A guide for Synchronous Generator Parameters Determination Using Dynamic Simulations Based on IEEE Standards

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***Abstract*—This paper shows, through simulations using the software Matlab/Simulink, its library Simpowersystems and the standars IEEE 115 – 1995, IEEE 1110 - 2002, how to perform load rejection tests for salient pole synchronous generator and sudden short-circuit test for cylindrical rotor synchronous generator and how to obtain the values of the synchronous generator electrical operational parameters which are important data to perform generator and electrical power system dynamic studies. The paper discuss the *d*-axis load rejection test, the *q*-axis load rejection test, the arbitrary axis load rejection test and sudden short-circuit test, saturation is not considered.**

***Index Terms*—Electrical machines, load rejection test, parameters determination, short-circuit test, Synchronous generator simulation.**

I. INTRODUCTION

THE synchronous generators are responsible for almost all electrical energy generated in the world today. In the studies of dynamics and control of electrical energy systems the dynamic mathematical modeling of the synchronous generators assumes a role of relevant importance so that this matter has been studied since the first large-scale electricity generation system in the world until now with high intensity.

Many papers have been written since the first one [1] until our days [2] about the synchronous generators definition, characterization and measurement of electrical parameters so that many test procedures for determining parameters were developed in such way that the IEEE, IEC and NEMA which are important standardization societies of the U.S.A and Europe on electricity subjects had considered necessary their standardization, as it can be seen in the standards [3], [4] and [5].

The synchronous generator fundamental electrical parameters are: the per phase stator windings electrical resistance (r_s), the field winding (r_{fd}), the d and q-axis damping winding electrical resistances (r_{kd} and r_{kq}), the per phase stator windings leakage reactance (x_{ls}), the field winding leakage reactance (x_{lf}), the d and q-axis damping winding leakage reactances (x_{lkd} and x_{lkq}) and also the d and q-axis generator magnetizing reactances (x_{md} and x_{mq}), however those parameters can be determined just only if the standard parameters are determined. The standard parameters of the synchronous generators are the d and q-axis synchronous reactances (x_d and x_q), the d and q-axis transient synchronous reactances (x'_d and x'_q), the d and q-axis sub-transient synchronous reactances (x''_d and x''_q), the d and q-axis open-circuit transient and sub-transient time constants (T'_{do}, T'_{qo}, T''_{do} and T''_{qo}) and the d and q-axis short-circuit transient and sub-transient time constants (T'_d, T'_q, T''_d and T''_q).

The synchronous generator standard parameters can be determined through load rejection tests and sudden short-circuit test, among other methods, while the fundamental parameters are calculated using mathematical relations as shown in [6], [7].

This paper shows how the standard parameters can be determined by the load rejection tests and sudden short-circuit test through simulations performed by using the software Matlab-Simulink-SimPowerSystems showing important details of how to calculate those parameters. Results of simulation of the load rejection tests at rated voltage are presented for a hydrogenerator (salient pole synchronous generator).

Results of simulation of the sudden short-circuit test are presented for a cylindrical rotor synchronous generator (turbogenerators), shown as an example in [7].

Round rotor synchronous generators must be represented by a mathematical model with more than one q-axis damping windings due to the solid iron rotor and the associate Skin Effect.

II. SYNCHRONOUS GENERATOR DYNAMIC MATHEMATICAL MODEL

The dynamic mathematical model of a synchronous generator with two q-axis damping winding utilized in the block called "synchronous machine" of the SimPowerSystems library of the software Matlab/Simulink, is composed by the set of differential equations as presented in [7] and also bellow (1). This library allows to the user to include the magnetic saturation model. In the simulations performed in this work the magnetic saturation effects are not taken into account. The electrical differential equations that describe the stator and the rotor windings are shown in (1) and are written in dq axis coordinate system which rotates at the rotor speed. The first three equations represent the stator windings (subscript s) and the following four equations represent the rotor windings.

