

Electrical Power Engineering Lab I

Test 1: Synchronous motor and generator

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1 Purpose of the experiment

This experiment explains the basic construction of a synchronous machine and the behaviour in both motor and generator modes.

The machine at first operates as a motor. The correlation between current, excitation and torque is investigated. Furthermore the performance of the machine as a generator connected to the mains is examined. Also the solitary operation is considered. The regulation characteristic will be measured and synchronization with mains is realized.

2 Preparation of the experiment

2.1 Construction of the synchronous machine

A synchronous machine is an induction machine where the rotational speed of the rotor and the rotational speed of the stator field are equal. The machine consists of three main parts:

- Stator, which carries the three phase winding,
- Rotor, with one DC winding or permanent magnets, and
- Slip rings or excitation machine (exciter) (in case of electrical excitation).

Normally synchronous machines are built as internal - field machines. Machines with poles $2p = 2$ have a round rotor (cylindrical/turbo-rotor) because of high centrifugal forces, while those with $2p = 4, 6, 8$ and more poles mostly have a salient-pole rotor (Fig. 1). The stator carries the three phase winding and must be made of laminated iron sheets in order to reduce eddy currents. Since the flux in the rotor is constant with time at a particular place on the rotor, the rotor can be built from massive steel. The excitation winding is generally supplied with DC through the slip rings. In order to reduce oscillations in case of a network fault, the machine has a damper winding. Besides that, this winding has a weakening effect on reverse rotating fields during the operation in an unsymmetrical network.

When a synchronous machine runs asynchronously, the damper winding acts similar to the cage rotor in an induction machine. This is the reason for using damper winding as a starting winding for an asynchronous start-up in the motor mode (see chapter 3.2.1). The machine is accelerated nearly to the synchronous rotational speed and run in synchronism by reluctance (salient pole machine) or by switching on supply to the excitation winding in synchronism.

The damper winding consists of bars located in the pole shoes through which are short-circuited to a cage by rings. In many cases the massive poles of the salient

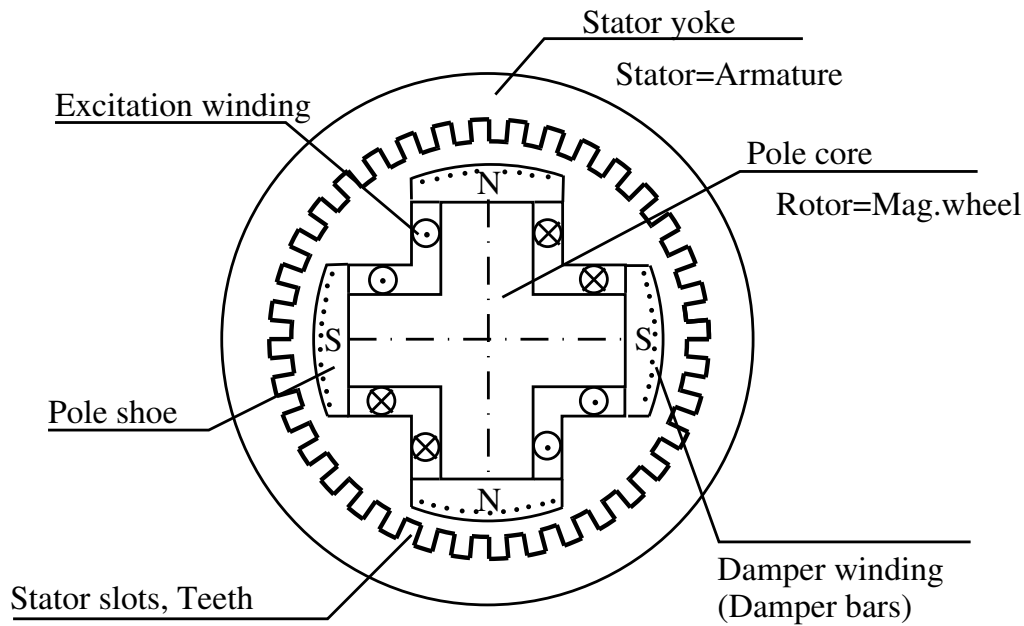


Figure 1: Synchronous machine, inner-pole type with salient-pole rotor

pole machine are also used as a damper winding. In that case the pole shoes are conductively connected to each other by rings.

2.2 Mode of operation

In the further descriptions an internal-field machine is assumed. Like in an induction machine, the stator slots carry a three-phase winding. The number of pole pairs is p and the supply frequency of the stator currents is f . The stator currents produce a rotating magnetic field of p pole pairs with the rotational speed $n = f/p$ ($[n] = 1/s$), i.e. a field, which in principle corresponds to the field of the same pole number and rotational speed produced by the DC excited rotor (e.g. according to Fig.1)

A constant torque can be produced only if the stator field and the DC excited rotor field rotate synchronously. If the rotational speed of the rotor and the rotational speed $n_0 = \frac{f}{p}$ (synchronous rotational speed) of the power system differ, then the machine falls out of step and a periodic torque alternating between a positive and negative maximum value appears, with an average value equal to zero. Furthermore the currents are inadmissibly high.

If the synchronous machine operates at mains, the machine first has to be synchronized. The terminal voltage of the generator at no-load at the instant of connection must be equal to the voltage of the power system in magnitude, frequency, phase sequence and phase lag (synchronization conditions) (see chapter 3.2.2).

For the examination of the synchronization conditions in addition to the synchroscope and null voltage detector, the dark connection and mixed connection can be used.

The frequency of the machine is influenced by the rotational speed of the prime mover, while the voltage magnitude is influenced by the excitation current.

