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Konstantin Raimla 122208IASM

# INDUSTRIAL WOOD-CHIP BOILER AUTOMATION AND COMBUSTION OPTIMISATION WITH SECONDARY AIR PI CONTROLLER TUNING

Master thesis

Supervisors: Kristina Vassiljeva

Associate Professor,

Vitali Vansovitš

Valmet Automation

Tallinn 2015

# Author’s declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

Author: Konstantin Raimla

15.05.2015

# Abstract

This master thesis is written at the Tallinn Technical University, Faculty of Information Technology, Department of Computer Control, in cooperation with Valmet Automation OY in Tallinn.

According to contract with Rapla district heating Valmet Automation OY provides biomass boiler complete automation and controller tuning to optimize boiler work. To establish control system and optimisation thesis author reviews biomass boiler system technology, different controller tuning methods and Valmet Automation hardware, software and technical material.

All acquired technical knowledge is used to create automation logic programs and applied those to industrial computer. Trial and Error tuning method is used to find parameters to all PI controllers. Study of combustion control is performed to find out which technique to use in practise to improve steady state combustion process control.

Secondary air control loop is chosen to control oxygen concentration in the furnace. Tests with real plant are carried out and analysed. Two open loop controller tuning methods are applied and results are analysed.

Finally the overall thesis is discussed and conclusions are drawn.

This thesis is written in English and is 57 pages long, including 5 chapters, 26 figures and 10 tables.

# Annotatsioon


**Industrial wood-chip boiler automation and combustion optimisation with secondary air PI controller tuning**

Lõputöö on kirjutatud Arvutisüsteemide õppekaval, Tallinna Tehnikaülikoolis, Infotehnoloogia teaduskonnas, Automaatika instituudis koostöös Valmet Automation OY-ga.

Valmet Automation OY ja AS Eraküte Rapla osakonna vahelise lepingu kohaselt teostab Valmet Automation katlamaja automatiseerimise ja kontrollerite häälestamise. Antud ülesande täitmiseks tutvub lõputöö autor biokatla süsteemide tehnoloogiaga, kontrollerite häälestamise meetotidega ja Valmet Automation OY riistvara, tarkvara ja tehniliste materjalidega.

Omandatud teadmised rakendatakse biokatla süsteemi kontroll-loogika loomise ja tööstusarvuti seadistamise näol. Kontrollerite häälestamiseks kasutatakse katse-eksitus meetodit. Tutvutakse biokatla põlemisprotsessi tehnoloogiaga, eesmärgiga leida sobiv metoodika põlemisprotsessi stabiilse režiimi hoidmiseks.

Hapniku konsentratsiooni hoidmiseks suitsugaasides valitakse sekundaarõhu juhtkontuur. Töös kuvatakse reaalajas läbi viitud testid ja nende analüüs. Kahte kontrolleri häälestamise meetodit rakendatakse sekundaarõhu juhtkontuurile ja testide tulemused analüüsitakse.

Lõpetuseks on välja toodud lõputöö arutelu ja järeldused.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 57 leheküljel, 5 peatükki, 26 joonist, 10 tabelit.

# Table of abbreviations and terms

| | |
|---|---|
| SOx | Sulphur Oxide |
| PI | Proportional-Integral |
| PID | Proportional-Integral-Derivative |
| ACN | Application and Control Node |
| ACN MR | ACN Mounted in Rail |
| CPU | Central Processing Unit |
| I/O | Input/Output |
| W x H x D | Width x Height x Depth |
| PSU | Power Supply Unit |
| BCU | Bus Controller Unit |
| CAD | Computer-Aided Design |
| NaOH | Sodium hydroxide |
| CHR | Chien-Hrones-Reswick |
| Z-N | Ziegler-Nichols |

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# Acknowledgments

First and foremost I wish to thank my supervisor, associate professor Kristina Vassiljeva. She has been supportive since the first day I began my studies at Tallinn University of Technology. Kristina has guided me through professional and thesis development. I appreciate her knowledge and skills in automation area.

I would like to thank Vitali Vansovitš for the assistance he provided with Biomass boiler project. His thrive to understand systems in depth powers everyone around him to ask one of the most important question – why it does/doesn't work?

I would also like to thank my parents, two sisters, and a brother. They were always supporting me and encouraging me with their best wishes.

Finally, I would like to thank IT Academic scholarship for providing me support during the studies.

# 1. Introduction

## 1.1. Background

Rapla district heating system in Estonia is manufacturing and selling heat to 110 households. For manufacturing they are using gas as fuel. The natural gas is transported to Estonia from Russia. Due to fact that gas prices have increased over the last couple of years, producer is forced to consider the use of local renewable resources. One possibility is wood chips. There are many reasons why to use biomass fuel as wood chips:

- Fuel comes from a renewable resource base,
- Biomass fuels can be expected to increase in price more slowly than competing fuels,
- Biomass has a negligible sulphur content, so its combustion does not contribute to the atmospheric build-up of oxides of sulphur (SOx),
- Biomass systems are relatively easy to convert to other fuels and so offer great flexibility for an uncertain energy future [1].

Rapla district heating system is under development to update its current system to biomass fire-tube boiler technology. All gas boilers will perform as a redundant heating system in addition to biomass boiler.

## 1.2. Objectives

The goal of this master thesis is to design industrial computer applications and implement them in a control system of biomass boiler. To achieve that goal it is needed to get knowledgeable about boiler technology, different process interlockings and provided technical documentation. Second goal is to implement and improve software based PI control loops. This work will cover on different PI control loop optimization techniques.

## 1.3. Scope

Rapla district heating system objective is to be able running only with biomass boiler system. Gas fuel boilers act as a redundant system and are not in the scope of this thesis. The focus is to create automation logic applications, develop and improve PI control loops for biomass boiler system. In order to simplify control logic creation every major part of boiler system is addressed singularly and then the logical connection between control areas are connected. Major parts of boiler system are:

- Storage yard, fuel handling and feeding,
- Flue gasses handling part including scrubber,
- Boiler including water pipelines,
- Ash disposal,
- Furnace.

Every major part of the system is operated with same control system hardware. Many different components, e.g. heat exchangers, hydro stations, conveyors, pumps and other auxiliary equipment, motors and movement sensors form whole boiler system. Author focuses on materials which are provided for him to obtain clear understanding of the automation concept.

Available documentation and tools include:

- Input/Output table with list of all field devices,
- Control diagrams,
- Valmet Automation CAD based engineering environment and manual.

# 2. Technical background

In this chapter, the theory of biomass boiler technology and its operating principles, as well as a description of automation equipment, PID controller and its optimization techniques, are given.

## 2.1. Biomass energy system

Biomass energy system needs integration of different components in order to make the whole system run smoothly. These components are fuel storage yard, fuel handling and combustion equipment, boiler equipment, flue gas cleaning devices, ash disposal equipment and control system to keep all equipment operating optimally (See Figure 1).

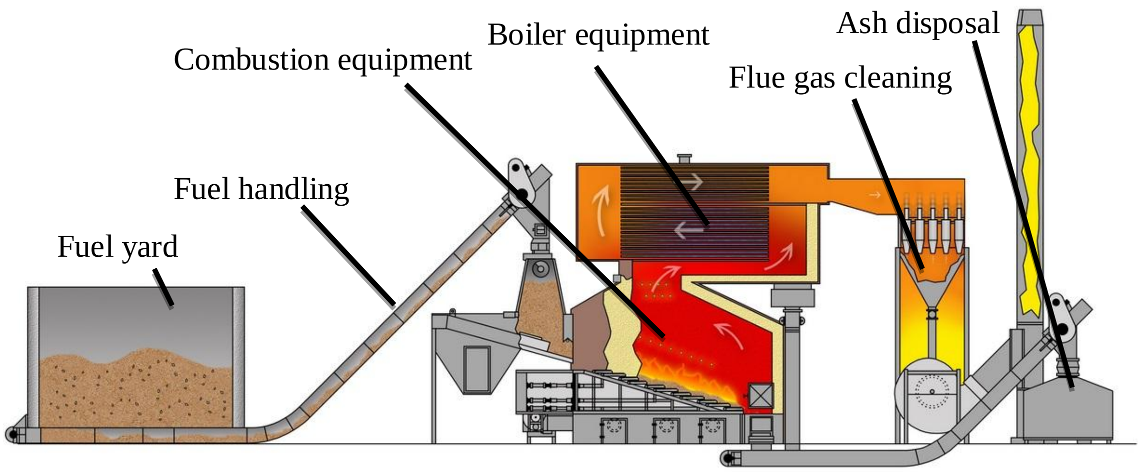


*Figure 1. Typical biomass energy system [2]*

### 2.1.1. Fuel storage yard

One common type of biomass storage is below-ground concrete bin, because of its advantages like trucks can self-unload using gravity without any other mechanical equipment [1]. Rapla fuel yard is rectangular concrete storage building with hydraulic scrapers. In one side of the building there is conveyer which is handling wood chips to mini-silo before combustion equipment. Hydraulic scrapers are pulling biomass towards conveyer chain. The main advantage of this solution is that delivery trucks can easily unload biomass onto concrete floor where scrapers transport the material. This kind of equipment does not need site personnel intervention. However in some cases where delivery trucks have unloaded biomass fuel indirectly onto the scrapers it is needed to use tractor to re-arrange biomass disposal.

### 2.1.2. Fuel handling

Stable fuel handling is crucial for maintaining complete combustion control. Rapla fuel yard is located next to boiler building in order to minimize extra energy used to get biomass fuel to combustion chamber. Fuel transportation is done by ladder-type chain conveyor. The conveyor deposits fuel into mini-silo which is connected to combustion chamber. One aspect of reliable combustion control is control over fuel feeding rate. Fuel feeding rate is controlled by hydraulic system which is pushing wood-chips from mini-silo to combustion chamber.

### 2.1.3. Combustion equipment

The furnace is the part of combustion appliance where burning takes place. Hydraulic system pushes automatically fuel into the furnace, air is added, and biomass fuel burns generating heat (See Figure 2).

Grates are located at the bottom of the furnace. There are various grate technologies available. One technology for combustion is burning of biomass on moving grates. Grate-fired boilers can almost burn any solid resources and fuels with high moisture content, therefore suitable for burning wood chips. Wood chips are transported along a moving grate and fuel is combusted before reaching to end. Intense combustion zone is created by secondary air above the burning bed. Primary air is supplied from below moving grate. Gathered ash is transported to end of the grate and then removed. Taking into account wood chips moisture content, cooling can be realized by water or by primary air. Main disadvantages of a grate-firing technique are poorer plant economy and increased fly ash. Nevertheless grate-firing technique is quite simple and therefore highly attractive [3].

Well-design grate control guarantees a homogeneous distribution of the fuel and primary air supply over the various grate areas. Inhomogeneous air supply may lead to slagging, higher fly-ash amounts and causes increase the excess oxygen needed for a complete combustion, resulting boiler heat losses [4].

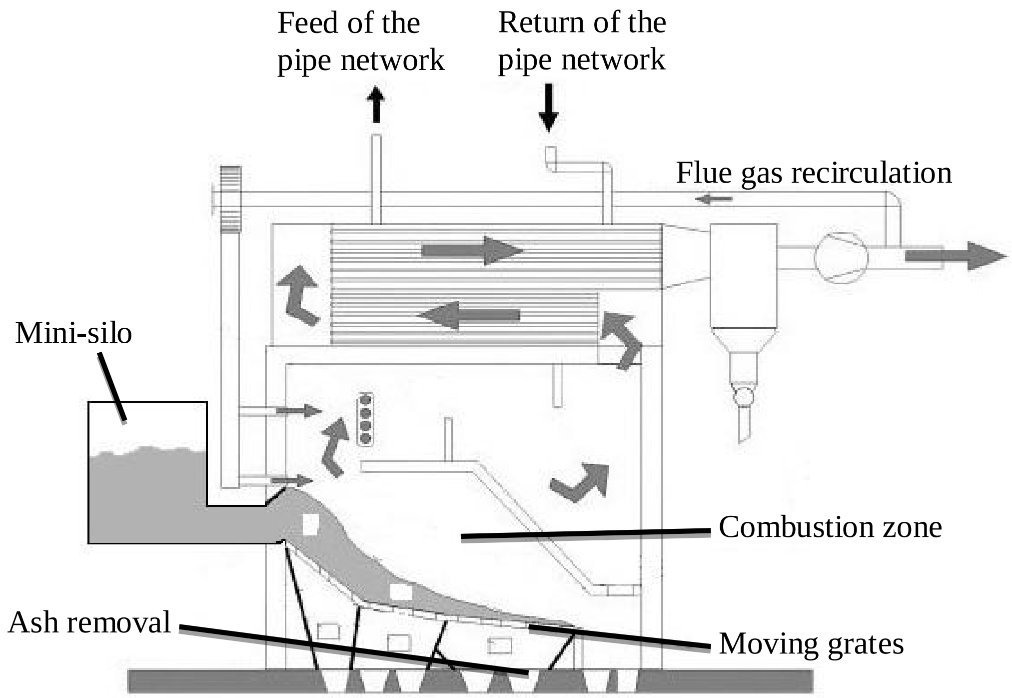


*Figure 2. Combustion equipment [4]*

### 2.1.4. Flue gas cleaning and ash disposal

Scrubbers are used in industrial process-air applications to eliminate potentially harmful dust and pollutants. Simplest type of wet scrubber for flue gas emissions control is spray tower (See Figure 3). The scrubber creates large liquid-to-gas areas so that flue gas may be absorbed by the scrubbing liquid [5]. Water is sprayed with high pressure through nozzles into the air flow. Harmful dust and pollutants are absorbed by water droplets created by nozzles. Water droplets are collected back to the water reservoir. Evaporated water is replaced by fresh water and chemicals. Dust and pollution products from the process are removed periodically through the drain.

