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Assessment of the accuracy of synchronous generator model parameter estimation based on noisy dynamic waveforms

Abstract. *In the paper, there are presented the results of parameter estimation of the mathematical model of a synchronous generator operating in a single-machine power system. Noisy dynamic waveforms caused by introducing a disturbance in the form of a step change in the reference voltage or a pseudorandom signal to the generator voltage regulator system were the basis of estimation. It was assumed that the generator load was close to the rated one. Finite and infinite impulse response zero-phase digital filters were used for filtering the waveforms. The least squares method was used for parameter estimation, and the gradient method was applied to minimization of the mean square error.*

Streszczenie. *W artykule przedstawiono wyniki estymacji parametrów modelu matematycznego generatora synchronicznego pracującego w jednomaszynowym systemie elektroenergetycznym. Podstawą estymacji są zaszumione przebiegi dynamiczne wywołane wprowadzeniem do układu regulacji napięcia generatora zakłócenia w postaci skokowej zmiany napięcia zadanego lub sygnału pseudolosowego. Założono, że generator pracuje blisko znamionowego obciążenia. Do filtracji przebiegów wykorzystano filtry cyfrowe o zerowym przesunięciu fazowym o skończonej i nieskończonej odpowiedzi impulsowej. Do estymacji parametrów wykorzystano metodę najmniejszych kwadratów, a do minimalizacji błędu średniokwadratowego metodę gradientową. (**Ocena dokładności estymacji parametrów modelu generatora synchronicznego przy wykorzystaniu zaszumionych przebiegów dynamicznych**).*

Keywords: parameter estimation, synchronous generator in power system, pseudorandom signals PRBS, waveform filtering, zero-phase filter
Słowa kluczowe: estymacja parametrów, generator synchroniczny w systemie elektroenergetycznym, sygnały pseudolosowe PRBS, filtracja przebiegów, filtr o zerowym przesunięciu fazowym

Introduction

In recent years there has been increased interest in the methods of electromagnetic parameter estimation of synchronous generators. There are two main groups of these methods: the methods using the results of measurements at the machine standstill [1,2,3,4] and the methods using the results of measurements at the rotating machine [5,6,7,8]. Regardless of the selected measuring method, the main problem of the parameter estimation of synchronous generator mathematical models is to remove the erroneous data and to filter the disturbances from measurement waveforms.

Disturbances in signals are the result of the measuring environment, as well as the presence of machines and electrical devices (current channels, drives, transformers), and converter systems (diodes, thyristors). The measured waveforms of voltages and currents are additionally distorted by a rectifier in the excitation winding circuit, a salient pole rotor as well as the slotting of stator and rotor cores. As a result, higher harmonics are observed in the spectrum of these waveforms in the steady state [8,9]. These harmonics as well as their effect on the magnetic flux are not taken into account in classical mathematical models.

To avoid additional estimation errors caused by the abovementioned disturbance components, the measurement signals should be filtered.

In the investigations, there was assumed that the dynamic waveforms caused by a small disturbance of the voltage regulator reference voltage in the form of a step change or a pseudorandom signal PRBS (*Pseudo Random Binary Sequence*) are the basis of parameter estimation [10]. It was also assumed that the generator was operating in a single-machine power system (PS) under a load close to the rated one [7,10,11].

There was examined the influence of a type and parameters of the filter used on the electromagnetic parameter estimation results of the generator model. There was applied the model GENROU (XT type) containing appropriate reactances and time constants of the generator [12, 13].

Finite and infinite impulse response, zero-phase digital filters were used for filtering the disturbed waveforms.

The method of investigations

Parameters of the synchronous generator mathematical model (in d and q axis) can be determined based on the dynamic waveforms caused by a disturbance of the steady operation of a generator cooperating with a power system. It was assumed that the disturbance was a small additional component in the form of a step change or a pseudorandom signal PRBS introduced to the voltage regulator reference voltage V_{ref}.

Fig. 1 shows the schematic diagram of the generating unit operating in a single-machine PS. The generating unit, including a turbine driven generator and an excitation system with a voltage regulator and a power system stabilizer, is connected to an infinite bus via a transmission line.