The subscript f is used for the field winding while the subscript k is used for the damping windings (kd for the direct axis damping winding and $kq1$ for the q-axis, number 1

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damping winding and *kq2* for the *q*-axis, number 2, damping winding). In the machine used as example in this work there is just one damping winding in the *q*-axis, designated as *kq2* as in [7].

$$
\begin{aligned}
&v_{qs}^{r} = -r_s i_{qs}^{r} + \frac{\omega_r}{\omega_b}\psi_{ds}^{r} + \frac{p}{\omega_b}\psi_{qs}^{r} && v_{0s} = -r_s i_{0s} + \frac{p}{\omega_b}\psi_{0s} \\
&v_{kq2}^{'r} = r_{kq2}^{'} i_{kq2}^{'r} + \frac{p}{\omega_b}\psi_{kq2}^{'r} && v_{kd}^{'r} = r_{kd}^{'} i_{kd}^{'r} + \frac{p}{\omega_b}\psi_{kd}^{'r} \\
&v_{ds}^{r} = -r_s i_{ds}^{r} - \frac{\omega_r}{\omega_b}\psi_{qs}^{r} + \frac{p}{\omega_b}\psi_{ds}^{r} && v_{kq1}^{'r} = r_{kq1}^{'} i_{kq1}^{'r} + \frac{p}{\omega_b}\psi_{kq1}^{'r} \\
&v_{fd}^{'r} = r_{fd}^{'} i_{fd}^{'r} + \frac{p}{\omega_b}\psi_{fd}^{'r}
\end{aligned}
\qquad (1)
$$

In these equations *v* represents the voltage of the several windings, *i* represents the electrical current circulating in the windings, Ψ represents the magnetic flux linking the windings, measured in *volts/s*, *p* is the differential operator (*d/dt*), ω_r is the angular speed of the rotor in *rad/s* referred to a two pole machine and ω_b is the reference angular speed (in this case is the synchronous angular speed corresponding to the rated frequency). The magnetic flux Ψ for each winding can be written as in (2). In this case v'^{r}_{kd}, v'^{r}_{kq1}, v'^{r}_{kq2} are nulls because the damping windings are short-circuited.

$$
\begin{aligned}
\psi_{qs}^{r} &= -x_{ls} i_{qs}^{r} + x_{mq}\left(-i_{qs}^{r} + i_{kq1}^{'r} + i_{kq2}^{'r}\right) \\
\psi_{ds}^{r} &= -x_{ls} i_{ds}^{r} + x_{md}\left(-i_{ds}^{r} + i_{fd}^{'r} + i_{kd}^{'r}\right) \\
\psi_{0s} &= -x_{ls} i_{0s} \\
\psi_{kq1}^{'r} &= x_{lkq1}^{'} i_{kq1}^{'r} + x_{mq}\left(-i_{qs}^{r} + i_{kq1}^{'r} + i_{kq2}^{'r}\right) \\
\psi_{kq2}^{'r} &= x_{lkq2}^{'} i_{kq2}^{'r} + x_{mq}\left(-i_{qs}^{r} + i_{kq1}^{'r} + i_{kq2}^{'r}\right) \\
\psi_{fd}^{'r} &= x_{lfd}^{'} i_{fd}^{'r} + x_{md}\left(-i_{ds}^{r} + i_{fd}^{'r} + i_{kd}^{'r}\right) \\
\psi_{kd}^{'r} &= x_{lkd}^{'} i_{kd}^{'r} + x_{md}\left(-i_{ds}^{r} + i_{fd}^{'r} + i_{kd}^{'r}\right)
\end{aligned}
\qquad (2)
$$

The electrical fundamental parameters of the synchronous generator were already defined and they are: r_s, r_{fd}, r_{kd}, r_{kq1}, r_{kq2}, x_{ls}, x_{lf}, x_{lkd}, x_{lkq1}, x_{lkq2}, x_{md} and x_{mq}. The direct-axis reactance (x_d) and the quadrature axis reactance (x_q) are given by (3).

$$
x_d = x_{ls} + x_{md}\,; \qquad x_q = x_{ls} + x_{mq} \qquad (3)
$$

The mechanical part of the machine is described by two differential equations as shown in (4):

$$
\begin{aligned}
p\delta &= \omega_r - \omega_s \\
\frac{2H}{\omega_s}\, p\omega_r &= T_m - \left(\psi_d i_{qs} - \psi_q i_{ds}\right) - T_{dam}
\end{aligned}
\qquad (4)
$$

In these equations *H* is the turbine-generator set inertia constant, T_m is the mechanical torque of the turbine and T_{dam} is a damping torque that represents, among others, the rotational losses of the rotating parts. Inside the rotational losses are the magnetic losses and the mechanical losses (windage and friction losses).

