Parameter Identification of Synchronous Machine By DC Chopper Excitation Signals

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Abstract

This paper presents an original approach to identifying the linear parameters of a salient-pole synchronous machine at standstill time response tests data. A new approach is proposed for the estimation of synchronous machine coupled to dc-chopper; using data recorded during steady-state operation of the chopper-machine unit. The time constant models and equivalent circuit models are estimated. This procedure consists of defining and conducting the standstill tests, identifying the model structure, estimating the corresponding parameters, and validating the resulting model. The signals used are chopper wave voltages exciting the machine at standstill and the resulting output current in the different windings. The results are presented from tests on the synchronous machine of 1.5 kVA/380V/1500rpm

1. Introduction

Synchronous machines parameters are currently determined from measurements performed on machines rotating in various conditions or from tests carried out at standstill. Measurements on rotating synchronous machines of more than 5 MVA that operates at steady state, direct starting transients or short-circuit are difficult to be carried out because of the high currents involved. To minimize the expensive power consumed in this type of tests, measurements at standstill has been developed [1-6].

The standstill modeling and measuring approaches have received great emphasis due to their relatively simple testing method where the d and q axes are decoupled. The standstill time response methods have overcome the drawbacks of the dynamics tests due to their relatively simple implementation and economically operation. A flux decay is induced to the stator of the tested machine positioned in the direct-axis or quadrature-axis, either by applying a voltage step or by short-circuiting the stator after it was supplied for a while with a DC voltage.

Therefore, we present an off-line parameters estimation for the synchronous machine coupled to dc-chopper.

A systematic identification procedure presented in section 3 is used to estimate the parameters of the machine time constant models and equivalent circuit models directly from the time response data. [7-9]. We estimate experimental data with analysis expressions, which contain machine parameters dedicated by a computer program.

In this present research work system identification model concepts and standstill time data are used to identify parameters of synchronous machine with the following specifications: 1.5kVA, 220/380V, 1500 rpm.

2. Modeling of the Ssynchronous Machine

The study of the electric machines based on the Park's transform was already treated in several works and specialized publications.

This model allows, by a change of reference frame, to pass from the stator system to the rotor system with elimination of certain variables. The change of reference frame makes it possible to pass to an equivalent bipolar machine.

The basic model consists to considering one salient-pole synchronous machine with one pair of poles to the rotor and a three-phase stator winding.

The field winding is on the rotor of the machine according to the axis of the salience (direct axis or longitudinal axis of the machine).

The presence of grid or cage of dampers to the rotor, are modeled by two equivalent circuits dampers; one on the direct axis and the other on the quadrature axis.

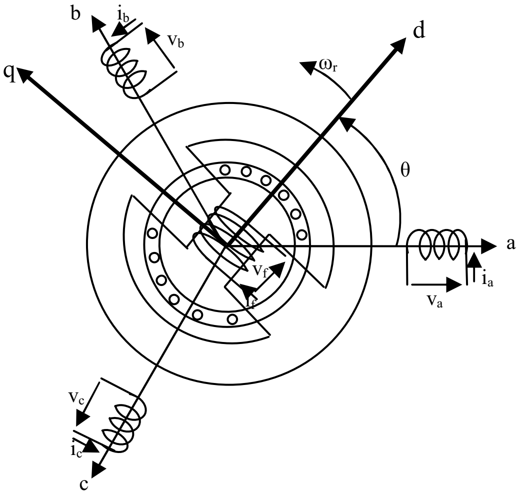


Fig. 1. Three-phase Synchronous machine with dampers

The Six windings representing the figure 1. are described by the following equations

$$\left.\begin{array}{l} V_a = R_a i_a + \dfrac{d\varphi_a}{dt} \\ V_b = R_a i_b + \dfrac{d\varphi_b}{dt} \\ V_c = R_a i_c + \dfrac{d\varphi_c}{dt} \end{array}\right\} \quad armature\ (Stator) \qquad (1.a)$$

$$\left.\begin{array}{l} V_f = R_f i_f + \dfrac{d\varphi_f}{dt} \\ 0 = R_D i_D + \dfrac{d\varphi_D}{dt} \\ 0 = R_Q i_Q + \dfrac{d\varphi_Q}{dt} \end{array}\right\} \quad field\ (Rotor) \qquad (1.b)$$

The voltage applied to the D and Q circuits are null, since they are in short-circuit

