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doi:10.15199/48.2019.01.56

Control of synchronous machines set with microprocessor-controlled excitation units in high-voltage tests station

***Abstract**. The paper presents idea and implementation of the control of synchronous motor-synchronous generator machines set used for supplying the high-voltage test station in the electrical equipment repair and service plant. In the excitation circuits of both machines the microprocessor-controlled excitation units were used. Possibilities of generator output voltage regulation by the field current control in the synchronous state of operation were introduced. Simulation model of Matlab-Simulink and results of simulation research was shown. Exemplary realization was disclosed. Verification measurements of the real machines set in the start-up process and synchronous state of operation were presented and discussed.*

Streszczenie.** W artykule przedstawiono realizację sterowania zespołem napędowym silnik synchroniczny - generator synchroniczny przeznaczonym do zasilania stacji prób wysokonapięciowych. W obwodach wzbudzenia obu maszyn zastosowano mikroprocesorowo sterowane bloki zasilania wzbudzenia. Przedstawiono możliwości sterowania napięciem wyjściowym. Zamieszczono model symulacyjny oraz wyniki badań symulacyjnych. Zaprezentowano przykładowe wdrożenie. Przedstawiono wyniki pomiarów w układzie rzeczywistym. **(Układ sterowania zespołem napędowym maszyn synchronicznych z mikroprocesorowo sterowanymi blokami wzbudzenia w stacji prób wysokonapięciowych)

Keywords: synchronous motor, synchronous generator, excitation, microprocessor control, voltage regulation, excitation
Słowa kluczowe: silnik synchroniczny, generator synchroniczny, sterowanie mikroprocesorowe, regulacja napięcia, układ wzbudzenia

Introduction

Electrical equipment repair and service plants perform various types of tests of examined equipment such as power transformers, generators, motors etc. There are often few hours tests with the strictly defined, required for the specific test voltage. The specificity of performed tests requires that it is possible to continuously adjust voltage in the range of tens of kilovolts. At the same time the voltage change on the test bench due to changes in load parameters should be compensated by the automatic control system.

These requirements can be met by the use of the synchronous generator with automatic, follow-up excitation circuit current control system cooperating with a suitable high-voltage transformer. The presented machines set with automatic control system was implemented in one of the Polish electrical equipment repair and service plant to supply high-voltage test station.

System idea

Figure 1 shows the block diagram of the synchronous motor-synchronous generator machines set with microprocessor-controlled power supply excitation units of both machines [1].

At the steady synchronous operation the synchronous machine can be described by a system of equations, which using per unit values is in the form [2-4]:

$$
\begin{aligned}
u_d &= r_s i_d - \omega_m \psi_q = r_s i_d - \omega_m x_q i_q \\
u_q &= r_s i_q + \omega_m \psi_d = r_s i_q + \omega_m x_d i_d + \omega_m x_{df} i_f \\
u_f &= r_f i_f \\
\psi_d &= x_d i_d + x_{df} i_f \\
\psi_q &= x_q i_q \\
m &= \psi_d i_q - \psi_q i_d
\end{aligned} \tag{1}
$$

where: u_d, u_q – stator voltages in d and q axis, i_d, i_q – stator currents in d and q axis, Ψ_d, Ψ_q – rotor magnetic flux linkages in d and q axis, x_d, x_q – synchronous reactances in d and q axis, x_{df} – stator d axis and field mutual reactance, ω_m - angular rotor speed, r_s – stator resistance, r_f – field resistance, u_f – excitation voltage, i_f – field current, m – load torque.

For the motor, the input values are voltages u_d, u_q, u_f and output value is rotational speed ω_m. For generator the input values are rotational speed ω_m and excitation voltage u_f and output values are voltages u_d, u_q.

The motor's load is the generator. The generator's load is dependent on power consumed by the connected device according to the equation

$$m = \frac{p}{\omega_m}, \tag{2}$$

where p – active power.