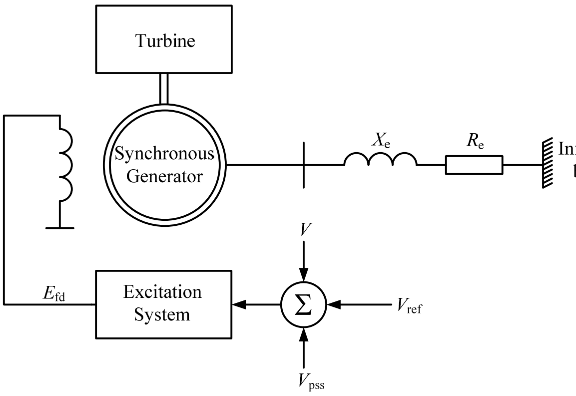

Fig. 1. Schematic diagram of the generating unit operating in a single-machine PS

The introduced disturbance resulted in changes of the waveforms of: currents and voltages of the stator in the direct and quadrature axes, the excitation current, the rotor angular speed and the machine load angle. The excitation system (with the voltage regulator and power system stabilizer) and the turbine with its governor influenced these waveforms.

The generating unit mathematical model developed in the environment of Matlab/Simulink was used for investigations. It is shown in Fig. 2. The model consists of:

the nonlinear synchronous generator model GENROU, the model of the static excitation system with the voltage regulator [11, 14], the model of the PSS3B two-input power system stabilizer and the IEEEG1 model of the steam turbine [13] with its governor. The phenomenon of saturation of the magnetic core by the machine main field was approximately taken into account in the synchronous generator model by means of a correction being a function of the stator flux linkage absolute value [12].

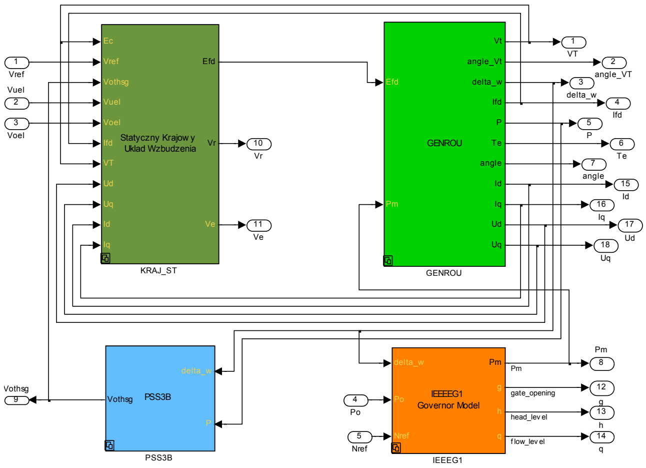

Fig. 2. Structural model of the generating unit in Matlab – Simulink environment

The waveforms generated by the generating unit mathematical model with known parameters, which were conventionally called the standard parameters, were the basis of estimation. Those waveforms were disturbed with Gaussian noise with zero mean value, thus approximately simulating the real measurement signals. Before performing the estimation, one should filter random data and noise from the waveforms. Even a small noise in the waveforms is strongly amplified when calculating derivatives. Using the filtered waveforms of the axial components of the stator and rotor currents and voltages as well as the waveform of the generator rotational speed, one can consider only the generator model in the estimation process, while the other elements of the generating unit can be omitted. Fig. 3 shows the input and output signals taken into account in the parameter estimation of the synchronous generator model.

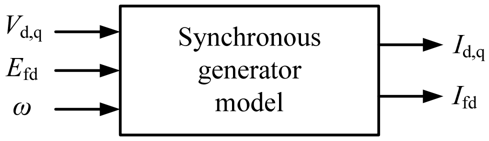

Fig. 3. The signals used for parameter estimation of the synchronous generator model

Parameters of the generator mathematical model were determined by minimization of the objective function in the form of the mean square error defined for the deviations (at the i-th time instants) between the filtered waveforms representing the measured waveforms (denoted by m) and the waveforms calculated by means of the simulation model for the searched vector of parameters $\boldsymbol{P} = [R, X_{\sigma}, X_{ad}, X'_{d}, X''_{d}, T''_{d0}, T''_{d0}, X_{aq}, X'_{q}, X''_{q}, T_{q0}, T''_{q0}]$ (denoted by s).

