Rapid Determination of the Over-Transient Longitudinal Reactance

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Abstract **- The paper presents an original method to determine the over-transient reactance by the longitudinal axis of a synchronous generator, starting from the symmetric three-phased sudden short-circuit test, from the dry run and symmetrical three-phased short-circuit tests. The current normative recommends determining the longitudinal over-transient reactance using sudden triphased short-circuit tests. This method, however, necessitates many computations and graphical plots. Plotting values is a source of errors that lead to un-realistic results, while the many computations are time consuming. The method we present in this work relies on phenomena in the stator and excitation windings of the synchronous generator that appear during test phases. We present the general equations necessary to compute the longitudinal over-transient reactance and the experimental results obtained by tests on an existing synchronous generator, using previously known methods. To collect parameter values during the symmetric triphased sudden short-circuit test, from the dry run test and symmetrical three-phased short-circuit test we used a 15 channel acquisition tool that allowed us to collect 25000 values per second per channel. Computations were done using LabView. Making the stator and excitation windings phenomena known to design engineers helps them to quickly check size determination computations, and to rapidly and correctly check parameter value determinations by testing. The method presented in this work is not found in the current electric machines regulations.**

Keywords - *synchronous generator, sudden short-circuit, longitudinal over-transitorial reactance.*

I. Introduction

When a sudden triphased short-circuits appear, high value currents appear in the statoric windings, in the excitation winding and damping winding, if there is one. These high value currents may endanger the winding integrity. The post short-circuit stator currents are caused by the polar electromotive voltage U_{eE}, determined by the resultant flux in the machine before the short-circuit happened.

Several parameters of the synchronous generator can be determined from the registration of the statoric currents variation. The most important are: the transient x'_d and over transient reactance x''_d, on the longitudinal axis, the transient x'_q and over-transient reactance x''_q, on the transversal axis, the time constants of the damping winding on the two axes T''_d and T''_q, the time constant of the excitation winding T'_d and the time constant of the stator winding T_a [1], [2], [10].

To determine the value of the over-transient longitudinal reactance by the sudden short-circuit test using classic methods, is arduous. The method to analyze the triphased symmetric sudden short-circuit necessitates reading the current values on the three phases (Fig. 1) and decomposing them into periodic and non-periodic components (Fig. 2) [3], [7]. Separating the mentioned components using the well-known method described in [1] is not rigorously scientific since it uses an average current peak value, ignoring the fact that the peak values occur at different times (see Fig.1 and Fig.2).

Taking an average current peak value influences the correct determination of both periodic and non-periodic components of the sudden triphased short-circuit currents: From the average of current phases' periodic components, the long-term short-circuit current amplitude $I_{sc}(\infty)$, is subtracted, giving the transient and over-transient short-circuit current component values $\Delta I'_{sc}$ and $\Delta I''_{sc}$. This value is, then, presented in half logarithmic coordinates and the current value $\Delta I'_{sc}(0)$, the longitudinal transient reactance value, and the time constant T'_d are determined. Eliminating the transient component $\Delta I'_{sc}(0)$, gives us the over-transient component variation of the triphased sudden short-circuit and its initial value $\Delta I''_{sc}(0)$, which allows us to compute the over-transient longitudinal reactance value, x''_d and the time constant T''_d.

We succinctly presented in the method [1] in the paragraph above showing that it is prone to errors due to graphical constructions, and that it is laborious. Furthermore, dampening the direct stator current when the d rotor axis is oriented by the short-circuited phases' axis and short-circuiting the excitation winding necessitates reading the current values in the short-circuited phases and separating their three winding current exponentials by graphical constructions.

This method allows us to compute the same values as in the sudden triphased short-circuit, but is even more laborious and more errors are easy to made.

The method presented in this paper allows a more rapid determination of the reactance using the results of the dry run test, of the persistent triphased symmetric short-circuit test, and of the sudden triphased short-circuit test.

During the sudden three-fazed short-circuit test, there are no voltage value restrictions on the three short-circuited phases, the over-transient longitudinal reactance not having saturated values. This is benefic because the short-circuit can be produced such that even the high current values that may occur will not jeopardize the synchronous generator.

The only restriction required is that the three mentioned tests are to be made at the same excitation current.