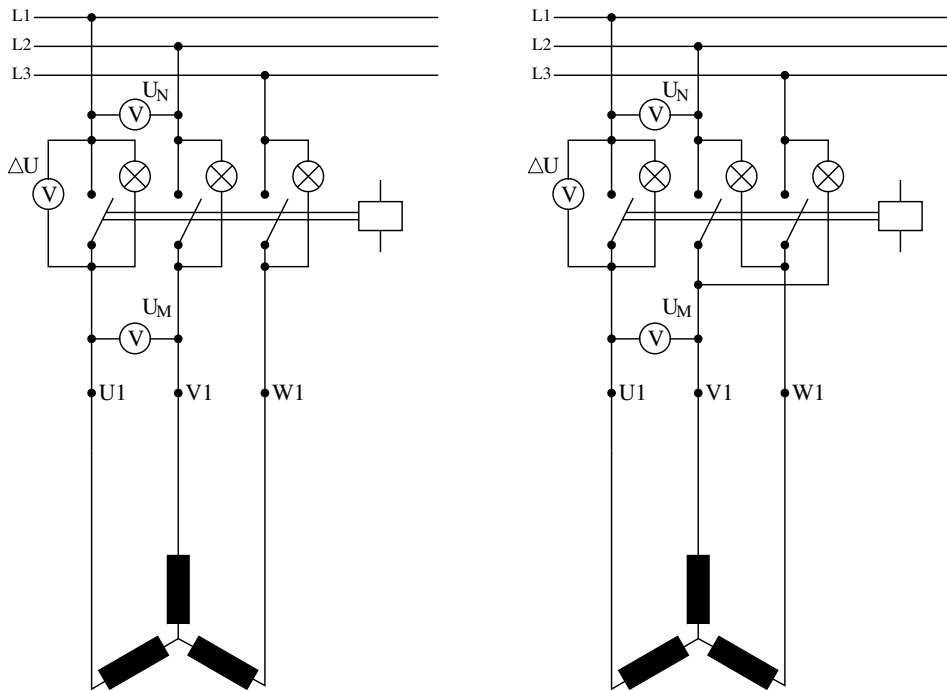


Figure 2: Dark connection (left) and mixed connection (right)

If the dark connection is applied, the generator will have the correct phase sequence if all the three lamps light up and go out at the same time. If the lamps light up one after the other, the phase sequence will be wrong and two terminals must be exchanged. Lamps light up and go out with the beat frequency as soon as the synchronization conditions are approximately fulfilled. At the switching instant the lamps must be dark. If mixed circuit is used, then the generator has the correct phase sequence if the lamps light up one after the other. By the direction of rotation of the glowing lights it can be concluded whether the machine runs too slow or too fast. Regarding the connection on the right side of Fig. 2, the lamp in branch L1-U1 must be off at the switching instant.

The single phase equivalent circuit diagram is presented in Fig. 3. In the generator reference-arrow system (GRS), the delivered current is positive. Delivered active power is positive in GRS and negative in LRS. Inductive reactive power absorption

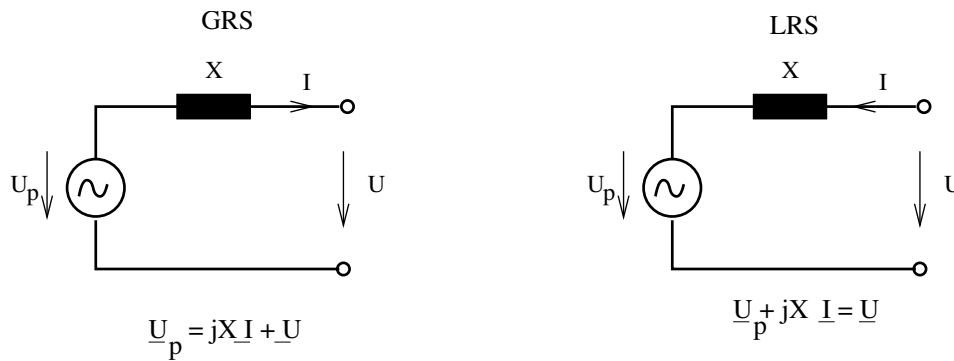


Figure 3: Single phase equivalent circuit of a synchronous machine

is equal to the capacitive reactive power delivery and vice versa independent of the chosen reference-arrow system. The voltage that only results from the DC excitation of the rotor is called the internal voltage \underline{U}_p . At no-load operation the internal voltage can be measured as the terminal voltage \underline{U} . The phase angle between the internal voltage and the terminal voltage is called angular displacement $\theta = \varphi_{\underline{U}_p} - \varphi_{\underline{U}}$.

If the excitation is changed after synchronization, without any torque effect at the shaft of the machine, the reactive power can be adjusted. With an increase of the excitation the current acts demagnetising as if the machine is a capacitor, and with a decrease of the excitation it acts magnetising, as if the machine is an inductor. That is why the synchronous machine is an ideal reactive power controllable generator. The adjustment of the reactive power is done by the regulation of the excitation current. The regulation of the active power during the operation at the interconnected systems can be only done by changing the driving torque at the shaft. This is for example, possible by an intervention at the speed controller of the driving machine in terms of higher or lower rotational speed, while the rotational speed of the machine remains constant. Besides this the angular displacement changes:

- **generator operation:** magnetic wheel is leading in the direction of rotation ($\theta > 0$),
- **motor operation:** magnetic wheel lags ($\theta < 0$).

The sign of the angular displacement is independent of the chosen reference-arrow system!

The angular displacement of a turbo machine (cylindrical rotor) in steady-state operation must not exceed 90° , otherwise the machine will fall out of step ($\theta_L = 90^\circ$, static pull-out torque). The angular displacement is smaller than 90° in a salient-pole machine.