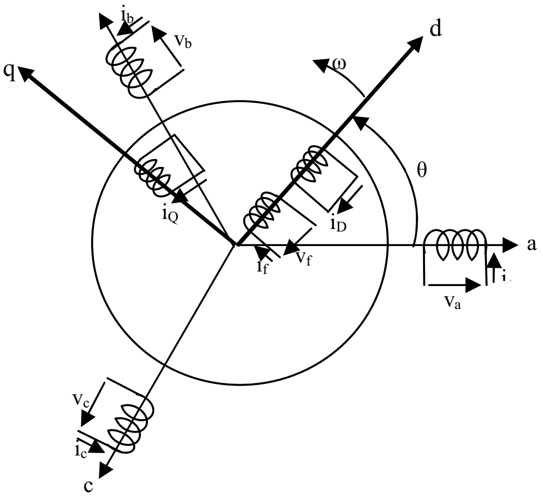


Fig. 2. Three-phase Synchronous machine, dampers assimilated to two windings in short-circuit

2.1. Choice of model's order

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 (2x2 model) as shown in fig 3. [9-12].

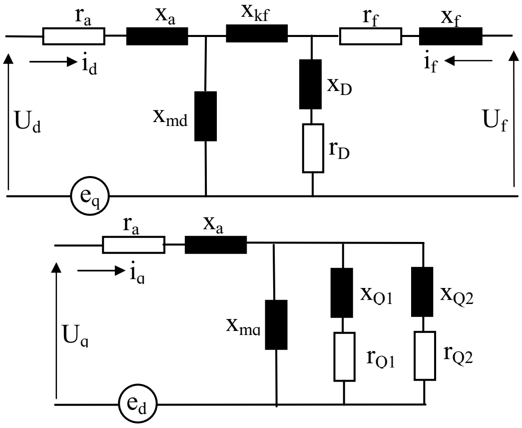


Fig. 3. Standard d-q axis circuit models

Damper circuits, especially those in the quadrature axis provide much of the damper torque. This particularly important in studies of small signal stability where conditions are examined about some operating point [9]. 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 non-linear features.

The q-axis dampers effects may be approximated be considering only two q axis rotor circuit, model 2x2. This model is also much in use for representing large power generators as there is, particularly, even with continuous waterwheel rotor dampers, only one physically identifiable circuit in the area between the salient poles.

By considering the figure 3, the equations of the machine are:

Voltage equations/

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

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

$$V_f(p) = r_f i_f(p) + p\varphi_f(p) \qquad (2.c)$$

$$0 = r_D i_D(p) + p\varphi_D(p) \qquad (2.e)$$

$$0 = r_Q i_Q(p) + p\varphi_Q(p) \qquad (2.f)$$

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

$$V_d(p) = r_a i_d(p) + p\varphi_d(p) + \omega_r \varphi_q(p) \qquad (3.a)$$

$$V_q(p) = r_a i_q(p) + p\varphi_q(p) - \omega_r \varphi_d(p) \qquad (3.b)$$

$$\varphi_d(p) = X_d(p) i_d(p) + G(p) V_f(p) \qquad (3.c)$$

$$\varphi_q(p) = X_q(p) i_q(p) \qquad (3.d)$$

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.

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.

2.2. Equations of the machine at standstill

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

- For the d-axis

$$V_d = [r_a + \frac{P}{\omega_0} X_d(p)] i_d + pG(p) v_f \qquad (4.a)$$

$$V_f = [r_f + \frac{p}{\omega_0} X_f(p)] i_f + \frac{p}{\omega_0} X_{md} i_d \qquad (4.b)$$

- For the q-axis

$$V_q = [r_a + \frac{p}{\omega_0} X_q(p)] i_q \qquad (4.c)$$

With the operational reactances are:

$$X_{d,q,f}(p) = X_{d,q,f} \frac{(1+pT'_{d,q,f})(1+pT''_{d,q,f})}{(1+pT'_{d0,q0,f0})(1+pT''_{d0,q0,f0})} \qquad (5.a)$$

And the operational function G(p) is:

$$G(p)=\frac{X_{md}}{r_f}\frac{1}{1+pT'_{d0}} \tag{5.b}$$

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.

