over a range of frequencies (Fig. 3 to Fig. 6).

The minimum frequency ($f_{\min}$) should be at least one order of magnitude less than that corresponding to the transient open circuit time constant of the generator, that is, $f_{\min} = \frac{0.016}{T'_{d0}}$. The maximum frequency for the test should be greater than twice the rated frequency of the machine being tested.

It is, therefore, suggested that despite the high measurement cost, it is preferable for the sake of accuracy to use at least 40 points/decade in the very low frequency range, such as, 1 to 100 MHz. The experience suggests that the users of the successful tests and model development, (1) careful rotor positioning for d-q axes and (2) accurate data acquisition in low frequency range.

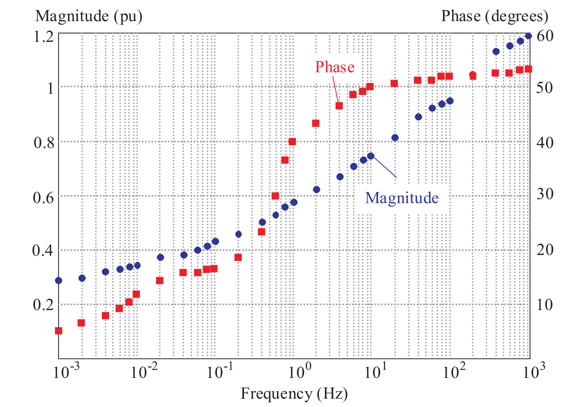


Fig. 3. d-axis Impedance (Field Shorted)

