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Application of the stationary DC decay test to industrial turbogenerator model parameter estimation

***Abstract**. In the paper there is presented measurement-based model parameter estimation in both d and q axis of a synchronous generator. The tests were carried out while the machine was at standstill. This is an interesting measurement method, especially when other tests are difficult to be performed. Optimisation of the appropriately formulated objective function was used for determining the considered model parameters. Matlab-Simulink package was used for computations.*

***Streszczenie.** W artykule przedstawiono wyniki pomiarowej estymacji parametrów w osi d i q modelu generatora. Testy pomiarowe przeprowadzono dla generatora znajdującego się na postoju. Jest to interesująca metoda pomiarowo-obliczeniowa, szczególnie kiedy inne testy są trudne lub niemożliwe do przeprowadzenia. Wyznaczenie parametrów zrealizowano w drodze optymalizacji odpowiednio sformułowanej funkcji celu. Do obliczeń wykorzystano pakiet Matlab-Simulink. (**Zastosowanie testu zaniku prądu stałego do estymacji parametrów modelu turbogeneratora przemysłowego**).*

Keywords: synchronous generator, mathematical models, parameter estimation, transient states.
Słowa kluczowe: generator synchroniczny, modele matematyczne, estymacja parametrów, stany nieustalone.

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Introduction

Estimation of synchronous generator electromagnetic parameters based on the dynamic waveforms of selected quantities recorded in a generating unit requires introducing an appropriate disturbance to the generating unit steady state [1, 2]. In industrial generating units installed e.g. in a coal-mine or a power plant the maintenance of regulation and control systems is simplified and maximally automated. It means that practical application of the test disturbances such as step changes in the voltage regulator reference voltage, power rejection tests and introduction of additional test signals e.g. pseudorandom signals PRBS described in literature [3, 4, 5] is considerably difficult. In such cases the methods realized based on measurements taken at machine standstill are an interesting alternative for needs of measurement-based estimation of synchronous generator electromagnetic parameters.

In the paper there are presented the methodology and the measurement results of electromagnetic parameter estimation of selected mathematical models of a synchronous generator with use of the stationary DC decay test [6, 7].

Investigations

Investigations were performed in two stages.

In the first stage test were carried out on a specially constructed laboratory stand equipped with a synchronous generator of the rated power P_n = 44 kW and the rated armature voltage U_n = 400 V.

The presented generator parameters had been determined before based on the measured transient waveforms at the rotating rotor. The obtained and presented in [5] results were the basis for verification of the correctness of the results obtained based on the waveforms recorded during the tests performed at machine standstill.

In the second stage the investigations were performed in Mikołaj Thermo Power Plant in which there was installed a synchronous generator of the ratings: S_n = 7.5 MVA, U_n = 6.3 kV and $\cos\varphi_n$ = 0.8.

Imitating the measurement conditions characteristic for industrial generating units e.g. for the investigated turbogenerator installed in the heat and power plant, it was assumed in the laboratory tests that the realization of the test disturbances (described in literature [2, 3, 5] and mentioned in the introduction) in the considered generating unit is difficult or even impossible. These limitations result from, among others, automation of the generating unit operation, presence of the closed and inaccessible (from the point of view of non-standard control) static excitation system or even lack of a generator breaker switch (generator together with the line disconnected in a distant station).

Because of the existing limitations, electromagnetic parameter estimation of the synchronous generator was realized based on the measurements taken at machine standstill. There was chosen the method based on recording the dynamic waveforms during the DC current decay in the armature winding at the motionless rotor [7]. The schematic diagram of the measuring system is shown in Fig. 1.

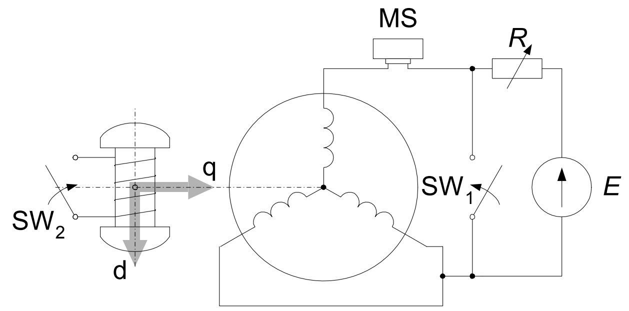


Fig.1. Schematic diagram of the measuring system for recording dynamic waveforms during current decay in the armaturę winding

In this system the windings of two armature phases were short-circuited. Such a series-parallel circuit was supplied from a DC voltage source. A variable resistor R connected in series with a voltage source E was used for regulation of the DC current flowing through connected armature windings. The regulation was recorded in a measuring system MS.

The closing of the switch SW_1 resulted in cutting off the current flow from the voltage source to the open- and short-circuited armature windings (switch SW_2) and the decaying current in the windings was recorded.