For estimation there was used the least squares method by defining the following objective function [7, 9]:

(1)

$$\varepsilon(\mathbf{P}) = \frac{1}{2}\sum_{i=1}^{n}\left(\left|\frac{I_{di}{}^{m} - I_{di}{}^{s}(\mathbf{P})}{I_{di}{}^{m}}\right|^{2} + \left|\frac{I_{fdi}{}^{m} - I_{fdi}{}^{s}(\mathbf{P})}{I_{fdi}{}^{m}}\right|^{2} + \left|\frac{I_{qi}{}^{m} - I_{qi}{}^{s}(\mathbf{P})}{I_{qi}{}^{m}}\right|^{2}\right),$$

where: $I_{di}{}^{m}$, $I_{fdi}{}^{m}$, $I_{qi}{}^{m}$, $I_{di}{}^{s}(\boldsymbol{P})$, $I_{fdi}{}^{s}(\boldsymbol{P})$, $I_{qi}{}^{s}(\boldsymbol{P})$ – instantaneous values of the appropriate output signals.

A gradient algorithm with constraints from the Optimization Toolbox for Matlab was used for the minimization of the objective function.

The parameter estimation was performed for a turbogenerator with the ratings: S_n = 117.5 MV·A, V_n = 13.8 kV, I_n = 4915 A, cosφ_n = 0.85, f_n = 50 Hz.

Figs. 4 and 5 show the noisy dynamic waveforms of the stator voltages and currents in the d and q axis as well as the generator field voltage when taking into account the influence of the power system stabilizer for the disturbance of the generator steady state in the form of the step (Fig. 4) and PRBS (Fig. 5) signal introduced in the generator voltage regulation channel.

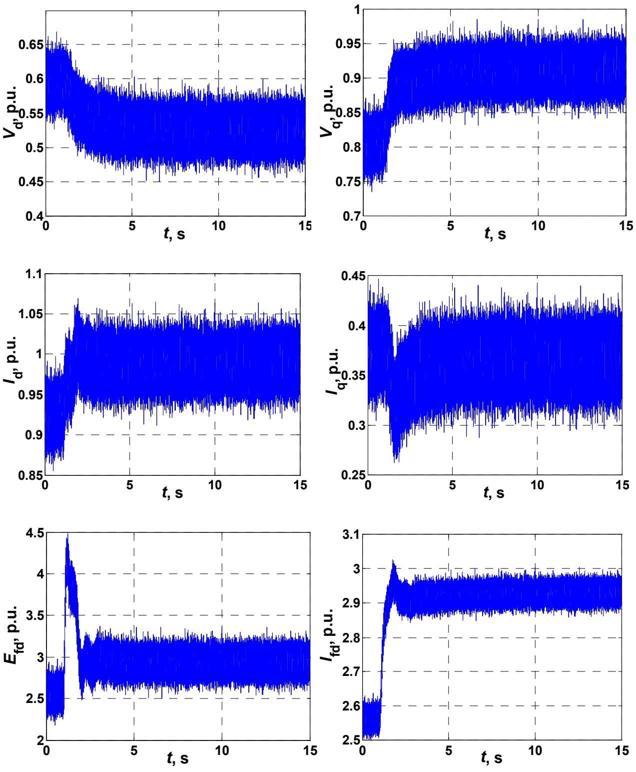

Fig. 4. Noisy waveforms of the stator voltages and currents in the d and q axis as well as the generator field voltage and excitation current at the step change of the voltage regulator reference voltage by +5%

It was assumed that before the disturbance the generator was operating under the rated load, cooperating with an infinite bus via a transmission line with the parameters R_e = 0, X_e = 0.3 (expressed in relative units).

It was assumed that the ratio of the power spectral density of particular signals (except the generator field voltage) to the noise power spectral density (SNR – *Signal-to-Noise Ratio*) was equal to 35 dB. Due to rectifiers in the excitation systems being the source of higher harmonics, a higher level of noises was taken into account in the field voltage (by assuming SNR = 20 dB). The waveforms of the electrical quantities of the stator were expressed in generator relative units, while those of the rotor in regulator relative units [14].