Assuming a constant shaft rotational speed of coupled machines with synchronous rotational speed, the generator output voltage regulation can be achieved by changing the current in the excitation circuit. The task of the motor is to provide adequate active power to the system.

Developed in cooperation with the author microprocessor-controlled power supply excitation unit for synchronous motor [1] realizing among others the field current control in standard version is equipped with reactive power and excitation current controllers. The device has been designed to supply excitation circuits of 6 kV synchronous machines with field current up to 400 A.

Using this device for generator output voltage control by the excitation current control required modifications in the control algorithm procedure. The hardware of the device remained unchanged.

In the start-up system of both machines instead of commonly used contactors, the devices use transistor switches to connect and disconnect inrush resistor in configuration which allows the flow of bi-directional induced transient current in the excitation winding during the motor start-up. The appropriate control strategy of thyristor rectifier and inrush resistor [5] improves the reliability and allows the long-lasting, trouble-free operation of machines set.

The use of microprocessor-controlled power supply excitation unit in the motor drive system allows to control motor's reactive power given from the operator panel, on the basis of 4-20 mA signal from any master device or on the basis of time characteristics defined in the device. The proper field current control algorithms taking into account limitations associated with the limit values of the excitation and stator currents and built-in excitation current forcing procedure during the supply voltage dips [6] allow safe synchronous motor operation in terms of allowable active power load.

The main controlled value of the system shown in Figure 1 is the output voltage on the high voltage side of the transformer. The voltage measurement can be carried out on the secondary side or on the primary side of the transformer with taking into account the transformer voltage ratio.

The generator driven by the motor in steady state is running at synchronous rotational speed. In this case, it is necessary to control only the limitations of the stator and the excitation currents of the generator realized by the microprocessor-controlled power supply excitation unit. The output voltage control range of the motor - generator machines set can be determined based on the static characteristics of both machines. To specify the behavior of the machines set in transient states the simulation tests are required.

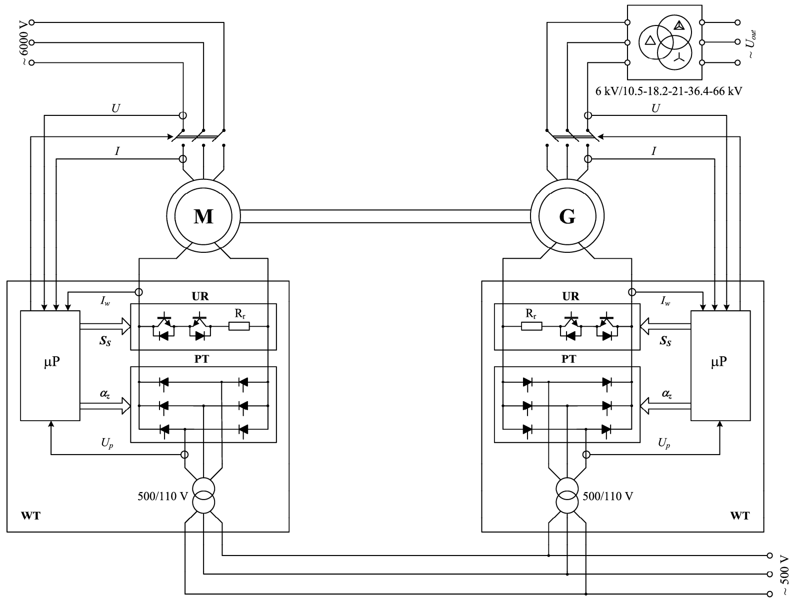

Fig.1. Block diagram of the machines set: M – synchronous motor, G – synchronous generator, WT - microprocessor-controlled power supply excitation unit, μP - microprocessor system, PT - thyristor rectifier, UR - start-up system, R_r – start-up resistor

