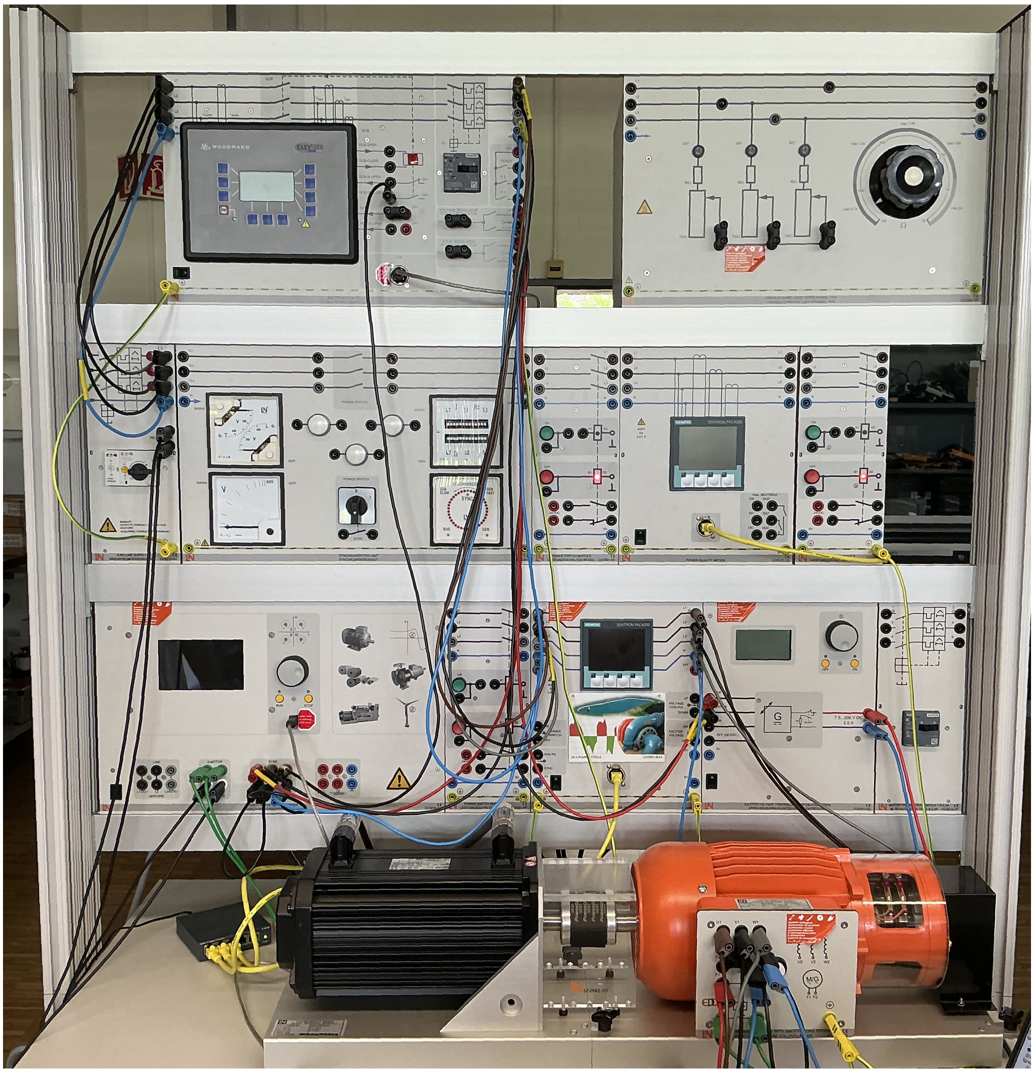
Lab report

EUG – Grid synchronisation and automatic generator control



Electric Power Grids

Group 4
Bürli Norman
Frongillo Matteo
Monti Antonio
Moos Michael

Contents

1 Introduction

In this lab experiment, the operation of the synchronous generator with grid connection is analyzed, with an emphasis on grid synchronization, automatic control of the generator, and power regulation in a pumped-storage power plant.

The first section of this lab involves manual synchronization of the generator using the dark lamp principle and automatic synchronization using the multifunctional relay and WOODWARD easygen-2500 controller. The behavior of the synchronous machine when working in parallel with the power grid is observed through active and reactive power control, including the influence of mechanical torque on active power and excitation on reactive power.

In the second section, the pumped storage power plant training set was used to perform semi-automatic power regulation in SCADA environment.

2 Grid synchronisation and automatic generator control course

Synchronisation of a synchronous generator with the electrical grid requires equal voltage magnitude, frequency, phase sequence and phase angle between generator and grid. If these conditions are not fulfilled, large transient currents and mechanical stresses may occur during connection.

2.1 Manual synchronisation with the aid of a dark lamp circuit

In this experiment, synchronisation was performed manually using the dark lamp method and a synchronoscope. For manual synchronisation of a synchronous generator to the power grid, the dark lamp synchronisation method was used. The lamps were connected between identical phases of the generator and the grid, as shown in Figure 1.

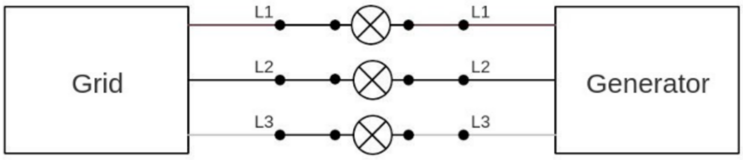


Figure 1: Dark lamp circuit

If the voltages of the generator and the grid were in opposite phase, all three lamps lit up brightly due to the high voltage difference. As the generator voltage approached the grid voltage in magnitude and phase angle, the voltage difference decreased and the lamps became darker. Synchronisation was achieved when the lamps were nearly dark, indicating that the phase voltages were closely matched. At this moment, the generator could be connected safely to the grid.