III. SIMULATION SCHEME FOR THE SYNCHRONOUS GENERATOR OPERATION

Fig. 1 shows the SimPowerSystems simulation diagram used in this work to perform the load rejection tests. The infinite bus block put at the generator terminals is used to maintain the generator terminal voltage fixed and constant during the simulation at a chosen value (in this case the rated voltage). The real power is defined by the input P_m which is the mechanical input power and the reactive power is adjusted by the field voltage v_f.

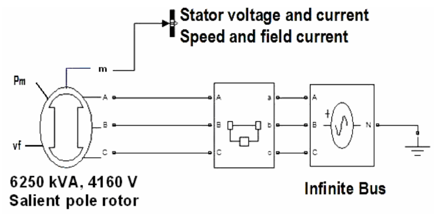

Fig. 1. Simpowersystems block diagram for generator load rejection test.

The generator mathematical dynamic modeling presented in the above figures are the same shown in (1) to (4). It can be observed in Fig. 2 that the terminals of the generator have a three-phase breaker just proper to perform the three-phase short-circuit between that will occur at time t = 20 s in the simulations.

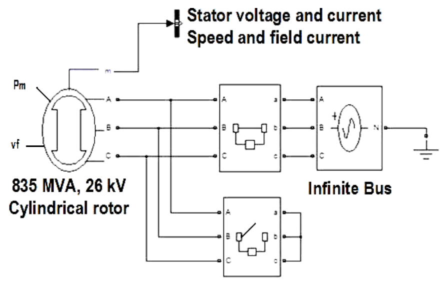

Fig. 2. Simpowersystems block diagram for generator short circuit test.

IV. SOME SYNCHRONOUS GENERATOR LOAD REJECTION TESTS AT RATED VOLTAGE

The load rejection tests aims to the determination of the synchronous *d* and *q*-axis permanent, transient and sub-transient reactances and also the open circuit transient and sub-transient *d* and *q*-axis time constants. There are three types of load rejection tests: 1) the "*d*-axis load rejection test" which permits to determine only x_d, x'_d, x''_d, T'_{do} and T''_{do}, 2) the "*q*-axis load rejection test" which permits to determine only x_q and x''_q and 3) the "arbitrary axis load rejection test" which permits to determine only x_q, x'_q, x''_q, T'_{qo} and T''_{qo}.

The parameters are determined from the envelope of the armature terminal voltage after de load rejection.

To perform the load rejection test the load must be switch off at the same time as the turbine is tripped, the excitation system must be in manual position and the voltage of the field winding must be maintained constant during the load rejection test. The short-circuit time constants can be calculated using the equations shown in the appendix A [13].

To perform the "*d*-axis load rejection test" it is necessary to have the generator connected to the electrical power system supplying zero active power and supplying or drawing reactive power and the field current must be adjusted. In this case the armature current and also the armature magnetic flux is aligned with the d-axis. The terminal phase voltages are acquired and its arithmetic average is calculated and plotted to allow the calculation of the reactances x_d, x'_d and x''_d. The field current is also acquired to allow the calculation of the time constants T'_{do} and T''_{do} as it will be shown later.

To perform the "q-axis load rejection test" it is necessary to have the generator connected to the electrical power system and the armature current having only the q component so the reactive power and the field current must be adjusted so that the power factor angle (φ) be equal to the power angle (δ). It it a test that requires a load angle measurement and so it is necessary to have an encoder installed in the generator shaft.

The terminal phase voltages are acquired and its arithmetic average are calculated and plotted to allow the calculation of the reactances x_q and x''_q. This test in not so efficient because it permits only the determination of x_q and x''_q. Those values can be determined also by the arbitrary axis load rejection test.