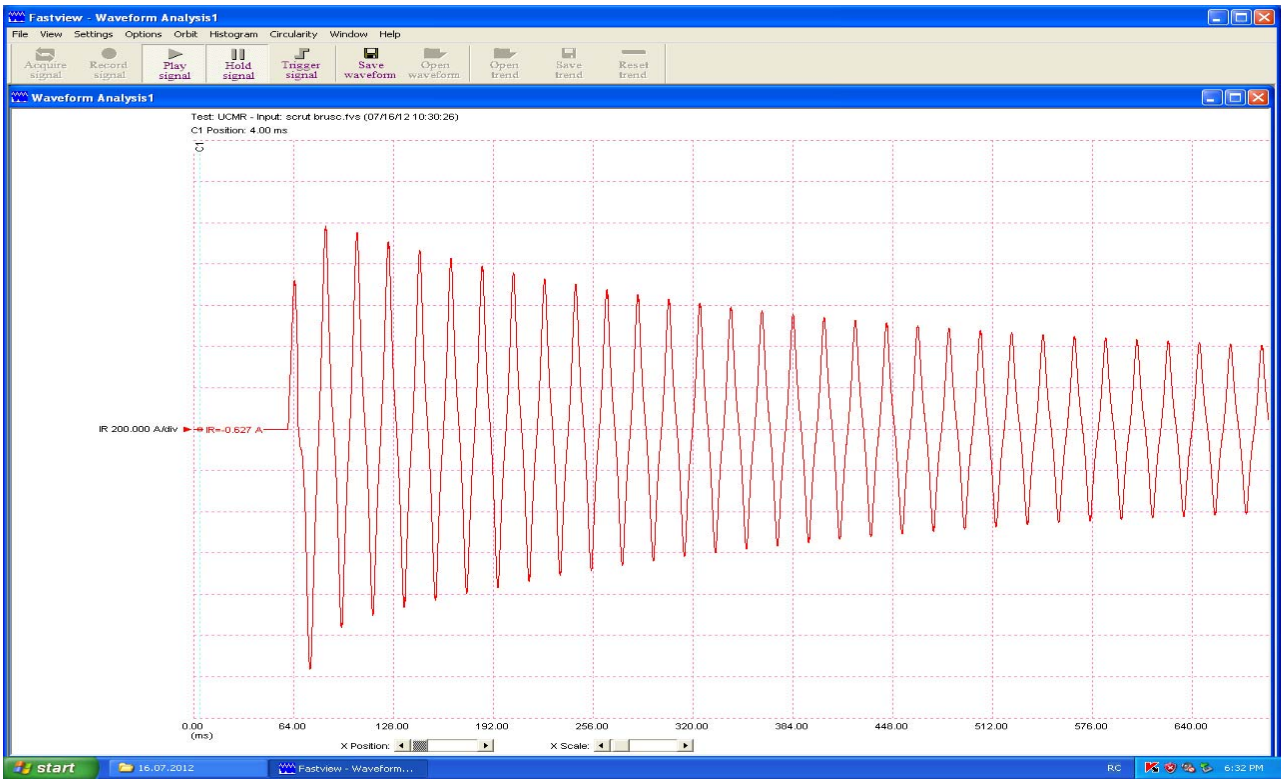

Fig. 1. a) Phase *R* current variation.

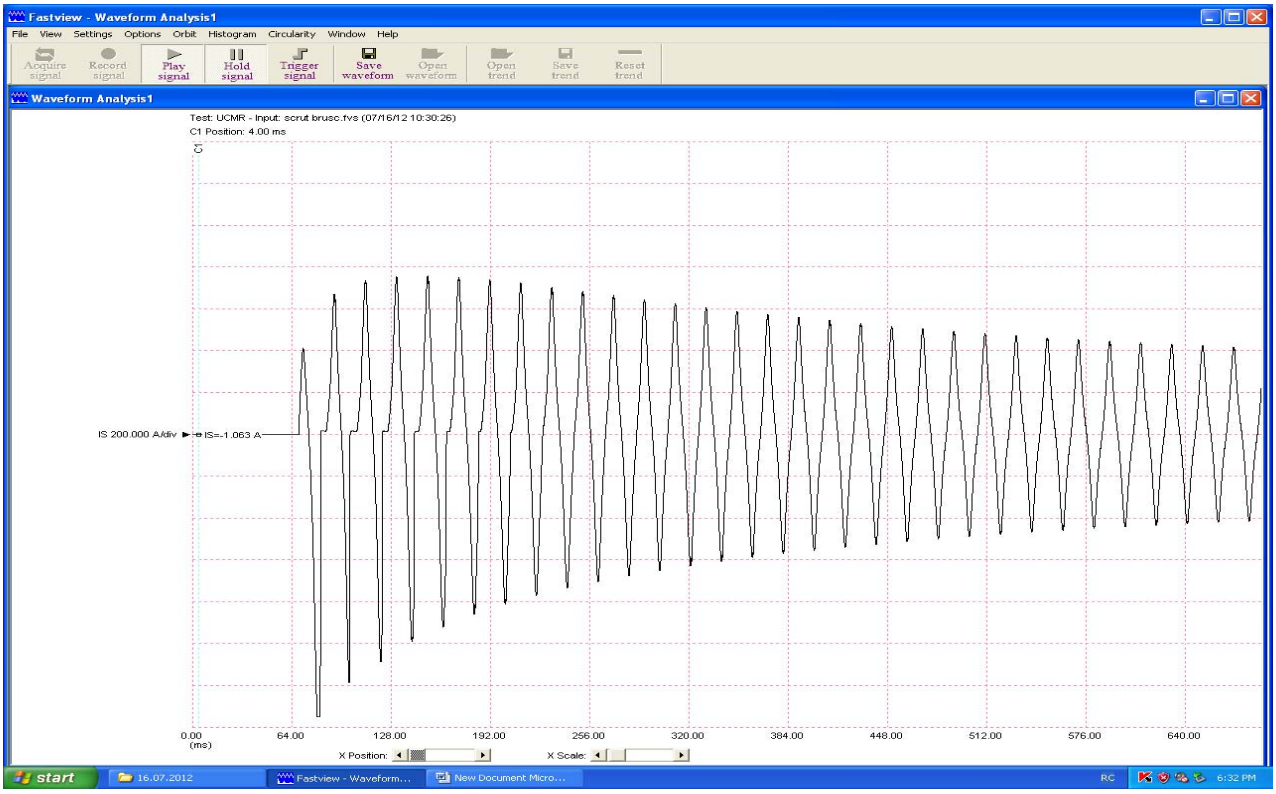

Fig. 1. b) Phase *S* current variation.

