Four-Quadrant Thyristor DC Drive

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1. Introduction

Thyristor DC drives are nowadays commonly used in the paper industry in the field of reeling drives. Traditional field of application are high power controlled centrifuge drives (food industry), extruder drives in rubber and plastic industry. The above mentioned applications are characterized by need of controlled torque in addition to speed control. Technological requirements usually include both driving and braking i.e. motoring and generating torque capability of the drive, in certain cases with speed reversal.

The power component of controlled DC drives is typically three-phase thyristor bridge converter with firing angle control, while the electromechanical component is a DC motor with separate (constant) or compound (mixed) field excitation.

In the frame of recent laboratory practice we study electrical features of a pair of mechanically coupled controlled DC drives, both are supplied by own thyristor converter. One of the drives works as motor with active power consumption, while the other works as generator, returning the brake energy back to the line.

2. Terminology and keywords

Power electronics, Converters AC-DC, Firing control, Controlled drives, Energy conversion

3. Laboratory practice target

1. Review of the MENTOR-II type four-quadrant thyristor converter's technical features, including principle of operation, basics of program settings and adjustments

2. Measurement and oscilloscope analysis of AC and DC side electrical quantities in different operating conditions (in all four quadrants)

3. Study the dynamic behavior of the drive arrangement under test by means of oscilloscope signal analysis

4. Evaluation and interpretation of the results in form of measurement protocol

4. Theoretical basis of the measurement practice

4.1. Structure of the three-phase thyristor converter

Thyristor converters, as typical, are built in three-phase bridge configuration. The base arrangement is the three-phase diode bridge (rectifier) see fig. 1. Its operation, specific voltage and current waveforms are presented and analyzed in detail in Lit. [4] Pp.175-178.
Four-quadrant Thyristor DC drive

Figure 1. Three-phase Diode Bridge

Advantage of the three-phase diode bridge arrangement is the simplicity and tolerable distortion factor of the line current (waveform is not far from sinusoidal fundamental), as it can be seen on Fig. 2.

![Three-phase Diode Bridge](image1.png)

Figure 2. Rectified voltage $U_a$ and input phase voltage/current Lit. [4]

Output voltage of diode rectifier cannot be influenced electronically, diode’s conduction state changes in the moment of the natural commutation.

4.2. Phase angle control of thyristor converters

Thyristor is the first semiconductor structure, used as power switch component. It can be switched on by small power gate signal, while switch-off cannot be achieved by gate control. Principles of operation can be found in Lit. [4] pp. 14-16.

Three phase thyristor converter circuit, feeding an ideal DC machine, (with all protection components) can be seen in Fig. 3. Output voltage $U_d$ (mean value $U_{d0}$) can be controlled by delaying thyristor gate pulses, influencing their conduction period. Gate pulse delay should be fixed to the moment of natural commutation (moment of beginning of diode conduction state), i.e. gate control is to be synchronized to the line. Method is known, as firing angle control, typical one-phase waveforms and quantitative relationships found in Lit. [4] pp.20-24.

![Thyristor converter, feeding an ideal DC machine](image3.png)

Figure 3. Thyristor converter, feeding an ideal DC machine
Disadvantage of the phase angle control is the phase shift of the input line current fundamental, resulting in an excess reactive power (Lit. [3] Chapter4.2.3.). Line power factor is a function of actual operating point of the drive.

Thyristor converter, feeding a DC motor with armature voltage $U_a$, provides one-polarity current $I_a>0$, and two-polarity output voltage $U_d$. In case converter operates in rectifier mode ($U_d>0$), machine works, as motor (see Fig.4., I. Quadrant), while inverter mode of converter ($U_d<0$) results in machine, working as generator (Fig. 4., II. Quadrant).

Three-phase converters are sensitive to input voltage phase sequence. Thyristor S1-S3-S5 on Fig.5. should be fired in time sequence accordingly to that of input phase voltages VR-VY-VB. Reversed phase sequence results in loss of control and malfunction of converter.

Specific feature of inverter mode operation in thyristor converters is the danger of the loss of commutation. In inverter mode of the converter, conducting thyristor can be switched off only by firing the next in sequence element (line commutation), unless conducting device will connect line voltage with motor armature voltage $U_a<0$. As result, a high surge current gets on (inverter turn-over), the overcurrent can be cleared only by fast-acting input blow fuses (F1+F3 on Fig. 3.)

Figure 4. Four quadrant and energy flow direction of DC drive


4.3. Electric stresses and protection elements in Thyristor Converters

Semiconductor crystal structures of thyristors are extremely sensitive to shortest (in order of μsec and less) electric stresses. Converter power circuit on Fig. 3. include usual protection components of thyristors. Absolute maximum values of thyristor stresses, not to be exceeded, are:

1. $U_{\text{max}}$: maximal peak value of anode-cathode voltage in forward and reverse direction. It can be limited by suppressor elements (varistors) V1+V6.
2. $dU/dt$: maximal rate-of-rise of forward voltage, should be limited by parallel R-C suppression networks
3. $t_q$: turn-off time, needed thyristor structure to be switch off. Turn-off time should be ensured by inverter-mode firing angle limitation.
4. $dI/dt$: maximal rate-of-rise of thyristor current, when switched on. This value can be limited by $L_2+L_4$ line side (commutation) chokes
5. $I_s$: Maximal surge current, usually defined for half period of line voltage (once fired thyristor cannot be switched off within voltage half period)
For over-current protection in circuits with DC voltage component (like DC thyristor converters), limitation is given in form of \( I^2 t \) integral for fusing. Fast-acting fuses F1-F4 are chosen to ensure fusing \( I^2 t \) value less, then the limiting value of the thyristors.

### 4.4. Anti-parallel thyristor converters, working without circulating current

Motor armature current is negative \((I_a<0)\) in the III. and IV. quadrants according to Fig. 4. Negative armature current can only be supplied by adding a negative converter (anti-parallel converter, Fig. 5.)

![Diagram of anti-parallel converters](image)

Figure 5. Four Quadrant DC Drive with anti-parallel Converters [1]

Output DC voltage mean value of three-phase bridge thyristor converter is a cosine function of the firing angle (Lit.[2] pp. 140). The positive and the negative converter would give reverse each other output voltages, if having equal firing angles. Therefore the two converter should have so called “complementary” phase-angle control \((\alpha_{neg}=180^\circ-\alpha_{pos})\). When positive converter have minimal phase angle \(\alpha\sim0\), the negative converter have maximal phase angle \(\alpha\sim180^\circ\). Technical solutions of Four-Quadrant DC Drives are discussed in Lit. [3] Chapter 2.4., and in Lit [5] Chapter 2.2.1.

In present test arrangement MENTOR-II type thyristor converters are used. They have structure, similar to that, shown in fig. 5. Circulating currents are excluded by control logic. At any moment only one (positive or negative) converter is enabled, depending on desired DC current direction. Simultaneous current flow of both converters would lead to line phase short circuit to be avoided.

### 4.5. Control methods of DC drives

Simple and widely used control structure of DC drives is armature voltage regulation with internal closed loop armature current control [5] pp. 9-10. There is no need of external sensors, and torque regulation/limitation can be achieved in most cases.

Closed loop control of armature current include phase angle control of thyristors, therefore current loop should be regarded, as dead-time, sampled, non-linear system. Continuous and discontinuous current conducting modes of converter result in different transfer function coefficients, requiring adaptive control.

Above mentioned control tasks are solved in a μP based digital controller by software way. Control loop parameters for actual motor will be determined and saved automatically by preliminary “self test” procedure.

Regulation of the armature voltage results a near constant speed operation of the drive, assuming, that excitation field is constant, motor is compensated, and torque is below the limiting value (speed-regulated drive)

Regulation of the armature current is often used in applications, demanding closed-loop control of the motor torque (torque-regulated drive). In case of accelerating torque in the selected quadrant, motor maximum speed must be clamped at a limit value [6]. MENTOR User Guide can be found at http://www.controlvh.hu web site.
Typical control algorithms of thyristor converter fed DC drives, and their linearized models are discussed in details in Lit. [5], Chapter 2.2.1.

5. Laboratory test arrangement

5.1. Structure of DC machine set

Two-machine set consists of two compensated type DC motors, with external excitation, linked mechanically with elastic coupling. Motors are fed by similar type MENTOR-II Thyristor Converters, but have different regulating features.

In accordance with Fig. 6., speed of the machine set is determined by Drive1 speed reference, while torque between the two machines will be adjusted by Drive2 torque reference. Arbitrary working point within maximal values of armature voltage and current can be adjusted for investigation.

Figure. 6. Mechanical speed-torque characteristics of drives under test

In operating point “A” (Fig. 6.) Drive1 works, as motor. Active power, fed by Drive1, will be returned back to the line by Drive 2, working, as generator (brake machine). The rotation directions of the motors are reversed.

Nominal values of machines G1, G2:

1. \(U_n = 220\) V armature voltage
2. \(I_n = 37\) A armature current
3. \(P_n = 8\) kW Electric power
4. \(n_n = 1500/\text{min}\) rotation speed
5. \(I_{gn} = 1\) A excitation current
6. \(L_a = \sim 8\) mHy armature inductance
7. \(R_a = \sim 0.3\) ohm armature resistance

5.2. MENTOR DC drive: structure and main parameters

Power schematics are identical to anti-parallel converters, shown on Fig. 5. Measurements of internal quantities are measured by sensors (Voltage, current, temperature, etc.), with digital signal processing. The main technical data of converter:

1. Type: MENTOR M45R
2. Manufacturer: Control Techniques/Emerson

3. Structure: Four-quadrant drive with anti-parallel thyristor converters, μP controlled

4. Input voltage: $3 \times 200\, \text{V} \pm 3 \times 480\, \text{V} \text{AC} 42\pm 60\, \text{Hz}$, false phase sequence protected

5. Input current: $3 \times 38\, \text{A continuous, 150% max. overload}$

6. Power factor: $0^{\circ}(\pm 0,90)$

7. Output voltage: $\pm 270\pm 600\, \text{V DC, depending on line voltage range}$

8. Output current: $45\, \text{A continuous, 150% overload}$

5.3. Functions of the control system

Main functions of the control system are:

1. Digital data processing of signals, gathered from internal and external sensors (Voltages, currents, speed, position, temperature, etc.)

2. Closed loop digital regulation, according to control strategy, including complex thyristor firing angle control

3. Configuration and data processing of inputs and outputs

4. Operation of local keypad, displays, serial communication ports

5. Monitoring tasks, alarm and trip functions, diagnostics

5.4. Operators’ menu system of parameters

Nowadays almost all technical features of controlled drives can be adjusted by software. Industrial drives are intended to cover widest variety of possible applications. MENTOR-II, used in recent test equipment, has similar, highly flexible software. Block diagram of controller structure consists of elements, for the most part freely adjustable by user.