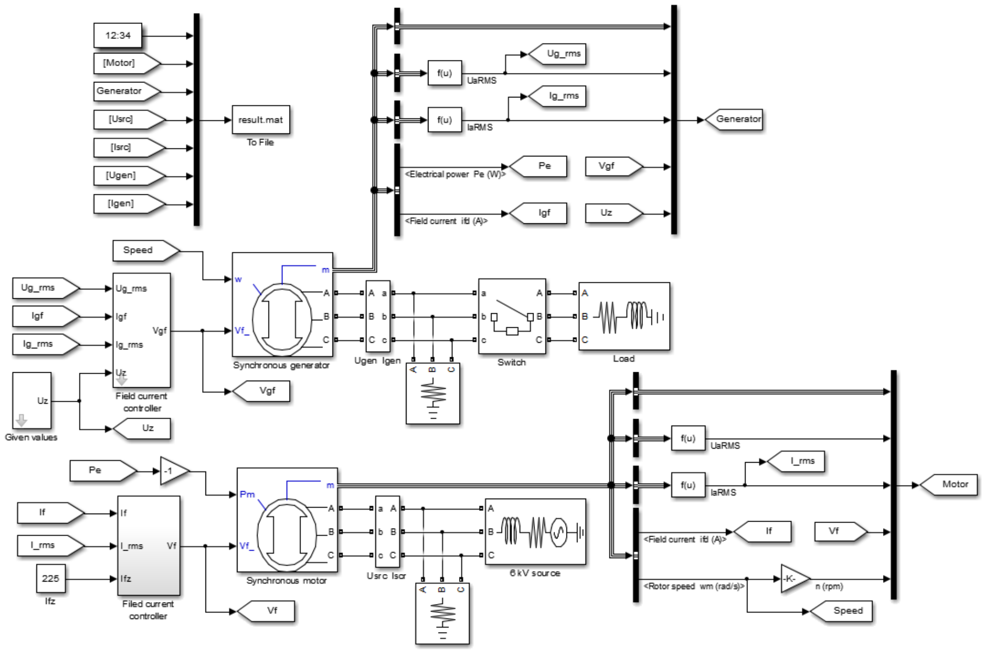

Fig.2. The simulation model of synchronous motor - synchronous generator machines set of Matlab-Simulink

Simulation researches

In order to determine the behavior of the machines in transient states and tuning of microprocessor control system controllers, the simulation model of synchronous motor-synchronous generator machines set, shown in Figure 2 was developed. Simulation studies were performed using Matlab-Simulink.

The motor's excitation current and the generator's output voltage regulation procedures with constraints resulting from the rated values of the stator and field current of both machines were implemented in the model. Motor and generator rated data are shown in Tables 1 and 2.

During the simulation the given value of the motor excitation current was assumed as 225 A ($0.9I_{fN}$). Maximum voltage value in the generator excitation winding was limited to 87.6 V ($1.2U_{fN}$).

Table 1. Rated data of GAe1610r/01 synchronous motor

Parameter	Value
Active power	2500 kW
Stator voltage	6000 V
Stator current	273 A
Excitation voltage	87 V
Field current	250 A
Frequency	50 Hz
Rotation speed	600 rpm
Power factor	0.9

Table 2. Rated data of GYd-1710sp/02 synchronous generator

Parameter	Value
Apparent power	3500 kW
Stator voltage	6300 V
Stator current	320 A
Excitation voltage	73 V
Field current	401 A
Frequency	50 Hz
Rotation speed	600 rpm
Power factor	1-0.1

Table 3. Output voltage and current of GYd-1710sp/02 generator for various winding connection types

Connection type	Output voltage		Output current	
star	U_N	6300 V	I_N	320 A
delta	$\frac{U_N}{\sqrt{3}}$	3637 V	$\sqrt{3}I_N$	554 A
double star	$\frac{U_N}{2}$	3150 V	$2I_N$	640 A
double delta	$\frac{U_N}{2\sqrt{3}}$	1818 V	$2\sqrt{3}I_N$	1108 A

The generator stator windings are made in the form of split windings, so that the machine can work with different output voltages and currents. The output current and voltage values for the various generator windings configuration are shown in Table 3. For simulation studies the star (Y) windings configuration was assumed.