In addition to the lamp circuit, the experimental setup included a dual-range voltmeter, a synchronoscope, a zero-voltmeter and a dual-range frequency meter. The voltmeter was used to compare the generator and grid voltages. The synchronoscope indicated the phase angle difference and the frequency difference between the generator and the grid. For synchronisation, the green LED SYNC must be alight. The zero-voltmeter measured the voltage difference between corresponding phases, which approached 0 V during synchronisation. The frequency meter displayed the frequencies of both systems, which had to match before connection.

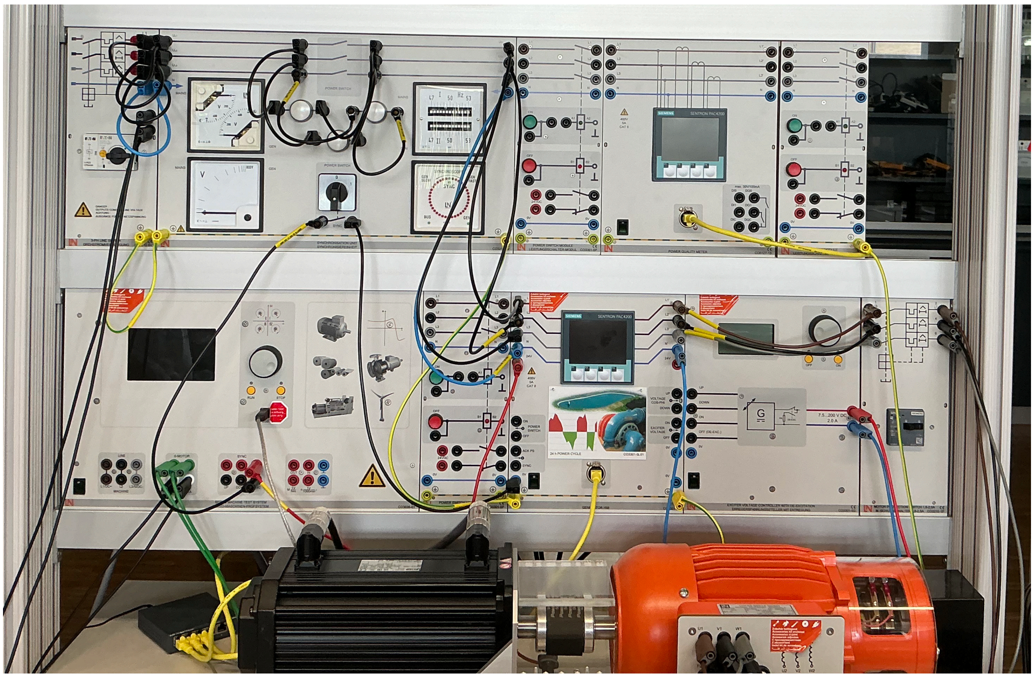


Figure 2: Experimental setup

Figure 2 shows the experimental setup used during the laboratory session. The generator was initially operated slightly above synchronous speed (+2 rpm). The excitation voltage was then adjusted until the generator voltage matched the grid voltage. Afterwards, the generator speed was reduced slowly until the synchronoscope rotated slowly and the phase angle approached synchronism. Once the synchronoscope indicated synchronous operation and the lamps became dark, the generator was connected to the grid using the synchronisation switch.

Figure 3 shows the measurement instruments and synchronoscope during the synchronisation process. On the top left, the dual-range voltmeter shows twice 400 V, the zero voltmeter below shows 0 volts. On the right side, the dual-range frequency meter shows both systems to be at 50 Hz, and below, the synchronoscope has the green SYNC LED alight.

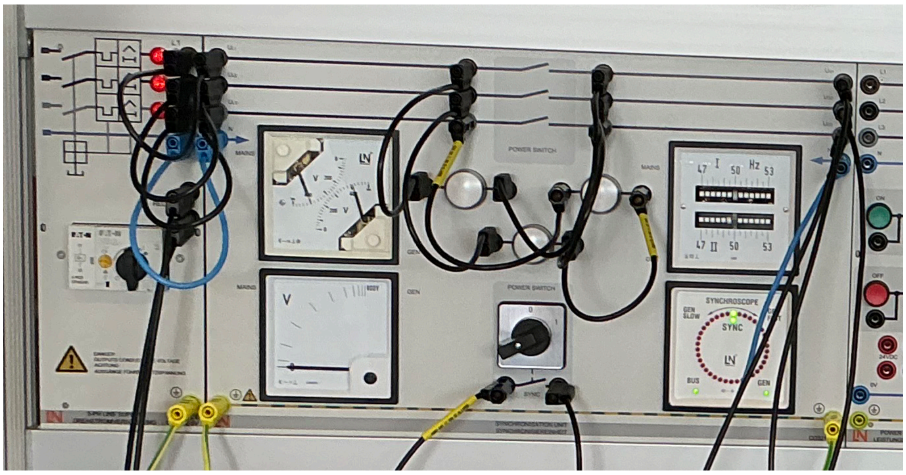


Figure 3: Meter close up

The experiment demonstrated that synchronisation can be achieved reliably using the dark lamp method. Furthermore, the experiment illustrated the importance of matching voltage, frequency and phase angle before connecting a synchronous generator to the electrical grid.

2.2 Automatic Grid Synchronization

Following the manual synchronization phase, the experiment transitioned to an automated grid-coupling procedure using the system's digital control. This method utilizes a centralized control unit to automatically monitor, adjust, and couple the synchronous generator to the electrical grid, eliminating human error and timing mistakes.

