Synchronous Generator Parameters Determination Using Dynamic Simulations Based on IEEE Standards

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Abstract—**This work presents the application of the load rejection test, a graphical and analytical method used to determine the direct- and quadrature-axis, transient, and sub-transient reactances and time constants of a salient-pole synchronous generator. To validate the obtained results, they are compared against those from a reference test performed using the same method. For a fair comparison, the generator parameters are maintained identical to those in the reference case. The primary objective of this study is to demonstrate that the load rejection method is both viable and replicable, making it suitable for consideration in future research and industrial applications.**

I. INTRODUCTION

One of the most important aspects of the study of dynamics and control of electrical power systems is having an accurate mathematical representation of each component of the system. The synchronous machine is one of the most critical components that must be correctly modeled and parameterized. For this, IEEE has developed a standard methodology, based on a set of tests to calculate the necessary parameters of the synchronous machine.

The standard parameters of the synchronous generators are the synchronous reactances on the d and q axes (x_d and x_q), the transient synchronous reactances on the d- and q-axis (x'_d and x'_q), and the sub-transient synchronous reactances on the d- and q-axis. (x''_d and x''_q), the transient and sub-transient time constants of the open-circuit axes d and q (T'_{do}, T'_{qo}, T''_{do} and T''_{qo}). The calculation of these standard parameters will lead to the determination of the fundamental electrical parameters of the synchronous generator.

This paper aims to demonstrate the accuracy of the system through a comparison of the load rejection test, as presented in [2], [3]. The tests and simulations are performed using MATLAB/Simulink and SimPowerSystems.

II. REQUIRED DATA TO PREFORM THE TEST

The fundamental parameters of the synchronous generator include: the per-phase stator winding electrical resistance (r_s), the field winding resistance (r_{fd}), the d- and q-axis damping winding resistances (r_{kd} and r_{kq}), the per-phase stator winding 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 the d- and q-axis magnetizing reactances (x_{md} and x_{mq}).

The values of these parameters are presented in Table I.

TABLE I
SIMULATION PARAMETERS OF THE GENERATOR

Nominal power: 6,250 kVA	
Line voltage: 4,160 V	
Number of pole pairs: 10	
Moment of inertia (H): 7.11s	
$R_s = 0.00636\,pu$	$X_{ls} = 0.1235\,pu$
$x_{mq} = 0.5078\,pu$	$x_{md} = 0.926\,pu$
$R_{kq} = 0.05366\,pu$	$x_{lkq} = 0.1678\,pu$
$R_{fd} = 0.00084\,pu$	$x_{lfd} = 0.2691\,pu$
$R_{kd} = 0.03578\,pu$	$x_{lkd} = 0.1119\,pu$

ª Parameter values obtained from [1].

The parameters presented in Table I were introduced into the Simulink diagram shown in Fig. 1. In this model, the salient-pole synchronous generator is connected in series with a three-phase breaker and an infinite bus.

Above the generator, the data extractor block is placed, from which the d- and q-axis voltages and currents could be obtained. The infinite bus is used to maintain the generator terminal voltage fixed at its nominal value during the simulation. The real power P_m represents the mechanical input
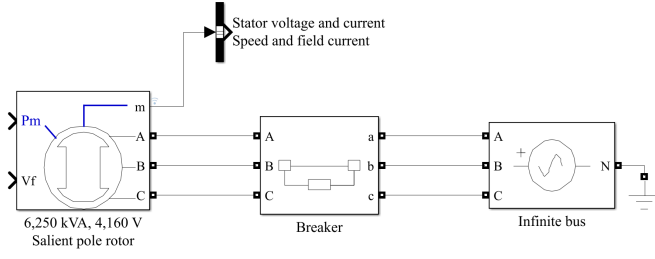
Fig. 1. Block diagram of the generator simulation setup in Simulink.

power of the generator, while v_f denotes the field voltage, which regulates the reactive power.