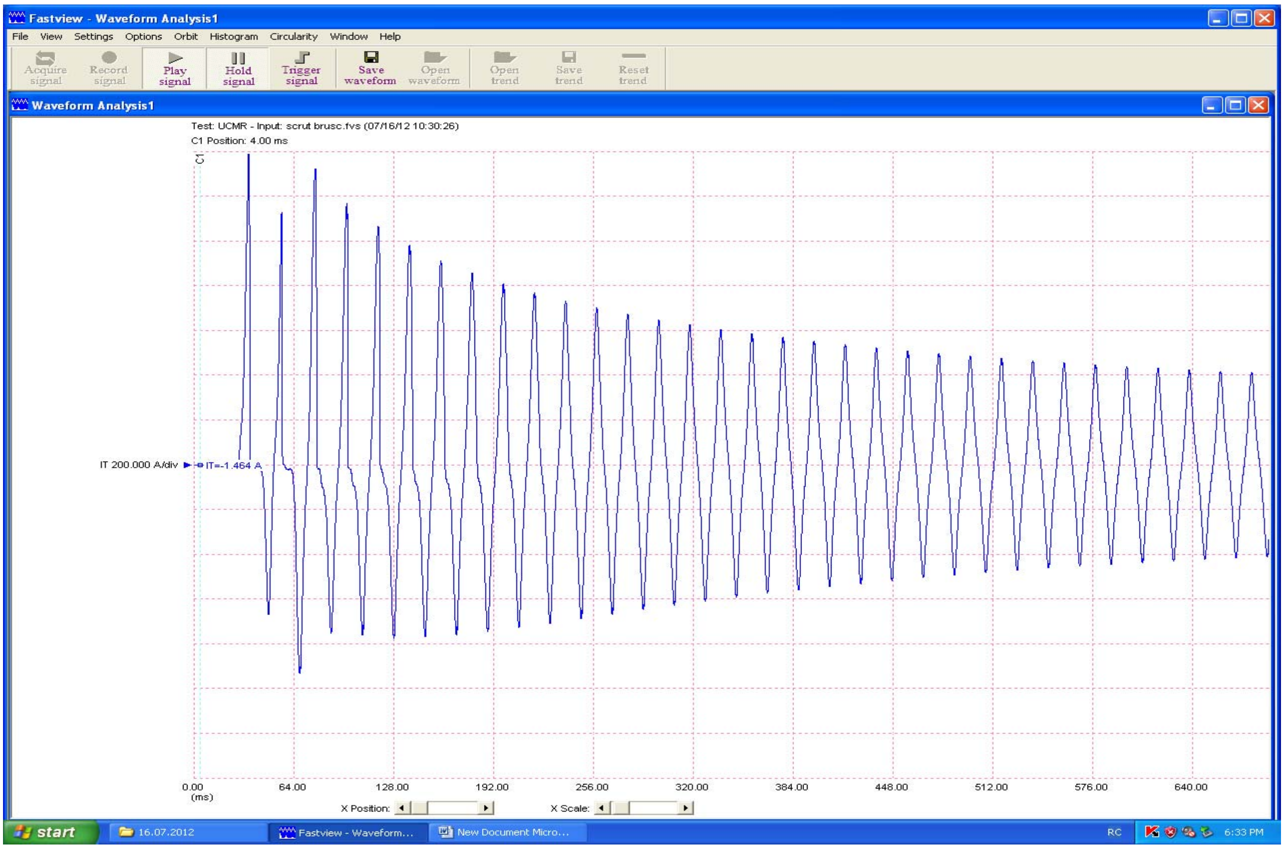

Fig. 1. c) Phase *T* current variations.