2.2.1 Synchronization with the Multifunctional Relay

The initial phase required a reconfiguration of the circuit in a way to shift control from the manual to the automated system. The team disconnected the manual wiring components, as the dark lamp circuit and manual synchronoscope were no longer required for this procedure. The circuit was modified to focus entirely on interfacing the machine with the automatic synchronization unit and the Multifunctional relay (CO3301-5W).

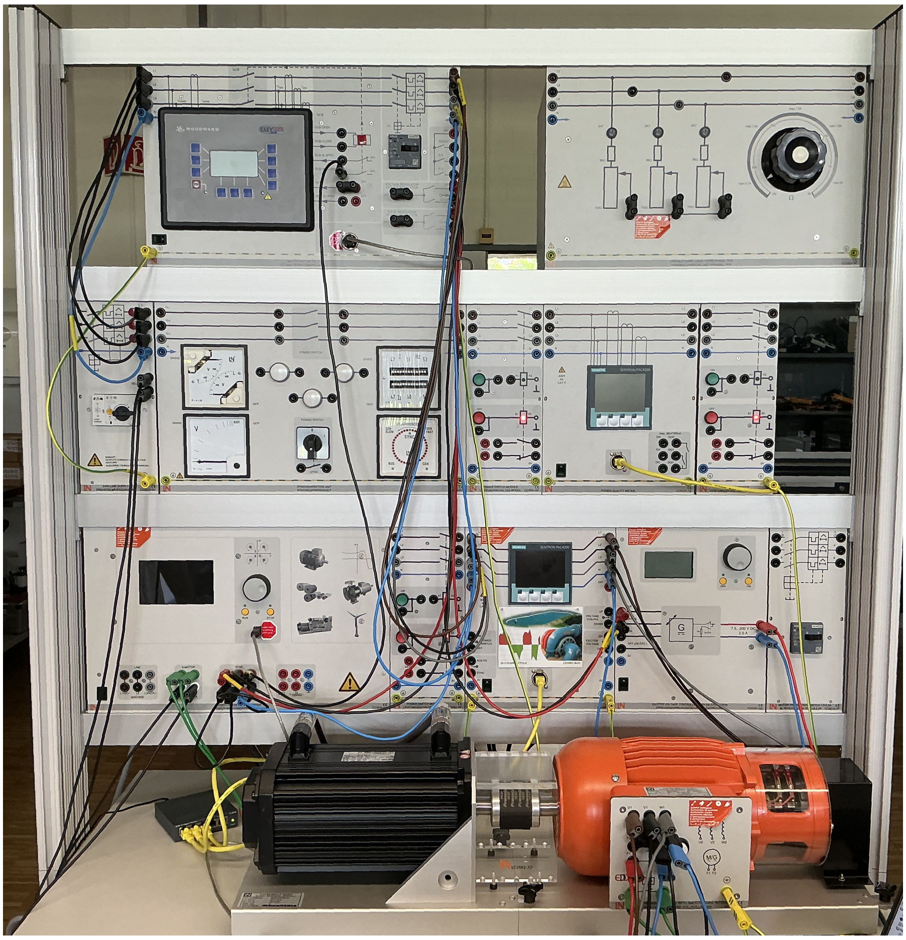


Figure 4: Final setup for synchronisation with Multifunctional relay

The machine setup was configured into ”Sync mode” via the control software touchscreen.

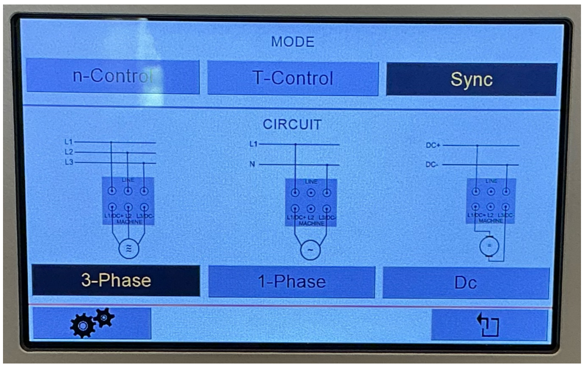


Figure 5: Setting the Sync Mode in the Servo machine test system

The initial baseline voltage for the system was set to 45 V. Following the step-by-step procedures outlined in the Laboratory Instructions for synchronous generator, the target control parameters were programmed into the user interface. Once a secure connection to the multifunctional relay unit was established, a software delay of 90 seconds was initiated to allow the system parameters to stabilize before execution. The team did not encounter issues with the time-out monitoring; increasing the delay to 120 s was therefore not needed.

Table 1: Table of the delay parameter from Labsoft

ID	Name	Parameter
3063	Time-out	90 s (default: 60 s)

2.2.2 Automatic Synchronization Execution

Once the parameters were set and the ”Run” command was executed, the integrated WOODWARD easygen-2500 control system took full autonomous control over the system. After starting it, the uncoupled generator was running at a standalone rotational speed of 1420 rpm and an un-synchronized frequency of 47 Hz.

