Fully automated parameter identification for synchronous machines

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1. Abstract

The article presents a fully automated identification method for the determination of the sub-subtransient, subtransient and transient characteristic parameters of large synchronous machines. The software allows for an identification of the parameters based on the measurements of the terminal currents during a three-phase short-circuit as defined in the international standards. Based on the identified parameters the equivalent circuit diagram (ecd) is established and it can be used as model of the synchronous machine for numerical simulations to be performed later.

The proposed way of proceeding proved to be reliable. The advantages of the suggested method lie in the inherent time saving, the higher accuracy and consequently in the consistency and reproducibility of the results.

2. Introduction

Performance tests are generally required for new developed hydro and turbogenerators. These tests include the sudden short-circuit test, which is carried out for the determination of the reactances and time constants of the machine. While these tests can be realized in the workshop for turbo- and small hydrogenerators, they have to be done on site for large hydrogenerators. For this purpose the recorded stator currents are analyzed based on a well-known process described in international standards [1].

The conventional way of identifying the transient parameters consists in representing the currents in a linear-logarithmic plot. Based on this representation the time constants and reactances can be identified manually. Proceeding this way has some major practical inconveniences. The manual elaboration is very time consuming and afflicted by inaccuracy all the more if the generator being tested has small sub-transient time constants.

3. Identification method

Synchronous machine theory allows for accurate predictions of the phase currents during a sudden three-phase short-circuit. The analytical description of the current in "phase a" is presented in expression (1). The expression is valid for a synchronous machine having two current circuits on the rotor, i.e. the currents in the damper winding and the current in the excitation winding .

$$i_a(t) = -\left\{ \frac{u_0}{x_d} + \left(\frac{u_0}{x_d^{'}} - \frac{u_0}{x_d} \right) \exp\left(\frac{-t}{T_d^{'}} \right) + \left(\frac{u_0}{x_d^{''}} - \frac{u_0}{x_d^{'}} \right) \exp\left(\frac{-t}{T_d^{''}} \right) \right\} . \cos(\omega t + \theta_0)$$

$$+ \frac{u_0}{x_2} \exp\left(\frac{-t}{T_a} \right) \cos(\theta_0) + \frac{u_0}{x_n} \exp\left(\frac{-t}{T_a} \right) . \cos(2.\omega t + \theta_0) \qquad (1)$$

Where:

u_0 : Terminal phase voltage immediately before the short-circuit

θ_0 : Rotor position in respect to the stator phase immediately before the short-circuit

x_d : d-axis synchronous reactance

x_d' : d-axis transient reactance

x_d'' : d-axis subtransient reactance

T_d' : d-axis transient short-circuit time constant

x_q'' : q-axis subtransient reactance

T_d'' : d-axis subtransient short-circuit time constant

T_a : Armature short-circuit time constant

$$x_2 = \frac{2.x_d''.x_q''}{x_d'' + x_q''} : \text{Negative sequence reactance} \qquad x_n = \frac{2.x_d''.x_q''}{x_d'' - x_q''}$$

The currents in the phase b and c can be derived from expression (1) by replacing θ_0 by $\theta_0 - 2.\pi/3$ respectively by $\theta_0 + 2.\pi/3$.

The machines addressed in this publication are large synchronous machines having a complete damper winding. For such machines it can be stated that $x_d'' \approx x_q''$, consequently the last term in expression (1) can be neglected.

According to the international standards, the conventional way to determine the transient parameters of the machine, consists in depicting the envelope of one of the phase currents as defined in expression (2) and represented in Fig. 1.