Signals indicating of actual winding configuration are led to the microprocessor-controlled excitation unit in generator. This makes it possible to determine the values of stator voltage and current flowing through the stator windings based on the measured generator output voltage and current.

There are many strategies to control excitation of the generator, including advanced methods using adaptive algorithms, fuzzy logic and neural networks [7-15] especially when the generator is one of the many energy distribution system components. In the described implementation the generator works stand alone.

The considered generator is characterized by a relatively large time constant of the field winding, which results in slow response to changes of excitation voltage. Tests carried out at the test station does not require a high dynamic of the control system. It is sufficient to maintain a required voltage of generator for a long time and possible correction e.g. as a result of object parameters changes caused by heating of winding. There are also carried out tests involving gradual, relatively slow voltage increase during load current measurement. For this reason, the software of the generator's microprocessor system uses a simple PID type voltage controller with the ability to operate in PI mode [16-19].

Figure 3 shows simulation results for generator stator windings in open-circuit mode of operation and given line-to-neutral voltage surges in the range of 0-1454 V, which corresponds to the phase-to-phase voltage of 0-2519 V (0-0.4U_N), and Figure 4 in the range of 0-3637 V which corresponds to the phase-to-phase voltage of 0-6300 V (0-U_N). Due to the absence of current in the stator windings of the generator, and consequently the absence of motor load by no active power in the generator, the motor stator current remained at a constant value of 78 A.

Figure 5 shows the simulation results for generator loaded by the RL type load with apparent power equal to the generator nominal apparent power and power factor $\cos\varphi$=0,83 and a given voltage surges such as conditions in Figure 4 (0-0.4U_N), and Figure 6 for voltage changes specified as conditions in Figure 5 (0-U_N).

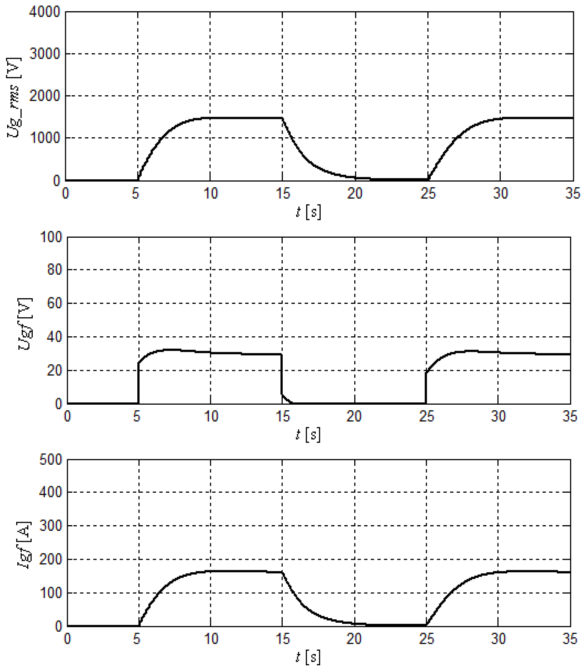

Fig.3. Simulation results for generator stator windings in open-circuit mode of operation and given voltage changes in range 0-0.4U_N: *Ug_rms* - generator RMS line-to-neutral voltage, *Ugf* - generator excitation voltage, *Igf* - generator field current, *I_rms* - motor RMS stator current