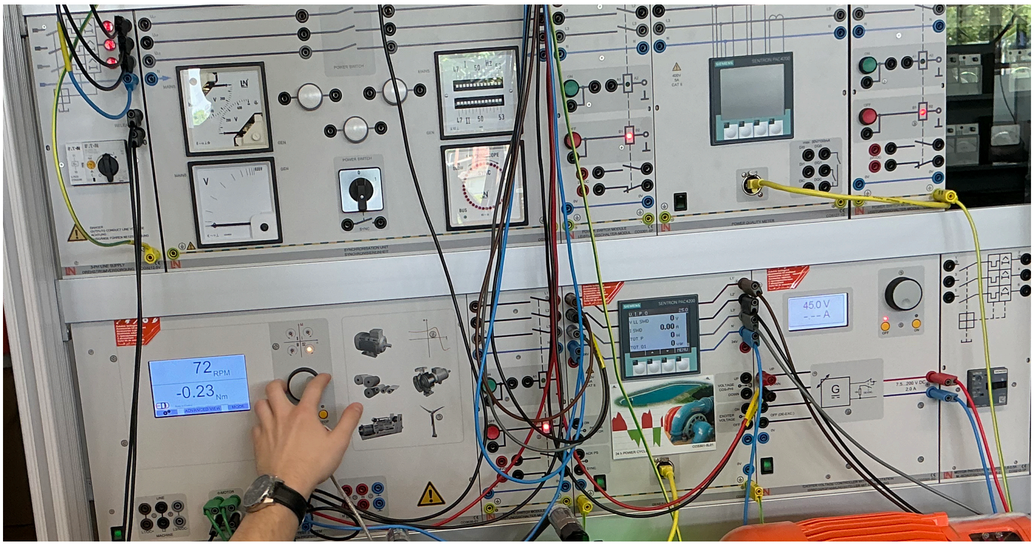
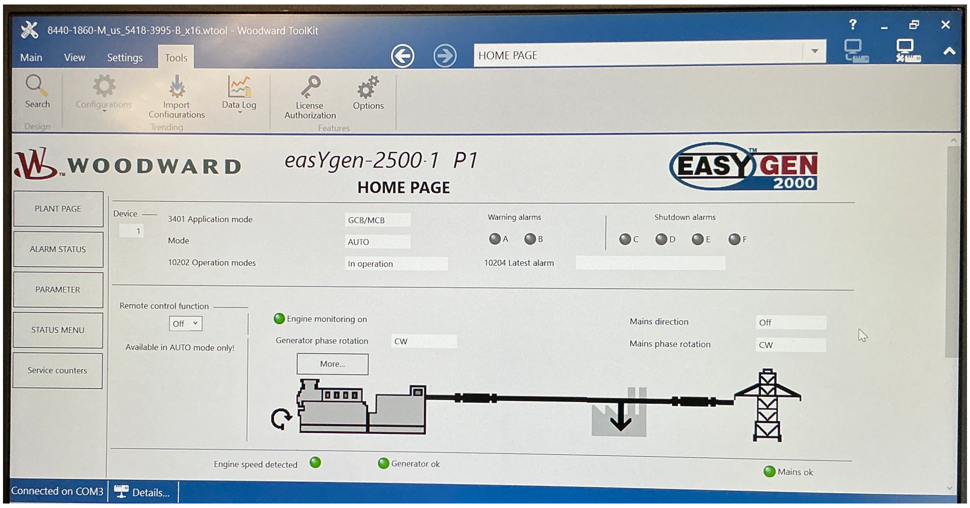


Figure 6: Setting the generator’s parameters

Recognizing that the generator frequency was below the rigid 50 Hz grid standard, the WOODWARD easygen-2500 controller automatically began increasing the prime mover’s RPM to bring the two systems into alignment. The automated control unit continuously modulated the system, driving the generator through a ramp-up sequence; the rotational speed was automatically accelerated from 1470 rpm up to the exact synchronous speed of 1500 rpm. The internal generator frequency was adjusted from 47 Hz up to the matching grid frequency of 50 Hz. The terminal voltage was regulated upwards from the initial 45 V to a synchronized 48 V, drawing a measured current of 0.61 A.

The control unit monitored the relative phase angle between the generator and the network. The exact instant all synchronization conditions such as equal voltage magnitude, frequency, and phase angle were achieved, the relay closed the internal contacts. This successful coupling was confirmed by an audible physical ”click” from the power switch module, and the software interface instantly updated the system status to all green lights.



Device 1

3401 Application mode GCB/MCB

Mode AUTO

10202 Operation modes In operation

Warning alarms ● A ● B

Shutdown alarms ● C ● D ● E ● F

10204 Latest alarm

Remote control function Off

Available in AUTO mode only!

● Engine monitoring on

Generator phase rotation CW

Mains direction Off

Mains phase rotation CW

Engine speed detected ●

● Generator ok

● Mains ok

Connected on COM3

Figure 7: Grid Overview showing that the generator is connected

2.3 Automatic active power control

2.3.1 Theory

A generator in island mode is feeding its own power system and delivers a frequency that depends on the speed it rotates. The speed then depends on the mechanical torque and the loads connected. For a constant speed the drive and load torque must be equal (steady state).

So, when the generator is connected to a three-phase grid, the speed it must rotate is determined by the grid's frequency. Before the generator can be connected, it must be synchronised in terms of terminal voltage under no-load condition in magnitude, frequency, phase sequence, and phase angle.

In grid-parallel mode, since the grid dictates the rotation speed, the active power output can only be adjusted by varying the drive torque at the generator shaft. Increasing the drive torque via the speed controller does not increase the actual speed but instead causes the rotor displacement angle to lead further in the direction of rotation. This shift in the rotor angle relative to the grid voltage is what facilitates the boost in active power output.

