EXPERIMENTAL INVESTIGATION

Laboratory test # 4/1

INVESTIGATION OF THREE-PHASE SYNCHRONOUS GENERATOR

Aim of the training is experimental determination of the generator characteristics and evaluation it short-circuit ratio.

Work program:

1. Connection of the circuit for testing.
2. Experimental determination of no-load characteristic.
3. Experimental determination of voltage regulation characteristic.
4. Experimental determination of excitation characteristic.
5. Experimental determination of short-circuit characteristic.
6. Evaluation of the generator short-circuit ratio.
7. The report execution.

The work procedure

<u>Stage 1</u> Connection of the circuit for testing.

Enter the generator nameplate data into Table 1.

Table 1

Synchronous generator nameplate data

Type	P_r	U_r	I_r	n_r	η_r	$cos\varphi$
-	kW	V	A	rpm	$\%$	-

Select instruments needed for testing the generator (see Fig. 1).

Connect the circuit and present it to an instructor for checking. While the circuit connection the fuses in the DC supply line must be taken out. Before running the generator, all the switches must be turned off. Set the rheostat in the motor field circuit into zero position; switch on the DC motor by means of *S3* and pushing the start button of the starting device.

Set maximum resistance of the generator excitation circuit. Energize the generator field winding by turning on the switch *S2*. Adjust the DC motor speed by means of resistance *R3* so that indication of the frequency meter equals the generator rated frequency 50 *Hz*.

Stage 2 Experimental determination of no-load characteristic.

The no-load characteristic of a synchronous generator is the relationship $E_0 = f(I_f)$, where E_0= the armature induced voltage under no-load, I_f= the generator field current, obtained at the rated generator speed (is checked by the voltage frequency that should be maintained equal 50 Hz by means of the resistor R3) and zero armature current $I = 0$ provided under the switch *S1* turned off.

Adjust the generator field current by means of the resistors R1 and R2 so that the armature voltage *U* is (1.2 … 1.3) of its rated value, and enter the values of the armature voltage and current into Table 2.

By reducing the field current, take data more for 7 points of the no-load characteristic, entering them into the table. The last point should be taken at zero value of the generator field current. At this voltage on the generator terminals equal to the residual voltage is obtained.

The curve obtained in the described way is the descending branch of no-load characteristic.

Table 2

No-load characteristic of synchronous generator

Test	I_f, A								
	E_0, V								
Calculated	I_f^*								
	E_o^*								

Stage 3 Experimental determination of voltage regulation characteristic.

The voltage regulation characteristics of a synchronous generator are the relationships $U = f(I)$, where U= voltage across the armature winding terminals under load, I= the armature current. The characteristics are determined under conditions: $I_f = const$, $\cos\varphi = const$, $n = n_r$. In this laboratory test the characteristic is determined at $\cos\varphi = 1$.

The rated value of rotational frequency is provided by adjusting resistor *R*3 so that the frequency is maintained equal the rated value 50 *Hz*.

Under turned off switch *S1*, fit the generator field current to get the rated voltage at no-load (*I*=0). The pair of values *I*=0 and $U = U_r$ are coordinates of the first point of the required characteristic.

Coordinates of other points of the characteristic are obtained under load with resistor *R*. Before their determination, set up maximum resistance *R* and turn on the switch *S1*. Then determine coordinates of more 7 points setting each the time greater value of the armature current by adjusting resistance *R* for every next point. Maximum armature current value in the test unit is limited by the DC drive motor rated armature current. The obtained pairs of the generator armature current and voltage enter in Table 3.

Table 3

Voltage regulation characteristic of synchronous generator

Test	I, A								
	U, V								
Calculated	I^*								
	U^*								

<u>Stage 4</u> Experimental determination of excitation characteristic at constant voltage.

The excitation characteristics of a synchronous generator are the relationships $I_f = f(I)$, where I_f= the field current, *I*= the armature current. The characteristics are determined under conditions: $U = const$, $\cos\varphi = const$, $n = n_r$. In this laboratory test the characteristic is determined at $\cos\varphi = 1$.

The rated value of rotational frequency is provided by adjusting resistor $R3$ so that the frequency is maintained equal the rated value 50 *Hz*.

Under turned off switch *S1*, fit the generator field current to get the rated voltage at no-load (*I*=0). The pair of values *I*=0 and I_f are coordinates of the first point of the required characteristic.

Coordinates of other points of the characteristic are obtained under load with resistor *R*. Before their determination, set up maximum resistance *R* and turn on the switch *S1*. Then determine coordinates of more 7 points setting each the time greater value of the armature current by means of resistor *R* and maintaining the voltage invariable by means of resistors *R1* and *R2*. Values of the armature and field currents obtained in each of these cases are coordinates of the excitation characteristic at the voltage value that was maintained. Maximum armature current value in the test unit is limited as in the stage # 3 by the DC drive motor rated armature current. The obtained pairs of the generator armature and field currents enter in Table 4.

