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An analysis of fault modes in an electrical power-generation system on a real-time simulator with a real automatic excitation controller of a synchronous generator

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Abstract. Excitation controllers of the power plant synchronous generators provide the necessary quality of the terminal voltage, reactive power control and generator stability at different operation modes, such as fault modes and particularly at a short-circuit on the power line. The paper proposes a "hardware-in-the-loop" technology for testing and diagnozing excitation controllers. According to this technology the excitation controller is connected to a computer real-time model of the power system with a synchronous generator. The real-time model of the power system is developed based on a numerical one-step method of average voltages at the integration step characterized by an increased numerical stability and high calculation performance. Research results are presented for the short-circuit states in the power network. They are obtained in a hybrid system with an excitation controller ("ARV-SDP1") connected to the computer real-time model of the power generation system with a synchronous generator. The impact of controller parameters on the damping properties of the synchronous generator excitation system is analyzed.

Keywords: synchronous generator, excitation system, hybrid model, mathematical modelling.

Analiza napak v elektroenergetskem sistemu na simulatorju v realnem času z avtomatskim regulatorjem vzbujanja sinhronskega generatorja

Regulatorji vzbujanja sinhronskih generatorjev zagotavljajo potrebno kakovost napetosti, nadzor jalove moči in stabilnost delovanja v primeru napak. V prispevku je predstavljena metoda strojne opreme v zanki za testiranje in diagnozo regulatorjev vzbujanja. Pri tej metodi je regulator vzbujanja v realnem času povezan na računalniški model električnega omrežja s sinhronskim generatorjem. Model omrežja smo razvili na podlagi numerične integracije povprečnih vrednosti napetosti. Dobljeni rezultati prikazujejo razmere v primeru kratkega stika v omrežju. Uporabili smo hibridni sistem z regulatorjem vzbujanja sinhronskega generatorja. Analizirali smo tudi vpliv parametrov regulatorja vzbujanja.

1 INTRODUCTION

A combination of computer models and physical objects (hardware-in-the-loop technology) in a single system essentially increases the research possibilities. A computer model, in particular, replaces the missing elements of the physical system [1,2,3]. Such hybrid models often combine a real-time computer model of a power part of the generation system with a physical control system. This combination allows testing, diagnostics of the control system and its pre-configuration in case of absence of a control object [4,5]. Computer models of hybrid systems must work in a real-time mode with an increased calculation accuracy and numerical stability [6].

One of the fields of using the hybrid models is power engineering where these models are used as testing tools for control systems [3,4]. In particular, to test an excitation control system of a power generator, the excitation controller is connected to a computer model of the generator unit which includes a generator driven by a turbine, generator transformer and power line to which the parallelly-operating generators are connected [5,7]. It should be noted that the generator excitation system is the main tool for controlling the power generation process. Therefore, testing an excitation system before putting it into operation and its periodic diagnostics are very important.

A hybrid model of a power generation system that combines real control devices and computer models of power schemes is useful for control systems synthesis and training of the power plant staff by using appropriate simulators.

The paper [7] describes a hybrid model of the power generation system on an example of the South-Ukrainian Nuclear Power Plant. The model created and put into operation at this power plant is used to diagnoze and adjust automatic excitation controllers and to train the operation staff. Special issue of the developers and operation staff of a power plant is the operation of an excitation and protection system at faults states resulting

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from a short-circuit on the power line. Simulation of such states in a hybrid system is quite simple and at no significant costs, as opposed to real experiments on a power unit, which is in most cases impossible. The paper analyzes these modes on a hybrid model using a real excitation controller.

2 RESEARCH METHOD

A. The functional scheme

The functional scheme of the hybrid model is shown in Fig. 1. The power scheme of the power generation system is realized in a form of a computer model and the control system (the automatic excitation controller) is real.

The power scheme contains the main synchronous generator (G), auxiliary generator (brushless synchronous machine), equivalent generator (SG2) of the parallel power blocks, turbine (TG), input transformer (TR1) of the main generator excitation system, generator transformers (TR2, TR3), and thyristor converter TC. The main generator is excited by a self-excitation scheme by a brushless exciter (AG), whose field current is controlled by a thyristor converter.