To perform the "arbitrary axis load rejection test" the synchronous machine is suddenly disconnected from the electrical system while the armature current has any value (both d and q-axis components). The load angle δ need to be monitored because it is necessary to have the d-axis armature voltage curve and the q-axis armature current at the load rejection instant ($v_t \sin\delta$, and i_q) as in [8], [13].

V. SIMULATION RESULTS

The proposed methods were applied to the salient pole and cylindrical rotor synchronous generator shown in the appendix B.

A. d-axis load rejection test

To determine d-axis operational parameters the generator must be supplying zero active power and maximum possible reactive power [4]. To implement this condition in the simulation it is necessary to enter a zero mechanical power as input data, that is $Pm = 0$ (zero active power) and a determined field voltage to which the machine provides the maximum possible reactive power in a tentative and error process. In the studied case the conditions at the time before the load rejection with the under excited machine are: $P_o = 0$ *pu*, $Q_o = 0.1239$ *pu (capacitive load)*, $Vt_o = 1$ *pu*, $it_o = 0.1239$ *pu*, $v_f = 0.87$ *pu*.

The dynamic of the generator terminal voltage can be seen in Fig. 3 where the load is rejected at time $t = 25$ *s*. For the calculation of operational reactances it is necessary to get the intersections of the tendencies of the terminal voltage with the terminal voltage axis at the time when the load rejection occurs. It can be better observed in Fig. 4, was done providing a better view of the envelope of the armature voltage behavior during the load rejection time. After the transient time, the terminal voltage becomes equal to the voltage induced by the field that is given by $E_t = 0.87$ *pu.* Thus one can calculate the d-axis operational reactances using the values of A, B and C shown in Fig. 3 as in [4] and [9] the expressions (5):

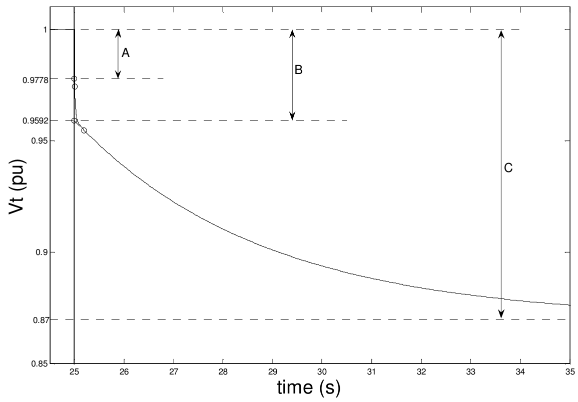

Fig. 3. Terminal voltage envelope during load rejection

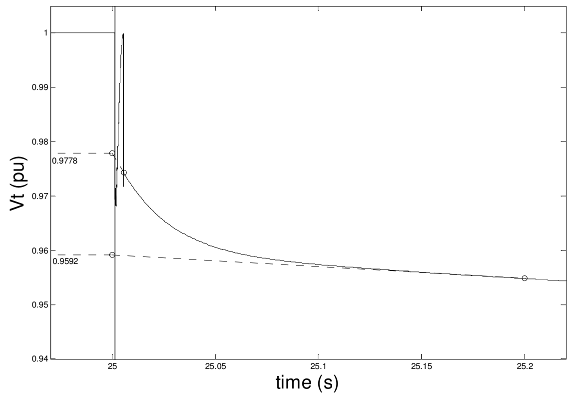

Fig. 4. Amplification of the Fig. 3

$$
\begin{aligned}
x_d &= \frac{C}{it_o} = \frac{1-0.87}{0.1239} = 1.0492\ pu \\
x'_d &= \frac{B}{it_o} = \frac{1-0.9592}{0.1239} = 0.3293\ pu \\
x''_d &= \frac{A}{it_o} = \frac{1-0.9778}{0.1239} = 0.1792\ pu
\end{aligned} \tag{5}
$$

To obtain the open circuit time constants the field current curve during the load rejection, shown in Fig. 5 and in Fig. 6, are used. T'_{do} and T''_{do} are the times required for the transient and sub-transient components of voltage to decrease to *1/e* or *0.368* times of its initial value as in [4] and [9], so they can be obtained as: $T'_{do} = 3.8008$ *s* and $T_{do} = 0.0245$ *s*.