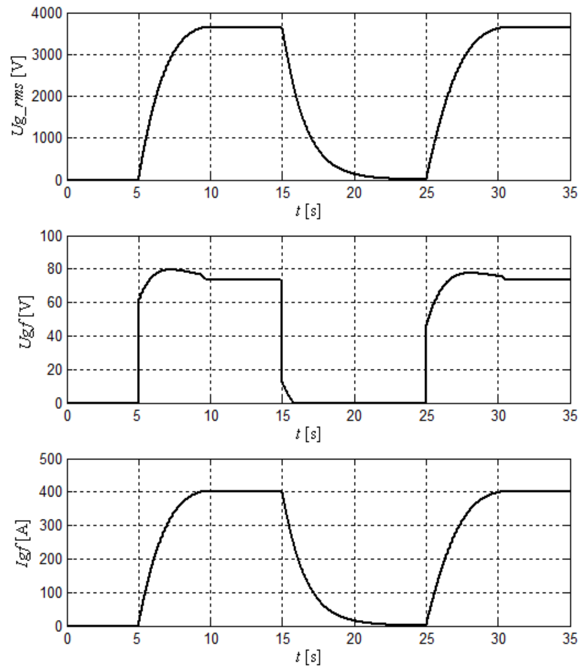

Fig.4. Simulation results for generator stator windings in open-circuit mode of operation and given voltage changes in range 0-U_N: *Ug_rms* - generator RMS line-to-neutral voltage, *Ugf* - generator excitation voltage, *Igf* - generator field current, *I_rms* - motor RMS stator current

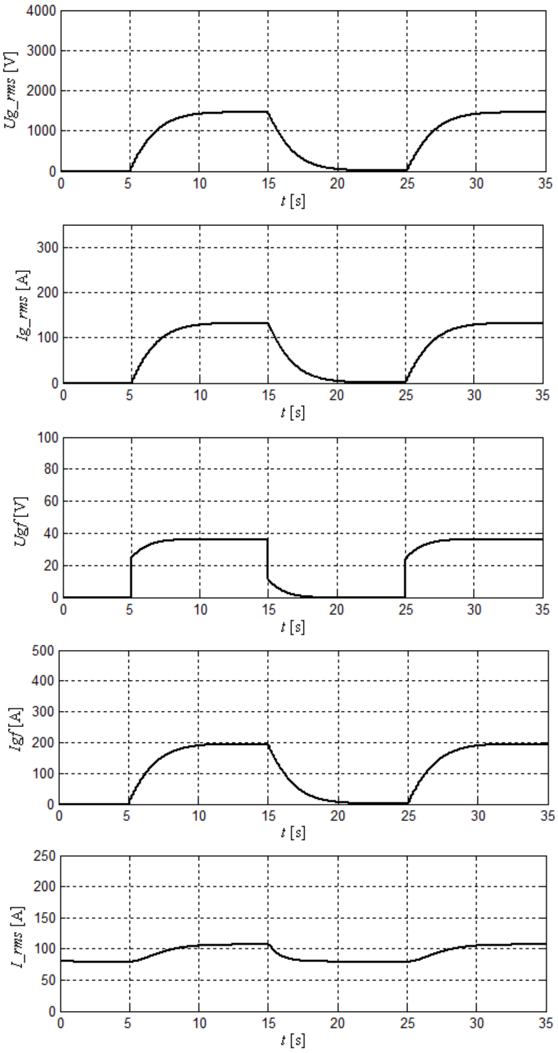

Fig.5. Simulation results for generator loaded by the RL type load and given voltage surges in range 0-0.4U_N: *Ug_rms* - generator RMS line-to-neutral voltage, *Ig_rms* - generator RMS stator current, *Ugf* - generator excitation voltage, *Igf* - generator field current, *I_rms* - motor RMS stator current

