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SEMI-AUTOMATIC COMBINED TESTING STATION FOR INDUSTRIAL LCL-FILTER REACTORS

POOLAUTOMAATNE TÖÖSTUSLIKE LCL-FILTRIREAKTORITE KOMBINEERITUD TESTIMISSEADE

MSc thesis

The author of this thesis
applies for the academic degree
Master of Science in Mechatronics

Tallinn 2016

AUTHOR'S DECLARATION

I declare that I have written this graduation thesis independently.

These materials have not been submitted for any academic degree.

All the works of other authors used in this thesis have been referenced.

The thesis was completed under the supervision of Ahti Põlder.

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The thesis complies with the requirements for graduation theses.

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Accepted for defence

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MSc THESIS TASK

Spring semester of 2015/16

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THESIS TOPIC:

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Engineering and economic problems to be solved:
In this master's thesis, the design processes of a universal reactor testing station is described and discussed in detail. The main parts discussed are concept devising, process planning, selection of components and mechanisms, evaluation of profitability, pre-testing, safety, legislation and system control.

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FOREWORD / EESSÕNA

The topic of this master's thesis is based on a practical project from Trafotek AS. The design project had been started earlier and was chosen to be described as the thesis topic for its suitability with the mechatronics curriculum. The project was managed and conducted mainly by the author with the help of the company-side supervisors. The author would like to thank Mikael Kortesluoma for his support in the practical side of the project and Ahti Põlder for his support in formatting the thesis work.

Magistritöö teema baseerub praktilisel projektil, mida arendatakse firmas Trafotek AS. Töös kirjeldatud seadme projekteerimisega alustati juba varem ning see valiti magistritöö teemaks mehhatroonika õppekavaga sobivuse põhjal. Projekti viis läbi ning arendas põhiliselt töö autor, mõningase abiga firmapoolsetelt juhendajatelt. Autor soovib tänada Mikael Kortesluoma tema abi eest projekti praktilise poolega ning Ahti Põlder'it juhendamise eest töö vormistamisel.

INTRODUCTION

Trafotek AS is the Estonian subsidiary of the Finnish company Trafotek OY. The group has factories also in China and Brazil. Trafotek designs, develops and manufactures industrial filters and reactors (Figure 1) as well as transformer solutions according to customer specification. The produced filters and reactors range from a current rating of 30 A to 6000 A and a voltage rating up to 12 kV. Filters and reactors can be either air or liquid-cooled. LCL filters, for example, are widely used in the renewable energy industry, where they are used after power inverters to efficiently condition the generated power before feeding it to the power grid. [1]

Figure 1. Trafotek LCL filter (on the left) and filter reactor (on the right)

In order to ensure the required quality and safety level of the filters and their reactors, their physical and electrical parameters are checked in several stages throughout the production. Electrical tests are mainly used to verify the quality of reactor construction and insulation. The tests are conducted to the filter reactors after their assembly (pre-testing) and also when the reactors have gone through the resin impregnation and final assembly stages (final testing). The following electrical tests can be conducted to the reactors in the different testing stages:

1. Dielectric withstand test of the insulation (phase-ground) at 3 - 4 kV AC
2. Inductance verification test using an LCR meter and reference values
3. Inductance measurement at a DC bias current (optional)
4. Surge voltage test with up to 6 kV peak waveform (optional)
5. Insulation resistance test at up to 5 kV (optional)

Currently the insulation withstand, inductance verification and insulation resistance tests are done manually by connecting the measurement devices to the reactors and comparing the measurement results to the reference values. The surge voltage and bias current inductance tests are conducted automatically, but the connection of the reactors is made and result reports managed manually.

For product types with higher quality requirements, it may be necessary to conduct a surge voltage test for every single reactor. This is currently a time-consuming task which requires testing engineers with special training. Trafotek decided to simplify and speed up the testing phase by designing a testing station which would handle connection of the reactors, conduction of tests and the test result data processing automatically. Such station would not require its operator to have special knowledge of electrical tests, connection schemes or test result analysis. The operator would have to select the correct reactor type from the list, hoist the reactors to and from the station, and react to any test failures by marking and separating the failed reactors for further investigation by the quality assurance team.

In this thesis, main parts of the testing station design process are described. The principle concept of the station will be presented and compared to the current methods and commercially available options. The positioning accuracy requirements and options are analysed, a selection of main components is made for the motorized reactor positioning system and the manual loading and unloading operation specification is devised and analysed. The safety requirements are researched and necessary suitable safety systems are devised. The electrical tests to be automated are presented and researched. Necessary additional hardware will be described. Finally, the concept of the control system is devised and presented.

For designing of the station and writing this thesis the following software were used: Microsoft Office 2013, SolidWorks 2012, CadSoft EAGLE 6.5.0, Festo PositioningDrives 2.3.10, GIMP 2.8.16

1 OVERVIEW OF THE CONCEPT AND EXISTING SOLUTIONS

1.1 Concept overview

The design of a testing station described in the introduction and discussed throughout this thesis began by defining the concept of the station. The very general idea was that the machine should be a box into which the reactors are fed on a conveyor line, and from which tested products would be received. Inside "the box", or the testing area, all operations required to conduct the necessary electrical tests would be done automatically. The test result would be clearly indicated and the test results saved to a database. The primitive idea of the machine is illustrated on Figure 2.

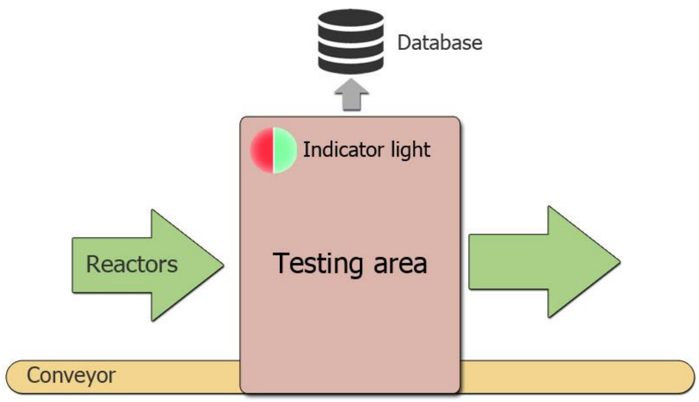


Figure 2. Primitive concept of the testing station

The next step in the concept design was to devise the necessary systems that would allow the required tests to be conducted in the testing area. The main idea of the closed testing area was to reduce the operator intervention as much as possible. Another important aspect was that the machine should be able to test reactors of different size. These requirements meant that there should be mechanisms in the testing area which would be able to automatically create electrical connections with the reactor bus bars with different dimensions and spacing for different reactor types. For satisfying this requirement, an electrical contacts positioning system was conceptualized. The principal illustration of the system mechanics is presented on Figure 3.

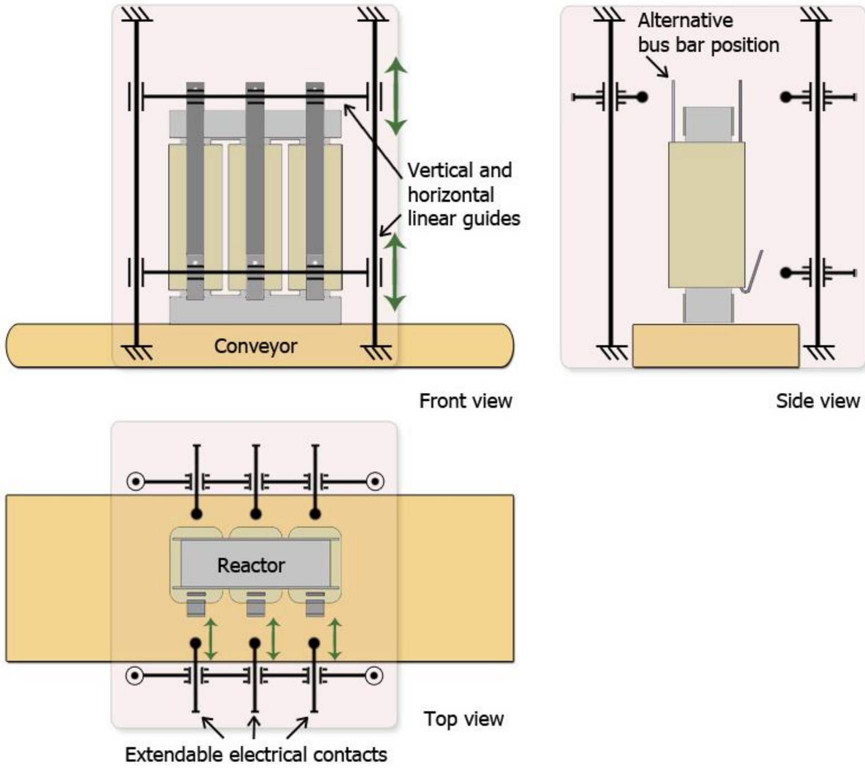


Figure 3. Electrical contacts positioning system concept

Contacts positioning

The devised concept of the electrical contacts positioning system consists of two sets of vertical linear guide rails. Two separate sets of horizontal guide rails would be attached to one of the vertical rail sets, and one additional horizontal axis to the other. The resulting planar positioning system would allow all six electrical contacts to be positioned adjacent to the reactor's bus bar connection areas. Extendable electrical contacts would enable the electrical connection to be made or broken quickly. The additional set of axes will allow a connection to be made when the bus bars of the reactor are on opposite sides of the coil. It is also noted that there would be an option to fix the middle electrical contact in the centre of the horizontal axis and position the reactor using the conveyor system if the middle bus bars would be aligned with the fixed electrical contact. As all produced types of three-phase reactors have symmetric bus bar positioning, the construction of the horizontal guides could be simplified by moving the two free contacts symmetrically in opposite directions relative to the middle contact.

Other considerations

Several other problems and parts of the testing facility were discussed in addition to the contacts positioning system and a list of topics to be researched and further developed was assembled. Some of the main topics are listed next.

- Suitable conveyor types
- Hoisting of the reactors
- Tipping guard system to keep the reactors upright on the conveyor
- Sizing of the machine
- Broadening of the positioning tolerances
- Required shielding and protective barriers
- Safety requirements and related legislation
- Safety devices
- Failure mode operation
- Control system options
- Requirements to testing cables, leads and contacts
- Cable management
- High voltage switching system
- Workstation location in the production layout
- Product identification and marking
- Required concept tests / pre-tests
- Efficiency calculation
- Budgeting

The main topics covered in this paper are underlined and are discussed in detail in the parts of the thesis: concept, positioning system, safety, electrical testing system and system control.

1.2 Existing solutions

Current method in Trafotek AS

The current generalized method of performing the surge voltage test in Trafotek Rae factory (Trafotek AS) can be described by the following list of steps:

1. Positioning and connecting the reactor
2. Software setup and testing
3. Recording results to database
4. Marking the product (passed / failed)
5. Disconnecting the reactor
6. Transporting reactor out / in

The surge test itself, the test result data collection and analysis are conducted by the custom testing system and its software by Solfas [2], but the positioning and connecting the reactors and configuring of the software is done manually.

Similar products on the market

One similar automation option was found; the Solfas IND1000 choke test system [3]. This test system allows several different electrical tests to be conducted with a single connection. The system also includes software for configuring test plans, running the tests and generating test reports, and a protective cabinet which can be installed on a conveyor line. The Solfas test system could also be customized according to customer testing needs. Main disadvantages of the IND1000 system are manual positioning and connecting of the reactors and also a considerably higher price tag compared to the system being designed in Trafotek AS. The option to use only the electrical testing equipment setup from the Solfas system will be considered and discussed with the equipment supplier, but this option is not included in this thesis.

1.3 Operation efficiency

Each manual and automatic operation like loading and unloading of the reactors, conveyor movement and electrical measurements must be executed in a defined timeframe for the process to be faster compared to the manual measurement method.

The durations of each step in the manual testing method currently in use at Trafotek AS were measured for one reactor, and the total process duration for six reactors was estimated based on the data for comparison with the automatic system. The estimation takes into account that only two reactors on one pallet can be used at the testing station, as there needs to be sufficient space for manually making the connections. The durations for manually testing one and six reactors are presented in Table 1.

Table 1. Manual measurement method duration

Step	**Duration, s**	**Duration (6 pcs), s**
Positioning	60	180
Connection	38	228
Surge test setup and testing	55	330
LCR inductance test	30	180
Recording results to database	20	120
Marking (Passed/Failed)	5	30
Disconnection	29	174
Transporting out	40	120
Total duration (min:s)	4:37	22:42

The pallet transportation, reactor hoisting and manual positioning durations were measured as described in section 2.7. Additionally, the duration of automatic reactor positioning and connecting was estimated to be 10 seconds, and the total testing duration 20 seconds. The estimated process durations for the automatic measurement of one and six reactors are presented in Table 2. As the duration of automated steps is expected to be less than the duration of reactor hoisting, the automated tasks will be finished before the hoisting is done in a continuous work process, and the automatic tasks will not add to the total duration of the operation.

Table 2. Automatic measurement method duration

Step	**Duration, s**	**Duration (6 pcs), s**
Transporting a pallet in	90	90
Positioning onto conveyor	45	270
Positioning	10	(Done simultaneously with loading and unloading)
Testing	20	
Positioning	10	
Unloading from the conveyor	45	270
Transporting a pallet out	90	90
Total duration (min:s)	5:10	12:00

Based on the measured and estimated data, the automatic process is expected to reduce the operator work time by 47% in addition to the advantages from improved safety and quality and automated data processing.

2 POSITIONING SYSTEM

2.1 General structure and requirements

To allow the station to be used for testing reactors with different dimensions, bus bar orientations and spacing, a system of movable testing contacts will be designed, which will provide electrical connection between testing devices and the bus bars of the reactor to be tested.

According to the principal concept of the testing station described in section 1.1 and the selection of horizontal contact positioning system solution described in section 2.4, the designed positioning system must be able to move reactors from the input end of a conveyor line to the testing area, where they must be stopped in a pre-defined position. After the required tests are conducted, the reactors must be transported to the output end of the conveyor. The system must be able to do this in a certain timeframe in order to give an advantage over the manual method of testing.

To keep the station technically as simple as possible, loading and unloading of the reactors to and from the conveyor will be done semi-manually, using existing crane systems in the production area. The major manual tasks of the workflow should be limited to transporting pallets with reactors to and from the station, and loading – unloading them to and from the conveyor.

