Krzysztof DOBRZYŃSKI

Gdańsk University of Technology
ORCID: 0000-0003-4217-0123

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Estimation of Synchronous Generator and AVR Parameters Based on Gradient and Genetic Methods

***Abstract**. The author present a method for the estimation of selected synchronous generator model and AVR parameters using a gradient and a genetic algorithm. The paper shows an example of model parameter estimation for a turbogenerator, based on the generator voltage time responses obtained during an active and reactive power rejection test.*

Streszczenie.** Autor przedstawia metodę estymacji wybranego modelu generatora synchronicznego i parametrów AVR z wykorzystaniem algorytmu gradientowego i genetycznego. W artykule przedstawiono przykład estymacji parametrów modelu turbogeneratora w oparciu o odpowiedzi napięciowe generatora uzyskane podczas testu zrzutu mocy czynnej i biernej.* (Estymacja parametrów generatora synchronicznego i AVR w oparciu o metody gradientowe i genetyczne***)

Keywords: estimation, gradient method, genetic method, synchronous generator model.
Słowa kluczowe: estymacja, metoda gradientowa, metoda genetyczna, model generatora synchronicznego.

Introduction

Power system performance after a disturbance is analysed on a system model in dedicated computational software. The quality of the results is determined by model accuracy and correct values of model parameters. The model parameter values may be obtained in various ways. Some selected parameters can be determined analytically [1]-[3], but the primary way for the other parameters is to obtain their values from the manufacturer. It can be difficult on the one hand, and on the other hand – if a simplified model is adopted – not possible for each model parameter. Sometimes also parameter values change during the object's lifetime as a result of modernisation (equipment) or changes in some settings (control systems). In this situation, a good way to obtain selected parameters is their estimation based on comparison of respective signals obtained from the actual object and the model. This paper presents the estimation of selected parameters of the dynamic model of a synchronous generator, which employs the gradient and the genetic methods in the estimation process. The process of parameter values estimation is carried out in developed application, that uses DIgSILENT PowerFactory® software as a computational engine for the power system time-domain simulations.

The developed tool combines the advantages of the PowerFactory power system modelling environment as a computing platform that produces simulation waveforms for any power unit, and the features of an external MS Windows application, giving freedom of programming. Such extensive software functionality would not be possible in only one of the environments. The PowerFactory programming language, DPL, is too poor to create complex applications. It lacks the capability of interweaving graphics, features convenient for users (drop-down lists, check-boxes, etc.), and advanced mathematical functions. On the other hand, the development of a professional simulation computer program, as advanced as PowerFactory is a very complex task. Proper representation of the actual power system performance is strongly linked to the proper identification of parameters included in the system model. The presented application enables convenient and efficient development and verification of power unit mathematical models.

Proposed estimation procedure

Parameter estimation of a mathematical model based on a real object response, i.e. system dynamics identification, is performed by comparing responses of the actual object and of the model for the parameters of which are subject to the estimation. In this process, the estimated parameters are automatically adopted so that the model response is as close to the actual object response as possible. A measure of the difference between the model and object responses is a scalar function. Quite commonly used function is the sum of squared distances between the model and object responses:

(1) $$F(\mathbf{X}) = \sum_{t=T_{\text{start}}}^{t=T_{\text{stop}}} \left(y_{\text{m}}(t) - y_{\text{o}}(t) \right)^2$$

where: F(**X**) – scalar function, **X** = {p_1, p_2, …, p_K} – estimated parameters vector; $y_m(t)$, $y_o(t)$ – model (m index) and object (o index) responses at time t, T_{start} – start time from which the function is calculated $F(\mathbf{X})$, T_{stop} – end time, until which the function is calculated $F(\mathbf{X})$.

The process of parameter estimation of model **X** for specific function $F(\mathbf{X})$ consists in minimizing it. This may be done using local or global extremum search algorithms [4]-[7]. The first group are gradient algorithms. These algorithms are characterised by relatively high speed. Their main limitation is their solution's dependence on the starting point. The other group may include Monte Carlo algorithms and genetic algorithms. Their advantage is the ability to search the full space spanned on estimated parameters vector X. Their disadvantage is the inability – or at least very limited ability – to precisely locate the F(X) function extremum.

