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Fachpraktikum

Elektrische Maschinen

Experiments with a 400/ 690 V Squirrel Cage Induction Machine

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1. Questions to answer before the experiment

- Describe the operation principle of an induction motor.
- Sketch the equivalent circuit of the induction machine and discuss the meaning of the components of this circuit.
- Sketch the torque-speed curve of an induction machine. Discuss shape of this curve. Show the motoring, braking and generating regions.

Nameplate data

The nameplate of an electrical machine gives a number of important characteristics of the motor.

Fill in the fields below using the information on the nameplate of the machine:

n_{rated} (rpm)	
n_s (rpm)	
s_{rated} (%)	
Number of pole pairs	
Efficiency at nominal operating point (%)	

2. Goal of the experiment

After carrying out the experiments, the students will be capable of:

- Understanding the main operation principle of an induction machine,
- Connecting a three-phase squirrel cage induction motor in a star and a delta as well as reversing its direction of rotation,
- Loading the machine and measuring its efficiency,
- Braking the machine and operating it as a generator,
- Reactive power compensation using capacitors.

3. The experimental setup

Modern electrical drive systems consist of an electrical machine and a drive circuit. In very simple terms, an electric drive system is a controlled conversion between electrical and mechanical power, the electrical machine is the part where this conversion actually occurs, and the drive circuit controls the conversion.

In order to understand a complete electrical drive system, a solid understanding of its fundamental components is essential. Therefore, this course deals with the electrical machines only. This experiment, specifically, covers the behavior of the induction machine connected directly to an electrical grid with little controllability (as seen later, certain uses of reversing or star-delta switches add limited controllability).

The induction machine is mechanically connected to a load machine. The load machine is connected to a drive circuit, called the *machine test system*. The machine test system has a sophisticated control, allowing full controllability on the load machine. This means, the load machine can develop a controlled torque or its speed can be controlled. It can emulate different load profiles i.e., it can be programmed to "act" like a fan, or like a flywheel, etc. The load machine can also drive the induction machine, if the generating mode of the induction machine is to be investigated. In this case, we can say the load machine is emulating, for example, the wind power in a wind turbine where an induction machine is used as a generator. In that sense, we can conclude that, the machine test system and the load machine actually make up a modern electrical drive system, which we use to analyze the basic operation principle of an induction machine.

The machine test system not only controls the load machine, but also measures the electrical input to the induction machine (but does not control the induction machine by changing this electrical input). The speed and the torque are also measured on the load machine side by the machine test system. Finally, the machine test system communicates with a PC and can send measured data for display on the PC. Furthermore, it can be controlled via the PC.

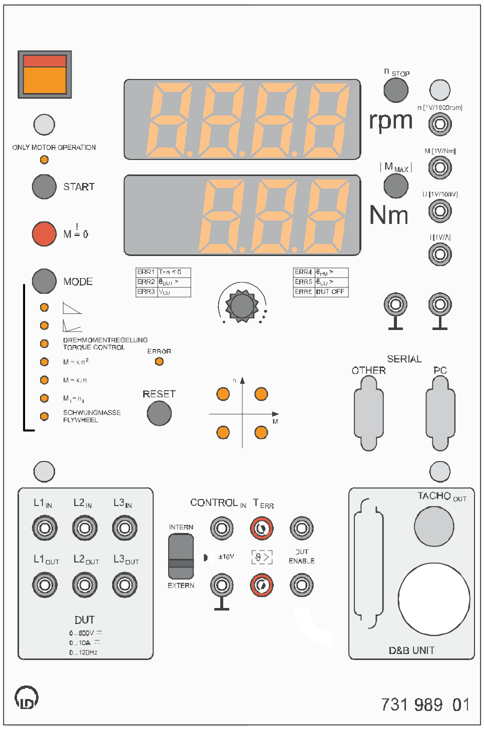

Figure 1. The machine test system.

4. Experiments

Starting up the induction motor

The induction machine investigated in this experiment is a three phase squirrel cage induction machine. Both terminals of all the three phases are taken out, such that the machine can be connected as star (wye, Y) or delta (Δ). Figure 1 shows the three phases of the induction machine.

- Using this information, complete wiring in Figure 2 for star (a) and delta (b) connections.