III. Synchronous generator load rejection tests

The references [2], [3] aim to approximate the design values of the generator through load rejection tests. These tests consist of switching off the load simultaneously with tripping the turbine. During the test, the excitation system must be in manual mode, and the field winding voltage must be maintained. This type of test is widely used, as it provides a well-established method for obtaining most of the generator parameters. Moreover, it is not dangerous to the generator and can be performed at full voltage and full load, or at reduced loads because it consist on sudden disconnection of the system or the load from the generator. All parameters except the moment of inertia, the stator and field winding resistances, and the leakage reactance can be determined using the various types of load rejection tests described below [1].

A. d-axis load rejection test

With the direct-axis load rejection test, it is possible to obtain the direct-axis reactance (x_d), the transient reactance (x'_d), and the sub-transient reactance (x''_d), as well as the corresponding transient (T'_{do}) and sub-transient (T''_{do}) time constants. To perform this test, the generator must be connected to the system under fully reactive load and zero power factor. To compute the terminal voltage of the generator, (1) is used, since Simulink operates with the direct- and quadrature-axis components.

$$|v_t| = \sqrt{v_q^2 + v_d^2} \tag{1}$$

To perform the test, the load rejection is applied at $t = 25$s. Once the terminal voltage is obtained and plotted, it is possible to take measurements and calculate approximations of the desired values. Since this is a graphical method, to obtain the response constants it is necessary to add tangent lines and extract the intersection values with the first sag. After the constants A, B, and C are obtained, (2)–(4) are used.

$$x_d = \frac{C}{i_o} \tag{2}$$

$$x'_d = \frac{B}{i_o} \tag{3}$$

$$x''_d = \frac{A}{i_o} \tag{4}$$

where i_o is the current at the time of the load rejection. To begin the simulation and the procedure for obtaining the constants A, B, and C, the diagram in Fig. 1 is implemented in Simulink using the parameters listed in Table I, and the terminal voltage v_t is plotted as shown in Fig. 2.
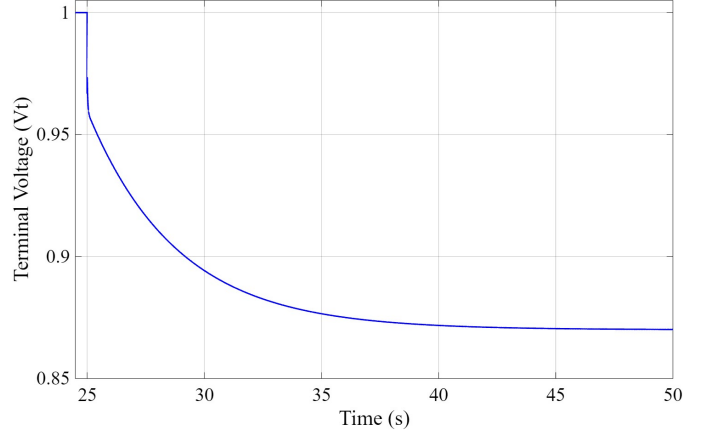

Fig. 2. Generator terminal voltage (v_t) during load rejection.

From Fig. 2, it is possible to extract the constants required to calculate the reactances using (2)–(4).

1) Obtaining A: The calculation of constant A begins by zooming in on the instant when the load rejection occurs in Fig. 2. As is well known, the rejection takes place at $t = 25$ s, as illustrated in Fig. 3.
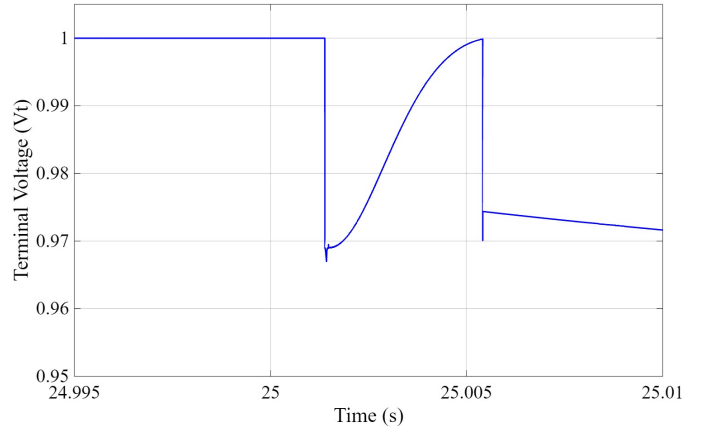

Fig. 3. Generator terminal voltage (v_t) at the instant of load rejection.

