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Testing of an Adaptive Algorithm for Estimating the Parameters of a Synchronous Generator Based on the Approximation of Electrical State Time Series

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Abstract: The results of testing the algorithms of the adaptive model of a synchronous generator using theoretical and real physical data are presented in this study. The adaptive model of a synchronous machine is an equations system, which describes both the static and transient operation of a generator. Parameters of the adaptive model are found using measurements of a generator's operational parameters. The single-machine model was created in Matlab/Simulink software to test the theoretical data. This single-machine model consists of a synchronous generator, a step-up transformer, and a transmission line. The test model also includes models of the automatic voltage regulator and steam turbine governor. The real electrodynamic model was used to verify the adaptive model of a synchronous machine. It consisted of four synchronous generators, with values of power capacity of 5 kW and 15 kW. The data logger with a sampling rate of 57.8 kHz was developed and installed to measure the operating parameters of each generator. As a result of testing on both models, the following values were estimated: inertia moment, d-axis and q-axis reactance, and load angle. These values were compared with the reference values. The adaptive model of a synchronous machine can be used in systems of emergency control and assessment of generator state.

Keywords: online measurement; parameter estimation; power systems dynamics; synchronous generator

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1. Introduction

There is a significant shift in the structure and parameters of modern power systems. It is being caused by the rapid development and application of digital technologies, new measurement devices and methods, and increasing renewable energy sources (RES) penetration [1]. The decreased total inertia and shorter transient duration times result in changing power system properties [2], which makes it necessary to devise modifications to conventional algorithms of emergency control systems in terms of their operation speed and additivity.

On the other hand, the development of devices that measure parameters of power systems states, such as phasor measurement units (PMU), open new ways of online monitoring synchronous generators (SG) [3].

The problems in question are solved using models of power system elements, the parameters of which are obtained as a result of testing or from the manufacturer's data. The impact of weather conditions and equipment aging on the parameters of power system elements are often not considered. As a consequence, the accuracy and robustness of solving the problem of power system operation and equipment state assessment may decrease.

The adaptive model of a synchronous machine was suggested to solve the mentioned problems by the authors in [3]. The parameters of a synchronous machine are estimated using measurements. This model can be used to develop emergency control systems, as well as algorithms for online assessments of the equipment state.

The purpose of this study is to test the adaptive model of a synchronous machine based on theoretical and real data.

2. Literature Review

Robust and accurate models of each element of a power system are required for studies related to power system analysis. It is even more relevant for power generation. SG is known to be the most frequently used type of electric generator [4].

Recently, special attention is being paid to the problem of SG parameter estimation, which can be also confirmed by the development of standardized test procedures by IEC and IEEE [5,6]. The significant number of procedures in these standards is based on the procedure for obtaining values from oscillograms of stator coil current that were made during a lab test three-phase short-circuit event. However, under closer inspection, it becomes clear that the methods using graphics are geometry-based, which means that there is a human factor involved. Moreover, a saturation of current transformers that are used to measure stator current represents the additional source of error. Despite the existing standard procedures of tests, there were many studies carried out to demonstrate different nonstandard methods of SG parameter estimation.

The proposed methods can be classified in two ways. Firstly, the methods can be divided into standstill [7–14] and online (real-time) procedures [15–35]. The specialized stationary methods are obligatory tests, which can be conducted during generator start-up, maintenance, and service operations [5,7]. Among the most widespread are the load rejection [15–19] and sudden short-circuit tests [20,21], which are standard test procedures [5,7].

The load rejection test includes two stages. The parameters of the d-axis are obtained in the first stage, while those of the q-axis are obtained in the second stage. The d-axis parameters are obtained when the excitation system of the generator is turned into manual mode, active power of the generator is determined by no-load conditions and reactive power is 0.1 p.u. When this operating point is reached, the circuit breaker can be switched off to initiate the simulation of load rejection. Then, the voltage of generator terminals is to be measured to obtain parameters [7,17]. In the same way, in the case of the q-axis test, the power factor of the generator should be equal to the rotation angle of the rotor. This is roughly achieved when the active power of the generator is 0.1 kW, and reactive power is about a few percent of rated capacity (as the load in d-axis test). When the condition is met, the second stage can be launched by switching off the circuit breaker.

The type of test used in [17] consists of slight raise of field voltage to reach initial generator excitation and a gradual increase in voltage at terminals of a generator to 1 p.u. The stator coil circuit is open.

Online methods do not require that the generator be switched off from the external power system. Operational data obtained from PMU are used to estimate SG parameters in [23–28]. The parameters are estimated using measuring voltages and currents of the stator and excitation system during the normal operation of the generator [29–32]. The test technique proposed in [33] is based on the measured values of the active and reactive power of the generator, in addition to voltages and currents of the stator and excitation system. The transient data of a generator during a remote two-phase fault can be used to identify unknown parameters of a generator [35]. The main drawback of online methods is the requirement to have different types of signals, which can dramatically increase the cost due to the necessity of buying additional equipment. Besides, it makes methods rather complicated. In addition, many online methods require values of the load angle, which are not always obtainable in real life [36].

A vast number of test procedures are carried out when a generator is idle. The chirp test is one of the most widespread tests. It is combined with a hybrid quasi-Newton genetic algorithm to estimate the parameters of the SG [14]. The chirp signal is a linear sine signal with a frequency sweep. The chirp test is performed by sending a chirp signal to the stator winding, with the field winding being short-circuited and the generator in an idle state. Parameters of the generator can be obtained by measuring the voltage and current of the stator, as well as the field current.