Since the first and the second type of the optimization algorithms are not devoid of disadvantages, but at the same time, they offer some advantages, and in some way they are complementary, they can be used together. The Monte Carlo or genetic algorithm can be used to indicate the area in which the global optimum is located, while the gradient algorithm can be used for precise location of the optimum point.

Therefore, in the proposed software, it is anticipated implementation of two algorithms, i.e. gradient algorithm and genetic algorithm.

For quality of the parameters estimation process (algorithm) assess objective function $F(\mathbf{X})$ (1) and function:

(2) $$\hat{F}(\mathbf{X}) = e^{-0.1F(\mathbf{X})}$$

were considered. Function $\hat{F}(\mathbf{X})$ is used here also, because of its features, and usefulness for the genetic algorithm. This function tends to unity, when the model and the real object responses match is increasing (function $F(\mathbf{X})$ tends to zero). It may therefore be regarded as a relative model fit to the real object. The value of this function equal to unity means that the two responses - the real object and the model - are the same, i.e. $F(\mathbf{X}) = 0$.

Model parameters can be estimated in two ways: by simultaneous estimation of several parameters, or just one parameter. The later approach is adopted if certain information of the values of some (other) parameters is available, and if some parameters are relatively well identified, but the (searched for) parameter has a decisive impact on the analyzed response.

The algorithm ability to correctly estimate the parameter depends on the number of estimated parameters, the process estimation defining attributes, and on the nature of the test, the response from which is used in the object dynamics identification process.

Guidelines for turbogenerator parameters estimation procedure

The presented generator parameter identification method requires performing of two tests on the generator. Both tests require tripping the generator from the power system and they differ from each other by the generator load before the tripping:

- Test 1 – generator active power should be close to zero, while the reactive power (absorbed or generated) at 10–30% of the rated apparent power
- Test 2 – generator active power should be at 10–30% of the rated apparent power, and reactive power should be close to zero.

Depending of the test, the generator's respective parameters are estimated:

- Test 1 – estimation of parameters of d-axis is possible: X_{d}, X_{d}, X''_{d}, T'_{d0}, T''_{d0}
- Test 2 – estimation of constant inertia H and parameters of q-axis is possible: X_{q} , X'_{q} , X''_{q} , T'_{q0}, T''_{q0}.

The parameters should be estimated in three steps, where the sequence of steps is relevant for the results' correctness.

Step 1

In step 1 the model parameters should be adopted, which are available from the unit manufacturer. These parameters include, inter alia: rated power S_{gr}, rated voltage V_{gr}, rated power factor $\cos\varphi r$, stator resistance R_{str}, stator leakage reactance X_{l}. If the data are not available from the manufacturer, for typical units they could be adopted from relevant literature references.

Step 2

In step 2 the generator model parameters of d-axis are estimated. In theory, all searched for parameters should be estimated at the same time, using waveforms obtained from reactive power load rejection test (Test 1).

For results comparison, used here should be the voltage waveform at the generator terminals, recorded as response to the generator circuit breaker opening.

The proposed gradient estimation method has difficulty with the determination of subtransient reactance X''_d and subtransient time constant T''_{d0}. Thus, firstly, before the estimation process starts, the subtransient reactance should be determined from the following formulas [8]:

(3)
$$X''_{\mathrm{d}} = \frac{\Delta V''}{I}$$

(4)
$$I = \frac{\sqrt{\left(\frac{P_{\mathrm{g}}}{S_{\mathrm{gr}}}\right)^2 + \left(\frac{Q_{\mathrm{g}}}{S_{\mathrm{gr}}}\right)^2}}{V_{\mathrm{g}}}$$

where: $\Delta V''$ – voltage step change after generator tripping, P_{g} – generator active power before tripping (should be close to zero), Q_{g} – generator reactive power before tripping, V_{g} – voltage at generator terminals before tripping, S_{gr} – generator rated apparent power.

The value of subtransient time constant T''_{d0} should be obtained from the manufacturer. If this is not possible, typical values (0.05–0.10 s) can be adopted. After determining these values, the other unknown values, i.e. X_{d}, X'_{d}, T'_{d0} can be estimated.

Step 3

In step 3 the parameters of q-axis: X_{q}, X'_{q}, X''_{q}, T'_{q0}, T''_{q0} and inertia constant H are estimated. Step 3 can be made only subject to adjustment of parameters of d-axis in accordance with step 2.