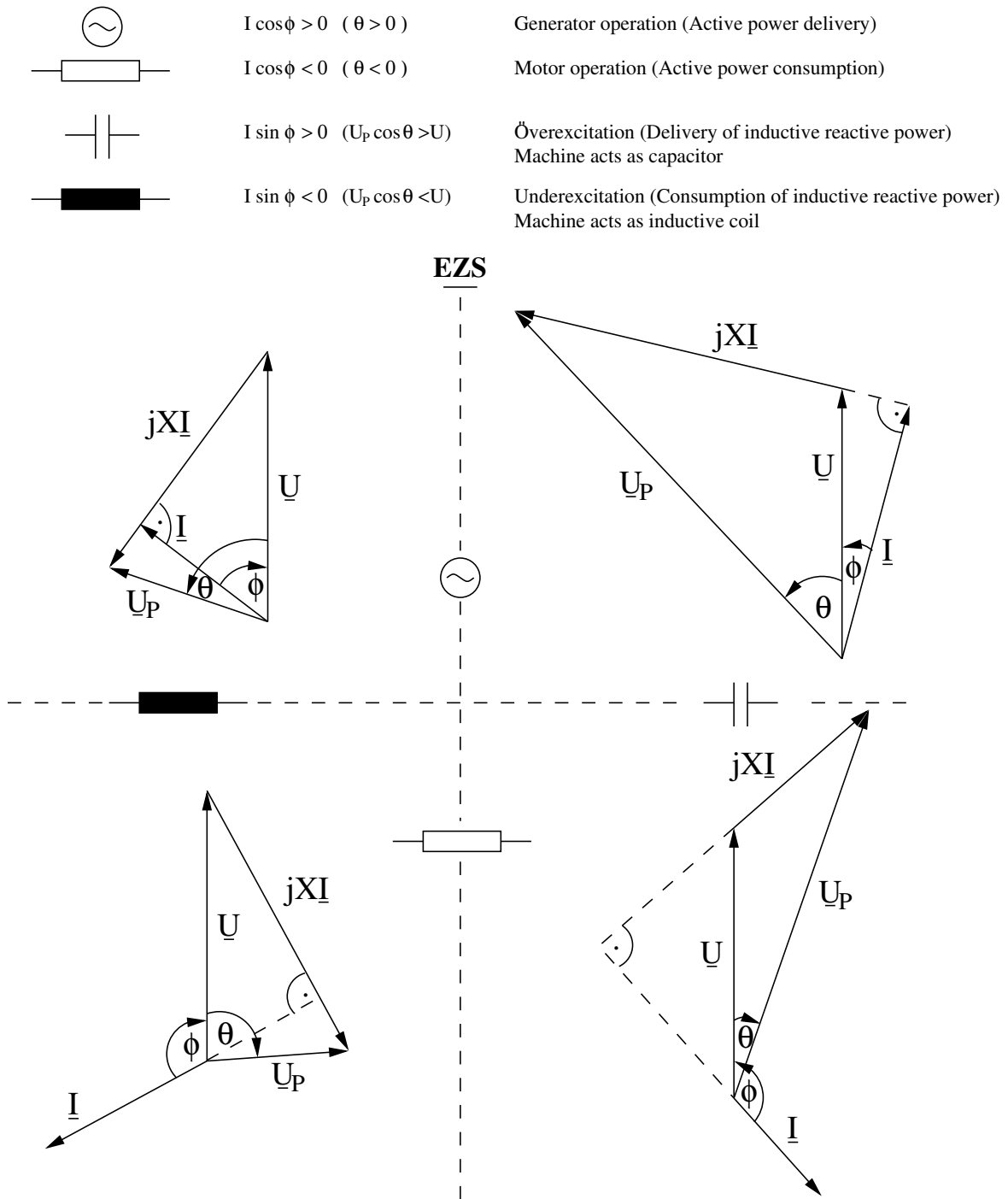


Figure 4: Operating ranges of a synchronous machine

Regarding the correlation between the torque and the angular displacement there is a certain analogy with a torsion spring. An oscillating system is created as a result of the interconnection of this torsion spring and the moment of inertia of the rotor. This system must not be excited with its natural frequency (a reciprocating engine as

driving machine must therefore be examined). Also, with every load impulse, swinging oscillations occur, which fade away due to the damper winding. Under inconvenient circumstances, e.g. with a large ohmic resistance between the power system and the machine due to under-dimensioned lines, the oscillations can remain.

2.3 Applications

Synchronous motors are used where a fixed speed is required at network supply and if there is a need for reactive power supply. In dynamic speed control drives, for e.g. in robots or servo drives, previously synchronous machines with permanent magnets have been used.

The synchronous machine as a reactive power generator, is used to prevent transmission of reactive power over a long line path. The armature current is increased by changing the excitation current at constant rotational speed and constant mechanical load. If the machine is for e.g. overexcited, the current phasor $I_{armature}$ is in the first quadrant (see Fig. 4) and its absolute value is larger than at straight active load, since now only reactive power is delivered to the network.

The minimum value of the stator current occurs according to the pure active power of the motor. If the stator current is drawn with respect to the excitation current, the well known V-curve is obtained. (see chapter 3.2.2).

More often the synchronous machine is used as a three-phase generator in power stations. Now a specific output up to 1500 MVA are made. Generators in thermal power stations are cylindrical-rotor machines, while for hydro power plants salient-pole machines are used. As a single-phase alternator, a synchronous machine serves to supply the $16\frac{2}{3}$ Hz railway network. For the local power supply a synchronous generator is placed in a small run-of-river power station, unit-type power stations combined with heat and power or in wind power plants. If due to the location there is no power supply possible then the generator runs in solitary operation. With that the voltage and frequency must be kept stable independent of the load by the regulation of the exciting current and the driving power: If the stator current increases due to an increased power demand, the voltage drop over the reactance increases. This would lead to a decrease of the terminal voltage. Therefore the excitation current must be increased until the terminal voltage reaches the rated value. (see chapter 3.3.2).