In [10,11] the combination of the genetic algorithm, and the Gauss–Newton method is used to obtain the parameters. Two tests of rotor deceleration are applied in these studies: sine cardinal perturbation [10] and step-voltage test [11]. These methods of testing are very similar to the aforementioned chirp test. Instead of a chirp signal, a sine signal is transmitted to the stator winding [10]. Apart from that, a step-voltage signal is transmitted between stator terminals [11]. In both cases, the field winding is short-circuited, and the rotor is stationary. Application of the quasi-random binary sequence of the field voltage in the field winding was demonstrated in [12,37]. At the same time, there is another test of rotor deceleration, which is called the DC-ux decay test [12,37]. During this test, the field winding should be short-circuited and the generator is to be stopped, as it is conducted in aforementioned rotor deceleration tests. At first, the flux of a machine is created by supplying the stator winding with direct current. When the field current is at a rated value, the direct current supply is switched off, with the stator winding being under short-circuit conditions. The form of the stator current signal during short-circuiting is used in obtaining the parameters of a generator.

A method or an algorithm of estimation of SG parameters is also an important aspect of test procedures. There is a great amount of methods presented in the literature: the least-squares method [14–16,25,29,33], metaheuristic algorithms [10,11,13,22,25,34,35], dynamic algorithms of estimation based on the Kalman filter [23,24,32], the conventional curve-based method [16], the interior point method [16,27], and the adaptive Bayesian parameter estimation combined with importance sampling [27]. One of the less practical optimization tools is the optimization Knitro solver [20], the method of output error and nonlinear mapping [30], the Hartley series [31], the Levenberg–Marquardt method [11], and the numerical procedure [21]. Moreover, many authors suggested using PMU-data-based methods [23,24]. PMU data includes the magnitude and angle of voltage, rotor position, angular velocity, stator current, and power at a generator bus. This data is required for the application of automatic data sampling [23,28]. The sampling of parameters can be undertaken using dynamic estimation. Test methods based on measurements of field, voltage, and current of armature were recently suggested [33,38]. Authors have shown the application of a huge variety of parameters estimation methods: nonlinear least-squares method [23,39], a combination of least-squares method and damping current observer [29,40], nonlinear mapping [30], the one-dimensional search method [34], and the maximum likelihood algorithm [37].

3. Algorithm of the Synchronous Machine Parameters Estimation

The adaptive model of a synchronous machine is an equations system, parameters of which are found using measurements of operational parameters of a synchronous machine both in static and transient modes of operation [3]. The adaptive mathematical model is based on the Park equations.

The following assumptions are used:

1. Torsion of SG shaft is zero.
2. Active power losses are found by re-adjusting experimental results to the current state of the SG.
3. The device of direct speed measurement is installed on the rotor of the SG.

The adaptive model of a synchronous machine can be used to estimate the following parameters:

4. Load angle.
5. Reactance of d-axis and q-axis.
6. Inertia moment of a turbine and rotating parts of the SG.

Input data of the adaptive model are:

- Rated parameters of the SG (rated active power capacity, power factor, number of pole pairs, rated voltage of stator winding, rated current of the stator winding, rated voltage of rotor winding, and rated current of rotor winding).
- Instantaneous values of stator voltage and stator current.
- Instantaneous values of field voltage and field current.
- Angular frequency of the rotor.

The flow chart of the adaptive model is shown in Figure 1. A detailed description of the model can be found in [3].

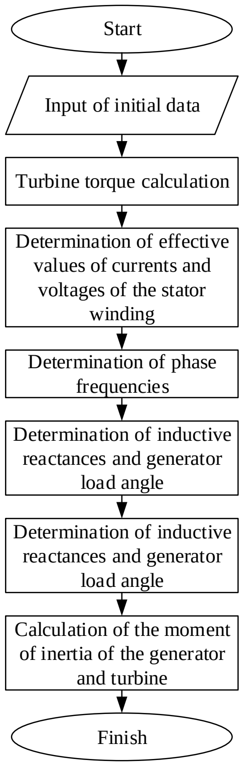

Figure 1. Flowchart of the adaptive model of a synchronous machine.

After the input data is processed, the measurements of voltage and current are scaled to measured physical parameters according to the results of measurement channels calibration. Then, turbine torque is found, and vectors of stator current and stator voltage are formed. When it is done, average values of current and voltage of field winding and exciter winding are found. After that, the following parameters can be found: AC frequency of stator winding, components of vectors of positive, negative, and zero sequences for stator voltage and stator current. The next step is a calculation of phase angle for phases A, B, and C of the stator winding, as well as positive, negative, and zero sequences. Then, the field current, reactance, and load angle are found using the equations of electrostatic equilibrium. Active power is calculated, and active power losses are re-adjusted according to the actual operational state of a synchronous machine. Finally, torque, inertia moment, and turbine power are found.

If there are no measurements of angular velocity, then its value is found based on system frequency values and the measured/calculated load angle of a synchronous machine.

The value of moment GD^2 can be used as the first approximation. The moment value is obtained during the design stage, and it is verified during tests. These values can be found in datasheets of synchronous machines and turbines.

If there is a necessity to reduce calculation time, then active power losses can be neglected. In this case, turbine torque can be found using active power output and angular velocity of the rotor.

To estimate the parameters of a synchronous generator, an approximation of the rotor motion equation is used using the least-squares method on sliding calculation windows. The approximated expression has the following form:

$$\tau_j \frac{S_{rated}}{\omega_0} \cdot \frac{d^2\delta}{dt^2} = P_t - P_e - P_d\left(\frac{d\delta}{dt} - \omega_0\right) - P_s\Delta\delta, \quad (1)$$

where δ—synchronous generator load angle; P_e—electromagnetic power (active three-phase generator power); P_t turbine power; τ_j—constant of inertia; P_d—damping factor; P_s—synchronizing power factor; ω_0—nominal mechanical speed of the rotor; S_{rated}—nominal generator power.