As in step 2, also here all parameters should be estimated simultaneously. In practice, in test 2 neither time constant T''_{q0} nor reactance X''_{q} can be correctly determined due to their minor impact on the voltage during load rejection. In this case, these parameters can be adopted as for d-axis, i.e.: $T''_{\mathrm{q0}} = T''_{\mathrm{d0}}$ and $X''_{\mathrm{q}} = X''_{\mathrm{d}}$. Such an approach will ultimately have no significant impact on the modelled system's electro-mechanical modes. Inertia constant H can be determined independently. For this purpose, either the generator velocity waveform recorded during active power load rejection (Test 2) should be used, or the following formula:

(5)
$$H = \frac{P_{\mathrm{g}}}{2S_{\mathrm{gr}}}\left(\frac{\omega_{\mathrm{r}}}{\frac{\mathrm{d}\omega}{\mathrm{d}t}}\right)$$

where: P_{g} – generator active power before generator tripping, ω_{r} – rated velocity, $\mathrm{d}\omega/\mathrm{d}t$ – rotor acceleration at time t_{0+}, i.e. immediately after generator circuit-breaker opening.

Guidelines for AVR parameters estimation procedure

To identify the AVR parameter a reference voltage step test is recommended. The test can be carried out for generator running on idle or for a generator operating synchronously with power system. During the test PSS should be deactivated.

During test the synchronous generator runs on idle, with nominal speed, and terminal voltage equal (or close) to its nominal value. Then generator voltage reference step is applied. Usually step from ±2% to ±5% of the generator nominal voltage is sufficient. The voltage reference step must not cause the AVR internal signals limits reaching. The important is that two voltage steps are necessary to do: first related to voltage step up and second related to voltage step down. Usually the test is run in the following way: with a given voltage reference value the voltage step up is applied ($+\Delta V_{\mathrm{ref}}$). Next during the same measuring, when system comes back to steady state the next voltage step (step down) is applied ($-\Delta V_{\mathrm{ref}}$). This means that the final value of voltage reference is equal to the initial. Another way (preferred here) is to run test with two independent voltage steps (up and down) from the same initial value of the voltage reference. This can be done in following sequence: steady state with initial value of voltage reference → +ΔV_{ref} → wait for steady state → -ΔV_{ref} → wait for steady state (voltage reference comes back to the initial value) → -ΔV_{ref} → wait for steady state. From such test the first and third responses of generator (time series) should be used for parameters estimation.

The following signals have to be recorded: generator terminal voltage, generator field voltage and current, shaft speed (or frequency). During the estimation process time response of generator terminal voltage or generator field voltage can be used.

During test the synchronous generator operates synchronously with power system and the generator voltage reference step is applied. The test is performed the same way as at generator running on idle. There are no requirements to the generator initial operating point.

The following signals have to be recorded: generator terminal voltage, active power, reactive power, generator field voltage and current, shaft speed (or frequency). During the estimation process time response of generator terminal voltage or generator field voltage is used.

Static (*exst1* – IEEE type ST1 excitation system model) and machine (*exac1a* – IEEE type AC1A excitation system model) AVR models are often use during generator modelling. In case of exst1 model parameters estimation process can be run after the synchronous generator, turbine and governor parameters are estimated (considered as correct). The considered estimation process can be divided into two steps.

Step 1

Set all parameters known form the manufacturer data, like: E_1, E_2, Se_1, Se_2 – saturation factors, V_{rmin}, V_{rmax} – controller min/max output, K_c – rectifier regulation constant, K_d – exciter armature reaction factor and K_e – exciter constant. The rest of the parameters are preset settings, which should be available from AVR commissioning tests:

- T_b – filter delay time,
- T_c – filter derivative time constant,
- T_f – stabilization path delay time,
- T_a – controller time constant.

Their initial values have to be set as accurate as possible. If any parameters are unknown a typical values should be used from standards.

Step 2

If first step is completed, the user has to run estimation of parameters:

- K_a – controller gain,
- T_r – measurement delay,
- K_f – stabilization path gain,
- T_e – exciter time constant.

These parameters should be estimated simultaneously using one of the tests described above: on idle or load generator operating.

Step 3

If time responses computed for obtained in the *Step 2* parameters differs from the measured response try to tune time constants T_b and T_c or/and T_f and repeat parameters estimation according to the *Step 2*.