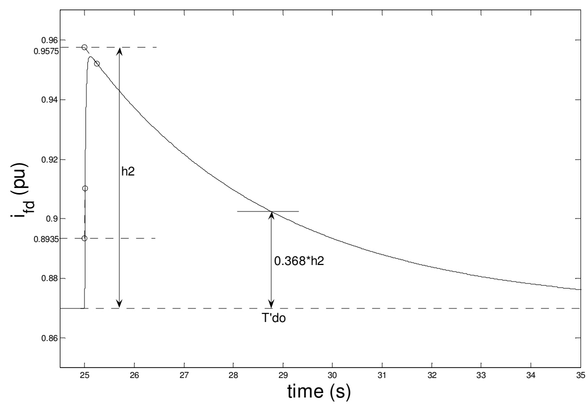

Fig. 5. Field current during the load rejection

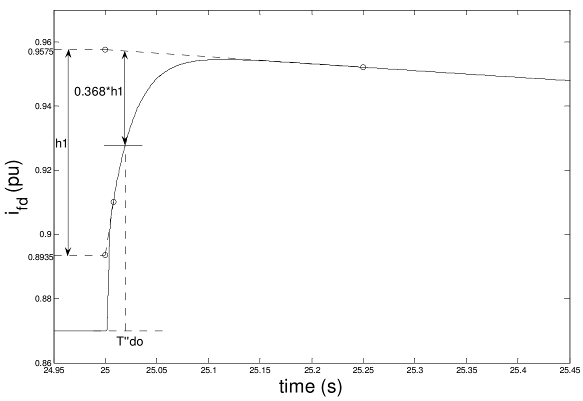

Fig. 6. Amplification of Fig. 5

B. *q-axis load rejection test*

The electrical conditions at the time immediately before the load rejection are: $P_o = 0.6249\ pu$, $Q_o = 0.3054\ pu$ *(capacitive load)*, $Vt_o = 1\ pu$, $it_o = iq_o = 0.6956\ pu$, $v_f = 0.87\ pu$, $\delta_o = \varphi_o = 26.05°$.

The identification process starts obtaining the A, B and C values shown in Fig. 7. Using the expressions given in [9], [4] and [10] x_q and x''_q can be calculated as shown in (6) and (7).

$$x_q = \frac{\sqrt{A^2 - C^2}}{iq_o} = \frac{\sqrt{1^2 - 0.9028^2}}{0.6956} = 0.6183\,pu \tag{6}$$

$$x''_q = \frac{\sqrt{A^2 - C^2} - \sqrt{A^2 - B^2}}{iq_o} = \frac{\sqrt{1^2 - 0.9028^2} - \sqrt{1^2 - 0.9642^2}}{0.6956} = 0.2372\,pu \tag{7}$$

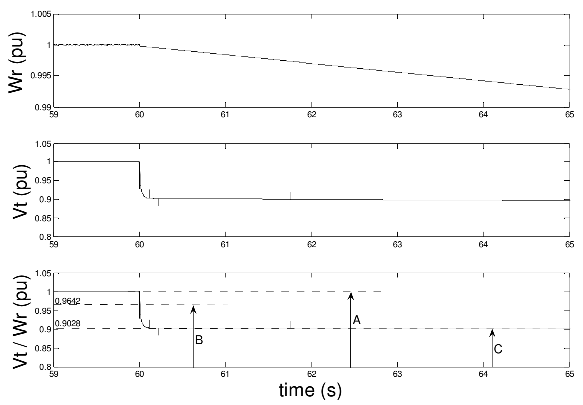

Fig. 7. Terminal voltage load rejection.