MENTOR-II controller has a lot of user definable/readable elements, called, ”parameter”, in amount exceeding 400. Parameters are divided into functional groups, named “menu”. MENTOR has 13 menus, each containing 20–39 parameters. The role of parameters and their connections are presented on partial flow-charts of the selected menu. [6]. Parameters can be divided into groups by their content, too:

1. Read-only digital variables: (measurement results, controller outputs, manufacturers fixed settings)

2. Adjustable digital variables: (references, limiting and min/max comparison values, closed loop parameters, security codes, source and destination parameter data)

3. Programmable logical variables – configuration bits (control structure, input/output, communication, monitoring system configuration)

Generally used base configurations are programmed by manufacturer in form of default parameter set, to reduce the number of parameters to be programmed in applications without high requirements and complexity. If needed, three level security code protection systems can be used against non-professional handling attempt. Laboratory test equipment demands only 10–15 parameters to be adjusted.

5.5. Drive control from local control panel

Laboratory tests demand manual control and adjustment of the drives. Therefore a minimal configuration control panel was built up, in accordance with Fig. 7. input/output control connections:

1. K1: Enable/disable (TB4/31) switch can disable system operation (in case for example power-on)

2. K2: Star/stop (TB3/21) Switch permits running (forward or reversed) of the motor
3. K3: +10V/-10V polarity change of the potentiometer adjusted reference (speed or torque)

4. P1: Ua armature voltage reference at (TB1/3) fixed input (±10V range)

5. P2: Ia armature current reference at (TB1/4) programmable input (±10V range)

5.6. Schematics of test arrangement and measuring instruments

Schematics of power parts and fix connected instruments presented on Fig.7. Input line phase voltages L1-L2-L3 are 3×120/200 V AC

Figure 8. Test arrangement

Specification of measuring instruments, as follows:

1. Uin: electrodynamic voltmeter in range 127 V AC (phase voltage)
2. In: electrodynamic ammeter in range 5 A (line current, transformed)
3. Pin: electrodynamic watt-meter U=127 V, I=5 A (one-phase active power)
4. Qin: electrodynamic watt-meter u=240 V, I=5 A (one-phase circuit for measuring reactive power)
5. AV1: 50 A/5 A AC current transformer (10:1 current ratio)
6. V1,V2: analog DC voltmeters in range 300V
7. A1,A2: analog DC ammeter, suited to 60 mV precision current shunt
8. RS1-2: 50 A/60 mV laboratory current shunts
9. PS1-2: HPH type excitation units 0±2.5 A
10. DSO: digital storage oscilloscope Goodwill GDS-1062, two channel, USB communication
11. PHA: FLUKE 41B one-phase power analyzer, with isolated data cable to serial port
12. CCL: FLUKE i310s AC/DC current clamp 30 A, 10 mV/A
13. DPR: TESTEC TT.SI9002 type high-voltage isolated probe 1:200, max. ±1400 V
14. PC: computer with communication and data processing SW

6. Laboratory test tasks

6.1. Measurement of converter line-side parameters in motor and generator mode

1. Be sure, drives are disconnected from mains. Put K1= disable; K2=stop; K3=+ positions, P1,P2 to minimum. Connect voltage probes of PHA analyzer to phase voltage U1, current clamp CCL put to measure phase current I1.
2. Switch on power mains, and control nominal excitation currents. Enable both drives to run by K1=enable, then K2=start switchover.
3. Adjust Drive1 speed reference to nominal armature voltage with P1, when running, increase torque, developed by Drive2 to 75% of nominal armature current with P2 of Drive2. Read and fix input quantities (Uin, In, Pin, Qin), measurement data of power analyzer save to internal memory.
4. Repeat measurement in 8 working points with decreasing armature voltage in range of forward nominal to reversed nominal with zero seed excluded. When finished, stop machines with K2=stop, after machines have stopped, suspend operation by K1=disable.

6.2. Oscilloscope waveform analysis of converter motor-side variables

1. Connect oscilloscope to PC/USB port, and get software started. Connect DPR adapter inputs to converter DC output Ua (CH1), CCL current clamp put to measure DC current Ia (CH2). Switch oscilloscope to line synchronization.
2. Similar to pp. 1.6.1, set the first operating point of the drives. Read and fix input quantities (Uin, In, Pin, Qin), as well, as DC quantities (V1, A1, V2, A2). Save waveforms of Ua, Ia on PC. Define effective and peak value of AC components by means of built-in measurement menu both for armature voltage and current.
3. Repeat measurement at minimal speed (~10% of nominal), and in reversed nominal voltage, then return to the first operating point.
6.3. Oscilloscope waveform analysis of voltage at phase-angle control

1. Study output voltage waveform $U_a$, scanning the full available range. Save to oscilloscope internal memory the output waveform with minimal firing angle to estimate moment of natural commutation. Set $U_a=100$ V, then compare on-line waveform with the reference saved previously. Measure firing angle delay, relative to natural commutation moment by time cursor.

2. Determine the commutation process feature on output voltage waveform. Measure the commutation period time at $U_a=$nominal, and $U_a=50$ V by time cursors. Document results on PC.

6.4. Analysis of torque reversal transient process

Set $U_a=$nominal, $I_a=0.75 \times$ nominal operating point. Investigate on oscilloscope the transition of armature current, when switch over Drive2 torque by $K_2$ from positive to negative and back. Current direction change require changeover of positive and negative converter operation. Fix and save armature current transition, measure the dead time between the active state of the two converter. Document results on PC.

7. Evaluation and documentation of test results

1. Document test arrangement with measuring kit specification

2. Define total apparent, active and reactive power of the converter in based on results of pp. 1.6.1. Include power factor (P.F.), measured by power analyzer. Build up the diagrams in function of armature voltage. Explain the results.

3. Calculate power losses of the machine group and converter Drive1 on the base of results of pp. 1.6.2. at nominal and minimal speeds. Identify the sources of the losses. Document AC component measurements and waveforms. Which of them will greatly affect DC motor operation, and why?

4. Determine firing angle of converter at $U_a=100$V, using result of pp.1.6.3. Compare experimental result with theoretical, calculated for actual $U_1$ input phase voltage.

5. Determine dead time of armature current in pp.1.6.4. What is the reason of it? Which quadrants are affected by this phenomenon?

8. Control questions and tasks

1. Calculate minimum of supply AC voltage to ensure nominal armature voltage for the machine in test equipment

2. On Fig. 6, horizontal axis is common for both speed “$n$” and voltage “$U_a$” , vertical axis is common for both torque “$M$” and current “$I_a$”. Explain theoretical base, why it can be done. What is neglected?

3. Determine and represent ideal-case input current waveform of three-phase diode rectifier when output current $I_a$, output inductance $L=\infty$, commutation neglected. Calculate effective values of input current and its fundamental too. Calculate distortion factor of input current.

4. Let Drive1 of test arrangement operating in quadrant III. Supposing steady-state, where is the operating point of Drive2 and why?

5. Converter under test is supplied from 3×127/220 Volt three-phase voltage with grounded neutral. Output voltage is analyzed by line-connected grounded equipment. Determine the isolation voltage of the input voltage probe adapter at maximal converter output voltage.

9. Literature


2. fejezet - Measurement of a synchronous servodrive with trapezoidal field

1. Scope of the measurement

AC drives becoming more and more important in the field of robot and machine tool control. In case of permanent magnet synchronous machines (PMSM) both machines with sinusoidal and trapezoidal field are applied. Last is often referred as brushless DC (BLDC) due to its similarities in commutation to the traditional DC machine.

Optimal control can be only achieved in both sinusoidal and trapezoidal case, when current vector control is applied, and the current vector is matched to the position of the rotor, to the shape of the field and to the torque required. This can be performed by using transistor based voltage inverters with pulse width modulation (PWM). In this measurement a machine with $\beta=180^\circ$ trapezoidal field will be investigated.

2. Theoretical background of the measurement

2.1. Supply of synchronous machines with trapezoidal field

An appropriate current waveform (matching the above requirements) can be chosen by knowing the pole voltage as a function of rotor angular position. Mechanical power and hence also the torque produced by one single phase can be calculated as the product of the pole voltage and the given phase current. According to this, constant power and torque can be achieved if the sum of the pole voltage and phase current products of all the individual phases is constant. For machines with trapezoidal field some types of current waveforms can be used.

The simplest supply is the so called one phase supply. In this case – neglecting the current overlapping during the commutations – there is always only one phase is carrying current. Positive torque can be produced by applying a positive current in those rotor angular position regions, when the pole voltage is positive. Matching in this case means that the current is constant when the pole voltage is also constant. This occurs in certain regions only when the speed is constant as well. Anyway, the pole voltage-rotor position function also has negative regions as well. This part is not utilized in one phase supply. It can be said that this kind of control has only one advantage compared to the two phase supply that the phase currents are flowing only in one direction, only unipolar supply is required. This is very similar to the supply of DC machines, with the difference that in this case the DC current is being carried by not only one, but three different windings, and the commutation is forced by an electronic controller instead of a mechanical device called commutator. Hence these drives are often referred as electronically commutated DC (ECDC) drives.

If one would like to utilize the negative regions of the pole voltages as well, then here constant, but negative currents should be applied to achieve a positive torque again. Hence, unlike in case of one phase control, bidirectional current flow is needed for each of the phases, which requires bipolar supply. In this case – neglecting the overlapping again – there are always two phases are carrying currents out of the three.

It is also possible to perform three phase conduction, when at a given time moment, all the three phases are carrying currents, however this is not used in practice.

In case of one- and two-phase supply, the main goal is the simple controllability even if it means that the idealized current waveforms can only be implemented with some errors in practice. Hence the torque with these drives is less smooth. When a smooth torque is critical, then machines with sinusoidal field are applied.

2.2. Current control of synchronous machines with trapezoidal field
Current control of synchronous machines with trapezoidal field can be realized in more ways: hysteresis control in individual phases, hysteresis control on the basis of a lookup table and PI current control with pulse with modulation.

3. Introduction of the measurement

3.1. Main components of the drive being studied

1. Synchronous servo drive (manufactured by Stromag):
   Synchronous servo electronic controller: \( U_{\text{max}} = 3 \times 240 \text{ V}, I_n = 25 \text{ A}, I_{\text{max}} = 50 \text{ A} \)
   Synchronous servo motor: \( M_n = 8 \text{ Nm}, I_n = 20 \text{ A}, I_{\text{max}} = 105 \text{ A}, K = 0.4 \text{ Nm/A}, \Theta = 0.006 \text{ kgm}^2, n_{\text{max}} = 3000/\text{min.} \)

1. Load machine:
   \( M_n = 20 \text{ Nm}, I_n = 25 \text{ A}, I_{\text{max}} = 170 \text{ A}, K = 0.8 \text{ Nm/A}, \Theta = 0.032 \text{ kgm}^2, n_{\text{max}} = 1200/\text{min.} \)

1. Transformer, 3×380/3×210 V, 2 kVA
2. Torque meter
3. Oscilloscope
4. Load resistor

3.2. Startup of the drive

1. Turn off the reference signal switch of the electronic controller, set the reference potentiometer to zero, and turn off the enable switch.
2. Turn on the 3×400 V 50 Hz connection
3. Enable the drive by the enable switch, set the desired reference signal and turn on the reference signal switch.