3 Experiment realization

3.1 Safety requirements

Voltage applied amounts up to 400 V; that is why the laboratory orders must be **strictly** respected, particularly these ones:

1. Setting up and changing of circuit connections is allowed only at **no voltage conditions**.
2. Before the beginning of operation the superintendent must be consulted and **every** connection must be inspected.
3. Adjustment of variable capacitors must be performed under no voltage conditions.
4. Before the experiment, every participant must inform himself about the location and function of the emergency devices.
5. Nominal values of the test machine can be exceeded only for a short period of time. Read the rated values of the machine from the rating plate on the machine.

	generator	motor
U_N		
I_N		
n_N		
P_N		
$\cos\varphi_N$		

3.2 Synchronous motor

3.2.1 Connection and starting

Experimental setup

1. Set the connection according to Fig. 5.
2. Is the machine connected in star or delta connection?

-
3. Which function has the starting resistance? Sketch the resulting connection of elements of the excitation circuit for both pushbutton positions.

Experiment realization

1. Set the switch of the control unit to $M = const.$
2. Set the starting resistance on $R = 30\Omega$.
3. Set the excitation current on 6, 8 A.
4. Switch the synchronous motor at the mains with free running pendulum machine and with pressed push button.
5. When the speed stops to increase, release the button. Describe the rotation speed behaviour immediately after the button is released.

-
6. Load the motor using the pendulum machine according to 1 and write down the rotation speed. Which effect occurs with increase of the load?
-

M/Nm	0	1	2	3	4	5	7
n/min ⁻¹							

Table 1: Speed/Torque characteristics of the synchronous motor

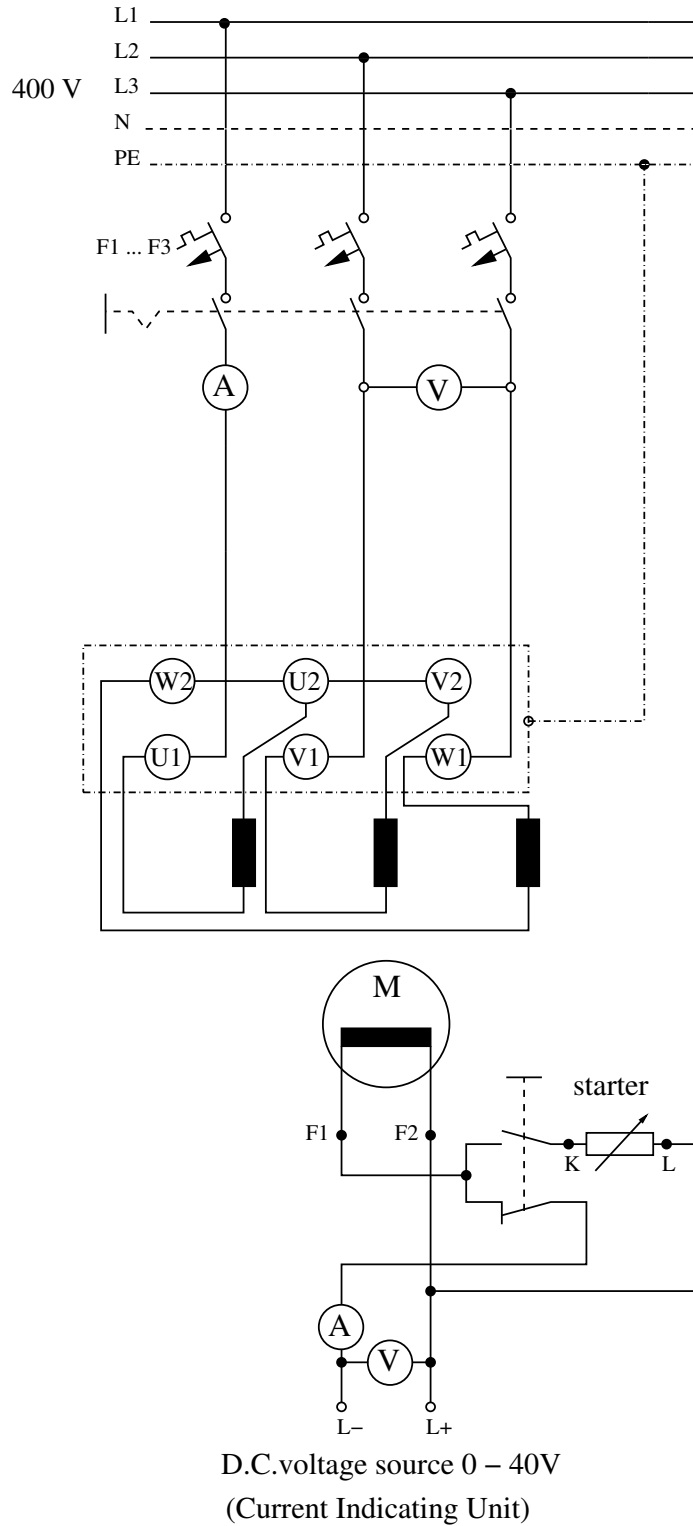


Figure 5: Connection for motor operation of the synchronous motor

3.2.2 V-characteristic

Experimental setup

Complete the connection according to Fig. 5 with the phase measuring instrument that enables the measuring of the phase shift between the phase voltage and the phase current of the synchronous motor.