The induction method was used for determining the position of the rotor d and q axis. To do it, the connected armature windings of the generator were supplied by AC current and there were determined the positions for which the highest and lowest value of the voltage induced at the open terminals of the field magnet (maximum for d axis and minimum for q axis) was observed.

Fig. 2 shows the photo of the test stand in Mikołaj Power Plant located in the turbogenerator excitation room.

Fig.2. Test stand for measurement of current decay in the generator armature winding located in the excitation room of Mikołaj Power Plant

R-L and X-T generator mathematical model

There were considered the mathematical models of synchronous generators expressed by resistances and inductances of the generator electric circuits (model R-L of type 2,2) as well as the models expressed by standard reactances and time constants of steady, transient and subtransient state (model of type X-T).

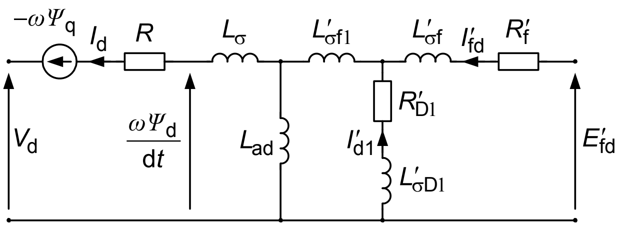


Fig. 3. Equivalent circuit in d axis of the synchronous generator expressed by resistances and inductances of electric circuits

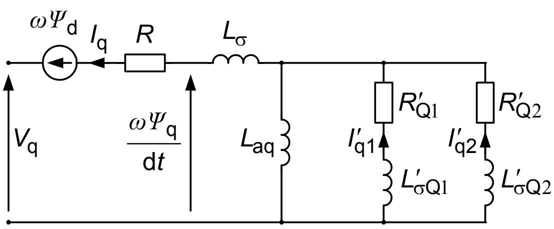


Fig. 4. Equivalent circuit in q axis of the synchronous generator expressed by resistances and inductances of electric circuits

Figs. 3 and 4 present the equivalent circuits of the synchronous machine in the direct and quadrature axis (circuit model). The voltage and flux linkage equations in the two-axis coordinate system corresponding to these circuits can be found in [8, 9].

The diagrams and equations for the model expressed by standard parameters can be found in [3, 10].

Parameter estimation results

Calculations of electromagnetic parameters of selected mathematical models of the synchronous generator were carried out based on the recorded dynamic waveforms of the armature current decay. Figure 5 shows the block diagram of the estimation process

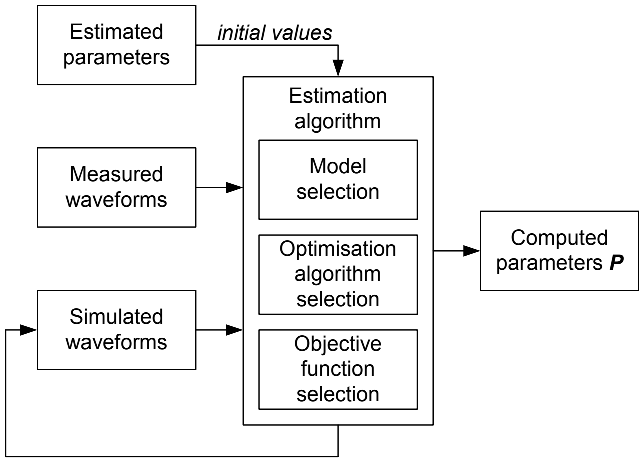


Fig.5. Estimation procedure lay out

The optimized objective functions for the parameters estimated in d and q axis have the form, respectively:

$$\varepsilon_d\left(\boldsymbol{P}\right) = \sum_{k=1}^{n}\left(I_{dmk} - I_{dak}\left(\boldsymbol{P}\right)\right)^2, \quad (1)$$

$$\varepsilon_q\left(\boldsymbol{P}\right) = \sum_{k=1}^{n}\left(I_{qmk} - I_{qak}\left(\boldsymbol{P}\right)\right)^2. \quad (2)$$

Each time in the functions there were taken into account the approximated waveforms (measured – index m) and the approximating waveforms (index a) obtained based on the model expressed by the searched parameters $\boldsymbol{P}$ of the current decaying in the connected armature windings.