Constant A is obtained by extending the "stable" voltage decay to its intersection with the first sag after the load rejection. This requires identifying the tangent to the terminal voltage following the transient oscillation and prolonging it until it intersects with the first sag. The voltage value at this intersection corresponds to constant A, as shown in Fig. 4.
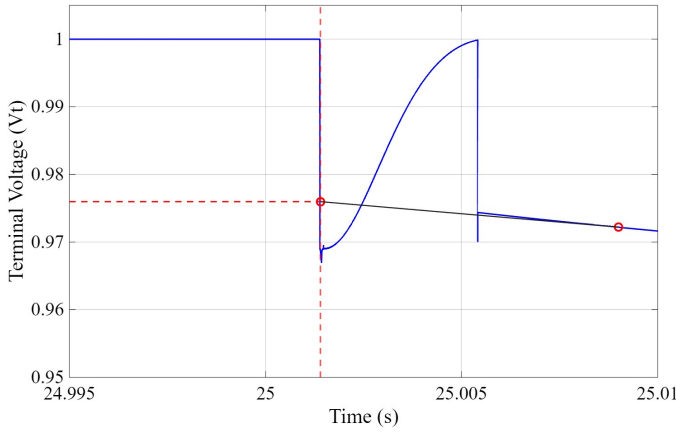
Fig. 4. Intersection point between the first sag and the tangent of the curve

Fig. 6. Intersection point between the first sag and the damped line

It is important to note that this is a graphical method, so, the interpretation of the person performing the test is a key factor in attempting to replicate the experiment. In this case, the best approximation to the curve was determined to be the tangent at $t = 25.009$, s. Extending this tangent to its intersection with the first sag yields a value of $A = 0.976$V.

2) Obtaining B: The calculation of constant B differs from that of A. Although the procedure is similar, the tangent in this case is taken from the decreasing portion of the voltage after the transient sag, rather than from the initial instants of the load rejection. By zooming in on the first milliseconds following the transient sag, the relevant curve can be identified, as shown in Fig. 5.
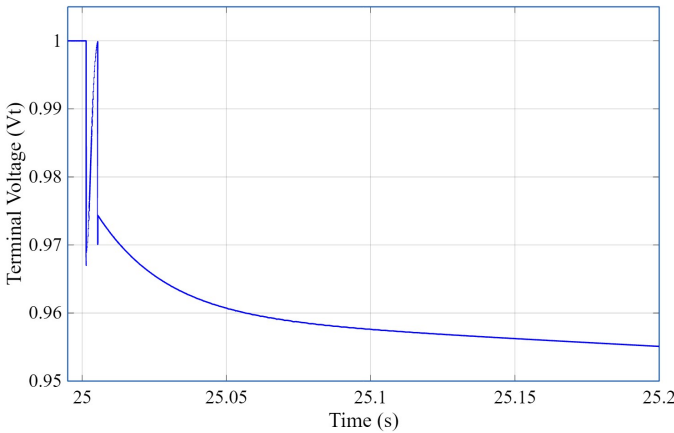

Fig. 5. Generator terminal voltage (v_t) after the load rejection.

In this figure, the mentioned curve can be observed. Around $t = 25.1$, s, a slight damping becomes noticeable. At this stage, a point on the curve is selected to obtain the tangent. As with constant A, the tangent line is then extended to intersect with the first sag. The voltage value at this intersection corresponds to the constant B, as illustrated in Fig. 6.