Experiment realization

1. Switch the synchronous machine at the mains according to the connection procedure 1 – 3 in 3.2.1.
2. Load the machine using the pendulum machine according to Tab. 2. Write down the values of the power factor and the phase current in Tab. 2.

M/Nm	0 Const.									
I_E /A	1	2	3	4	5	6	7	8	9	10
I/A										
$\cos \varphi$										

M/Nm	2 Const.									
I_E /A			3	4	5	6	7	8	9	10
I/A										
$\cos \varphi$										

M/Nm	4 Const.									
I_E /A					5	6	7	8	9	10
I/A										
$\cos \varphi$										

Table 2: V-characteristic: Measurement values

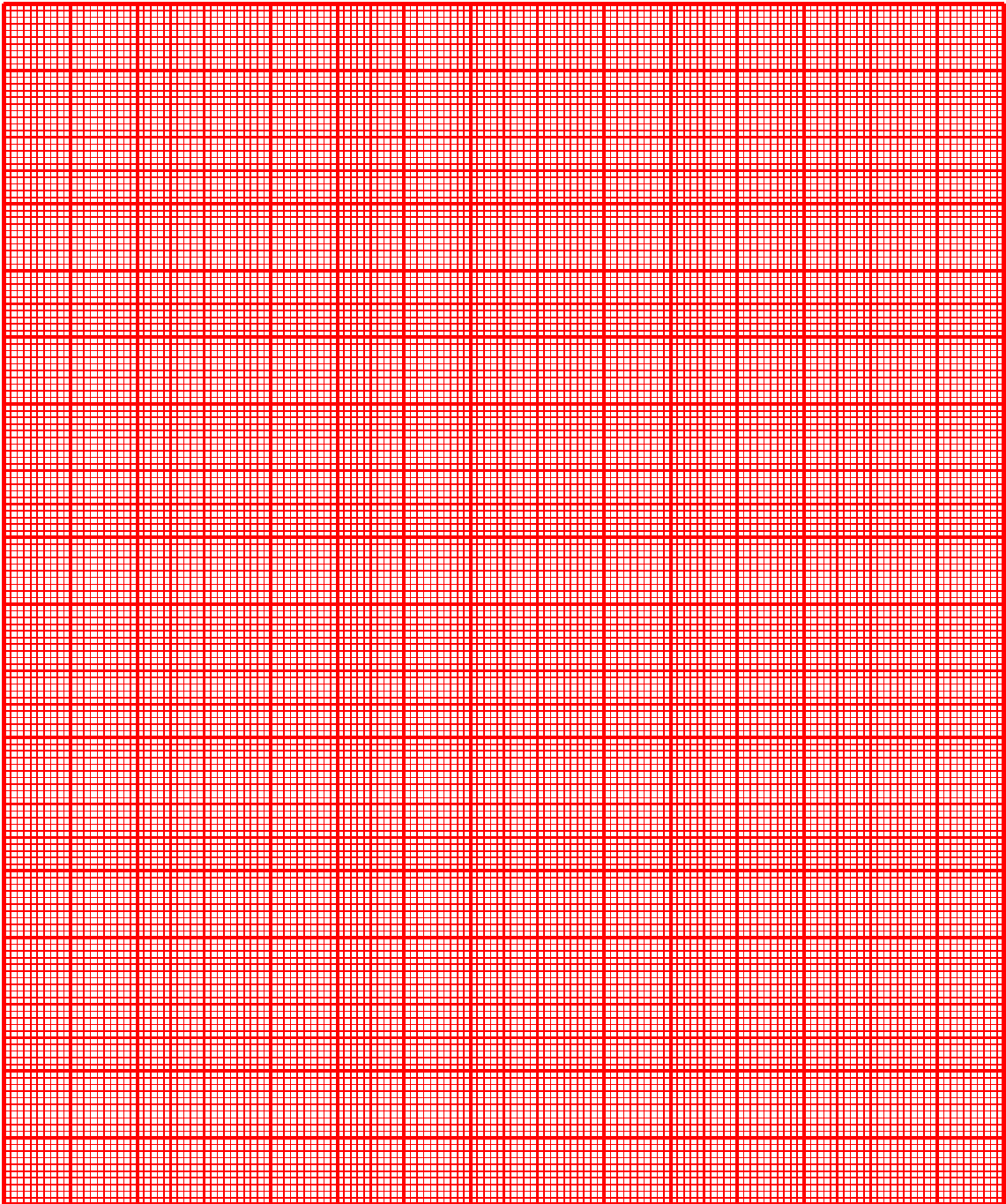


Figure 6: Graph for the V-characteristic ($I = f(I_E)|_{M=const.}$)

Analysis

1. Draw the characteristics of the phase current in dependency of the excitation current at a constant load in the diagram on Fig. 6.
2. Mark the points at which the motor has consumed pure active power. Connect the points.
3. Is the inductive power consumed or delivered in overexcited operation?

Generator reference-arrow system (GRS)? _____

Load reference-arrow system (LRS)? _____

4. Mark the areas of over excitation and under excitation in the diagram.
5. Now the motor is more loaded at the constant excitation current. How does this influence the machine's reactive power delivery/absorption in GRS/LRS?

At over excitation? _____

At under excitation? _____

3.3 Synchronous generator

3.3.1 Operation at constant-voltage constant frequency system, synchronization

Experimental setup

Set up the connection according to Fig. 7.