3.3. Applied metering devices

1. Torque meter
2. Handheld multimeter

4. Measurement tasks

4.1. Measurement of the pole flux and pole voltage

Disable the electronic controller, and speed up the synchronous motor by the DC load machine connected to its shaft. Investigate the space vector (Park-vector) of the pole flux and pole voltage and the time functions. Explain differences from theoretical (idealized) shapes. Verify the rightness of the mechanical connection between the position encoder and the synchronous machine. This can be done on the basis of \( I_1 \) and \( I_b \) position signals.

4.2. Investigation of voltage, flux and current

Connect the DC load machine to the \( R_T \) load resistor. Operate the synchronous machine as a motor, and investigate the \( u, \Psi, \) and \( i \) vectors and the \( u_a, \Psi_a, i_a \) phase quantities in both rotational directions. Determine which kind of supply is used in this device.

4.3. Investigation of synchronization
Verify the synchronization (matching) of the currents to the rotor position on the basis of $I_a$, $I_b$ and the $i_c$ signals for both rotational directions and for both motor and generator modes. Generator mode can be achieved only in transient state. Explain the differences of synchronization between motor and generator modes. Investigate the synchronization during a transient from motor to generation mode.

**Figure 1:** Schematics of the measuring system

### 4.4. Verification of the speed metering

Verify the operation of the speed metering electronics in both rotational directions on the basis of the $I_a$, $I_b$ and $n$ signals!

### 4.5. Measurement of the torque-speed curve of the drive

On the basis of the torque signal of the torque meter or on the basis of the dc current of the load machine, take the torque-speed curve of the drive. Explain the results!

### 4.6. Investigation of time functions of speed and currents

Investigate the $n(t)$ and $i(t)$ curves of the drives at step changes in the reference signal and at reversals by using the oscilloscope! Perform the measurement both with and without load.

### 4.7. Investigation of the effects of step changes in the load

Investigate the effects of both positive and negative step changes to the $n(t)$ and to the $i(t)$ functions!
Measurement of a synchronous servodrive with trapezoidal field

4.8. Investigation of reference signal following abilities

Apply a signal generator! Set a constant reference signal, and add a sinusoidal, then a square signal to it. Investigate the signal following abilities of the drive on the basis of \( n(t) \), \( n(t) \) and \( i(t) \). Take the Bode-diagram (both amplitude and phase) of the closed control circuit.

5. Investigations with computer simulations

The simulation investigates the control loop of a drive with a \( \beta=180^\circ \) synchronous servo motor. The matching rules should be kept also for the transient states. In these states, the magnitude of the pole voltage changes proportionally with the speed. The value of the current reference signal is determined by the torque requests of the outer speed control loop.

5.1. Hysteresis current control in individual phases

For this method, a current reference signal is required for each phases, and deviations are calculated in each phases. Tolerance bands \( (\pm \Delta I) \) determines the allowable deviations from the reference signal. When the tolerance bands are the same for all three phases, then in a vector diagram, it defines a hexagon with \( 2\Delta I \) distance between its opposite sides. Simulation shows, that in this case, the current vector remains within this hexagon, except in two cases:

1. Sometimes into the triangles neighboring to the sides. The reason of it that the star point of the machine is floating; hence the three currents cannot be controlled independently.

2. In every 60 electrical degrees with a big overshoot. The reason of it that the reference signal jumps in every 60 degrees, which cannot be followed by the current immediately because of the inductances of the machines.

5.2. Current vector control based on a lookup table

The controller senses when the current error vector reaches one side of the tolerance hexagon. The necessary switching state of the inverter is determined by a lookup table value. This value depends on two things. Firstly, which side of the hexagon was reached, and secondly, which is 60 degree sector contains the voltage vector affecting the change of the error. The simulation shows, that the current vector with this method always remains within the tolerance hexagon with no exceptions.

5.3. Analogue PI control with PWM

Parameters of the PI controller can be varied from the simulation software. The inverter controller switches the appropriate voltages to the appropriate in every 60 degrees.

5.4. The simulation program

The program is written in Pascal language. The system is described by its state equations. Solution is found by a Runge-Kutta method. The points of intervention are determined by an iterative process.

The initial conditions and parameters can be varied by V, simulation can be started by G. Plots can be made by A, and exit is possible by K. When starting the simulation, the simulation time and the control method have to be selected. One has to define the tolerance band and the drawing mode.

It is possible to investigate the time function of the current vector or the current error vector (magnified). At the end of the simulation, it is possible to post-process the stored data, or to plot different quantities like phase currents, speed, torque, etc. The default integration step is 0.05, which means 159 \( \mu s \). The relative time scale can be converted to real according to the following equation: \( t_{\text{real}} = \frac{t_{\text{relative}}}{w_n} \), where \( w_n \approx 314 \text{ rad/s} \).

6. Test questions

1. What kind of electrical machines are applied in servo drives?
Measurement of a synchronous
servodrive with trapezoidal field

2. What kind of supply modes are commonly used for trapezoidal field machines?

3. Why synchronous machines with trapezoidal field are often referred as ECDC machines?

4. How to calculate the torque of synchronous machines with trapezoidal field?

5. What is the pole voltage, where and how is it possible to measure?

6. Why there are always some torque ripples in case of synchronous machines with trapezoidal field?

Questions to think about

1. What kind of drives operates with unipolar (unidirectional current) supply?

2. What are the advantages and disadvantages of unipolar supply?

3. In case of which unipolarly supplied machine is it possible to increase the torque by driving the iron core to saturation?

7. References

3. fejezet - Measurement of a synchronous servo drive with sinusoidal field

1. Scope of the measurement

AC drives becoming more and more important in the field of robot and machine tool control. In case of permanent magnet synchronous machines (PMSM) both machines with sinusoidal and trapezoidal field are applied. Last is often referred as brushless DC (BLDC) due to its similarities in commutation to the traditional DC machine.

Optimal control can be only achieved in both sinusoidal and trapezoidal case, when current vector control is applied, and the current vector is matched to the position of the rotor, to the shape of the field and to the torque required.

The purpose of the measurement is to familiarize an industrial purpose synchronous servo drive. The drive is fully digital and masterminded by a microcontroller. The control level is selectable. It can be operated in position or in speed control mode. Speed control is active in both cases, as control loops are cascaded. The innermost loop is the current control loop, which consists of a digital, three phase PI type controller and a pulse width modulator. The drive can be operated from a PC, parameters are adjustable, and also graphical representation of different quantities is possible. The reference signal can be a voltage (potentiometer) or a frequency (function generator) level. During the measurement, both control of the drive and investigation of the results are done by using a personal computer.

2. Theoretical background of the measurement

2.1. Supply of a synchronous machine with sinusoidal field

An appropriate current waveform, matching the machines magnetic field shape can be chosen on the basis of the pole voltage as a function of angular position of the rotor. Mechanical power and hence also the torque produced by one single phase can be calculated as the product of the pole voltage and the given phase current. According to this, constant power and torque can be achieved if the sum of the pole voltage and phase current products of all the individual phases is constant. In case of synchronous machines with sinusoidal field, the sinusoidally distributed rotor field can be described by a pole flux Park vector, which rotates together with the rotor, when looking from a stationary coordinate system. In an idealized case, the magnitude of this pole flux vector is constant. In case of a constant speed, the pole voltage induced by the pole flux is constant and also sinusoidal. The Park vector of this voltage is also rotating with a constant speed. For a constant mechanical power and torque, a three phase sinusoidal current system is needed with a frequency equal to that of the pole voltage. Actually in case of synchronous machines with sinusoidal field, the matched supply means sinusoidal currents synchronized to the angular position of the rotor. Best servo features can be achieved by a current vector control, which keeps the torque angle (the angle between the current and the pole flux) at ±90°. The servo drive of this measurement performs such a control throughout the whole speed range. This control is often referred as normal (not field weakening) mode. An ideal current vector controller ensures the above angle even in case of transients (startup, reversals, etc).

2.2. Current control of synchronous machines with sinusoidal field

Current control of synchronous machines with trapezoidal field can be realized in more ways: hysteresis control in individual phases, hysteresis control on the basis of a lookup table and PI current control with pulse with modulation.

3. Introduction of the measurement
3.1. Main components of the drive being studied

1. Synchronous servo drive (manufactured by SEM, England):

   Synchronous servo electronics: \( U_{\text{max}}=3\cdot380 \text{ V}, I_c=5 \text{ A}, I_{\text{max}}=10 \text{ A} \)

   Frequency of PWM is 9.26 kHz. Current control and a pulse width modulation is performed by an ASIC NOVOCHIP developed by NOVOTRON, other tasks are performed by a Hitachi H8 microcontroller. Evaluation of the resolver signals is done by a 2S82 Analog Devices IC.

   Main parameters of the digital control:
   1. Current control: PI type, cycle time is 54 \( \mu \text{s} \),
   2. Speed control: PI type, cycle time is 432 \( \mu \text{s} \),
   3. Position control: PD type, cycle time is 432 \( \mu \text{s} \).

   Synchronous servo machine: \( M_n=3.8 \text{ Nm}, I_{\text{rms}}=4 \text{ A}, I_{\text{max}}=24 \text{ A}, K=64 \text{ V/1000 rpm}=0.611 \text{ Vs/rad}, n_{\text{max}}=6000 \text{ rpm} \).

   The „K” constant means that e.g. at the 6000 rpm maximum speed the peak value of the line to line pole voltage is 384 V. In this case the no load phase voltages at the terminals are 221.7 V peak. The supply is connected directly to the 3×400 V, 50 Hz grid, hence the voltage level of the inner DC link is about 560 V. The inverter can produce a \( \sqrt{3} \cdot 320 \text{ V} \) peak phase voltages, which means that it can operate the machine at maximum speed without field weakening.

2. Load machine (EZG703 DC machine, manufactured by EVIG, Hungary):

   \( M_n=3 \text{ Nm}, I_n=13 \text{ A}, I_{\text{max}}=80 \text{ A}, K=0.24 \text{ Nm/A}, \Theta=0.00192 \text{ kgm}^2, n_{\text{max}}=2500 \text{ rpm} \).

   1. Torque meter: for torque metering and it also provides Park vector components of voltages, currents and flux.
   2. Oscilloscope
   3. Load resistor

3.2. Startup of the drive

1. Turn on the 3×400 V, 50 Hz grid. The device performs a self-test following it. On the display, the 1,2,...,9 numbers and a flashing u letter indicates the standby.

2. The software for the drive can be started by ND21.com-mal, which is found in a directory with the same name. Menu options are shown in the left part of the screen, after start, it is the main menu. In the right part of the screen a coordinate system appears, showing its timescale, and the quantities to plot. In the right bottom corner, there is an error message, which can be erased by DEL. Instead of it the temperature of the motor can be seen, if there is no error. In the top right corner, there is a message indicating the present state of the drive. Some examples are:

3. The main menu contains the following items:

   To choose an item, one has to press the key in the bracelets; step back is possible by pressing the r button or SPACE.

3.3. Usage of the drive

Basic settings of the drive [G] should not be modified. For the first trials, set the limitations [M] to low values. Setting of speed control is possible from the main menu [D] and from demo [d] as well.