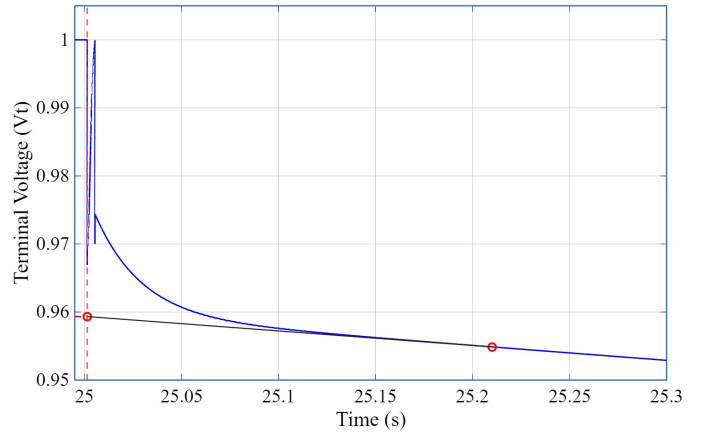The tangent was created at $t = 25.21$s and the value of the intersection is equal to $B = 0.9593$V.

3) Obtaining C: The procedure to obtain C is simpler than for the previous constants, since this value corresponds directly to the field voltage. This can be verified in Fig. 2, where after the sub-transient and transient states decay, the system reaches a new steady state determined by the field voltage (set at the beginning of the simulation in manual configuration, as required for this method, without automatic control). Applying the same tangent method confirms this result, as shown in Fig. 7.
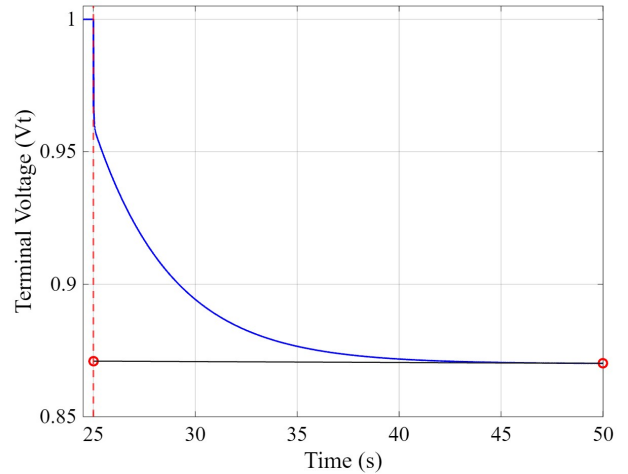

Fig. 7. Intersection at the stability point after the load rejection

The tangent at this time $t = 50$s and its intersection correspond to $C = 0.8710$V.

4) Obtaining T''_{do}: To obtain the sub-transient time, either Fig. 1 or the field current response can be used. For illustration purposes, the field current shown in Fig. 8 is considered.

To determine the sub-transient time, the curve of the field current after the load rejection is extended and the curve of the second transient is extended too until the time the load was rejected. The value of voltage between this two intersections will be our h_1 value. This is better shown in Fig. 9
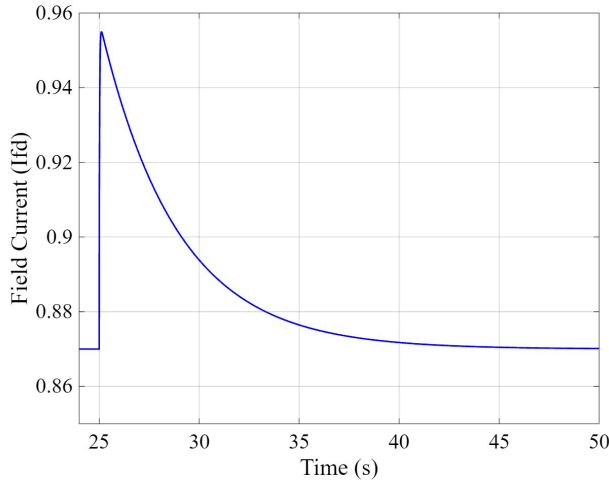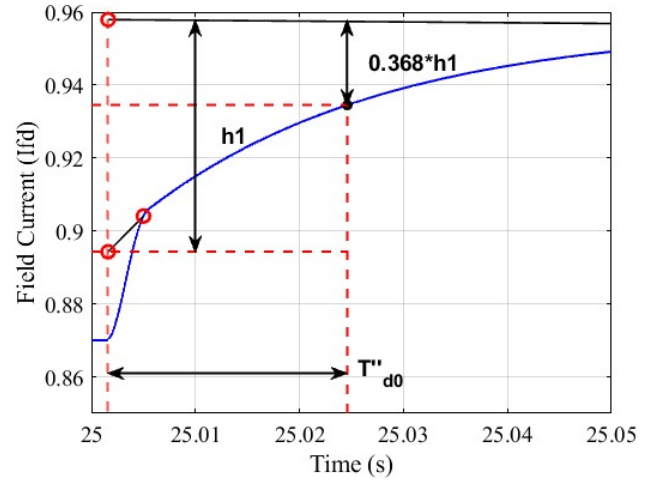
Fig. 8. Current behavior during load rejection test