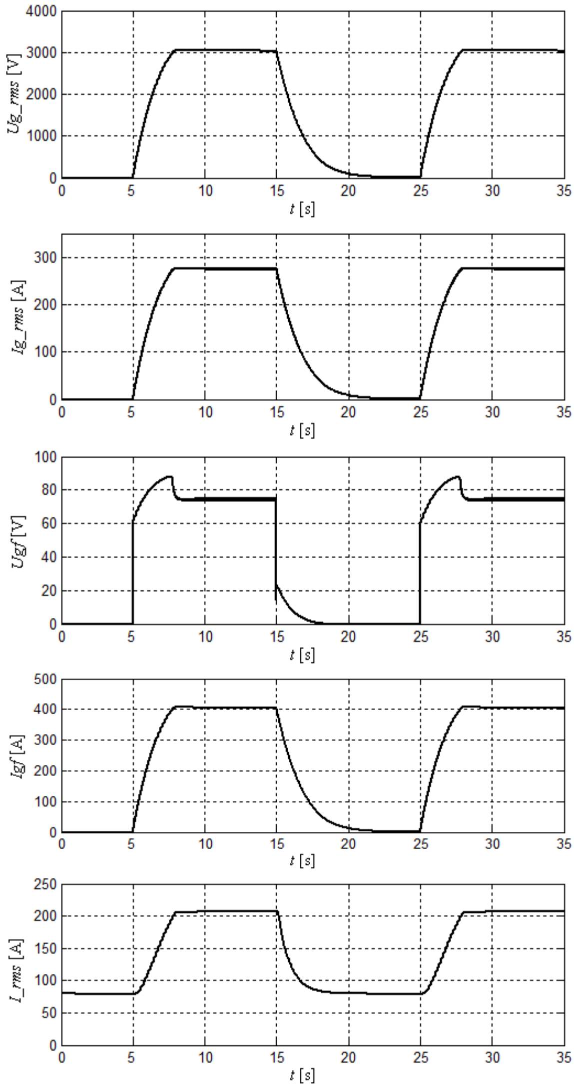

Fig.6. Simulation results for generator loaded by the RL type load and given voltage surges in range 0-U_N: *Ug_rms* - generator RMS line-to-neutral voltage, *Ig_rms* - generator RMS stator current, *Ugf* - generator excitation voltage, *Igf* - generator field current, *I_rms* - motor RMS stator current

As can be seen in Figure 6 the generator field current was reduced to the nominal value by the correction block of the controller responsible for controlling the field current. Therefore it was not possible to achieve the given nominal voltage value.

With the increase in the load active power the stator current increase in relation to the field current and the decisive role takes up the limitation related to the stator current rated value. By the increasing the load of generator active power, the motor load increases too, and the motor stator current also increase.

There were also carried out simulation tests for the generator stator windings in a short circuit mode of operation. In this case, it is not possible to control the generator by using a voltage controller. To investigate the impact of changes in the field current to the short-circuit current in a generator the field current controller was used.

Figure 7 shows the simulation results for the generator stator windings in a short circuit mode of operation and given field current surges in the range of 0-200 A (0-0.5I_{fN}).

As can be seen in Figure 7 under the action of the correction block associated with the stator current rated value the field current has been reduced to the value of 130 A, resulting with limiting of the stator current value to 320 A (I_N).

The simulation research allowed to determine the behavior of the machines set at the forced changes of controlled values and tuning of controllers and correction blocks associated with the rated values of currents.

Measurement verification

Presented system was developed and implemented in one of the electrical equipment repair and service plant in Poland by JJA Progress company in cooperation and under the supervision of the author.

Operation of the machines set starts from the start-up of the motor when generator is switched off. Figure 8 shows the waveforms measured during motor start-up procedure executed by the microprocessor-controlled power supply excitation unit for motor [1, 20].

The microprocessor controls the switch in the 6 kV switchgear station for motor supplying. At the initial start-up phase the start-up resistor is connected to the motor excitation winding. Its task is to limit the voltage in the excitation winding during high slip machine operation. After reaching rotational speed close to the synchronous rotational speed the thyristor rectifier is switching-on to the excitation circuit and start-up resistor is disconnected.

After pulling-up the rotor to synchronous operation the microprocessor system realize the reactive power or field current regulation algorithm. For the case shown in Figure 8 after switching-on of the excitation voltage the thyristor converter operates with firing angle corresponding to the nominal field current for 3 seconds.

Next, the field current is reduced to a preset value, resulting from the implemented reactive power or field current regulation procedure.