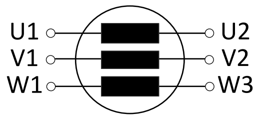

Figure 2. Phases of the induction machine.

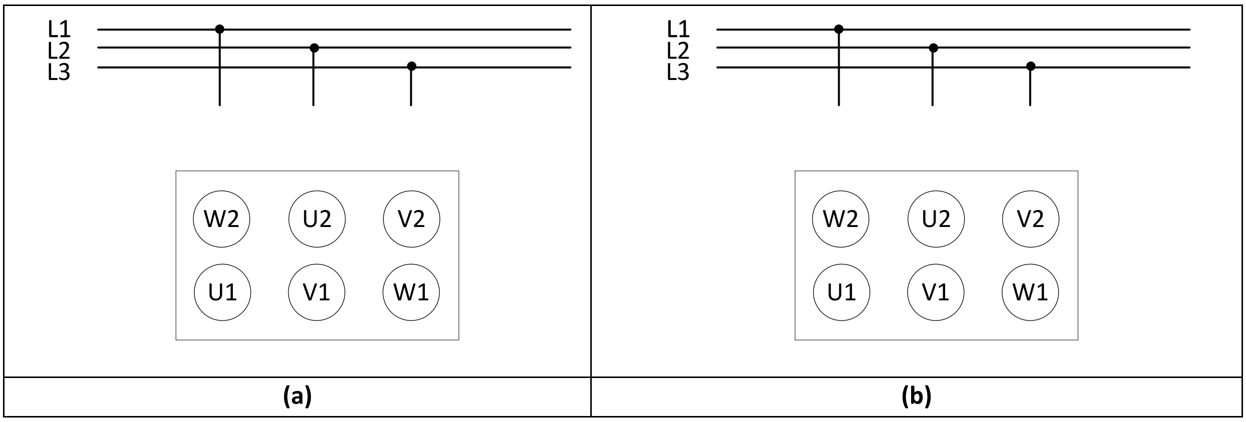

Figure 3. Wiring diagram for star (a) and delta (b) connection.

In this experiment a star-delta switch is used to be able to switch from one configuration to the other quickly and easily. Please study the diagram on the switch and see how it works.

Make sure the *Output terminals 400 I/O* switch is off – there is no voltage at terminals L1-L2-L3. Make the following connections.

- L1-L2-L3 from the output terminals to L1-L2-L3 on the machine test system.
- Out1-out2-out3 on machine test system to L1-L2-L3 of the star-delta switch.
- All the six outputs of the star-delta switch to the machine terminals with the same names.
- PE connection from all the used parts with PE connection to the PE terminal on the table. Yellow-green is the standard color for PE connections.

After completing the steps above, the basic circuit for starting up the induction machine is ready. However, a small modification is needed to be able to measure the phase current of the machine.

- Insert the ammeter in the measurement box on the table denoted by input A (Figure 4) on the table between the machine and the star-delta switch, on the phase U. (U1 from the star-delta switch connected to terminal I of the ammeter, the blue terminal of the ammeter is connected to the terminal U1 of the induction machine.)

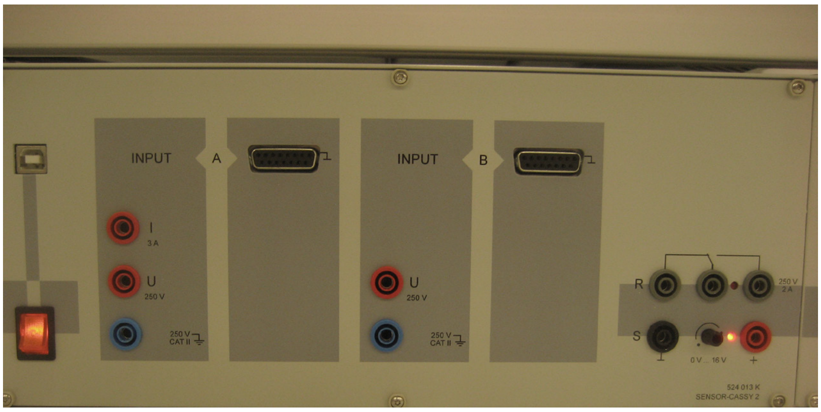

Figure 4. The ammeter on the table.