2.2 Dimensional and accuracy requirements

The designed positioning device is required to have the accuracy, precision, speed and flexibility necessary for its reliable operation with different reactor models. The device design has to find the right balance between the mentioned properties and the simplicity, maintainability and price. The aim is to find a solution with the least number of parts and a reasonable price tag, while keeping the system as reliable as possible and as accurate as needed for its purpose.

In order to choose specific requirement values for the system, three baseline reactor types are chosen and their properties analysed. Type 1 represents the smallest and Type 2 the largest of the most common reactor types. Type 3 is a reactor type with a slightly different design that is used to define the maximum reactor size the system could be used with. The type 3 reactor differs from the other types by its bus bar arrangement: type 1 and 2 have six bus bars on the same side of the reactor: three on the lower side, three on the upper side. The type 3 reactor has all six bus bars on the upper side of the reactor: three on one side and three on the opposite side. The main relevant properties of the reactor types are presented in Table 3.

Table 3. Baseline reactor properties

Reactor type	**Bus bar spacing (horizontal), mm**	**Bus bar spacing (vertical), mm**	**Total height, mm**	**Contact surface; w x h, mm**	**Mass, kg**	**Bus bar positioning**
Type 1	110	290	350	40 x 30	60	Same side
Type 2	110	554	550	40 x 40	104	Same side
Type 3	185	240	1200	80 x 80	440	Opposite sides

The dimensional requirements of the positioning system are based on the baseline types' dimensions and are presented in Table 4. Set requirements also take into account some additional nuances of the reactor design and their production process. For most reactors with 40 mm wide bus bars, the tolerance for horizontal positioning of the bus bars is ±2 mm. It is estimated that the conveyor will be able to position the reactors within ±8 mm and that the operator positions the reactor in its jig within ±2 mm. With all of the tolerances added up, the displacement of each bus bar can be ±12 mm from its theoretical centre position and the guaranteed horizontal bus bar contact surface from the same position is 8 mm to either side, as illustrated on Figure 4. The required minimal positioning accuracy of the designed system presented in Table 4 is based on this estimation of added tolerances. The vertical positioning accuracy is chosen to be equal to the discussed horizontal value.

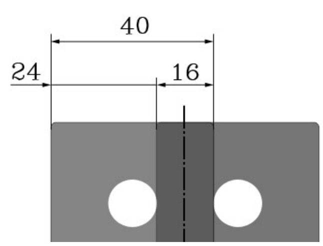


Figure 4. Effect of positioning tolerances

Table 4. Initial dimensional requirements of the positioning system

Positioning accuracy (horizontal), mm	±8
Positioning accuracy (vertical), mm	±8
Horizontal contact spacing; min. – max., mm	110 - 185
Vertical contact spacing; min. – max., mm	200 - 1000
Conveyor load capacity, kg	3 x 450

2.3 Conveyor

A suitable conveyor kit is necessary for transporting and positioning the reactors in the testing area and transporting them out. As the cost and space requirements for the station are tight, the conveyor should not be much larger or more complex than necessary for a safe and smooth workflow. The main criteria for the conveyor are its dimensions, load capacity and positioning accuracy.

Conveyor types

Three different motorized conveyor types were compared to find the best suitable option for the particular application: belt-, roller- and chain conveyors. The comparison is made between conveyor types for manufacturing applications. The conveyor types are compared in Table 5 and the selection process described next. [4]

Table 5. Comparison of conveyor types

Conveyor type	**Advantages**	**Disadvantages**
Belt conveyor	• Relatively light weight • Low noise level • Competitive price • Can transport fine materials (gapless transport surface) • Suitable for inclines and declines • High safety	• Limited load capacity: ~250 kg/m • Smooth turns are complicated
Roller conveyor	• Relatively simple construction • High load capacity • Wide selection of rollers available • Different roller drive options	• Noisier than belt conveyors • Roller step limits the load footprint • Possible slip of the rollers
Chain conveyor	• Highest load capacity • Possibility to use recirculating base plates	• Noisiest of the compared types • Chain maintenance

Conveyor selection

General requirements for the station set in section 2.1 were considered for choosing the suitable conveyor type. The required maximum load weight capacity of the conveyor was calculated based on the weight of three reactors of the largest type. To account for uncertainties and possible uneven distribution of the load during loading, a safety factor $S = 1{,}2$ was used [5]. The weight of the largest reactor is 440 kg and the selected minimum weight capacity is $3 \cdot 440\ kg \cdot 1{,}2 = 1584\ kg \approx 1600\ kg$. During the CAD model design of the station, it was empirically found that in order to fit the testing area frame in the middle of the conveyor and still have adequate room for loading and unloading the reactors, the length of the conveyor should be 3 metres. As stated in Table 5, the load capacity of belt conveyors is limited to 250 kg/m, so this conveyor type is not suitable for the current application. Roller conveyors are used at several stations in the factory, so the maintenance crew is familiar with this conveyor type and there are spare parts readily available. Roller conveyor type is chosen to be used for the design of the station, but it is noted that depending on the materials of the reactor base plate and the conveyor roller coating material, there may occur slip of the conveyor rolls, which could lead to inaccurate and unreliable positioning of the reactors. Chain conveyor options and price comparisons with the roller option will be researched, but this topic will not be covered in this thesis paper.

Rollers of the conveyor must withstand the load of the reactors and thus have a suitable load rating. The load is not spread evenly throughout the conveyor's length, so in order to set a load rating requirement for the rollers, the load weight distribution per metre was calculated based on the weight and footprint size of the largest reactor type. The footprint length of the largest type reactor is 400 mm, resulting in a load weight distribution of *440 kg / 0,4 m = 1100 kg/m*. In case of a roller with a diameter of 80 mm and a space of 10 mm between the rollers, there would be eleven rollers per one metre and the load capacity of one roller should be at least *1100 kg / 11 rollers = 100 kg*. As the materials and loads are well known, a safety factor of 1,5 was used [5] and the minimum required load rating of the used roller type was set to 150 kg. A suitable roller type would be Fastrax Type 500 conveyor roller with a load capacity of 200 kg per roller [6].

A summary of the requirements set for the conveyor system is presented in Table 6.

Table 6. Requirements for the conveyor system

Transport area (length x width)	3,0 m x 0,5 m
Load weight capacity	≥ 1600 kg
Roller load rating	≥ 150 kg
Positioning speed	1 m / 8 s
Positioning capability	Encoder
Positioning accuracy	$\pm 8\ mm$ or better

Conveyor drive

The workflow in the middle of a testing job (from when the 3rd reactor has been loaded to the conveyor until when the 3rd from last reactor is unloaded) will be:

1. A reactor is loaded onto the conveyor
2. The tested reactor is unloaded
3. The conveyor is operated.

Each time the conveyor will be advanced, there will be two reactors on it: one will be positioned into the testing area and the other one will be moved from the testing area to the unloading area. The maximum load to be moved by the conveyor is $2 \cdot 440\ kg = 880\ kg$.

In order to meet the positioning speed expectations regarded in Table 2, the reactor should be positioned and the electrical connections established in 10 seconds. To leave time for contact manipulators to make the connections, the available time for the conveyor to position the reactor is set to 8 seconds. This is considered as the maximum duration of each operation cycle of the conveyor when transporting the reactors on the conveyor. With constant acceleration, the maximum velocity of the load will be twice the average velocity: $v_{max} = 2 \cdot v_{avg} = 2 \cdot (1{,}0\ m\ /\ 8\ s) = 0{,}25\ m/s$. The acceleration of the load would therefore be $a = 0{,}25\ m/s\ /\ 4\ s = 0{,}0625\ m/s^2$. A graph of the theoretical displacement, velocity and acceleration of the load during one operation cycle is presented on Figure 5.

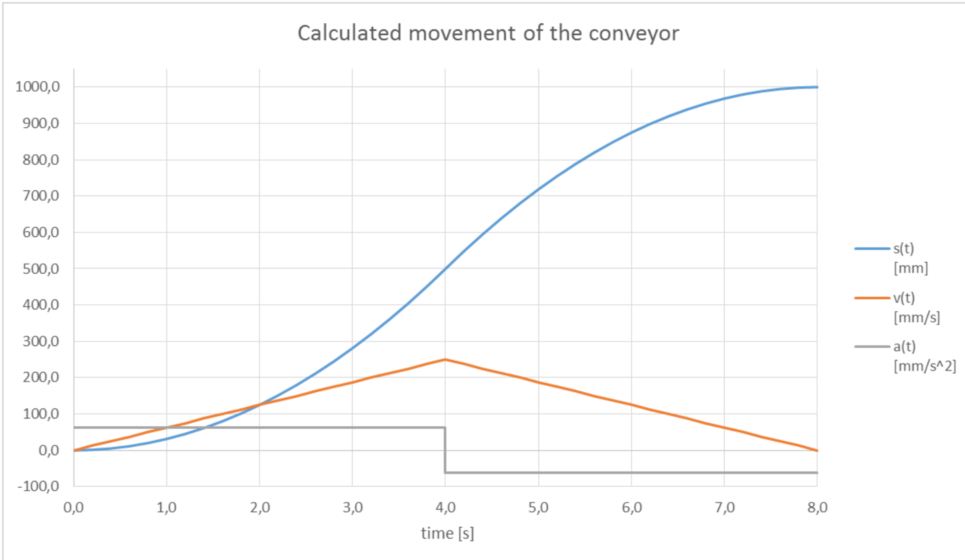


Figure 5. Displacement (blue), velocity (orange) and acceleration (grey) of the reactor

For torque calculations of the conveyor drive, the lever-arm torque formula is used, where the applied force is found using Newton's second law of motion, $F = m \cdot a$:

$$T = F \cdot r = \frac{m \cdot a \cdot D}{2}, \tag{2.1}$$

T – torque,

F – force applied to the lever arm,

r – radius of the lever arm,

m – mass of the load,

a – acceleration of the load,

D – diameter of the conveyor roller.

To calculate the required output torque and rotation rate of the conveyor drive motor, the following assumptions are made:

- The conveyor rollers are chain-driven
- Diameter of the conveyor rollers is 80 mm
- The drive sprocket is the same size as roller sprockets

In order to compensate for the unknown rolling resistance between the rollers and the reactor base plate, other mechanical resistances in the system and possible uneven movement, a safety factor S = 3,5 which is greater than a typical safety factor used in motor sizing [7] is selected to calculate the required torque.

The required torque T_{req} is calculated from the mass and acceleration of the load and the diameters of the roller and its sprocket using Formula 2.1. [7]

$$T_{req} = S \cdot \frac{m \cdot a \cdot D_{roller}}{2} = \frac{3{,}5 \cdot 880 \cdot 0{,}0625 \cdot 0{,}08}{2} \approx 7{,}7\ Nm.$$

The required rotation rate of the drive is calculated from the maximum velocity of the load during the positioning and the roller diameter.

$$n = \frac{v \cdot 60}{\pi \cdot D} = \frac{0{,}25 \cdot 60}{0{,}08 \cdot \pi} \approx 60\ min^{-1}. \quad (2.2)$$

From the MiniTec catalogue [8] a suitable planetary gear motor SEW Spiroplan WA10DT56 was selected. The main technical data of the motor are presented in Table 7. The recommended frequency converter for all MiniTec conveyor motors, SEW MC07B (0.37 kW) was chosen as the motor driver.

Table 7. SEW Spiroplan WA10DT56 technical data

Output torque	13 Nm
Output rotation rate	67 min^{-1}
Power rating	120 W

The conveyor system is planned to be ordered from Tech Automation OÜ who is the Estonian reseller of MiniTec products. The system will be assembled from MiniTec structural profiles and parts, except for the conveyor rollers. According to the reseller, it is difficult to estimate the positioning accuracy of the conveyor system, as it is largely dependent on the control algorithm of the drive. The drives selected in sections 2.4 and 2.6 leave a 15,8 mm positioning tolerance field (~1,6% of the positioning distance of 1000 mm) for the conveyor from the requirements listed in Table 4. It is considered to be sufficient, but additional verification tests need to be carried out using a similar conveyor system.

2.4 Horizontal linear drive system

A horizontal drive system was designed for positioning the electrical contacts of the test station according to different reactor types to be tested. Requirements for the horizontal linear drive system were set according to the properties of the baseline reactor types (Table 3). The drive system has to be capable of freely changing the spacing of the electrical contacts within the range of the minimum and maximum bus bar spacing of the described reactor types. To allow for a simpler construction, it was decided that the middle contact will be fixed to the centre of the drive system. A conceptual illustration of the horizontal guide system is presented on Figure 6.

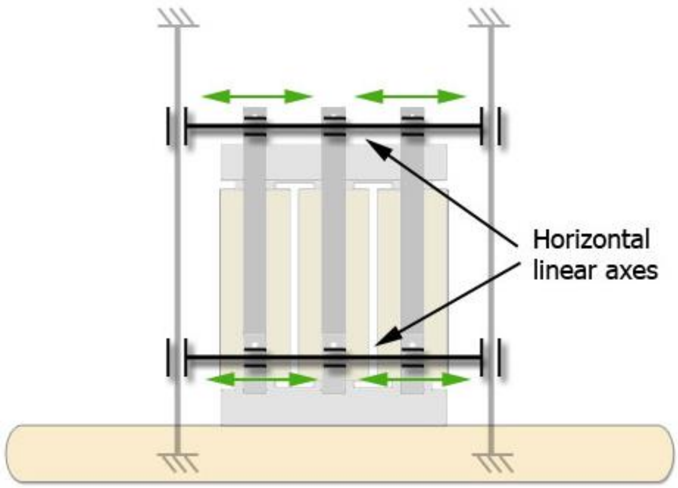


Figure 6. Horizontal linear drive axis on the concept drawing

Two different drive system constructions were compared and the more suitable one was chosen as described next.

Lead screw option

A linear drive system with two lead screw-driven slides on a single guide rail was considered. The two slides would have bronze bushings with inner threads of opposite handedness. The MiniTec VEN 45x90 H system lead screw would consist of two halves with threads matching the bronze bushings. The two opposite-handedness screws would be coupled in the middle with a shaft coupler and the connected lead screws would be driven by a single electric motor.