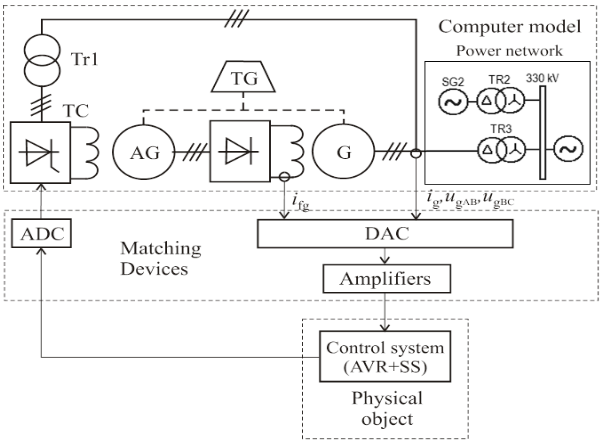


Figure 1. Functional scheme of the hybrid model.

The signals of the generator output terminal voltage (u_{gAB}, u_{gBC}), the generator stator phase current (i_g), the generator field current (i_{fg}) are coming from the computer model to the excitation controller. The control voltage of the controlled rectifier (thyristor converter (TC) in the computer model) is applied from the excitation controller.

The physical automatic excitation controller of the “ARV-SDP1” type of the South-Ukrainian Nuclear Power Plant is used as a control system. It contains control loops for the terminal voltage (automatic voltage controller AVR), frequency and first derivative with respect to the time of the frequency (system stabilizer (SS)). The AVR contains also control channels for the first- and second-time derivatives of generator voltage, and the control channel for the first-time derivative of field current of the synchronous generator. The presence of these channels is typical for the excitation controller of a strong action [10] and provides an intense damping of oscillations at the output of the synchronous generator.

Taking into consideration the transfer functions of the sensory system and data transmission line, the excitation controller is described by the following equation [10]:

$$\begin{aligned}\Delta U_{reg} &= W_B(s)[W_V(s)K_{0U}\Delta U_g\left(K_U + K_{1U}W_{dV}(s)\right) + \\ &+ K_{1If}W_F(s)\Delta I_f - W_{fr}(s)\left(K_{0F} + K_{1F}W_{dfr}(s)\right)\Delta\omega + \\ &+ K_f W_{Uf}(s)\Delta U_f\,]\end{aligned} \quad , \quad (1)$$

where $W_B(s)$ is the amplifier transfer function; $W_V(s)$ is the transfer function of the voltage control unit; $W_{dV}(s)$ is the transfer function of the voltage differentiator channel; $W_F(s)$ is the transfer function of the field current derivative control unit; $W_{fr}(s)$ is the transfer function of the frequency regulation unit; $W_{dfr}(s)$ is the transfer function of the frequency differentiator channel; $W_{Uf}(s)$ is the transfer function of the excitation voltage feedback; ω is the angular frequency of the generator terminal voltage; K_{0U}, K_{1U}, K_{1If}, K_{0F}, K_{1F}, K_{Uf} are the tuning coefficients.

According to Eq. 1, the schematic diagram of excitation controller is shown in Fig. 2 [10].

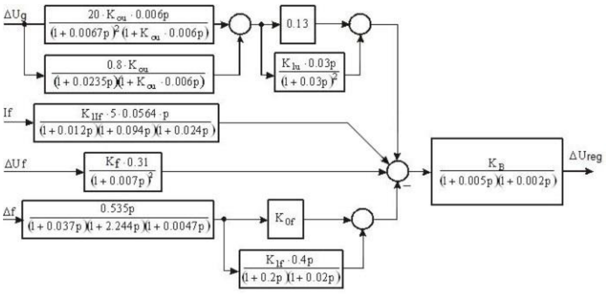


Figure 2. Schematic diagram of the excitation controller.