Experiment realization

1. Which synchronization conditions must be fulfilled and how are you going to accomplish that?

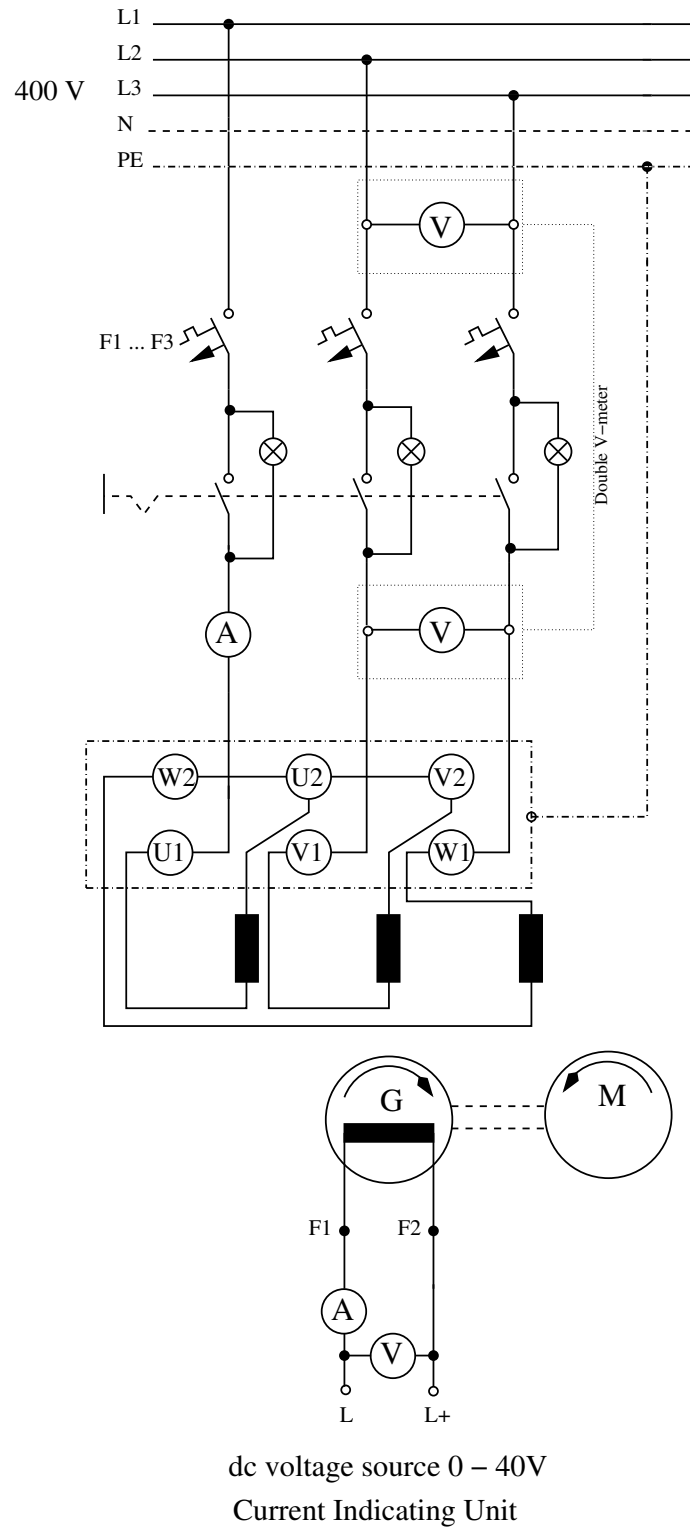


Figure 7: Connection for stiff system operation

2. Switch the control unit of the pendulum machine on $n = const$; drive the synchronous machine using the pendulum machine and adjust the rotation speed as closely as possible on 1500 min^{-1} .
3. Secure that the synchronization conditions are fulfilled and switch on the machine in proper moment parallel to mains.
4. Write down the values of the torque and the excitation current.

M	I_E

5. How can the reactive power delivery be changed at the constant mechanical load on the shaft?

6. How can the active power delivery be changed at the constant excitation current?

7. Vary the excitation current. Do not exceed the rated values! What is the response of the terminal current on excitation current changes?

8. Vary the driving torque of the pendulum machine. Do not exceed the rated values! What is the terminal current response?

9. Recover the values of the torque and the excitation current immediately after synchronization. Disconnect the synchronous generator from the mains.

3.3.2 Solitary operation, no-load characteristic

In this and the following experiments, the synchronous machine operates as a generator in solitary operation. The speed and the terminal voltage are not rigidly connected on the network, but freely adjusted after loading.

The no-load characteristic provides information about magnetic utilization of the machine. The terminal voltage as a function of the excitation current will be taken at the operation with constant rotation speed and no load

Experimental setup

Set up the connection according to Fig. 8.

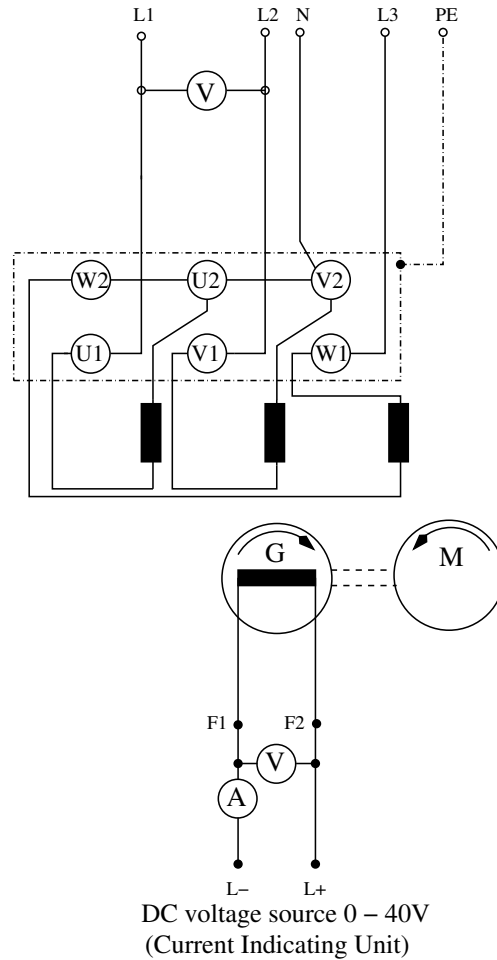


Figure 8: Connection for the detection of the no-load characteristic

Experiment realization

1. Drive the synchronous machine at nominal speed using the pendulum machine and open terminals.
2. Change the excitation current according to Tab. 3 and write down the no-load voltage U_0 of the terminal.