The reduced operational admittances of d-axis and q-axis are reduced from the input-output signals

$$Y_{d,q}(p)=\frac{i_{d,q}(p)}{V_{d,q(p)}} \tag{6.a}$$

Or in other terms:

$$Y_{d,q}(p)=\frac{1+p(T'_{d0,q0}+T''_{d0,q0})+p^2T'_{d0,q0}T''_{d0,q0}}{r_a+p(r_a(T'_{d0,q0}+T''_{d0})+\frac{x_{d,q}}{\omega_0})+p^2(r_aT'_{d0}T''_{d0}+\frac{x_{d,q}}{\omega_0}(T'_{d,q}+T''_{d,q})+p^3\frac{x_d}{\omega_0}T'_{d,q}T''_{d,q}}$$

The reduced operational admittances take the following forms

$$H_{d,q}(p)=\frac{b_0+b_1.p+b_2.p^2}{1+a_1.p+a_2.p^2+a_3.p^3} \tag{6.b}$$

The synchronous machine parameters are identified from:

$$b_0=\frac{1}{r_a}\ ;\quad b_1=\frac{T'_{d0,q0}+T''_{d0,q0}}{r_a}\ ;\quad b_2=\frac{T'_{d0,q0}T''_{d0,q0}}{r_a} \tag{6.c}$$

$$a_1=T'_{d0,q0}+T''_{d0,q0}+\frac{x_{d,q}}{\omega_0 r_a} \tag{6.d}$$

$$a_2=\frac{x_{d,q}}{\omega_0 r_a}(T'_{d,q}+T''_{d,q})+T'_{d0,q0}T''_{d0,q0} \tag{6.e}$$

$$a_3=\frac{x_{d,q}}{\omega_0 r_a}T'_{d,q}T''_{d,q} \tag{6.f}$$

The equations (6.a) to (6.f) show that to determine the various parameters and time-constants of the machine, the problem amounts calculating the constants a_1, a_2, a_3, b_0, b_1 and b_2 by using the non-linear methods of programming.

For that we used a program, which makes it possible to calculate from the input-output signals for each axis (figures 5 to 8), the six parameters quoted above.

The objective of our estimation task is to make the simulated model response matches as the actual response by minimizing the error between the estimated model response and the actual response. For minimizing this error, a good optimisation technique is needed. Our approach is based on Levenberg-Marquardt algorithm.

3. Estimation of the synchronous machine parameters

In this section, the practical aspects of measurements are described and machine conditions for standstill tests are also given. 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 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 that corresponds to the quadrature axis [9-15].

The duty cycle ratio is completely controlled by using the command sequence to the gate. In our experiment, the main thyristor is periodically fired at time t=T/2, where T is the switching period.

Fig. 4 shows the experimental procedure of identification.

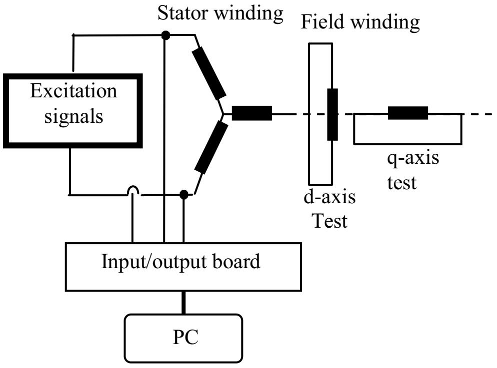


Fig. 4. Experimental procedure of identification

The machine is not saturated during standstill tests; in fact, the machine must be done from tests, which supply voltages (1 to 2%) of the nominal values.

3.1. Experimental procedure.

The method used to measure the various parameters is presented as follows :

$$G(p)=\frac{I_{fd}(p)}{pI_d(p)}\quad\text{for}\quad E_{fd}=0 \tag{7.a}$$

Short-circuited field winding: with a shorted field winding (V_f=0), the d- and q- axis operational admittances are given:

$$Y_{d,q}(p)=\frac{i_{d,q}(p)}{v_{d,q}(p)}\quad\text{for}\quad V_f=0 \tag{7.b}$$

Short-circuited d-axis stator winding: with a d-axis armature shorted (Vd = 0), the field winding parameters can be obtained by:

$$Y_f(p)=\frac{i_f(p)}{v_f(p)}\quad\text{for}\quad V_d=0 \tag{7.c}$$

To estimate the parameters in two axes of the synchronous machine, we use a sampling period of T_e=1/150ms and N=1000 data points sample are collected.