Table 4

Excitation characteristic of synchronous generator at $U = \cdots V$

Test	I, A								
	I_f, A								
Calculated	I^*								
	I_f^*								

<u>Stage 5</u> Experimental determination of short-circuit characteristic.

The short circuit characteristic is the relationship $I_s = f(I_f)$ where I_s= is the current consumed by the generator under condition of three-phase short-circuit. At these conditions $U = 0$. The speed should be maintained equal n_r.

As under short-circuit the voltage on the generator terminals is zero the frequency meter does not operate, and execution the sort-circuit test at the rated speed is provided by means of preliminary bringing up the speed to the rated value under no-load operation at open armature circuit by setting the frequency meter indication equal 50 *Hz*.

Connection of the armature winding circuit for this test is shown in Fig. 2.

Before the short-circuit test put switch S1 in the turned off position and start the drive DC motor as it s explained in division “Stage 1”. Adjusting resistor ***R3*** obtain the frequency of generator voltage equal 50 *Hz.* By means of resistors ***R1*** and ***R2*** reduce the generator voltage to possible minimal value.

Begin the short circuit test putting the switch *S1* into turn on position. First adjust the field current I_f to obtain the short circuit current $I_s = I_r$. This pair of the field current and armature current values represents the first point of the curve.

Then determine else four points of the characteristics reducing the armature current by means of the resistance R_1 and R_2 increase.

The obtained data enter into Table 5.

Table 5

Short-circuit characteristic of synchronous generator

Test	I_s, A					
	I_f, A					
Calculated	I_s^*					
	I_f^*					

<u>Stage 6</u> Evaluation of the generator short-circuit ratio

Using the open-circuit and short-circuit characteristics determine the generator short-circuit ratio.

Drawing up the report

The prepared report must include:

1. The number and title of the test and its aim
2. The work program
3. The synchronous generator nameplate data (Table 1)
4. Circuit diagram (Fig. 1)

5. Experimental and calculated data for plotting the no-load characteristic (Table 2) and its graphical representation in per-units

6. Experimental and calculated data for plotting the voltage regulation characteristic (Table 3) and its graphical representation in per-units

7. Experimental and calculated data for plotting the excitation characteristic (Table 4) and its graphical representation in per-units

8. Experimental and calculated data for plotting the short-circuit characteristic (Table 5) and its graphical representation in per-units

9. Evaluation of the generator short-circuit ratio (SCR).

Methodical guideline

The armature voltage and current and the field current in per-units are found by the following expressions:

$$U^* = \frac{U}{U_r}, \quad I^* \frac{I}{I_r}, \quad I_f^* = \frac{I_f}{I_{f0}}$$

where I_{f0} = the field current value at which the armature no-load (open-circuit) voltage equals the generator rated voltage.

To stage 2

Plot a curve according to the data of Table 2 in pr-units. This curve is the descending branch of the no-load open-circuit characteristic. To get the average characteristic, which does not depend on hysteresis, shift the curve in the direction of abscissa axis so that is passes through the coordinate origin (see Fig. 3). In the same coordinate system plot the normal no-load characteristic given in Table 6. Compare these two curves.

Table 6

Normal open-circuit characteristic for salient pole synchronous machines

I_f^*	0	0.5	1.0	1.5	2.0	2.5
E_f^*	0	0.55	1.0	1.22	1.32	1.4

To stage 6

The short-circuit ratio is found as the ratio of the armature short-circuit current I_{s0} taking place under the field current I_{f0}, at which the armature no-load voltage has the rated value, to the armature rated current:

$$SCR = \frac{I_{s0}}{I_r} = I_{s0}^*.$$

The armature current I_{s0}^* value in per-unit is immediately determined from the short circuit characteristic at $I_f^* = 1$.