The parameters of the excitation controller used in the hybrid model are given in the appendix.

The matching devices provide a communication between the computer model and the excitation controller. Their functions are: analog-to-digital and digital-to-analog conversion (the excitation controller is analog) and matching the signal level and amplification.

B. The basic principles of the mathematical model creation

The mathematical model of the power part of a power generation system is set up based on the numerical one-step method of average voltages at the integration step [8]. The features of this method are high calculation accuracy and numerical stability.

Using this method provides algebraization of differential equations describing typical elements of electric systems and determines the currents of the branches at the end of the integration step for a known average at the step values of the applied voltages, current derivative (for the first-order method, current derivatives are not necessary) and initial conditions. The current derivatives are calculated according to the theory of mathematical modeling of electromechanical systems described in [9].

C. Mathematical models of the power scheme elements

The mathematical model of the synchronous machine is made in phase coordinates and takes into account the non-linearity of the magnetic circuit characteristics, and the impact of the rotor damper system. The calculation scheme of a synchronous machine as eight-pole is shown in Fig. 3. The damping system of the synchronous machine is represented by two short-circuited windings oriented on axes d and q.

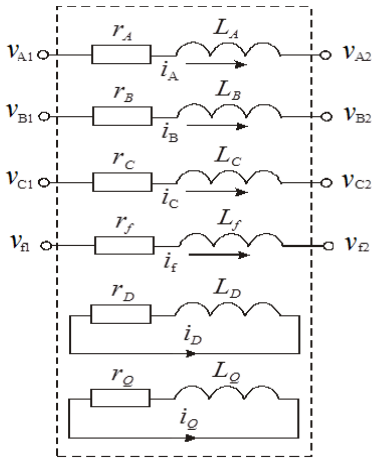


Figure 3. Calculation scheme of the synchronous machine.

The equation for the stator and excitation circuits of the synchronous machine (external circuits) using the second-order method is written as:

$$\frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t}\vec{v}^{I}dt-\frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t}\vec{v}^{II}dt-\breve{R}_{ee}\vec{i}_{ee0}+\frac{\breve{R}_{ee}}{3}\vec{i}_{ee0}- \qquad (2)$$

$$-\frac{\breve{R}_{ee}\Delta t}{6}\frac{di_{ee0}}{dt}-\frac{\breve{R}_{ee}}{3}i_{ee1}-\frac{1}{\Delta t}\left(\vec{\psi}_{ee1}-\vec{\psi}_{ee0}\right)=0$$

The equation for the internal circuits of the synchronous machine is written as:

$$\breve{R}_{ii}\vec{i}_{ii0}-\frac{\breve{R}_{ii}}{3}\vec{i}_{ii0}+\frac{\breve{R}_{ii}\Delta t}{6}\frac{di_{ii0}}{dt}+\frac{\breve{R}_{ii}}{3}\vec{i}_{ii1}+\frac{1}{\Delta t}\left(\vec{\psi}_{ii1}-\vec{\psi}_{ii0}\right)=0$$

(3)

where $\vec{v}^{I}=\left(v_{A1},v_{B1},v_{C1},v_{f1}\right)^T$, $\vec{v}^{II}=\left(v_{A2},v_{B2},v_{C2},v_{f2}\right)^T$ are the vectors of the terminals potentials; $\vec{i}_{ee}=\left(i_A,i_B,i_C,i_f\right)^T$, $\vec{i}_{ii}=(i_D,i_Q)^T$ are the vectors of the currents in the internal and external branches; $\vec{\Psi}_{ee}=\left(\Psi_A,\Psi_B,\Psi_C,\Psi_f\right)^T$ $\vec{\Psi}_{ii}=(\Psi_D,\Psi_Q)^T$ are the vectors of flux linkages; $\breve{R}_{ii}=diag\left(r_D,r_Q\right)$, $\breve{R}_{ee}=diag\left(r_A,r_B,r_C,r_f\right)$are the matrices of the winding resistances. Indices 0 and 1 are the value of the variable at the beginning and at the end of the integration step.