- Connect the computer to the table using the USB connector on the table (not the one on the controller). This will enable reading the ammeter measurement on the computer.

- Make sure the star-delta switch is in off position, and then power up the table by turning the output terminals 400 I/O switch on.

- Start the machine test system. It should say OFF on its screen. Reset it using the reset button if it is not in OFF position.

- Start the software CASSY Lab 2. Click on the symbol showing the ammeter that is used. Click close. Chose RMS value (AC component) over a period of 20 ms.

- Double check the table before starting the machine. Make sure there are no unused cables, notebooks, calculators lying around. Make sure the emergency switch is easily reachable. Also make sure the switches and the machine test system can be reached without touching any cables. Change the cables with ones with appropriate length, if necessary. Make sure there is nothing in the vicinity of the shaft.

- Set the machine in star configuration using the star-delta switch.

- Power up the machine by turning the output terminals 400 I/O switch on.

- Let the machine reach a constant speed. Note the speed and the phase current:

  - n_Y =
  - I_Y =

- Turn the output terminals 400 I/O switch off.

- Set the machine in a delta configuration using the star-delta switch.

- Start the machine using the output terminals 400 I/O switch.

- Note the speed of the shaft and the phase current:
  - n_Δ =
  - I_Δ =
- Stop the machine by turning the output terminals 400 I/O switch off.
- The measured speed is called the no-load speed of this machine. Remember the operation principle of the induction machine and discuss the relationship of the measured no-load speed and the synchronous speed n_s of this machine.
- Compare the measured values for star and delta configurations of the machine phases. Discuss the results.
- Independent of the star or delta configuration, how do you expect the machine current to look like immediately after powering the machine and after the machine has reached a higher speed? *Hint:* How does the rotor resistance depend on the speed?
- What are the problems with high starting currents? How can those problems be avoided?

Changing the direction of rotation

To change the direction of rotation of an induction motor, the direction of the stator flux needs to be changed. How can this be done?

- On the output terminals of the table, switch any two phases L1-L2-L3 to change the direction of rotation.
- Switch to a star connection using the star-delta switch. Turn the power on using the the output terminals 400 I/O switch. Compare the speed, the direction of rotation and the current with the previous measurements for star connection.
- Turn the output terminals 400 I/O switch off.
- Switch to a delta connection using the star-delta switch. Turn the power on using the output terminals 400 I/O switch. Compare the speed, the direction of rotation and the current with the previous measurements for delta connection.
- Turn the output terminals 400 I/O switch off.

Measuring the efficiency of the induction motor

- Calculate the nominal (rated) torque of the induction machine using the data given on its nameplate.
    - T_{rated} =
- Close CASSY Lab 2. Do not save the changes.
- Connect the computer to the machine test system using the USB cable.
- Start the software MOMO.
- Make sure 0.3 kW is selected in Options tab->Select power class.
- Make sure the squirrel-cage motor 400/690 V is selected in Machine tab.
- Click on the Show/hide measurement cursor button to make the cursor visible.
- Open additional data display under Presentation-> Additional data display.
- On the MOMO main window, adjust the buttons on the left to have the speed (N), input power (P1), output power (P2), voltage (V), current (I), power factor (cos(phi)) and efficiency (ETA) on the additional data display.
- Make sure the star-delta switch is in delta position. Start the machine using the output terminals 400 I/O switch.
- Adjust the mode of the machine test system to the torque control using the MODE button on it.
- Start the controller using the orange button and set the torque value to the nominal torque value. Read the mechanical power at this operating point. Adjust the torque value if necessary such that the machine develops its nominal power. Once the nominal power is reached, read and fill the following fields:
    - N =
    - T =
    - V =
    - I =
    - $\cos(\Theta)$ =
    - η =
    - Pin =
    - Pout =
- Deactivate the torque-control by pressing the orange button on the machine test system.

- Turn the output terminals 400 I/O switch off.

- Double check the input power (P1), output power (P2) and the efficiency (η, ETA) calculated by the control unit using the voltage (V), current (I), power factor (cos(Θ)), speed (N) and torque (T) measurements done by the control unit. Note that the measured voltage is the phase voltage of a star connected source, and the current is the line current of that source.