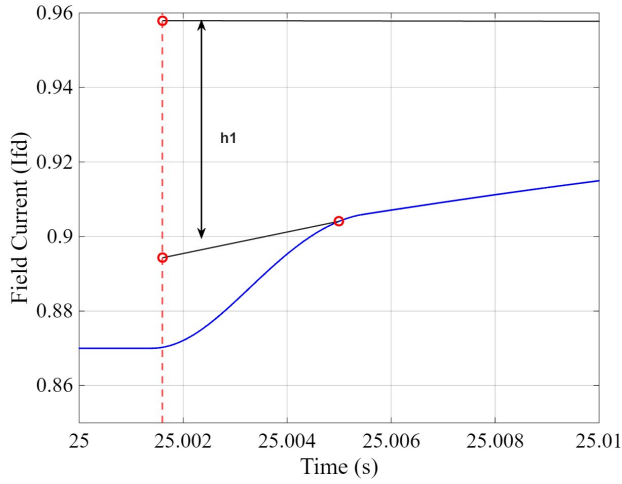Fig. 10. Graphical determination of T''_{do} from the field current response.

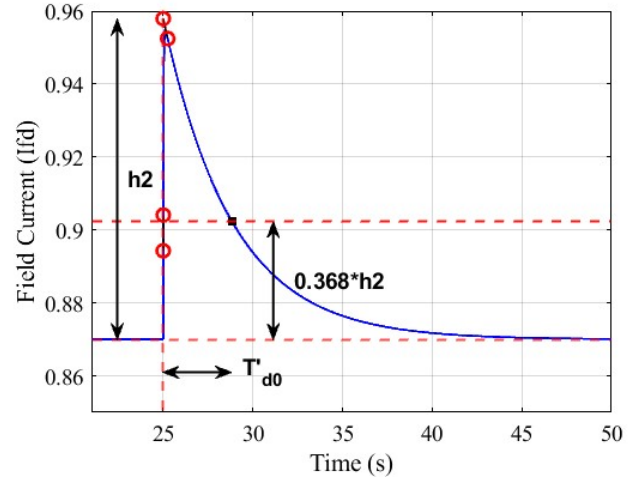Fig. 9. Graphical determination of h_1 from the field current response

Fig. 11. Graphical determination of T''_{do} from the field current response.

The sub-transient time corresponds to the time required for h_1 to decay to h_1/e in the tangent relation. By evaluating this exponential decay and plotting the corresponding point on the curve, the sub-transient time constant can be determined. Using $h_1 = 0.0637$ and $h_{1T} = 0.02434$, the point obtained by subtracting h_{1T} from the upper tangent allows identifying the sub-transient time T''_{do}, as shown in Fig. 10.

From Fig. 10, the sub-transient time results in $T''_{do} = 0.022995$s, expressed as the difference between the time of the plotted point and the instant at which the load rejection started.

5) Obtaining T'_{do}: To obtain the transient time, the same procedure as for the sub-transient time is followed. However, instead of considering the intersection between tangents, the upper tangent is compared with the value after the load rejection occurs, as shown in Fig. 11.

From Fig. 11, the transient time results in $T'_{do} = 3.829693$s, expressed as the difference between the value obtained from the plot and the time when the load rejection began.

After all this analysis and with all the constants calculated, now it is time to use (2)-(4) to calculate the values of the respective reactances. after measuring the output current value before the load rejection test begin, the value $i_o = 0.1239$A is obtained. after applying the constants obtained before and i_o we find the calculated reactances presented in Table II.