Choosing the [D] menu point, gives a big help in appropriate setting of the speed controller, as it makes possible to observe the reactions of the drive in test mode for reference signal steps, reversals and cyclic reversals.
Reference signal steps [Drehzahlsollwert] can be set by [N] or [n], reversal is possible by [d]. The cycle time of the test mode can be set by [T]. The reference signal should not be changed during the runs!

The drive can be started by [g] and can be stopped by [s]. In case of an error or unexpected event, it can be disabled by [Esc].

From [d] point of the main menu, the type of control can be selected. This can be speed [d] or position [p]. Positioning tests can be started also from here by [a].

Parameters of speed control can be set in the [d] menu point of the main menu. These are the reference signal [n], the ramp time [a], the maximum speed [N], the maximum current [i] and the [d] rotational direction. This last can be set by a + or – sign, while the others require decimal values. If speed control was previously set to test mode from [D] menu point of the main menu, then it can be overridden by [R].

Parameters for position control are: the position reference signal step [x] (in mm dimension), the length of one full revolution [*] (in mm dimension), the speed of the motor [n], which means the speed of the desired positioning, and the ramp of the speed [a], which prescribes the acceleration. [i] determines the direction of positioning. When a too high speed is given to the speed of positioning, the drive stops with an „Überlauf” signal.

Controller parameters can be set at [p] menu point of the main menu. Here it is possible to filter the speed signal, and to set P and I parts of the speed controller and P and D parts of the position controller. Settings can be seen as hexadecimal values and in percents from a graph. When one operates the drive in speed control mode, settings of the position controller (Lageregler) can be turned off by [@].

Choosing [o] in the main menu takes us to the oscilloscope submenu. Here it is possible to set two signals to plot (any of the phase currents, speed, position or torque, and also their reference (Sollwert) or feedback (Istwert) signals). Trigger level can be also set, as well as step up or step down edge sensing. One can choose the time base as well. Contents of the screen can be stored by [h] (hold). Settings are valid only if the switch [a] is in „yes” state. The drawbacks of the oscilloscope function are the low resolution and the fixed vertical scale. The oscillographs can be stored into directories.

By [a] menu point of the main menu it is possible to adjust inner parameters (RAM, EEPROM, ASIC) of the system. RAM parameters can be named according to the RAM-Monitor. Writing and reading is done through hexadecimal values. The parameters of the current controller can be set among the parameters of ASIC [A]. The proportional part can be set by [p] and the integration part by [i] (both are in hexadecimal values).

3.4. Applied metering devices

1. Computerized data acquisition and processing system
2. Torque meter

4. Measurement tasks

4.1. Introduction of the drive

Getting started with the drive. Practice the reference signal definition, mode selection, setting of the oscilloscope functions, etc.

4.2. Verification of the EMK compensation, setting of the current controller

From the [G] submenu of the main menu, verify the setting of the EMK (pole voltage or back EMF). This should be 64V/1000 rpm (64mV/Umdrehung)! Following this, set the current controller in a speed controlled test mode. Eg. set the oscilloscope to the iasoll, iast signals, with nsoll trigger signal with, -1 delay and 5 ms time base. Basic setting of the current controller is P=0Ch and I=02H. Good settings result in minimal phase delay and no overshoots.
4.3. Settings of the speed controller

Here it is also advised to do the settings in test mode. The oscilloscope settings should be eg. nsoll with nist trigger signal and 200 ms time base. In the [p] menu point of the main menu vary the parameters of the controller. The goal is to achieve a fast convergence with minimum overshoots.

4.4. Settings of the position controller

The settings of the position controller should be done also in the [p] menu point of the main menu with „Lageregler: ein” (position control: on) state. It has to be taken into account that the position encoder resets itself after every full revolution. Hence the position signal is a saw signal instead of being continuous. The position reference signal should be also like this. Let’s try to make such position steps, when this plotting mode is not too annoying. It is recommended to set the oscilloscope signals to be lagesoll, lageist, the trigger signal should be lagesoll, and the time base should be between 100 ms and 200 ms. One should achieve positioning without overshots with good settings.

4.5. Investigation of Park vectors

By using the torque meter, one should investigate the Park vectors of the voltage, current and flux.

4.6. Investigation of dynamic properties of the drive

Investigate the startup and reversals of the machine on the basis of Park vector generated by the torque meter. Compare the measured and the simulated values!

5. Investigation of results simulated with a computer

Simulation investigates the control of the synchronous servo machine in the measurement. The supply should be matched even in case of transients, when the magnitude and frequency of pole voltage change proportionally with the speed. The value of the current reference signal is determined by the torque requirement of the outer speed control loop.

5.1. Hysteresis current control in individual phases

For this method, a current reference signal is required for each phases, and deviations are calculated in each phases. Tolerance bands (±ΔI) determines the allowable deviations from the reference signal. When the tolerance bands are the same for all three phases, then in a vector diagram, it defines a hexagon with 2ΔI distance between its opposite sides. Simulation shows, that in this case, the current vector most of the time remains within this hexagon. Sometime it exits into the triangles neighbouring to the sides. The reason of it that the star point of the machine is floating; hence the three currents cannot be controlled independently.

5.2. Current vector control based on a lookup table

The controller senses when the current error vector reaches one side of the tolerance hexagon. The necessary switching state of the inverter is determined by a lookup table value. This value depends on two things. Firstly, which side of the hexagon was reached, and secondly, which is 60 degree sector contains the voltage vector affecting the change of the error. The simulation shows, that the current vector with this method always remains within the tolerance hexagon with no exceptions. In case of this method some control strategies exists, eg. it is possible to decrease the error as quickly as possible, or opposite, as slowly as possible. The resultant switching frequency is a good measure of the effectivity of these strategies.

5.3. Analogue PI control with PWM

Parameters of the PI controller can be varied from the simulation software.

5.4. The simulation program
The program is written in Pascal language. The system is described by its state equations. Solution is found by a Runge-Kutta method. The points of intervention are determined by an iterative process.

The initial conditions and parameters can be varied by V, simulation can be started by G. Plots can be made by A, and exit is possible by K. When starting the simulation, the simulation time and the control method have to be selected. One has to define the tolerance band and the drawing mode.

It is possible to investigate the time function of the current vector or the current error vector (magnified). At the end of the simulation, it is possible to post-process the stored data, or to plot different quantities like phase currents, speed, torque, etc. The default integration step is 0.05, which means 159 µs. The relative time scale can be converted to real according to the following equation: \( t_{\text{relative}} = w_n t_{\text{real}} \), where \( w_n = 314 \text{ rad/s} \).

6. Test questions

1. What kind of electrical machines are applied in servo drives?

2. What kind of supply is necessary for synchronous machines with sinusoidal field?

3. Is it always necessary to make field weakening in case of synchronous machines with sinusoidal field?

4. How to calculate the torque of synchronous machines with sinusoidal field?

5. What is the pole voltage (back EMF) and how is it possible to measure it?

6. What are the advantages of synchronous machines with sinusoidal field over synchronous machines with trapezoidal field?

Questions to think about

1. If there are oscillations in the speed control, how should one modify the proportional gain of the controller?

2. How is it possible to verify the goodness of the position control?

3. In which case one may expect the lower switching frequency with hysteresis control? In case the error decreases as quickly as possible or in case it decreases as slowly as possible?

7. References

4. fejezet - Permanent magnet synchronous servo drive with field-oriented control by DSP

1. The aim of the measurement

1. Becoming familiar with a modern motor control DSP and using it.
2. Investigation of a modern DSP based variable frequency drive.
3. Becoming familiar with a modern, project based graphical development environment and using it.
4. Fix-point modelling, simulation and code development in MATLAB.
5. Investigation of digital control algorithms.
6. Investigation of permanent magnet synchronous servo drive with field-oriented control.
7. Investigation of modern data processing and sensing methods.

2. The modern motor control DSP

The used DSP is a 32 bit fix-point processor. The 512 KB size SRAM can be used for program and data, while a 16 KB size E2ROM is a program memory.
By the MCWIN2812 program (Motion Control Kit 2812) on the PC many hardware control applications (Processor Evaluation Control, Fig.1.) can be open. Among them the most important and useful is the demonstration of the Pulse Width Modulation (PWM) control of the voltage source inverter (VSI). Besides, the AD converters, the timers and the position encoder evaluation (QEP) of the DSP can be examined.
3. Investigation of the modern DSP based frequency converter-fed drive.

The main parts of the AC drive controlled by the TMS320F2812 DSP are: the power circuit, the DSP board, the AC motor and the personal computer.

The task of the power circuit are rectifying the grid voltage, sensing the motor current and the rotor position, and communicating with the DSP board. The rectifier is available only in larger power drives. It can operate with single-phase ($U_{\text{max}}=60-240$ V) or three-phase ($U_{\text{max}}=50-120$ V) supply. In the investigated drive the supply is single-phase (230 V).

The DSP board gets the sensed signals from the power circuit, and depending on the application (speed or position control) it calculates the acting signals of the current vector control.

The acting signals control the IGBTs of the VSI. The sensed signals can be displayed by using the communication between the DSP board and the PC by a program (MCWIN2812).

The DSP board communicates with the PC through RS-232 series interface, while the power circuit is reached through an MC-Bus-on (Motion Control Bus, Fig.2.). The supply voltage of the DSP board is 3.3 V.

Fig.2. The scheme of the drive system.
4. **Using the modern project-based graphical development environment**

The block scheme of the drive can be built by MatLab Simulink, and using the fix-point support and the Real Time Workshop of MatLab a C code can be generated. It can be used to generate runnable code (by assembler), which can be uploaded to the DSP memory.
The other two graphical application of the MCWIN2812 are displaying the sensed and the acting signals, and developing, investigating drive control projects by the DMC Developer.

5. Fix-point modelling, simulation and program development in Matlab

To simulate the control method the MatLab can be used effectively.
6. Investigating the digital control algorithms

6.1. The limits of the PI controllers

The controllers in the speed control scheme are PI type. They have proportional and integral parts.

The control programs generated SIMULINK are not incremental type algorithms. The problems associated with the limitations persist:

*If only the output is limited, the integrator does not stop.*

The integrator must be stopped at reaching the limit of the output. It is called conditional limitation:

The problem can be solved by a switch; in case of limitation zero value is connected (switched) to the input of the integrator. However a delay element is necessary in the feedback to control the switch, since it is not available at starting. It is the result of the sampling. If the feedback signal is delayed by one sampling period, the error signal also must be delayed by the same extent.

![Discrete PI controller with conditional limitation](image)
7. Investigation of the permanent magnet synchronous servo drive with field-oriented control

The control scheme of the drive is presented in Fig.7.

Fig.7. The control scheme of the control.

The speed control of the permanent magnet synchronous motor is implemented by field-oriented current vector control synchronised to the rotor position.

The motor currents are available after AD conversion. Since the current vector control is done in synchronously rotating reference frame, the sensed currents must be transformed to this $d$-$q$ coordinate system. To do it the position of the rotor (in electrical angle) is necessary ($\theta$). The current controllers are discrete PI controllers. The $d$ current reference is zero, while the $q$ current reference is set by the output of the speed controller (it is the torque producing current component). The PI speed controller decreases the difference between the speed reference and the real motor speed. The output of the current controllers is the reference voltages in $d$-$q$, which must be transformed to stationary reference frame. Using these phase reference voltages the DSP board generates control signals for the IGBTS of VSI by space vector modulation method.