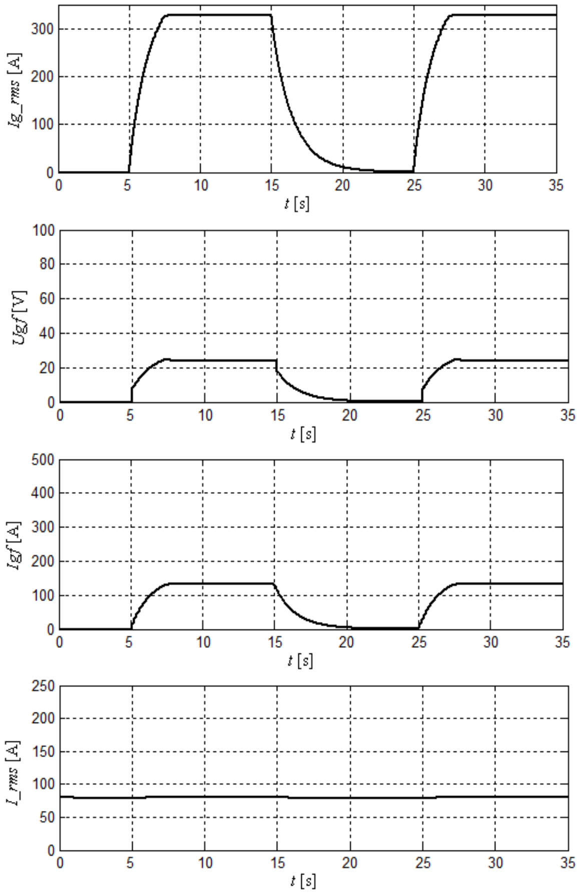

Fig.7. Simulation results for the generator stator windings in a short circuit mode of operation and given field current surges in range $0.5I_{fN}$: *Ig_rms* - generator RMS stator current, *Ugf* - generator excitation voltage , *Igf* - generator field current, *I_rms* - motor RMS stator current

The motor starting process shown in Figure 8 can be considered as difficult conditions start-up process due to high moment of inertia caused by the mass of the machines set rotating elements of about 20 tons and finite short-circuit power of switchgear station. On the other hand, a large moment of inertia of the rotating mass improves stability of the machines in the case of generator load changes during the synchronous operation. The power supply grid impedance significantly reduces inrush current, but the drop of the motor supply voltage causes a significant reduction of starting torque [20].

Near-synchronous rotational speed is achieved about 16 seconds after switching-on the motor supply voltage. Start-up procedure executed by a microprocessor-controlled motor excitation supply unit was realized as timed mode [20]. Control of the generator output voltage by the generator's microprocessor-controlled excitation unit is possible during a synchronous operation of machines set.

Figure 9 presents the results of measurements of the generator in star (Y) windings configuration and in the short-circuit mode of operation. Changes of generator field current were forced in the range 0-130 A (0-0.33I_{fN}) so as to achieve a change of the stator current in the range 0-320 A (0-I_N).

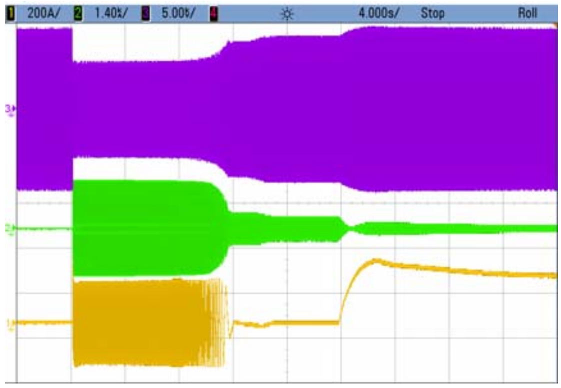

Fig.8. Start-up procedure of motor of machines set: 1 – current of excitation circuit, 2 - stator current, 3 - phase-to-phase voltage at the switchgear station