B. q-axis load rejection test

The quadrature-axis load rejection test is used to determine the x_q and x''_q parameters of the synchronous machine. In this test, it is required that the synchronous machine remains connected to the power system while ensuring that the armature current contains exclusively the q-axis component. To achieve this condition, both the reactive power and the field current

TABLE III
Q-AXIS TEST RESULTS

Parameters Standard	Calculated Values
x_q	0.6112
x''_q	0.2495

[a]all reactance parameters are in PU

are adjusted until the power factor angle (ϕ) is equal to the power angle (δ).

During the test, the terminal phase voltages are measured, their arithmetic average is computed, and the resulting waveform is used to determine the reactances x_q and x''_q.

The electrical conditions at the time immediately before the load rejection are: $P_o = 0.6249\ pu$, $Q_o = 0.3054\ pu$ (capacitive load), $V_{t_o} = 1\ pu$, $it_o = i_{q_o} = 0.6892\ pu$, $v_f = 0.87\ pu$, $\delta_o = \phi_o = 25.79°$.

After obtaining the values $A = 1$ p.u., $B = 0.9684$ p.u. and $C = 0.9069$ p.u. from Fig. 12, it is possible to calculate x_q and x''_q as shown in (7) and (8).

$$x_q = \frac{\sqrt{A^2 - C^2}}{i_{q_o}} = 0.6112\ p.u \tag{5}$$

$$x''_q = \frac{\sqrt{A^2 - C^2} - \sqrt{A^2 - B^2}}{i_{q_o}} = 0.2495\ p.u \tag{6}$$

C. Arbitrary axis load rejection test

The arbitrary axis load rejection test is a practical method, described in the IEEE 115 standard and detailed in [1], [2], for determining the quadrature-axis (q-axis) parameters. This test begins from a realistic operating condition where the generator supplies both active (P) and reactive (Q) power, ensuring the armature current has components on both the direct-axis (i_d) and quadrature-axis (i_q).

The procedure involves bringing the generator to a steady-state operating point, after which the load is suddenly rejected. Following the rejection, the terminal voltage ($|v_t|$) and rotor angle (δ) signals are recorded. The key signal for the analysis is the d-axis voltage component, calculated as:

$$v_d(t) = v_t(t) \cdot \sin(\delta(t)) \tag{7}$$

To determine the time constants, the v_d signal is plotted on a linear time axis and a logarithmic amplitude axis, as shown in Fig. 13. On this plot, the portion corresponding to the sub-transient decay is identified, a straight line is drawn following its trend, and it is extrapolated back to the instant of rejection ($t = 60\ s$) to find the initial sub-transient voltage component, denoted as h.

Fig. 13. Graphical determination of T''_{qo} from the direct axes voltage.

Based on the graphical outputs of the simulation, key values were extracted to support the analysis:

- Pre-rejection conditions ($t = 60^-$ s):
  - q-axis current, $i_{q0} = 0.5872$ pu.
  - d-axis voltage, $V_{d0} = 0.3657$ pu.
- Transient analysis ($t \geq 60$ s):
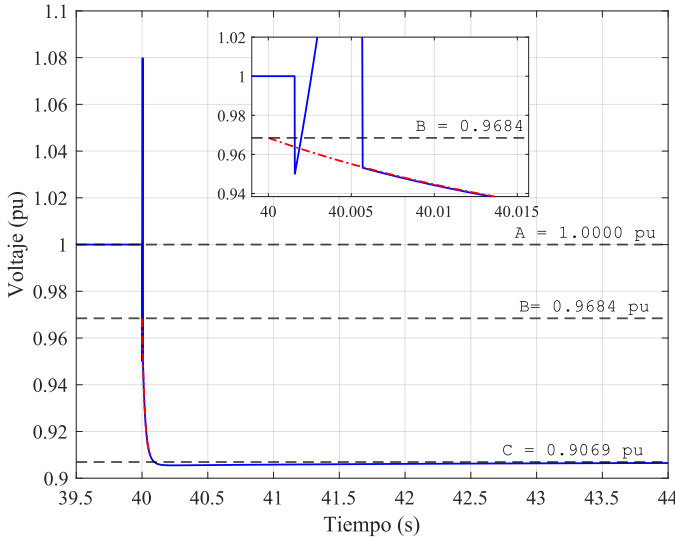 - Initial sub-transient component, $h = 0.2517$ pu.