Flue gas holds energy what is absorbed by water droplets. In order to increase district heating capacity the water, which is heated up and collected in water reservoir, is pumped through heat exchanger [6].

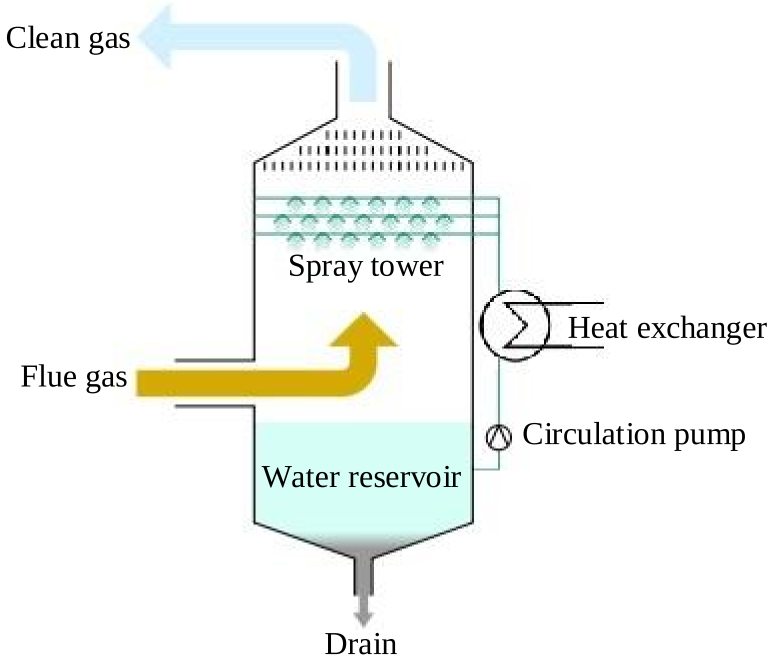


*Figure 3. Spray tower scrubber [7]*

Ash accumulates inside combustion chamber and heat exchanger. Ash which is accumulated below and at the end of the grate is removed by automatic screw motors. Screw motor collects the ash and transports it outside the combustion chamber onto ash conveyor. Conveyor transports the ash outside boiler building into lift-able container. Lift-able container can be changed by trucks when needed.

Flue gases contain fine ash which accumulates regularly on the heat exchangers. There are different solutions, but one used at Rapla site is pneumatic cleaning shoot blower. This technology reduces frequency of manual cleaning.

### 2.1.5. Control system

Control system has many input signals from sensors, motors, pumps, valves and hydraulic units. All signals are collected and manipulated according to control logic in order to achieve accurate combustion control. Typical control scenario takes in account load needed and accordingly increases or decreases rates at which fuel and air are fed to combustion chamber. Other variable readings which can be used to build up more efficient and stable burning process control are boiler water temperature, exhaust gas oxygen content and outdoor temperature. Additional readings make control system more complex and expensive. Wrong control logic can lead to premature equipment ware-out or even safety hazards.

## 2.2. Automation equipment

### 2.2.1. ACN MR process controller

Application and Control Node Mounted in Rail (ACN MR) is an industrial computer. Industrial computers are highly reliable and robust programmable electronic devices that obtain data, execute predefined instructions, perform mathematical and logical calculations, and output results. Software in Central Processing Unit (CPU) executes instructions and controls the operations of hardware components. Computer can have one or more interfaces to transmit and receive data from predefined locations. Industrial computers differ from office or home computers by their functions [8]. ACN MR brings out those differences by its design.

ACN MR has been specially developed to run industrial applications and designed to perform massive data-processing, withstand various industrial environments, simple Input/Output interface and with various device connecting possibilities. Table 1 presents an overview of ACN MR technical specification.

*Table 1. ACN MR technical specification*

| Property | Setting |
|---|---|
| Dimensions [W x H x D] | 60 x 125 x 95 mm |
| Weight | 1100 g |
| Protection | IP20 |
| RAM memory | 512 MB |
| Processor | Intel Atom 1.1 GHz |
| SD card | 2 GB |
| Ethernet ports | 5 |
| USB ports | 2 |
| Operating temperature | 0 °C … +70 °C |
| Storage temperature | -20 °C … +70 °C |
| Power supply | 18…36 VDC |
| Power consumption | 10 W |
| Maximal number of I/O channels | 2000 |
| Control cycles | 20 ms...64 s, typical 400 ms, special case 5 ms |
| Operating system | Real-time operating system |

### 2.2.2. Input/Output cards

Input/Output (I/O) cards are performing communication between control system and field devices. Inputs are the signals which are received by the control system and the outputs are the signals sent to field devices. Field devices can be different sensors, motors, pumps, conveyors, valves etc.

ACN MR can have up to 32 different I/O cards in one group. Group consists of Power Supply Unit (PSU), Bus Controller Unit (BCU) and I/O cards. ACN MR acts as a BCU when I/O cards are connected directly to it. Figure 4 shows the setup of one possible group with 8 I/O cards.

To extend the number of I/O cards a parallel group can be added with additional 32 I/O cards. The new group consist of PSU, BCU and I/O cards. The BCU is connected via Ethernet directly to ACN MR. These two groups together make a pair and using this connection principle a maximum number of 256 I/O cards can be attached to one ACN.

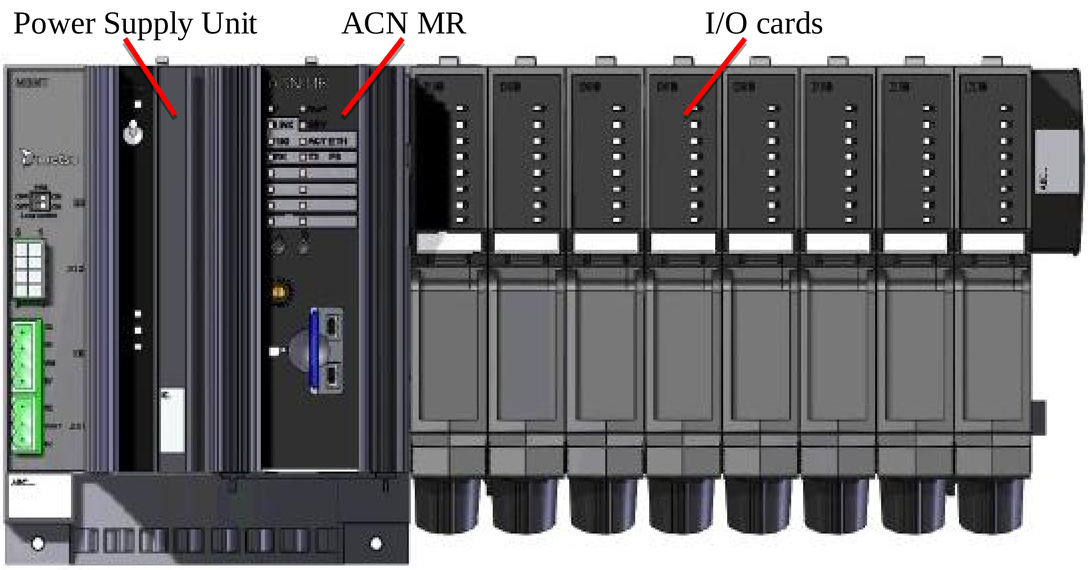


*Figure 4. ACN MR process controller with power supply and I/O cards [9]*

Table 2 presents an overview of basic I/O card types what can be used in group setup.

*Table 2. I/O card types*

| **Type** | **Description** |
|---|---|
| AI8 | 8 channel analog input card used to measure analog current and voltage signals. Measuring range 0/4...20 mA current signals and 0/2...10 V voltage signals. |
| AO4 | 4 channel analog output card used to give current and voltage signals to various actuators and analog controllers. The outputs of the card are 0/4...20 mA current signals and 0/2...10 V voltage signals. |
| DI8P | 8 channel digital input card used to read contact data, two–wire proximity switches or PNP type switches. |
| DO8P | 8 channel digital output card which includes a channel–specific current–limited voltage supply. Each channel of the unit has output which is carried out with a mechanical relay. The type of the output is a switch which is normally open. |

### 2.2.3. Engineering environment software

ACN MR runs under real-time operating system. All applications made with engineering tool are downloaded to ACN MR from engineering environment and then executed there cyclically. Engineering tools can be installed on a computer running Windows operating system. Engineering tool is called The Function Block Computer-Aided Designer (FB CAD). The tool is used for designing function block diagrams for process control loops and interface applications. Function block diagrams are saved in a common database located on the Engineering Server. At the same time, a function block diagram is a graphical document of an application, which is loaded in the runtime environment (ACN MR). This ensures that the documentation is always up-to-date.

Figure 5 presents an overview how The Function Block CAD environment looks in general, more detailed overview is presented in Appendix 1. In the centre of Figure 5 there are always logic function blocks which have their unique order number. On the left there are inputs. Inputs can be signals from the I/O cards or from other control applications. On the right there are outputs. Outputs can be signals to the I/O cards, to other applications or operator displays.

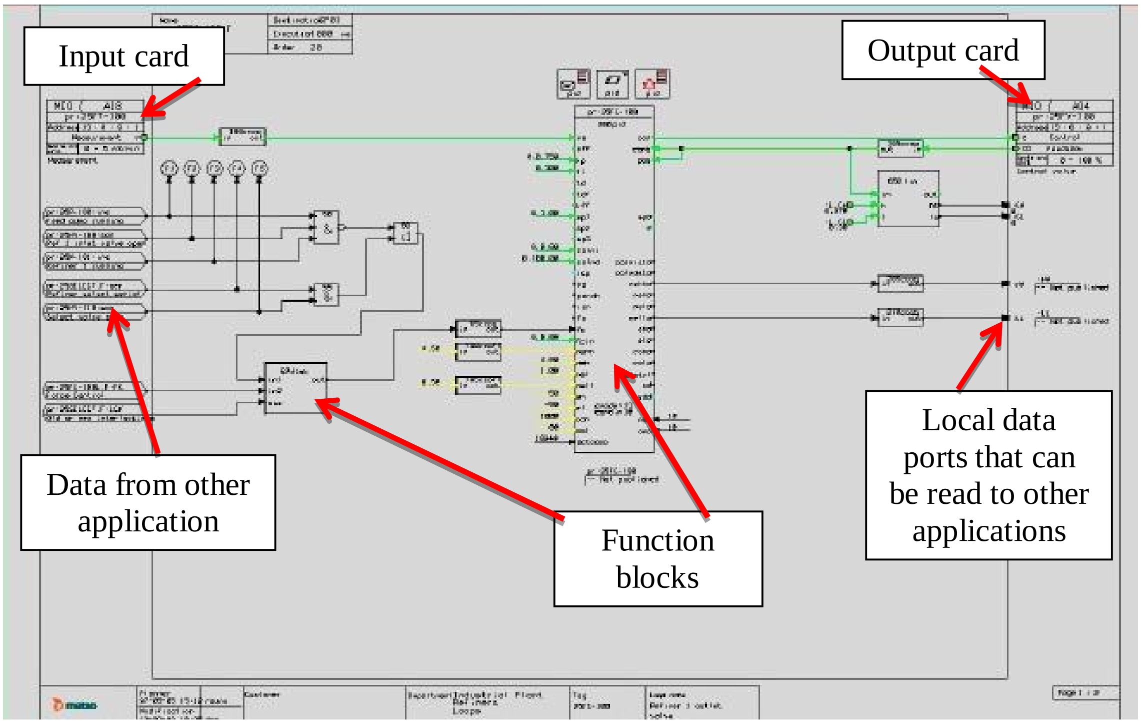


*Figure 5. The Function Block CAD [9]*

## 2.3. PID control

### 2.3.1. Brief history

Proportional-Integral-Derivative (PID) control is the most common control algorithm used in industry. PID control is often combined with logic, sequential functions, selectors, and simple function blocks to build the complicated automation systems used for today's industries. PID has evolved together with changes in technology. Nowadays it is often implemented in digital form using microprocessors rather than mechanics and pneumatics. The microprocessor has given new potentialities to PID controller like automatic tuning, gain scheduling, and continuous adaptation. Practically all PID controllers made today are implemented using microprocessors [10].

The PID structure consists of three components, the Proportional, Integral and Derivative. These components are described singularly hereafter.

### 2.3.2. Proportional component

Proportional control is the basic continuous control mode. Proportional action responses only to a change in the magnitude of the error. Equation (1) presents a proportional component expression

$$u(t) = K_\mathrm{p} e(t) = K_\mathrm{p}(r(t) - y(t)) \tag{1}$$

where $K_\mathrm{p}$ is the proportional gain, $r$ the reference variable, $y$ the measured process variable, $u$ is the control signal and $e$ is the control error. With pure Proportional control it is possible that steady state error will occur. Steady-state error is defined as the difference between the set point and the process variable as time goes to infinity. The error will decrease with increasing gain, but the tendency towards oscillation will also increase. Equation (2) presents steady state error as

$$e_\mathrm{ss} = \lim_{t \to \infty}(r(t) - y(t)) \tag{2}$$

where $r$ is the set point, $e_\mathrm{ss}$ the steady state error and $y$ the measured process variable. In order to solve Proportional control steady state error problem, without using excessive control gain, the integral component can be introduced.