Sample results of turbogenerator parameters estimation

The analysed generator was a 426 MVA unit. In this extended abstract only the parameter values estimation by using of gradient method are presented.

Step 1

In *Step 1* selected parameters were adopted as obtained from the manufacturer.

Step 2

The estimation of parameters of d-axis is reduced to four values: X_d, X'_d, T'_{d0}, T''_{d0}. (which actual values were: X_d = 2.6; X'_d = 0.33; T'_{d0} = 9.2 s; T''_{d0} = 0.042 s, while the initial values assumed for estimation were: X_d = 2; X'_d = 0.5; T'_{d0} = 5 s; T''_{d0} = 0.1 s) During the estimation process, the generator response after reactive power rejection test (Test 1) was used. The results of the estimation are shown in Fig. 1, where measured generator voltage time response is compared with voltage computed for initial and final (found by gradient method) parameter set.

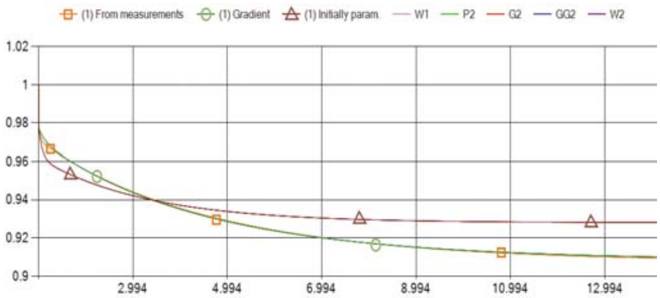

Fig.1. Estimation results of turbogenerator model parameters of d-axis

The d-axis parameter set, found by gradient method (X_d = 2.56; X'_d = 0.33; T'_{d0} = 8.6 s; T''_{d0} = 0.15 s) is similar to actual generator parameters. The generator voltage time response computed for found parameters set (marked with dots) matches measured generator voltage time response (marked with squares).

Step 3

In *Step 3* the parameters of q-axis and inertia constant H were estimated. The voltage time response obtained after partial active power load rejection test (Test 2), were used.

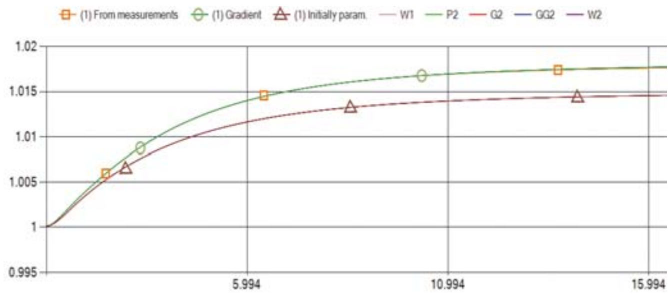

Fig.2. Estimation results of turbogenerator model parameters of q-axis

In Fig. 2 the results of the value estimation of parameters of q-axis are shown. The generator voltage time response computed for estimated parameters set: X_q = 2.64; X'_q = 0.70; H = 3.16 s; T'_{q0} = 1.14 s; T''_{q0} = 0.15 s (marked with dots) matches measured generator voltage time response (marked with squares). Estimated parameter set does not differ significantly from actual generator parameters: X_q = 2.48; X'_q = 0.53; H = 3.23 s; T'_{q0} = 1.10 s; T''_{q0} = 0.065 s.

Sample results of AVR parameters estimation

The analysed generator was a 426 MVA unit. In this extended abstract only the parameter values estimation by using of gradient method are presented.

Below presents example of the AVR with machine exciter (*exac1a* model) for turbo generator of rated power 270 MVA parameters estimation. The parameters estimation was based on time responses calculated for two step changes: generator voltage increase (+5%) and next voltage decreasing (-5%). Generator running on idle. The parameters estimation results, run with use of two optimization methods, i.e. gradient method and genetic one, are shown.

Table I shows set of correct and initial parameter values of the AVR model. The parameters marked with italic were assumed ones (to be identified). The others parameters were assumed as known (correct).

