Experimental Measurements of the Rotor Oscillations in an Synchronous Generator During the Three-Phased Sudden Short-Circuit Test

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***Abstract*—This work presents a method to determine rotor oscillations during a three-phased sudden short-circuit test of a synchronous generator. To our best current knowledge, no such similar method is yet published in the technical literature. During the periodic and non-periodic component separation of the three phase currents, it was found that the time difference between the currents' extreme values, for any of the three phase currents, does not have a 10 ms constant value, as in the stationary phase. Investigating why this happens we found that these variations are caused by the rotor oscillations. Certain parameters of a synchronous generator's rotor and of the rotor's oscillations are measured during the sudden three-phased short-circuit test. Based on these readings, with the method presented in this paper, we can compute the rotor's mechanical oscillation amplitudes and the transient process durations. Using the measured values, the equation describing the rotor's mechanical oscillations, independent of its power, can be re-written. Knowledge of the oscillation amplitudes and their durations is necessary for a correct loop control design and in establishing the generator's performance.**

***Keywords*—analytical model, frequency, synchronous generator, tests.**

I. Introduction

Studies in the specific literature present several methods to determine the position of the synchronous generator's rotor, during stationary or dynamic regime [1-3]. This paper does not present yet another such method, but aims to establish the mathematical equation that describes the mechanical oscillations of the synchronous machine's rotor, starting from three-phased short-circuit current readings. We show in the following that the equation we will establish models the rotor's oscillations.

In reading the synchronous generator's three-phase current a data acquisition kit was used. The kit recorded 500 instantaneous values every $4 \cdot 10^{-5}$ s, from the moment of the sudden three-phased short-circuit to the moment of the thermal short-circuit current.

In the periodic and non-periodic component separation of the three phase currents it was observed that the transition period between two zero passages of one phase current was non-constant, varying around the 10 ms value, value which corresponds to the 50Hz frequency. These variations are due to the mechanical oscillations of the rotor caused by the sudden three-phased short-circuit [4-6]. The variation of the period between two consecutive extreme current values (maximum or minimum) is periodic.

II. Data Processing

Is denoted with t_i the time at which a current extreme value occurred (where i is the number of the reading with $i = 0, 1, 2, 3, \ldots, n$ and n is 500 in this case). It is used t_i^* to denote the time value closest to t_i which is a multiple of 10 ms. It is used t_i^* as the horizontal axes in the graphs that plot the rotor position's variations.

Knowing the synchronous generator's rotative speed the time intervals can be converted into rotative speed intervals and then into variations of the angle by which the rotor's axis departs from its centre position [7-9].

Fig. 1 shows the rotor's position during the rotor's oscillations.

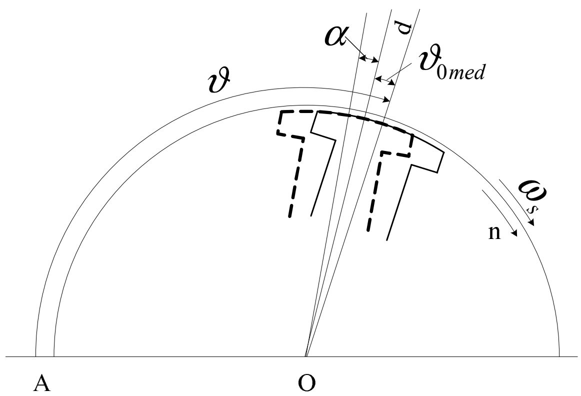

Fig. 1. Rotor is positions during oscillations.

Let α denote the angle by which the rotor's axis wanders from its centre position after a short-circuit occurred [7]. The

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value of the α angle is strictly positive if the interior angle ϑ_0 is greater than ϑ_{0med}, situation that corresponds to the time differences $t_i - t_{i-1}$ being greater than 10 ms and to a breaking course of the rotor [10,11]. This breaking course is caused by the electromagnetic couple between the rotor's source and the magnetic fields of the short-circuit currents.

The value of the α angle is strictly negative if the internal angle ϑ_0 is smaller than ϑ_{0med}, which corresponds to time differences $t_i - t_{i-1}$ less than 10 ms and to an accelerating course of the rotor.