### 2.3.3. Integral component

Integral component is proportional to the integral of the control error. Equation (3) presents it as

$$u(t) = K_\mathrm{i} \int_0^t e(\tau)\mathrm{d}\tau \qquad (3)$$

where $K_\mathrm{i}$ is the integral gain. Integral action is related to the past values of the control error. Transfer function is shown in equation (4) as follows

$$C(s) = \frac{K_\mathrm{i}}{s} \qquad (4)$$

Integral component is able to neutralize steady state error by finding correct set point without having to know the process static gain. It is not common to use Integral component alone. Integral control is combined with Proportional resulting PI control. The combination is favourable because it combines advantages of both types. The control signal in PI control is presented in equation (5)

$$u = K_\mathrm{p} \left( \frac{1}{T_\mathrm{i}} \int e\mathrm{d}t + e \right) \qquad (5)$$

where $T_\mathrm{i}$ is the integral time of the controller. Figure 5 illustrates PI controller configuration.

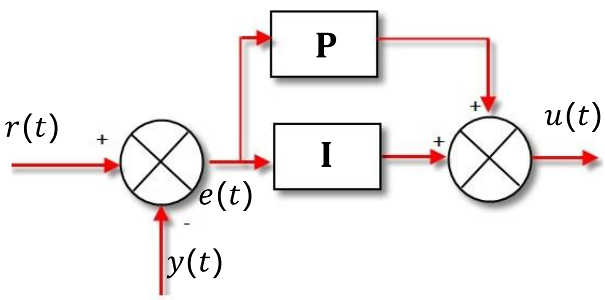


*Figure 6. PI controller block diagram [11]*

### 2.3.4. Derivative component

Both Proportional and Integral components do not attempt to predict future control errors. A Derivative (D) component has a control action based on the rate of change of the error signal. D is proportional to the change in the error and an ideal control law is expressed as

$$u(t) = K_\mathrm{d} \frac{\mathrm{d}e(t)}{\mathrm{d}t} \tag{6}$$

where $K_\mathrm{d}$ is the derivative gain.

In practice D component is usually combined with at least a Proportional component, resulting PD control [10, 12].

## 2.4. PID tuning methods

Tuning a control loop is the adjustment of its control parameters ($K_\mathrm{p}, T_\mathrm{i}, T_\mathrm{d}$) to achieve design objectives for specific control response. Main dilemma is between speed and stability of the control. Fast control action usually results poor stability and oscillations. Very stable control, on the other hand, responses poorly to set point change.

Widely spread criterion for controller tuning is to adjust the controller so that control response curve has an amplitude decay ratio of one-quarter. The decay ratio reflects the rate of decay of the sinusoidal control response [13]. In Figure 7 is presented one-quarter decay ratio control criteria.

In many cases one-quarter decay control criterion is not sufficient. Sometimes it is needed to tune the controller so that there are no overshoots or tune it in order to adjust control for constantly changing set point. Before tuning a controller it is important to specify requirements for the system under control [12].

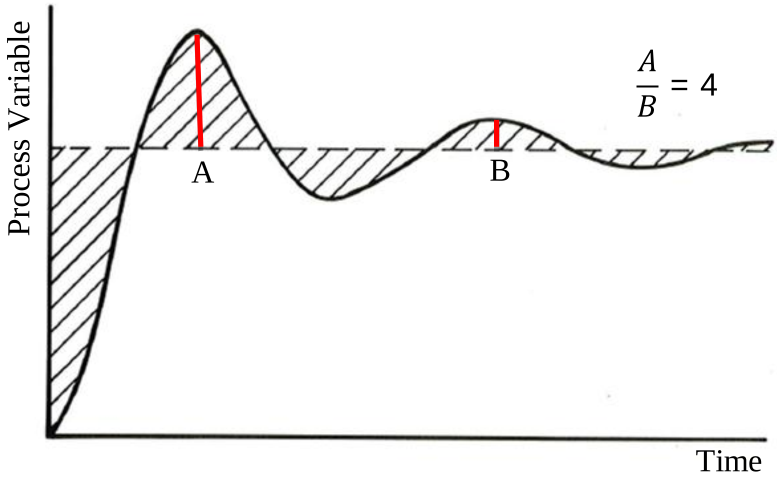


*Figure 7. One-quarter decay ratio control criteria [14]*

### 2.4.1. Trial and Error Method

Tuning a controller without systematic approach is called Trial and Error method. It is important to know how different control parameters affect the control actions. Table 3 presents effects of PID parameters on speed and stability.

*Table 3. Effects of PID parameters on speed and stability*

| | **Speed** | **Stability** |
|---|---|---|
| $K_p$ **increases** | increases | reduces |
| $T_i$ **increases** | reduces | increases |
| $T_d$ **increases** | increases | increases |

Table 3 contains an information of basic rule and do not apply to all systems, therefore there can be some exceptions. In Trial and Error method the proportional component is the main control, while keeping integral and derivative switched off [12]. After tuned proportional component to desired performance, integral and then derivative component can be tuned.

Example cases while tuning controller are following:

- Big oscillation – proportional $K_p$ should be decreased,
- Output shows over damped response – proportional $K_p$ should be increased,
- Output oscillates and output stays above set point longer than under set point for a positive set point change – integral time $T_i$ should be increased,
- Output oscillates and output stays under set point longer than above set point for a positive set point change – integral time $T_i$ should be decreased,
- Output shows high-frequency oscillation – derivative time $T_d$ should be decreased [15].

### 2.4.2. The Ziegler-Nichols Step Response Method

The step response method is an experimental open-loop tuning method. A step change in input is introduced to control signal and process response is logged for analysis. Main advantage of this method is its simplicity, but the biggest disadvantage is that it is relatively sensitive to disturbances.

After making step change in input several parameters can be measured which include: Transportation lag or dead-time $L$, the time for response to change or time constant $T$. Transportation lag is the amount of time delay between the output step-change and the first indication of process variable change. Figure 8 presents an "S-shaped" process response curve to a step change.

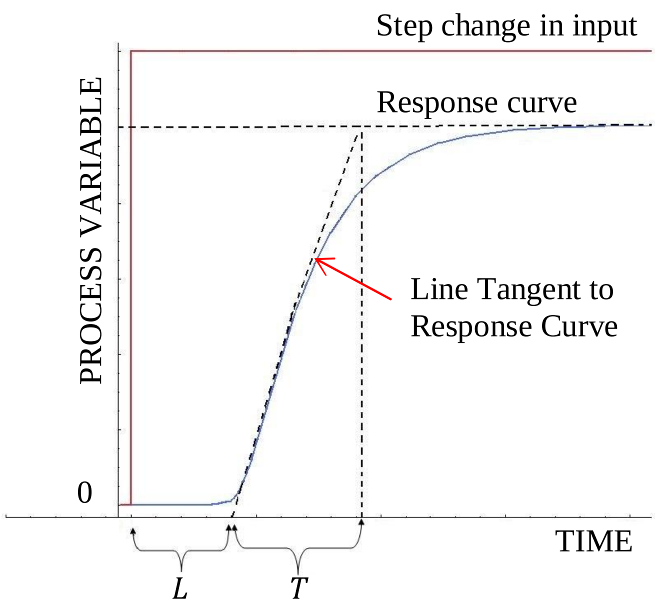


*Figure 8. Process response curve to step change [16]*

Ziegler and Nichols suggested to set the values of $K_c$, $T_i$ and $T_d$ according to the formulas shown in Table 4.

*Table 4. PID parameters according to Ziegler-Nichols step response method*

| Type of controller | $K_c$ | $T_i$ | $T_d$ |
|---|---|---|---|
| **P** | $T/L$ | $\infty$ | 0 |
| **PI** | $0.9\,T/L$ | $L/0.3$ | 0 |
| **PID** | $1.2\,T/L$ | $2L$ | $0.5L$ |

### 2.4.3. The Ziegler-Nichols Frequency Response Method

The Ziegler-Nichols frequency response method is a closed-loop tuning method. Method uses system response at the ultimate frequency. The controller is connected as a proportional controller, while integral and derivative components disconnected. Controller ultimate gain $K_u$ is adjusted so that constant oscillation is in present.

Figure 9 presents constant amplitude oscillation where $P_\mathrm{u}$ is the ultimate period and $A$ is the amplitude.

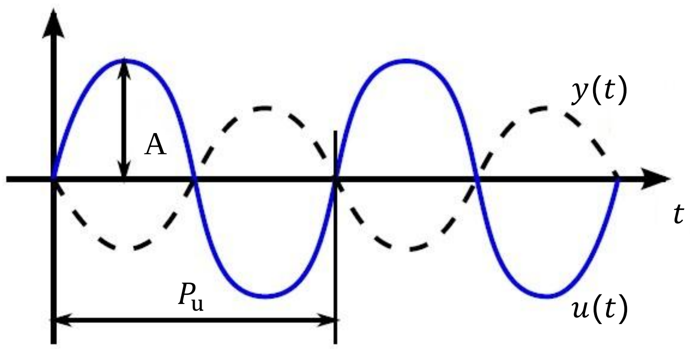


*Figure 9. Constant amplitude oscillation [15]*

The advantages of this method are that it is very easy to apply, only proportional component is needed. The disadvantage is that constant oscillation means unstable operation. This holds a potential to cause trouble in a process and therefore it is not used in this work [12, 17].

### 2.4.4. The Cohen-Coon Method

The Cohen-Coon Method is similar to the Ziegler-Nichols step response method. The difference to Ziegler-Nichols method comes with the fact that Cohen-Coon method is more demanding in calculations [18]. This method is not applied in the thesis, because Ziegler-Nichols method was chosen and additional tests were excluded.

### 2.4.5. The Tyreus-Luyben Method

This method is similar to Ziegler-Nichols frequency method. The difference is that it gives higher closed-loop damping coefficient and performance is sacrificed for robustness [12]. Method holds a potential to cause trouble in a process and therefore it is not used in this work [12, 17].

### 2.4.6. Chien-Hrones-Reswick Tuning Algorithm

The Chien-Hrones-Reswick (CHR) tuning method focuses on set point response or disturbance response, developed from the base of Ziegler-Nichols´s method [19]. This method provides formulas for 0% and 20% overshoot for set point response or disturbance response shown in Table 5 and Table 6 accordingly. Chien-Hrones-Reswick tuning rules give better dumping [20].

*Table 5. CHR tuning for set point regulation*

| Type of controller | With 0% overshoot | | | With 20% overshoot | | |
|---|---|---|---|---|---|---|
| | $K_c$ | $T_i$ | $T_d$ | $K$ | $T_i$ | $T_d$ |
| **P** | $0.3\frac{T}{K_p L}$ | – | – | $0.7\frac{T}{K_p L}$ | – | – |
| **PI** | $0.35\frac{T}{K_p L}$ | $1.2T$ | – | $0.6\frac{T}{K_p L}$ | $T$ | – |
| **PID** | $0.6\frac{T}{K_p L}$ | $T$ | $0.5L$ | $0.95\frac{T}{K_p L}$ | $1.4T$ | $0.47L$ |

*Table 6. CHR tuning for disturbance rejection*

| Type of controller | With 0% overshoot | | | With 20% overshoot | | |
|---|---|---|---|---|---|---|
| | $K_c$ | $T_i$ | $T_d$ | $K$ | $T_i$ | $T_d$ |
| **P** | $0.3\frac{T}{K_p L}$ | – | – | $0.7\frac{T}{K_p L}$ | – | – |
| **PI** | $0.6\frac{T}{K_p L}$ | $4L$ | – | $0.7\frac{T}{K_p L}$ | $2.3L$ | – |
| **PID** | $0.95\frac{T}{K_p L}$ | $2.4L$ | $0.42L$ | $1.2\frac{T}{K_p L}$ | $2L$ | $0.42L$ |

# 3. Implementation of control applications

Author’s contribution to the boiler house project was to develop all control logics except boilers *Main Controller*. Boiler *Main Controller* controls biomass boiler and gas boilers together. Applications were created based on control diagrams which were provided to author by Valmet Automation OY. Control programs were tested in simulation environment before applying them to real plant. I/O acceptance test was carried out on the field and then real plant test and modifications were made. In this chapter, the Engineering Environment functional blocks overviews, as well as a description of Trail and Error tuning procedure and applied control diagrams are given.

## 3.1. Functional blocks

The Function Block CAD environment contains wide range of predefined function blocks to be used to build up applications according to control diagrams. Main used function blocks are described hereafter.

### 3.1.1. Motor function block

The motor control function block drives a binary output ON or OFF; the effect of the output on the controlled device is read back as feedback in the ON/OFF format also. The feedback data gives the status of the controlled device, and it shows whether the control takes effect within the specified response time. Symbolic representation is shown in Figure 10. Explanations of abbreviations in Figure 10 are the following:

ins – Motor status, which is generally brought in directly from the field,
m – Manual control mode,
a – Automatic control mode,
ma – Manual/auto selection,
foff – Forced control OFF,
e1, e2 – External data (e.g. safety switch) which forces the motor to stop,
cur – Motor current reading for load calculation,
on – motor control output to the field to drive the motor ON/OFF status,
onb – ON control read back.

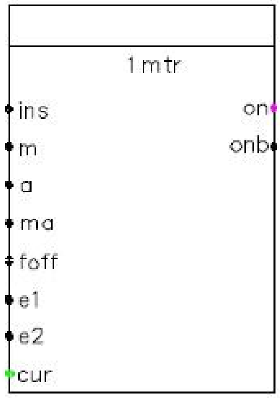


*Figure 10. Simple motor control function block [9]*

### 3.1.2. PID function block

The PID controller function block generates its control output (con) on the basis of active set point (spa) and measured value (me). The function of PID is to keep the measured value equal to the set point regardless of any disturbances. In principle, the output can be calculated from the following formula shown in Equation (7)

$$con = K_\mathrm{p} * \left[(spa - me) + \frac{T_\mathrm{s}}{T_\mathrm{i}} \int (spa - me)\,\mathrm{d}t + T_\mathrm{d} \frac{\mathrm{d}me}{\mathrm{d}t}\right] \tag{7}$$

where $K_\mathrm{p}$ is proportional tuning term, $spa$ as active set point, $me$ as measured value, $T_\mathrm{s}$ as execution interval, $T_\mathrm{i}$ as integral tuning term and $T_\mathrm{d}$ as derivative tuning term. Simple PID function block is presented in Figure 11.