Table 1. Correct and Initial EXAC1A Model Data Set

Parameter	Unit	Correct Value	Initial value for estimation
T_r	s	0	0.2
T_b	s	0.5	0.5
T_c	s	17	17
K_a	p.u.	*1400*	*1000*
T_a	s	0.05	0.05
T_e	s	*0.4*	*1.0*
K_f	p.u.	*0.11*	*0.2*
T_f	s	2	2
K_c	p.u.	0.72	0.72
K_d	p.u.	-0.62	-0.62
K_e	p.u.	0.43	0.43
E_1	p.u.	6.1	6.1
Se_1	p.u.	0	0
E_2	p.u.	8.1	8.1
Se_2	p.u.	0.2	0.2
V_{rmin}	p.u.	-4.26	-4.26

The number of parameters for estimation is limited here because of the following assumption. The modern digital controller (e.g. AVR) manual gives information about the AVR transfer function. Therefore, the time constants that are parameters of the transfer function can be considered as correct (does not need estimation). But there remain some unknown delays and/or inertias and gains that are related to AC/DC converters, filters, measuring algorithms, etc. Therefore the gain set at the real AVR can differ from the overall (and model) gain. It should be estimated. Simultaneously, the inertia blocks with time constants T_a or T_r can be estimated too, to imitate the unknown delays and inertias.

Table 2. EXAC1A Model Estimated Parameters – Genetic Method – Generator Terminal Voltage

Parameter	Unit	Correct Value	Initial value	Estimation value
T_r	s	0	0.2	0.1175
K_a	p.u.	1400	1000	500
T_e	s	0.4	1	0.7214
K_f	p.u.	0.11	0.5	0.1229

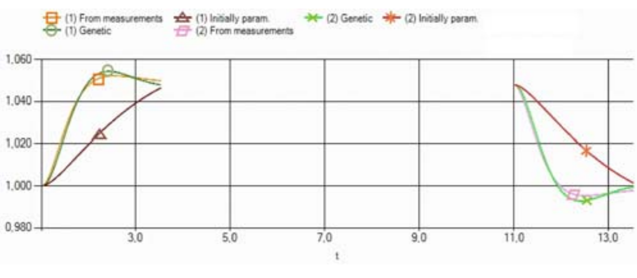

Fig.3. Voltage reference step change (±5%) test, generator on idle run – Exac1a parameters estimation results based on genetic method use

Attempt with genetic method and generator terminal voltage

Results of the AVR parameter estimation, by genetic method, are shown in Table II and Figures 3. In this case used generator terminal voltage. Obtained parameters don't give good fitting to right waveform (Fig. 3).

Attempt with gradient method and generator terminal voltage

The voltage time responses (Fig. 4) show, that gradient method allows for a better responses fit, while there are visible differences in responses for genetic method. This is confirmed by the obtained parameters (Table III) that are very close (except gain K_a) to the correct ones when gradient method is used.

Table 3. EXAC1A Model Estimated Parameters – Gradient Method – Generator Terminal

Parameter	Unit	Correct Value	Initial value	Estimation value
T_r	s	0	0.2	0
K_a	p.u.	1400	1000	1998.28
T_e	s	0.4	1	0.409
K_f	p.u.	0.11	0.5	0.1094

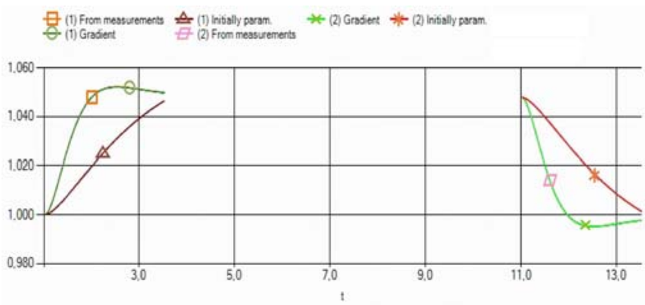

Fig.4. Voltage reference step change (±5%) test, generator on idle run – Exac1a parameters estimation results based on gradient method use

Attempt with gradient method and generator terminal voltage

Table IV shows the AVR parameter estimation results obtained by genetic method and excitation voltage use, while figure 5 shows time response for obtained (estimated) AVR parameters. The field voltage time responses (Fig. 5) show good fitting of the waveforms. The obtained parameters values are almost equal to the correct ones. This leads to conclusion that the excitation voltage response is good signal for the controller (AVR) gain estimation.