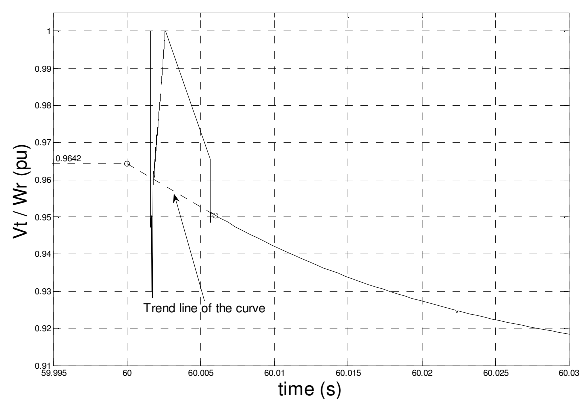

Fig. 8. Amplification of Fig. 7

C. *Arbitrary axis load rejection test*

The electrical quantities values at the instant immediately before the load rejection are: $P_o = 0.8437\ pu$, $Q_o = 0.5222\ pu$ (*Inductive Load*), $Vt_o = 1.0003\ pu$, $it_o = 0.9920\ pu$, $v_f = 1.7688\ pu$, $\delta_o = 21.619°$. Using the expressions given in [8] and the data shown in Fig. 9 and in Fig. 10 the parameters x_q and x''_q can be calculated as:

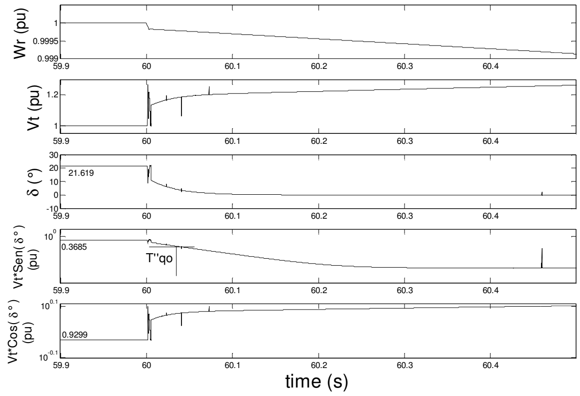

Fig. 9. Rated voltage load rejection.

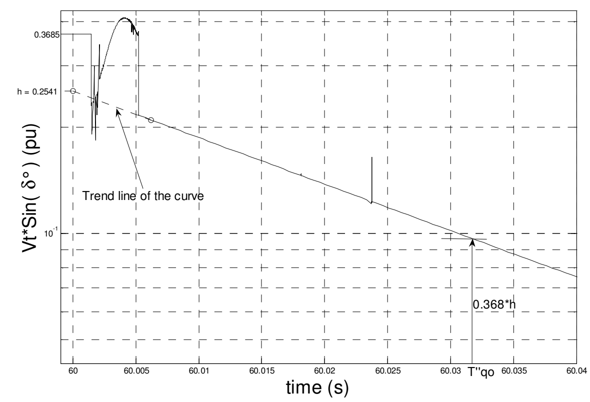

Fig. 10. Amplification of Rated voltage load rejection.

$$x_q = \frac{\left(V_t sen\delta\right)_o}{i_{qo}} = \frac{0.3685}{0.5918} = 0.6227\ pu \tag{8}$$

$$x''_q = x_q - \frac{\left(V_t sen\delta\right)''_o}{i_{qo}} = 0.6227 - \frac{0.2541}{0.5918} = 0.1933\,pu \tag{9}$$

Salient pole synchronous generators don't have x'_q but in [8] there is an expression to calculate it. T''_{qo} is the time required for the sub-transient components of voltage to decrease to *1/e* or *0.368* times its initial value as in [4] and [9]. $T''_{qo} = 0.0328\ s$.

D. *Sudden short circuited test at rated voltage*

A no-load sudden three-phase short-circuit simulation is simulated with zero mechanical torque of the turbine at the moment of the short-circuit and also during the short-circuit.

The field voltage at the instant of the short-circuit was the appropriate value to have the rated voltage at the terminals of the unloaded generator with reactive power also zero.

Fig. 11-a) shows the dynamic behavior of the armature current during the short-circuit from the instant the short-circuit until they reach the steady state.

In the Fig. 11-b) one can observe that the field current shows a variation due to magnetic induction of the stator winding currents in the field during the short-circuit. As the exciter is a constant voltage source, after the short-circuit transient, the field current goes back to its value before the short-circuit.

Taking advantage of the facilities that the software presents to make several types of plots it is possible to build the upper envelopes of the three which are shown in Fig. 11-c) and repeated in Fig. 11-d).