I_E/A	0	1	2	3	4	5	6	7	8
U_0/V									

Table 3: No-load experiment

Analysis

1. Draw the no-load characteristic in the diagram Fig. 9.
2. Explain the behaviour of the no-load characteristic.

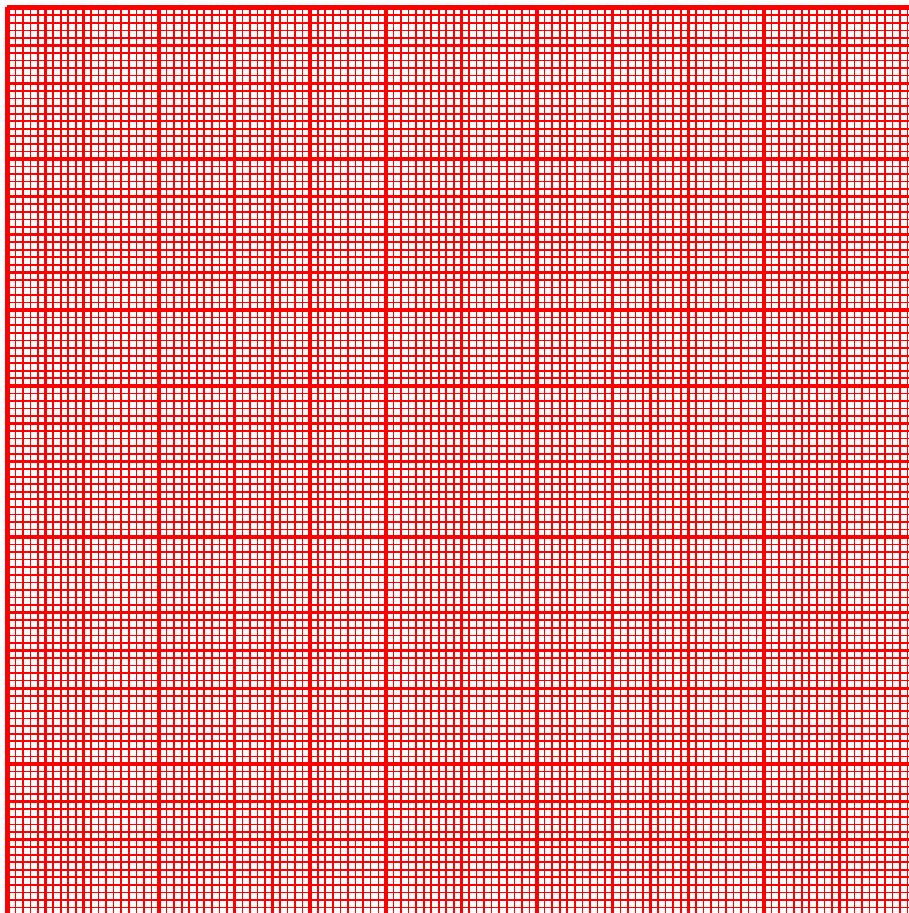


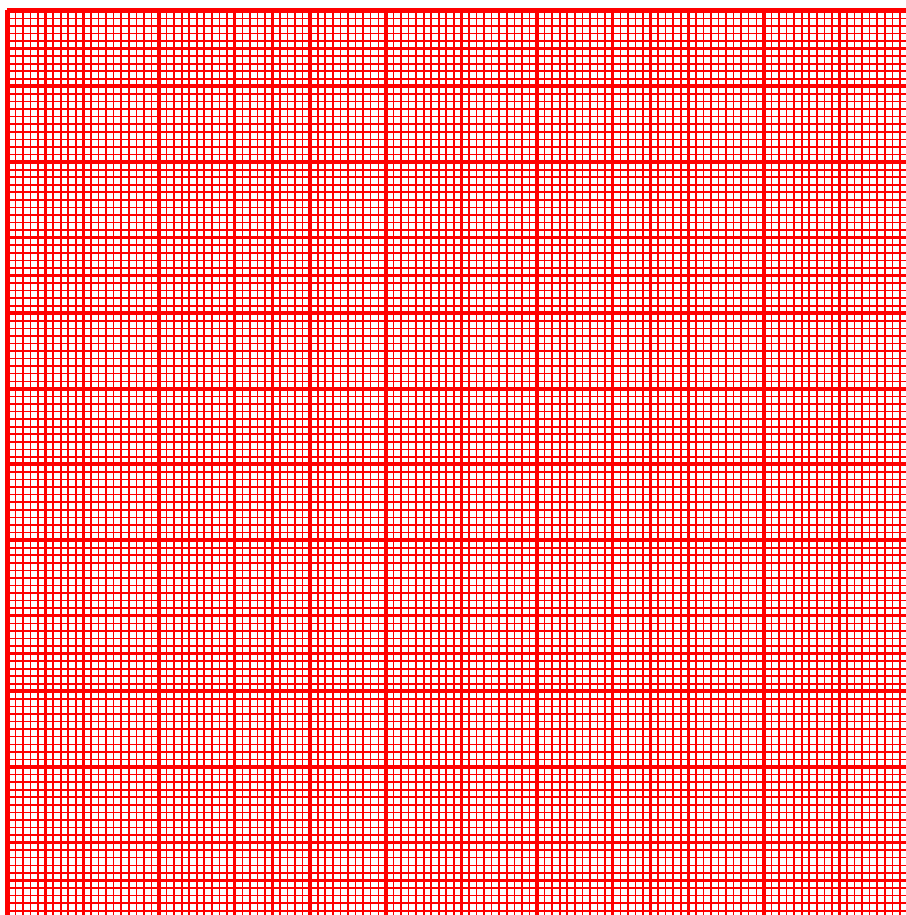
Figure 9: Graph for the no-load characteristic ($U_0 = f(I_E)$)