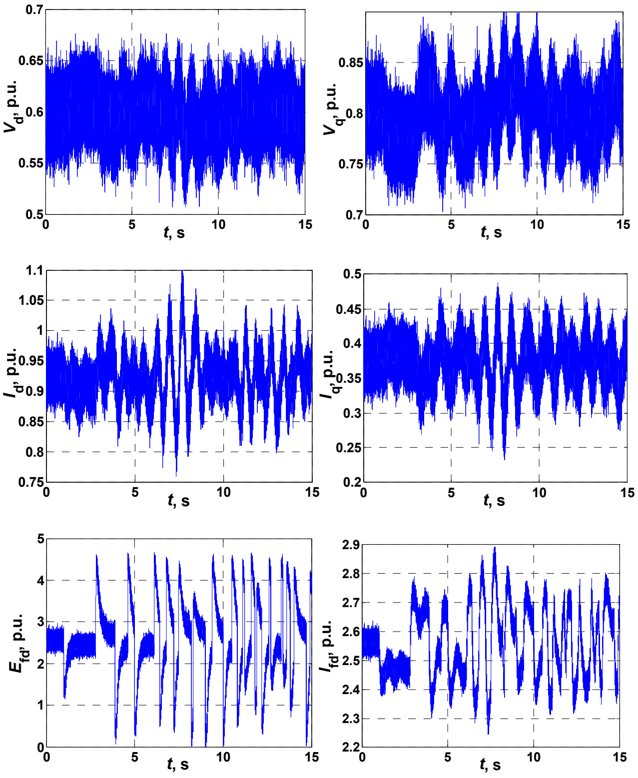

Fig. 5. Noisy waveforms of the stator voltages and currents in the d and q axis as well as the generator field voltage and excitation current when disturbing the machine steady operation with a PRBS signal

Filtration of the waveforms

Three-phase voltages and currents of the stator of frequency 50 Hz as well as the field voltage and excitation current were the measured electrical quantities of the generator. It is convenient to transform the stator voltages and currents to the Park (dq0) coordinate system. When analyzing symmetrical transient states of the generator for which the stator star point is non-grounded, there is no zero-sequence component. The voltages and currents of the stator in the dq0 coordinate system as well as the field voltage and excitation current contain mainly a constant component. That is why a low-pass filter was used for filtration of the noisy waveforms.

Among low-pass filters, there can be distinguished finite and infinite impulse response filters (FIR – *Finite Impulse Response*, IIR – *Infinite Impulse Response*). Each filter introduces a phase shift unwanted from the point of view of parameter estimation. FIR filters can be designed to be linear-phase. It provides a constant group delay and, in consequence, does not result in a change of the filtered signal shape. This property is important when there are variations in the power system frequency in transient states. The FIR filter was designed using the time window method from Matlab Filter Design Toolbox [16]. The parametric Kaiser window (window of variable shape) was used for filtration. Changing the length and shape of the window one can change the steepness of the characteristic in the transition band and the attenuation of the filter in the stopband [17].

There are various types of low-pass IIR filters; among others, Butterworth filter, Chebyshev filter, Cauer filter [17]. Chebyshev and Cauer filters are characterized by a "wavy" amplitude characteristic in the passband. It can result in errors arising in the process of electromagnetic parameter estimation of a synchronous generator. Butterworth filters do not have this drawback. They do not provide a constant group delay, however it is possible to design a filter with a maximally flat amplitude characteristic in the passband. This is done at the expense of the amplitude characteristic slope in the transition band (between the pass and stopbands). Increase in the order of the filter results in a simultaneous increase in the steepness of the amplitude characteristic in the stopband and flattening this characteristic in the passband [17].

Zero-phase filtering (Fig. 6) was used for elimination of the delays introduced by the filter.

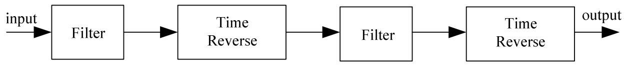

Fig. 6. Schematic diagram of zero-phase filtering

Zero-phase filtering is based on filtering a signal twice by the same filter, which results in increasing the resultant filter order twice. Moreover, the signal time sequence is reversed twice in this filtration. It aims at restoring the original order of the samples. Zero-phase filtering provides elimination of the effect of the filter phase response on the signal phase angle, independently of the type of filtering.

The noisy waveforms generated by the power system mathematical model were recorded at the sampling rate f_s = 10 kHz.