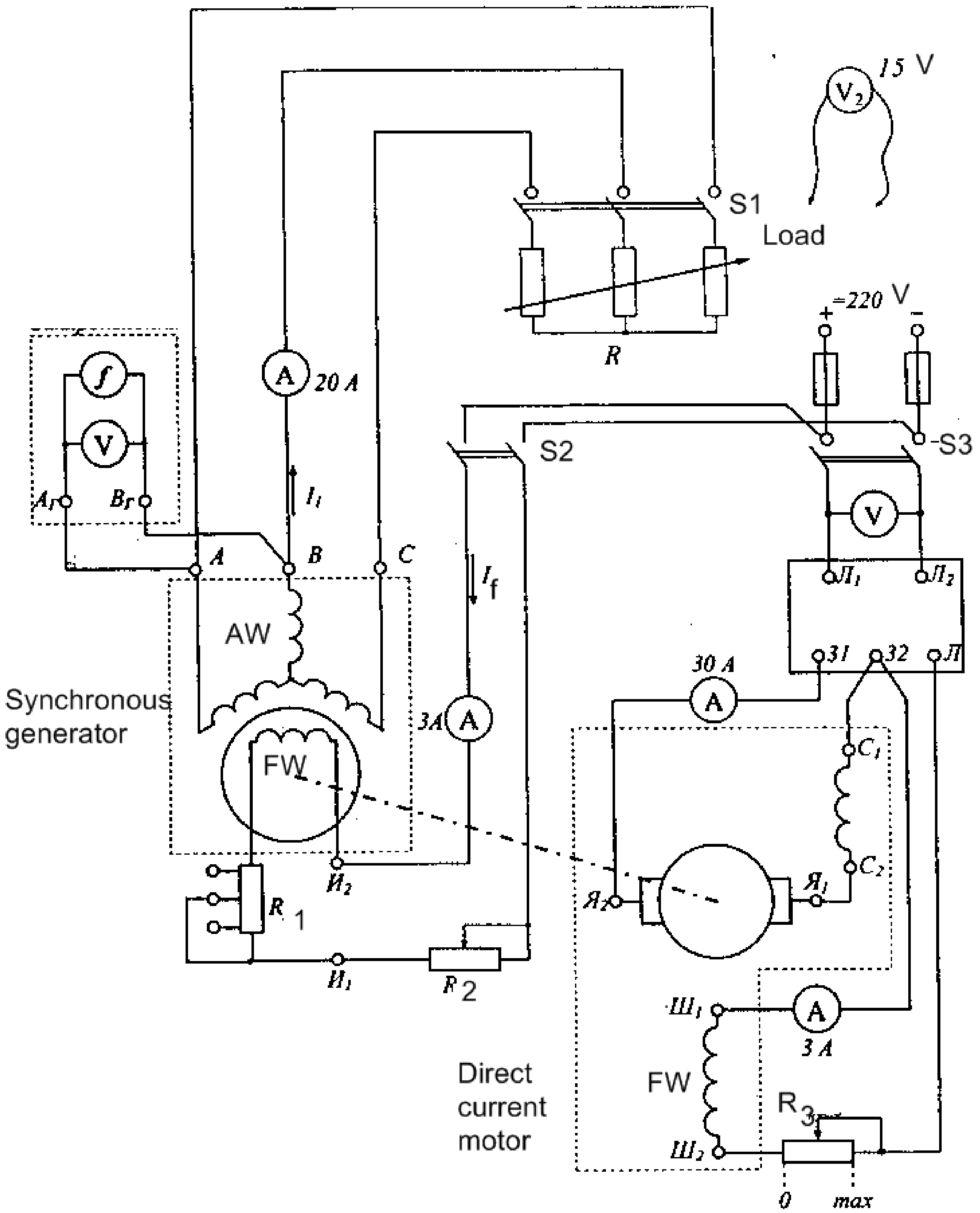


Figure 1

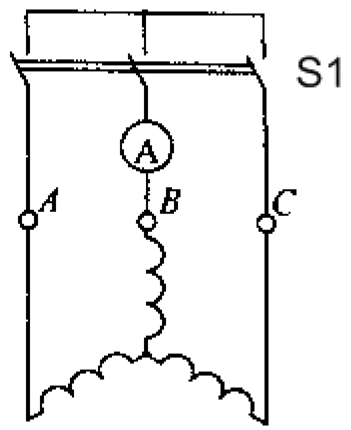
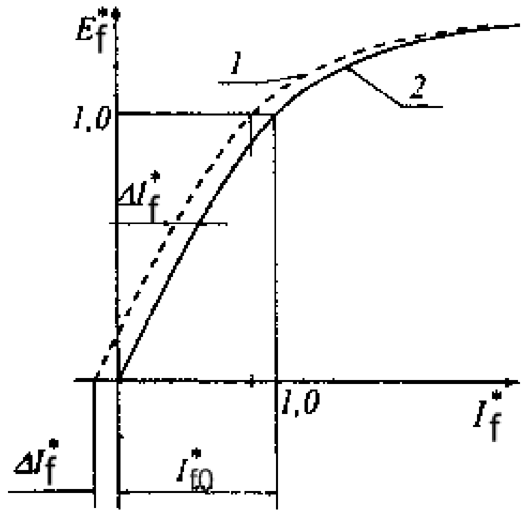