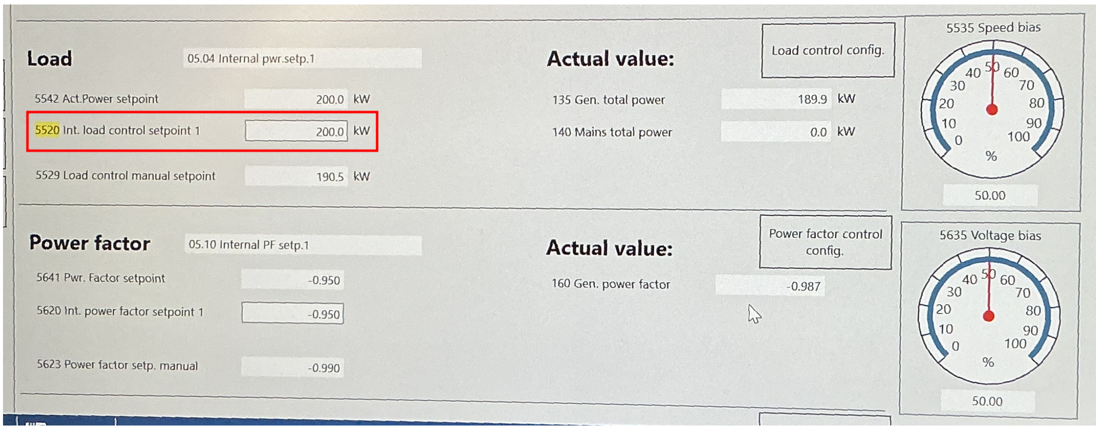
A machine with non-salient pole or drum-type rotors operating at constant excitation current and steady state can fall out of sync if a rotor displacement angle of 90° is exceeded. To prevent this from happening, a generator needs a power controller. The controller will automatically correct the setpoint value specified for the output power.

To manage the exchange of reactive power with the grid, the generator's excitation current must be controlled. An over-excited generator supplies lagging reactive power (acting like a capacitor) and an under-excited generator consumes lagging reactive power from the grid. By utilizing a $\cos\Phi$ controller within the multifunction relay, the excitation voltage is automatically adjusted to maintain the desired power factor.

In this part of the experiment, the $\cos\Phi$ controller of the multifunction relay is tested to see how it works. The controller compares the generator's power factor with a setpoint value and provides feedback control pulses to the excitation voltage actuator. This way a generator can run at a desired $\cos\Phi$ level.

2.3.2 Conducting the experiment

Before the experiment is started, the parameters are checked as shown in Figure 8. The 5520 initial load control setpoint 1 is set to 200 [kW]. The generator is then connected to the three-phase grid using the multifunction relay. The experiment is to change the setpoint value from 200 [kW] to 300 [kW] and then 400 [kW] and observe how the output of apparent (S), active (P) and reactive power (Q) is.



Load 05.04 Internal pwr.setp.1

5542 Act.Power setpoint 200.0 kW

5520 Int. load control setpoint 1 200.0 kW

5529 Load control manual setpoint 190.5 kW

Actual value:

135 Gen. total power 189.9 kW

140 Mains total power 0.0 kW

Power factor 05.10 Internal PF setp.1

5641 Pwr. Factor setpoint -0.950

5620 Int. power factor setpoint 1 -0.950

5623 Power factor setp. manual -0.990

Actual value:

160 Gen. power factor -0.987

5535 Speed bias 50.00

5635 Voltage bias 50.00

Figure 8: Software control of setpoint values

After the setpoint is changed, a wait time is added until the system has settled into steady state. Then the values are collected from the controller (Figure 9) and put into Table 2. The software then plots the measurements as seen in Figure 10.

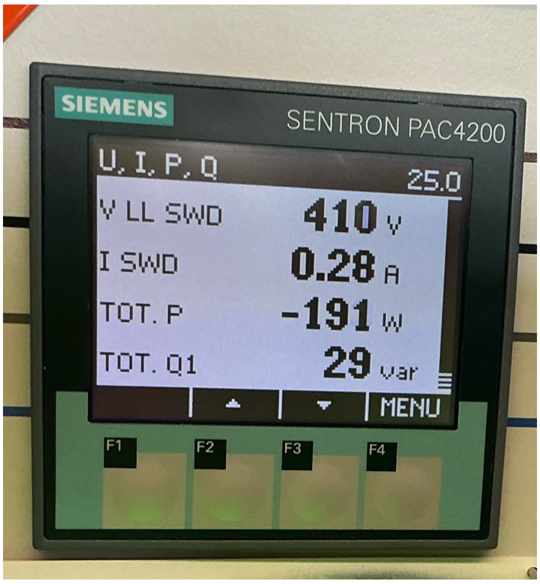


Figure 9: cos Φ controller

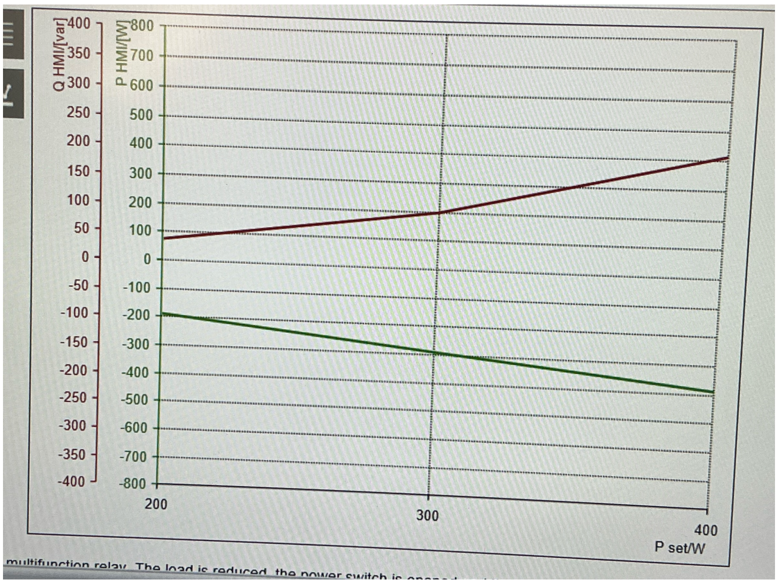


Figure 10: Graph setpoint and measured values

Table 2: Measured values S, P, Q of setpoints

P set (kW)	**200**	**300**	**400**
S HMI (VA)	196	310	445
P HMI (W)	-193	-292	-390
Q HMI (Var)	35	99	207