The angle ϑ may vary and can be expressed depending on the average value of the internal angle ϑ_{0med}, on the angular deviation α, and on the synchronous angular frequency $\omega_s = 2 \cdot \pi \cdot f$ using the following equation:

$$\vartheta = \vartheta_{0med} + \alpha + \omega_s \cdot t \quad (1)$$

Because we have that:

$$\frac{d^2\vartheta}{dt^2} = \frac{d^2\alpha}{dt^2} \quad (2)$$

the rotor is motion equation in the immediate time period after the sudden three-phased short-circuit can be expressed as:

$$\frac{J}{p} \cdot \frac{d^2\alpha}{dt^2} = M_m + M_{sc} \quad (3)$$

where J is the rotative moment of the rotative components, p is the synchronous generator's number of pole pairs, M_m is the driving torque of the synchronous spindle motor after the working and the ventilation losses were deducted, since they are considered to be constant, and M_{sc} is the synchronous generator's electromagnetic couple during the short-circuit conditions [7-9].

The magnetic couple M_{sc} can be expressed by:

$$M_{sc} = \frac{p \cdot 3}{\omega_s} \cdot U_{eE}^2 \left[\frac{\sin(\gamma - 2\beta)}{Z_d} + \frac{\sin\beta}{Z_{md}} \right] \quad (4)$$

and

$$\gamma = arctg \frac{R_{md}}{X_{md}} \qquad \beta = arctg \frac{R_d}{X_d} \quad (5)$$

where R_{md}, and X_{md} are the longitudinal resistance and reactance, respectively, R_d, X_d are the synchronous longitudinal resistance and reactance, respectively, and U_{eE} is the polar electromotive force.

Since the constant driving torque of the synchronous spindle motor is constant, there will be free oscillations in the synchronous generator studied in this work. These oscillations can be expressed as:

$$\frac{J}{p} \cdot \frac{d^2\alpha}{dt^2} + k_a \cdot \frac{d\alpha}{dt} + M_s \cdot \alpha = 0 \quad (6)$$

where k_a, given by the relation (7), is a synchronous generator constant and M_s is the pull-in torque:

$$k_a = \frac{2 \cdot M_k}{\omega_s \cdot s_k} \quad (7)$$

In relation (7) M_k, and s_k are the critical couple and the critical glide that occur during the oscillations of the asynchronous working regime of the synchronous generator studied here.

The time variations of the rotor position's angle, α, computed based on the readings of this synchronous generator, are shown in Fig. 2.

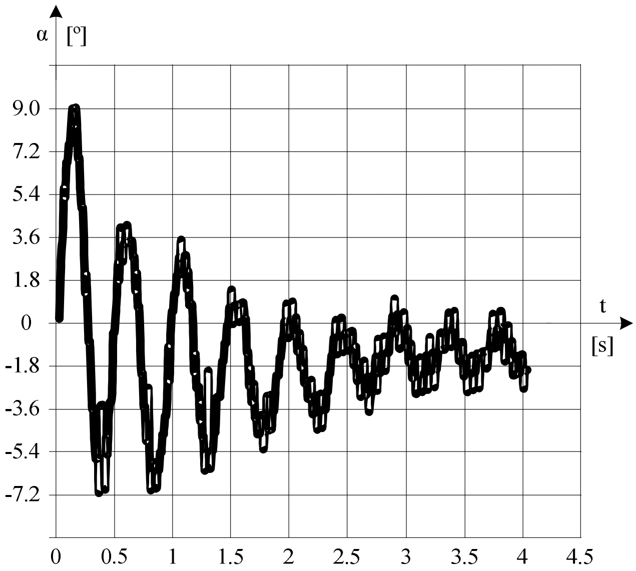

Fig. 2. Variations in time of the rotor position is angle α.

It can be observed immediately that the variation has the following exponential form:

$$\alpha = C \cdot e^{-\frac{t}{T_D}} \cdot \cos(\nu \cdot t + \varphi_0) \quad (8)$$

where C, T_D, ν and φ_0 are constants to be determined.

The initial conditions $t = 0$, $\alpha = 0$ do not provide information on C, T_D, or ν, but we can write:

$$\varphi_0 = (2k+1)\cdot\frac{\pi}{2} \qquad (9)$$

The values for T_D and C can be obtained from the restrictions on the values of the time t, $t = ¼\cdot T_0$ where the deviation α has a positive maximum α_{max}, and $t = ¾\cdot T_0$ when the deviation α has a negative minimum α_{min}, which resulted from the rotor oscillations measurements. T_0 is the rotor's oscillation period value is obtained from the data readings shown in Fig. 2.