The flux linkage changing of the external and internal circuit of the synchronous machine at the integration step is:

$$\vec{\psi}_{ee1}-\vec{\psi}_{ee0}=\breve{L}_{ee1}\cdot\vec{i}_{ee1}+\breve{L}_{ei1}\cdot\vec{i}_{ii1}-\breve{L}_{ee0}\cdot\vec{i}_{ee0}-\breve{L}_{ei0}\cdot\vec{i}_{ii0}\,, \qquad (4)$$

$$\vec{\psi}_{ii1}-\vec{\psi}_{ii0}=\breve{L}_{ii}\cdot\vec{i}_{ii1}+\breve{L}_{ie1}\cdot\vec{i}_{ee1}-\breve{L}_{ii}\cdot\vec{i}_{ii0}-\breve{L}_{ie0}\cdot\vec{i}_{ee0}\,, \qquad (5)$$

where $\vec{L}_{ee}$ is the matrix (4×4) of the self- and mutual inductances of the external circuit in which the diagonal elements are the self-inductances of the phase and field winding, and all the others are the mutual inductances of appropriate windings; $\vec{L}_{ei},\vec{L}_{ie}$ are the matrices of the mutual inductances between the external and internal circuit; $\breve{L}_{ii}=diag\left(L_{DD},L_{QQ}\right)$ is the matrix of the damper system inductances. These inductances are calculated on the basis of electromagnetic parameters of the synchronous generator and rotor angle.

When taking into consideration the non-linearity of the magnetic circuit characteristic, the mutual inductance (L_{ad}) is the function of magnetization current (given as a table for the magnetization curve).

Eqs. (2) and (3) using Eqs. (4) and (5) are written as:

$$\frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t}\vec{v}^{I}dt-\frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t}\vec{v}^{II}dt-\breve{R}\vec{i}_{ee1}-E=0\,, \qquad (6)$$

where

$$\vec{E}=\frac{\breve{R}_{ee}\Delta t}{6}\frac{di_{ee0}}{dt}-\frac{\breve{L}_{ei1}\breve{R}_{ii}^{*-1}}{\Delta t}\frac{\breve{R}_{ii}\Delta t}{6}\frac{di_{ii0}}{dt}+\left(\breve{R}_{ee}-\breve{R}_{ee0}^{*}+\frac{\breve{L}_{ei1}\breve{R}_{ii}^{*-1}\breve{L}_{ie0}}{\Delta t^2}\right)\vec{i}_{ee0}-$$

$$-\left(\frac{1}{\Delta t}\breve{L}_{ei0}-\frac{1}{\Delta t}\breve{L}_{ei1}+\frac{1}{\Delta t}\breve{L}_{ei1}\breve{R}_{ii1}^{*-1}\breve{R}_{ii}\right)\vec{i}_{ii0}$$ is the step e.m.f. determined by the initial conditions; $\breve{R}_{ee0}^{*}=\left(\frac{\breve{R}_{ee}}{3}+\frac{\breve{L}_{ee0}}{\Delta t}\right)$, $\breve{R}_{ee1}^{*}=\left(\frac{\breve{R}_{ee}}{3}+\frac{\breve{L}_{ee1}}{\Delta t}\right)$ are the matrices of the step resistances of the external circuit at the beginning and end of the step; $\breve{R}_{ii}^{*}=\left(\frac{\breve{R}_{ii}}{3}+\frac{\breve{L}_{ii}}{\Delta t}\right)$ is the matrix of the step resistance of the internal circuit; $\breve{R}=\breve{R}_{ee1}^{*}-\breve{R}_{ii1}^{*-1}\frac{\breve{L}_{ie1}\breve{L}_{ei1}}{\Delta t^2}$.

Eq. 6 allows to determine the currents of the external and internal circuit at the end of the step based on the current values at the beginning of the step ($\vec{i}_{ee0}$ and $\vec{i}_{ii0}$), average at the step values of the terminal potentials and electromagnetic parameters of the generator winding.