In Fig. 11-d) it is shown the arithmetic average of the three envelope curves. Subtracting from the average phase current the direct current component that represents the envelope of the steady state short-circuit one can have a dynamic part of the envelope of the short-circuit current.

This curve can be used to calculate the *d*-axis parameters of the synchronous generator that are the *d*-axis transient reactance (x'_d) and sub-transient reactance (x''_d) and also the *d*-axis short-circuit transient (T'_d) and sub-transient (T''_d) reactances which are important parameters of synchronous generators.

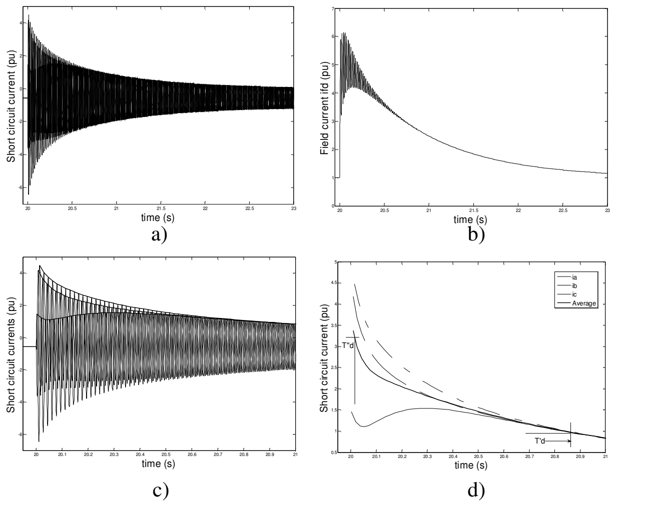

Fig. 11. a)Transient short-circuit phase currents of phases a, b and c, b) Transient field current during the short circuit, c) Envelope of the phase a, b and c short-circuit currents, d) Upper envelope of the phase a, b and c short-circuit currents.

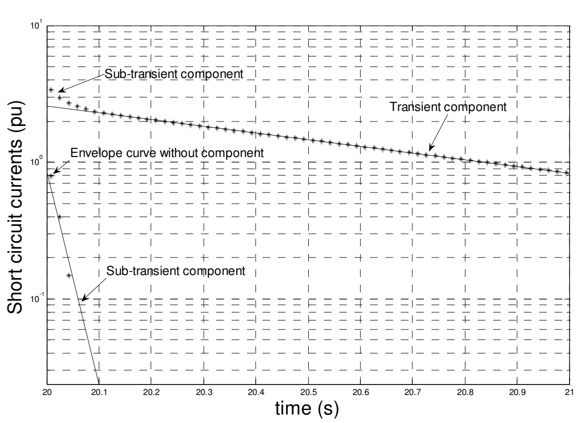

Fig. 12. Envelope of the average stator short-circuit current in semi log scale.

To determine these parameters [3], [4] the average curve envelope, without the steady state component is placed in a semi log plot so that the points of intersection of the curves with the axis of currents could be gotten as shown in Fig. 12.

Thus the reactances x_d, x'_d and x''_d are calculated for the cylindrical rotor synchronous generator by:

$$
\begin{aligned}
x_d &= \frac{E_o}{I_{cc}} = \frac{1}{0.5557} = 1.7995\ pu \\
x'_d &= \frac{E_o}{I_{cc} + I'_{cc}} = \frac{1}{0.5557 + 2.5777} = 0.3191\ pu \\
x''_d &= \frac{E_o}{I_{cc} + I'_{cc} + I''_{cc}} = \frac{1}{0.5557 + 2.5777 + 1.1245} = 0.2348\ pu
\end{aligned}
\tag{10}
$$

E_o is the terminal voltage of the generator at the instant of short-circuit. In this case the short-circuit was done at rated voltage $E_o = 1$ *pu*. For the time constants calculation it is used the Fig. 15 where $T'_d = 0.8863$ *s* and $T''_d = 0.0311$ *s* are the times in seconds required for the transient and sub-transient components of the current *d*-axis decrease to *1/e* or 0.368 times its initial value.