Table 1 provides a comparison of the algorithm of the adaptive model of a synchronous generator with some of the algorithms discussed previously in the literature review.

Table 1. A comparison of the algorithm of the adaptive model of a synchronous generator with the existing methods.

Method	Advantages	Disadvantages
Adaptive model of a synchronous generator [3]	High adaptability to a set of input measurements, and high accuracy	The complexity of setting and determining the parameters of the algorithm
Least-squares method [14]	Productivity	High sensitivity to ejections in the original data
Kalman filter [23]	High resistance to noise in raw data, high accuracy	Significant computing power is required
The interior point method [16]	Effective work with small data samples	Insufficient reliability, the possible discrepancy between the iterative procedure for finding the optimum
The Levenberg–Marquardt method [11]	Productivity	Insufficient reliability, the possible discrepancy between the iterative procedure for finding the optimum
The maximum likelihood algorithm [37]	Productivity	Data samples of considerable length are required to perform the operation of the method

Distinctive features of the algorithm of the adaptive model of a synchronous generator [3] are high adaptability to a set of input measurements, low computational costs, and high accuracy in determining the parameters of synchronous machines.

4. Model Testing Results

To test the methodology for assessing the parameters of a synchronous generator, a four-machine model was used, the graphics of which are shown in Figure 2.

The test system consists of two power districts interconnected by two 230 kV lines with a length of 220 km. Two synchronous salient-pole generators with a capacity of 900 MVA are installed in each of the subsystems. Each synchronous generator is supplied with standard models of an automatic voltage regulator (AVR), power system stabilizer (PSS), and a steam turbine model.

To simulate an electromechanical transient, a three-phase short circuit was considered on one of the two parallel 230 kV lines. The start time of the short circuit is chosen to be 10 s, and its duration is 0.2 s.

The parameters of the mathematical model are given in [41] (Section 12.8 "Special techniques for analyses of very large systems", Example 12.6).

Figure 3 shows the results of estimating the inertia constant for SG 3 with a computational window of 100 ms.

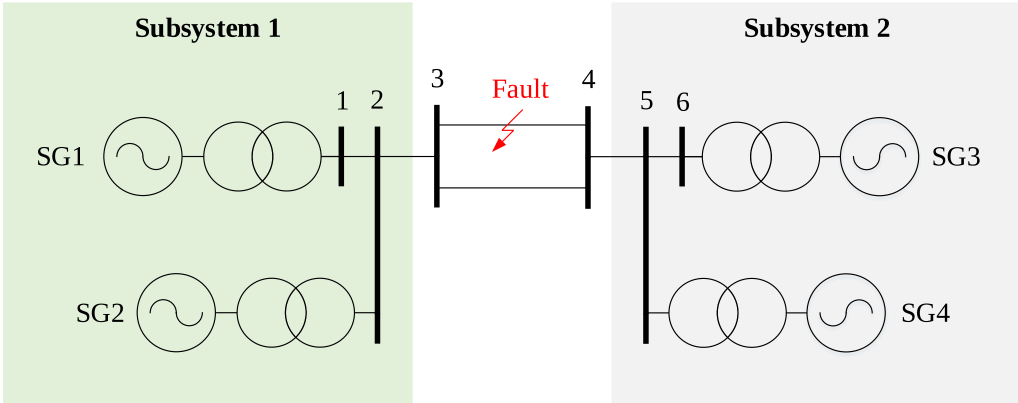

Figure 2. Test model.