When the synchronous generator has no breaking couple (which means that there is no damper winding), the free oscillation frequency, f_0, is [12]:

$$f_0 = \frac{1}{T_0} = \frac{\nu}{2\pi} = \frac{1}{2\pi}\cdot\sqrt{\frac{p\cdot M_s}{J}} \qquad (10)$$

Therefore:

$$\alpha_{\max} = C\cdot e^{-\frac{T_0}{4\cdot T_D}}\cos\left(\nu\cdot\frac{T_0}{4}-\frac{\pi}{2}\right) \qquad (11)$$

$$\alpha_{\min} = C\cdot e^{-\frac{3\cdot T_0}{4\cdot T_D}}\cos\left(\nu\frac{3\cdot T_0}{4}-\frac{\pi}{2}\right) \qquad (12)$$

Using (10) and from equations (11) and (12) we get:

$$\alpha_{\max} = C\cdot e^{-\frac{T_0}{4\cdot T_D}} \qquad (13)$$

$$\alpha_{\min} = -C\cdot e^{-\frac{3\cdot T_0}{4\cdot T_D}} \qquad (14)$$

where α_{min} has actually a negative value.

From equations (11) and (12) we can infer that:

$$\frac{\alpha_{\max}}{\alpha_{\min}} = e^{\frac{T_0}{2\cdot T_D}}\cdot\frac{\cos\left(\nu\cdot\frac{T_0}{4}-\frac{\pi}{2}\right)}{\cos\left(\nu\frac{3\cdot T_0}{4}-\frac{\pi}{2}\right)} \qquad (15)$$

Then, the value for T_D using equation (15) is:

$$T_D = \frac{T_0}{2\cdot\ln\frac{\alpha_{\max}}{\alpha_{\min}} - \ln\left[\frac{\cos\left(\nu\cdot\frac{T_0}{4}-\frac{\pi}{2}\right)}{\cos\left(\nu\cdot\frac{3\cdot T_0}{4}-\frac{\pi}{2}\right)}\right]} \qquad (16)$$

From (10), (13) and (14) it is:

$$T_D = \frac{T_0}{2\cdot\ln\frac{\alpha_{\max}}{-\alpha_{\min}}} \qquad (17)$$

C's value can be read from either formula (11) or (12):

$$C = \alpha_{\max}\cdot e^{\frac{T_0}{4\cdot T_D}}\cdot\frac{1}{\cos\left(\nu\cdot\frac{T_0}{4}-\frac{\pi}{2}\right)} \qquad (18)$$

At the same time, from formulae (10) and (17) get:

$$C = \alpha_{\max}\cdot e^{\frac{T_0}{4\cdot T_D}} = \alpha_{\max}\cdot e^{\frac{1}{2}\ln\frac{\alpha_{\max}}{-\alpha_{\min}}} \qquad (19)$$

Formula (10) gives the generator's pull-in torque M_s:

$$M_s = \frac{4\cdot\beta\cdot J}{p} \qquad (20)$$

that is, if we know the rotational inertia, the number of pole pairs, and the angle ν, we can determine the synchronous generator's pull-in torque.

Since the values for C, T_D, ν and φ_0 are now known, it is immediately possible to write the exponential function that expresses the rotor's oscillations:

$$\alpha = \alpha_{\max}\cdot e^{\frac{1}{2}\ln\frac{\alpha_{\max}}{-\alpha_{\min}}}\cdot e^{-\frac{2\cdot t}{T_0}\cdot\ln\frac{\alpha_{\max}}{-\alpha_{\min}}}\cos\left(\frac{2\pi}{T_0}\cdot t-\frac{\pi}{2}\right) \qquad (21)$$

In formula (21 shows that the α angle variation depends only on α_{max}, α_{min} and T_0 which are given by the rotor's oscillations and can be found by data acquisition of the current values during the sudden short-circuit test.