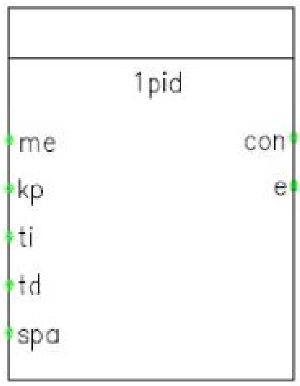


*Figure 11. Basic PID function block [9]*

### 3.1.3. Pulse function block

Pulse function block is used to generate pulses whose duration can be configured. In initialization cycle the function block will apply to its output (pout) a value corresponding to the starting status (ssta). In the cycles following the initialization the output will remain at the status (ssta), unless a change corresponding to configuration parameter uds (rising or falling edge) has occurred in the control input (cntrl). If a change corresponding to uds occurs in the control input (cntrl), output (pout) will change to the opposite state of starting status (ssta). The pulse lasts for the time defined by the pulse input (pl), divided into the number of execution cycles. The time elapsed from the start of the pulse can be read from the ppp output. Symbolic representation is shown in Figure 12.

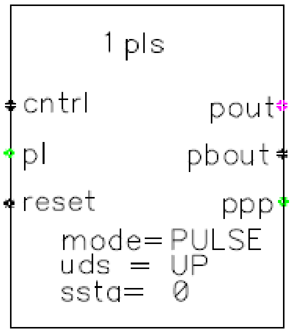


*Figure 12. Symbolic representation of pulse function block [9]*

The operation principle of pulse function block is presented in Figure 13.

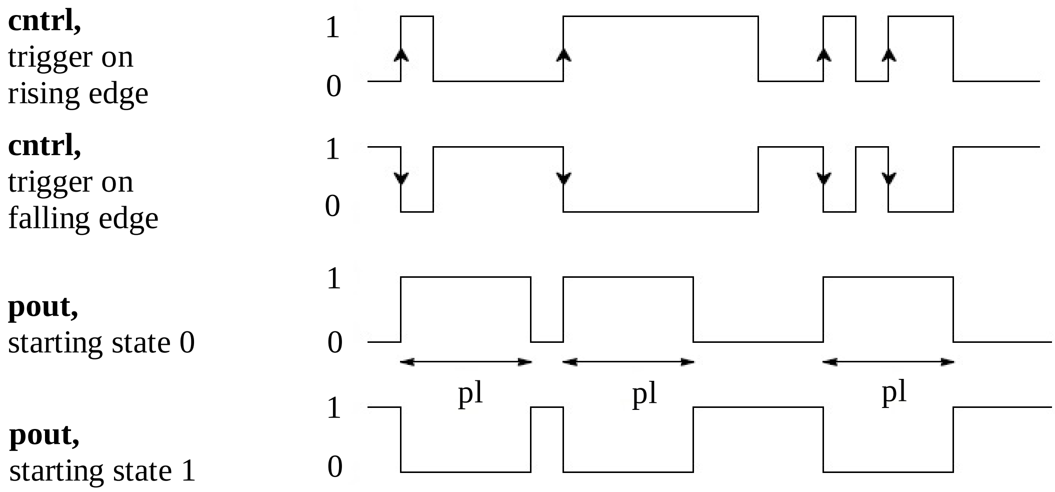


*Figure 13. Function diagram for pulse function block [9]*

### 3.1.4. Counter function block

The counter function block has three operating modes:

Continuous – Input in does not affect the counting and the counter is incremented/decremented with the value of input delta,

Rising – Rising edges of input in are counted and the counter is incremented/decremented by one,

Falling – Falling edges of input in are counted and the counter is incremented/decremented by one.

When the counter goes below the low limit *min* or exceeds the high limit *max*, the limit output *lim* is set to 1. It is also possible to configure a turnaround counter (when the counter reaches the limit *min* or *max*, then the counter turns around and its value is incremented or decremented by *max* - *min* or *min* + *max*).

The function block also includes a cumulative counter which is incremented always when the counter is handled. The cumulative counter has values $n * x$, where $n = 0, 1, \ldots$ and $x = 1$ or delta. The reset, clr and hold signals are available for managing the function block. Figure 14 presents symbolical representation of a counter function block.

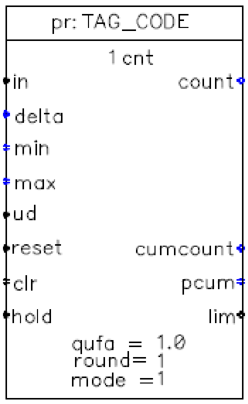


*Figure 14. Counter function block symbolic representation [9]*

### 3.1.5. ON/OFF valve function block

The ON/OFF valve function block can be used to control actuators which typically have the states OPEN and CLOSE. The basic application is to drive an auxiliary solenoid valve which drives pneumatically the main valve.

### 3.1.6. Valve function block

The valve function block has been designed for the control of motor actuators. Typically it is used as a motor valve positioner. The function block does not use the actuator's possible position data for positioning; instead, the required control is determined on the basis of the actuator's operating time and other configuration parameters.

Function block operates in incremental mode so that its input represents the desired position change. Block normally gets the desired position change from a controller's output or other calculation.

### 3.1.7. Motor actuator function block

Typical actuators controlled with motor actuator function block include motor valves, dampers and guide vanes. On certain preconditions block may also be used for the control of hydraulic valves and conveyor type actuators.

Block can control an open/close/stop actuator. Function Block can be used as positioner driving the actuator to a position target. Positioning can be based on either position measurement or operating time of the actuator. It can be used together with PID function block as a controller in a motor actuator loop.

### 3.1.8. Copy function block

This function blocks permits conditional copying of data. If the copying condition is true, the block reads the *in* input and copies it to the *out* output as it is. If the copying condition is false, the output is maintained at its previous value; in other words, the block does not write anything to its output. This function block is very useful to build up logics around other function blocks. Copy function block has different copying modes listed hereafter:

Mode 0 – copying when condition (cnd) is 1,
Mode 1 – copying on rising edge of cnd input,
Mode 2 – copying on falling edge of cnd input,
Mode 3 – copying when change is detected in condition (cnd),
Mode 4 – copy when condition (cnd) is 0.

Figure 15 shows symbolic representation of a copy function block.

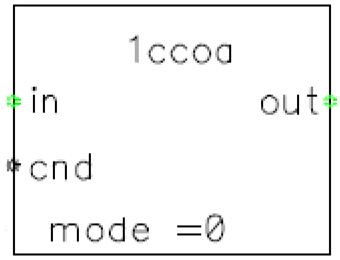


*Figure 15. Symbolic presentation of copy function block [9]*

### 3.1.9. Logic function blocks

These function blocks perform the logical operations AND, OR, XOR, NOT, RS flip−flop, SR flip−flop and are used frequently for building up control logics.

### 3.1.10. Calculation function block

Calculation function black provides possibility to write computations in C# programming language into the block. It is usually used to manipulate read data from field.

## 3.2. Trial and Error tuning procedure

All PI controllers used for process control are tuned with Trial and Error method. This chapter will give overview of how the tuning method was applied in practise. Steps are the following:

- Gathering basic information about the process - deciding desired behaviour,
- Integral and Derivative components are switched off and adjustment of Proportional component to desired state, while ignoring offset,
- Adjustment of Integral component to remove offset.

Derivative component was not included. When the process is noisy the Derivative component reacts to them with similar disturbance frequency. As a result to rapid change in controller output, the field devices can be damaged. Therefore PI controller is more commonly used in industry applications.

Adjustments for Proportional component are made using factor of two, example 0.25, 0.5, 1.0, 2.0. Effects of PID parameters on speed and stability presented in Table 3 are basis of adjustment decisions.

Trial and Error procedure involves a repeated sequence of following:

- Obtaining a response from change in the loop,
- Analysing loop reaction according to desired behaviour,
- Adjusting the tuning parameters.

## 3.3. Control diagrams

Control diagrams describe the control equipment relationships, interlocks and application PI connections. Diagrams are developed for process control system for each critical activity. Control diagrams are basis for developing control applications.

The more covered topic is combustion control. In order to give complete understanding of the plant control, every control area showed in Figure 1 is briefly discussed before combustion control hereafter.

### 3.3.1. Fuel yard

Rapla fuel yard is rectangular concrete storage building with hydraulic cylinder scrapers. When scrapers have pulled fuel onto the conveyer then the fuel is transported to mini-silo which is located on the furnace entrance. Figure 1 shows fuel yard graphically and Figure 2 shows the location of mini-silo.

In order to handle wood chips from fuel yard to mini-silo following equipment is needed:

- 2 hydro stations,
- 16 manual valves,
- 4 solenoid valves,
- conveyor chain motor,
- hydro station temperature sensors,
- 6 hydro cylinders (scrapers),
- 12 end-switches,
- 2 pressure sensors,
- 2 oil level switches,
- 2 safety switches.

Hydro stations provide necessary oil pressure to move hydro cylinders which are connected to scrappers. Scrappers pull biomass fuel (wood chips) onto the conveyor.

For safety reasons every hydro station has low oil level switch, high pressure indicator and safety switch.

Manual valves allow operator to close oil supply to certain hydro cylinders in case of need (e.g. cylinder breakdown). 4 solenoid valves are operated by control system logic in order to direct oil pressure to push or pull scrappers. Every hydro cylinder has 2 end-switches which indicate position of the cylinder piston. Fuel yard control logic depends on chain conveyor status. While conveyor motor is not working the scrappers are stopped. Figure 16 presents hydro station working logic in automatic mode.

Solenoid valves control which way hydro cylinders are moving. Their control logic is built so, that cylinder can be moved forward, backward or stopped in intermediate position. Control logic for fuel yard hydro cylinders is presented in Figure 17. Hydro cylinder application is using inputs from 12 end-switches. Every cylinder has OPENED end-switch and CLOSED end-switch. According to logic hydro cylinders change states from OPEN to CLOSE when all three cylinders are in OPENED state. One hydro station with 2 solenoid valves and 3 hydro cylinders with end-switches combine a group. Both groups have identical control logic and the operator can choose which group is active. Groups can also be active simultaneously.

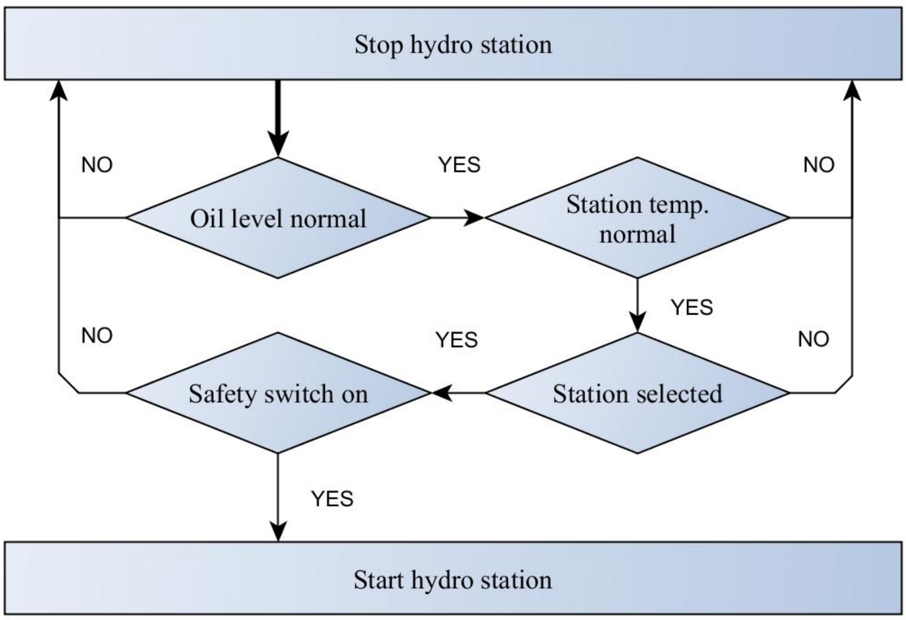


*Figure 16. Hydro station working logic*

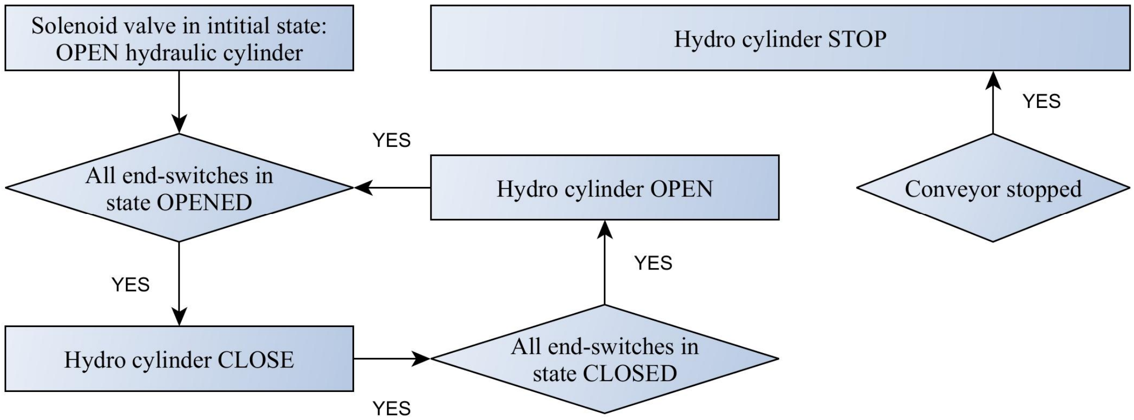


*Figure 17. Hydro cylinder control logic*

The Function Block CAD application for fuel yard group 1 is presented in Appendix 2.