Timing belt drive option

The other option considered was a standard product series from Festo: a dual-slide timing belt driven linear actuator, on which the slides are attached to the different sides of a timing belt loop, allowing the slides to move in opposite directions while driven by a single electric motor. The Festo ELGG-series is available in different sizes, has an option of a fixed middle support, and offers different suitable servo and stepper motor options. Some of the main properties of the two considered options are compared in Table 8.

Table 8. Comparison of the horizontal linear drive system options

	VEN 45x90 H system [8]	**ELGG drive system [9]**
Product type	Customized assembly	Standard product
Original purpose	Manual adjusting unit	Motorized positioning drive
Guide	Aluminium profile	2 x round steel guide
Bearings	Hard plastic slides	Recirculating ball bearings
Driving component	Lead screw	Timing belt
Weight	Heavier	Lighter

Both options use special aluminium profiles in their construction and the standard prices of both systems were similar. The lead screw system of the VEN option means that a less powerful and thus lighter motor could be used, but at the same time positioning speed would be reduced.

Selection

The Festo ELGG-TB-35 drive system with a central support and two slides with opposite moving direction was selected to be used as the horizontal positioning system of the electrical contacts. The main characteristics in favour of the ELGG series were minimalistic yet functional construction, light weight and the availability of axis kits including a motor and motor driver. Another favourable factor was the availability of configuration and calculation tools such as the Festo online catalogue [10] and the PositioningDrives software [11], which helped to save design time by providing information and automated calculations for the linear axis and electrical drive configurations suitable for the application. An illustration of the ELGG axis from the CAD model of the testing station is presented on Figure 7.

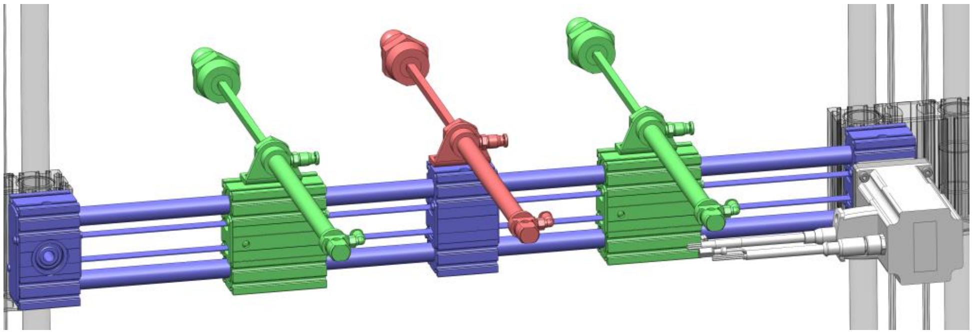


Figure 7. Festo ELGG axis as the horizontal positioning drive system.

Dimensioning and calculations

The length of the horizontal axis was selected empirically using the CAD model. The length was defined by the horizontal bus bar spacing of the base-type reactors, vertical axis type and additional space necessary in the testing area structure for cabling, tipping guard mechanism and other parts. The suitable total length of the axis was found to be 671 mm and according to the documentation of the ELGG axis [9] the resulting working stroke of the axis is 183 mm. The selected working stroke length will allow the contacts to be positioned within a spacing range of 70 – 240 mm, which covers the bus bar spacing range of 110 – 185 mm (Table 3) and leaves a considerable reserve. The positioning repeatability of the ELGG is 0,1 mm [9], which satisfies the positioning requirements set in Table 4 with considerable overhead. The motor and motor driver for the linear axis are selected from the list of suitable motors in the Festo catalogue.

The total mass of moving parts consists of the masses of two axis slides and two contact manipulator assemblies (green on Figure 7). The positioning distance is the maximum stroke of each slide and the positioning cycle duration is the summed duration of acceleration and deceleration of the moving parts. The positioning duration is selected, considering the duration of the conveyor movement and that the movement would be fast enough to allow for a reasonably quick readjustment. The positioning time is chosen to be 2,0 seconds. Table 9 lists the data used for motor selection.

Table 9. Source data for calculation of the required torque

Variable	Symbol	Value
Total moving mass	m	2,2 kg
Effective diameter of the pulley [12]	D	18,46 mm
Positioning distance	s	0,18 m
Positioning cycle duration	t	2,0 s
Safety factor	S	3,0

The maximum speed v_{max} and acceleration a of the moving mass are calculated based on the positioning distance and the required positioning duration.

$$v_{max} = 2 \cdot v_{avg} = 2 \cdot \frac{s}{t} = 2 \cdot \frac{0{,}18}{2} = 0{,}18\,\frac{m}{s}$$

$$a = \frac{v_{max}}{0{,}5 \cdot t} = \frac{0{,}18}{1} = 0{,}18\,\frac{m}{s^2}$$

Calculations of required torque T_{req} and rotating rate n of the motor are based on formulas 2.1 and 2.2, and the data presented in Table 9.

$$T_{req} = 3 \cdot \frac{2{,}2 \cdot 0{,}18 \cdot 0{,}01846}{2} \approx 0{,}011\ Nm$$

$$n = \frac{0{,}18 \cdot 60}{\pi \cdot 0{,}01846} \approx 187\ min^{-1}$$

A comparison between suitable servo and stepper motor options from the EMMS-series was made. The lightest suitable servo motor EMMS-AS-55S [13] has a nominal torque of 0,34 Nm, while the output torque of the smallest suitable stepper motor EMMS-ST-57S [14] is 0,8 Nm. Servo motors can operate at significantly higher speeds and dynamic loads [15], but as this is a relatively low-speed drive with constant loads, the stepper motor option is preferred. Lower price even with a closed loop controller option is also an advantage of the stepper motor. EMMS-ST-57S stepper motor was selected as the motor to be used in the horizontal linear actuator assembly.

For the motor controller, the optimized controller option for the stepper motors CMMO-ST with IO-link interface [16] was selected. The CMMO-ST controller is operated using IO-link or Modbus interface for positioning to preset or manually specified positions.

2.5 Contact manipulator

A contact manipulator mechanism will be attached on top of each slide and the centre support piece of the horizontal electrical contact positioning axes. The mechanism will allow reactors to be connected to the measurement circuit of the testing station without the operator's intervention. The principal mechanism of the actuator is illustrated on the left in Figure 8. The contact manipulators will be actuated after the contacts have been moved to positions adjacent to the reactor's bus bars based on the coordinates read from a dedicated data table of a company database.

The contact manipulator system should be as light as possible, as any additional weight will reduce the speed of operation, require more powerful positioning drive motors and also shorten the lifetime of the linear guide systems. To keep the actuator construction simple and its weight as low as possible, a pneumatic cylinder with an attached electrical contact is chosen to be used as the contact manipulator. A drawing of the pneumatic actuator is presented in Figure 8 on the right of.

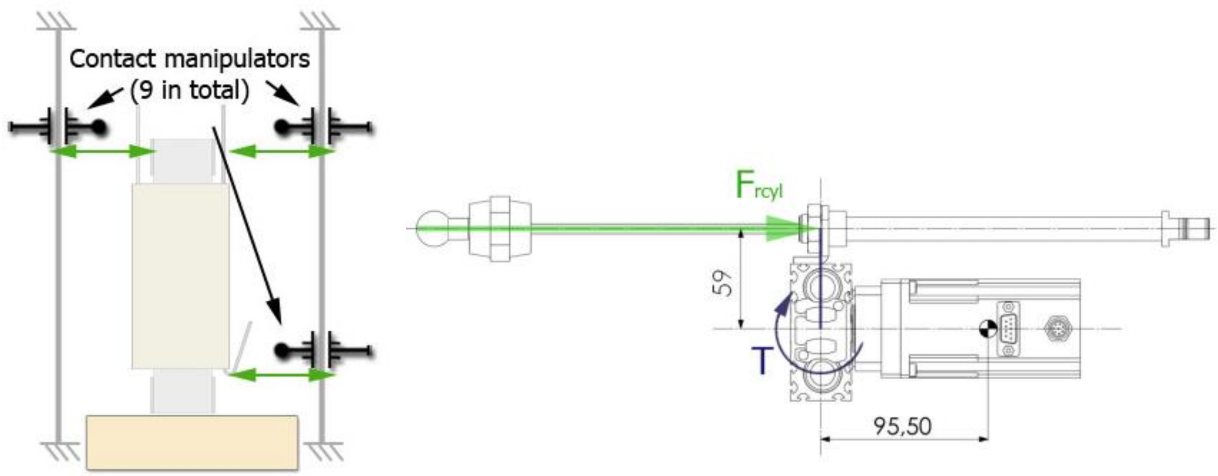


Figure 8. Contact manipulator concept (on the left) and technical drawing (on the right)

Calculations and dimensioning

The contact drivers will exert force to the bus bars of the tested reactor and so the reaction force is applied to the frame of the machine through two linear guide systems, which will be strained by the reaction forces and their resulting moments. The strain will reduce the lifetime of the guide systems, but as the slides will be stopped for the duration of the applied strain, the effect is less than it would be in case of a dynamic moving load. The maximum allowed moment relative to the centre line in the direction of the horizontal axis guide rails for the axis type selected in section 2.4 (ELGG-TB-35) is 1,0 Nm. As seen from the drawing on Figure 8, the moment arm of the force in the direction of the cylinder to the centre of the profile is 59 mm. By solving the moment arm torque equation $T = r \cdot F$ for the reaction force F_{rcyl}, the magnitude of the maximum allowed force is calculated. As there are always three manipulators working at the same time, the maximum force applied by one cylinder is one third of the total force.

$$F_{tot} = \frac{T}{r} = \frac{1,0}{0,059} 16,95\ N$$

$$F_{cyl} = \frac{F_{tot}}{3} = 5,6\ N.$$

The cylinder used for the manipulator was chosen from the Festo catalogue. As the found maximum force is relatively small, a cylinder with the smallest diameter was found which was available in the desired piston stroke of 160 mm. The selected cylinder, DSNU-12-160 [17] has a piston diameter of 12 mm. Using the pressure definition, the compressed air pressure used for the cylinders should not exceed $p_{max} = F_{cyl} / A_{piston} = 5,6 / 0,000113 \approx 50$ kPa = 0,5 bar. The air pressure of the system will be regulated using a compressed air conditioning block to 0,5 bar.

Due to the low pressure used in the pneumatic system, it is necessary to use the low friction version of the DNSU-series cylinder, which has the minimum operating pressure of 0,45 bar [17]. Additional tests will be conducted in Trafotek to verify if the pressure is sufficient to create a reliable electrical contact with the bus bars and if the cylinders will operate fast enough to create the connections in 2 seconds or less, as the conveyor positioning duration is 8 seconds (Table 6) and the expected total positioning duration 10 seconds (Table 2).

2.6 Vertical linear drive system

The vertical drive system serves the purpose of positioning the electrical contacts vertically adjacent to the bus bars of the reactor to be tested. A conceptual illustration of the vertical axes is presented on Figure 9. As the vertical spacing of bus bar connection points can vary from 290 to 554 mm, and also the height of the reactors measured from their base varies from 350 to 1200 mm, the vertical adjustment range needs to be larger than that of the horizontal axis. Also, both horizontal contact axes need to be adjustable independently. One of the main problems to solve for the vertical system was figuring out a suitable way of incorporating two independently driven slide groups onto one axis set.

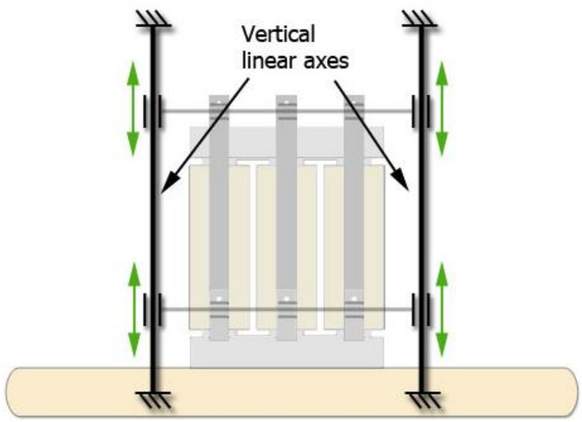


Figure 9. Vertical linear drive axes on the conceptual drawing

Two different linear drive systems were considered for the vertical linear guide axes. The different options were compared and their suitability for the application was assessed. The more suitable option was selected to be used in the machine design.

MiniTec LR 6 linear guide system

The MiniTec LR 6 Z 45 linear guide system consists of a 45 x 45 mm aluminium profile, a rail with steel guide shafts, a slide with four concave surface ball bearings, a timing belt and two timing belt reverse units in each end of the aluminium profile. The 45 x 45 mm profile is similar to standard profile types available on the market, but has a cut-away along one side for the belt return path. This means that the system is not directly integrable to the station's frame profiles.

Festo ELGR linear axis

The ELGR linear axis series is similar to the ELGG axis system chosen to be used for the horizontal positioning drive system (Section 2.4), but includes only a single slide. An additional non-driven slide can also be added onto the guide rails without disrupting the belt drive system. The two considered options are compared on Table 10.

Table 10. Comparison of vertical linear drive system options

	LR 6 guide system [8]	**ELGR drive system [12]**
Product type	Customized assembly	Standard product
Guide	Ø 6 mm steel rods	2 x round steel guide
Bearings	Radial ball bearings	Recirculating ball bearings
Weight	Heavier	Lighter

Selection

The Festo ELGR drive system was chosen as the vertical linear drive. The decision was based on the facts that the ELGR drive system is a standard product, can be ordered with an additional non-driven slide, which would enable two separately driven axes to be constructed between two ELGR-series guides. Other relevant factors were lightweight and economical design and similarity to the chosen horizontal axis system – same type of electrical drives and drivers could be used, which would simplify the task of controlling of the drives. The ELGR has similar positioning repeatability to the ELGG series: 0,1 mm [12], so the requirements set in Table 4 are fulfilled.

Construction options

Two construction options were considered when designing the electrical contacts positioning system: one of the options used a single driven slide on one vertical axis to move a horizontal axis assembly. The mechanical connection of the axes would be made with a corner piece between the slide of the vertical axis and the centre support of the horizontal axis. This option was called the "cross" construction. The other option used a driven slide on one vertical axis and a non-driven slide on the other to move a horizontal axis assembly. This construction used special hardware to mount the end pieces of the horizontal axis directly to each of the slides of the vertical axes. This option was called the "H" construction. The CAD model representations of the two construction options are illustrated on Figure 10.