The waveforms recorded are shown in the following figures

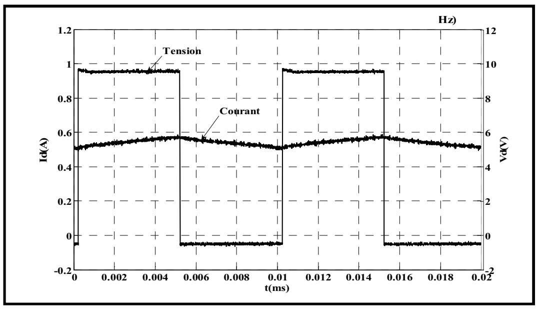


Fig. 5. D-axis stator voltage and current for field winding open

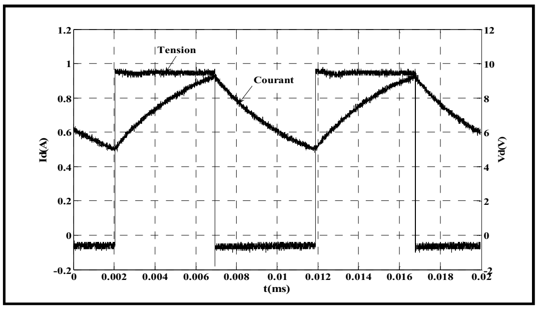


Fig. 6. d-axis stator voltage and current for field shorted

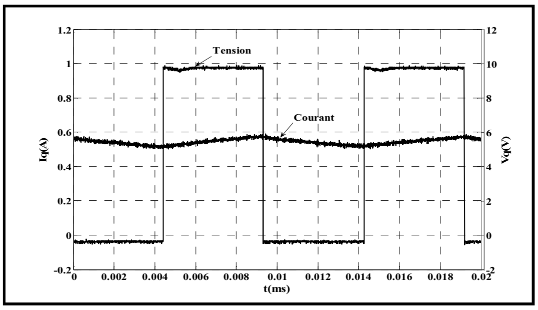


Fig. 7. Q-axis stator voltage and current for field winding open

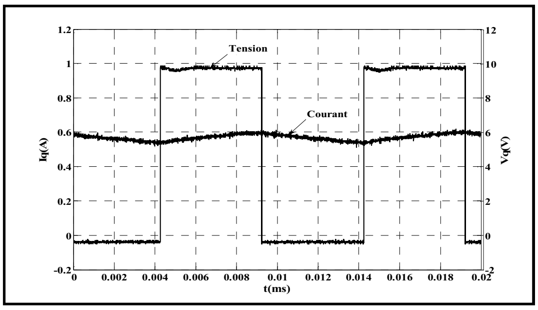


Fig. 8. Q-axis stator voltage and current for field shorted.

3.2 Experimental results

The various identified parameters are presented in table 1.

Table1: synchronous machine parameters

Synchronous Machine parameters	
Parameters	values
R_a(p.u)	0.149
R_f (p.u)	4.95
T'_d (s)	0.1856
T''_d (s)	0.0490
T'_{d0} (s)	1.0907
T''_{d0} (s)	0.4350
T'_q (s)	0.1476
T''_q (s)	0.0461
T'_{q0} (s)	0.9022
T''_{q0} (s)	0.4631
X_d (p.u)	2.0667
X'_d (p.u)	0.3516
X_q (p.u)	1.3378
X'_q (p.u)	0.2089
X''_d (p.u)	0.0396
X''_q (p.u)	0.0218

We note that the used technique made it possible to identify all the parameters of machine's model in the two axes d and q.

4. Influence of input signals frequency

During the tests we raised same the signals presented above but has various frequencies (50Hz, 100Hz, 150Hz, 175Hz, 200Hz) and we calculated same way, that already presented before (for 150Hz), the parameters of the machine. The results obtained are gathered in the table below

Table 2. Values of the reactance at different frequencies

Reactance (pu)	Frequency f(Hz)				
	50	100	150	175	200
x_d	0.517	0.580	0.588	0.571	0.585
x_q	0.352	0.380	0.380	0.414	0.401
x'_d	0.152	0.140	0.143	0.158	0.145
x'_q	0.091	0.110	0.119	0.092	0.105
x''_d	0.074	0.080	0.079	0.086	0.073
x''_q	0.041	0.062	0.057	0.056	0.058

On the curves of figure 9 we traced the evolution of the reactance according to the frequency. It is to be retained that for a beach of frequency little extended (50hz to 200Hz) the values of the calculated reactance are comparable, especially between 100Hz and 150Hz. This encourages us to say that the sampling rate the most adapted is in this beach (what is in conformity with the Shannon's theorem). It would be interesting to further increase the frequency of the signal of excitations in order to really see the effect of the frequency on the various parameters.