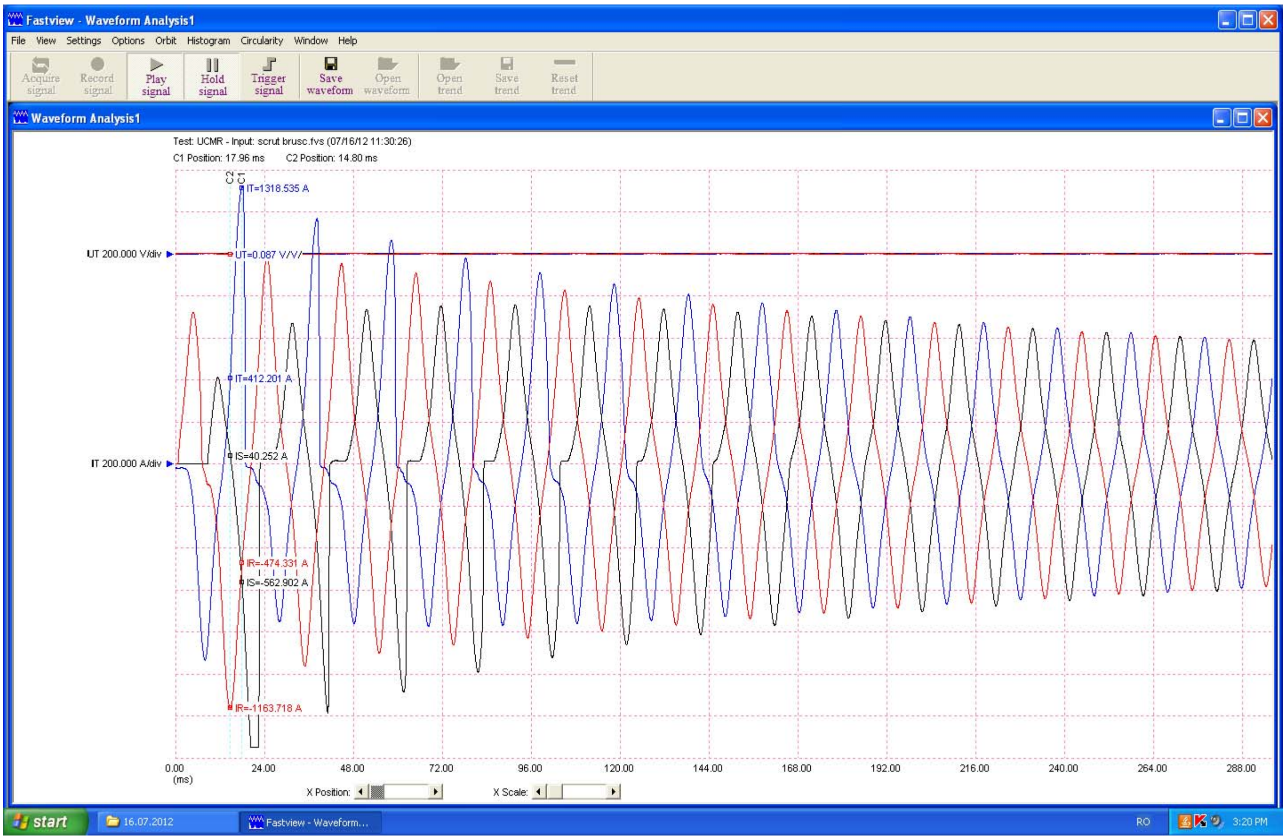

Fig. 2 Sudden triphased short-circuit current variations in time.

II. Theoretical Elements Of The Synchronous Generator At Suddent Short-Circuit

In the field literature, the phenomena in the stator phases are analyzed focusing on the transient currents variation that appear, for different values of the angle β_0. This is the angle between the axis of the statoric phase, taken as reference, and axis d, according to which the statoric winding is positioned [4], [5], [6]. Thus are established relations that describe the transient current variations in the stator phases and in the excitation winding. These relations allow us to determine the dampening time constants for the respective currents, the transient and over-transient reactance values, as well as the various windings dispersion coefficients.

Because the stator winding phases are, in fact, inductions, during the sudden triphased short-circuit, the short-circuit currents determine a reaction flux with a longitudinal demagnetizing character. This flux tends to close through the rotor on the same route the constant resultant flux closes, in the moment just prior to the short-circuit. This tendency could determine an abrupt lowering of the machine resultant flux, previous to the short-circuit. To balance this, high transient currents occur in the rotor winding, currents that oppose the flux lowering, conserving the flux to the value prior to the short-circuit.

The process analysis for the symmetric triphased short-circuit condition is based on the synchronous machine equations, with stator related sizes:

$$\begin{aligned} u_d &= R_s \cdot i_d + \frac{d\psi_d}{dt} - \omega \cdot \psi_q \\ u_q &= R_s \cdot i_q + \omega \cdot \psi_d + \frac{d\psi_q}{dt} \\ u_E &= R_E \cdot i_E + \frac{d\psi_E}{dt} \\ 0 &= R_D \cdot i_D + \frac{d\psi_D}{dt} \\ 0 &= R_Q \cdot i_Q + \frac{d\psi_Q}{dt} \end{aligned} \qquad (1)$$

Detailing the fluxes according to the flux inductions and currents, we have [8], [9]:

$$\begin{aligned} \psi_d &= L_d \cdot i_d + L_{dh} \cdot i_E + L_{dh} \cdot i_D \\ \psi_q &= L_q \cdot i_q + L_{qh} \cdot i_Q \\ \psi_E &= L_E \cdot i_E + L_{dh} \cdot i_d + L_{dh} \cdot i_D \\ \psi_D &= L_D \cdot i_D + L_{dh} \cdot i_d + L_{dh} \cdot i_E \\ \psi_Q &= L_Q \cdot i_Q + L_{qh} \cdot i_q \end{aligned} \qquad (2)$$

where:

$$\begin{aligned} &L_d = L_{dh} + L_{s\sigma}; \quad L_q = L_{qh} + L_{s\sigma} \\ &L_D = L_{dh} + L_{D\sigma}; \quad L_E = L_{dh} + L_{E\sigma} \quad L_Q = L_{qh} + L_{Q\sigma} \end{aligned} \qquad (3)$$

In equation (1) and (2) u_d, u_q, and u_E represent stator winding voltage components by axes d, q, and by the excitation winding, i_d, i_q represent the longitudinal and transversal components of the statoric current I, and i_E, i_D, i_Q represent the currents in the excitation winding and the damping windings, respectively, by axis d and q reported to the stator. The instantaneous electric angle speed of the rotor, which is considered constant, is identified as ω, Ψ_d, Ψ_q are the fluxes determined by the statoric windings corresponding to axes d and q, Ψ_E, Ψ_D, Ψ_Q are the fluxes determined by the excitation winding, and by the damping windings after axis d and q. In these equations L_{dh}, L_{qh} denote the mutual principal inductivities by axis d and q, respectively. L_E is the excitation winding inductivity computed as the sum of mutual principal inductivity by axis d, L_{dh} and the dispersion inductions of the stator winding $L_{s\sigma}$, respectively that of excitation $L_{E\sigma}$, according to equation (3). The afferent inductivities to the damping's windings L_D, L_Q are similarly calculated.