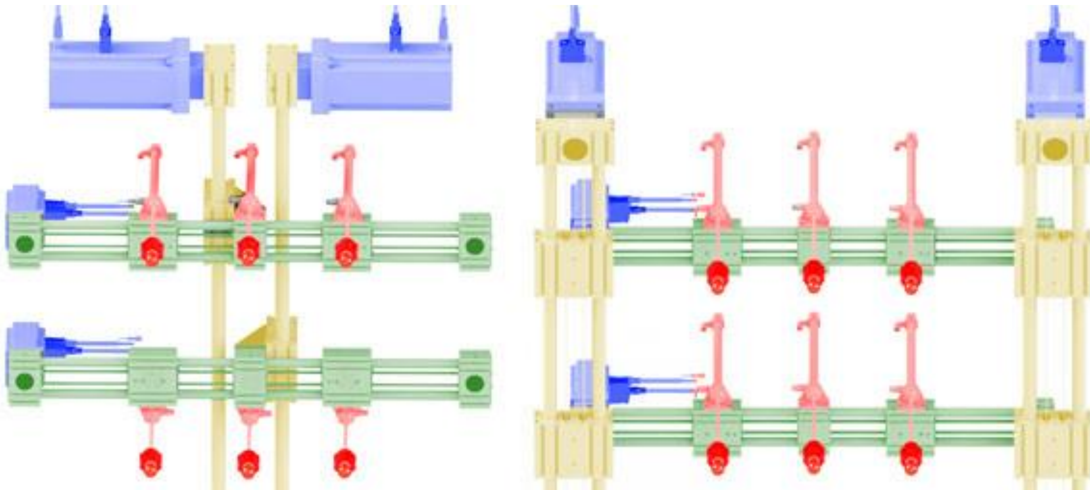


Figure 10. Positioning system constructions: "cross" (on the left) and "H” (on the right)

The “cross” construction would have less moving parts and standard ELGR drive axes could be used. On the other hand, the construction would require custom corner brackets and the weight of the horizontal axis motor would create considerable unwanted moments which would strain the mounting points and parts of the vertical axis. The direction of moment at the slides of the vertical axes resulting from the forces of the contact manipulators would also be unfavourable.

The “H” construction would require customized ELGR axes with one driven and one non-driven slide, but would support the weight of the horizontal drive motors better and distribute the resulting moments more evenly. The moment created by the contact manipulators would also be oriented more favourably. The “H” option will result in a more sturdy and durable construction and is chosen to be used in the design of the station. It is noted that as only one of the vertical slides are driven, unwanted stresses will occur in the horizontal axis guide rails. A design verification test should be carried out to identify the extent of that stress. A support beam can be added parallel to the horizontal axes if found necessary.

Mechanical and electrical calculations

The vertical axis stroke should ideally be equal to the height of the highest reactor, which is 1100 mm (Table 3). As the maximum stroke length of the ELGR guides with 35 mm profile is limited to 800 mm, the next profile size is selected. The 45 mm profile option is limited to the stroke length of 1000 mm, but using the CAD model it was empirically found to be sufficient to enable suitable electrical contact positioning for all baseline reactor types. In order to verify the suitability of Festo ELGR-TB-45-1000 axis, the moment applied to the axis by the force of the pneumatic contact manipulators is calculated and checked against the maximum allowed moment about the corresponding axis.

As the horizontal axis will be mounted to the centre of the vertical axis slides, the moment arm from the centre of the vertical slide is equal in length to that used in section 2.5 ($r_{cyl} = 59\ mm$). The total reaction force applied to the electrical contacts F_{tot} is calculated in the same section. The other significant forces that create torques about the slide are the gravitational forces of the horizontal slide drive motors. Mass of the horizontal axis motor is $m_{mot} = 1{,}1\ kg$ [12] and the distance of its centre of gravity from the middle plane of the slide is $r_{mot} = 96\ mm$. The forces are assumed to be distributed equally between the slides of the two vertical axes. To consider the fact that one of the vertical axes pair will hold two horizontal actuators, the forces calculated for one horizontal axis are doubled, as recommended in the documentation of the ELGR series [12] for the case of multiple moments. The maximum resulting torque about the z-axis (the axis intersecting and perpendicular to the centre line of the two guide rails) T_{vz} is calculated.

$$F_{cyl} = \frac{F_{tot}}{2} = \frac{16{,}95}{2} \approx 8{,}5\ N$$

$$F_{mot} = m_{mot} \cdot g = 1{,}1 \cdot 9{,}81 \approx 10{,}7\ N$$

$$T_{vz} = 2 \cdot (F_{cyl} \cdot r_{cyl} + F_{mot} \cdot r_{mot}) = 2 \cdot (8{,}5 \cdot 0{,}059 + 10{,}7 \cdot 0{,}096) \approx 3{,}1\ Nm$$

The maximum permissible moment about the z-axis of the slide for ELGR-TB-45 is $M_{zmax} = 8\ Nm$. The total permissible moment applied to the slides of the vertical axes is not exceeded during the operation of the contact manipulator if the air pressure used to drive the pneumatic cylinders is 0,5 bar and the resulting safety factor for moment about z-axis of the slide is $S = 8\ /\ 3{,}1 \approx 2{,}6$.

The motor for the vertical axes is selected from the EMMS-ST stepper motor series as for the horizontal axis. The required torque and speed of the motor were calculated based on moving mass and the required positioning duration. The total mass of moving parts consists of the mass of a horizontal axis assembly (7,0 kg), including motor and contact manipulators, and two vertical axis slides (3,4 kg). The positioning distance is the stroke length of the axis and the positioning cycle duration is selected to be equal to that of the horizontal axis ($t = 2,0\ s$). The data used in calculations is presented in Table 11.

Table 11. Torque calculation data

Variable	**Symbol**	**Value**
Total moving mass	m_{tot}	10,4 kg
Effective diameter of the pulley	D	24,83 mm
Displacement	s	1,0 m
Positioning cycle time	t	2,0 s
Safety factor	S	3,0

$$v_{max} = 2 \cdot \frac{s}{t} = 2 \cdot \frac{1,0}{2,0} = 1,0\,\frac{m}{s}$$

$$a = \frac{v_{max}}{0,5 \cdot t} = \frac{1,0}{0,5 \cdot 2,0} = 1,0\,\frac{m}{s^2}$$

The calculations are made based on formulas 2.1 and 2.3, with the added consideration of the gravitational acceleration for the moving mass.

$$T_{req} = S \cdot \frac{m_{tot} \cdot (a+g) \cdot D}{2} = 3 \cdot \frac{10,4 \cdot (9,81+1,0) \cdot 0,02483}{2} \approx 4,2\ Nm$$

$$n_{req} = \frac{1,0 \cdot 60}{\pi \cdot 0,02483} \approx 770\ min^{-1}$$

From the EMMS-ST motor series documentation, the closest option to the motor with the required torque and speed is EMMS-ST-87M with nominal torque of 5,9 Nm and maximum rotating rate of 550 min^{-1}. The maximum speed of the motor results in a positioning cycle duration of 2,8 seconds, so 3,0 seconds is selected as the final vertical positioning cycle duration and the EMMS-ST-87M is selected for use in the vertical positioning axes. Because the horizontal axes must be held in place also when the drive is stopped, the motor is selected with an electrical brake option. For the motor driver, the CMMO-ST series driver is chosen similarly to the horizontal positioning axes.

2.7 Manual loading and unloading

Although the designed workstation will be used to automate a manual task, some operations in the workstation workflow will still need to be done by the operators. The manual tasks most relevant to the speed and efficiency of the station are loading and unloading of reactors to and from the conveyor. As the speed of conducting the tests is expected to be greater than the combined loading and unloading speed, a correct and complete analysis and design of this process is important to the final profitability of the station. The loading and unloading specification is presented next.

Preconditions

The pallets in the previous work stage need to be loaded with reactors in a way that allows them to be easily lifted off the pallet one-by-one without damaging or having to move the rest of the reactors. All of the reactors should be facing the same way and the space between every two adjacent reactors should be at least 50 mm.

Loading operation

1. A pallet with at least 6 reactors is transported from the buffer location of the previous work operation to the loading area of the station. The loading area will be clearly marked on the factory floor with yellow tape that is also used elsewhere in the factory for similar purposes.
2. A nylon base plate with a positioning corner jig is placed on the conveyor in the marked position range. The correct orientation of the nylon plate will be marked on the plate and the side of the conveyor.
3. A reactor is hoisted from the pallet and positioned onto the nylon base plate. When lowering the reactor onto the plate, it will be positioned in the corner jig. The orientation of each specific reactor type will be displayed on the station's HMI when each work is opened in the interface system.
4. The tipping guard system will be attached and/or adjusted if necessary to prevent the reactor from accidentally tipping over on the conveyor.
5. The operator will verify that the movement path of the reactor and the working area of the machine are clear and that it is safe to continue. A button will be pressed to signal the machine that the manual positioning operation is complete and the work cycle can be continued.

Unloading operation

1. An empty pallet is positioned to the unloading area of the station. The unloading area will be marked on the factory floor using tape similarly to the loading area.
2. As the station will finish the required tests and has received the required signals from the operator that indicate that the unloading and loading operations are complete (the output end of the conveyor is clear and optionally a new reactor is on the input end of the conveyor), it will retract the electrical contacts and advance the conveyor, transporting the tested reactor to the unloading position of the conveyor.
3. The operator will detach the tipping guard and hoist the reactor from the conveyor to the pallet. The hoist will be left to a position where it cannot accidentally damage any reactors.

Critical parts of the operations

The most critical parts regarding the speed and smooth flow of the loading and unloading operations are listed next.

- Positioning of the reactors on the source pallet: the pallet and reactors on it need to be oriented according to specification to allow the loading operation to be conducted in a smooth and uniform manner.
- Positioning in the corner jig: each reactor must be precisely positioned in the corner jig to guarantee that the reactor will be stopped at the correct position in the testing area and that the bus bars will line up with the electrical contacts. If a reactor is not positioned in the jig correctly, it might be necessary to reverse the conveyor and re-position the reactor.
- General safety: general safety rules for hoisting operations must be followed to ensure the health and safety of the workers. Extra caution must be taken when loading and unloading the reactors so as not to damage the reactors or the machine.

Lifting test

A practical lifting test was conducted to verify the positioning jig concept and to time the lifting operations. The test setup and results are briefly described next.

1. The reactor base plate was built of a nylon sheet and steel profiles
2. The base plate and positioning jig were tested on a conveyor using a scrap product
3. The lift-on and lift-off operations were timed and the results gathered
4. A conclusion was made based on the test and timing estimates were updated accordingly

The pallet transport time was timed to be ~90 s. A photo of the lifting test is presented on Figure 11 and the hoisting operation test results are presented in Table 12.

Figure 11. Lifting test in progress.

Table 12. Lift test results

Nr	Lift on, s	Lift off, s
1	34	~~52~~
2	~~50~~	44
3	44	38
Average	**39**	**41**

(green)	- experienced operator
	- inexperienced worker
~~50~~	- first try, excluded from calculation

The test results show that with some practice, both the lift-on and lift-off operations could be done in about 40 seconds. Considering that the final setup would have cranes of more suitable size the real durations will probably be around 35-40 seconds. Both the loading and unloading operation durations are estimated to be 45 s in the station calculations. According to the test results, the anticipated processing time of 6 reactors (1 Euro-pallet) was 12 minutes (Table 2).

2.8 Positioning system CAD model

A CAD model of the station was developed and updated throughout the process of devising the positioning system and selecting its components. The existing models of relevant reactor types were used to define the dimensions of the conveyor, the testing area frame and the linear axes built into the frame. A partial CAD model is presented on Figure 12 to illustrate the construction and placement of the reactor positioning system parts described so far. For clarity, only the conveyor and the station frame (orange), the horizontal (yellow) and vertical (green) electrical contact positioning axes, the control hardware (white) and the reactors (blue) on their base plates (light blue) are displayed on the illustration.

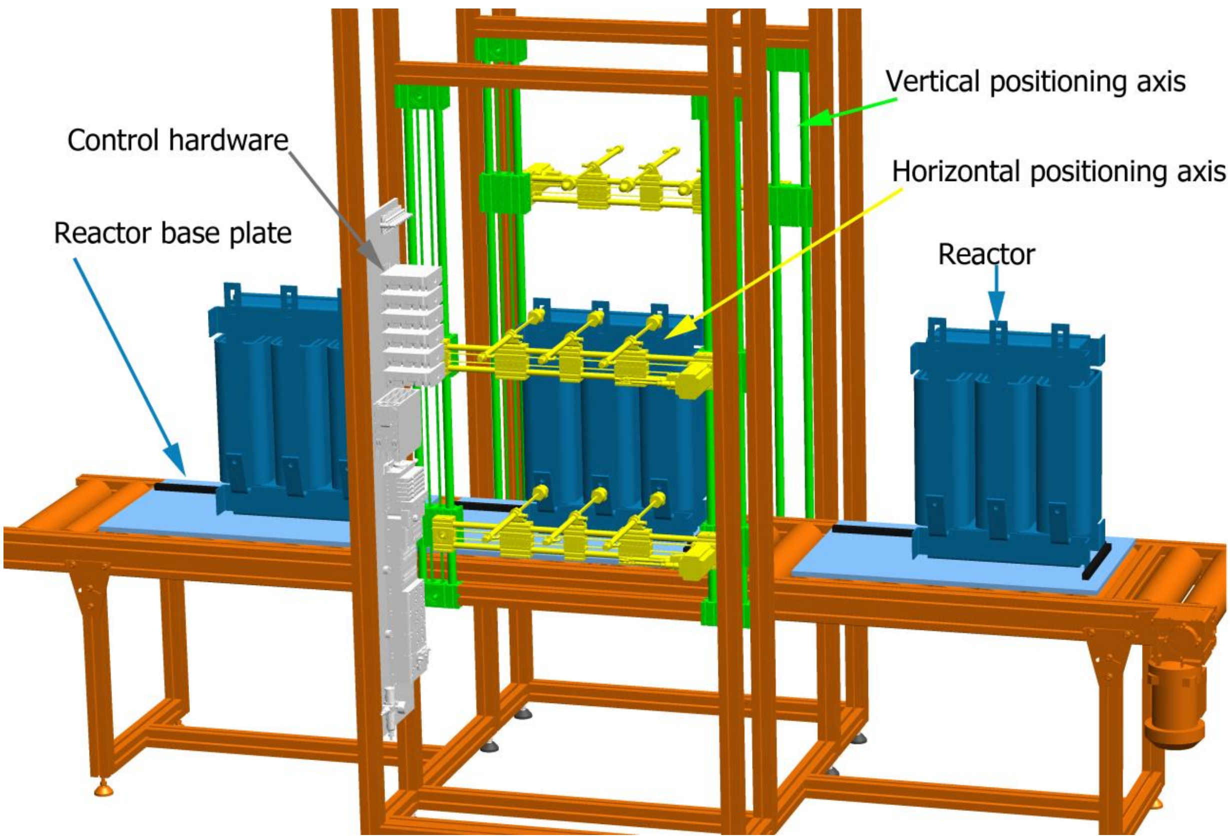


Figure 12. Partial CAD model of the station

3 SAFETY

3.1 Safety legislation

All electrical devices should be designed with regard to the safety of their operators, other humans and animals and its surrounding environment. One of the principal aims of the designed station is to increase operator safety and reduce the subject-specific technical knowledge level necessary for conducting the regular electrical tests. The testing station which is being designed in Trafotek AS has components operating at low (<1000 V) and medium (1 kV to 52 kV) voltage ratings. Although there is no designated European Union directive for medium voltage electrical equipment, the EU legislation does set specific requirements for all low-voltage electrical equipment [18] and for all equipment considered to be machinery [19]. Furthermore, additional safety requirements set in the international standard IEC61010-1 [20] are regarded, as the designed station can be considered as an equipment for measurement.