Figure 2



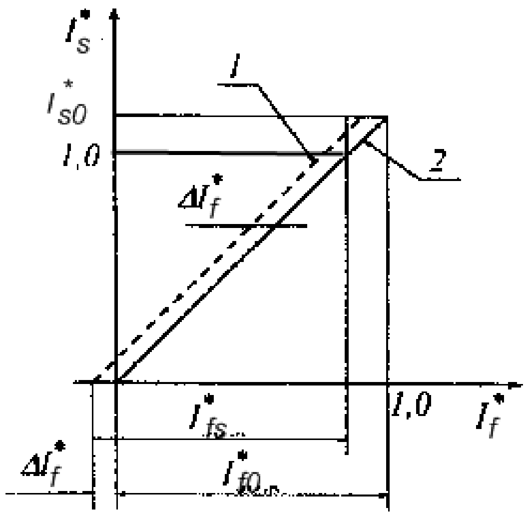


Figure 3

Figure 4

EXPERIMENTAL INVESTIGATION

Laboratory test # 4/2

INVESTIGATION OF PARALLEL OPERATION OF SYNCRONOUS GENERATOR CONNECTED TO GRID

Aim of the training is study of switching a synchronous generator for parallel operation with a grid by method of ideal synchronizing and investigation of generator parallel operation under conditions of field current adjustment at different load.

Work program:

8. Acquaintance with the generator nameplate data and circuit assembling.
9. Connection of the alternator in parallel to large power system.
10. Experimental determination of the generator V-curve characteristics.
11. Transfer of the synchronous machine from generator to motor mode.

The work procedure

Stage 1 Acquaintance with the generator nameplate data and the circuit assembling

Enter the alternator nameplate data into Table 1.

Table 1

Alternator nameplate data

Type	U_r, V	I_r, A	P_r, kW	n_r, rpm	f_r, Hz	$\cos\varphi$

Following the Safety Rules, assemble the circuit according to the diagram given in Fig. 1.

Stage 2 Connection of the alternator in parallel to large power system

After checking the circuit by an instructor, begin the further program execution.

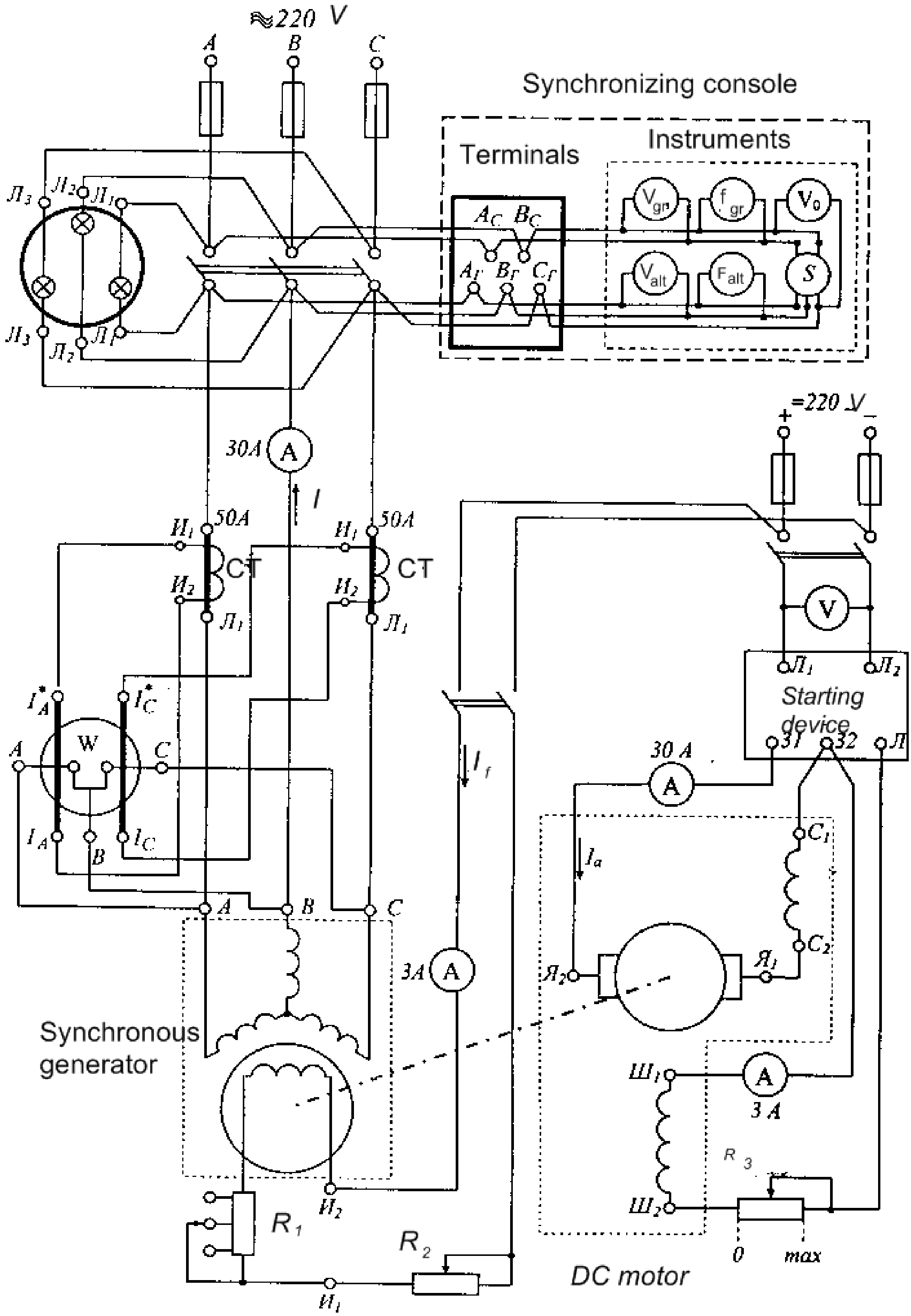


Fig.1 Circuit of parallel alternator connection to grid

Before connection the alternator in parallel to the grid, follow the steps below:

1. Be sure that the switches *S1*, *S2* and *S3* are in turn off positions, rheostats *R1* and *R2* are set into position of maximum resistance, and rheostat *R3* is set into position of zero resistance.
2. Insert the fuses to the lines *A, B, C* and to DC lines (+, -).
3. Start the DC driving motor by turning on the switch *S3* and then pushing the "Start" button at the starting device.
4. Execute consequently the steps to fulfill conditions of the synchronous machine ideal synchronizing with the grid to which it is to be connected for parallel operation:
   - Turn on the switch S3 to energize the alternator field winding. Adjust the drive motor speed with the help of resistor R3 to obtain the alternator frequency equal to the grid frequency using readings of the frequency meters f_{gr} and f_{alt}. In the same time watch that the alternator voltage would not exceed the voltmeter maximum scale value and not be considerably greater its rated value, adjusting, if necessary, the resistors *R1* and *R2*. As the result, fulfillment the first condition of ideal synchronizing $f_{gr} = f_{alt}$ is provided.
   - Adjusting the alternator excitation current by means of the resistors *R1* and *R2*, set the alternator voltage U_{alt} equal the grid voltage U_{gr} using the voltmeters V_{alt} and V_{gr} readings. As the result, fulfillment the second condition of ideal synchronizing $U_{alt} = U_{gr}$ is provided.
   - Changing briefly the alternator speed by means of *R3* achieve that the synchroscope needle would point to the red line on its scale. As the result, fulfillment of the third condition of ideal synchronizing is provided: phase displacement angle between appropriate alternator and grid voltages $\alpha = 0$. (Pay attention that fulfillment of the condition $\alpha = 0$ may be establish not only by the electromagnetic synchroscope but also with the help of lamp synchroscope – in version shown in Fig. 1 the lamps go out when fulfillment of condition $\alpha = 0$ is achieved, and with the help of zero voltmeter V_0 which will give reading equal zero).

After fulfillment the ideal synchronizing conditions, turn on the switch *S1* connecting the alternator to the grid. After connection the generator to the grid it is in no-load operating conditions, its armature current equals zero.

Stage 3 Experimental determination of the generator V-curve characteristics

V-curve characteristics is a set of curves representing the relationships $I = f(I_f)$ determined at *U=const*, *f=const* for different values of the load active power *P=const*.

In this experiment *V*-curves are determined at Active power values $P = 0, 0.2P_r$ and $0.4P_r$ which are obtained by adjusting the driving torque by means of setting proper values of the DC motor field current with the help of rheostat *R3*.

Measured values of the quantities are entered into Table 2.

For each the load power P value, the normal alternator field current I_{fn} is determined as the field current value at which the armature current *I* is minimal. Enter the measured values I_{fn}, I_{min} and P into the left column of Table 2. The pairs of values (I_{fn}, I_{min}) are coordinates of the lowest points of V-curves for the given values of P.

To avoid the machine pulling out of synchronism under load, the alternator field current must not be less than 0.25 of its normal value I_{fn} for the given load.

Maximum values of the field current should be taken so that the armature current would be roughly equal to its rated value.

Changing the field current is provided with the help of resistors R1 and R2.

Table 2

Data for plotting *V*-curve characteristics

P, kW	Lowest point	Underexcitation		Overexcitation	
		I_{fn}, A	I, A	I_{fn}, A	I, A
	I_{fn} = A I = A				
	I_{fn} = A I = A				
	I_{fn} = A I = A				

For each *V*-curve a descending (underexcitation) and ascending (overexcitation) branch is determined. It is recommended to begin measurements from the maximum value of the armature current at overexcitation lowering the field current step by step and to finish them at the highest point of the underexcitation branch. Entering the measurement results into the Table pay attention that the values of I_f and I are filled into proper columns with account whether the underexcitation or overexcitation branch is determined.

Stage4 Transfer of the synchronous machine from generator to motor mode

Each an electric machine is convertible, i.e. it may be transferred from generator to motor mode and otherwise. A machine connected to the grid works as a generator when driven torque is applied to its shaft. To transfer the machine to a motor mode it is necessary to apply the retarding torque to its shaft.