VI. TABLE OF RESULTS

Table I shows the operational parameter values obtained in the load rejection simulation tests as well as the design values of the Salient pole synchronous generator calculated, presented in the appendix B. The design values are used as the input of the simulations and for to calculate the standard *d* and *q* parameters of the generator as in [7], [13].

For the cylindrical rotor synchronous generator with design values presented in the appendix B can calculate the standard parameters of *d*-axis as in [7] using as equations the appendix A too.

Table II shows the standard parameters values [7] obtained in the sudden three-phase short-circuit test as well as the design values calculated of the cylindrical rotor synchronous generator.

VII. CONCLUSIONS

It was verified through simulations using the software Matlab/Simulink/SimPowerSystems that the load rejection tests provide reliable values for the operational parameters of the synchronous generator. The values obtained in the simulation comply very well with the synchronous generator design operational parameters which were used as input in the simulations. This way one can use the simulation tests procedure and parameters calculation to show the importance of the dynamic mathematical modeling of synchronous generator and also to use it as a previous simulation to provided a guide for the procedures to be taken in the plant or in the laboratory when load rejection tests are required for parameters determination. Simulations and data mathematical treatment can also be improved using simulation results.

This work was done before the last revision of the IEEE Std 115^{TM}-2009 [12] was published.

TABLE I

PARAMETERS IN PU OF THE SALIENT POLE SYNCHRONOUS GENERATOR

Parameters Standard	Load Rejection D-Axis	Load Rejection Q-Axis	Load Rejection Arbitrary Axis	Calculated	Design Values
T'_{do}	3.8008	-	-	-	3.7724
T''_{do}	0.0245	-	-	-	0.0238
T''_{qo}	-	-	0.0328	-	0.0334
x_d	1.0492	-	-	-	1.0495
x_q	-	0.6183	0.6227	-	0.6313
x'_d	0.3293	-	-	-	0.3320
x''_d	0.1792	-	-	-	0.1963
x''_q	-	0.2372	0.1933	-	0.2496
T'_d	-	-	-	1.1929	1.1939
T''_d	-	-	-	0.0133	0.0140
T''_q	-	-	-	0.0102	0.0132

TABLE II

PARAMETERS IN PU OF THE CYLINDRICAL ROTOR SYNCHRONOUS GENERATOR

Parameters Standard	Sudden Short Circuit	Calculated	Design Values
T''_{do}	-	0.0423	0.0420
T'_{do}	-	4.9981	5.0008
T''_d	0.0311	-	0.0315
T'_d	0.8863	-	0.8890
x_d	1.7995	-	1.8000
x'_d	0.3191	-	0.3200
x''_d	0.2348	-	0.2400

APPENDIX A

$$T''_d = T''_{do}\frac{x''_d T'_{do}}{x_d T'_d}; \qquad T'_d = x'_d \frac{T'_{do}}{x_d}; \qquad T''_q = \frac{x''_q}{x_q} T''_{qo};$$

APPENDIX B

Salient pole synchronous generator design data: 6250 kVA, 4160 V, 60 Hz, 0.85 pf, 20 $poles$, $r_s = 0.00636$ pu, $x_{ls} = 0.1235$ pu, $r_{kd} = 0.03578$ pu, $r_{kq} = 0.05366$ pu, $r_{fd} = 0.0084$ pu, $x_{lkd} = 0.1119$ pu, $x_{lkq} = 0.1678$ pu, $x_{lfd} = 0.2691$ pu, $H = 7.11$ s.

Cylindrical rotor synchronous generator design data: 835 MVA, 26 kV, 60 Hz, 0.85 pf, 2 $poles$, $r_s = 0.003$ pu, $x_{ls} = 0.19$ pu, $r_{kd} = 0.01334$ pu, $r_{kq1} = 0.00178$ pu, $r_{kq2} = 0.00841$ pu, $r_{fd} = 0.000929$ pu, $x_{lkd} = 0.08125$ pu, $x_{lkq1} = 0.8125$ pu, $x_{lkq2} = 0.0939$ pu, $x_{lfd} = 0.1414$ pu, $H = 5.6$ s.

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