An overview of the applicable directives and standards is presented as a list following which safety notes and requirements from each regulation are listed and explained in more detail.

- IEC 61010-1: Safety Requirements for Electrical Equipment for Measurement, Control, and Laboratory Use
- 2006/42/EC: Directive on Machinery
- 2014/35/EU: Low voltage Directive

Safety requirements for electrical measurement equipment (IEC 61010-1)

The IEC 61010 Part 1 relates to electrical measurement equipment integrated into manufacturing facilities intended for testing electronic devices. This means the standard regulates the LCR tester, surge voltage tester and their connected switching devices, cabling and electrical contacts, as parts of the integrated measuring equipment. The standard states requirements for design and construction to protect the operators and surrounding area against the following:

- Electrical shock or burn
- Mechanical hazards
- Excessive temperature and fire hazards
- Effects of radiation (including sonic radiation)
- Liberated gases, explosions and implosions

Directive on Machinery (2006/42/EC)

According to the Directive on Machinery, all machinery, with the exceptions listed in Article 1 of the directive, that are made available on the market or put into use in the European Union, must:

- Satisfy the health and safety requirements listed in Annex 1 of the directive
- Include the technical file for machinery described in Annex 7 of the directive
- Include relevant information, such as instructions
- Have their conformity assessed according to Article 12 of the directive
- Include an EC declaration and have the CE marking affixed to it

In addition, the manufacturer must carry out risk assessment to determine possible hazards related to the machinery and use appropriate measures to reduce the risks for the machinery to conform to the health and safety regulations. The designed testing station does not fall under any of the excluded machinery types, so the directive must be followed in the design and manufacture of the station. The directive provides an extensive list of regulations categorized to several topics and sub-topics.

Low voltage Directive (2014/35/EU)

The Low voltage Directive states that the regulation relates to *making available on the market* of specified electrical equipment. This means that the directive must be followed only when the equipment will be made available on the European market; in exchange of money or for free. The safety requirements set in Annex 1 of the regulation are listed next in a simplified style.

1. The installation and connecting of the equipment must be safe for the personnel
2. The equipment must be designed in such way that it:
    a. Will not cause injuries from direct or indirect contact during normal operation
    b. Will not produce dangerous temperatures, arcs or radiation
    c. Offers adequate protection from possible non-electrical dangers
    d. Is insulated suitably
    e. Meets the expected mechanical requirements for safe operation
    f. Is resistant to non-mechanical influences in its intended environment
    g. Does not pose danger in case of foreseeable overload conditions

If the machine will be placed on the market, it must also follow all other articles of the directive and must include technical documentation and must have the CE-mark affixed to it, indicating its compliance with the directive. The station is not planned to be sold or otherwise put on the market at the time of design, but for extended options in the future, the directive will still be regarded to.

The IEC 61010-1 standard is applicable to the electrical measuring equipment embedded in the testing station. Although it is not mandatory to follow the standard in the EU, the safety requirements will be followed when designing the equipment to ensure the safety of the operators. The Directive of Machinery is compulsory to follow in the EU for all machinery, including the station described in this thesis. The safety requirements set in the directive will be regarded as the main rules regarding safety in the design and assembly process. As the low voltage Directive relates only to equipment being put on the EU market, but all of its safety requirements are also covered in the Directive of Machinery, it will also be considered during this project.

3.2 Safety analysis

In order to minimize the risk of injury and damage, a comprehensive safety analysis was conducted on the designed machinery and work process. The workflow of the testing station was analysed and the most relevant potential hazardous situations were mapped. For each hazard a preventive measure in the form of a safety device, design requirement or other appropriate means was devised. The hazards and the preventive measures are presented on Table 13. The main preventive measure groups are listed below.

- Mechanical safety devices for restricting operator access to hazardous areas
- Mechanical devices for restricting movement of reactors and parts of the machine
- Electrical sensors for detecting the presence of objects in an area
- Electrical indicators for informing the operator and others of the status of the machine
- Safety labels for reminding and directing attention to possible hazards
- Thorough documentation of the station: operator and maintenance manuals

Table 13. Identified potential hazards and preventive safety measures

Work operation	**Identified potential hazards**	**Preventive measures**
Pallet transport	• Foot crushed by pallet or pallet truck • Pallet crashed into the machine • Reactors tipping over and getting damaged on the pallet	• Warning labels • Marking on the floor • Stoppers on the floor • Operator training
Loading and unloading of reactors	• Hand caught between or crushed by lifting equipment and reactor • Reactor detaching from lifting equipment • Accidentally signalling the machine that lifting operation is complete	• Warning labels • Operator training • Electrical safety devices
Conveyor movement	• Hand caught between a reactor and machine • Reactor tipping over • Reactor hitting the frame of the machine • Conveyor drive malfunction • Reactor falling off the conveyor's end	• Warning labels • Electrical safety devices • Mechanical safeguards
Contact positioning	• Hand caught in the contact positioning mechanism • Hand caught between a contact and a bus bar • Reactor tipping over • Positioning drive malfunction	• Warning labels • Electrical safety devices • Mechanical safeguards • Machine covers
Electrical testing	• Electrical shock • Short-circuit • Arcing or fire due to bad contact	• Electrical safety devices • Programmatic safety checks

3.3 Mechanical safety features

Mechanical devices will be used to limit the access to dangerous areas and to limit the movement of mechanisms and the reactors. The mechanical safety devices also serve the purpose of preventing serious injury or damage in case of a failure in the electrical devices of the station. The positioning drive systems from Festo have integrated limit sensors and the motor drivers handle their signals, so these devices are excluded from this section.

The following areas are considered as dangerous for the operator and will be restricted mechanically:

- The area of electrical contact positioning system movement
- The area near high voltage devices and connectors
- The area of reactor entrance to and exit from the testing area frame

Otherwise potential mechanism or test piece movements that will be limited using additional stoppers or other mechanical devices:

- The movement of reactor and its base plates over the sides and ends of the conveyor
- The tipping of reactors on their base plates

Tipping guard design and concept testing

To prevent the reactors from tipping over on the conveyor, a mechanical guard system will be used which will physically block the reactor from tilting. For keeping the machine as simple as possible and the costs as low as possible, it was decided that the tipping guard mechanism should not be electronically actuated; it should have a durable mechanical design which would offer the necessary degree of functionality and flexibility. Several different designs were devised and considered. Three of the designs are described and compared next, and a conclusion is made based on the comparison. The comparison is presented on Table 14.

Four-link sliding magnet system

This mechanism would consist of two guide rails positioned over the testing area, onto which four tool trolley slides would move; two trolleys on each rail. Four links of hollow metal profile would connect a permanent switchable magnet to all four trolleys. The magnet would be tiltable on an axis where the links and the magnet meet. When the magnet is lifted or lowered to adjust for the reactor's height, the two trolleys on each rail would move closer or further apart.

Single adjustable constrainer bar

The mechanism would consist of a single beam of metal profile and a mechanism to adjust and lock it at any chosen height. The constrainer bar would be set slightly higher than the reactor, so that the reactor could move freely under the bar. If the reactor were to be tilted, its tilting angle would be constrained by the bar. The main disadvantage for this system is that a reactor of different height cannot be processed by the station when there are still other reactors on the conveyor. That would mean the constant work flow would be interrupted between batches of different reactor types.

Recirculating carabiners

A guide rail system would be used for this system which would allow tool trolleys to move from the input side of the station to the output side above the reactors, and recirculate back to the input side by using gravitational force. The tool trolleys would carry tool balancers with carabiners, which could be attached to each reactor. The tool balancer spool should be lockable at any position to be able to constrain reactors of different height.

Table 14. Tipping guard design comparison

Design	Pros	Cons
Four-link sliding magnet	• Easily attachable and detachable • Height adjustable per reactor	• Height adjustment needs a spring or damper system • Requires long slider rails for higher reactors • Three sliding mechanisms are required
Single adjustable constrainer bar	• Few moving parts • Simple and effective • No need to attach the reactors	• Only reactors of same height can be processed at once • Requires a locking mechanism
Recirculating carabiners	• Height reliably adjustable per reactor • Assembled of standard parts and products	• Requires special lockable tool balancers • Reactors must have an attachment point

Concept testing of the magnet system

It was not known if the 100 kg hoisting magnet is suitable for supporting an assembled reactor as necessary. Furthermore, a similar double-rail slider mechanism had not been used in the factory as well, so a practical test of both concepts was planned and conducted. As it was uncertain if this mechanism is at all suitable for the task, locally available materials were used for building a test rig. The test had to confirm or disprove:

- If the 100 kg magnet attaches to the reactor well enough to prevent tipping of the reactor
- If the link mechanism is able to constrain the reactor movement sufficiently

A test was conducted with a sample reactor which corresponds to the main reactor type this station is planned to be used for. The test rig represented a simplified version of the design, having only two links instead of four. It was expected that if this weaker construction will support the reactor enough, the concept of the more rigid design could also be verified, and further tests could be done if needed. The design sketch model and the constructed test rig are presented on Figure 13.

Figure 13.Four-link tipping guard design (on the left) and concept testing rig (on the right)

The test showed that although the test rig construction was constructed with little regard to its rigidity, the system would prevent a reactor from tipping over even if it were intentionally pushed or kicked to make it happen. This was also verified at different heights of the reactor. It was concluded that the design would be rigid enough to keep a reactor from tipping over. Additionally, it was found that the 100 kg magnet would provide sufficient magnetic force and contact with the reactor core and brackets. However, the magnetic guard system turned out to be too wide to accommodate three guard systems to the length of the testing area. It also lacked the possibility to return the magnets. It was also noted that although not likely, the magnets could possibly cause some deviations in the measurements.

Different designs were considered and one of them tested. The tested system concept was proven, but the design was found to have critical shortcomings, which ruled out the use of that design. As the next step, concept of the recirculating carabiner system will be tested, but as the tests have not been conducted at the time of writing this paper, it will not be covered here.

3.4 Electrical safety components

As summarized in Table 13, several possible hazards are identified in the operating process of the designed station. In this section, the list of hazards is analysed to find the ones which could be prevented or reduced by the use of electrical safety components or devices, such as presence and proximity sensors, indicators, switches and buttons. Relevant hazards from Table 13 and the appropriate electrical safety devices for controlling those hazards are listed in Table 15.

Table 15. Required electrical safety devices

Work operation	**Possible hazard**	**Electrical safety devices**
Loading and unloading of reactors	• Accidentally signalling the machine that lifting operation is complete	• Signalling buttons with mechanical covers • Optical presence sensors
Conveyor movement	• Conveyor drive malfunction • Reactor falling off the conveyor’s end	• Safety relays • Optical presence sensors • Inductive proximity sensors • Mechanical limit switches
Contact positioning	• Hand caught in the contact positioning mechanism • Positioning drive malfunction	• Mechanical safety switches • Inductive limit sensors
Electrical testing	• Electrical shock • Short-circuit	• Safety relays • Circuit breakers

The required electrical safety components are discussed next; their location in the testing station, method of operation and required additional equipment is analysed and set.

Confirmation buttons with mechanical covers

Control buttons will be used in the system for making the operator confirm the completion of a loading or un-loading operation and signalling the control system that the tipping guard system is attached in case of a loading operation and that it is safe for the machine to operate the conveyor. The confirmation buttons should be located at the loading and unloading areas so that it would be convenient for the operator to use them. Preferably the operator should not need to take additional steps to reach the buttons, so they should be located at the reach of the operator during the loading and unloading operations.

There is risk of the operator accidentally pushing the confirmation buttons when hoisting or positioning the reactors if the buttons are in the hands reach of the operator. This hazard could be controlled by using push-buttons with mechanical safety covers or by using two hand control buttons which should be pressed simultaneously in order to give a valid confirmation signal. Two hand control buttons with mechanical covers could be used in the loading end of the conveyor, as the operator would have both hands free after positioning the reactor onto the conveyor and attaching the tipping guard system. On the unloading end though, the operator should be able to give the confirmation signal already when the reactor has been hoisted away from the conveyor, but has not yet been lowered onto a pallet. In this situation, the operator might need to use one hand to hold the hoist control or guide the reactor with one hand, so two hand buttons would not be suitable there. One possible option at the unloading end of the conveyor would be to use a foot switch and hand switch combination

Protective relays and circuit breakers

In order for the station to remain safe during a system failure, it should be possible to detect foreseeable fault conditions and react accordingly, as there are electrical control and testing devices used which create a potential risk of electric shock to the operator or short-circuits in the electrical systems. For detecting electric fault conditions, protective relays can be used. A protective relay can for example be used to detect short-circuits or ground faults in the system, or a runaway situation of the drive. Circuit breakers should be used in combination with the safety relays to switch off the entire station or relevant parts of the station according to the generated fault signal. An additional main fuse will be used at the main power connector.