8. Investigation of modern data processing and sensing methods

For current measurement it must be considered, that the motor voltages are pulse type (caused by the PWM), which causes current pulsation. The pulsation depends on the electrical time constant of the motor and on the switching frequency. To get the closest sensed value to the fundamental harmonic, the current sensing should be done at the middle of the PWM pulses (Fig.8.).

Fig.8. The measuring instants of the phase currents.
5. fejezet - Measurements with a stepping-motor drive

1. Purpose of this exercise

To introduce the problems related to the design of high quality and high torque stepping motor drives. Introduction of the drive and its positioning capabilities with „key-cutter” model.

2. Theoretical basics

2.1. Application of stepping motors

Stepping motors are widely used for positioning applications because of their easy controllability and because it is very easy to connect them to digital electronics. They have the great advantage that it is possible to solve positioning without a position control system. Also there is usually no need for position sensing. There are many different constructions; they are often used as a low power drive. The most common versions are two-, three-, four-, and five-phase ones. Usually the full step angle is between $0.72^\circ$ and $15^\circ$. The number of steps for $0.72^\circ$ angle motor in half-stepping mode is 1000, which is really close to the resolution of an incremental position transmitter with digital output.

Stepping motors are divided into three big categories: variable reluctance, permanent magnet and hybrid. The hybrid one is special construction uniting the advantages of the other two. It possess the following qualities: high torque, small step-angle, high precision, good dynamics, it is practically impossible to demagnetize the permanent magnet, with a one-pole-pair permanent magnet it is possible to achieve high electrical- / mechanical-angle ratio.

2.2. The power supply of stepping motors

With different types of stepping motors it is necessary to create different one- or two-way magnetic field. While with the variable reluctance stepping motors it is enough to create one-way field, with the machines containing permanent magnet it can be useful to create a two-way field. This way higher torque can be achieved.

All stepping motors share the quality that in stepping mode the currents for the phases are not aligned with the angle of the rotor. This means that they are out of synchronism and it is not necessary to make a current shape which will result a constant, ripple-free torque. In this sense the operation of the stepping motor is similar to a synchronous machine connected directly to the grid. Under these circumstances the synchronous operation is safe and in order to avoid falling out of the synchronism the load of the drive is strictly limited. Because of this nowadays drives similarly to the synchronous ones with sinusoidal field are also created with aligned phase currents or at least they are in synchronism. In these cases it is necessary to use position sensing.

3. Details for the measurement

3.1. Main components of the drive

1. Hybrid stepping motor (type 23D-6209 A):
   1. two phase stator windings: 4.7 A, 1.7V,
   2. rotor with permanent magnet
   3. stator/rotor tooth number: 48/50
   4. full step angle: $1.8^\circ$,
   5. at the end of the axis there is 1:36 reduction gearing with timing belt
1. Electric circuits for motor’s power supply:
   1. power supply for the motor and for the auxiliary mode
   2. 2 full-bridge transistor-based phase current control chopper with control unit
   3. \( U_t = 50 \, \text{V}, \, I_n = 2.3 \, \text{A} \).

1. Moving optical sensor:
   installed on the belt drive to simulate “key-cutting”. If it senses something transparent, it moves forward. If it reaches the key, it senses dark and it switches into reverse. There is a dead zone in which it stops the motor.

1. Oscilloscope:
   for checking the current and voltage signals.

![Figure 1: Main components of the drive](image)

### 3.2. Drive startup

1. Turn on the 230 V/50 Hz network.

2. Turn on the main-switch named “HÁLÓZAT”. At this moment, the motor receives controlled current (the chopper makes a chirping sound). At startup the current will appear in certain phases based on the state of the internal counter. According to this the position of the motor will be random in an \( \pm 7.2^\circ \) interval.

3. The motor can be started with the forward (“ELŐRE”) or the reverse (“HÁTRA”) switch. With the positioning (“POZÍCIONÁLÁS”) switch the key-cutter mode can be started if the sample was placed in front of the sensor previously. If there are more than one switch in ON position or the sensor reached final state the motor stops.

### 3.3. Power supply and control of the stepping motor drive

The motor’s stepping frequency is supplied by an NE555 timer circuit, which operates the counter forward and reverse. The stepping frequency can be adjusted by a potentiometer on the front panel. An actual state of the counter determines the two control signals repeated in every 8\(^\circ\) clock-cycle. These signals control the two phase current controller. The control is half-step mode, 0.9\(^\circ\) per clock-cycle. The shapes of the phase currents are in Fig. 2. The 8 step cycles are indicated by Roman numerals.
Figure 2.: Phase currents and current vector

The vector-diagram shows that there are 8 possible current vectors. If we use full-step mode either sector II, IV, VI, VIII or sector I, III, V, VII aren’t in use. The frequency of the phase current indicated on Fig. 2. is constant. When reversing the direction $i_B$ switches to $-i_B$. Fig. 2. indicates this with dashed lines and with vectors I’, II’,…

Figure 3.: The control of the phase current

The phase currents are produced by two completely identical full-bridge choppers. The phase current controller for phase A is shown in Fig. 3.

For the time of interval I, II, and III T1 and T4 transistors receive ON signal. During this the T1 is constantly ON while T4 is switching according to the two-point current controller. The current controller is set for constant 2.3 A current amplitude. For the time of interval V, VI, VII T2 and T3 transistors take over the role of T1 and T4. Meanwhile the current controller receives negative current signal. The time-dependence of phase A’s current and voltage are indicated on Fig. 4.

Figure 4.: The control of the phase current
4. Measurement exercises

4.1. Inspection of the phase currents

With constant stepping frequency check the phase currents with an oscilloscope! Determine the type of the phase current control! Why was this type selected? Why is the periodicity of the current ripple changing? How phase currents change when we change direction of the rotation? Check current vector with the oscilloscope! What this figure tells you?

4.2. Inspection of one phase current and voltage

With constant stepping frequency check the voltage and current of one phase with the oscilloscope! Examine what type of control was realized with this setup! What voltage level does the stepping motor gets in different modes? What is the reason for this? Follow up the phase’s pole-voltage level! What is the role of the field weakening in stepping motor drives? Why is the switching frequency of the transistors changing?

4.3. Inspection of positioning with the key-cutter model

Check the operation of the key-cutter! What type of control technique is equivalent with this in case of analog controlled DC-machines? What are the other ways to solve this task with a stepping motor?

4.4. Rotation speed measurements

Measure/calculate the rotation speed of the stepping motor drive at certain stepping frequency! Based on which signal or signals can we do this measurement? What data do we need to calculate the rotation speed?

5. Questions

1. Where stepping motor drives are used?
2. What are the types of stepping motor?
3. What are the features of a hybrid stepping motors?
4. What are typical types of power supplies of a hybrid stepping motor? What are the advantages and disadvantages of these power supplies?
5. What is the equivalent circuit of a hybrid stepping motor with bipolar power supply?
6. What is pole voltage and can you measure it?
7. How the inductivity of the hybrid stepping motor is changing in the function of rotation angle? Why?
8. How can we calculate the stepping number and stepping angle of a hybrid stepping motor with bipolar power supply in full step mode?
9. Based on the data you received draw the stator and the rotor of the stepping motor!

Questions to think about

1. Which types of drives can we use with unipolar power supply (one-way current)?
2. What are the advantages and disadvantages of unipolar power supply? Why are bipolar drives more common?
3. With which type of stepping motor is it regular to use unipolar and bipolar power supply?
4. With which type of unipolar power supplied rotating machine is it possible to increase torque by using coil current to saturate the iron parts?
5. At which type of drive is it regular to have connectors at both ends of the phase coils? What can be the result of current control if the coil not only gets positive and negative but also – because of short circuiting the coil – zero voltage?

6. Why is the half step mode is better than the full step mode?

7. Is it possible to increase the accuracy of a stepping motor drive with micro step mode?

6. References

6. fejezet - Critical current measurement of HTS wires

1. Superconductivity

Superconducting materials have to characteristic macroscopic feature in their superconducting state. The first is the zero resistivity (for DC currents), and the second is the Meissner effect. In the Meissner state (which is a superconducting state) the magnetic flux is expelled from the whole interior of the superconducting material except from a very thin boundary layer, characterized by the London penetration depth. In this state, superconductors are not only perfect conductors, but ideal diamagnets as well, with zero relative permeability.

Superconductors show their unique and extraordinary features only in case of certain physical circumstances. Depending on these circumstances, superconductors can be in normal state (no unique features are shown) or in superconducting state (ideal conductor, and diamagnetic).

Superconductivity is a thermo dynamical state, which is reached when the temperature of the superconductor, the external magnetic field and the currents flowing in the superconductor are under their critical value. These parameters are affecting each other, hence at 77 K the critical current density of a HTS superconductor is much smaller than at 20 K.

The pressure also affects the critical parameters, by increasing the pressure, the critical temperature increases.

Usually the temperature is regarded as independent parameter (the pressure is considered to be atmospheric), and critical current density and critical magnetic field is given as a function of the temperature. The critical temperature is considered to be the temperature where the normal-superconducting transition occurs, when the external magnetic field and the current density in the superconductor is zero.

Hence superconductors have three critical parameters:

1. Critical current density $J_c(T,H)$ [A/cm$^2$]
2. Critical magnetic field $H_c(T,J)$ [A/m]
3. Critical temperature $T_c(p)$ [K]

On the basis of these parameters, at a given pressure, the superconducting state can be illustrated by a space in a $T,J,H$ coordinate system, surrounded by the so called critical surface.

![Critical Surface Diagram](image)

Figure 6-1. The critical surface, simple state diagram of superconductors

There are two different types of superconductors according to their behavior in superconducting state. Type I superconductors are always in Meissner state, which means that there cannot be magnetic flux in their interior while they are in superconducting state. Critical magnetic field of these materials are very low even extrapolated to 0 K, hence they are not used in industrial applications.
In case of type II superconductors (NbTi, Nb₃Sn, YBa₂Cu₃O₇, Bi₂Sr₂Ca₂Cu₃O₁₀), the so called mixed state is also possible in superconducting state. In this state, the magnetic flux goes through on certain parts of the superconducting material in the form of flux vortices. At the location of the vortices the material is in normal state, but vortices are surrounded by superconducting regions, where currents are whirling around the vortices.

Flux vortices begin to be created, when the external magnetic field exceeds a limit called first (or lower) critical magnetic field ($H_{c1}$). Below this value the superconductor is in Meissner state, above it we find the mixed state. The flux vortices are always carrying the same flux quantum. By increasing the macroscopic amount of flux passing through a superconductor, the density of the vortices is increased. By doing so, one may reach the second (or upper) critical magnetic field ($H_{c2}$). At this point, the whole superconductor goes into normal state.

$H_{c1}$, which is the limit between the Meissner and the Mixed state is a small value similarly than that of the type I superconductors. $H_{c2}$ can be a very big value according to some hundred Teslas extrapolated to 0 K.