Table 4. EXAC1A Model Estimated Parameters – Genetic Method – Excitation Voltage

Parameter	Unit	Correct Value	Initial value	Estimation value
T_r	s	0	0.2	0.0338
K_a	p.u.	1400	1000	1337.74
T_e	s	0.4	1	0.4088
K_f	p.u.	0.11	0.5	0.1161

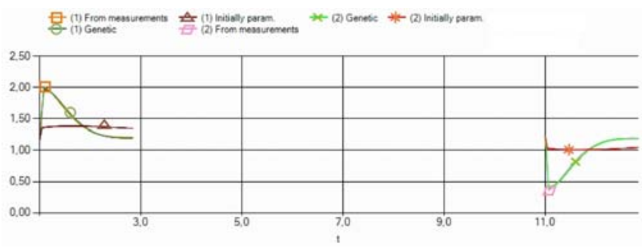

Fig.5. Voltage reference step change (±5%) test, generator on idle run – Exac1a parameters estimation results based on excitation voltage, genetic method used

Below presents example of the AVR (Fig. 6) for hydro generator of rated power 47 MVA working in Island power system. The parameters estimation was based on time responses calculated for two step changes: generator voltage increase (+10%) and next voltage decreasing (-10%). Generator running on idle. The parameters estimation results are shown with use of genetic method.

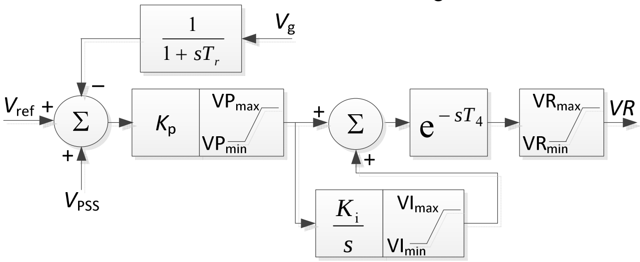

Fig.6. AVR for hydro generator diagram

Table IV shows the AVR parameter estimation results obtained by genetic method and excitation voltage use. Values put in parentheses are suggest by manual of AVR, but unknown for tested controller.

Table 5. Initial and Estimated AVR Model Data Set

Parameter	Unit	Correct Value	Initial value	Estimation value
T_r	s	(0.01)	0.01	-
K_p	p.u.	8[a]	8	20
K_i	p.u.	0.15[a]	0.15	0.2
T_4	s	(0.04)	0.04	-
VP_{min}	p.u.	(-10)	-10	-
VP_{max}	p.u.	(10)	10	-
VI_{min}	p.u.	(=VR_{min})	0.02	-
VI_{max}	p.u.	(=VR_{max})	1.15	-
VR_{min}	p.u.	0.2[b]	0.2	-1
VR_{max}	p.u.	1.15[a]	1.15	2

a. First step; b. Second step;

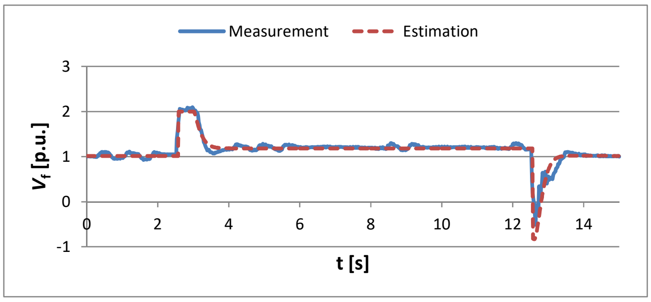

Fig.7. Voltage reference step change (-10%) test, generator on idle run – AVR parameters estimation results based on genetic method use. Second step

Estimation made with two steps. In first step K_p, K_i and VR_{max} parameters were estimated. In this step used voltage reference step change (+10%) test. In second step used voltage reference step change (-10%) test and estimated of VR_{min} parameter. Field excitation voltage waveforms obtained with estimated parameters and measurement from object shown on Fig. 7.

Conclusions

The paper presents the results of an application that allows for verification and estimation of parameters of dynamic models of generation unit components. The presented examples show that using voltage waveforms recorded during generator load rejection or running on idle tests, and genetic and gradient optimisation methods, it is possible to correctly determine the selected parameters of the dynamic model of a synchronous generator.

Author: *dr inż. Krzysztof Dobrzyński, Politechnika Gdańska, Wydział Elektrotechniki i Automatyki, Katedra Elektroenergetyki, ul. G. Narutowicza 11/12, 80-233 Gdańsk, E-mail: krzysztof.dobrzynski@pg.edu.pl.*

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