Optical presence sensors

Optical sensor pairs will be installed across the width of the conveyor at the loading and unloading areas of the conveyor. Those sensors, set to an appropriate height and angle across the conveyor, will indicate to the control system if there are reactors present at each area. This will help identify false confirmation signals from the operator and also provide data about the durations of loading and unloading operations.

Limit switches and proximity sensors

Mechanical or inductive limit switches should be used for all electric drive systems in the station. Electric drives are used in the contact positioning system and the conveyor drive system. Festo ELGR and ELGG linear drive kits used in the contacts positioning system include inductive limit switches which are used by their accompanied motor drivers to automatically prevent any damage to the linear drives in case of conflicts or failures, so no additional sensors will be used for the linear drives.

Mechanical limit switches will be used at both ends of the station’s conveyor to disable the conveyor drive system if an object is present at either edge of the conveyor. The limit switches in combination with mechanical barriers will control the hazard of reactors falling off the ends of the conveyor or damage of the conveyor or its drive in case of a false confirmation signal from the operator.

An additional inductive proximity sensor will be installed to the side of the conveyor to detect the moment when a reactor enters the testing area. This signal will then be used as a reference point from which the control system will calculate the conveyor position which the reactor will be stopped at to align its middle bus bar with the centre electrical contact.

Different types of electrical devices will be used in the testing station design for controlling the relevant hazards which arise from the technical systems and solutions used for the desirable functionality and operation of the testing station. A list of required devices has been compiled and is presented in Table 16.

Table 16. Electrical safety devices

Device	**Qty**	**Position**	**Purpose**
Push-button with cover	3	Loading and un-loading area	Confirmation signal from the operator
Foot pedal with cover	1	Unloading area	Same as above
Circuit breaker	2	Main fuse box	Automatic safety power switches for the testing equipment and the rest of the devices
Optical presence sensor	2	Loading and un-loading area	Verification of the operator’s confirmation signal, statistical data collection
Mechanical limit switch	2	Both ends of the conveyor	Safeguard against conveyor overload and damage
Inductive proximity sensor	1	Input end of the testing area	Reference signal for reactor positioning

3.5 Instructions documentation

The applicable legislation and referenced standards discussed in section 3.1 – the safety regulations from the Directive of Machinery and IEC 61010-1 standard require that relevant machinery and equipment put into use must include adequate instruction manuals for operation and maintenance. In this section, the main topics and points which will be included in the required manuals are listed. All instructions and manuals will be written in English and translated also to Estonian and Russian. The information contained in the instructions is listed next for the operation and the maintenance manuals. Both manuals will include the identification information of the station and its manufacturer and the EC declaration of the station.

Operation instructions information

- General description of the machine and its intended use
- Electrical data: required line voltage, power consumption
- General drawings of the machine and its intended layout
- Information of the normal operation conditions and limits of the machine
- Information and instructions about required safety measures and protective equipment
- Information about the residual risks
- Instruction of safe operation in foreseeable fault conditions
- Information about regular maintenance which can be done by the operator and information of maintenance tasks that should be done by technicians
- Noise emission data

Maintenance instructions information

- Detailed drawings and schematics of the station and its distinctive sub-systems
- Detailed electrical data and specifications for the station as a whole and its electrical components
- A description of the normal condition of the station and the range of allowed deviations from that condition
- Information on maintenance safety and pre-maintenance procedures
- Assembly, connection and functionality testing instructions
- Instructions and normal intervals of adjustment and maintenance tasks
- The list and possible sources of likely spare parts

4 ELECTRICAL TESTING SYSTEM

4.1 Electrical tests

In the testing phase, two electrical test are performed: an inductance confirmation using an LCR meter, and a surge voltage test for each coil. The LCR inductance test shows if the deviation of actual inductance from the nominal is within the specified tolerance range. The test shows if the reactor coil and core are assembled correctly and with required quality. A surge voltage test, which is most commonly used in the electrical motor manufacturing industry [21], verifies that the winding layer insulation of the reactor is correctly installed and that it is undamaged. These tests, combined with the AC high voltage test between each coil and the reactor core, which is done manually after the assembly of each reactor, would in most cases be enough to guarantee that each assembled reactor satisfies the quality requirements of Trafotek and its customers.

LCR inductance measurement

An LCR meter is not able to accurately measure the absolute inductance value of a power filter reactor, as the inductance of a reactor varies with current. Filter reactor inductance specifications are given at their nominal current rating, and to validate the absolute inductance of a reactor, the measurement has to be done at its nominal current. Commercial LCR meters typically supply only very low current of less than 1 mA, making it impossible to test the reactor at its working current. As discussed further in section 4.4, LCR meters have, however, relatively good accuracy in a narrow measurement range, making it possible to compare reactors that ideally would be identical. This option is well suitable for the designed testing station, as the purpose of the station will be testing batches of several reactors of the same type. [22]

Surge voltage and PD tests

In the field of industrial reactor manufacturing, the surge voltage test is one of the few available options that are used to detect manufacturing defects in the layer insulation material of the reactors. As the resistance of a high-current reactor coil is very small, often in the range of micro-ohms, and the number of layers in a coil can be less than ten, it is a challenge to create sufficient voltage difference between two adjacent winding in order to assess the dielectric strength of the insulating material. Surge voltage test uses a short pulse of energy with an electrical potential in the range of kilovolts, to create a sufficient potential difference between the winding layers for assessing the state of the layer insulation material. [21]

PD (*partial discharge*) tests are widely used in the electric motor manufacturing field for early detection of motor winding material insulation deterioration. A partial discharge is a condition where an electrical discharge bridges a gap of gas or insulating material between conductors only partially. A PD test uses either ultra-high frequency radio wave, ultrasonic or electromagnetic emission sensors to detect the occurring partial discharges. The measured signal is then filtered for background noise reduction and analysed by special computer software. The measurement is not a quantitative measurement, but uses signal analyse techniques to detect and evaluate the partial discharges. [23][24]

The Solfas STA900 surge voltage testing system [25] offers a combined solution for conducting surge voltage tests and PD tests using the same test signal and a PD detector. The system includes PC software which provides an interface for conducting the tests and analyses the detected PD signals. The designed test station will use only the surge voltage source of the STA900 system and its software for automated surge testing, but research will be carried out to investigate the possibilities of integrating the PD measurement part of the system to the testing station.

4.2 Signal multiplexer

Because the same electrical contacts will be used to perform tests with two different devices the electrical contact connections need to be switched between the two testers. Additionally, because the surge test needs to be done for each coil separately, the measuring system needs to be able to connect or disconnect each contact to or from the electrical circuit. For this purpose, a high voltage signal multiplexer is needed.

Required connections for inductance measurement and for surge voltage tests were considered and a concept schematic was drawn up which would allow all necessary connections to be made. This schematic was used to look for suitable multiplexer options from the market and to design a custom multiplexer specifically for this system. The main required switching configurations of the device are illustrated on Figure 14 and the whole conceptual schematic of the multiplexer is added to the thesis as APPENDIX 1: Signal multiplexer Schematic

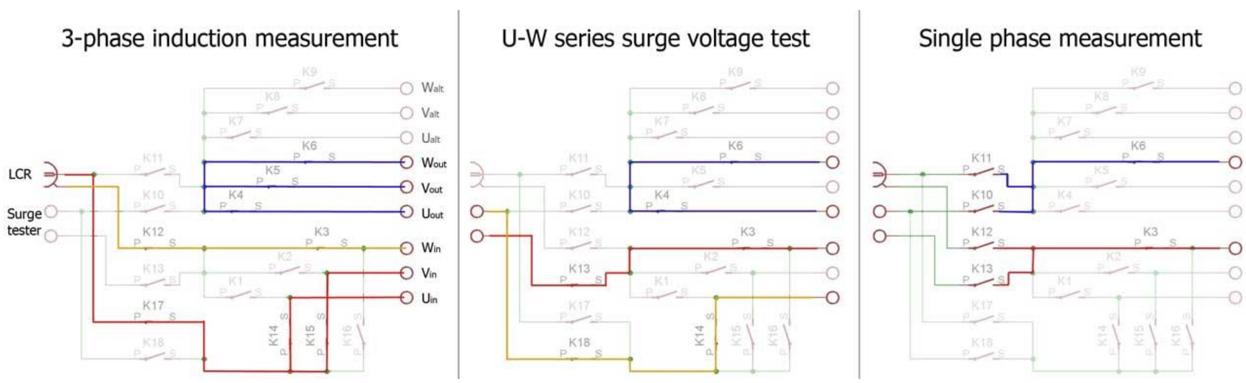


Figure 14. Test signal multiplexer configurations

The typical surge test voltage of the selected Solfas STA900 tester is 3 kV, but the test can be done at up to 6 kV, so the multiplexer relays should have the open state dielectric strength of at least 6 kV. As the switching is done between the tests, the relays do not need to be able to switch live voltages in that range. Nevertheless, relays with at least 6 kV live signal switching capability will be required for the six main relays at the inputs of the testers for added safety.

As the requirements for the multiplexer are very specific to the task and as the commercially available devices are relatively expensive [26], it was decided that a custom application-specific multiplexer device should be designed and built for the testing station. The designed multiplexer will consist of the following main parts:

- Power conditioning block
- Input buffer (using opto-isolators)
- High voltage switching circuit
- Terminal blocks

At the time of writing this thesis work, the electrical design of the multiplexer is in its conceptual stage and so the specific component selection or the manufacture of the device will not be covered.

4.3 Measurement data processing

When connection to the reactor bus bars is established, the control application in the PC uses driver libraries provided by the test equipment manufacturers to conduct the electrical tests and retrieve the measurement data. The measurement data is then processed and compared with reference values from the ERP database to decide if the reactor passes or fails the tests. The result is indicated to the operator on the PC screen and is also recorded in the ERP database.

LCR tester

A data connection to the LCR tester is established via a USB port and National instruments VISA (*Virtual Instrument Software Architecture*) interface libraries. The VISA libraries allow to control the LCR tester from a C# application using the same text-based commands which are used in case of GPIO control and which are specified in the device manual [22]. There are sample C# functions available by the National Instruments that allow to asynchronously send commands to and read data from the LCR meter. The sample functions will be modified to suit the software to be developed.

Surge tester

At the time of writing this thesis paper, it is unknown if the surge tester manufacturer will be able to provide the software functionality necessary to conduct the surge tests in a software library form. In the worst case scenario, a macro will be written which will automatically operate the Windows application provided by test system manufacturer.

4.4 Measurement accuracy

In most cases, the reactors manufactured in Trafotek are required to have an inductance variation of less than 10% of the nominal inductance value. The LCR meter measurement of low impedance inductors, such as the reactors manufactured in Trafotek, is inaccurate unless a bias current is used to bring the core magnetic flux of the reactor to its operating level. The Wayne Kerr 4300 series LCR meter planned to be used in the designed testing station has 10 mΩ as the lower impedance value on which a 10% measurement accuracy is guaranteed. It is, however, been proven that the non-linearity of a modern commercial LCR meter can be less than 0,02% in a narrow measurement range. [27] This can confirm the practice that an LCR meter can be used to compare the inductances of two reactors of the same type with good repeatability, although the inductance value is not measured at its nominal operating current. As the LCR meter included in the design has the basic impedance accuracy of 0,1% in a range from 2 Ω to 1 MΩ, and the frequency accuracy of 0,15%, it is considered to give sufficiently repeatable measurement values in a narrow range around all points of its measurement range for comparing the inductances of ideally identical reactors.

The surge tester accuracy is not quantitatively provided by its manufacturer, but the tests are specified to be conducted according to relevant IEC standards and are therefore considered as suitable for the designed application.

The measurement results from the testing equipment is transferred to the PC control application using serial communication via USB ports, so no additional expected uncertainties are introduced to the results in the data transfer.

5 SYSTEM CONTROL

5.1 Control system overview

The testing station build deadline was postponed to a later date from the initial target, so the priority of the project was lowered. At the time of writing this thesis paper, the practical software development tasks have not been started. In this chapter, the planned general structure of the system control hardware and software are described. As there is yet no software code written, it will not be presented here. Instead, the main software interfaces and classes which are planned to be used in the development part, are discussed.

The control system is designed to be separated to two main parts: a PLC that will control the operation and coordinate the co-operation of the different parts of the station. The PLC will control the sequence of machine operation steps, except the measuring device control, according to its program. It will receive signals from all of the electrical controls and sensors, receive commands and data from and send data to the PC control program and will control all of the indicators and actuators of the station.

The second main part of the control system is the PC application that serves as an interface between the user, the company database, the PLC and the measuring equipment. The application will handle data connection with the database, like reading and saving positioning and test configuration information about specified reactor types and logging of the measurement results and statistical data about the operation of the machine. The PC application will handle testing equipment control and data processing and will have a user interface for convenient control and configuration. A principle schematic of the control system architecture is presented on Figure 15.

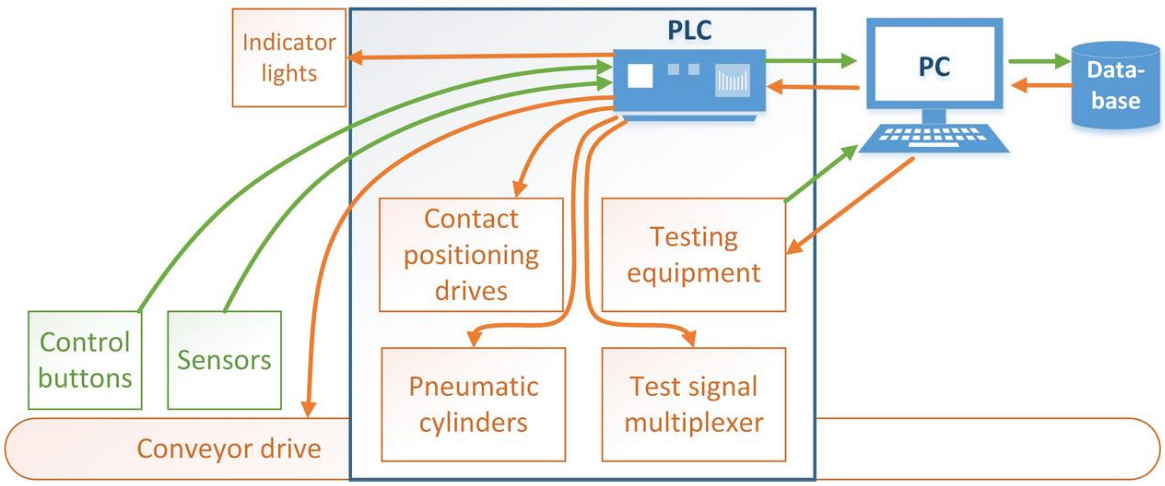


Figure 15. System control diagram

Control hardware

The PLC of the testing station must have a sufficient number of inputs and outputs to be able to process all of the signals from the buttons, sensors and motor controllers and control all of the positioning system motors and indicator lights of the station. The required types and number of inputs, outputs and special ports required for the control of the station are listed in Table 17. Port types are named as follows: *DI – digital input; DO – digital output; AO – analogue output*.