Chain conveyor is working according to mini-silo level. When mini-silo is full the chain conveyor stops working and starts again after mini-silo´s level is not high and predefined time delay has passed. Chain conveyor has may interlocks due to safety reasons, they are described in Figure 18.

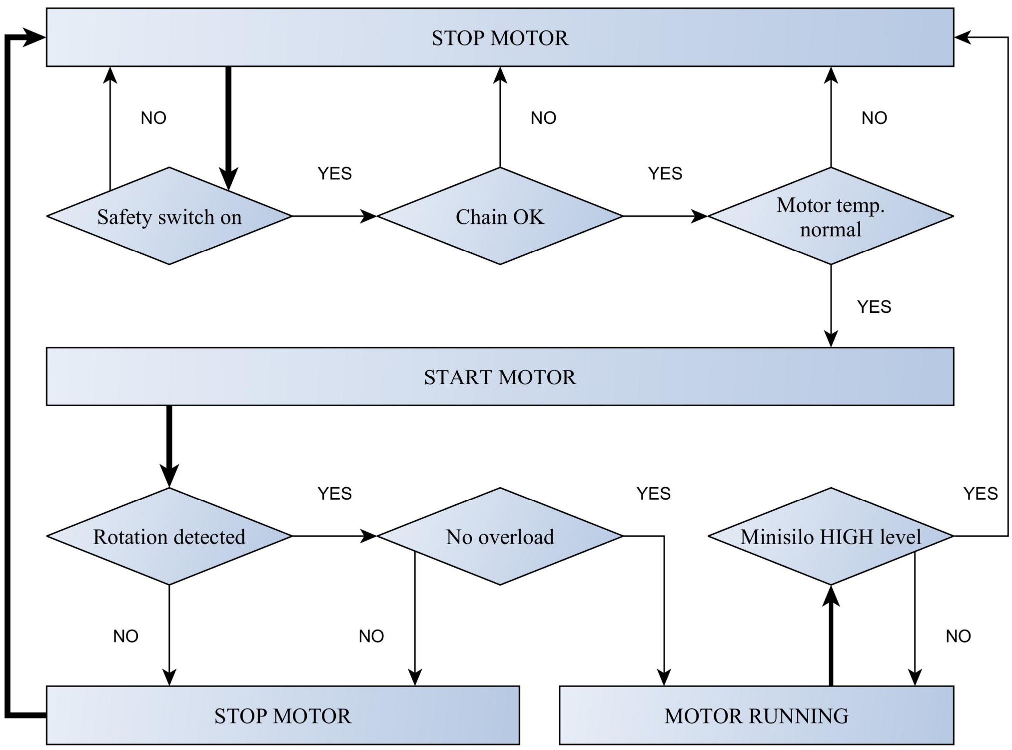


*Figure 18. Chain conveyor control logic*

### 3.3.2. Fuel feeding from mini-silo

In order to handle fuel from mini-silo to combustion chamber the following equipment is needed:

- 1 fuel feeder hydro station,
- 2 fuel feeding cylinders with 2 end-switches,
- 1 fire protection valve hydro station,
- 1 fire protection valve cylinder with 2 end-switches,
- temperature sensor in mini-silo,
- 1 hydro station oil level switch,
- 1 hydro station oil pressure high switch,
- 2 mini-silo level switches,
- 2 safety switches,
- 2 solenoid valves.

Hydro stations provide necessary oil pressure to move hydro cylinders. Logic selects one or another direction for cylinder movement by opening/closing required valves. Fire protection cylinder goes to close direction when temperature inside mini-silo is over allowable level as safety measure.

Fuel to combustion chamber is pushed by 2 fuel feeding cylinders synchronously. Feeding rate is set by operator or calculated by control application. Interlocks of fuel feeder cylinders are described in Figure 19. State OPENED from the angle of hydro cylinder means that piston is fully pushed out.

The Functional Block CAD application for fuel feeding from mini-silo is presented in Appendix 3.

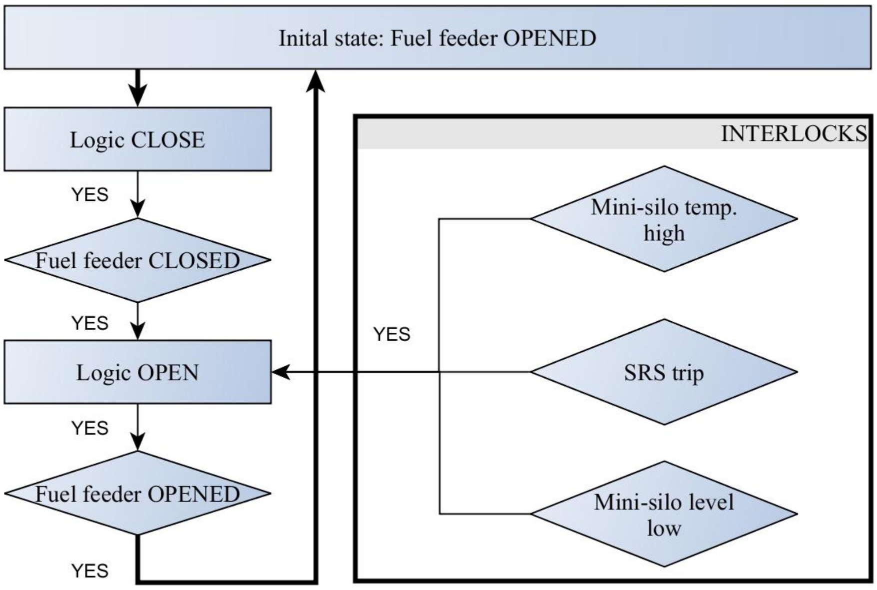


*Figure 19. Fuel feeder working logic*

### 3.3.3. Flue gases and scrubber

Flue gasses are exhaust from furnace burning process. It contains a small percentage of a number of pollutants, such as particulate matter, carbon monoxide, nitrogen oxides, and sulphur oxides. In order to pollute environment less all flue gasses are directed through piping to scrubber for cleaning process. Following equipment is needed:

- furnace pressure sensor ($PI_1$),
- flue gas fan,
- 3 flue gas valves,
- raw water valve,
- scrubber level low indicator ($LI_1$),
- scrubber consistency sensor ($QS_1$),
- 2 sludge pumps,
- NaOH pump,
- scrubber pump ($SCP_1$),
- scrubber pump ($SCP_2$),
- scrubber temperature sensor ($TI_1$),
- scrubber heat exchanger pump,
- before heat exchanger temperature sensors ($TI_2$),
- after heat exchanger temperature sensors ($TI_3$),
- heat exchanger water inflow temperature sensor ($TI_4$),
- heat exchanger water outflow temperature sensor ($TI_5$),
- Ph sensor ($QI_1$),
- Safety switch for all motors, fans.

Flue gas fan is controlled by software PI controller. Flue gas fan has to hold furnace pressure around $-50\ Pa$ to avoid flue gas leaks inside boiler house. Regarding typical ranges [21] and pressure response following parameters presented below where found. Measurements are provided by furnace pressure sensor. PI controller parameters are tuned using Trial and Error tuning method and are the following:

- $K_c$ = 1,
- $T_i$ = 25.

Flue gas valves are in use to direct gasses through or bypass scrubber. When scrubber pumps are not working then interlocking is active which does not allow directing flue gasses through scrubber.

Scrubber consistency sensor $QS_1$ indicates when dust and pollution products from the scrubbing process are accumulated. They are removed periodically through the drain with sludge pumps.

Scrubber pump $SCP_1$ is circulating water from scrubber water reservoir to spray tower. The pump working speed is controlled by software PI block. Measurement input (me) for PI is calculated by function showed with Equation (8)

$$me_{inp} = TI_3 - TI_2 \tag{8}$$

Active set point is decided by operator. Control parameters are tuned using Trial and Error tuning method for accuracy. In order to achieve accuracy low controller gain and high integral action is used. Derivative component is turned off [21]. Parameters are the following:

- $K_c$ = 0.75,
- $T_i$ = 35.

NaOH pump work according to Ph sensor $QI_1$. $QI_1$ is digital sensor switch with logical state normally open. The sensor is calibrated so that when the consistency is big it will give out logical close (closed contact, signal 1) what starts NaOH pump. NaOH pump works during the time defined by operator.

Scrubber water valve works with similar logic as NaOH pump, but uses scrubber low level indicator $LI_1$ for input.

Energy what is absorbed by water droplets is directed through heat exchanger. This method allows to increase district heating capacity. Heat exchanger pump is controlled by software PI controller. Measurement input (me) for controller is calculated by function showed with Equation (9)

$$me_{\text{inp}} = TI_3 - TI_4 \tag{9}$$

PI control parameters are tuned for accuracy by using Trial and Error tuning method. Parameters are the following:

- $K_c$ = 0.8,
- $T_i$ = 30.

### 3.3.4. Boiler control

Boiler is situated on top of furnace (See Figure 1). Combustion process is generating heat which is transferred to water inside boiler. If the water would be stationary then it would overheat and boil, that could cause damage to water boiler. In order to control boiler properly and distribute generated heat to district following equipment is needed:

- boiler output temperature,
- boiler input temperature,
- boiler input pressure,
- recirculation pump,
- output water valve,
- input water pump,
- boiler power out sensor,
- safety switches for pumps, valves.

Recirculation pump is controlled by software PI. Measurement input (me) for PI is provided from boiler input temperature sensor. Control parameters are tuned regarding that temperature response is fairly slow [21]. Using Trial and Error tuning method, parameters provided for PI controller are the following:

- $K_c$ = 2,
- $T_i$ = 40.

Output water valve is operated by software PI controller. PI controller gets its measurement input (me) from boiler temperature out sensor. Active set point is given to valve by operator which is 115 °C. PI control parameters are tuned considering that process dynamics are quite slow [21]. Using Trial and Error tuning method, parameters provided for PI controller are the following:

- $K_c = 3$,
- $T_i = 250$.

### 3.3.5. Ash disposal

Ash which is accumulated below and end of the grate is removed by 4 screw motors. Screw motors collect the ash and transport it outside the combustion chamber onto ash conveyor. Conveyor motor transports the ash outside boiler building into lift-able container. In order to distribute ash inside container evenly another screw motor is used.

List of equipment needed is the following:

- furnace screw 1-4,
- ash chain conveyor motor,
- container screw motor,
- conveyor chain rotating sensor,
- motor high load sensors,
- safety switches for motors.

Conveyor and screw motors are working by operator defined timings. Figure 20 shows the logical relations between motors.

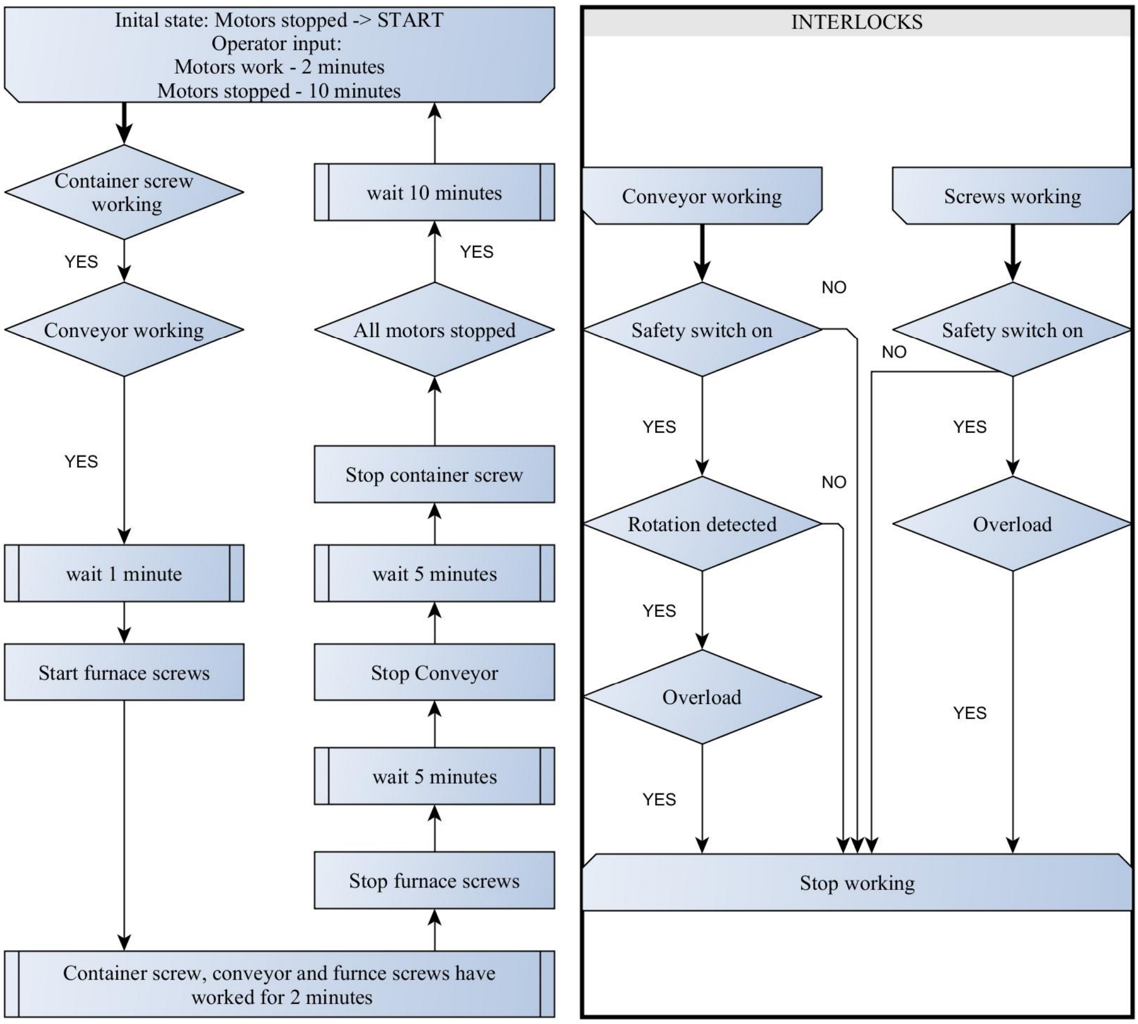


*Figure 20. Conveyor and screw motors working logic*

The Functional Block CAD application for ash disposal is presented in Appendix 4.