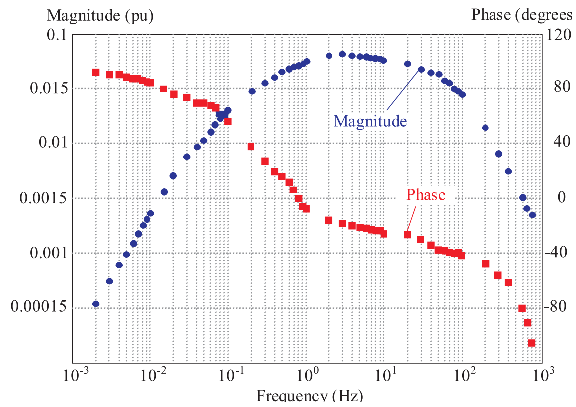


Fig. 4. Standstill Armature to Field Transfer Impedance

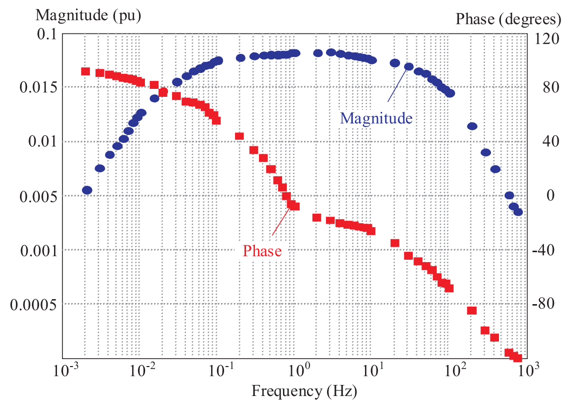


Fig. 5. Standstill Armature Field Transfer Function $pG(p)$

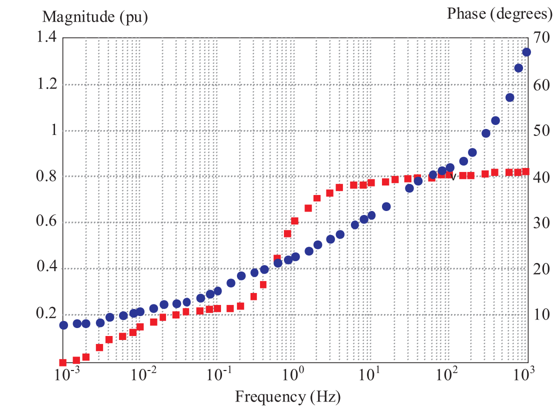


Fig. 6. q-axis Impedance

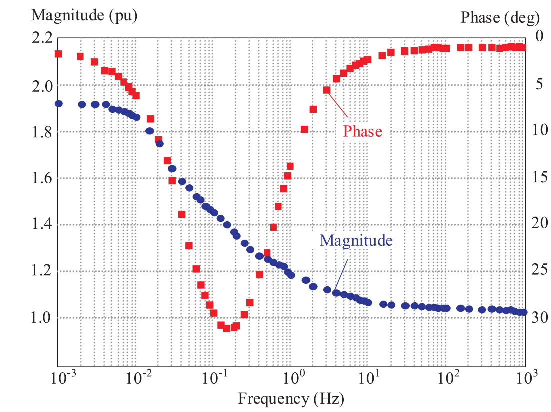
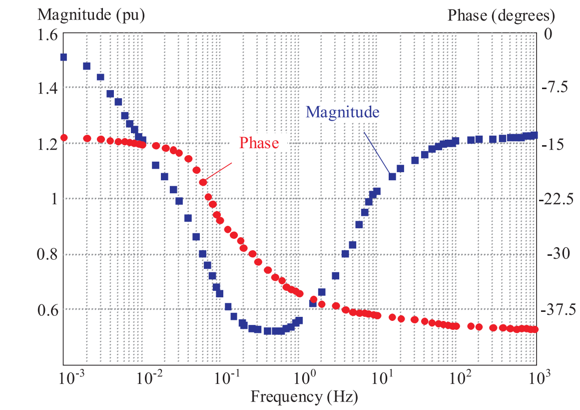


Fig. 7. d-axis Operational Impedance (Field Shorted)



mm **Fig. 8.** q-axis Operational Impedance (Field Shorted)

C. *Measurable parameters at standstill*

According to the various test setups, the tests that we have realized correspond to the following equations:

$$Z_d = -\frac{\Delta e_d(p)}{\Delta i_d(p)}\bigg|_{\Delta efd=0}, \qquad \text{(5a)}$$

$$Z_q = -\frac{\Delta e_q(p)}{\Delta i_q(p)}, \qquad \text{(5b)}$$

$$G(p) = \frac{\Delta e_d(p)}{p\Delta e_{fd}(p)}\bigg|_{\Delta id=0}. \qquad \text{(5c)}$$

An alternative method of measuring this parameter is suggested as follows:

$$pG(p) = \frac{\Delta e_{fd}(p)}{\Delta i_d(p)}\bigg|_{\Delta efd=0}. \qquad \text{(5d)}$$

The advantage of the latter form is that it can be measured at the same time as $Z_d(p)$. A fourth measurable parameter at standstill is the armature to field transfer impedance:

$$Z_{af0}(p) = -\frac{\Delta e_{fd}(p)}{\Delta i_d(p)}\bigg|_{\Delta ifd=0}. \qquad \text{(5e)}$$

Table 1. Synchronous Machine Parameter Values Identified

Parameters	Values
R_a (pu)	0.150
R_f (pu)	4.942
T'_d (s)	0.1842
T''_d (s)	0.0475
T'_{d0} (s)	1.0706
T''_{d0} (s)	0.4290
T'_q (s)	0.1450
T''_q (s)	0.0390
T'_{q0} (s)	0.8995
T''_{q0} (s)	0.4520
X_d (pu)	1.8850
X'_d (pu)	0.3450
X_q (pu)	1.3825
X'_q (pu)	0.2130
X''_d (pu)	0.380
X''_q (pu)	0.203

The relationships between the measured quantities and desired variables are given by: – d-axis parameters

$$L_d(p) = \frac{Z_d(p) - R_a}{p}\,, \tag{6a}$$

where

$$Z_d(p) = \frac{1}{2} Z_{armd}(p)\,, \tag{6b}$$

$$R_z = \frac{1}{2}\Big[\lim_{s\to 0} |Z_{armd}(p)|\Big] \tag{6c}$$

and $p = j\omega$.