At the installation used in this laboratory test, direction and magnitude of the torque applied to the shaft of synchronous machine depend on magnitude of the DC motor field current which may be adjusted by changing resistance of rheostat ***R1***. At some value of the DC motor field current the applied torque covers the inner synchronous machine retarding torque, and the synchronous machine is in ideal no-load conditions. This is revealed by zero indication of the wattmeter.

Reducing of the DC field current in respect to this value provides application a driving torque to the synchronous machine shaft and transition the machine into generator mode. This is revealed by positive indication of the wattmeter.

Increasing of the DC field current in respect to the indicated value provides application a retarding torque to the synchronous machine shaft and transition the machine into motor mode. This is revealed by negative indication of the wattmeter.

Adjusting the DC motor field current, obtain the synchronous machine operation in no-load, generator and motor conditions.

Stage 4 The report execution

The prepared report must include:

1. The number and title of the test and its aim
2. The synchronous generator nameplate data (Table 1)
3. The circuit diagram (Fig. 1)
4. The alternator *V*-curve characteristics all plotted in mutual coordinate axes.

Methodical guideline

In this laboratory work switching the synchronous machine for parallel operation with the grid is performed by use of the method if ideal synchronizing. The conditions of the ideal synchronizing the synchronous machine with the grid that have to be fulfilled before switching on are the following:

- Equality of the machine (f_{alt}) and the grid (f_{gr}) frequency: $f_{alt} = f_{gr}$

- Equality of the machine (U) and the grid (U_{gr}) rms voltage: $U = U_{gr}$
- Phase displacement between the generator and grid voltage equals zero
- Identical phase sequence of the synchronous machine and the grid.

Order of these conditions fulfillment and the machine switching onto the grid is described in div. "*Stage 2*".

Test questions

1. What conditions must be fulfilled before switching a synchronous machine in parallel to a grid by the method of ideal synchronizing?
2. How to adjust the synchronous machine frequency before switching it for parallel operation with a grid?
3. How to adjust the synchronous machine voltage before switching it for parallel operation with a grid?
4. How to provide equal phases of the synchronous machine and the grid voltage before switching it for parallel operation with a grid?
5. Explain principle of operation of a lamp synchroscope.
6. Explain why voltmeter V_0 gives zero indication when fulfillment of ideal synchronizing conditions is provided. What will be its indication if some of the conditions are not fulfilled?
7. Explain why the alternator field current decrease below definite value under it parallel operation at load causes pulling it out of synchronism.
8. In what cases the armature current of a generator operating in parallel with a grid is lagging or leading with respect to the grid voltage, and the same with respect to the generator voltage?
9. How to load an alternator at it parallel connection to a grid?
10. How to change the armature current reactive component at the alternator parallel operation?

EXPERIMENTAL INVESTIGATION

Laboratory test # 4/3

ASYNCHRONOUS START AND INVESTIGATION OF SYNCRONOUS MOTOR AT FIED CURRENT ADJUSTMENT

Aim of the training is study a synchronous motor asynchronous start performance and experimental determination of synchronous motor characteristics at field current adjustment.

Work program:

1. Acquaintance with the synchronous motor nameplate data and circuit assembling.
2. Performance of the motor asynchronous start.
3. Experimental determinations of the synchronous motor *V*-curve characteristics and dependencies of the power factor and consumed active power on the motor field current.
4. The report execution.

The work procedure

<u>Stage 1</u> Acquaintance with the synchronous motor nameplate data and circuit assembling

Enter the synchronous motor nameplate data into Table 1.

Table 1

Synchronous motor nameplate data

Type	P_r, kW_r	U_r, V	I_r, A	n_r, rpm	$\eta_r, \%$	$\cos\varphi_r$

Following the Safety Rules, assemble the circuit according to the diagram given in Fig. 1.

<u>Stage 2</u> Performance of the motor asynchronous start

After checking the circuit by an instructor, begin the further program execution.

Be sure that the switches *S1, S3, S4* and *S5* are in turn off positions, switch S2 have been set into position “*Start*”, switch *S6* – into turn on position, the switches in the loading rheostat circuits have been turned off, and the rheostat *R1* handle put on the red mark. The last provides obtaining roughly normal field current after pulling the motor in synchronism.

Put the commutating plugs of the current transformers into their central socket contacts providing their primary short-circuiting for the starting period to protect current circuits of the wattmeter and phase meter against great motor starting current.

After that put the fuses into the feeding lines and initiate the start by turning the switch *S1* on.

After the rotor achieves the steady speed of rotation that takes place at the slip equal 0.03 … 0.05, disconnect resistance *r* by turning off the switch *S6* and connect the motor field winding to the exciter by turning on the switch *S5*. This provides pulling the motor in rotation with the synchronous speed.

When the transient of pulling the motor in synchronism have been over, connect the ammeter with measurement limit of 30 *A* to the feeding line *B* turning on the appropriate contact of the switch *S3* and after that turning off the switch S2 (to avoid brake of the line). Adjust the motor field current to obtain roughly minimum armature current.