Table 1. Parameter estimation results in d axis of the R-L type 2,2 model of the synchronous generator installed in the laboratory

Parameters of R-L type 2,2 synchronous generator model in d axis				
		value	lower bound	upper bound
R_{D1}	[p.u.]	0.0155	0.0100	0.0170
$L_{\sigma D1}$	[p.u.]	0.7118	0.6000	0.7800
R_f	[p.u.]	0.0059	0.0050	0.0065
$L_{\sigma f}$	[p.u.]	0.1548	0.1300	0.1700
L_{ad}	[p.u.]	1.5297	1.3700	1.6800
Non-estimated parameters (measured in steady state)				
R	[p.u.]	0.0160		
L_σ	[p.u.]	0.0970		

Table 2. Parameter estimation results in q axis of the R-L type 2,2 model of the synchronous generator installed in the laboratory

Parameters of R-L type 2,2 synchronous generator model in q axis				
		value	lower bound	upper bound
R_{Q1}	[p.u.]	0.1444	0.1300	0.1500
$L_{\sigma Q1}$	[p.u.]	1.5120	1.3600	1.6600
R_{Q2}	[p.u.]	2.5668	2.3100	2.8200
$L_{\sigma Q2}$	[p.u.]	2.1432	1.9200	2.3500
L_{aq}	[p.u.]	0.7560	0.6800	0.8300

The exemplary dynamic waveforms of the armature decay current (approximated signal and the final approximating waveform) obtained on the laboratory test stand are shown in the following figures: Fig. 6a at the short-circuited field magnet winding located along the armature flow and Fig. 6b at the open field magnet winding located crosswise the armature flow. In Tabs. 1 and 2 there are listed the obtained results of parameter estimation in d and q axis of the chosen circuit model of the synchronous generator.

a)

b)

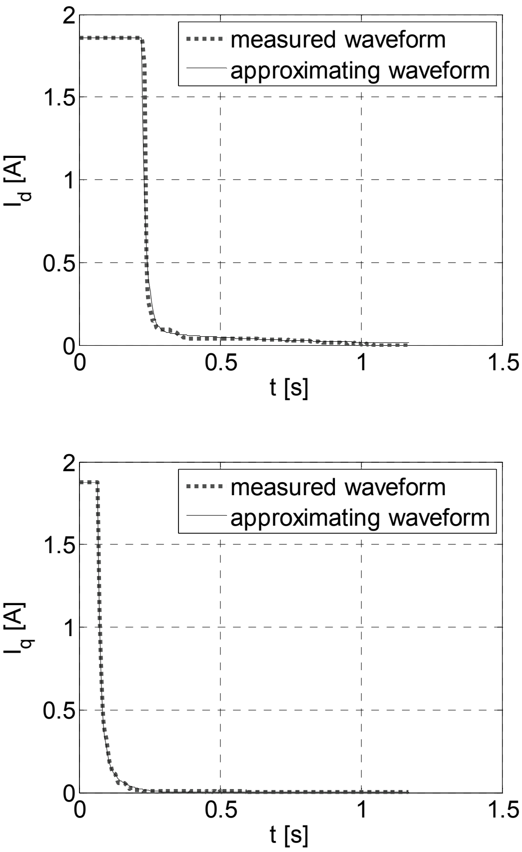


Fig.6. Dynamic waveforms of the armaturę decay current of the generator installed in the laboratory (approximated signal and the final approximating waveform): at short-circuited field magnet winding located along the armature flow – d axis (a) and open field magnet winding located crosswise the armature flow – q axis (b)

Tab. 3 presents the results obtained before for the circuit model which were converted into standard parameters. They are given to enable comparison with the values obtained from calculations for the model XT and those based on the measurements of transient states at rotating rotor [5].

Table 3. Parameter estimation results in both axes of the (X-T) model of the synchronous generator installed in the laboratory

Parameters of (X-T) synchronous generator model				
		R-L type 22 converted into XT	calculated at motionless rotor (XT)	calculated at rotating rotor (XT)
X_d	[p.u.]	1.6297	1.6766	1.6250
X'_d	[p.u.]	0.2406	0.2379	0.2600
X''_d	[p.u.]	0.2174	0.2161	0.2300
T'_{d0}	[s]	0.9137	0.9381	0.9410
T''_{d0}	[s]	0.1755	0.1845	0.1732
X_q	[p.u.]	0.8560	0.9280	0.8200
X'_q	[p.u.]	0.6040	0.6520	0.5800
X''_q	[p.u.]	0.5924	0.6366	0.5700
T'_{q0}	[s]	0.0500	0.0500	0.0500
T''_{q0}	[s]	0.0027	0.0022	0.0027
Non-estimated parameters (measured in steady state)				
R	[p.u.]	0.0160		
X_σ	[p.u.]	0.0970		

The obtained consistence of the parameter estimation results for the waveforms of the recorded transient states at the motionless and rotating machine rotor was the basis of measurements for an industrial turbogenerator.

The exemplary dynamic waveforms of the armature decay current (approximated signal and the final approximating waveform) obtained for the generator installed in Mikołaj Heat and Power Plant are shown in Figs. 7a and 7b. The obtained results of parameter estimation in d and q axis of the chosen models of the synchronous generator are given in Tabs. 4, 5 and 6.