In the sudden three-phased short-circuit case, voltages u_d and u_q in the first two equations of (1) are null. Processing the first, third and fourth equations of (2) under these conditions, gives us:

$$\begin{aligned} L_{dh} \cdot \frac{di_d}{dt} + L_{s\sigma} \cdot \frac{di_d}{dt} &= -L_{dh} \cdot \frac{di_E}{dt} - L_{dh} \cdot \frac{di_D}{dt} \\ L_{dh} \cdot \frac{di_E}{dt} + L_{E\sigma} \cdot \frac{di_E}{dt} &= -L_{dh} \cdot \frac{di_d}{dt} - L_{dh} \cdot \frac{di_D}{dt} \\ L_{dh} \cdot \frac{di_D}{dt} + L_{D\sigma} \cdot \frac{di_D}{dt} &= -L_{dh} \cdot \frac{di_d}{dt} - L_{dh} \cdot \frac{di_E}{dt} \end{aligned} \qquad (4)$$

Neglecting the damping winding dispersion flux by the d axis, decision justifiable for machines with no damping winding, from equations (4) results that all the other dispersion fluxes are null, which is not in accordance with reality. This finding can be expressed as follows: if the dispersion winding is neglected, all dispersions should be neglected. The conclusion is that in the calculations of synchronous machines neglecting of any dispersion is not admitted, even when a damping cage is missing.

$$\underline{U} = \underline{U_{eE}} - j \cdot X_d \cdot \underline{I_d} - j \cdot X_q \cdot \underline{I_q} \qquad (5)$$

Since the sudden short-circuit terminal voltage U is zero, and the last element in equation (5) can be neglected, due to the inductive character of the short-circuit current, we obtain:

$$U_{eE} = X_d \cdot I_d \qquad (6)$$

This relation allows us to compute the polar electromotive voltage U_{eE}, given by the presumably constant resultant flux, previous to the short-circuit, when the synchronous longitudinal reactance X_d is known, and I_d is determined from the test of permanent short-circuit.

At sudden short-circuit, the reactance X_d becomes X''_d and I_d becomes I''_{d3}. This current is obtained from the short-circuit current readings on the three phases, as being the average of the three peaks that occurred immediately after the stator phases short-circuit [1].

Consequently, the value of the over-transient longitudinal reactance X''_d is given by the relation:

$$X''_d = \frac{U_{eE}}{I''_{d3}} \qquad (7)$$

We note that the method we propose to determine the over-transient longitudinal reactance is quick and easy to apply.

III. Practical Application Of The Method

For the test we used a three-phased synchronous generator with the following nominal data: S_n = 353 kVA, U_n = 400 V, I_n = 509 A, n = 300 rot./min, $cos\ \varphi$ = 0.85, f = 50 Hz, and Y connection. To apply the method presented in the previous section the following stages must be followed:

Stage a. Plot the dry run characteristic, $U=f(I_E)$ by well established methods;

Stage b. Read the triphased sustained short-circuit current variations (Fig. 3) and compute their average values for each excitation current value;

Stage c. Plot the short-circuit run characteristic, $I = f(I_E)$, and the dry run characteristic (Fig. 4);

All the tests and computations to determine the over-transient longitudinal reactance were made on the same excitation current I_{Ep} = 28.6 A.

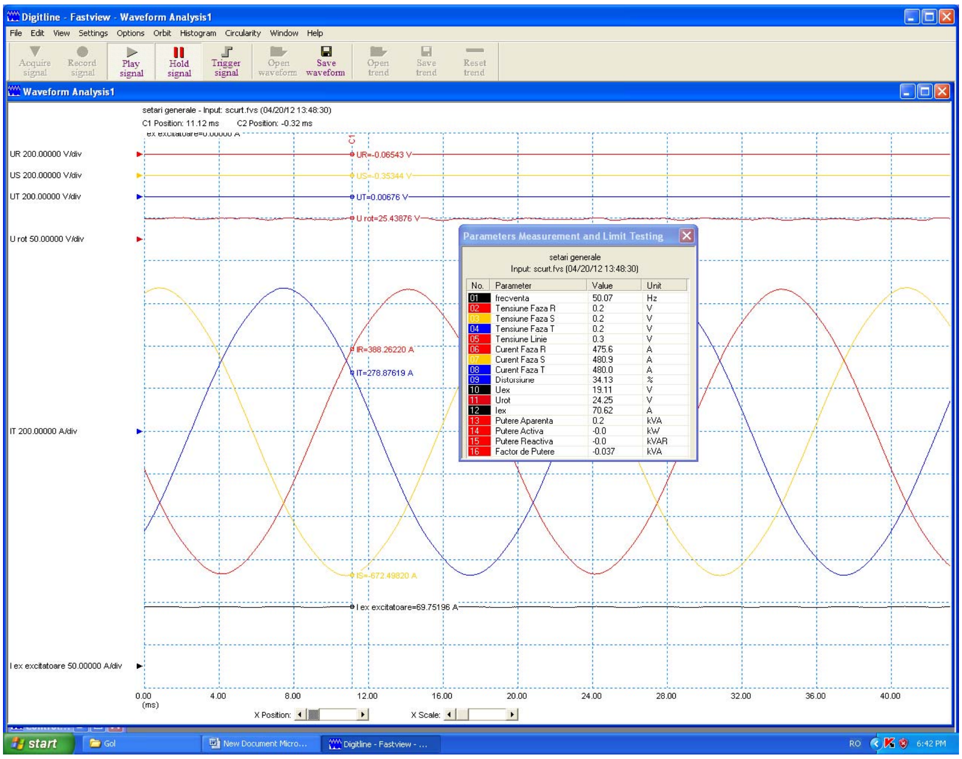

Fig. 3 Phase currents variations during the sustained triphased, symmetric short-circuit run of a synchronous generator.