In the course of the characteristics determination, use the ammeter with limits of 30 *A* or 10 *A* depending on the armature current value. To switch between the ammeters it is necessary to turn on the branch of ammeter you intend to use and after that to turn off the branch of ammeter used before to avoid the feeding line brake up.

To bring the wattmeter and the phase meter into operation take off the plugs of the central socket contacts of the current transformers and put them in their proper sockets in correspondence to the current value in the lines.

The machine is ready for further testing. Do not forget to define the wattmeter scale division value.

Stage 3 *Experimental determinations of the synchronous motor characteristics*

The characteristics must be determined for no-load condition and two values of the load at which the motor consumes active power equal to 0.3 and 0.5 of the rated power. Loading the motor is provided by loading the DC generator driven by the synchronous motor. The load is defined by the loading rheostat resistance increasing with the loading rheostat resistance decrease and with the DC generator field current increase. In the course of testing adjust the DC generator field current so that the voltage across its terminal has the rated value.

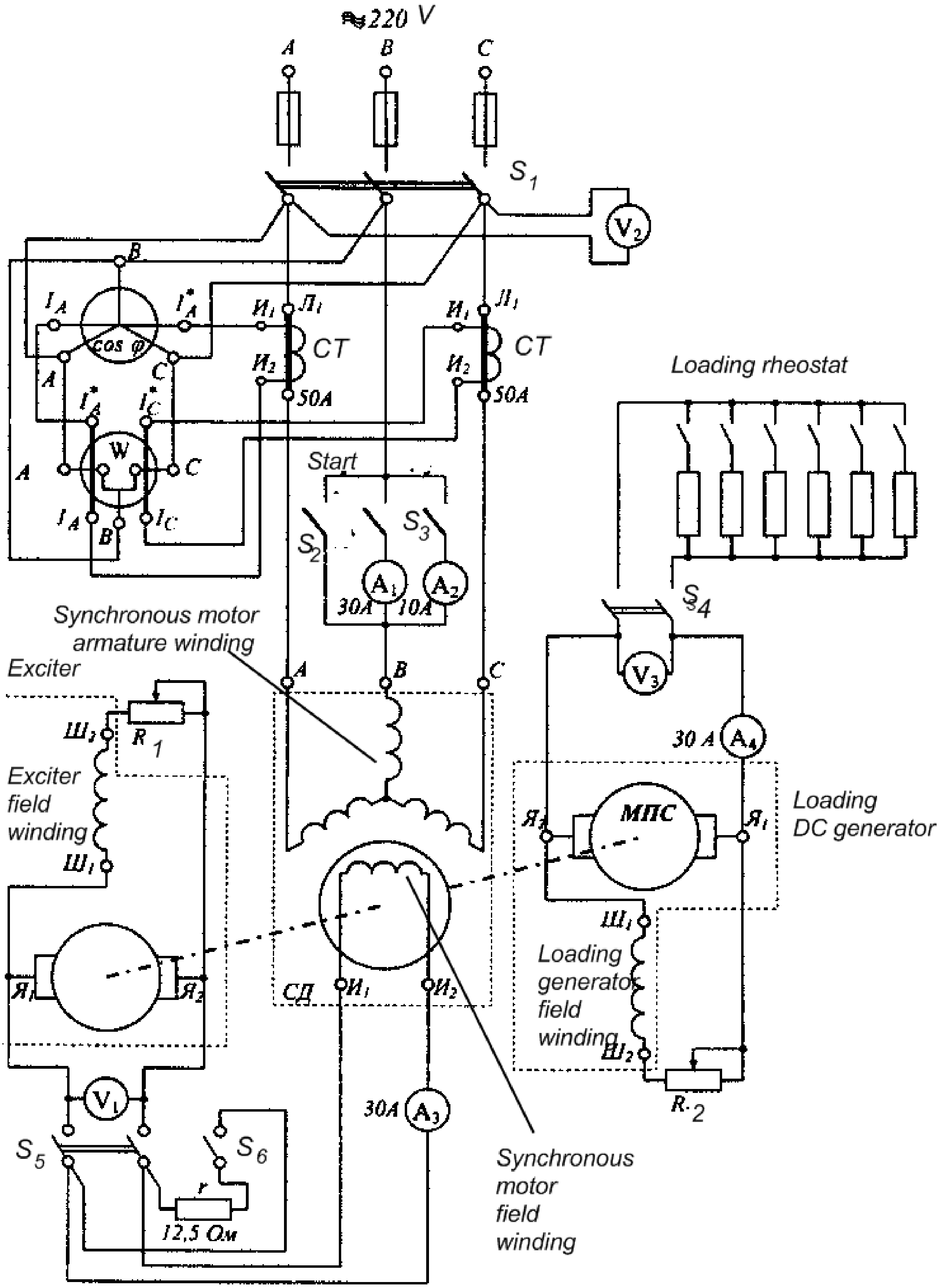


Figure 1 Circuit diagram of test bench

The quantities measured values enter in Table 2.