2.3.3 Results and conclusion

The graph in Figure 10 shows the relation of setpoint power P [kW] to the measured values of active (P HMI [W]) and reactive (Q HMI [Var]) power. As the setpoint is increased from 200 to 400 [kW], the magnitude of the active power increases from 193 to 390 [W]. Simultaneously, the reactive power increases from 35 to 207 [Var].

This result shows that the active power controller successfully responds to the setpoint changes. The simultaneous rise in reactive power suggests that the system maintains a specific cos Φ, because more active power is transferred, the excitation is adjusted to provide the necessary lagging reactive power to the grid in grid-parallel operation.

3 Pumped-storage power stations

A pumped-storage power plant uses electricity to pump water from a lower-level reservoir to an upper-level reservoir where extra electricity production capacity is available. Water flowing back down from the upper reservoir to the lower one powers the synchronous machine acting as a generator. The test system replaces hydraulics with an electrical motor-generator unit, a multifunction relay, and the SCADA.

The active and reactive power compensation experiment was not conducted; hence, only the theoretical concept of its operation is analyzed.

3.1 Power regulation

The conducted experiment involved semi-automatic changes. In such an operating mode, the automatic controls start up and synchronize the machine, and the operator specifies the required values of active/reactive power in the SCADA.

3.1.1 Theory

In grid-parallel mode, the speed of the machine is determined by the grid frequency. For a four-pole machine operating at a frequency of 50 Hz, the synchronous speed will be around 1500 rpm.

The reactive power is controlled using excitation. If the excitation is increased, the machine is over-excited and supplies reactive power to the grid. If the excitation is decreased, the machine is under-excited and absorbs reactive power from the grid.

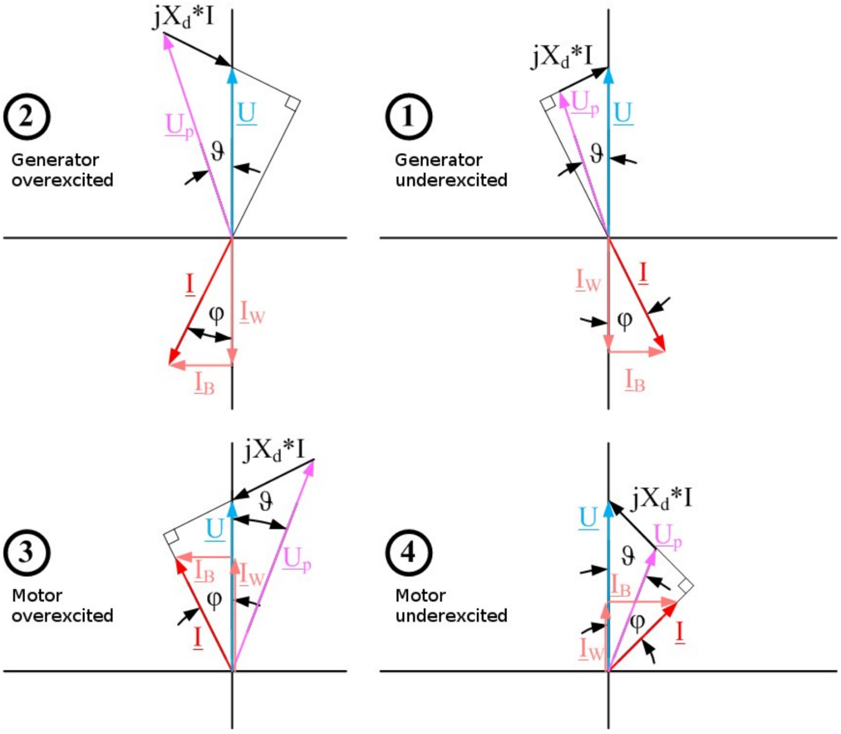


Figure 11: Voltages and currents of a synchronous machine during four-quadrant operation

The active and reactive power sliders then define P and Q as percentages of this apparent power limit:

$$P_{\text{set}} = \frac{P_{\%}}{100} S_{\text{max}}, \qquad Q_{\text{set}} = \frac{Q_{\%}}{100} S_{\text{max}}.$$

3.1.2 Experimental setup

This experiment involved the following equipment: pumped-storage training system, synchronous machine, test bench for servo machine, excitation voltage controller, multifunction relay, power supply, measuring units, and SCADA Viewer.

The connection of the machine to the network was carried out using the multifunction relay, which performed the automatic synchronization and protection operations.