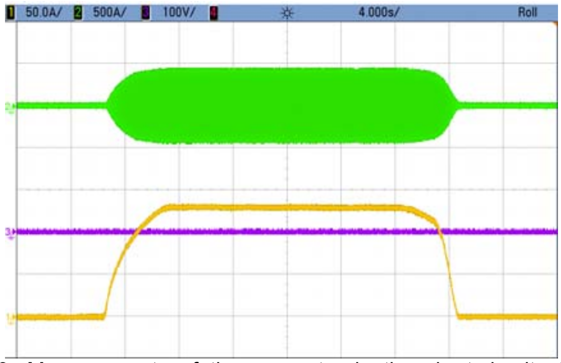

Fig.9. Measurements of the generator in the short-circuit stator windings mode of operation: 1 – field current, 2 – stator current, 3 - stator phase-to-phase voltage

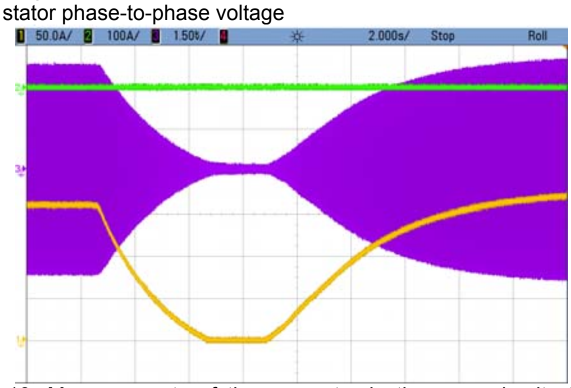

Fig.10. Measurements of the generator in the open-circuit stator windings mode of operation: 1 – field current, 2 – stator current, 3 - stator phase-to-phase voltage

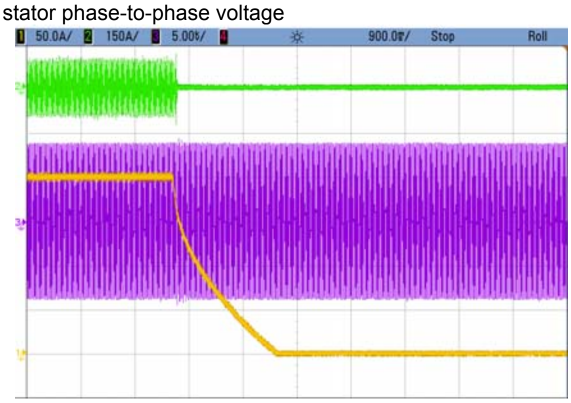

Fig.11. Discharging excitation circuit energy during engine shutdown: 1 – field current, 2 - stator current, 3 - phase-to-phase voltage at the switchgear station

Figure 10 shows the results of measurements of the generator in star (Y) windings configuration and in the open-circuit mode of operation and forced changes of field current. The filed current was changed in the range of 0-160 A (0-0.4I_{fN}) which resulted in a change of the generator output voltage in the range 0-2.6 kV (0-0.4U_N).

Turning off the machines set is done by opening the 6 kV switches of both machines and executing the procedure for discharging energy from the excitation circuits. For this purpose the thyristor converters of excitation supply units of motor and generator are driven to inverter operation. The excitation circuit energy discharging procedure prevents the thyristor rectifier to arc-through work [5]. The excitation circuit energy discharging process after turning off the stator supply voltage of the engine is shown in Figure 11.

Summary and conclusions

The article presents simulation researches and practical implementation of control system of synchronous machines in high-voltage tests station.

Developed synchronous motor-synchronous generator machines set control system enables smooth adjustment of the generator output voltage. It also allows automatic voltage fluctuations compensation caused by generator load changes.

Procedures of automatic reactive power control implemented in the motor of the machines set allow to use it as continuous compensator of the reactive power in the supply grid.

Use of the microprocessor-controlled excitation power supply units of the synchronous machines allow to automate start-up process, voltage control and turning off the machines set.

Thanks to use of a master control unit and implementation of procedures for remote communication between devices the control of the system's operation directly from the place of the tests is allowed.

Obtained measurements confirm the correct operation of the implemented system.

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