Table 17. Required PLC ports

Mechanism / Device	**PLC Inputs**	**PLC Outputs**	**Notes**
Contacts positioning		6 x IO-link	Serial communication ports
Conveyor	2 x DI	3 x DO 1 x AO/PWM	Control with digital direction and analogue speed signal.
Multiplexer relays		18 x DO	
Sensors	7 x DI		Sensors in Table 16 + 2 inputs for conveyor encoder
Buttons / indicators	3 x DI	2 x DO	Confirmation signals in Table 16 + combined emergency stop signal
Total	12 x DI	23 x DO 1 x AO/PWM 6 x IO-link	

The setup in the initial design of the control hardware consisted of a 24 V power supply, Siemens S1200-series PLC with additional digital input-output and motor controller interface modules, stepper motor controllers, a pneumatic air conditioning block, pneumatic valve block and pneumatic flow control valves from Festo and cabling to connect all of the listed components. A CAD draft version of the initial setup is presented on the left in Figure 16. After some research and consultation with engineers from Festo, a more compact and efficient solution was found for the testing station. The chosen solution was a Festo CPX-series modular terminal [28], which incorporates the following modules into one interconnected device:

- PLC
- IO-link interfaces for motor controllers
- Digital input-output modules for sensors and indicators
- Pneumatic valve block

The control terminal is illustrated on the right in Figure 16. Some of the most obvious advantages of the system are its compact size, reduced cabling, simplified maintenance and the support of freeware CoDeSys programming software. The control system will use the power supply, air conditioning block and pneumatic flow control valves from the initial hardware setup.

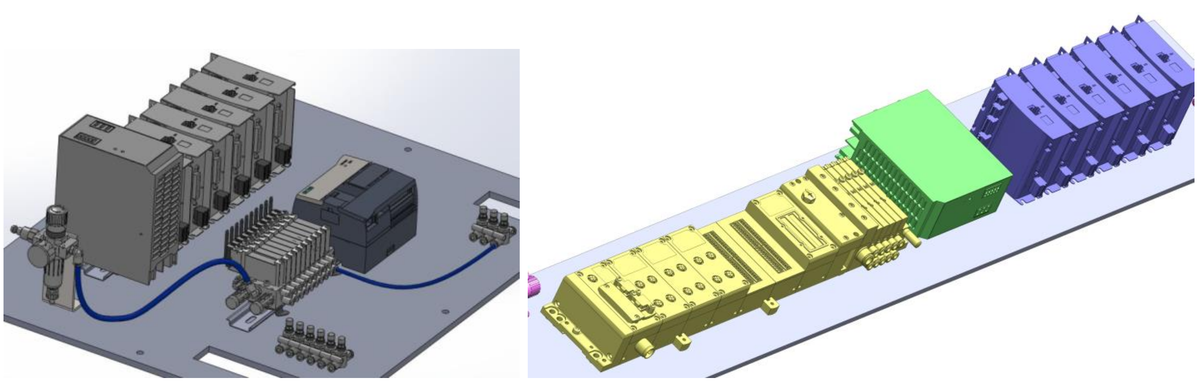


Figure 16. Control hardware assembly: initial (on the left) and final (on the right)

5.2 PLC program

For programming the Festo PLC, the freeware developing software CoDeSys [29] will be used. In the developing environment, the programs will be written in ladder logic visual programming language. The ladder program will consist of custom function blocks, each of which will be dedicated to a specific task. The PLC program will have the following set of main tasks and corresponding function blocks:

- Reacting to emergency signals
- Receiving positioning data from the PC
- Reading the operator confirmation signals
- Sending positioning commands to the contacts positioning motors
- Positioning the reactor by controlling the conveyor drive
- Controlling the pneumatic cylinders
- Controlling the multiplexer relays according to commands from the PC
- Coordinating the sequence of above tasks (task pointer control)

Practical development of the PLC program has not started at the time of writing this thesis and therefore its structure will not be discussed in further detail.

5.3 PC control application / HMI

There will be a PC with regular user interface devices (display, mouse and keyboard) embedded in the testing station system. The PC will exchange data between the company database, the operator and the PLC, and will allow configuring of the machine. The control application will be written in C# language in Microsoft Visual Studio [30]. The PC application will have the following main purposes and tasks:

- Receiving information from the operator about the testing tasks
- Reading, configuring and saving of reactor type information to and from the corresponding data tables in the company database
- Sending positioning commands to the PLC
- Controlling and reading measurement data from the testing equipment
- Writing measurement data to the corresponding data table in the company database
- Displaying information about the status of the station
- Generating and logging operation and status messages of the station

The PC application will use the main program functions presented in Table 18. The functions will be specifically written for this application. For the convenience of programming, debugging and developing the system, there will be custom classes defined for reactor configurations, test results and log entries. Each created class instance (object) will hold a set of variables about a specific configuration, test result or log entry, and will allow convenient storage and manipulation of these data sets. The ReactorConfigurator class will also include functions for modifying its individual properties. The ReactorConfiguration and TestResult classes will have the properties and variables presented in Table 19.

Table 18. PC application main function list

Function name	Parameters	Return value
GetConfiguration	Item ID	ReactorConfiguration class instance
SaveConfiguration	ReactorConfiguration class instance	True / false (Saved / failed to save)
SaveResult	TestResult class instance	
WriteDbLog	LogEntry class instance	

Table 19. Custom object class properties

ReactorConfiguration class	TestResult class
• Item ID • Nominal LCR meter inductance reading • Surge voltage test parameters • Conveyor positioning coordinate • Contacts positioning coordinates (bus bar spacing) • Custom notes, messages and flags	• Item ID • Work number • Reactor sequence / serial number • Measured inductance • Surge test result and data • Operator name • Date and time

The station's PC will have an Ethernet connection to the company domain network. A link to the company database will be established using a suitable C# ODBC (*Open Database Connectivity*) [31] interface library. Once a connection is established, information from data tables can be read and written using standard SQL queries. A custom interface class will be written that will translate data table rows to custom class instances described further in this section and vice versa. For the station, there will be three dedicated data tables and for security, the domain user created for the station will have access to only those specific data tables. The three data tables will store the following information:

1. Reactor type configurations
2. Reactor measurement results
3. High priority log info entries and error messages

The PC will also serve as the main HMI (*Human-Machine Interface*) of the testing station. It will run a Windows operating system in kiosk-mode: instead of the Windows Explorer, the custom control application will be loaded at the windows start-up. Windows Forms GUI (*graphical user interface*) libraries will be used to build a visual interface for the control program. The GUI will be used to provide the following functionality for the operator:

- Searching for open works in the ERP (*Enterprise Resources Planning*) system
- Search and load testing configurations by reactor type
- Create, modify and save testing configurations
- Start, pause and stop the currently loaded testing operation
- Observe the status of the station and its components
- Access and browse the station log
- Send messages to the development and maintenance e-mails

Practical development of the PC control application has not started at the time of writing this thesis and is still in the conceptual phase.

SUMMARY

In this master's thesis, the design process of a semi-automated filter reactor testing station in Trafotek AS was described. The devised design uses linear actuators in cooperation with a motorized conveyor to automatically align electrical contacts with the bus bars of the reactors to be tested. Each reactor which is loaded onto the conveyor is positioned and electrical connection is made with its bus bars. Two electrical tests are then automatically conducted, their results displayed to the station operator and saved to the company data base.

First, the device concept is presented and explained. The novelty of the design is shown through the introduction of current testing methods and similar commercially available options. The profitability of the device is displayed using time consumption measurements and estimations for the current and planned testing method.

The positioning system concept was then dissected, positioning accuracy requirements were set according to the dimensions and assembly tolerances of the main reactor types planned to be tested. The three main parts of the positioning system – the horizontal and vertical linear actuators and the conveyor were selected by comparing different construction options and suitable motors were selected for the three parts based on the loads to be moved and operation speed requirements. A suitable pneumatic cylinder was selected for the electrical contact manipulator and the necessary compressed air system pressure was calculated.

The devised work flow of the testing station includes manual work operations for loading and unloading the reactors to and from the conveyor. As the operations are found to play an important role in the overall efficiency of the machine, the loading and unloading operations are analysed, critical factors of the operation were found. A practical test is described, which had been conducted during the design for lifting operation duration estimation. Finally, a view of the CAD model which has been developed is presented.

As the station is designed for testing heavy, over 400 kg reactors using high voltages, the safety considerations of the machine were researched and analysed in detail. Related safety legislation had been researched and the safety requirements of the applicable regulations were introduced. Risk analysis of the station was conducted and appropriate measures set to reduce the risks. Mechanical safety devices to be used were introduced, several design options for a tipping guard were provided. A practical concept verification test which has been conducted is described and its results provided. Required electrical sensors and devices for control and safety systems were listed and their purposes and operation modes explained. The safety legislation sets, among others, requirements for accompanying documentation of a machine. The requirements are presented for operation- and maintenance instruction manuals.

Relevant theory about the planned electrical tests is summarised and the test equipment to be used is described. The concept of a signal multiplexer used for high voltage test signal switching, is described. Measurement result processing and accuracy topics are also shortly covered.

An overview is provided of the system control concept and its structure. The selection of a PLC from two options is described and justified and finally, the PLC program and the PC application general structures are some programming methods are introduced.

As the design project is a work in progress in Trafotek AS at the time of writing the thesis, many of the topics discussed in this paper are presented as only general concepts. This relates mainly to the electrical testing system and the system control parts of the thesis.

The design process of the testing station has provided valuable experience and information about the process of machine design, electric drive options for linear actuators, safety legislation regarding machinery and electrical testing of industrial reactors.

KOKKUVÕTE

Käesolevas magistritöös kirjeldati poolautomaatse filtrireaktorite testseadme projekteerimist firmas Trafotek AS. Kavandatud disainis kasutatakse lineaarajameid ning motoriseeritud konveierit reaktorite automaatseks paigutamiseks seadme testialas ning elektriliste kontaktide joondamiseks reaktori voolulattidega selliselt, et oleks võimalik eri tüüpi reaktoreid lülitada testseadmete vooluringi. Seadmega ühendus loodud, teostatakse reaktoriga automaatselt kaks elektrilist testi, testi tulemus kuvatakse seadme ekraanil ning salvestatakse ka firma andmebaasi.

Projekti kirjeldust alustatakse testseadme tööpõhimõtte seletusega. Disaini uudsust selgitatakse selle võrdlusega hetkel kasutusel oleva manuaalsema testimismeetodi ning turul saadaval oleva lahendusega. Lahenduse tasuvus tõestatakse manuaalse ning planeeritava automatiseeritud meetodi mõõdetud ning hinnatud ajakulude võrdluse põhjal.

Järgnevalt selgitati reaktorite paigutussüsteemi põhimõtet, määrati paigutustäpsuse nõuded vastavalt testimiseks planeeritavate põhi-reaktoritüüpide mõõtmetele ning koostetolerantsidele. Tehti valik paigutussüsteemi põhiosadele: konveierile, horisontaalsele ning vertikaalsele elektriliste kontaktide lineaarajamile. Valikud tehti mitme võimaliku variandi võrdlemisel ning sobivaima lahenduse põhjendamisel. Kõigile kolmele nimetatud osale tehti ka valik mootorile, võttes arvesse liikuvate osade masse ning nõudeid masina tööoperatsioonide kiirustele. Veel tehti valik elektriliste kontaktide manipulaatori pneumosilindrile ning vastavalt paigutussüsteemi juhikute tugevusele ning pneumosilindri mõõtmetele valiti sobilik pneumosüsteemi töörõhk.

Testseadme tööoperatsioonide hulka kuuluvad ka manuaalsed tööetapid, milleks on reaktorite konveierile ning sellelt maha laadimine. Kuna leitakse, et nende tööetappide kiirusel on oluline roll seadme üldisele efektiivsusele, analüüsitakse antud operatsioone põhjalikult ning leitakse nende kriitilised kohad. Kirjeldadakse ka praktilist testi, mis on läbi viidud, hindamaks laadimise ning mahalaadimise operatsioonide ajakulu. Töö paigutusseadmete osa võetakse kokku illustratsiooniga testseadme osalisest CAD-mudelist, millel illustreeritakse osas valitud komponente ning neist moodustatavat konstruktsiooni.

Kuna seade disainitakse raskete, üle 400 kg kaaluvate reaktorite testimiseks kõrgete pingete juures, pöörati suurt tähelepanu seadme ohutusele. Uuriti seadusandlust, mille alla projekteeritav seade kuuluda võib ning toodi välja seonduvate regulatsioonide ohutusnõuded. Seadme kontseptsioonile viidi läbi ohutusanalüüs, mille käigus loetleti olulisemad seadme omapärast tulenevad riskid ning määrati abinõud nende riskide piiramiseks. Selgitati vajalikke mehaanilisi ohutus-seadmeid ja konstruktsioone; pakuti välja mitu varianti reaktori ümberkukkumis-kaitse mehhanismile. Kirjeldatakse praktilist testi, mis oli läbi viidud ühe sellise mehhanismi tööpõhimõtete kinnitamiseks. Lisaks nimetati elektrilised andurid mis on vajalikud juhtsüsteemi tarbeks ning ohutuse tagamiseks. Loetleti andurid, nende eesmärgid seadmes ning tööpõhimõtted. Ohutuse alased regulatsioonid määravad muu hulgas ka nõuded seadme dokumentatioonile, seal hulgas juhenditele. Ohutuse osa lõpuks esitatakse regulatsionidele tuginedes põhilised teemad ning punktid, mille peaksid seadme kasutus- ja hooldusjuhendid katma.