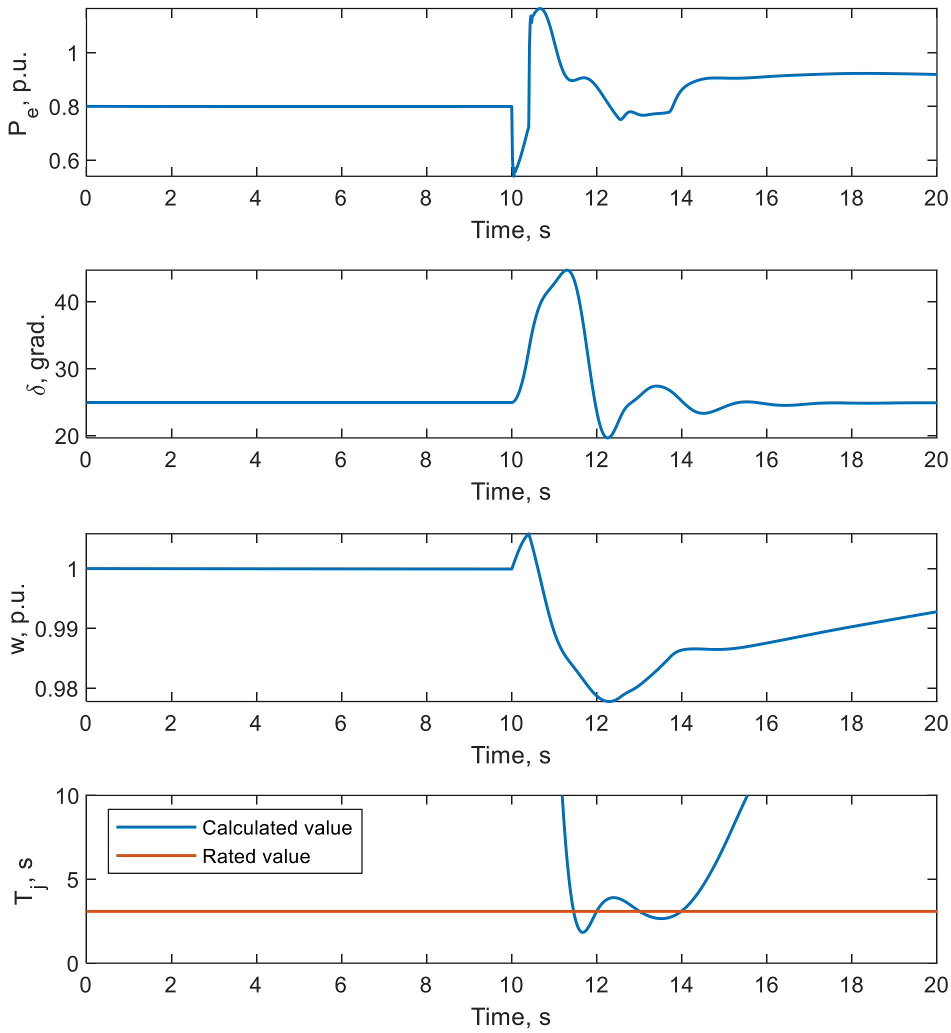

Figure 3. Calculated SG 3 constant inertia value.

Figure 3 shows the following measurements: active power (Pe), load angle (δ), angular velocity of the rotor (w), constant inertia value (Tj). The calculated value of the constant inertia is determined by averaging over an interval of 11–15 s. The boundaries of this interval are chosen expertly. In the future, it is planned to develop a methodology that allows the adaptive determination of the time interval for the transition process to calculate the time constant of a synchronous generator. Figure 3 represents the fluctuations in the calculated value of the time constant of the synchronous generator, caused by the influence of the excitation system.

Figure 4 shows a comparison of the calculated values of the constant inertia of the synchronous generator 3 for different calculation windows.

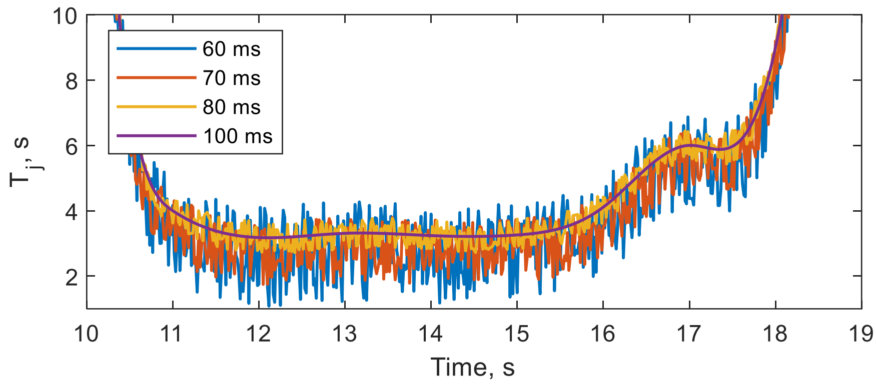

Figure 4. Comparison of the calculated constant inertia value for SG 3 with computational windows from 60 to 100 ms.

A decrease in the calculation window leads to an increase in the spread in the value of the inertia constants of the synchronous generator. In the considered example, when the computational window decreases below 60 ms, negative values of the constant of inertia are observed.

The error in estimating the constant inertia value of SG 3 for a computational window of 100 ms is 1.29%.

Figure 5 shows the values of the synchronizing power factor and the damping factor of SG 3.

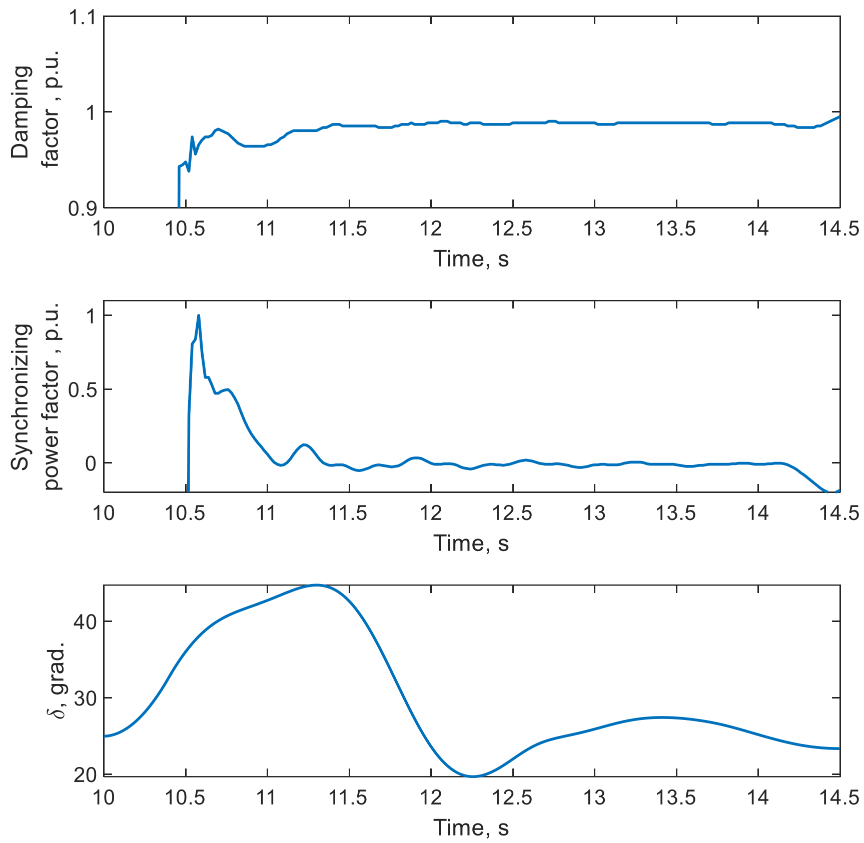

Figure 5. Calculated values of the synchronizing power factor and the damping factor of SG 3.