$$i_a \updownarrow = 2 * \left\{ \frac{u_0}{x_d} + \left(\frac{u_0}{x_d'} - \frac{u_0}{x_d} \right) \exp\left(\frac{-t}{T_d'} \right) + \left(\frac{u_0}{x_d''} - \frac{u_0}{x_d'} \right) \exp\left(\frac{-t}{T_d''} \right) \right\} \qquad (2)$$
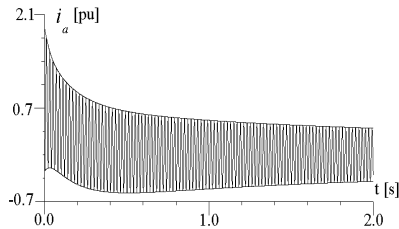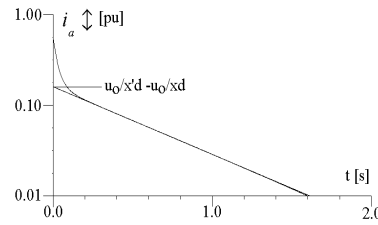

Fig. 1: Stator current phase a
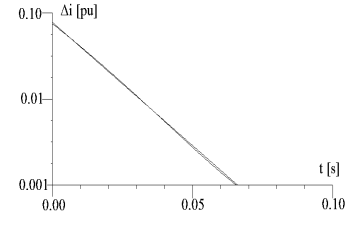

Fig. 2: Transient envelope

Fig. 3: Subtransient envelope

Then the envelope is represented in a linear-logarithmic scale as shown in Fig. 2. Finally it is possible to identify the different parameters by measuring the slop of the lines and the intersection of their extrapolation with the ordinate as indicated in Fig. 2 and 3.

The described classical approach presents some practical inconveniences such as the manual elaboration of the envelope and the unsatisfying accuracy of the extrapolation and determination of the slop and intersection. The explained manipulations are even more delicate to accomplish if the considered synchronous machine features three current circuits on the rotor such as hydrogenerators with solid poles or turbogenerators. Due to the manual procedure with its inherent limited accuracy, the results depend on the person carrying out the measurements, which is hard to acceptable from a scientific point of view.

The suggested method using dedicated software allows for a more accurate procedure. Furthermore the new procedure can be carried out directly after measuring the currents without further time delay, giving the commissioning engineer the assurance that the measurements were carried out in a correct way.

4. Principle scheme of the automated identification method

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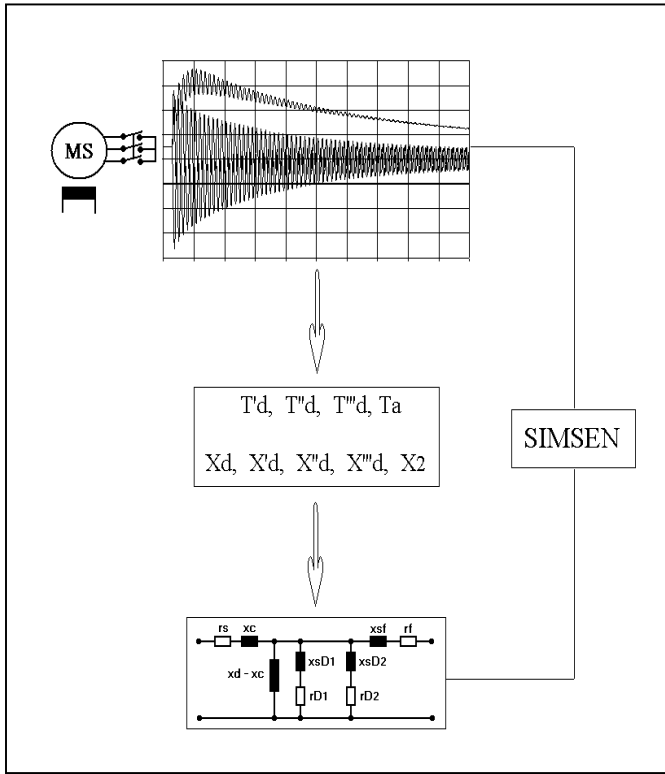
The basic procedure is laid out in Fig. 4 and will be explained in the following.

Based on the measured phase and excitation currents during the three-phase short-circuit test, the software identifies the characteristic reactances and time constants of the machine and determines the corresponding equivalent circuit diagram based on the theory described in [2] and [3]. The equivalent circuit diagram is than transferred to a simulation program (in that case we use a simulation package SIMSEN ® developed at the EPFL, for more information one can refer to: http://simsen.epfl.ch) and a numerical simulation of the same three-phase short-circuit test is performed. The results of this numerical simulation must be the same as those measured during the real test .