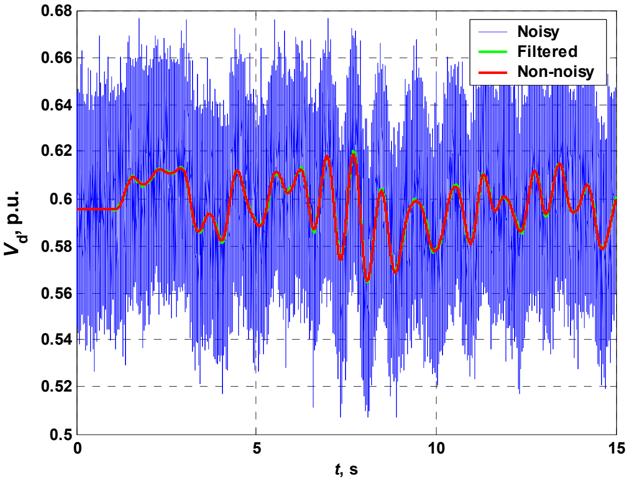

Fig. 7. Exemplary waveform of the armature? stator? voltage in the d axis before and after filtration

The exemplary waveforms of the stator voltage in the d axis are shown in Fig. 7. They are: the waveform of the voltage generated by the mathematical model of the generating unit ("non-noisy" waveform), the waveform of the voltage disturbed with Gaussian noise ("noisy" waveform) and the waveform after filtration by the proposed filter ("filtered" waveform). To illustrate the differences between the non-noisy waveform and the filtered one, there was introduced a percentage error waveform defined by the formula:

$$\varepsilon_{V_{di\%}} = \left(\frac{V_{di} - V_{di}^{\,n}}{V_{di}^{\,n}}\right)\cdot 100, \tag{2}$$

where: V_{di}, $V_{di}^{\,n}$ – instantaneous values of the filtered and non-noisy voltage (n) of the generator stator in the d axis.

The waveform of errors calculated according to (2) is shown in Fig. 8. It can be seen that the maximum error is small because it does not exceed 0.4%.

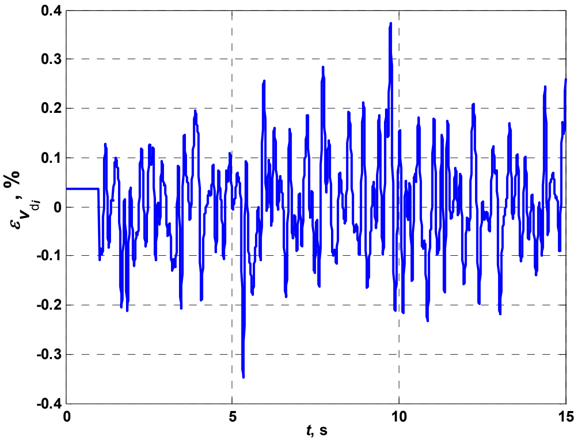

Fig. 8. Exemplary waveform of errors resulting from filtration of the stator voltage in the d axis

The filtered voltage waveform was obtained with the use of a Butterworth filter with the following parameters: the passband edge frequency f_{pass} = 4 Hz and the stopband edge frequency f_{stop} = 30 Hz.

Results of electromagnetic parameter estimation

The parameter estimation of the generator model in the d and q axes was performed for the waveforms shown in Figs. 4 and 5 after their filtration by the presented above Butterworth filter. Figs. 9 and 10 present the filtered output waveforms of the generator being the basis of estimation (Aftfilt) and the simulation waveforms calculated for the generator parameters determined in the first iteration (Aftest). After completion of the estimation process, the filtered waveforms were practically the same as the simulation ones.

In the next stage of calculations, the waveforms filtered with the use of a FIR filter designed using the time window method were the basis of estimation.

Tables 1 and 2 present the final results of parameter estimation of the synchronous generator model and the percentage errors. When minimizing the objective function (1), it was assumed that the initial values of the generator model parameters differed from the standard parameters by 50%.

Table 1. Parameter estimation results for the pseudorandom signal

Parameter	Standard value	FIR	Error	IIR	Error
			%		%
X_{ad}	1.7006	1.7018	0.072	1.6937	0.406
X'_{d}	0.2298	0.2291	0.311	0.2292	0.248
X''_{d}	0.0842	0.0859	1.998	0.0884	4.994
T'_{d0}, s	6.9938	6.9968	0.042	6.9897	0.058
T''_{d0}, s	0.0448	0.0439	2.072	0.0456	1.763
X_{aq}	1.622	1.6173	0.288	1.6343	0.759
X'_{q}	0.465	0.4680	0.635	0.4653	0.073
X''_{q}	0.0842	0.1032	22.61	0.0808	4.073
T'_{q0}, s	2.054	1.9913	3.051	2.0785	1.192
T''_{q0}, s	0.082	0.0826	0.736	0.0792	3.413
R	0.0013	0.0022	72.87	0.0014	10.790
X_{σ}	0.113	0.1141	0.938	0.1131	0.068

The Levenberg-Marquardt gradient algorithm implemented in Matlab was used for minimization of the mean square error defined by formula (1).