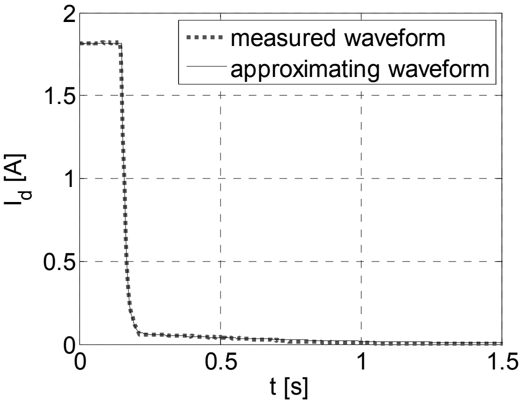
Table 4. Parameter estimation results in d axis of the R-L type 2,2 model of the synchronous generator installed in Mikołaj Heat and Power Plant

Parameters of R-L type 2,2 synchronous generator model in d axis				
		value	lower bound	upper bound
R_{D1}	[p.u.]	0.0100	0.0048	0.0143
$L_{\sigma D1}$	[p.u.]	0.0234	0.0148	0.0445
R_f	[p.u.]	0.0012	0.0005	0.0014
$L_{\sigma f}$	[p.u.]	0.0500	0.0297	0.0890
L_{ad}	[p.u.]	1.6625	0.8752	2.6256
Non-estimated parameters (measured in steady state)				
R	[p.u.]	0.0220		
L_σ	[p.u.]	0.1000		

Table 5. Parameter estimation results in d axis of the R-L type 2,2 model of the synchronous generator installed in Mikołaj Heat and Power Plant

Parameters of R-L type 2,2 synchronous generator model in q axis				
		value	lower bound	upper bound
R_{Q1}	[p.u.]	0.1986	0.0679	0.2037
$L_{\sigma Q1}$	[p.u.]	0.6768	0.6675	2.0026
R_{Q2}	[p.u.]	2.2622	0.7958	2.3873
$L_{\sigma Q2}$	[p.u.]	1.0576	0.9998	2.9994
L_{aq}	[p.u.]	1.1988	0.4005	1.2015

a)



b)

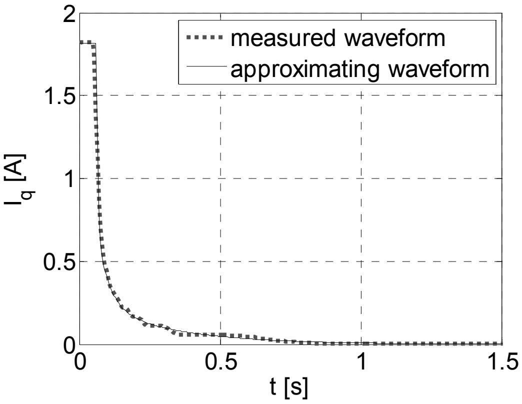


Fig.7. Dynamic waveforms of the armaturę decay current of the turbogenerator installed in Mikołaj Heat and Power Plant (approximated signal and the final approximating waveform): at short-circuited field magnet winding located along the armature flow – d axis (a) and open field magnet winding located crosswise the armature flow – q axis (b)

Table 6. Parameter estimation results in both axes of the (X-T) model of the synchronous generator installed in Mikołaj Heat and Power Plant

Parameters of (X-T) synchronous generator model				
		value	lower bound	upper bound
X_d	[p.u.]	1.7625	0.9250	2.7750
X'_d	[p.u.]	0.1485	0.0800	0.2400
X''_d	[p.u.]	0.1158	0.0600	0.1800
T'_{d0}	[s]	4.5383	3.0000	9.0000
T''_{d0}	[s]	0.0228	0.0150	0.0450
X_q	[p.u.]	1.2988	0.4500	1.3500
X'_q	[p.u.]	0.5326	0.3000	0.9000
X''_q	[p.u.]	0.4070	0.2500	0.7500
T'_{q0}	[s]	0.0301	0.0250	0.0750
T''_{q0}	[s]	0.0021	0.0025	0.0075
Non-estimated parameters (measured in steady state)				
R	[p.u.]	0.0220		
X_σ	[p.u.]	0.1000		

Conclusions

From the calculations carried out in the laboratory and, next those for the generator installed in the heat and power plant (representing real industrial generating units) it follows that the chosen method of the armature current decay is an interesting alternative to the methods based on measurements during machine operation. It is confirmed by the consistence of the obtained estimation results at the motionless and rotating machine rotor.

In a practical application on a generating unit the presented method requires making a small number of switchings and recording only one measurement signal. Additionally, for the considered turbogenerator installed in Mikołaj Heat and Power Plant and equipped with an "impenetrable" (from the point of view of the service staff) control system the described method was the only one accepted by the staff.

If application of other methods, especially those connected with introducing test disturbances to the steady state operation of a turbine set, is possible, the presented method is a good tool for complementing and verifying the obtained results.

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