Fig. 4 : Basic procedure

Theoretically all parameters in expression (1) could be identified using an approach based on the least square method as long as the speed of the machine is constant. In reality, due to the torque occurring during the test, the speed and therefore the electrical pulsation ω are not constant. Consequently a least square method is not appropriate.

An other possibility would be to transfer the measured currents into a d-q coordinate system using the Park transformation . This approach would lead to incorrect results for the same reason as the previous one.
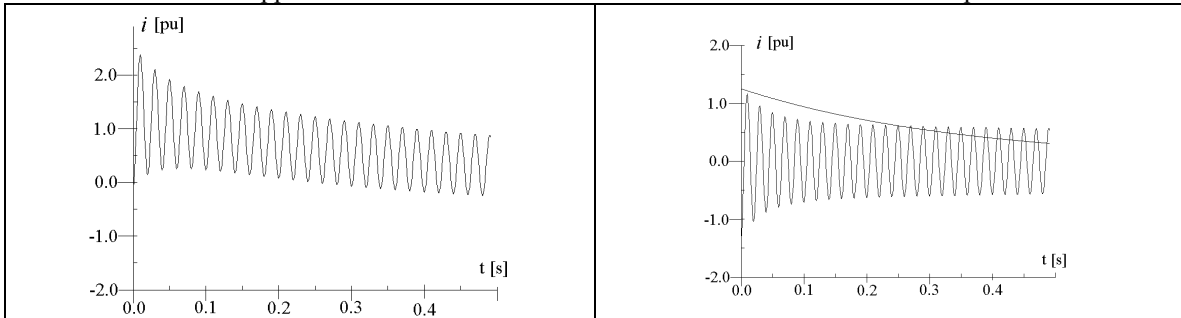

Fig. 5: Stator current before and after filtering of the non-periodic component

For the mentioned reason we have to fall back on the conventional method for the first stage of the identification method, which consist in determining the envelope of the phase current. The determination of the envelope is made in two steps in order to achieve a better accuracy. In a first step the non-periodic component of each phase current is separated from the alternative component using numerical filters as shown in Fig. 5.

The second step consists in identifying the envelope of the filtered currents. After filtering, and neglecting the first term in expression (1) at the double of the electrical frequency, all three currents have the same envelope as represented in Fig. 6.

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Once the envelope of the currents $i_a \updownarrow$ was identified a least square approach is used to determine the transient parameters of expression (2). More precisely the method is applied separately to the two different time intervals:

subtransient time interval from 0 to 100 ms

transient time interval from 200 to 2000 ms

First the transient parameters are identified using the envelope in the transient time interval. Then the sub-subtransient and the subtransient parameters are identified using the envelope in the corresponding time intervals and the already determined transient parameters
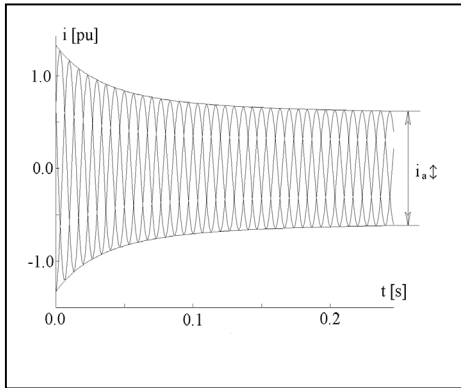

Fig. 6: Envelope of the 3 currents

The identification in different time intervals is necessary in order to give an equivalent importance to all the parameters considering that the sub-subtransient and the subtransient time constants are much smaller than the transient time constant and considering the exponential variation of the stator currents

After the described operations the parameters $x_d, x_d', x_d'', T_d', T_d''$ are identified for a synchronous machine with two current circuits on the rotor. For machine having three circuits on the rotor x_d''', T_d''' are identified in addition at this stage.