Fig. 12. Graphical determination of A, B & C from the terminal voltage.

The calculated reactances via this method are being shown in Table III.

– Time of decay to 36.8%, $t_{\text{end}} = 60.0329$ s.

1) Synchronous Reactance (x_q): This is calculated as the ratio of the d-axis voltage to the q-axis current in the initial steady state.

$$x_q = \frac{V_{d0}}{i_{q0}} = \frac{0.3657}{0.5872} = 0.6228 \text{ pu} \tag{8}$$

2) Sub-transient Reactance (x_q''): This is calculated from the instantaneous change in voltage (h) caused by the damper windings.

$$x_q'' = x_q - \frac{h}{i_{q0}} = 0.6228 - \frac{0.2517}{0.5872} = 0.1942 \text{ pu} \tag{9}$$

3) Sub-transient Time Constant (T_{qo}''): This is defined as the duration of the sub-transient decay. It is calculated as the difference between the instant the signal reaches 36.8% of h (t_{end}) and the start of the event ($t_{\text{start}} = 60\,\text{s}$).

$$T_{qo}'' = t_{\text{end}} - t_{\text{start}} = 60.0329 - 60.0 = 0.0329 \text{ s} \tag{10}$$

The q-axis transient parameters, x_q' and T_{qo}', are not calculated for salient pole generators because the standard model for this machine lacks a winding on the quadrature-axis capable of producing a slow transient effect. Specifically, the slow transient phenomena are governed by the main field winding, which, by construction, exists only on the direct-axis (d-axis). The quadrature-axis (q-axis), in contrast, only contains damper windings. Since these damper windings are responsible for the fast sub-transient phenomena, the q-axis can only exhibit a sub-transient response. Consequently, the transient reactance and its corresponding time constant are not defined for this model.

TABLE IV
ARBITRARY-AXIS TEST RESULTS

Parameters Standard	Calculated Values
x_q	0.6228
x_q''	0.1942
T_{qo}''	0.0329 s

[a]all reactance parameters are in PU

IV. CONCLUSIONS

This graphical method is particularly useful when it is not possible to obtain the equivalent reactances typically required for stability studies. In general, the remaining generator parameters are obtained through physical testing. Another advantage of this method is that the data required to perform it can be derived from the nameplate information of the synchronous machine. Therefore, even if the generator is already installed, the test can still be carried out and the parameters accurately determined.

This work successfully demonstrated that load rejection tests, when performed in a controlled simulation environment, constitute a viable and replicable method for determining the standard parameters of a salient-pole synchronous generator. The results obtained from the d-axis, q-axis, and arbitrary-axis tests exhibit strong agreement with the generator's design values, thereby confirming the validity of the methodology presented in [2], [3]. A comparison between the obtained values and the generator's design values is shown in Table V.

TABLE V
COMPARISON OF CALCULATED AND DESIGN VALUES

Parameters Standard	Load Rejection			Synchronous machine values	Error%
	D-Axis	Q-Axis	Arbitrary Axis	Design Values	
T_{do}'	3.8269	-	-	3.7724	1.4447
T_{do}''	0.0229	-	-	0.0238	3.7815
T_{qo}''	-	-	0.0329	0.0334	1.4970
X_d	1.0492	-	-	1.0495	0.0285
X_q	-	0.6112	0.6228	0.6313	2.2651
X_d'	0.3282	-	-	0.3320	1.1445
X_d''	0.1938	-	-	0.1963	1.2735
X_q''	-	0.2495	0.1942	0.2496	11.1177

[a]Errors calculated using the average of multiple values.

After analyzing the error column in Table V, it can be observed that the method, when properly adjusted, can yield highly accurate results. It is also noticeable that, although the q-axis and the arbitrary axis may produce similar values, slight differences can occur, and in some cases, one may approximate the design values more closely than the other. Nevertheless, the method proves to be both replicable and reliable, provided it is carefully adjusted and correctly calculated.

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