### 3.3.6. Combustion control

An optimal combustion is realised through intelligent configuration of the furnace and the temperature control system in combustion zone. This is achieved by applying control of primary and secondary air intake, fuel adding control, adjustment of grate movement frequency and added recirculating flue gasses. Figure 21 presents combustion zone inputs and outputs.

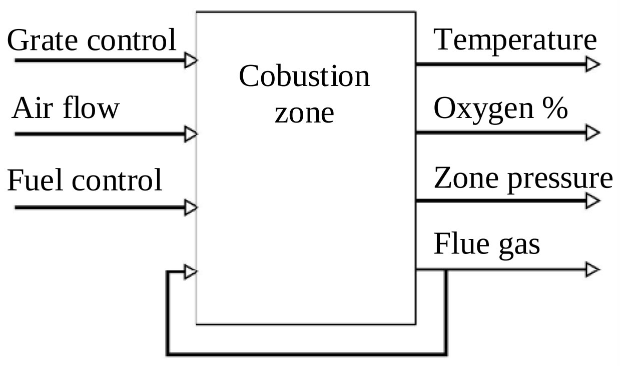


*Figure 21. Combustion zone inputs and outputs*

It is necessary to control all combustion zone inputs to achieve desirable system output. All equipment needed and control logics are described hereafter.

Equipment needed for fuel control is described in section 3.3.2 Fuel feeding from mini-silo. Feeding rate of fuel is realized with relational table. This solution has some disadvantages. If the fuel quality variations are big then relation table will provide inaccurate control for feeding rate. Due to testing proposes relational table solution was kept.

In order to realize air input for combustion zone following equipment is needed:

- primary air fan,
- secondary air fan,
- flue gas recirculation fan,
- oxygen in flue gas sensor,
- 3 primary air valves,
- 4 secondary air valves,
- boiler output temperature sensor,
- flue gas recirculation valve.

Primary and secondary air valves are controlled manually by operator. Operator can control which area of combustion is getting more air. By doing this operator can specify where in the furnace combustion takes place.

Primary air fan control is realized by relational table. Work load for fan motor is proportional to fuel feeding rate. Primary air is fed under the grate. Relational table takes in account that too much under grate air can lift off ash and char particles in combustion bed, therefore limit for working load is 65 %.

The oxygen concentration in flue gases is controlled by secondary air flow. Secondary air fan control is realized with software PI controller. The controller gets its measurement (me) reading from oxygen in flue gas sensor. Set point for oxygen level is 5 %. Controller has 20 % limitation for control output, therefor if the oxygen level is bigger than 5 % the controller cannot give output 0 % for fan motor. This ensures that air what is needed for burning is always provided. Using Trial and Error tuning method, parameters provided for PI controller are the following:

- $K_c$ = 0.7,
- $T_i$ = 90.

The recirculated flue gas is extracted from the boiler outlet flue gases. The flue gas is returned through a separate duct with fan to the combustion air duct. Recirculated flue gas fan is controlled by software PI controller. Controller takes in count measurement (me) input from furnace temperature sensor. Set point is 1050 °C. Controller starts to work when furnace temperature is above 1100 °C and stops when temperature is below 990 °C. Using Trial and Error tuning method, parameters provided for PI controller are the following:

- $K_c$ = 1.2,
- $T_i$ = 15.

Wood chips are transported along the moving grate and fuel is combusted before reaching to the end of the grate. Equipment needed for realizing grate movement is following:

- grate hydro station,
- 2 solenoid valves,
- 4 hydro cylinders,
- 4 end-switches,
- hydro station safety switch.

Moving grates are divided into two groups. Every group has 1 solenoid valve, 2 hydro cylinders, 2 end-switches and common hydro station. One group moves furnace upper part of grates, and other lower part of grates. Solenoid valves control which way hydro cylinders are moving. Their control logic is built so, that cylinder can be moved forward, backward or stopped.

Control logic for grate movement cylinders is presented in Figure 22. Logic application for one group is using inputs from 2 end-switches. Both hydro cylinder groups have OPENED end-switch and CLOSED end-switch. According to logic hydro cylinders change states from OPEN to CLOSE when cylinders are in OPENED state.

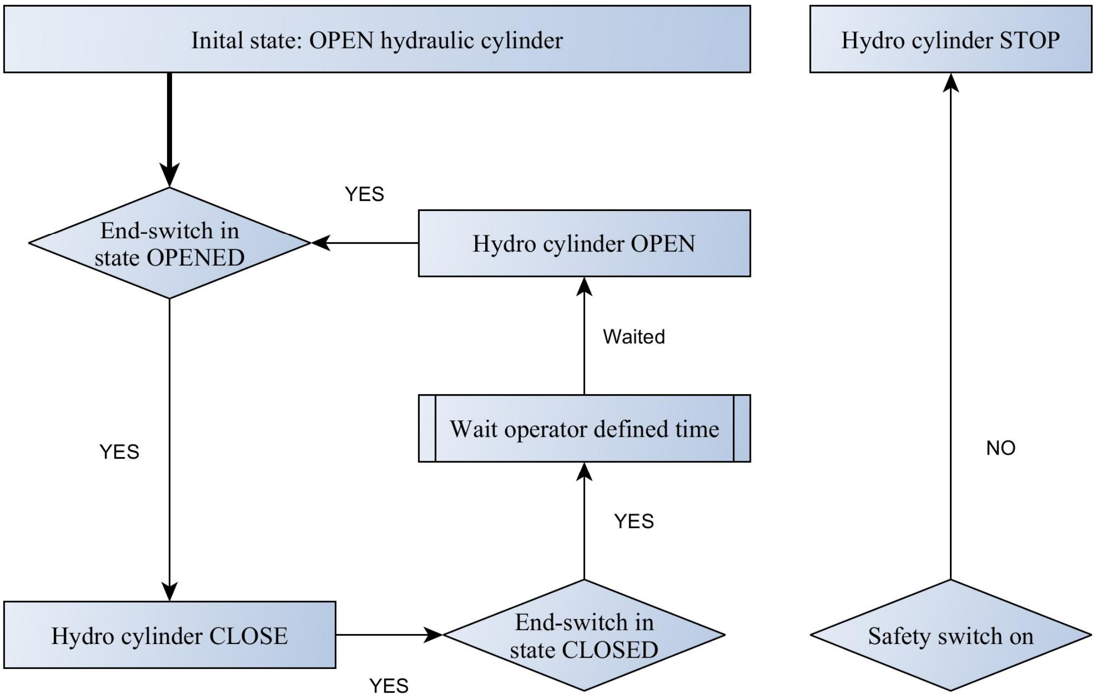


*Figure 22. Grate solenoid valve working logic*

Cylinders are controlled according by operator predefined time periods which are developed by operator experience. Functional Block CAD application for grate control is presented in Appendix 5.

# 4. Optimizing combustion trough oxygen control

In this chapter, the motivation behind chosen optimization method, as well as a descriptions how Step Response, Chien-Hrones-Reswick tuning method and Ziegler-Nichols tuning method where applied and analysed, are given.

## 4.1. Motivation

According to district heating need boiler has to hold power near 2 MW so that water temperature output to district is 65 ℃. In order to do that constantly it is necessary to hold boiler in steady state operation. Biggest disturbance for the process is fuel variety [22]. The moisture continent can vary in the fuel wood chips.

Wood chips moisture continent affects oxygen concentration in furnace. Oxygen concentration disturbance in turn affects furnace temperature [4]. In order to keep boiler output power near 2 MW the combustion inputs, fuel control and grate control shown in Figure 21 and Table 7, are kept constant. The secondary air controller acts to readings from oxygen concentration. When fuel varies and oxygen concentration raises then furnace temperature rises. Trial and Error method developed PI secondary air controller responses and lowers oxygen concentration. Figure 23 presents Trial and Error method of tuned PI controller working characteristics.

*Table 7. The initial values for tests*

<table>
<tr><th>Combustion inputs</th><th>Valve 1</th><th>Valve 2</th><th>Valve 3</th><th>Valve 4</th><th>Fan speed</th><th>Moving time</th></tr>
<tr><td>Grate control</td><td colspan="5">–</td><td>5 sec upper, 10 sec lower group</td></tr>
<tr><td>Secondary air</td><td>16 %</td><td>26 %</td><td>41 %</td><td>71 %</td><td>Modified</td><td rowspan="2">–</td></tr>
<tr><td>Primary air</td><td>5%</td><td>5 %</td><td>90 %</td><td>–</td><td>37 %</td></tr>
<tr><td>Fuel control</td><td colspan="5">–</td><td>37 times per hour</td></tr>
</table>

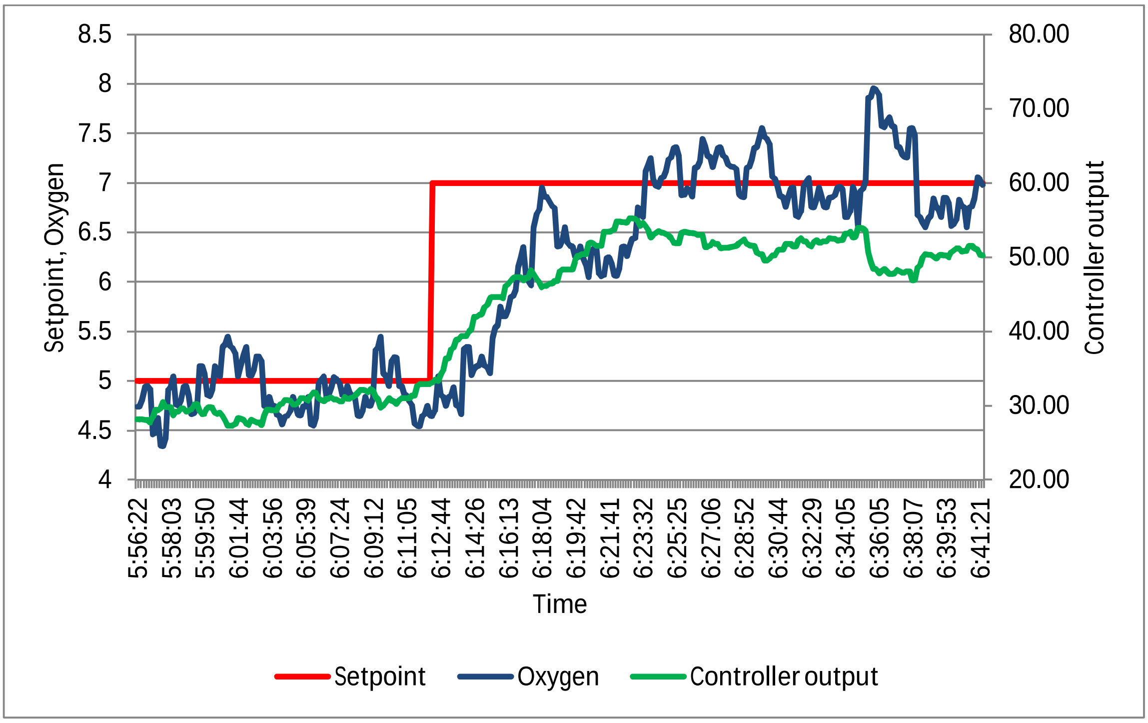


*Figure 23. Secondary air PI controller characteristics*

Set point step change is introduced to simulate disturbance for the controller. Time to get from active steady state to new steady state is 11 minutes and 21 seconds. At 6:34:44 disturbance is introduced and oxygen concentration raises. Disturbance is 3 minute long excess air from valve what is regularly closed.

Goal is to design, using other than Trial and Error method, faster and more accurate controller.

## 4.2. Step Response

A simple experiment to perform is the step response test. Here, we assume a unit step is applied to the system. From the results of this test, the data may be used to obtain approximations of the system.

### 4.2.1. Test data

Test is carried out with secondary air control loop. Following combustion inputs are kept constant: grate movement, fuel feeding rate and primary air. Flue gas circulation fan is turned off and steady state is achieved, because roughly same quality fuel is used throughout the test.

Controller output change is introduced to process. Figure 24 presents step response test result.