The missing parameters x_2, T_a can be identified using the non-periodic components of the phase currents.

The characteristic parameters in the quadrature-axis can either be obtained by other tests or from the electrical layout of the machine [4].
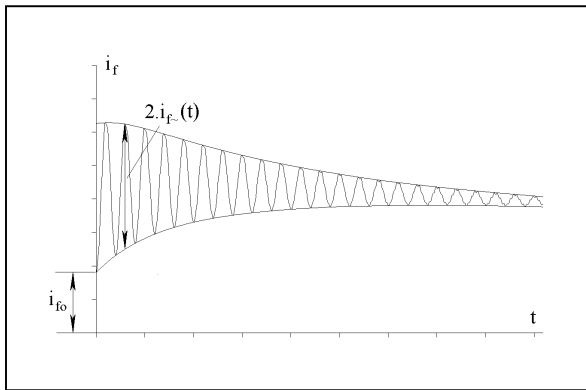

Fig. 7: Field current

Finally the transfer from the characteristic parameters to the elements of the equivalent circuit diagram can be done using the method suggested by Canay [2], [3]. For this purpose the ratio between the oscillating component of the excitation current at the beginning of the short-circuit and the dc value of the same current before the short-circuit has to be known $\frac{i_{f\sim}(0)}{i_{f0}}$. Both values are represented in Fig. 7

5. Application examples

The suggested method was successfully tested on a few machines including large hydrogenerators as well as turbogenerators. The process proved to be reliable and the inherent time saving was well appreciated by our commissioning engineers. In the following two representative examples will be discussed.

The first example is a hydrogenerator with a rated power of 32.6 MVA and a rated voltage of 10.5 kV (laminated poles with complete damper winding). The following characteristic quantities were identified using the presented approach, afterwards Canay's method led to the following values for the elements of the equivalent diagram in the direct-axis.

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xd	= 1.0	[pu]		xc	= 0.137524	[pu]
x'd	= 0.3996	[pu]		xd-xc	= 0.862476	[pu]
x''d	= 0.2778	[pu]		xsf	= 0.38267	[pu]
T'd	= 1.3402	[s]		rf	= 0.0011928	[pu]
T''d	= 0.03498	[s]		xsD1	= 0.29808	[pu]
Ta	= 0.16065	[s]		rD1	= 0.035297	[pu]
x_2	=.xxxxxx	[s]		rs	= 0.005577	[pu]
Characteristic quantities			Fig. 8 : Equivalent circuit	Equivalent circuit elements		

Fig. 9 shows a comparison between the amplitude of the phasor of the measured phase current and the same value derived from the simulation results based on the presented equivalent circuit diagram.