To obtain r_a, we plot the real component of this impedance as a function of frequency, and we extrapolate it to zero frequency to get the dc resistance of the two phases of the armature winding in series. Then we calculate $pG(p)$ by:

$$\frac{\Delta i_{fd}(p)}{\Delta i_d(p)} = \frac{\sqrt{3}\Delta i_{fd}(p)}{2\Delta i(p)}\,. \tag{6d}$$

Finally, we measure the ratio $\frac{\Delta e_{fd}}{\Delta i}$, and we calculate

$$Z_{af0} = \frac{\Delta e_{fd}(p)}{\Delta i_d(p)} = \frac{\sqrt{3}}{2}\Big(\frac{\Delta e_{fd}(p)}{\Delta i(p)}\Big)\,. \tag{6e}$$

– q-axis parameters

$$L_q(p) = \frac{Z_q(p) - R_a}{p}\,, \tag{7a}$$

where

$$Z_q(p) = \frac{1}{2} Z_{armq}(p) \tag{7b}$$

and

$$R_z = \frac{1}{2}\big[\lim_{s\to 0} |Z_{armq}(p)|\big]\,. \tag{7c}$$

Figure 7 represents the direct axis operational inductances for each frequency at which $Z_d(p)$ was measured.

The quadrature-axis operational reactance, $X_q(p)$, plotted in Fig. 8, is obtained in the same way from $Z_d(p)$.

Table 1 presents the parameter vaues of a synchronous machine from tests using in this study.

4 CONCLUSION

A step-by-step procedure to identify the parameter values of the d-q axis synchronous machine models using the standstill Frequency response testing is presented in this paper.

A three-phase salient-pole laboratory machine rated 1.5 kVA and 380 V is tested at standstill and its parameters are estimated. Both the transfer function model and the equivalent circuit model parameters are identified.

The standstill test concept is preferred because there is no interaction between the direct and the quadrature axis, and it can be concluded that the parameter identification for both axis may be carried out separately. This tests method had been used successfully on our synchronous machine at standstill and gave all the Parks model parameters. Among the advantages claimed for the SSFR is that the tests are safe and relatively inexpensive.

Furthermore, the information about the quadrature axis, as well as the direct axis of the machine is obtained. We notice that, it can be possible to realize a parameter estimation of large power synchronous machine or turbo generators.

The results show that the machine linear parameters are accurately estimated to represent the machine at standstill condition.

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List of symbols

e_d, e_q	direct and quadrature-axis armature voltage
e_{fd}	field voltage
i_{fd}	field current
$G(p)$	armature to field transfer function
i	instantaneous value of armature current during test
i_d, i_q	direct and quadrature-axis armature current
Z_{armd}	Operational impedance measured between two armature terminals during direct-axis tests

Z_{armq}	Operational impedance measured between two armature terminals during quadrature-axis tests
P	Laplace's operator
ω, ω_0	angular and rated speed
φ_d, φ_q	flux leakage in the direct and quadrature axis
X_f	field leakage reactance
X_d, X_q	d- and q-axis synchronous reactances
X_{md}, X_{mq}	d- and q-axis magnetizing reactances
X_{Q1}, X_{Q2}	q-axis damper leakage reactance
r_{Q1}, r_{Q2}	q-axis damper resistances
$Y_{d,q}(p)$	d- and q-axis operational admittances
T'_d, T'_{d0}	d-axis transient open circuit and short-circuit time constant
T'_q, T'_{q0}	q-axis transient open circuit and short-circuit time constant
T''_d, T''_{d0}	d-axis subtransient open circuit and short-circuit time constant
T''_q, T''_{q0}	q-axis subtransient open circuit and short-circuit time constant
r_a, r_f	armature and field resistances
V_d, V_q	d- and q-axis stator voltages
i_d, i_q	d- and q-axis stator currents
V_f, i_f	d-axis field voltage and current

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