Elektriliste testide osas esitatakse ülevaatlikult planeeritavate testide iseärasused ning teoreetilised alused. Kirjeldatakse testisignaali multiplekserit (lülitusseadet), nõudeid sellele ning esitatakse spetsiaalselt sellele rakendusele disainitava multiplekseri esialgne osaline disain. Antakse ka lühike ülevaade planeeritavast mõõtetulemuste töötlusest ning elektriliste testide mõõtetäpsusest.

Magistritöö viimases osas antakse lühiülevaade seadme juhtsüsteemi kavandatavast ülesehitusest, kirjeldatakse PLC (programmeeritava loogikakontrolleri) valikut Siemensi ning Festo variantide vahel, PLC programmi ning Windows operatsioonisüsteemile loodavat juhtprogrammi, mis toimiks lülina seadme ning firma andmebaasi vahel ning samaaegselt ka seadme kasutajaliidesena.

Kuna seadme projekteerimine käesoleva magistritöö kirjutamise ajal on veel käimas, on mitmed töös kirjeldatavad teemad kaetud ainult osaliselt või kirjeldadakse vaid kavandatavaid lahendusi. Põhilised osad, mille kohta ei ole kirjutamise ajal veel projekteeritud konkreetseid lahendusi, on elektriliste testide süsteem ning juhtsüsteem kaasneva tarkvaraga.

Seadme projekteerimisel on saadud väärtuslikke kogemusi ning teadmisi masinaehituse ning tööstuslike reaktorite elektriliste testide kohta, samuti lineaarajamite variantide ning ohutusalase seadusandluse ning standardite kohta.

REFERENCES

[1] Trafotek products [WWW] http://www.trafotek.fi/products/filters/ (19.05.2016)

[2] Solfas website [WWW] http://www.solfas.de/en/home.html (19.05.2016)

[3] Solfas IND1000 choke test system [WWW] http://www.solfas.de/fileadmin/user_upload/Produktblaetter/IND/IND1000_PB_EN_V11.pdf (19.05.2016)

[4] Mitchel, P. Tool and Manufacturing Engineers Handbook: Material and Part Handling in Manufacturing. Fourth edition. Dearborn, Michigan: Society of Manufacturing Engineers, 1998

[5] Ullman, D.G The Mechanical Design Process. Second edition. McGraw-Hill Education, 2009

[6] Fastrax conveyor roller brochure [WWW] http://www.conveyorrollers.co.uk/files/downloads/fastrax-conveyor-roller-brochure.pdf (19.05.2016)

[7] Oriental Motors motor sizing guide [WWW] http://www.orientalmotor.com/support/motor-sizing.html (19.05.2016)

[8] MiniTec Catalogue [WWW] http://www.minitec.de/en/index.php?id=193102 (19.05.2016)

[9] Festo ELGG specification [WWW] https://www.festo.com/cat/et_ee/data/doc_ENGB/PDF/EN/ELGG_EN.PDF (19.05.2016)

[10] Festo online catalogue [WWW] https://www.festo.com/cat/et_ee/products (19.05.2016)

[11] Festo PositioningDrives software [WWW] https://www.festo.com/cms/et_ee/50554.htm (19.05.2016)

[12] Festo ELGR specification [WWW] https://www.festo.com/cat/et_ee/data/doc_ENGB/PDF/EN/ELGR_EN.PDF (19.05.2016)

[13] Festo EMMS-AS Servo motors [WWW]
https://www.festo.com/cat/et_ee/data/doc_ENGB/PDF/EN/EMMS-AS_EN.PDF (19.05.2016)

[14] Festo EMMS-ST stepper motors [WWW]
https://www.festo.com/cat/et_ee/data/doc_ENGB/PDF/EN/EMMS-ST_EN.PDF (19.05.2016)

[15] Advanced Micro Controls Inc.: Stepper vs Servo [WWW]
http://www.amci.com/tutorials/tutorials-stepper-vs-servo.asp (19.05.2016)

[16] Festo CMMO-ST motor controller [WWW]
https://www.festo.com/cat/et_ee/data/doc_ENGB/PDF/EN/CMMO-ST_EN.PDF (19.05.2016)

[17] Festo DSNU round pneumatic cylinders [WWW]
https://www.festo.com/cat/et_ee/data/doc_ENGB/PDF/EN/DSNU_EN.PDF (19.05.2016)

[18] Directive 2014/35/EU of the European Parliament and of the Council. (2014). 2014/35/EU. Strasbourg: European Council and the Parliament

[19] Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast). (2006). 2006/42/EC. Strasbourg: European Council and the Parliament

[20] Safety requirements for electrical equipment for measurement, control, and laboratory use. (2010). Part 1. General requirements. IEC 61010-1:2010. International Electrotechnical Commission

[21] Wilson, John. Current State of Surge Testing Induction Machines [WWW]
http://www.existest.com/appnotes/Baker/Teoria%20Surge.pdf (19.05.2016)

[22] Wayne Kerr 4300 series LCR meter [WWW]
http://www.waynekerrtest.com/specification/4300%20Series%20Specification.pdf (19.05.2016)

[23] PDAcademy [WWW] http://www.partial-discharge-academy.com/pd-fault-detection (19.05.2016)

[24] Paoletti, G., Golubev, A. Partial Discharge Theory and Technologies related to Medium Voltage Electrical Equipment [WWW] http://es.eaton.com/InsulGardSalesTool/Documentation/IEEE-IAS%20PD-Machines-PaolettiGolubev.pdf (19.05.2016)

[25] Solfas STA900 specification [WWW] http://www.solfas.de/fileadmin/_migrated/content_uploads/STA900_Datasheet_EN_02.pdf (19.05.2016)

[26] Pickering 3kV multiplexer [WWW] http://www.pickeringtest.com/en-ee/product/8-channel-multiplexer-3kv-isolation (19.05.2016)

[27] Kiyoshi Suzuki, Akiu Yamazaki and Katsumi Yokoi. Non-Linearity Evaluation Method of Four-Terminal-Pair (4TP) LCR Meter [WWW] http://www.ncsli.org/i/c/TransactionLib/C01_6A2.pdf (19.05.2016)

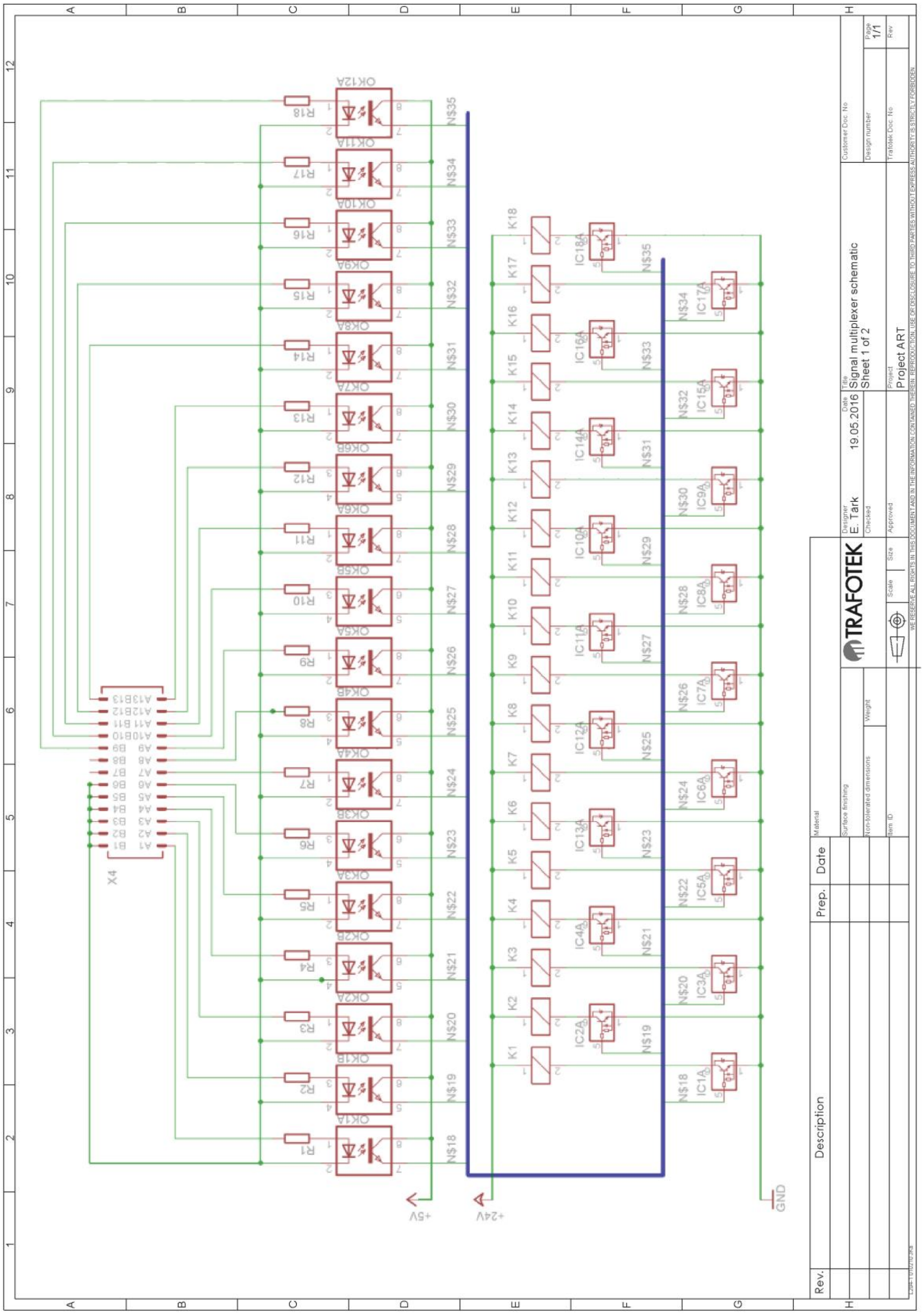
[28] Festo CPX modular terminal [WWW] https://www.festo.com/net/SupportPortal/Files/13686/PSIplus_CPX_en_V15_135154_L.pdf (19.05.2016)

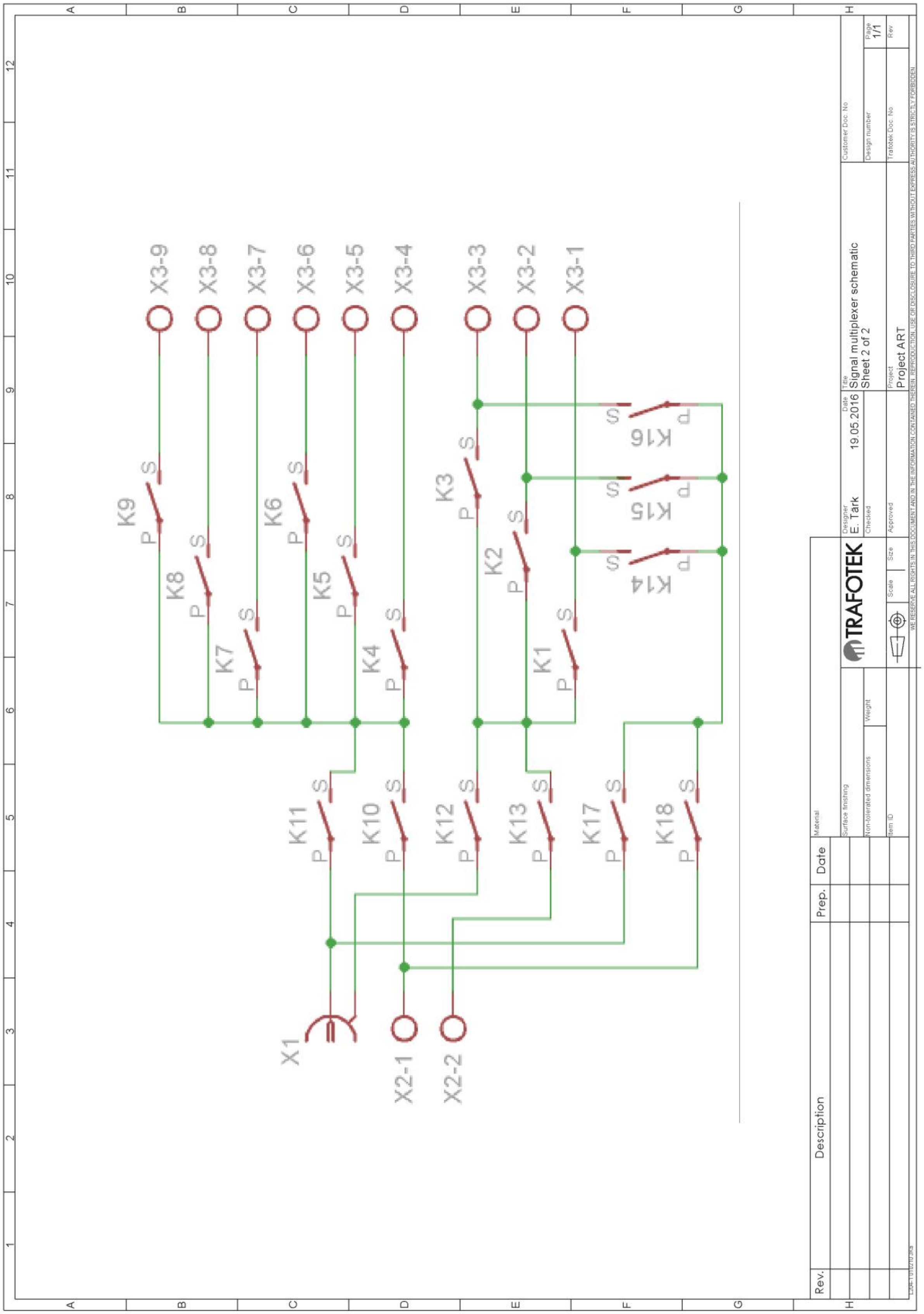
[29] CoDeSys [WWW] https://www.codesys.com/ (19.05.2016)

[30] Microsoft Visual Studio [WWW] https://www.visualstudio.com/ (19.05.2016)

[31] OBDC documentation [WWW] https://msdn.microsoft.com/en-us/library/ms710252(v=vs.85).aspx (19.05.2016)

APPENDIX 1: Signal multiplexer Schematic

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Designer
E. Tark
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19.05.2016
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Signal multiplexer schematic
Sheet 2 of 2
Project
Project ART
Rev.
Description
Prep.
Date