Fig. 9:Measured and simulated phasor current
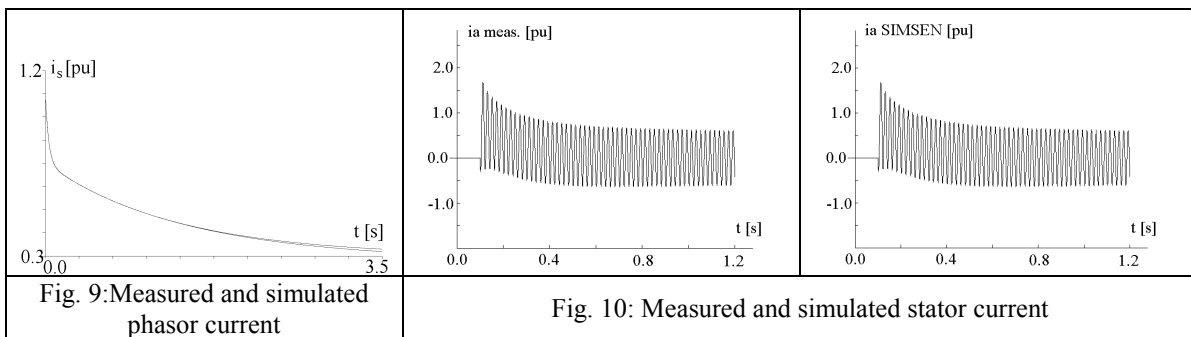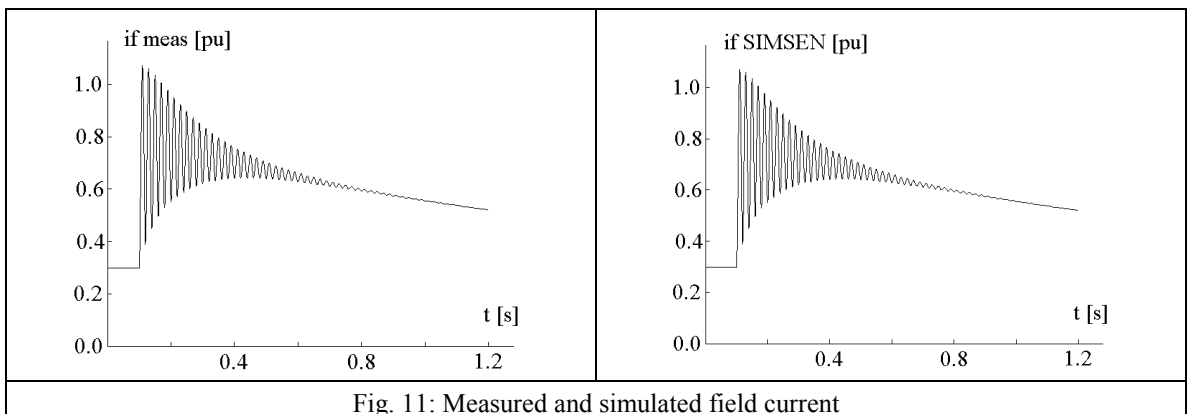
Fig. 10: Measured and simulated stator current

Fig. 10 shows a comparison between the measured and simulated phase current. Finally the measured and simulated excitation currents are compared in Fig. 11.

Fig. 11: Measured and simulated field current

The second example is a 190 MVA turbogenerator with a rated voltage of 13 kV. The following characteristic quantities were identified:
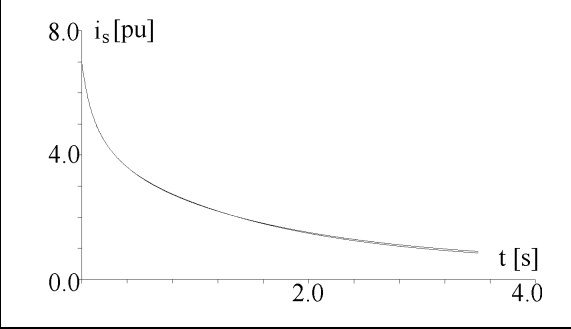
xd	=	2.09	[pu]		
x'd	=	0.23119	[pu]		
x''d	=	0.16242	[pu]		
x'''d	=	0.142836	[pu]		
T'd	=	1.48492	[s]		
T''d	=	0.178334	[s]		
T'''d	=	0.052755	[s]		
Ta	=	0.46732	[s]		
Characteristic quantities			Fig. 12: Phasor current, comparison measurement-backwards simulation..		

Fig. 12 shows a comparison between the amplitude of the phasor of the measured phase current and the same value derived from the simulation results.

6. CONCLUSIONS

The suggested automated approach presents considerable advantages compared to the conventional manually carried out procedure of parameter identification. Namely the advantages lie in the inherent time saving, the higher accuracy and consequently in the consistency and reproducibility of the results. The method was successfully tested on a few machines. Representatively the results of a large hydrogenerator and a turbogenerator were presented. The identified parameters were used to build a simulation model of the generators. Three-phase short-circuit under identical conditions were carried out and the simulated currents were compared to the measured ones. For both examples the measured and simulated values show a perfect match confirming the reliability of the method. Because of the mentioned advantages and the good results ASTOM intends to apply the suggested method more systematically in future generator performance tests.

7. REFERENCES

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