The values of the damping factor and the synchronizing power factor are determined after the elimination of the short circuit and the development of the electromechanical transient process.

An error in calculating the value of the damping factor and synchronizing power is impossible due to the lack of reference values.

5. Results of Real Physical Model Testing

5.1. Description of the Real Physical Model and Measurement System

The electrodynamic model [42] was used for testing the parameter calculation algorithm for the adaptive model of a synchronous machine. This model consists of more than 1000 real physical models of SG, prime motors, transformers, transmission lines, and complex load and DC transmission lines. The test system was arranged to conduct the test procedures (Figure 6).

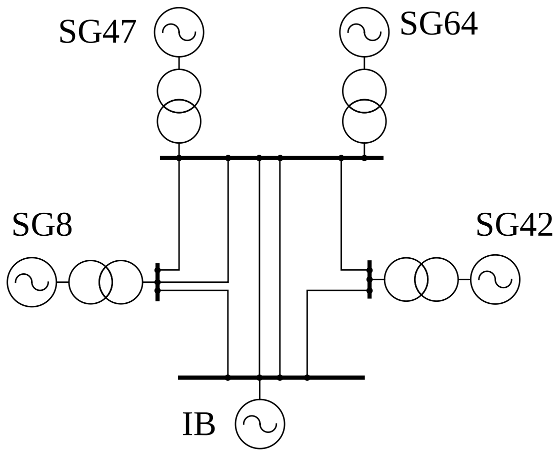

Figure 6. Diagram of the test system.

Parameters of the SG in the test system are shown in Table 2.

SGs of the test system are equipped with the AVR and prime motor (DC motor) governor.

The data logger was developed for logging operational parameters of SGs. The algorithms of electric parameters estimation, presented in various studies [43], were implemented.

A general view of the examined physical model is provided in Figure 7. The utilized synchronous generators and prime movers are given in Figure 8.

The use of a physical model of a power system makes it possible to test the algorithm of an adaptive model of a synchronous generator on data as close as possible to real power systems. The measurements obtained have ejections, noise, and asymmetry, which makes it possible to demonstrate the operation of the algorithm in the most unfavorable conditions.

The data logger comprises external transducer units, which measure instantaneous values of electric parameters with a sampling rate of 57.8 kHz. In addition, the logger contains the control unit, connected with external units by optic fiber cables. The control unit is an industrial-type computer with a PCI-Express bus, where up to 4 special modules of synchronous control are installed. These modules control external units using optic cables. Each module can be connected to 4 external units, and it controls the processes of sampling and transmission digitized analog signals from each external unit, with a transmission frequency of 16 mHz up to 400 m. The module of synchronous control with interface RS-485 can be connected to an external UTC GPS receiver to achieve synchronization of measurements, with an accuracy of 1 µs. In the control unit, a timestamp is applied to digitized measurement signals from external units, the data is buffered and then this data is transmitted via a bus interface to the memory buffer of the CPU for further processing.

The developed recorder is presented in Figure 9.

Table 2. Parameters of synchronous generators.

Parameter	Value
SG 8	
Rotor type	Salient pole
Rated apparent capacity	15 kVA
Power factor	0.8
Rated voltage	230 V
Rated stator current	37.5 A
Base impedance	3.52 Ω
SG 42	
Rotor type	Nonsalient pole
Rated apparent capacity	5 kVA
Power factor	0.8
Rated voltage	230 V
Rated stator current	12.55 A
Base impedance	10.58 Ω
SG 47	
Rotor type	Nonsalient pole
Rated apparent capacity	5 kVA
Power factor	0.8
Rated voltage	230 V
Rated stator current	12.55 A
Base impedance	10.58 Ω
SG 64	
Rotor type	Nonsalient pole
Rated apparent capacity	5 kVA
Power factor	0.8
Rated voltage	230 V
Rated stator current	12.55 A
Base impedance	10.58 Ω

Figure 7. General view of the physical model of the power system.

Figure 8. The synchronous generators and prime movers were used in testing.

Figure 9. Photo of the developed recorder.

To connect the recorder to the physical model of the power system, the applied measurement circuit diagram is used (Figure 10).

Figure 10 shows the following clarification: a gray rectangle shows a schematic representation of the developed recorder and for connection, the input circuits are connected through three current transformers (CT) pumped to the phase conductors of the studied synchronous generator.

The unit of measurement transducer has a two-channel power supply source. The supply voltage is 85–250 V AC with a frequency of 50 Hz or 120–300 V DC. The power supply source ensures the galvanic isolation of each channel.

The record of transients received from data loggers on each SG is shown in Figure 11.

The developed recorder was tested on a series of experiments in which various transient processes were simulated based on a physical model.

Based on the results of the SG data logger operation, the following conclusions were made:

- The technical results obtained during the testing confirmed the logger's operability and provision of the required quality indicators of measurements such as measurement errors, high measurement sampling rate (57.8 kHz), and measurement synchronization accuracy—up to 1 μs.
- Logger operating experience has confirmed its technical and design solutions in terms of establishing optical communications between its central part (the logger control unit) and remote units (measurement transducers). It can allow the central part of the recorder to be placed on premises remotely from power equipment.

- The prospects for the further use of the logger should be associated with the development of the hardware platform development and the modernization of the measuring communications infrastructure.