    - P1 = f(V,I,cos(Θ)) =
    - P1 =
    - P2 = f(T,N) =
    - P2 =
    - η = f(P1,P2) = P2/P1
    - η =

Torque-speed characteristic for motoring range

In the following step, we will the sophisticated control algorithm of the machine test system and control the load machine to load the induction machine in its whole motoring range automatically. Once the start and stop speed references are set in MOMO, the machine test system will sweep the speed of the system and measure the torque as well as the input current and voltage of the induction machine. This information will be used to plot the performance of the induction machine through its whole motoring range.

- Note down the maximum and minimum speed of the motoring range of the induction machine:

    - $n_{motor,min}$ =
    - $n_{motor,min}$ =

- Check the star-delta connection and make sure the motor in delta configuration.

- Make sure the controller is powered up and in idle mode (OFF is written on its display).

- In MOMO's main window, make sure the buttons T, V, I, P1, P2 and cos(phi) are pushed and the rest are not.

- In Measurement->Settings set the operating mode to Load characteristic. Set the maximum (start) and minimum (stop) speeds as calculated above. This means that the load machine will start the speed sweep from the maximum value and load the induction machine until it slows down and reaches the minimum speed.

- Click on the button in MOMO to turn the controller on.

- Click on to take measurement automatically.

- Start measurement by clicking on . Wait until the measurement is finished.

- Turn the controller off either using orange switch or the  button in MOMO.
- Stop the induction motor using the output terminals 400 I/O switch.
- Switch to star connection using the star-delta switch.
- Start the induction machine using the output terminals 400 I/O switch.
- In MOMO, turn on the controller using the  button.
- Start the measurements by .
- Turn the controller off either using orange switch on the controller or the  button.
- Stop the induction motor using the output terminals 400 I/O switch.
- Compare the machine performance with star and delta connections.

- Comparing starting current and torque of star and delta connections, it can be seen that the startup current can be limited by starting the machine in star connection and later switching to delta. However, this may not always be possible. Discuss the load contitions where a star-delta startup can be used.

Generator and brake operation

Both in generator and brake mode, mechanical power is fed into the induction machine, i.e., the speed and torque have negative signs, and the induction machine applies torque to slow the shaft down.

In generator operation, the mechanical power is converter into electrical power, and sent to the electrical grid that the induction machine is connected to. However, even working as a generator, the induction machine needs the magnetizing current to come from an external source. Therefore, the grid supplies reactive power to the induction machine, while the induction machine pushes active power into the grid.

During the brake mode, the induction machine takes active power from the grid and uses it to slow down. In this mode of operation, power flows into the electrical machine both from the electrical mechanical sides, and this power is burned in the machine. Therefore, this mode of operation may lead to overheating of the machine if it lasts for a long time.

Let’s first investigate the brake mode.

- Make sure the Output terminals 400 I/O switch is off.

- Insert the reversing switch between machine tests system output (Out1 – Out2 – Out3) and the star-delta switch input. The reversing switch works similar to the star-delta switch, but simply changes the order of the phases, thus reversing the direction of the stator field.
- Make sure the machine in delta connection.
- Restart MOMO. Make sure P1, P2, V, T and I are being displayed.
- In Measurement-> Settings uncheck the box “Only motor operation”. Choose Flywheel mode and close the window. This will operate the load machine as if it was a flywheel i.e., emulate additional inertia connected to the shaft.
- In MOMO, turn on the controller using the  button.
- *Read the following steps until the end of the braking mode measurement before going further. The following steps need to be applied in short time, and you need to know your next move in advance!*
- Set the reversing switch in position 1.
- Start the measurement in MOMO by pressing . Press spacebar to start recording in MOMO and keep pressing it until the end of this test.
- Start the machine using the Output terminals 400 I/O switch.
- Note that the speed is increasing much slower now, due to the additional virtual inertia.
- Once the machine reaches 500 rpm, set the reversing switch in position 0. This stops the power flow to the induction machine. The speed decreases slowly due to the virtual inertia.
- After a few seconds, put the reversing switch in position 2. This reverses the stator field direction and puts the induction machine in braking mode. Note that the speed is decreasing faster, due to the negative torque.
- Once the speed is below 100 rpm, put the reversing switch back to position 0 and stop the braking mode.
- Stop recording the data (release space bar).
- Exit the flywheel mode by pressing the orange button on the controller.
- Turn the output terminals 400 I/O switch off.
- Discuss the results.