Table 2

Experimental data for plotting synchronous motor characteristics

P, kW	Lowest point	Underexcitation			Overexcitation		
		I_{fn}, A	I, A	$\cos\varphi$	I_{fn}, A	I, A	$\cos\varphi$
	I_{fn} = A						
	I = A						
	I_{fn} = A						
	I = A						
	I_{fn} = A						
	I = A						

To avoid the machine pulling out of synchronism under load, the alternator field current must not be less than 0.25 of its normal value I_{fn} for the given load.

Maximum values of the field current should be taken so that the armature current would be roughly equal to its rated value.

Changing the field current is provided with the help of resistor R1.

For each *V*-curve a descending (underexcitation) and ascending (overexcitation) branch is determined. It is recommended to begin measurements from the maximum value of the armature current at overexcitation lowering the field current step by step and to finish them at the highest point of the underexcitation branch. Entering the measurement results into the table pay attention that the values of I_f, I and $\cos\varphi$ are filled into proper columns with account whether the underexcitation or overexcitation branch is determined.

Using the data of Table 2, plot *V*-curves and dependences $\cos\varphi = f(I_f)$ for the specified values of active power *P*.

<u>Stage 4</u> The report execution

The prepared report must include:

1. The number and title of the test and its aim
2. The synchronous motor nameplate data (Table 1)
3. The circuit diagram (Fig. 1)

4. The motor *V*-curves and the charts $\cos\varphi = f(I_f)$ plotted in the same coordinate axes.

Methodical guideline

To Stage 2

A synchronous motor itself does not develop the starting torque as at great relative speed of the armature rotating field with respect to the rotor excitation field the synchronous torque alternates with high frequency and its average value for the period equals zero.

In the laboratory asynchronous start of a synchronous motor is performed under the rated armature voltage. In salient-pole machines such a start is provided with use of the motor damping (starting) winding which action is similar to an induction motor squirrel cage. For starting period the synchronous motor rotor acceleration is provided by the asynchronous torque having the same nature as the torque of induction motor. During the start the synchronous motor field winding is disconnected from the exciter. The rotor acceleration lasts till decreasing the rotor slip in the bounds of 0.03 … 0.05. After that the field winding is connected to the exciter (DC current source), and the rotor is pulled in synchronism under the action of the synchronous torque.

At starting the motor field winding is closed for the resistor r, which resistance about 8 … 10 times as great as the field winding resistance R_f, to avoid overvoltage at the winding leads. Shortening the winding is not admissible as the motor can stuck in this case at a reduced speed (about a half of synchronous speed) due to distortion of the starting asynchronous torque curve caused by the single-axis effect.

Sometimes small salient-pole synchronous motors have no damping winding but their pole shoes are made of solid steel. In such motors the asynchronous starting torque is provided by eddy currents induced in the solid pole shoes.

Salient-pole motors also have no damping winding. Starting asynchronous torque is produced in such a motor due to eddy currents induced in its solid rotor core.

Asynchronous start of large synchronous motors used in industry is carried out under reduced voltage that provides considerable decrease of starting current.

In the laboratory the synchronous motor excited from the DC generator-exciter which is placed on the shaft of this motor. Such excitation is one of possible ways of self-excitation.

To Stage 3

A motor *V*-curve characteristics is a set of curves representing the relationships $I = f(I_f)$ determined at *U=const*, *f=const* for different values of the load on the shaft power $P_2 = const$. At some value of the field current I_{fn} called the normal field current the armature current is minimal. The armature current under normal excitation is purely active, and the motor power factor $\cos\varphi = 1$.

At $I_f < I_{fn}$ the motor operates at underexcitation and its power factor $\cos\varphi < 1$ is lagging.

At $I_f > I_{fn}$ the motor operates at overexcitation and its power factor $\cos\varphi < 1$ is leading.

As a rule the synchronous motors are destined for operation under full load at leading power factor $\cos\varphi = 0.8 \ldots 0.9$ and generate the reactive power which compensates reactive power consumed by other inductive loads.

In this laboratory test loading the synchronous motor is provided by the DC generator connected to the motor by its shaft and loaded with the loading rheostat.

Test questions

1. Owing to what torque does pulling the rotor in synchronism occur?
2. How is loading the motor while testing made?
3. Does the armature current have reactive component at the field current not equal its normal value?
4. What components does the armature current of an underexcited synchronous motor operating under load have?
5. What components does the armature current of an overexcited synchronous motor operating under load have?
6. Why are synchronous motors intended usually for operation with leading power factor?
7. On what reason the synchronous motor field winding may not be short-circuited while asynchronous start?
8. By what means is the starting torque of a synchronous motor produced under asynchronous start?