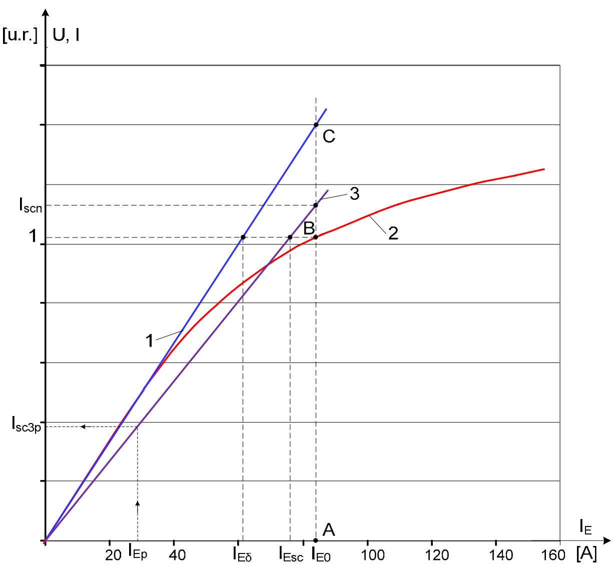

Fig. 4 The dry run and short-circuit run of the synchronous generator.

Processing the data readings at the dry run and sustained triphased, symmetric short-circuit tests we obtained the plots in Fig. 4. In this figure, 1 denotes the air gap line, 2 denotes the dry run, and 3 is the sustained short-circuit run characteristics. From this figure we find the sustained short-circuit current: I_{sc3} = 195 A.

From the same figure we determine the value of the longitudinal synchronous reactance x_d, in [p.u.] with the following relation:

$$x_d = \frac{I_n}{I_{scn}} = \frac{I_{Esc}}{I_{E0}} = 0.9 \ \ [p.u.] \qquad (8)$$

or X_d = 0.4086 Ω.

Using these values in relation (6) we obtain the polar electromotive voltage value:

$$U_{eE} = X_d \cdot I_d = 79.94 \ \ [V] \qquad (9)$$

Stage d. Read the phase current variations in sudden short-circuit for the same excitation current value

$I_{Ep} = 28.6$ A. Reading the three stator currents values during the short-circuit run (Fig. 1 and Fig. 2), for the $I_{Ep} = 28.6$ A excitation current, we obtain the following current peak values: $I_R = 1163.718$ A, $I_S = 1350.275$ A, and $I_T = 1318.535$ A.

These values give the sudden three-phased short-circuit average current value $I''_{d3} = 1277.51$ A.

Stage e. Use equation (7) to obtain the over-transient longitudinal reactance value:

$$X''_d = \frac{79.94}{1277.51} = 0.0626 \ \ [\Omega] \tag{10}$$

which in relative units is $x''_d = 0.138$ [p.u.].

During the sudden triphased short-circuit run we need to decompose the currents in periodic (Fig. 5) and non-periodic (Fig. 6) components.

Analyzing the plot data is done using exponentials expressed with half-logarithmic coordinates [7] (Fig. 7) and (Fig. 8).

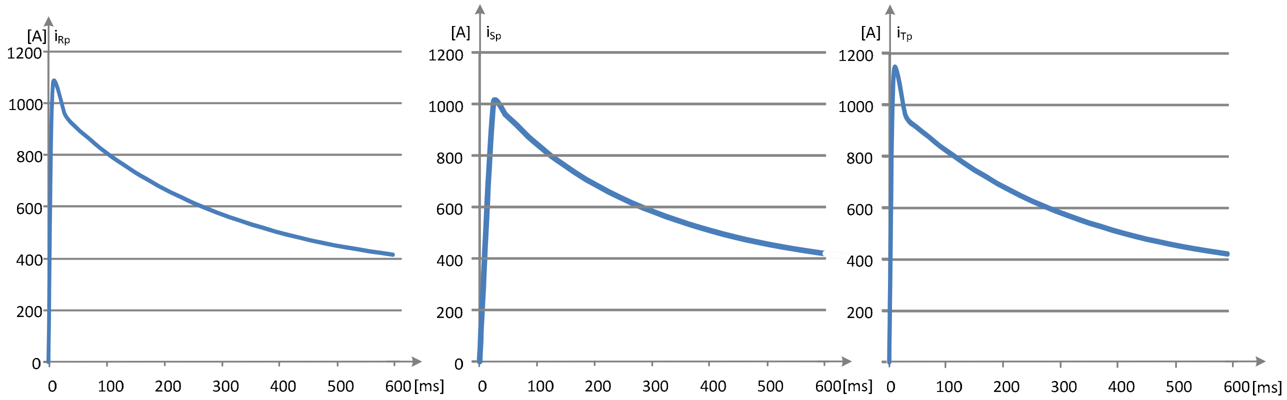

Fig. 5 Variation of the periodic current component during the triphased sudden short-circuit.