In industrial applications, type II superconductors are used. They are doped in order to have a stable flux vortex distribution pinned by artificial defects caused by the additives. (The movement of flux vortices is dissipative, hence clean superconductors cannot be used, due to their very low critical field and current density). Flux pinning by using dopants or sometimes irradiation is very important to enhance the superconducting properties.

Superconductors can be classified on the basis of their critical temperature as well. Low temperature superconductors (LTS) have critical temperatures lower than 20 K, medium temperature superconductors (MTS) have critical temperatures between 20 K and 77 K, and high temperature superconductors (HTS) have critical temperatures above 77 K.

Type I superconductors are low temperature superconductors as well. Most elementary superconductors, such as Hg, Nb, Sn are belonging to this type.

Most widely used superconductors are Nb₃Sn and NbTi, which are low temperature, type II superconductors. Medium temperature, type II superconductor is the MgB₂, and the most important type II, HTSs are YBa₂Cu₃O₇ (YBCO in short form), és a Bi₂Sr₂CaₙCuₙO₂ₙ₊₄ (BSCCO, “bisco” in short form). (BSCCO is a family of materials, where the general composition is the following: Bi₂Sr₂CaₙCuₙO₂ₙ₊₄, where n=1, 2, and 3 are the most studied materials. Regarding applications, Bi₂Sr₂Ca₃Cu₃O₁₀ (n=3) is the most important member of this family.

2. The critical current

We already know that exceeding any of the critical parameters, the superconductor goes into normal state. For the measurement we also have to know the way this transition occurs. In the following figure, electric field strengths over different YBCO wires are shown as a function of the current density [I. Bradea, G. Aldica: A DEVICE FOR CRITICAL CURRENT MEASUREMENT IN HIGH-TC CERAMIC SUPERCONDUCTORS, National Institute for Materials Physics, Bucharest – Magurele, Romania]. It can be seen that there is a region where the field strength starts to rapidly increase.
The transition is continuous, without any sudden jumps. Hence a field strength value is determined “artificially” to give the border between superconducting and normal state. This value is the 1 μV/cm, which is also shown in the figure above.

3. Purpose of the measurement

Purpose of the measurement is to determine the critical current of different HTS wires. Both YBCO and BSCCO wires are available for the measurement.

4. Measurement tasks

1. Take the E(J) curve of a copper wire at room temperature and at 77 K with DC currents and with 50 Hz AC currents
2. Take the E(J) curve of an YBCO wire at room temperature and at 77 K with DC currents and with 50 Hz AC currents
3. Take the E(J) curve of a BSCCO wire at room temperature and at 77 K with DC currents and with 50 Hz AC currents
4. Compare the results and evaluate them from an engineer’s point of view!

5. Fundamentals

During the measurements, current and voltage should be measured on the wires. The current density can be determined by knowing the cross section of the wires, supposing that the current distribution is homogenous. Voltage can be measured between any two points of the wires in the active part, far from the supply connections. The larger the distance between the points, the bigger the voltage we get, hence it increases the
precision of the measurement. Electric field strength can be calculated by the ratio of the measured voltage and the distance of the points. (Here we suppose that the specific resistance of the wires is homogenous along their length.

Picture of the measurement method (four wire measurement) can be seen in Figure 6-3.

![Four wire measurement diagram](image)

Figure 6-3 E(J) measurement

HTS wires are composites, made of very thin superconductor filaments and silver or copper matrix around them. The matrix ensures the thermal balance of the filaments, and takes over the current when the superconducting part goes to normal state, as they are running in parallel.

In case of AC currents there are hysteresis losses in the superconducting filaments and eddy-current losses in the matrix. Hence critical currents for AC are smaller.

### 6. Execution of the measurements

Measurements can be performed by using high current DC and AC supplies (e.g. 5 V, 80 A). These supplies have built in current limiters; hence they can act as current supplies and voltage supplies as well. For the measurement of voltage, it is recommended to use a nanovoltmeter.

The taken U(I) curve should be converted to E(J), according to the length and active cross section of the measured wire.

The figure below shows result of a DC measurement of a 10 cm long YBCO wire. Data was taken by a nanovoltmeter. Critical current is about 51 A in this case.
Figure 6-4 U(I) results of a 10 cm long YBCO wire (DC measurement)
7. fejezet - SUPERCONDUCTING FAULT CURRENT LIMITER

1. Objective

The objective of this experiment is to measure the characteristics of one phase inductive type superconducting fault current limiter (FCL) built with a melt textured YBCO ring.

2. Defining terms and theoretical background

1. Fault current limiter (FCL)

The fault current limiter is a device capable of limiting currents in electric networks during fault conditions caused by short-circuits and overloads.

A superconducting fault current limiter is essentially variable impedance inserted to the circuit to be protected. Two main types of the FCL-s are the inductive and resistive ones.

1. Fault current:

a surge current that occurs in a power utility system as a result of overloads or short-circuits.

1. Inductive type fault current limiter

The device is essentially a transformer with the primary winding connected in series with the circuit to be protected and the secondary winding (the superconducting ring) is short-circuited (Fig.1.).

![Fig. 1. Operation modes of the FCL](image)

Under normal operating condition of the circuit the superconducting ring is in superconducting state. The FCL works like a short-circuited transformer, inserting very small impedance into the circuit.

Under fault (or short circuit) conditions – when the current in the primary coil exceeds the nominal value, the current in the secondary coil increases and when the value of the critical current is exceeded, the superconducting ring changes its state from superconducting to normal (and its resistance became a finite value). The impedance of the FCL changes fast from the small value till large impedance. In this case the FCL is like a no load transformer, which can limit the current of the circuit.

3. Tasks
1. Measurement No.4.1.: Measurement of the characteristics of the FCL model with a copper ring modeling a short-circuited secondary coil (without superconducting ring)

2. Measurement No.4.2.: Measurement of the characteristics of the FCL model in reactance mode (without any secondary coil)

3. Measurement No.4.3.: Measurement of the I-V characteristics of the superconducting FCL (superconducting ring at 77 K)

4. Measurement No.4.4.: Comparison of the characteristics

5. Measurement No.4.5.: Measurement of the transient process (voltage and current wave forms) in the circuit with the superconducting FCL, caused by the short-circuit.

4. Principle of the measurement

Fig.2. Photo of the FCL

The transformer type FCL consists of a laminated iron core without air gap, a primary coil with 200 turns. The secondary coil is modeled by a copper ring in the case of Measurement No.4.1 and it is a real superconducting ring in the cases of Measurement No. 4.3 and 4.5. The design of the model is shown in Fig.2.

Fig. 3. Structure of the FCL

For understanding of the phenomenon of the impedance change of the FCL, the superconducting and the normal state of the HTS secondary coil will be analyzed separately by modeling the two states as follows:

1. Superconducting state of the secondary coil (normal operation conditions of the circuit, very small impedance) will be modeled by a copper ring.

2. Normal state of the secondary superconducting coil (fault conditions, limitation mode, and increased impedance) is modeled by removing the copper ring.

3. The real transition phenomena will be analyzed by using YBCO superconducting ring as a secondary coil.
The characteristics of the FCL with different secondary coils (copper and YBCO) should be presented by plots obtained from measurements of the current and voltage drop across the primary coil connected to the circuit to be protected.

5. Carrying out of the measurement (measuring method)

The measuring arrangement is shown in Fig. 4. With help of an autotransformer, the voltage applied to the circuit may be controlled within the range of 0-127 V. The primary coil of the FCL is connected in series into the circuit. The “Switch” serves for modeling the fault condition like a short-circuit.

The following measurements will be fulfilled:

1. **Modeling of the normal operational condition** when the secondary coil is in superconducting state (very small impedance): modeled by a copper ring as a secondary coil.

The current in the circuit (IFCL) and the voltage drop across the FCL (UFCL) will be measured while the voltage of the power supply is controlled in the range of 0-127 V and the I-V curve will be plotted.

1. **Modeling of the fault condition** when the secondary coil is in normal state (increased impedance): modeled by removing the copper ring.
The current in the circuit (IFCL) and the voltage drop across the FCL (UFCL) will be measured while the voltage of the power supply is controlled in the range of 0-127 V and the I-V curve will be plotted.

1. **Measurement of the superconducting FCL (overload) when the secondary coil is a YBCO ring cooled down by liquid nitrogen.**

   The current in the circuit (IFCL) and the voltage drop on the FCL (UFCL) will be measured while the voltage of the power supply unit is controlled in the range of 0-127 V, driving the YBCO ring from the superconducting state to the normal one and vica versa and the I-V curve will be plotted.

1. **Measurement of the superconducting FCL (short circuit) when the secondary coil is the YBCO ring cooled down by liquid nitrogen.**

   By using the „Switch” a sudden short circuit will be created for analyzing the transient process in the circuit.

**6. Recording the results**

**7. Modeling of the normal operational condition (shorted secondary circuit)**

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<th>I (A)</th>
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**8. Modeling of the fault condition (reactance)**

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**9. Measurement of the superconducting FCL (overload)**

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<td>U (V)</td>
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<td>Normal -&gt; Limitation</td>
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<td>U (V)</td>
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10. **Measurement of the superconducting FCL (short circuit)**

The results will be recorded in file form.

11. **Evaluation**

Compare of the plotted curves of measurements of the 2.7, 2.8, and 2.9.

Analyze of the results of the measurement of the 2.10.

12. **Conclusions should be done by the students on the base of the obtained results.**
8. fejezet - Measurement of a flywheel energy storage device with high temperature superconducting bearings

1. Introduction

1.1. Superconductivity

Superconducting materials have to characteristic macroscopic feature in their superconducting state. The first is the zero resistivity (for DC currents), and the second is the Meissner effect. In the Meissner state (which is a superconducting state) the magnetic flux is expelled from the whole interior of the superconducting material except from a very thin boundary layer, characterized by the London penetration depth. In this state, superconductors are not only perfect conductors, but ideal diamagnets as well, with zero relative permeability.

Superconductors show their unique and extraordinary features only in case of certain physical circumstances. Depending on these circumstances, superconductors can be in normal state (no unique features are shown) or in superconducting state (ideal conductor, and diamagnetic).

Superconductivity is a thermo dynamical state, which is reached when the temperature of the superconductor, the external magnetic field and the currents flowing in the superconductor are under their critical value. These parameters are affecting each other; hence at 77 K the critical current density of a HTS superconductor is much smaller than at 20 K.

The pressure also affects the critical parameters, by increasing the pressure, the critical temperature increases.

Usually the temperature is regarded as independent parameter (the pressure is considered to be atmospheric), and critical current density and critical magnetic field is given as a function of the temperature. The critical temperature is considered to be the temperature where the normal–superconducting transition occurs, when the external magnetic field and the current density in the superconductor is zero.

Hence superconductors have three critical parameters:

1. Critical current density \( J_c(T,H) \) [A/cm²]
2. Critical magnetic field \( H_c(T,J) \) [A/m]
3. Critical temperature \( T_c(p) \) [K]

On the basis of these parameters, at a given pressure, the superconducting state can be illustrated by a space in a T, J, H coordinate system, surrounded by the so called critical surface.