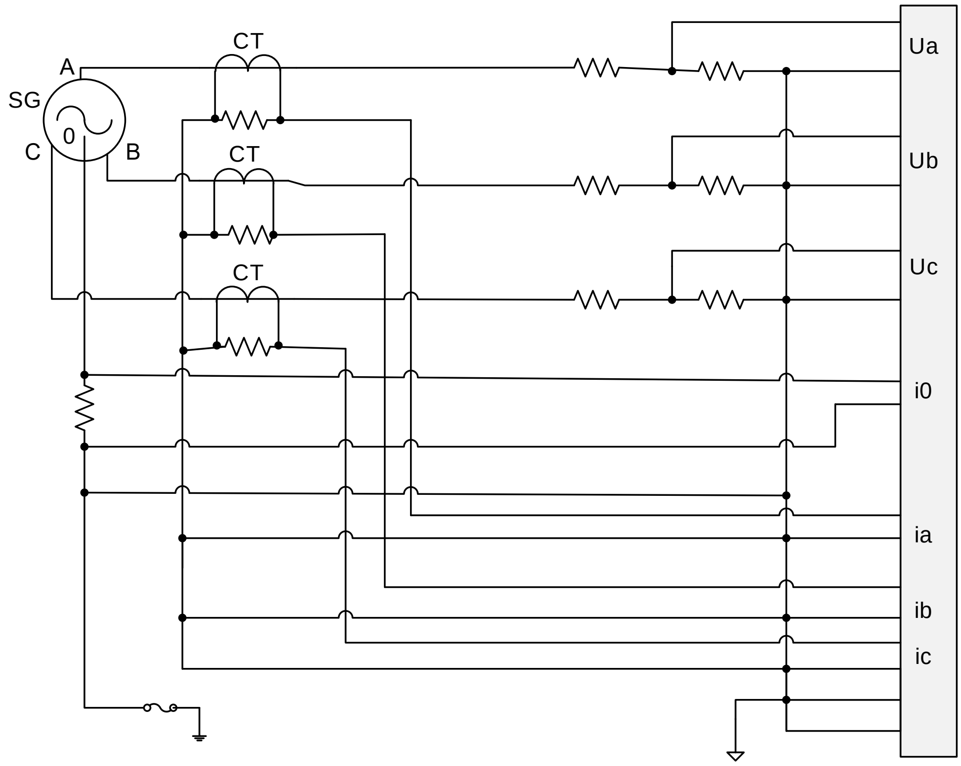

Figure 10. Connection diagram of the measuring circuits of the developed recorder.

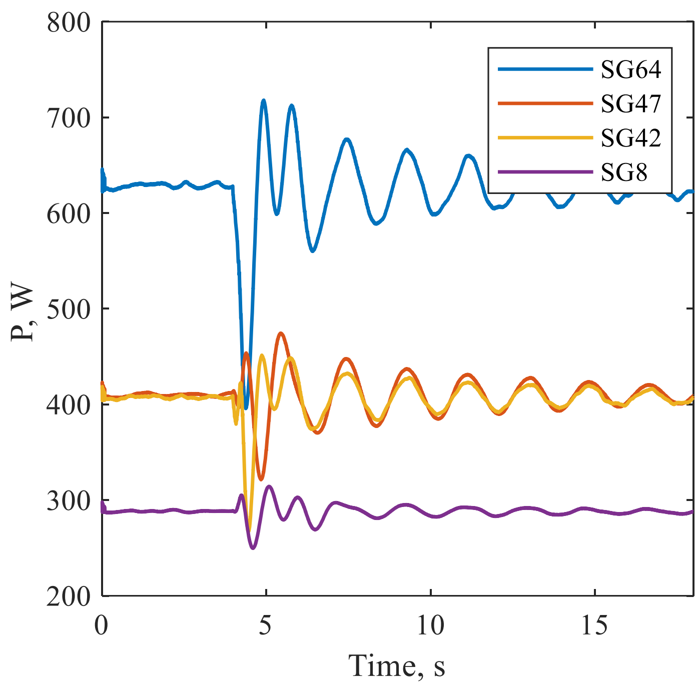

Figure 11. Active power measurements during a transient operation in the test physical model.

5.2. Estimation of the Parameters of the Synchronous Machines

Figures 12–16 show the change in the torque angle, the field current, the calculated positive sequence resistances, and X_d and X_q values of SG 64 when regulating the active power.

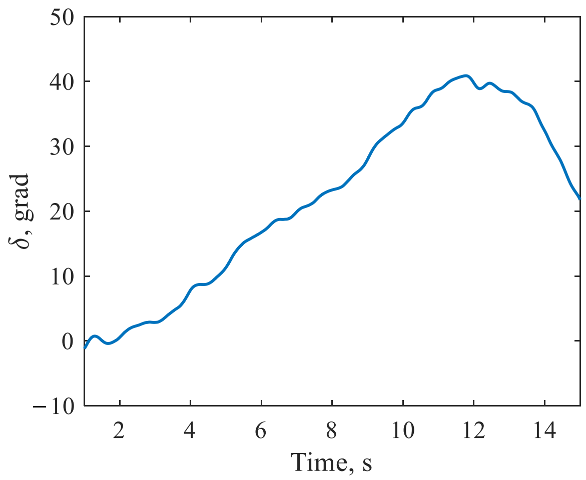

Figure 12. Change in load angle.

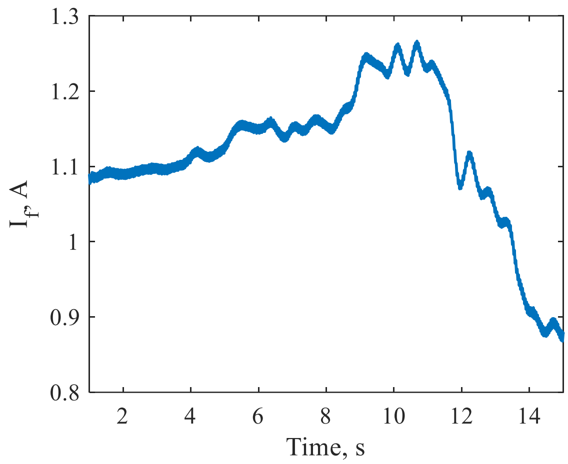

Figure 13. Change in field current.