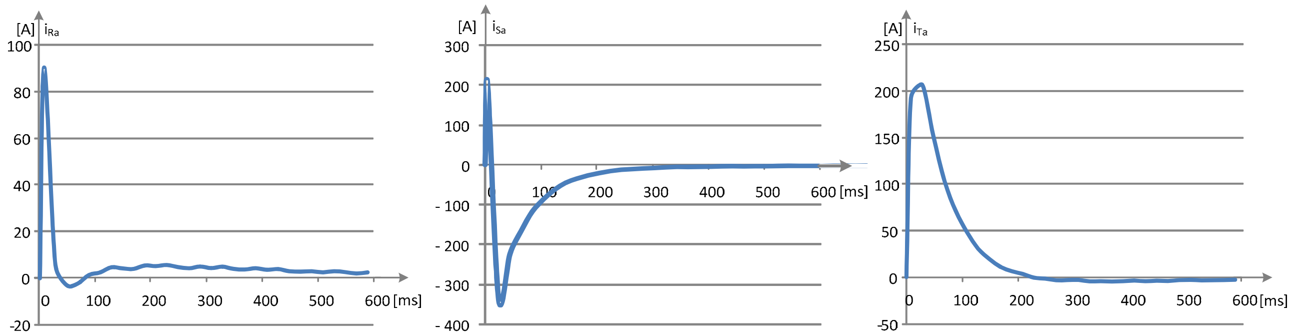

Fig. 6 Variation of the non-periodic current component during the triphased sudden short-circuit.

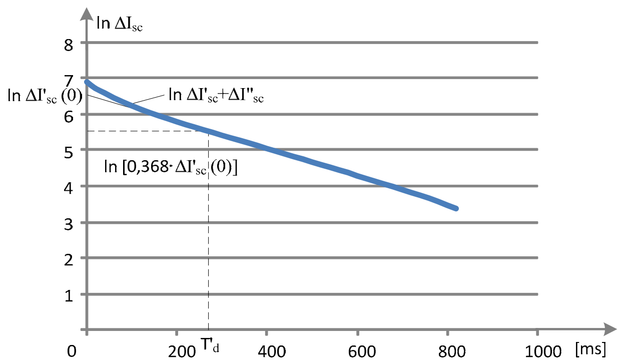

Fig. 7 Transient component variation for the sudden triphased short-circuit current, expressed using half-logarithmic coordinates.

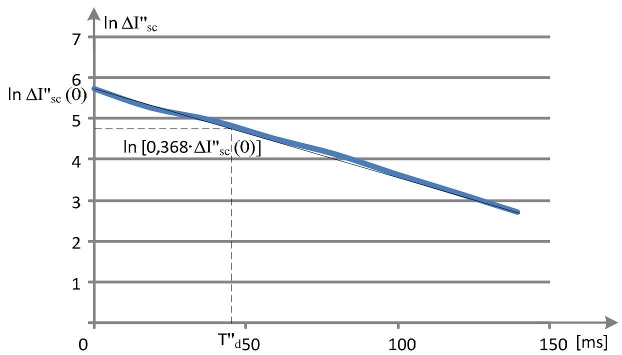

Fig. 8 Over-transient component variation for the sudden triphased short-circuit current, expressed using half-logarithmic coordinates.

Doing the data analysis and computations, we obtain the following value of the over-transient longitudinal reactance: $x''_d = 0.142$ [p.u.].

This method necessitates several graphical plots and manipulations. The difference between the value obtained by our proposed method, as a reference, and the actual value is very small, 2.9%.

Dampening the direct stator current when the *d* rotor axis is positioned by the two short-circuited phases' axis, and short-circuiting the excitation winding [7, 2] necessitates reading the current values during their short-circuit (Fig. 9). Determining the over-transient longitudinal reactance needs the build-up of three exponential plots using half-logarithmic coordinates (Figures 10, 11, and 12).