![Superconducting state diagram](image)

Figure 8-1 The critical surface, simple state diagram of superconductors
There are two different types of superconductors according to their behavior in superconducting state. Type I superconductors are always in Meissner state, which means that there can not be magnetic flux in their interior while they are in superconducting state. Critical magnetic field of these materials are very low even extrapolated to 0 K, hence they are not used in industrial applications.

In case of type II superconductors (NbTi, Nb3Sn, YBa2Cu3O7, Bi2Sr2CaCu2O10), the so called mixed state is also possible in superconducting state. In this state, the magnetic flux goes through on certain parts of the superconducting material in the form of flux vortices. At the location of the vortices the material is in normal state, but vortices are surrounded by superconducting regions, where currents are whirling around the vortices.

Flux vortices begin to be created, when the external magnetic field exceeds a limit called first (or lower) critical magnetic field \( H_{c1} \). Below this value the superconductor is in Meissner state, above it we find the mixed state. The flux vortices are always carrying the same flux quantum. By increasing the macroscopic amount of flux passing through a superconductor, the density of the vortices is increased. By doing so, one may reach the second (or upper) critical magnetic field \( H_{c2} \). At this point, the whole superconductor goes into normal state.

\( H_{c1} \), which is the limit between the Meissner and the Mixed state is a small value similarly than that of the type I superconductors. \( H_{c2} \) can be a very big value according to some hundred Teslas extrapolated to 0 K.

In industrial applications, type II superconductors are used. They are doped in order to have a stable flux vortex distribution pinned by artificial defects caused by the additives. (The movement of flux vortices is dissipative, hence clean superconductors cannot be used, due to their very low critical field and current density). Flux pinning by using dopants or sometimes irradiation is very important to enhance the superconducting properties.

Superconductors can be classified on the basis of their critical temperature as well. Low temperature superconductors (LTS) have critical temperatures lower than 20 K, medium temperature superconductors (MTS) have critical temperatures between 20 K and 77 K, and high temperature superconductors (HTS) have critical temperatures above 77 K.

Type I superconductors are low temperature superconductors as well. Most elementary superconductors, such as Hg, Nb, Sn are belonging to this type.

Most widely used superconductors are Nb3Sn and NbTi, which are low temperature, type II superconductors. Medium temperature, type II superconductor is the MgB2, and the most important type II, HTSs are YBa2Cu3O7 (YBCO in short form), és a Bi2Sr2CaCu2O8 (BSCCO, ‘bisco’ in short form). (BSCCO is a family of materials, where the general composition is the following: Bi x Sr y Ca z Cu n O 2n+4, where n=1, 2, 3 are the most studied materials. Regarding applications, Bi2Sr2CaCu2O10 (n=3) is the most important member of this family.

1.2. Flywheel energy storage

Kinetic energy stored in a rotating mass (flywheel) can be calculated by the following formula:

\[
E_{\text{kin}} = \frac{1}{2} \Theta \cdot \omega^2,
\]

(1-1)

where \( \Theta \) is the moment of inertia of the rotating mass, related to the axis of rotation) and \( \omega \) is the angular speed of the rotation.

Energy density is also a very important feature of energy storage systems. This can be calculated as:

\[
e = \frac{E}{m},
\]

(1-2)

where \( m \) is the rotating mass, \( E \) is the stored energy. In case of some storage types, the volumetric density is more critical than the gravimetric, but in case of flywheels this latter is more important.

To compare different storage methods it is better to calculate the energy density for the whole storage system not only the energy storage part:
Measurement of a flywheel energy storage device with high temperature superconducting bearings

\[
e_{\text{tot}} = \frac{E}{m_{\text{tot}}}
\]

where \( m_{\text{tot}} \) is the total mass of the energy storage system. In case of flywheel energy storage systems with superconducting bearings this includes the mass of the vacuum, cooling, electronic system as well as the mass of the flywheel and the energy converter (rotating machine). System level energy density is often only a fragment of the energy density of the storage part only.

A general way to calculate the system level energy density for flywheel energy storages is the following [a G. Genta: Kinetic Energy Storage, Butterworth, 1985, London]:

\[
e_{\text{tot}} = \alpha' \cdot \alpha'' \cdot \alpha''' \cdot \frac{K R_{\text{m}}}{\rho},
\]

(1-4)

where \( K \) is the so called shape factor (determined by the flywheel geometry), \( R_{\text{m}} \) is the tensile strength of the flywheel material, and \( \rho \) is the density of it. The product containing these three variables \((K R_{\text{m}}/\rho)\) gives the theoretically achievable energy density of the given flywheel.

\( \alpha' \) is the safety factor (ratio of the maximum equivalent stress in the flywheel material in normal operation and the tensile strength), \( \alpha'' \) is the discharge factor, ratio of the useful and the total stored energy, which can be calculated on the basis of the maximum and minimum operational speeds of the energy storage.

\[
\alpha'' = \left(1 - \frac{\sigma_{\text{max}}}{\sigma_{\text{m}}}ight)
\]

(1-5)

\( \alpha''' \) is the ratio of the flywheel and the total system mass:

\[
\alpha''' = \frac{m_{\text{fly}}}{m_{\text{tot}}}
\]

(1-6)

According to their energy density, flywheel energy storages can be classified as follows: []:

1. Low energy density class: \( e<10 \text{ Wh/kg (36 kJ/kg)} \)
2. Medium energy density class: \( 10 \text{ Wh/kg (36 kJ/kg)} \leq e \leq 25 \text{ Wh/kg (90 kJ/kg)} \)
3. High energy density class: \( e>25 \text{ Wh/kg (90 kJ/kg)} \)

(If we consider the earth as a flywheel, and its shape is approximated as a perfect sphere, then it falls into the medium energy density class with its approximately 12 Wh/kg energy density []).)

According to (1-4) high energy density can be achieved by using materials with low density and high tensile strength in flywheels with shape factors as high as possible. The following table shows the theoretically achievable maximum energy density values \((R_{\text{m}}/\rho)\) for some flywheel materials:


<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile strength [GPa]</th>
<th>Density [kg/m³]</th>
<th>( R_{\text{m}}/\rho ) [Wh/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>steel*</td>
<td>0.25</td>
<td>5.00</td>
<td>7900.00</td>
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</table>
Measurement of a flywheel energy storage device with high temperature superconducting bearings

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Modulus (GPa)</th>
<th>Young's Modulus (GPa)</th>
<th>Shear Modulus (GPa)</th>
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<td>Aluminum alloys</td>
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<td>72.22</td>
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<tr>
<td>Berilium fibers</td>
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<td>490.20</td>
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<tr>
<td>Boron fibers</td>
<td>3.50</td>
<td>396.83</td>
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<tr>
<td>E-glass fibers</td>
<td>2.40</td>
<td>262.47</td>
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<tr>
<td>S-glass fibers</td>
<td>4.50</td>
<td>502.01</td>
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<tr>
<td>Kevlår 49 (aramide fiber)</td>
<td>3.60</td>
<td>694.44</td>
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<tr>
<td>Spectra 1000</td>
<td>3.00</td>
<td>859.11</td>
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<tr>
<td>Spectra 2000</td>
<td>3.51</td>
<td>1005.15</td>
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<td>Zylon fiber</td>
<td>5.80</td>
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<tr>
<td>Carbon fibers</td>
<td>1.00</td>
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<tr>
<td>Nanotube (theoretical data)</td>
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<td>32051.28</td>
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</tr>
<tr>
<td>Nanotube (measured data)</td>
<td>65.00</td>
<td>13888.89</td>
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*in case of steel, the upper value is for steel wires with small diameter

These values could be achieved if the shape factor and all alpha factors would be unity. This is unfortunately not possible, at system level the achievable energy density is between 2-12% of the above theoretical one.

1.3. Flywheel energy storage system with superconducting bearings

Flywheel energy storage system with superconducting bearings is a lot more than the flywheel itself. The most important drawback of flywheel energy storage is the high self-discharge rate caused by the rotational losses. Superconducting bearings are applied to eliminate the mechanical friction between the stator and rotating part. In case of a well built superconducting bearing, the equivalent frictional loss coefficient (including the losses of cooling), are in the order of $10^{-6}$. In case of the best traditional bearings this value is about $10^{-4}$.

However, with superconducting bearings the bearing losses can be reduced significantly, also the windage losses (air friction) and other losses should be decreased as well. Hence flywheel energy storage systems are operated in vacuum (in industrial systems the vacuum level is typically in the order of $10^{-3}$ mbar).

In a flywheel system beside the windage losses there may be significant electromagnetic losses such as hysteresis and eddy current losses. Part of these losses arises in the superconducting bearing (mostly hysteresis losses in the superconductor, and eddy current losses in the permanent magnets due to the imperfections of the magnetic fields, and another part arises in the motor/generator (energy converter unit) of the system as iron and copper losses.
For the operation of the system appropriate cooling is necessary (for the bearings and for the energy converter as well), a vacuum system is also necessary, as well as power electronics with appropriate control, communication and monitoring abilities. Because of the above complexity of such a system, flywheel energy storages are considered to be very complicated at system level despite the simple storage method behind.

Systems with superconducting bearings are still not available commercially. Systems with active magnetic bearings (AMBs) are used in so called dynamic UPS systems (above 200 kW flywheels are used instead of batteries). Systems for frequency regulation of power systems are also available with AMBs, eg. Beacon Power Corporation manufactures such units with 100 kW unit power and 15 min nominal charge/discharge time (25 kWh nominal unit capacity). These units can form a smart grid of flywheels with powers up to 20 MW.

1.4. Superconducting bearings

A superconducting bearing – in its simplest form – covers a permanent magnet with axis symmetric magnetic field and a type II superconductor pair. The superconductor is cooled down within the field of the permanent magnet, and hence “traps” the magnetic field. After becoming superconducting, the superconductor will act to preserve its flux, which results in a stable levitation in all directions, without any external control need.

Rotation is only possible with small losses, if the magnetic field of the rotating part (in this case that of the permanent magnet) is axis symmetric. In this case the rotation does not result any change in the magnetic field from the point of view of the superconductor. Hence the superconductor will not act against the rotation, and there will be no drag force. In reality perfectly symmetric magnetic field cannot be made, hence there are always small drag forces (losses) between the rotating magnets and the superconductor.

In practice there are axial flux and radial flux bearings. The flux distribution of these two types can be seen in Figure 8-2.

Figure 8-2 Magnetic field of an axial and radial flux superconducting bearing []

2. Goal of the measurement

Goal of this measurement is to get experience about a flywheel energy storage system with superconducting bearings, to measure some spin down curves, and evaluate the losses of the rotor on the basis of these measured curves.

3. Measurement tasks

1. Measurement of a spin down curve of a flywheel with superconducting bearings at about 10⁻³ mbar, constant pressure from 8000 rpm top speed (10 minute)
2. Measurement of a spin down curve of a flywheel with superconducting bearings at about 10⁻¹ mbar, constant pressure from 8000 rpm top speed (10 minute)
3. Measurement of a spin down curve of a flywheel with superconducting bearings at changing pressure between 10⁻³ mbar and 10⁻¹ mbar from 8000 rpm top speed. The time of the pressure change and the measurement should be about 10 seconds!
4. Determine the different loss components (hysteresis, eddy-current, windage)
5. Compare the results and evaluate them from an engineer’s point of view!