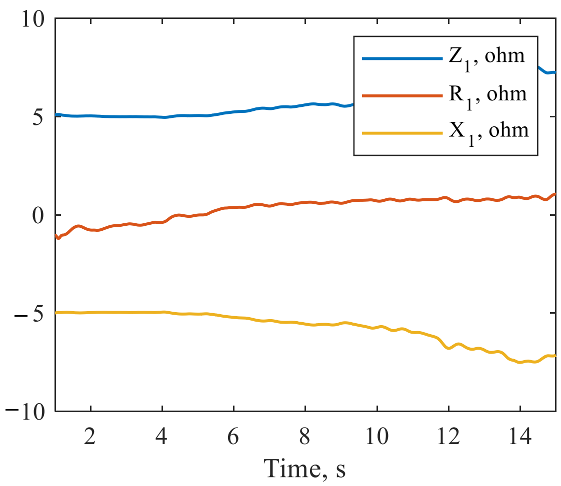

Figure 14. Change in calculated positive phase sequence resistances Z_1, X_1, R_1.

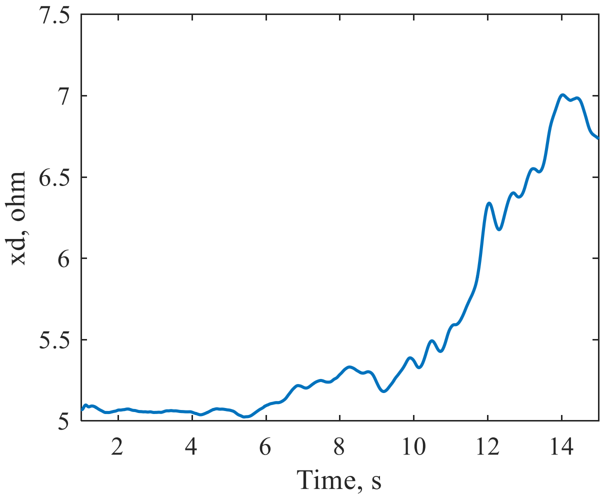

Figure 15. Change in calculated X_d.

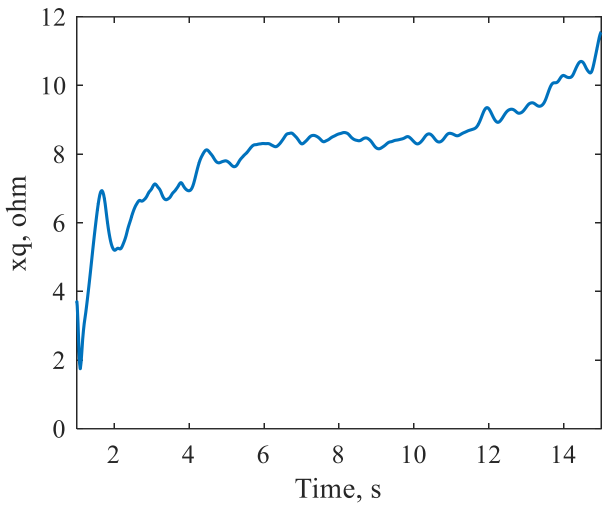

Figure 16. Change in calculated Xq.

Figure 12 shows the load angle of the considered synchronous generator. Before the disturbance, the synchronous generator worked in idle mode, so its initial load angle is close to 0 degrees. Figure 13 shows the value of the excitation current of a synchronous generator, which in turn shows the influence of the automatic excitation controller in the process of disturbance. The influence of the excitation controller is reflected in the increase in the current If in the transient process. Figure 14 shows the values of active (R_1), reactive (X_1) and full (Z_1) resistance of the synchronous generator. The negative value of the reactance is caused by the selected coordinate system. Figures 15 and 16 show the resistance along the d and q axes. It can be seen that, during the transient process, the values of X_d and X_q increase, a process which is caused by the effect of the transition between the transient and synchronous resistance of the synchronous machine during the development of the electromechanical transient process.

Figure 17 shows the calculated X_d of SG 64 in a sudden 3-phase undervoltage short-circuit test corresponding to the unloaded generator and the X_d reference values. The short circuit is cleared until a steady short circuit current is reached.

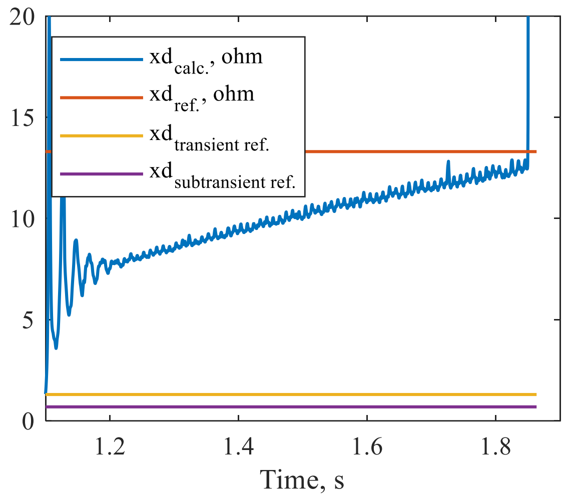

Figure 17. The calculated value of X_d in the experiment of a sudden three-phase short circuit.