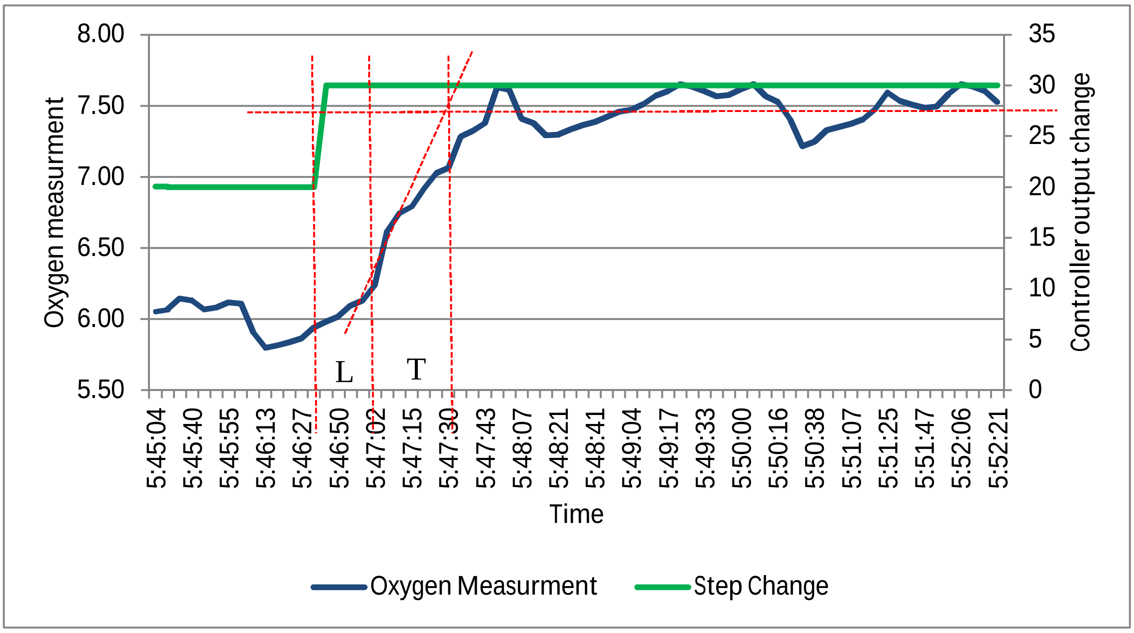


*Figure 24. Step response test result*

After making step change in input following parameters are acquired: dead-time $L$, time constant $T$, controller output difference $\Delta CO$, process variable difference $\Delta PV$ and process gain $K_{\mathrm{p}}$ . Table 8 presents relevant data for parameter calculations.

*Table 8. Data from Step Response test*

| | **Time** | **Calculation** | **Parameter value** |
|---|---|---|---|
| Step change | 5:46:47 $(a)$ | – | |
| First sign of change | 5:47:02 $(b)$ | | |
| New steady-state | 5:47:30 $(c)$ | | |
| Dead-time, $L$ | – | $b - a = 0{:}00{:}15$ | 15 seconds |
| Time constant, $T$ | | $c - b = 0{:}00{:}28$ | 28 seconds |
| Step difference, $\Delta CO$ | | $30 - 20 = 10$ | 10 % |
| Oxygen difference, $\Delta PV$ | | $7.5 - 6 = 1.5$ | 1.5 % |
| Process gain, $K_{\mathrm{p}}$ | | $K_{\mathrm{p}} = \frac{\Delta PV}{\Delta CO} = \frac{1.5}{10}$ | 0.15 % |

## 4.3. Applying Chien-Hrones-Reswick tuning method

Chien-Hrones-Reswick disturbance rejection method was developed to focus on disturbance response and therefore it is chosen for the first test [19]. The objective is to achieve quickest response without overshoot. According to Table 6 disturbance rejection with 0% overshoot following parameters presented in Table 9 were calculated and applied to controller.

*Table 9. Chien-Hrones-Reswick tuning method calculated parameters*

| Type of controller | With 0% overshoot | |
|---|---|---|
| | $\boldsymbol{K_c}$ | $\boldsymbol{T_i}$ |
| **PI** | $0.6\frac{T}{K_p L} = 0.6\frac{28}{0.15*15} = 7.5$ | $4L = 4*15 = 60$ |

Figure 24 presents process control data after controller parameter changes at 6:37:58.

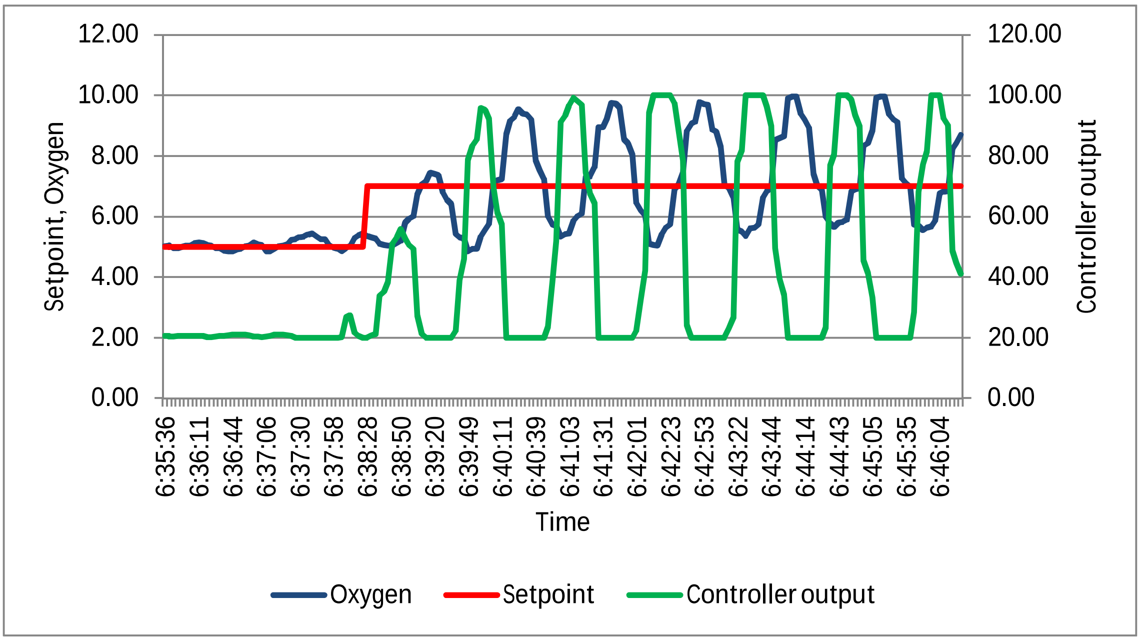


*Figure 25. Process control data with CHR parameters*

#### 4.3.1. Chien-Hrones-Reswick analysis

From the Figure 25 it is notable that process control is unstable. There is big oscillation in controller output what makes oxygen concentration raise and then drop rapidly. Controller parameters are not acceptable. Big Proportional component is causing oscillations. The one reason can be that acquired system model is not sufficiently precise. Suitable method or new model acquisition is needed to tune the controller.

### 4.4. Applying Ziegler-Nichols tuning method

Ziegler-Nichols (Z-N) tuning method is well known because of its simplicity and adequate tuning results for most loops [15]. According to Table 4 following parameters presented in Table 10 were calculated and applied to controller.

*Table 10. Ziegler-Nichols tuning method calculated parameters*

| Type of controller | $K_c$ | $T_i$ |
|---|---|---|
| PI | $0.9\frac{T}{L} = 0.9\frac{28}{15} = 1.68$ | $\frac{L}{0.3} = \frac{15}{0.3} = 50$ |

Figure 26 presents process control data after controller parameter changes at 7:27:10.

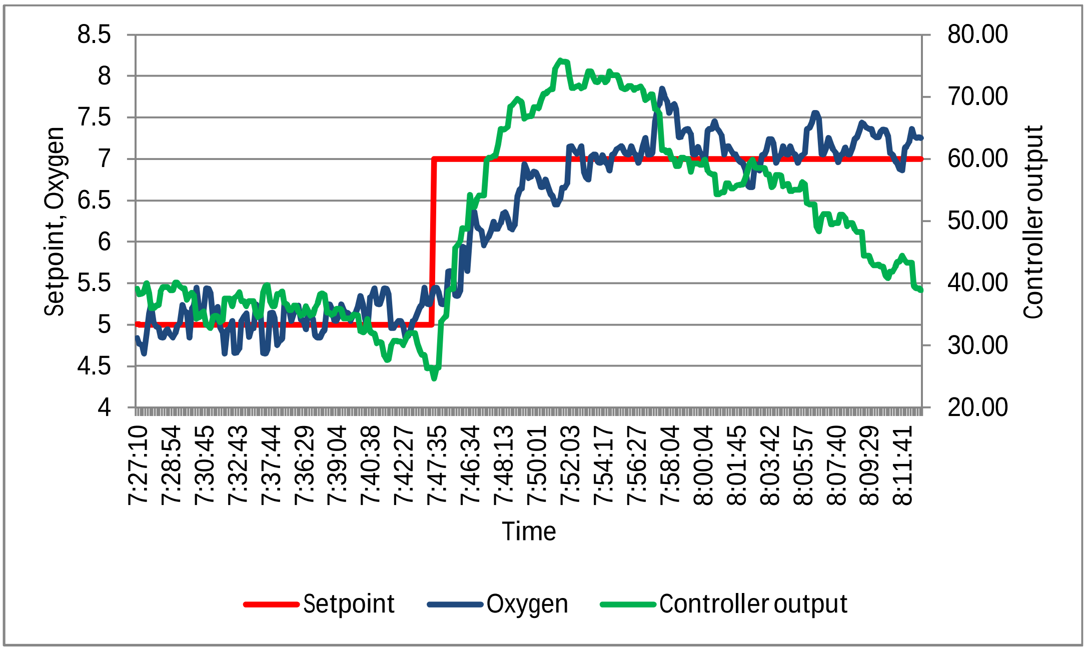


*Figure 26. Process control data with Z-N parameters*

### 4.4.1. Ziegler-Nichols analysis

Set point step change is introduced to simulate disturbance for the controller. Time to get from active steady state to new steady state is 7 minutes and 45 seconds. This is better by 3 minutes and 36 seconds than control response showed in Figure 23. At 7:56:54 oxygen concentration raises, potential cause can be better quality wood chips. Wood chips quality was valued on the basis of one truckload shipment and when fuel scrappers started to pull wood chips from another pile the combustion disturbance was introduced after approximately 20 minutes.

Important is to notice that controller response is more rapid than showed in Figure 23. This gives faster disturbance rejection. Controller output approximately 75 % is applied because secondary air valves limit air flow to combustion zone and therefore air fan has to work faster in order to control oxygen content. Controller output moves forward to stabilization in the end of test presented in Figure 26, resulting better control than presented in Figure 23.

It was complicated to carry out longer tests on the real system, because tests demanded to disrupt boilers normal operation, which in client's side meant losing money. After tests were finished Trial and Error method developed PI parameters were restored ($K_c$ = 0.7, $T_i$ = 90). In the future it is needed to carry out deeper study on biomass combustion technology, process model acquisition and simulation environment to justify optimization for the client.

# 5. Conclusions

The goal of this master thesis has been to design industrial computer applications and implement a control system for biomass fire-tube boiler. Second goal was to implement and improve software based PI control loops. At the start of the thesis, a study was performed on the technical background of biomass boiler systems. When boiler system overview was acquired then followed Valmet Automation hardware and software study with the purpose to familiarize with the engineering tools which are available to apply automation for boiler system. In order to achieve second goal of PI control loops optimisation, the various controller tuning methods were reviewed and three of them were applied to real system.

Discussions over implemented control logics were given. Author realized that the best and the most efficient way of implementing control logics is a continuous interaction with a client and field engineers. Only such an approach gives complete system overview and understanding of the system technology under automation.

Tests which were carried out on real boiler system revealed more suitable secondary air controller parameters. Chien-Hrones-Reswick tuning method in practise did not give satisfactory results. It was proposed as quickest response method, in such case big Proportional component caused oscillatory process response. Controller tuning method which gave satisfactory results was Ziegler-Nichols method. Controller output change was sufficiently fast and stable to react to oxygen concentration changes.

It is necessary to make future tests for higher boiler power running modes. It is possible that found parameters for air controller are only suitable for 2 MW power running mode. Author sees that there are possibilities for future development regarding Rapla Biomass boiler. One possibility is to acquire most used steady state power working modes and develop for each mode specific controller parameters. Other possibility is to take into account moisture continent in fuel to adjust boiler combustion control.

To summarize, throughout the work it was necessary to gather information on boiler technology to be able to achieve both thesis goals. Boiler system automation and improved steady state combustion control for 2 MW boiler output was achieved.