After the oscillation dampens, the value of the internal angle differs from the value it had before the sudden short-circuit. We denote this angular difference with α_{st}. To obtain a graphical representation of the generated function as similar as possible to the acquisitioned effects and values, we need to apply specific corrections, which lead to the fact that the generated function is written differently, depending on the analysed time interval [12-13]:

- when $t \in [0; T_0]$:

$$\alpha = \alpha_{\max} \cdot e^{\frac{1}{2}\ln\frac{\alpha_{\max}}{-\alpha_{\min}}} \cdot e^{-\frac{2\cdot t}{T_0}\cdot\ln\frac{\alpha_{\max}}{-\alpha_{\min}}} \cos\left(\frac{2\pi}{T_0}\cdot t - \frac{\pi}{2}\right) \quad (22)$$

- when $t \in (T_0; 2\cdot T_0)$:

$$\alpha = \alpha_{\max} \cdot e^{\frac{1}{2}\ln\frac{\alpha_{\max}}{-\alpha_{\min}}} \cdot e^{-\frac{2\cdot t}{T_0}\cdot\ln\frac{\alpha_{\max}}{-\alpha_{\min}}} \cos\left(\frac{2\pi}{T_0}\cdot t - \frac{\pi}{2}\right) - \frac{\alpha_{st}}{2} \quad (23)$$

- when $t \geq 2\cdot T_0$:

$$\alpha = \alpha_{\max} \cdot e^{\frac{1}{2}\ln\frac{\alpha_{\max}}{-\alpha_{\min}}} \cdot e^{-\frac{2\cdot t}{T_0}\cdot\ln\frac{\alpha_{\max}}{-\alpha_{\min}}} \cos\left(\frac{2\pi}{T_0}\cdot t - \frac{\pi}{2}\right) - \alpha_{st} \quad (24)$$

Plugging the numerical values obtained from the readings of the three-phased sudden short-circuit into the theoretical equations (8) is a new method, that by confirming the experimental results, gives further weight to the proposed method.

III. Testing the Proposed Method

To experiment our method we use a 350 kVA synchronous generator, driven by a 300 kW synchronous motor, both engines having the same design. The three-phased generator investigated is being fed at 400 V, with the nominal current of 509 A, 0.85 power factor and 300 rot/min. To read the values of the different variables (voltages and current values) before and after the short-circuits, a VPA 124 data acquisition kit is used. To protect the synchronous generator, the short-circuit voltage was 107 V, that is $0.46 \cdot U_n$ [14]. The peak current point occurred on the phase closest to the *d* axis, and measured 1350 A ($2.65 \cdot I_n$), which is non-hazardous if we considered the short period of time (about 400 ms) during which its value dropped under the 509 A, the nominal current. From the readings on the three phase currents we found that the time interval between two consecutive zero passages varies, which led us to conclude that, during the rated speed, the rotor's position oscillates around the centred rotor position.

Computing the angle variations, we obtained the time variations of the rotor position's angle, α, shown in Fig. 2. From here we find that $T_0 = 0.5\ s$ ($f_0 = 2\ Hz$), $\alpha_{max} = 9.20^o$, $\alpha_{min} = -7.29^o$, $\varphi_0 = \pi/2$, and $\nu = 2\pi f_0 = 4\pi$. Finding that the rotor oscillation frequency is 2 Hz is in concordance with the theoretical works presented in [5].

Using formula (17) gives C = 10.34º, and using formulae (18-19) gives $T_D = 1.073$ s. Again, from Fig. 2, we find the stationary internal angle $\alpha_{st} = 1.1^o$.

It is possible, now, to instantiate relations (22), (23), and (24) as:

- for $t \in [0; 0.5]$ s:

$$\alpha = 10.34 \cdot e^{-t\cdot 0.932} \cos\left(4\pi\cdot t - \frac{\pi}{2}\right) \quad (25)$$

- for $t \in (0.5; 1)$ s:

$$\alpha = 10.34 \cdot e^{-t\cdot 0.932} \cos\left(4\pi\cdot t - \frac{\pi}{2}\right) - 0.55 \quad (26)$$

- for $t \geq 1$ s:

$$\alpha = 10.34 \cdot e^{-t\cdot 0.932} \cos\left(4\pi\cdot t - \frac{\pi}{2}\right) - 1.1 \quad (27)$$

Plotting out the last three equations, (25), (26), and (27), we obtain the graph in Fig. 3, which reproduces the rotor's oscillations in the short-circuited synchronous generator.