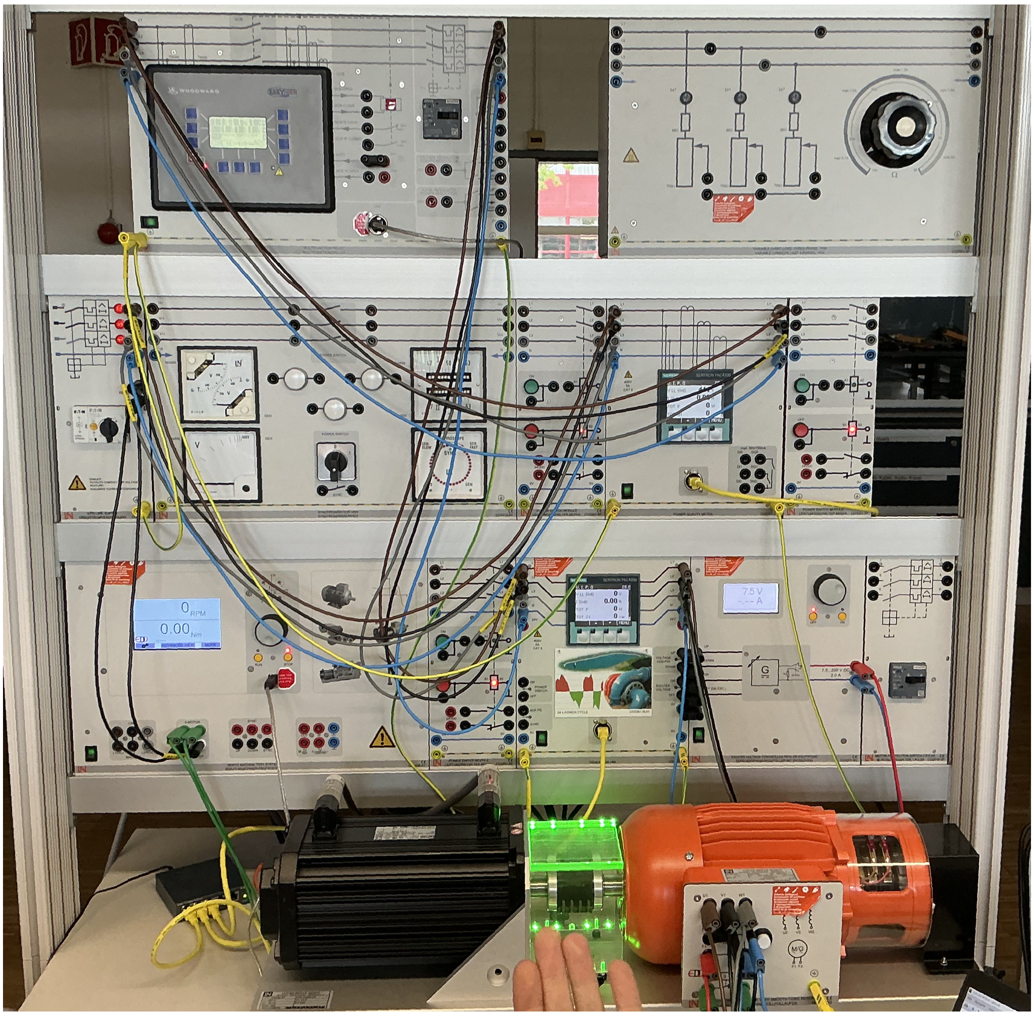


Figure 12: Pumped-storage laboratory setup

The voltage excitation was initially switched off. The multifunction relay was put into AUTO mode, and then using the SCADA interface, the machine was started, and the power was referenced. In the semi-automatic testing process, the load following feature remained disabled, thus allowing the active and reactive power to be manually controlled through the SCADA sliders.

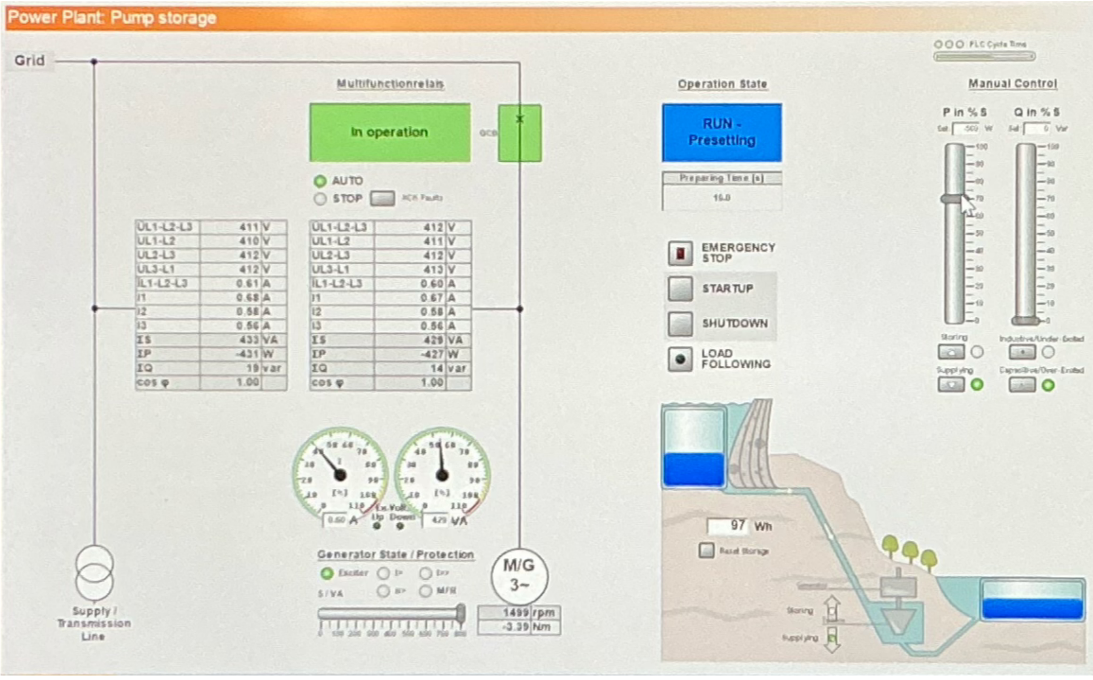
3.1.3 Procedure

The experiment was conducted as follows:

1. Parameter file named `EUG3_400V_50Hz.pvc` was loaded on the SCADA viewer.
2. The servo-machine test stand, three-phase power supply, and excitation system were arranged as per lab guidelines.
3. Multi-function relay was set to AUTO mode.
4. SCADA diagnostics were initialized, and the synchronous machine was operated by STARTUP command.
5. As soon as the generator circuit breaker was closed, LOAD FOLLOWING was not turned ON.
6. The limit of apparent power and active/reactive power references were imposed through SCADA sliders manually.
7. Machine speed, torque, voltage, active/reactive power, and power factor were measured by SCADA interface and attached sensors.
8. The experiment was ended using the SCADA shutdown procedure.