Experiment realization

1. Drive the synchronous machine at constant nominal speed using the pendulum machine.
2. Adjust the excitation current so there is the nominal voltage on the terminal in no-load operation.
3. Load the machine at constant excitation current according to Tab. 4.

Ohmic load step	∞	100	95	90	85	80	75	70	65	60	55
U/V											
I/A											

Table 4: Load characteristic

Figure 11: Graph for the load characteristic ($U = f(I)|_{I_E=const.}$)

Analysis

1. Enter the measured values in the diagram Fig. 11.
2. Which intolerable effect appears for connected consumer with increasing load of the machine? How can it be reduced?

3.3.4 Load characteristic at constant terminal voltage (excitation characteristic)**Experimental setup**

Connect the machine according to 3.3.3.

Experiment realization

1. Drive the synchronous machine at constant nominal speed using the pendulum machine.
2. Adjust the excitation current so there is the nominal voltage on the terminal in no-load operation.
3. Load the machine according to Tab. 5. Keep the terminal voltage constant while changing the excitation appropriately. Write down values of the phase current and the excitation current in Tab. 5.

Ohmic load step	∞	100	95	90	85	80	75	70	65	60
I/A										
I_E/A										

Table 5: Excitation regulation curve (ohmic load)

4. Repeat the experiment with pure inductive i.e. capacitive load.
Caution: Connect the capacitor steps only at $I_E=0$ to avoid possible damage of the installation by peak values that occur with capacitive load connection!

Ind. load step	0	1	2	3	4	5	6
I/A							
I_E/A							

Table 6: Excitation regulation curve (inductive load)

Cap. load step	0	1	2	3	4	5	6
I/A							
I_E/A							

Table 7: Excitation regulation curve (capacitive load)

Analysis

1. Write down measured values in the diagram Fig. 12.
2. Explain the obtained characteristics.

3. Explain by means of the equivalent circuit diagram of a synchronous generator, how the reactance of a (turbo) generator can be determined.

4. Draw the phasor diagram of the measuring point at inductive load (step 4) for a reactance of $X = 185\Omega$.

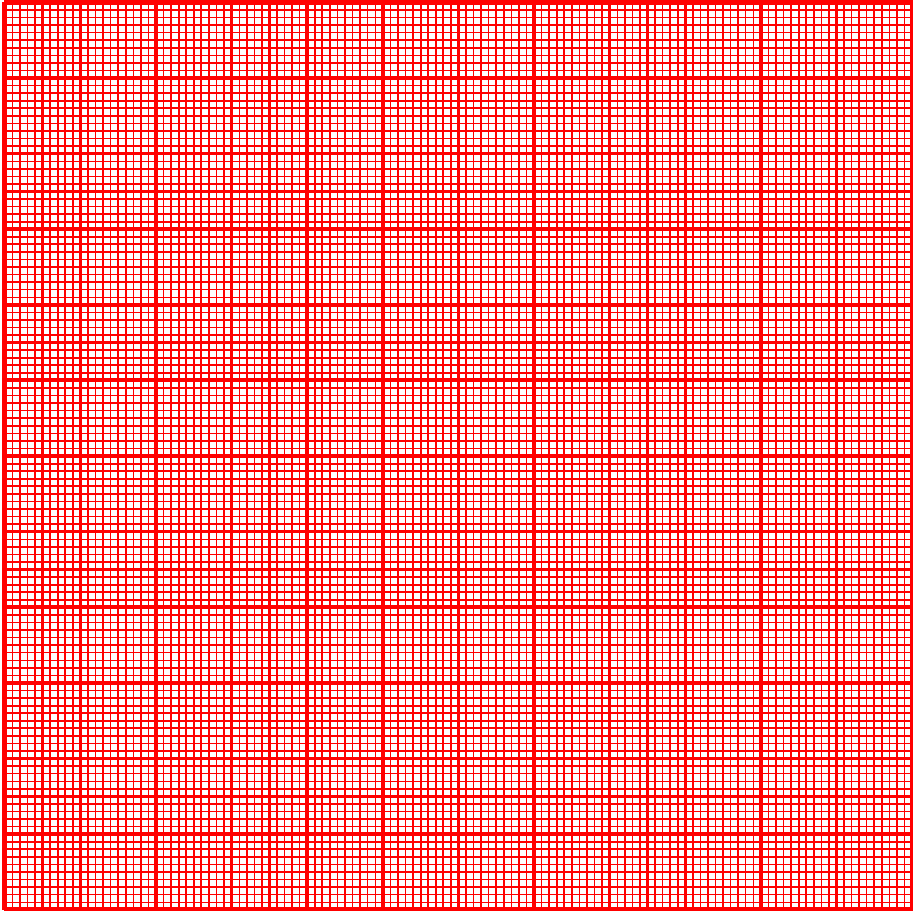


Figure 12: Graph for the excitation regulation curves ($I_E = f(I)|_{U=const.}$)