The rotor speed is determined from the equation of the mechanical state: $J\dfrac{d\omega}{dt}=T_g+T_t$,

where T_g is the electromagnetic torque of the machine, J is the moment of inertia of the unit, T_t is the turbine torque determined by taking into consideration the action of the active-power controller and speed controller as part of the turbine control system.

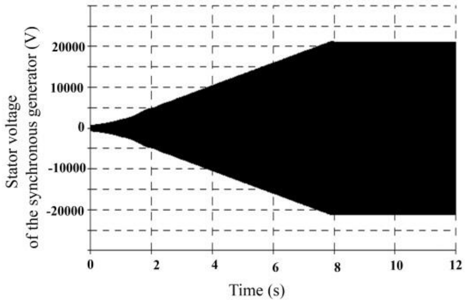
The semiconductor switches are presented as a serial connected resistance and inductance with a low value in the "on" state and a high value in the "off" state. The switch turns off at the time its current crosses zero from the positive to the negative value (these times are calculated by solving algebraic equations for the current of the commutating switch). The switch "turn-on" times are defined from logical equations on the basis of the information received from the excitation controller.

The described models of the elements are connected in the power scheme model according to the algorithm described in [7].

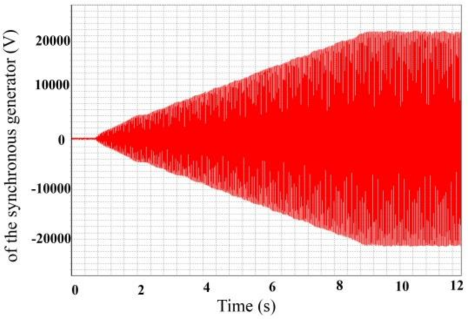
The original object-oriented program environment [11], realised on C++, is used to create the computer model as a combination of objects – models of typical elements (synchronous machine, semiconductor converter, power transformer, power line, etc.).

3 RESEARCH RESULTS

The adequacy of the developed hybrid model is assessed by comparing the simulation and experimental results obtained from the South-Ukrainian Nuclear Power Plant. In Figs. 4 and 5 they are shown for the generator initial excitation regime. The nature of the increase in the generator voltage in this mode is defined by the action of the excitation controller and is practically the same as in the hybrid model, where the excitation controller works with a power-system computer model, and on experimental oscillograms. The mean-square deviation for the characteristic points is about 8%, which is a good result.

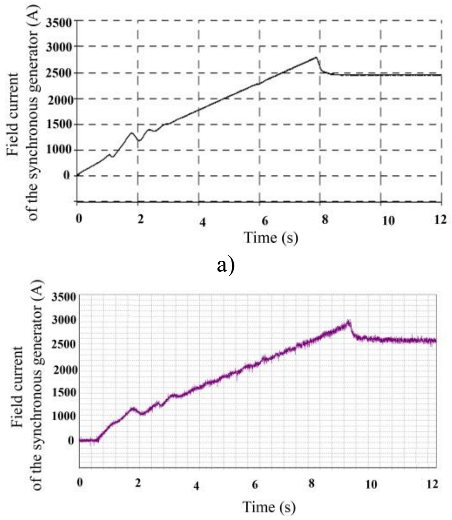


a)



b)

Figure 4. Stator voltage of the synchronous generator: a – hybrid modeling results, b – experimental results.



a)

b)

Figure 5. Field current of the synchronous generator: a – hybrid modeling results, b – experimental results.

Fig. 6 shows the obtained hybrid model oscillograms of a long-term three-phase short circuit on the terminals of the generator transformer (TR3).

The short circuit continues for 0.1 s with a further protection act and comes back to a normal mode. This is the worst type of the fault mode. It is characterized by an increase in the stator current (Fig. 6.b, Fig. 8.b) and a decrease in the stator voltage of the synchronous generator (Fig. 6.a, Fig. 8.a). At a short circuit, the excitation controller increases the field current of the synchronous generator following the decrease in the terminal voltage (Figs. 6.d and 7.d). The excitation is performed to hold the generator in synchronism in case of a decrease in the average value of the generator electromagnetic torque due to a short circuit (Fig. 6.c) and an increase in the rotation speed. The disadvantage of the self-excitation system is that there is no possibility of forcing excitation at a short circuit (Figs. 6.e and 7.e) due to the low level of the terminal voltage which is the input voltage of the controlled rectifier.