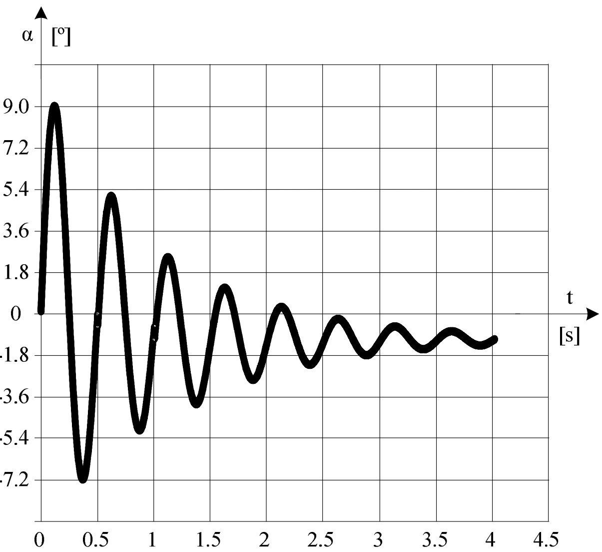

Fig. 3. Time variation of the rotor position angle α using the functions in relations (25), (26), and (27).

It can be easily noticed that the rate of the curve shown by the rotor position angle, α, measured in practical experiments, coincides with the rate of the curve determined theoretically and known from the specific literature. This, in our opinion, gives more weight to the proposed method.

Comparing the plots in Fig. 2 and Fig. 3 similar variations are observed. When the values for C, T_D, ν, φ_0 and α_{st} are correctly found, the function expressed by the last three relations truthfully reproduces the position angle's variation during the rotor mechanical oscillations caused by the sudden three-phased short-circuit.

If the investigated time period is extended to 10 s, the position angle's variation allows us to find the total dampening time of the rotor's mechanical oscillations. Fig. 4 shows that, for this concrete example, the total dampening time is 8.5s. This value is determined by a detailed analysis of the variation pattern [6]. From Fig. 4 we can also read the α_{st} value, which cannot be exactly determined from fig. 3.

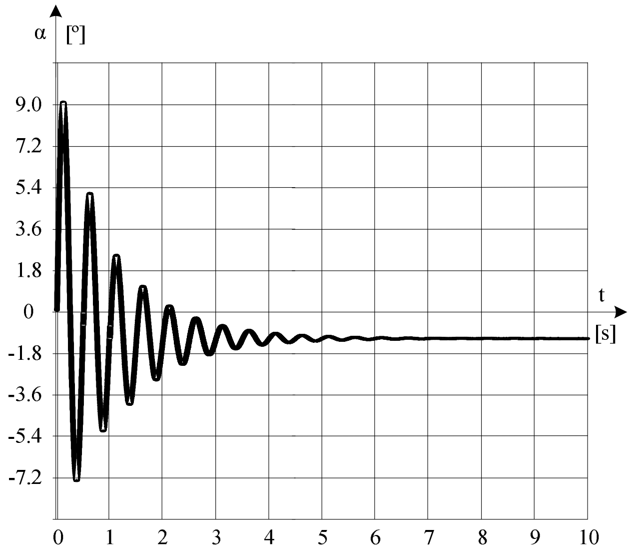

Fig. 4. The time variation of the rotor position angle α up to its stable state.

With the adequate corrections, the method used to compute the values for C, T_D, v, φ_0 and α_{st} can be applied to other non-stationary functioning regimes of the synchronous generator.

Similar oscillations occur when starting an asynchronous engine by connecting it to a synchronous generator through joints, due to its low apparent resistance at the connection time [12,13]. In this case, the rotor's angular speed stabilizes in about 10 s, which is in concordance with the results obtained by our proposed method.

In concrete cases, like the sudden variations in charge, the value of the α_{st} angle can be also found by computations [17-18], which avoids the need of data readings up to the mechanical oscillation's dampening.

In the case of faulty functioning of the synchronous generator, when, again, rotor mechanical oscillations occur, the angle can be computed as well.

IV. CONCLUSION

The method proposed in this work brings several advantages in investigating high-power generators:

1. Data readings under 1 s are non-hazardous and allow detecting mechanical phenomena that may take up to 10 s;

2. The method allows finding the pull-in torque of the synchronous generator when the rotative moment of the rotating parts is known;

3. Knowing the values for C, T_D, v, φ_0 and α_{st} allows us to write the function that describes the mechanical oscillations and their dampening process.

The proposed method can be applied to any synchronous generator, independent of the power or rotation speed, needing only small alterations of the time intervals and the angle α.

With this method it is possible detect rotor oscillations in other functioning regimes of the synchronous generator, as well. Knowing the dampening period of the mechanical oscillations and their amplitude is necessary in the design and manufacture of the frequency control loops, voltage control loops and the field current control loops.

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