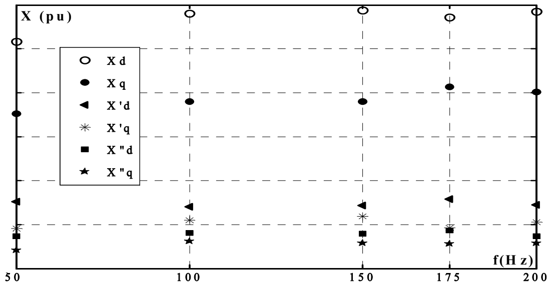
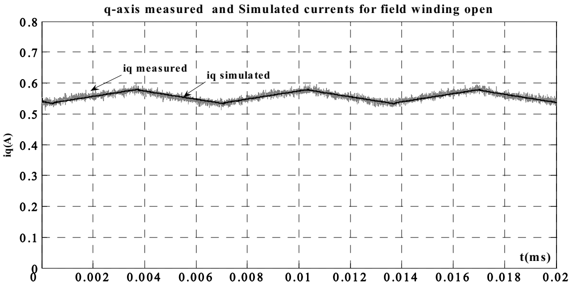
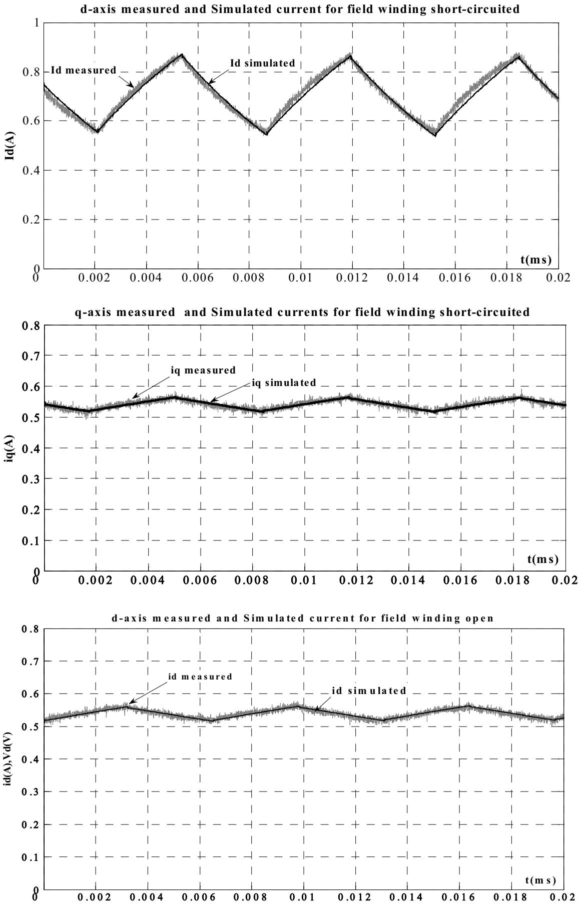


Fig. 9. Reactance curves at different frequencies

5. Model Validation

The estimated d-q axis models are verified by comparing their simulated d-q axis stator and field currents responses against the measured standstill response (figs 10). It is again observed that the estimated model responses match the measured responses well.





Figs. 10. comparison between real data output and simulated data output

The time domain approach offers a method, which can yield useful models, particularly in the data, is interpreted correctly. Taking into account the difficulties associated to the classical test analysis, the identification of synchronous machine is more and more oriented to the static tests. Nevertheless, the choice of supply signals is so important than the choice of model.

6. Conclusion

This paper presents a step-by-step procedure to identify the parameter values of the d-q axis synchronous machine models using the standstill time-domain data analysis.

A three-phase salient-pole laboratory machine is tested at standstill and its parameters are estimated. Both the transfer function model and the equivalent circuit model parameters are identified using the Levemberg-Marquardt optimisation algorithm.

The validation of the estimation synchronous machine model parameters is performed by direct comparisons between the measured and simulated standstill time domain response. The results show that the machine linear parameters are accurately estimated to represent the machine standstill condition.

Among the advantages claimed for the time-domain approach at standstill is that the tests are safe and relatively inexpensive.

Furthermore, information's about the quadrature axis, as well as the direct axis of the machine are obtained.

7. List of Symbols

p:	Laplace's operator
ω,ω_0:	angular and rated speed
Φ_k :	induction flux in winding k (k=a, b, c, f, D, Q)
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
$Y_{d,q}(p)$:	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 sub-transient open circuit and short-circuit time constant
T''_q, T''_{q0}:	q-axis sub-transient 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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