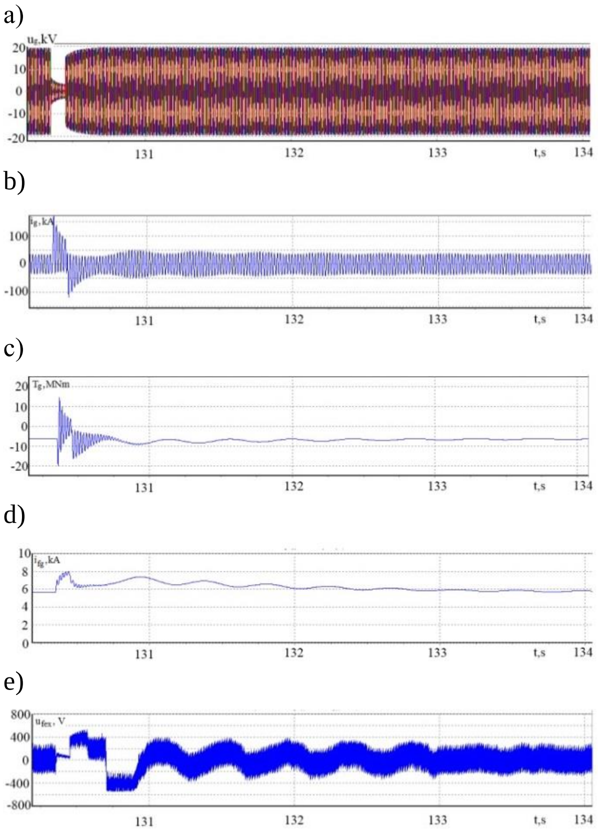


Figure 6. Stator voltage (a), stator current (b), electromagnetic torque (c) and field current (d) of the synchronous generator, field voltage (e) of the exciter in a three-phase short-circuit fault mode on the terminals of the synchronous generator transformer.

The oscilograms of a two-phase short circuit on the power line are shown in Fig. 7. The duration of the short circuit is 0.08 s. In this case, the increase in the stator current (Fig. 7.b) and the decrease in the stator voltage of the synchronous generator are low (Fig. 7.a) as determined by the distance of the synchronous generator from the point of the short circuit occurrence.

In the short-circuit fault mode, there are considerable fluctuations of the electromagnetic torque (Fig. 7.c) and a notable decrease in the average value of the electromagnetic torque (approximately down to zero in case of a three-phase short circuit on the terminals of a synchronous generator transformer) because of the interrupted generator synchronous operation with the power line at a short circuit. In case of a two-phase short circuit, the peak value of the electromagnetic torque at the beginning of the short circuit exceeds the torque nominal value 2.2 times. Stator current in a transient mode has an aperiodic component (Fig. 8.b) which depends on the moment of the short-circuit occurrence.