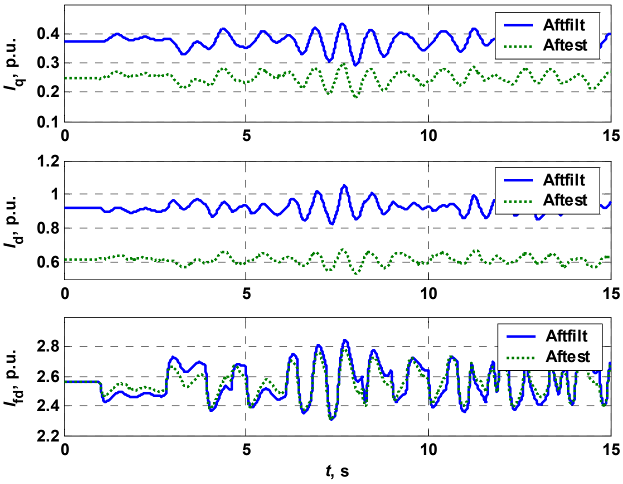

Fig. 9. Filtered and simulation output waveforms in the first iteration step for a disturbance in the form of the PRBS signal

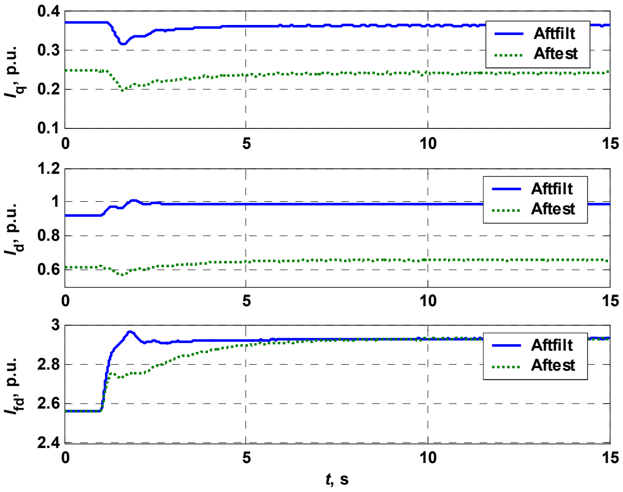

Fig. 10. Filtered and simulation output waveforms in the first iteration step for a disturbance in the form of the step signal

Table 2. Parameter estimation results for the step signal

Parameter	Standard value	FIR	Error	IIR	Error
			%		%
X_{ad}	1.7006	1.6877	0.755	1.6992	0.080
X'_{d}	0.2298	0.2298	0.014	0.2297	0.030
X''_{d}	0.0842	0.0816	3.112	0.0842	0.042
T'_{d0}, s	6.9938	7.0316	0.540	7.0232	0.421
T''_{d0}, s	0.0448	0.0444	0.966	0.0452	0.867
X_{aq}	1.622	1.6564	1.380	1.6251	0.189
X'_{q}	0.465	0.4638	0.248	0.4654	0.079
X''_{q}	0.0842	0.0558	33.77	0.0815	3.260
T'_{q0}, s	2.054	2.1535	4.841	2.0712	0.838
T''_{q0}, s	0.082	0.0527	35.68	0.0767	6.501
R	0.0013	0.0014	6.459	0.0014	6.082
X_{σ}	0.113	0.1131	0.111	0.1131	0.126

Conclusions

Based on the conducted investigations, one can state that most of the calculated electromagnetic parameters of the synchronous generator was loaded with a small error when using the zero-phase filtering (for both disturbances of the generator steady operation). Smaller estimation errors were obtained for the Butterworth filter. Of the parameters, the most difficult to determine are the stator resistance and the subtransient reactance in the q axis, independently of the filter used in the investigations. Similar difficulties in determining these parameters are mentioned in [11, 19]. It should be noted that the stator resistance of high power synchronous generators is small compared to the synchronous resistance. Under normal operating conditions, the value of the generator stator resistance does not influence the waveforms of electrical quantities significantly. The large error of stator resistance estimation can be avoided by assuming in the computational model the resistance from the catalogue data provided by manufacturers or the resistance determined by the technical method instead of the estimation of this parameter.

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