In the event of a short circuit, the synchronous generator is characterized by a super-transient resistance, which is reflected in a sharp decrease in the X_d value in Figure 17. Further, during the transient process, the synchronous generator is characterized by a transient and synchronous X_d value, which is shown in Figure 17 as a gradual increase in X_d over time. Thus, the proposed adaptive model of a synchronous machine makes it possible to obtain the nature of the change in the value of X_d at the rate of the transient process.

A comparison of the inductive resistance determination results, according to the experiment of a 3-phase short circuit with reference values is shown in Table 3.

Table 3. Comparison of the reactance estimation results according during a 3-phase short circuit.

Parameter	Calculated Values, Ω	Reference Values, Ω	Error, %
X_d	14.43	13.30	7.25
X_d'	1.25	1.30	4.00
X_d''	0.76	0.69	9.21

The inertia, J, of the SG and turbine rotating masses was calculated based on the experimental data of SG 64-rated load rejection and power rise.

The torque of a DC motor decreases to the value of the load torque (the torque that covers the loss) as the shaft load decreases as well. In this case, the governor limits the angular speed. The accepted assumption about the constancy of the primary motor moment is not met. After the load rejection, the SG goes immediately into damped oscillations mode: motor mode–generator mode.

As a result, oscillations in the primary motor moment appear. Thus, there is a continuous change in the excess torque that sets the acceleration/deceleration of the rotor. A constant change in the moment of the primary motor leads to the fact that the method of estimating the inertia moment is applied at small intervals between the points of the angular velocity time derivative which gives a large spread in the values of inertia moment. The proposed algorithm allows us to obtain the inertia moment at large intervals of angular velocity change with a relative constancy of the excess torque.

The results of the SG 64 parameters calculation are shown in Figures 18 and 19. The values of J = 0 are used as an indicator of time points for which the conditions for estimating the value of J are not met.

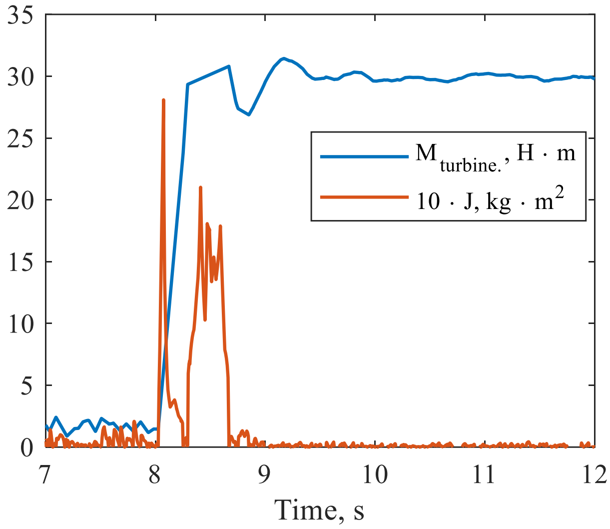

Figure 18. Values of the inertia moment *J* at load rise of SG 64.

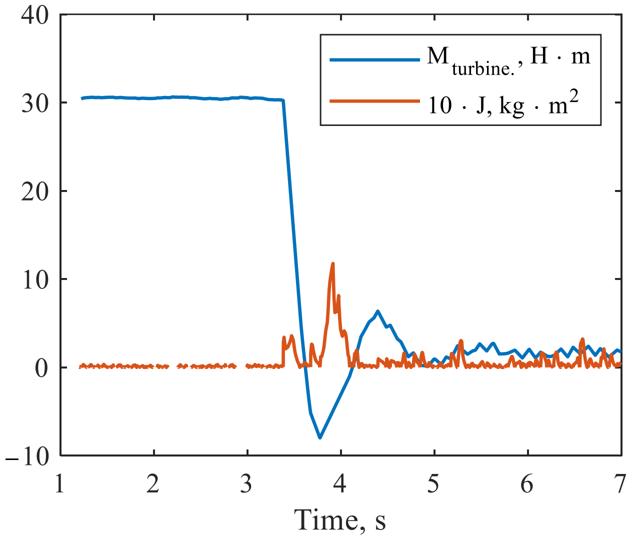

Figure 19. Values of the inertia moment *J* at load rejection of SG 64.

The adaptive model of the synchronous generator makes it possible to determine the value of the moment of inertia (*J*) only in the intervals of transients characterized by a change in the turbine moment that is reflected in Figures 18 and 19. Further research will be aimed at developing a methodology for determining the time intervals for finding the moment of inertia of a synchronous generator and a turbine.

According to the results of load rejection and load rise experiments, the average value of SG and turbine inertia moment was 1.52 kg·m^2, which differs from the reference value by 2%.

6. Conclusions

The calculations to test the methods for determining the SG parameters based on the experimental results were performed. It is confirmed that applied methods allow the instantaneous values of the parameters to be estimated:

- SG load angle;
- d-axis reactance X_d and q-axis reactance X_q for a known value of the torque angle;
- Inertia moment.

The algorithm for estimation of the inertia moment of SG rotating mass and the turbine (drive motor is DC machine) is suitable at the primary motor torque to be constant.

With continuous changes in the primary motor torque, the algorithm application shows unstable results. Primarily, this is due to the rapid change in SG torque (including the SG falling in motor mode and vice versa) the values of which determine the conditional value of the primary motor torque when the time derivative of angular velocity is equal to zero with its small fluctuations.

Further work will be related to the development of a methodology for adaptive emergency control of power system modes based on the estimated data of a synchronous generator. The second direction of further work is the development of a technique that allows the determination of the time interval for the flow of the transient process, leading to the possibility of determining the parameters of a synchronous generator.

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