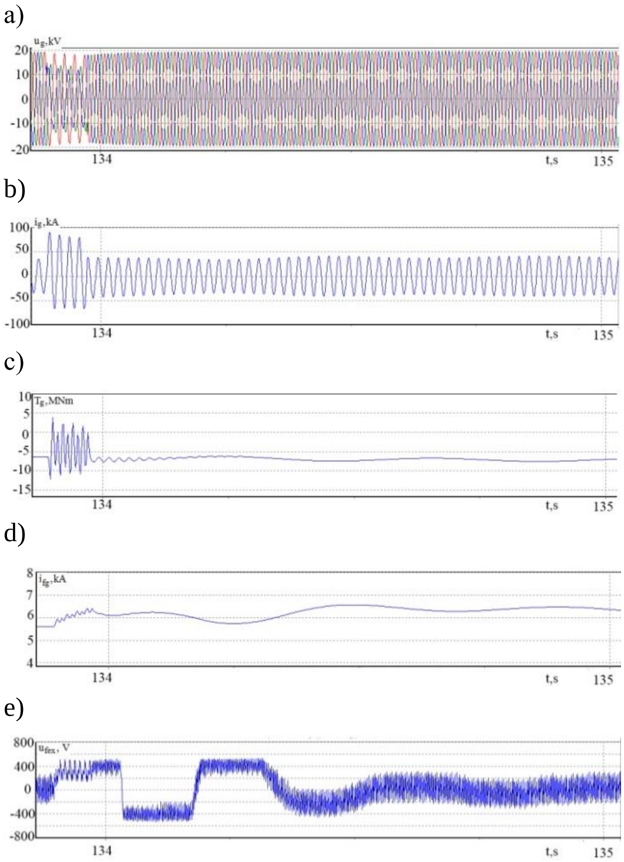


Figure 7. Stator voltage (a), stator current (b), electromagnetic torque (c) and field current (d) of the synchronous generator, field voltage (e) of the exciter in case of a two-phase short circuit on the power line.

By connecting the excitation controller to the power-scheme computer model the effect of setting the excitation controller to the quality of transient processes is analyzed.

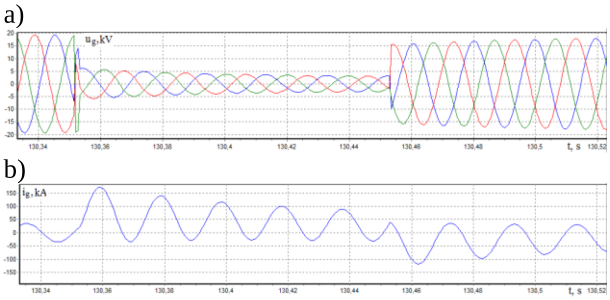


Figure 8. Stator voltage (a), stator current (b) of the synchronous generator in a three-phase short-circuit fault mode on the power line.

The gain coefficient of the generator voltage (K_{ou}), the gain coefficient of the first-time derivative of field current (K_{1If}) and the gain coefficient of the field voltage (K_f) significantly affect the damping quality. Using the described hybrid modeling approach allows choosing the necessary values of these coefficients.

4 CONCLUSION

To analyze a short-circuit fault mode in a power generation system and set a turbogenerator excitation controller in a power plant, a new approach is proposed. In this approach, an excitation controller is connected to a real-time computer model of the power scheme. Using the proposed numerical one-step method of average voltages at the integration step ensures a high numerical stability and calculation accuracy by taking into account the nonlinearity of the synchronous generator and semiconductor converters.

Our analysis confirms the high damping properties of the used strong-action excitation controller ensuring the power generator in synchronization with a fast of restoration (up to 4 s) of the operating mode at a most critical type of a long duration three-phase short circuit on the transformer terminals.

APPENDIX A

The parameters of the power scheme of the electric power generation system are:

The main synchronous generator (TBB-1000): the nominal power (S_n) is 1111 MVA; the nominal voltage (U_n) is 24000 V; the nominal current (I_n) is 27230 A; the field current in a no-load regime (i_f) is 2300 A, the field current in nominal regime (i_{fn}) is 7030 A, the resistance of the field winding (r_f) is 0.057 Om; the reactance (X_d) is 2.35 r.u.; the moment of inertia (J) is 600000 kgm^2.

The auxiliary generator (BVD-4600-1500): the nominal power (P_n) is 4 MW, the nominal voltage (U_n) is 518 V; the nominal current (I_n) is 7750 A; the resistance of the field winding (r_f) is 0.37 Om, the reactance (X_d) is 1.31 r.u, the nominal frequency is 150 Hz, and the moment of inertia (J) is 20000 kgm^2.

The parameters of the excitation controller are: K_{ou} is 30, K_{1u} is 1.0, K_{1If} is 1.5, K_f is 1.0, and K_{1f} is 0.5.

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