3.1.4 Results

Figure 13 presents the SCADA display during the semi-automatic power regulation test. The multi-function relay was active, and the machine was in RUN mode. The motor-generator system was running at roughly synchronous speed.



UL1-L2-L3	411	V
UL1-L2	410	V
UL2-L3	412	V
UL3-L1	412	V
IL1-L2-L3	0.61	A
I1	0.68	A
I2	0.58	A
I3	0.56	A
ΣS	433	VA
ΣP	-431	W
ΣQ	19	var
cos φ	1.00	

UL1-L2-L3	412	V
UL1-L2	411	V
UL2-L3	412	V
UL3-L1	413	V
IL1-L2-L3	0.60	A
I1	0.67	A
I2	0.58	A
I3	0.56	A
ΣS	429	VA
ΣP	-427	W
ΣQ	14	var
cos φ	1.00	

Figure 13: SCADA interface during semi-automatic power regulation

The main measured values in SCADA are summarised in Table 3, with the Manual Control values of $P_{\text{set}} = 70\%\ S_{\text{max}} \approx 560$ [W] and $Q_{\text{set}} = 0\%\ S_{\text{max}} = 0$ [Var].

Table 3: Observed operating values during semi-automatic power regulation

Quantity	Measured value	Unit
Operating state	RUN – Presetting	–
Machine speed	1499	rpm
Torque	-3.39	Nm
Grid line-to-line voltage	411	V
Generator line-to-line voltage	412	V
Generator apparent power S	429	VA
Generator active power P	-427	W
Generator reactive power Q	14	Var
Power factor cos Φ	1.00	–
Stored energy display	97	Wh

Moreover, the local test stand machine also exhibited a speed near 1500 rpm, implying that the machine had been synchronized with the frequency of the grid network. The torque variation proved that the active power reference was implemented mechanically rather than through speed alteration.

3.1.5 Analysis and conclusion

The results of the experiments were consistent with the expected behaviour of a grid-connected synchronous machine. Once synchronised, the speed of the machine remained constant, equal to the synchronous speed determined by the 50 Hz frequency of the grid. Therefore, an increase in active power was achieved not by changing the speed, but rather by changing the load angle and torque.

The value of reactive power was quite small in comparison with the value of active power and the power factor was very close to 1.00. Thus, excitation was regulated in such a way that very little reactive power was transferred back to the grid. The small non-zero value of Q may be due to some losses in the machine and the tolerance of the controller, as well as the fact that measurements were made while the system had not yet settled onto a steady state.

Semi-automatic start-up is a procedure where the user specifies the power references manually, while the PLC and multifunction relay conduct all other actions to complete the process of start-up. In contrast to fully automatic procedures, here the operator must press a button to turn on the generator.

The semi-automatic pumped-storage experiment showed how a synchronous motor-generator set can be started, synchronised and power-controlled through a SCADA interface. The observed active power was controlled through torque, while the reactive power remained close to zero due to excitation control.

3.2 Active and reactive power compensation

During the active-reactive power compensation test experiment, the LOAD FOLLOWING feature of SCADA will be used. In this case, the system computes the values of active and reactive power at the balance node and controls the motor-generator to provide compensation for the externally added load. The active power compensation applies only to a resistive load while both active and reactive power compensations apply to the inductive load. This is done with the objective of minimizing the value of net power flow at the balance node to near zero within the limits of current, reactive power and the apparent power available in the machine.

The above-mentioned compensation was not done during the laboratory experiments. The anticipated behavior should be that once the load switch is closed, the system adjusts the output of the motor-generator upward or downward until the $\sum P$ and $\sum Q$ values at the balance node are minimized. Active power compensation is achieved by changing the torque and therefore the active power output of the motor-generator set. Reactive power compensation is achieved by changing the excitation of the synchronous machine.

4 Conclusions

From the EUG practice session, the actual behavior of a synchronous generator was analyzed during grid synchronization, automatic synchronization, and pumped storage operations.

Manual synchronization showed that voltage magnitude, frequency, phase sequence, and phase angle must be matched before the generator is connected to the grid in order to avoid excessive electrical and mechanical stresses. Automatic synchronization showed that the multifunction relay and the WOODWARD easygen-2500 controller can adjust speed, voltage, and phase angle before closing the breaker in a more repeatable and less operator-dependent way.

For the operation of grid-parallel systems, it was seen from the measurements that active power control takes place by varying the mechanical torque whereas reactive power is controlled through excitation.

In the pumped-storage training system, the SCADA interface enabled semi-automatic start-up, synchronization, and power regulation. The machine operated close to synchronous speed, and the measured power factor remained at unity (1.00), indicating that only a small amount of reactive power was exchanged with the grid.

A Appendix

List of Figures

List of Tables

Declarations on the use of AI tools

“*ChatGPT 5.5*” was used to enhance vocabulary and as a fact-checker.
All sentences originate from our own ideas and were refined with the support of this tool.
`https://chatgpt.com/`