Next, we investigate the generating mode.

- Restart MOMO. Make sure P1, P2, Q, V, T and I are being displayed.
- In MOMO main window, make sure Take measurement automatically button  is pressed.

- Start the machine in delta configuration using the output terminals 400 I/O switch.
- Start the controller by clicking on the  button.
- In Measurement-> Settings chose Run-up characteristic. Make sure Only motor operation is unchecked. Set the start speed to 1350 rpm and the stop speed to 1650 rpm.
- Once the speed is set to 1350 rpm, start the measurement by clicking on .
- After the measurement is done, deactivate the machine test system by pressing on the orange button or .
- Turn the output terminals 400 I/O switch off.
- Discuss the results. Can the induction machine be used as a generator in the absence of a grid (island operation)? Why?

Reactive Power Compensation for Squirrel Cage Motors

As it was described above, the magnetizing current has to be supplied to the induction machine regardless of its mode of operation (motoring, generating etc.). In other words, the induction machine needs a certain amount of reactive power in order to operate. When the machine is connected to an electrical grid, the grid supplies the reactive power. This results in additional ohmic losses.

A capacitor bank can be connected in parallel to the machine, to compensate the reactive power. In this case, the capacitors create the necessary reactive power for the induction machine, and the grid does not need to supply the reactive power any more.

- Calculate the reactive power of a capacitor bank of three 2uF capacitors, in delta configuration, connected to a 50 Hz, 400 V grid.

- In Figure 6, complete the wiring such that the capacitors and the induction machine are in delta configuration.

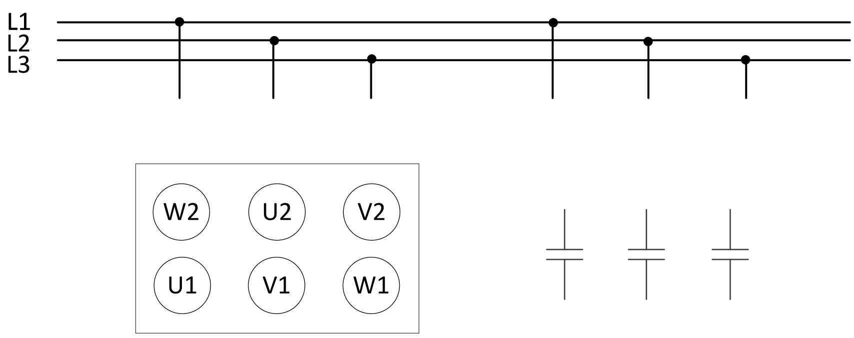

Figure 5. The connection of the induction machine and compensation capacitors.

- Restart MOMO
- In MOMO's main window, make sure the buttons T, I, Q, P1, P2 and cos(phi) are pushed and the rest are not.
- Start the machine in delta configuration.
- In Measurement->Settings set the operating mode to Load characteristic. Set the speed to 1500 rpm and stop speeds to 0 rpm.
- Click on the button in MOMO to turn the controller on.
- Click on to take measurement automatically.
- Start measurement by clicking on . Wait until the measurement is finished.
- Turn the controller off either using orange switch or the button in MOMO.
- Stop the induction motor using the output terminals 400 I/O switch.
- Make the capacitor bank connection according to Figure 6. (C=2 uF)
- Start the induction motor using the output terminals 400 I/O switch.
- Click on the button in MOMO to turn the controller on.
- Click on to take measurement automatically.
- Start measurement by clicking on . Wait until the measurement is finished.
- Turn the controller off either using orange switch or the button in MOMO.
- Stop the induction motor using the output terminals 400 I/O switch.
- ***Please be aware that even after turning the power off, the capacitors may have stored energy that may cause severe injuries!!!***
- Discuss the effect of compensating capacitors. How much reactive power has been compensated?