4. Theoretical basics of the measurement
During the measurement several spin-down curves of the flywheel are taken. On the basis of these curves the losses can be determined mathematically. The general mathematical form of the spin-down curve is the following:

$$\frac{d\omega(t)}{dt} = -A\omega^x(t) - B\omega(t) - C,$$

(1-7)

where A, B, C loss coefficients represent the windage, eddy-current and hysteresis losses accordingly. The exponent x depends on the type of the flow (laminar or turbulent), and the pressure in some cases. In our case we can suppose x=1 in the whole pressure and speed range.

Using to this approach, A and B cannot be separated mathematically, as they are both coefficients of $\omega(t)$. However, if we take into account the pressure dependence of A, then the separation becomes possible. The enhanced equation taking into account this dependence is the following:

$$\frac{d\omega(t)}{dt} = -(p(t)\cdot A\cdot B)^x\omega(t) - C,$$

(1-8)

where p(t) is the momentary pressure.

5. Execution of the measurements

Before starting the measurements, the flywheel energy storage rotor and stator parts should be placed appropriately into the vacuum chamber. In case of the rotor, the levitation height should be set to about 5 mm. The distance strongly affects the losses. The stator and the rotor should be centered.

After placement of the parts, the chamber should be closed, and evacuation should be started by turning on the rotary vane pump first. The diffusion pump (high vacuum pump) is only allowed to be turned on, when the pressure reaches about $10^{-2}$ mbar inside the chamber. The cooling circuit of the diffusion pump is to be verified.

Cooling of the superconductor(s) can be started at $10^{-1}$ mbar pressure, temperature can be monitored by the built in pt100 resistive sensor.

After reaching a stable vacuum level, the rotor should be accelerated to 8,000 rpm by changing the DC supply on its controller. Reaching the top speed, the supply cables of the machine should be disconnected in order to eliminate all possible external losses.

After doing so, the spin-down curve can be taken. During the measurements the frequency of the induced voltage is measured directly, this should be converted to mechanical angular speed. There are 8 magnetic poles on the rotor.

Measurements should be done at different vacuum levels. By using the rotary pump only, about $10^{-2}$ mbar can be reached, while using the diffusion pump as well, about $10^{-3}$-$10^{-6}$ ultimate pressure can be reached depending on the cleanliness and state of the vacuum chamber.

There is an inlet valve on the chamber, which allows making rapid changes in the internal pressure by letting in some air.

This is an example result of a measurement with the system:
Measurement of a flywheel energy storage device with high temperature superconducting bearings

Figure 8-3. Change of the pressure inside the chamber as a function of time [iv Kohári Zalán: Szupravezetős csapágyazású, kompakt lendkerekes energiatároló optimalizálása, PhD értekezés, 2011]

Figure 8-4. Change of the mechanical speed of the flywheel as a function of time

On the basis of these functions, the following evaluation can be done:

Figure 8-5 Loss components as a function of angular speed

6. Literature
9. fejezet - Villamos gépek és hajtások labor II.

1. Aim of measurement

The aim of the measurement is to examine the operation and basic characteristics of solar and fuel cells.

2. Theory

2.1. Operation of solar cells

Photoelectric converters convert the energy of photons to electric energy directly (solar cells), or converts electric energy to light (e.g. photo diodes).

Photons of light create additional charge carriers inside the material of the cell thus time-constant voltage (the so-called photovoltaic voltage) appears. These charge carriers start to move because of the inner local electric field, they accumulate, so charge and photo voltage appears. Practical use of solar cells emerged when photo-voltaic phenomenon was discovered in p-n doped semiconductors (Figure 1).

![Figure 1.: structure of photo-voltaic generator](image1.png)

Fast development of semiconductor technology started in the 50’s. Photo-electric generators produced nowadays have conversion efficiency about 10-15%, their electric power can reach some 10 kWs.

Photo-electric generators are competitive solutions even today, comparing to other relative low power energy sources. Their operational costs are lower than of diesel or petrol aggregators, which are energy suppliers of distant settlements nowadays, besides, several other applications are possible, for example water pumps, irrigation, electricity in developing countries, and additional energy sources.

V-I characteristic of solar cell

Current, voltage and power of solar cells depend on the load (Figure 2) so choosing optimal load is important during their use. Maximal power can be taken out if the load equals to the inner resistance of the solar cell.

Current, voltage, inner resistance and output power significantly depend on intensity of light. In solar power plants, cells are rotated constantly in order to set the optimal angle of incoming light. Also, power optimizing electronics are often used.

![Figure 2.: V-I and R-P characteristics of solar cell](image2.png)
2.2. Operation of fuel cells

Inside an internal combustion engine, fuel, for example hydrogen and oxidant (oxygen) are mixed directly. This results in that electrons move directly from fuel molecules to oxygen molecules. The disordered movement of resulted molecules having high velocity creates linear motion of pistons in the engine. The conversion efficiency of this system is limited by the thermodynamic discipline (Carnot-efficiency).

Inside a fuel cell, the fuel and the oxidant molecules cannot mix (see Figure 3). Anode covered with catalyst has the feature that it can detach electrons from hydrogen molecules/atoms. These electrons go through the external circuit connected to the cell while hydrogen ions can enter the electrolyte. Electrons get to cathode through the external load, where they connect to the oxygen ions, and create neutral water molecules with the hydrogen ions.

Figure 3.: Structure and operation of fuel cell

While we can get only 25-30% of hydrogen burning as mechanical work inside a thermodynamic process, even 80% of chemical energy of hydrogen can be used as electric energy in a fuel cell. As can be seen, there is a significant difference between the two methods of burning hydrogen.

there are a lot of construction for fuel cells. This fact means that there are no significant technical and economic advantages of one solution over the other. In this measurement we use hydrogen fed proton exchange membrane (PEM) fuel cell.

Efficiency of electrolysis and fuel cell

During electrolysis, the following processes appear on the anode and cathode:

anode: \(2 \text{H}_2\text{O} \rightarrow 4\text{e}^- + 4\text{H}^+ + \text{O}_2\),  cathode: \(4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2\)

altogether:

\(2 \text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2\)

In the fuel cell, during burning, the opposite process appears.

The efficiency of electrolysis is the quotient of electric and chemical energy:

\[\eta = \frac{W_{el}}{W_{H_2}}\]

where

\[W_{el} = n \cdot V \cdot I \cdot t\]

\[W_{H_2} = n \cdot H_i\]

where \(H_i\) is calorie of hydrogen (266,1 kJ/mol), \(R=8,31 \text{ J/(mol K)}\), and

\[W_{el} = U \cdot I \cdot t\]

so efficiency can be expressed as:
\[ \eta = \frac{H_p \cdot V}{R \cdot T \cdot U \cdot I \cdot t} \]

**V-I characteristic of electrolysis and fuel cell**

Electrolysis starts when the so-called *decomposition voltage* appears between the electrodes (Figure 4). Decomposition voltage depends on temperature, its values is 1.2-1.6 V at room temperature.

**V-I characteristic of fuel cell** is linear except around no-load operation (Figure 4). If characteristic is non-linear during the measurement, this means that hydrogen of oxygen supply is insufficient.

![Figure 4: Characteristics of electrolysis and fuel cell](image)

### 3. Measurement guide

#### 3.1. Circuit diagram for solar cell measurement

Place the lamp to the solar cell as close as possible.

Current flowing in the circuit can be measured with the constant 5 Ω resistance (I=U/R). The voltages are connected to the Analog1 and Analog2 (U1 and U2) inputs of the data acquisition device.

#### 3.2. Circuit diagram for fuel cell measurement

Gases required for the operation of fuel cell are produced with electrolysis and are fed into the cell with using rubber tubes.

#### 3.3. Instruments used

1. Data acquisition device (e.g. COBRA or Labview)
2. Multimeters

### 4. Measurements

#### 4.1. V-I and P-R characteristics of a solar cell

Measure the V-I characteristic of solar cell!

At the beginning of the measurement minimize the resistance of the potentiometer and check that Analog2 signal does not overflow. Start the measurement and increase resistance continuously for about 1 minute.
After measuring, convert voltage to current \( (I = \frac{U^2}{R}) \). Plot current vs. voltage.

Calculate the R-P characteristic! Plot the curve.

**Evaluation:**

What voltage and current result in maximal power? Is there significant deviation from the theoretical curves?

### 4.2. V-I characteristics of a fuel cell

Measure the V-I characteristic of the fuel cell!

**To prepare the measurement:**

1. Check that the vessels of the electrolyzing unit are filled with water (if not, open the vessels, lift the ends of the rubber pipes, pour distilled water into them, close the vessels). Connect the rubber pipes to the outlet of the vessels. Insert the other end of the pipes into the plastic pot containing distilled water.

2. Switch on the power supply of the electrolysis cell. Set the current to 2A. The gas bubbles appear in the cell. When rubber pipes contain no water and bubbles continuously appear at their end, connect the pipes to the upper end of the fuel cell. Be sure that no water remains in the pipe. (It can close the way of the gas.)

3. Wait for some minutes to obtain appropriate amount of gas. Measure the output voltage and current. Use the appropriate range set for measuring current.

4. Using different resistors (0.5-20 ohms) measure the current and the voltage. Wait some minutes during each of the measurement to obtain stable state of the cell. Short circuiting the fuel cell is strictly prohibited!

5. Plot the V-I values.

**Evaluation:**

What is the value of no-load voltage of the fuel cell? Is there significant deviation from the theoretical curves?

What load resistance is required to obtain maximal power?

### 4.3. V-I characteristics of electrolysis

Measure the V-I characteristic of the electrolyzing cell!

**To prepare the measurement:**

1. Switch off the power supply, connect the volt- and ammeter.

2. Remove the rubber pipes from the fuel cell.

3. Set current limit to 2A. Wait 1 minute to stabilize the process of electrolysis.

4. By reducing the voltage in 6-8 steps register the voltage and current values at each voltage level. Always wait for 30 s before registering the data to get stable electrolysis.

5. Draw the V-I curve.

**Evaluation:**

What is the decomposition voltage of the electrolysis? Is there significant deviation from the theoretical curves?

### 4.4. Additional measurements

Plot the V-I and P characteristics of the solar cell with lower light intensity and different distances.

### 5. Check your knowledge
1. What is the operating principle of solar cells?
2. Describe the construction of a solar cell!
3. What is the operating principle of fuel cells?
4. Describe the construction of a fuel cell!
5. What is the difference between the operation principle of a fuel cell and an internal combustion engine?
6. How can we calculate the efficiency of electrolysis and fuel cell?
7. What is the definition of decomposition voltage of electrolysis?
8. What load should we use to maximize the power of a voltage source?
9. How can we measure the inner resistance of a voltage source?

**Use your brain…**

1. What does the efficiency of a solar cell depend on?
2. How can the efficiency of a solar cell be increased?
3. Can we operate the solar cell “vica-versa” (can it give light under voltage)?
4. What kind of uncertainties can you identify during measuring the characteristics of fuel cell?
5. Why don’t we use fuel cell airplanes at the moment?