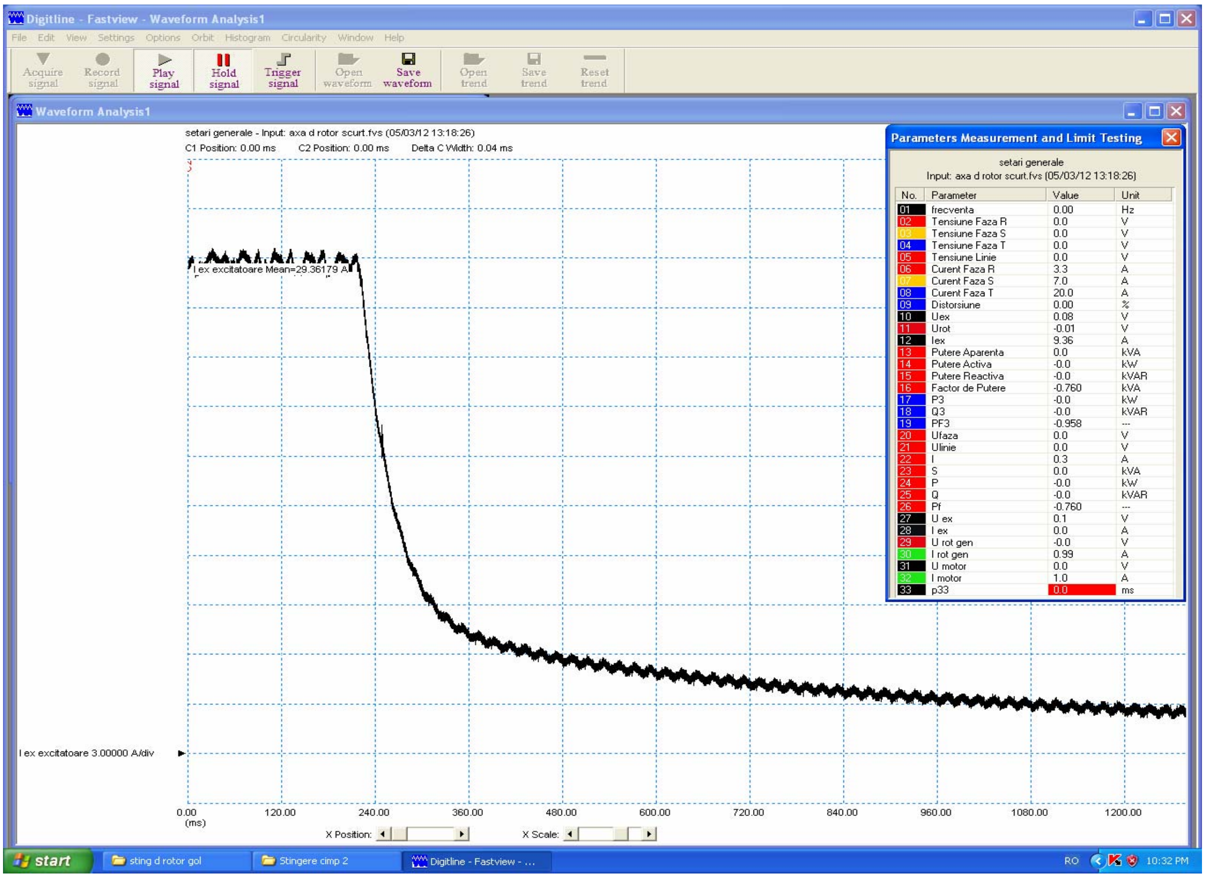

Fig. 9 The achizition dampening the direct stator current when the *d* rotor axis is positioned by the two short-circuited phases' axis, and short-circuiting the excitation winding.

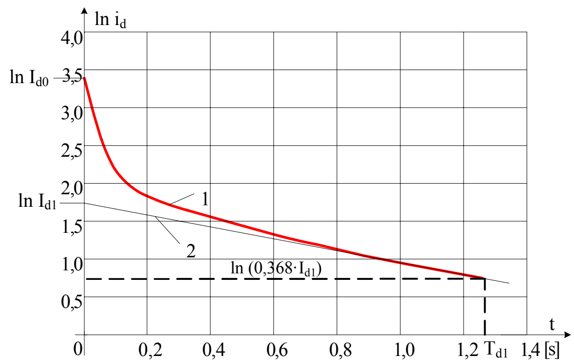

Fig. 10 Determining the current I_d's first exponential by damping the direct current.

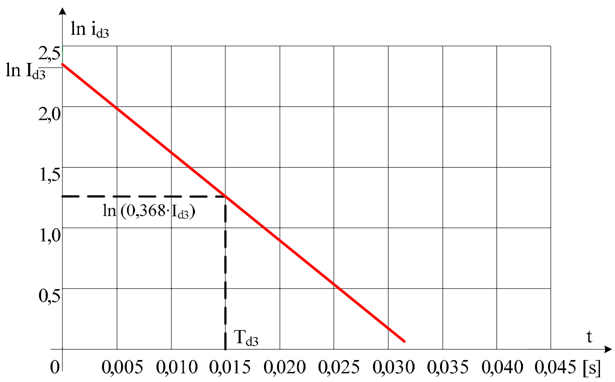

Fig. 12 Determining the current I_d's third exponential by damping the direct current.

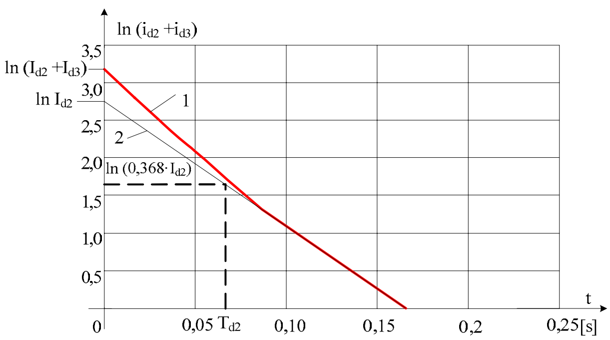

Fig. 11 Determining the current I_d's second exponential by damping the direct current.

Analyzing and working on the three exponentials we obtain the over-transient longitudinal reactance value x''_d = 0.160 [p.u.]. This method is much more laborious than the previous one, and may introduce more errors. It is these errors that may induce the 15.94% difference between the reference and the actual reactance values.

IV. Conclusions

The proposed method allows a rapid and correct determination of the over-transient reactance values from the usual tests to which any synchronous generator is subjected to before being operational active or during maintenance.

We showed in Section III that the over-transient longitudinal value obtained by the proposed method is very close to the values obtained by the most correct method known to now, namely, the sudden triphased short-circuit test run followed by the current decomposition into periodic and non-periodic phases.

This observation reinforces our confidence in the truthfulness of the proposed method. The method's simplicity can lead other researchers and synchronous generator designers to use it in testing other electrical machines, independent of their nominal power.

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