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# APPENDIX 1 – THE FUNCTION BLOCK CAD ENVIRONMENT

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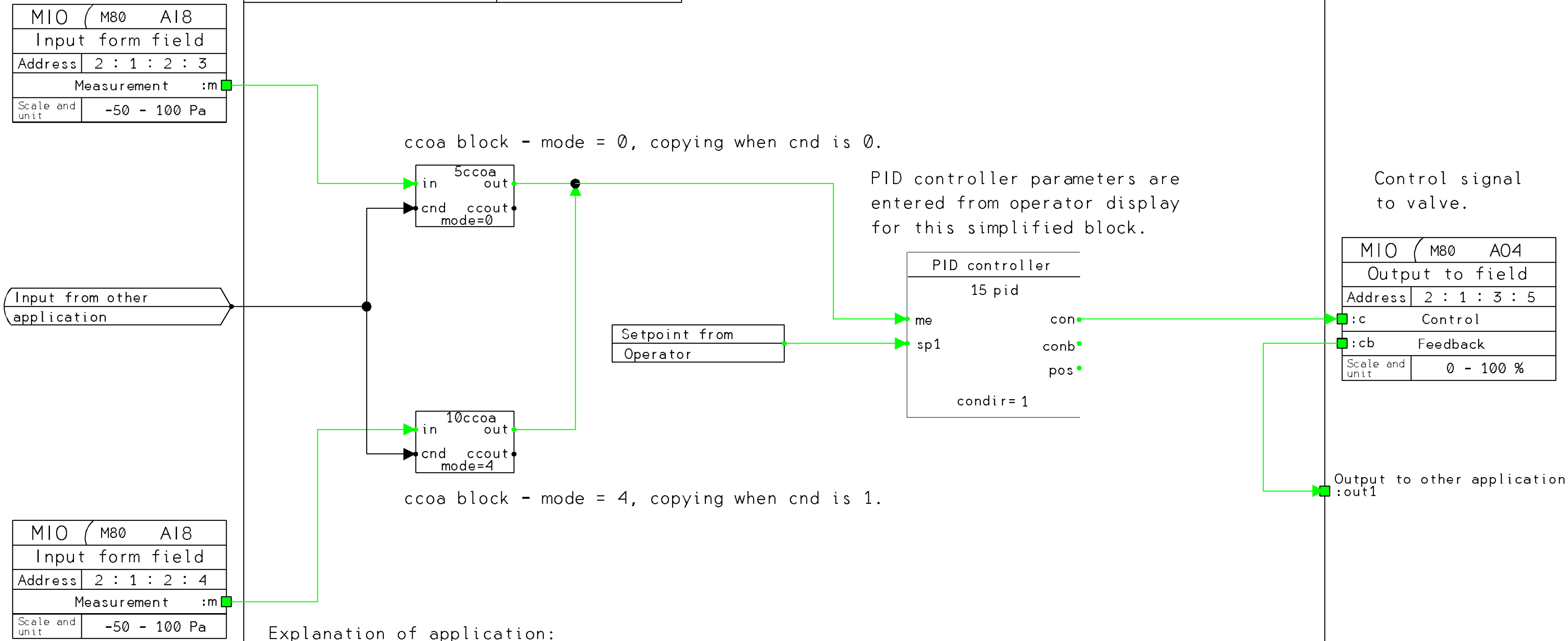
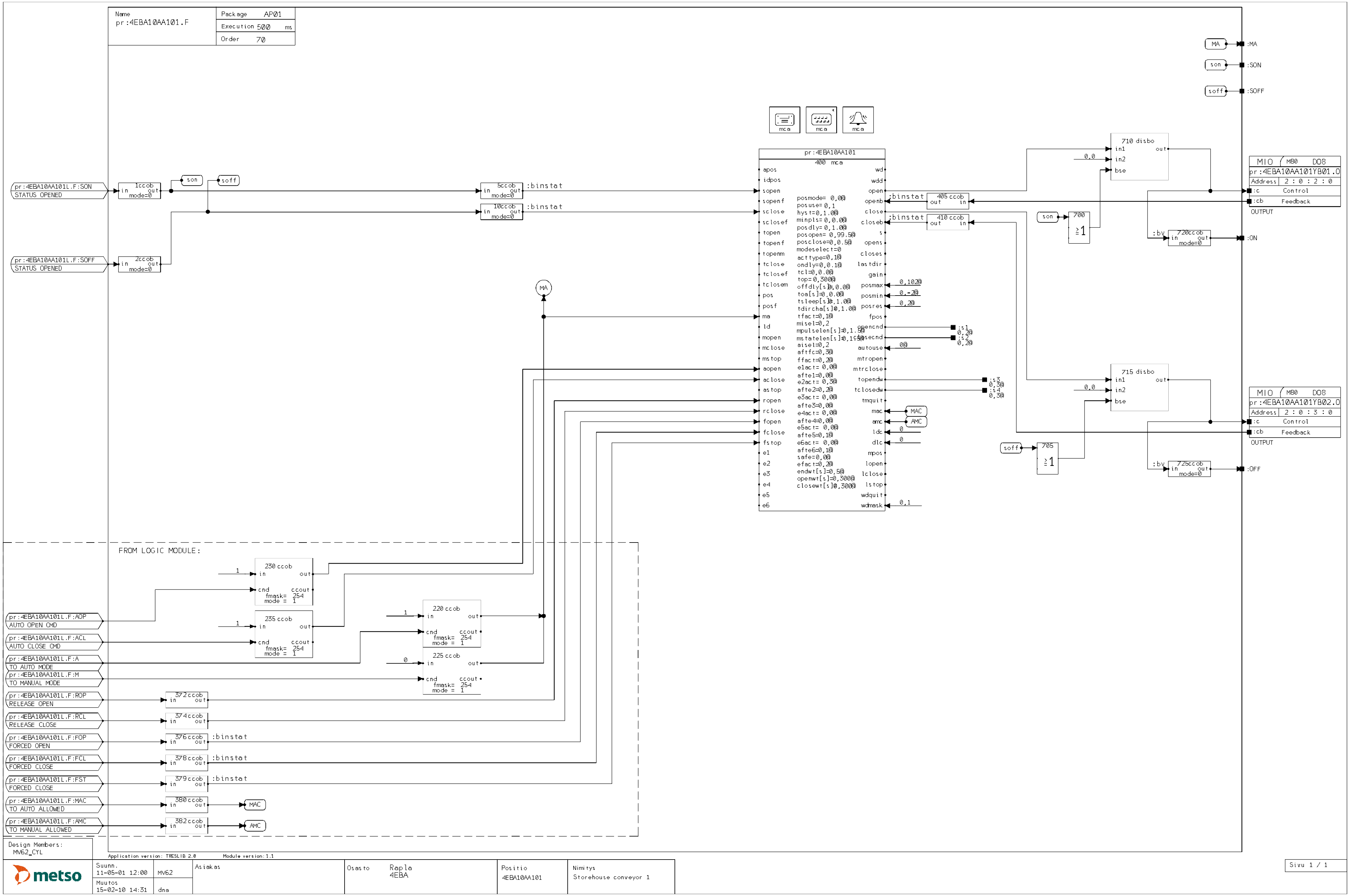



Explanation of application:

Here is shown how redundandacy is realized - two pressure sensors give readings from the field. Digital signal from other application, which is monitoring sensor failure, is read into ccoa block. Input from other application gives out signal 0, when active sensor is without failure. Input from other application gives out signal 1, when active sensor is with failure. Therefore when active sensor brokes the ccoa block switches mesurment reading which is sent to PID block.

| metso | Planner 15-05-18 09:49 | treraimlko | Customer | Department | Tag TAG_CODE_EXAMPLE | Loop name | Page 1 / 1 |
|---|---|---|---|---|---|---|---|
| | Modification 15-05-18 10:46 | treraimlko | | | | | |

# APPENDIX 2 – FUEL YARD GROUP 1 APPLICATION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STATUS OPENED
pr:4EBA10AA101L.F:SOFF
STATUS OPENED
1ccob
2ccob
5ccob
10ccob
:binstat
son
soff
MA
:MA
:SON
:SOFF
pr:4EBA10AA101
400 mca
apos
idpos
sopen
sopenf
sclose
sclosef
topen
topenf
topenm
tclose
tclosef
tclosem
pos
posf
ma
ld
mopen
mclose
mstop
aopen
aclose
astop
ropen
rclose
fopen
fclose
fstop
e1
e2
e3
e4
e5
e6
posmode= 0,00
posuse=0,1
hyst=0,1.00
minpls=0,0.00
posdly=0,1.00
posopen=0,99.50
posclose=0,0.50
modeselect=0
acttype=0,10
ondly=0,0.10
tcl=0,0.00
top=0,3000
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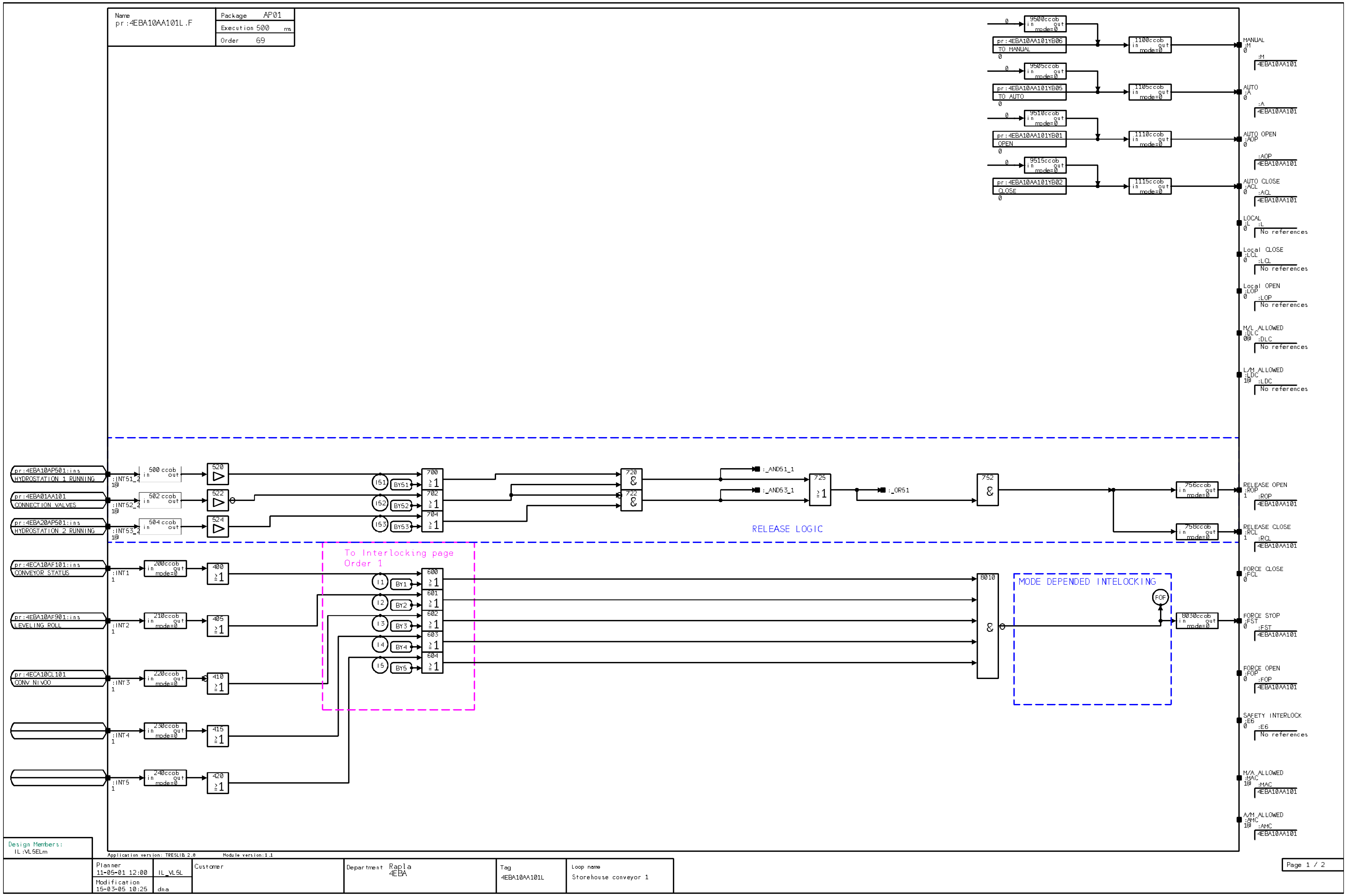
toa[s]=0,0.00
tsleep[s]=0,1.00
tdircha[s]=0,1.00
tfact=0,10
misel=0,2
mpulselen[s]=0,1.50
mstatelen[s]=0,1.50
aisel=0,2
affc=0,30
ffact=0,20
e1act= 0,00
afte1=0,00
e2act= 0,30
afte2=0,20
e3act= 0,00
afte3=0,00
e4act= 0,00
afte4=0,00
e5act= 0,00
afte5=0,10
e6act= 0,00
afte6=0,10
safe=0,00
efact=0,20
endwt[s]=0,50
openwt[s]=0,3000
closewt[s]=0,3000
wd
wdd
open
openb
close
closeb
s
opens
closes
lastdir
gain
posmax
posmin
posres
fpos
opencnd
closecnd
autouse
mtropen
mtrclose
topendw
tclosedw
tmquit
mac
amc
ldc
dlc
mpos
lopen
lclose
lstop
wdquit
wdmask
0,1020
0,-20
0,20
:s1
0,20
:s2
0,20
00
:s3
0,30
:s4
0,30
MAC
AMC
0
0,1
405 ccob
410 ccob
mca
700
705
≥1
710 disbo
715 disbo
in1
in2
bse
out
0,0
720ccob
725ccob
:bv
:ON
:OFF
MIO MB0 DO8
pr:4EBA10AA101YB01.0
Address 2 : 0 : 2 : 0
:c Control
:cb Feedback
OUTPUT
pr:4EBA10AA101YB02.0
Address 2 : 0 : 3 : 0
FROM LOGIC MODULE:
230 ccob
235 ccob
220 ccob
225 ccob
cnd
ccout
fmask= 254
mode = 1
pr:4EBA10AA101L.F:AOP
AUTO OPEN CMD
pr:4EBA10AA101L.F:ACL
AUTO CLOSE CMD
pr:4EBA10AA101L.F:A
TO AUTO MODE
pr:4EBA10AA101L.F:M
TO MANUAL MODE
pr:4EBA10AA101L.F:ROP
RELEASE OPEN
pr:4EBA10AA101L.F:RCL
RELEASE CLOSE
pr:4EBA10AA101L.F:FOP
FORCED OPEN
pr:4EBA10AA101L.F:FCL
FORCED CLOSE
pr:4EBA10AA101L.F:FST
FORCED CLOSE
pr:4EBA10AA101L.F:MAC
TO AUTO ALLOWED
pr:4EBA10AA101L.F:AMC
TO MANUAL ALLOWED
372ccob
374ccob
376ccob
378ccob
379ccob
380ccob
382ccob
Design Members:
MV62_CYL
Application version: TRESLIB 2.0
Module version: 1.1
metso
Suunn.
11-05-01 12:00
MV62
Muutos
15-02-10 14:31
dna
Asiakas
Osasto
Rapla
4EBA
Positio
4EBA10AA101
Nimitys
Storehouse conveyor 1
Sivu 1 / 1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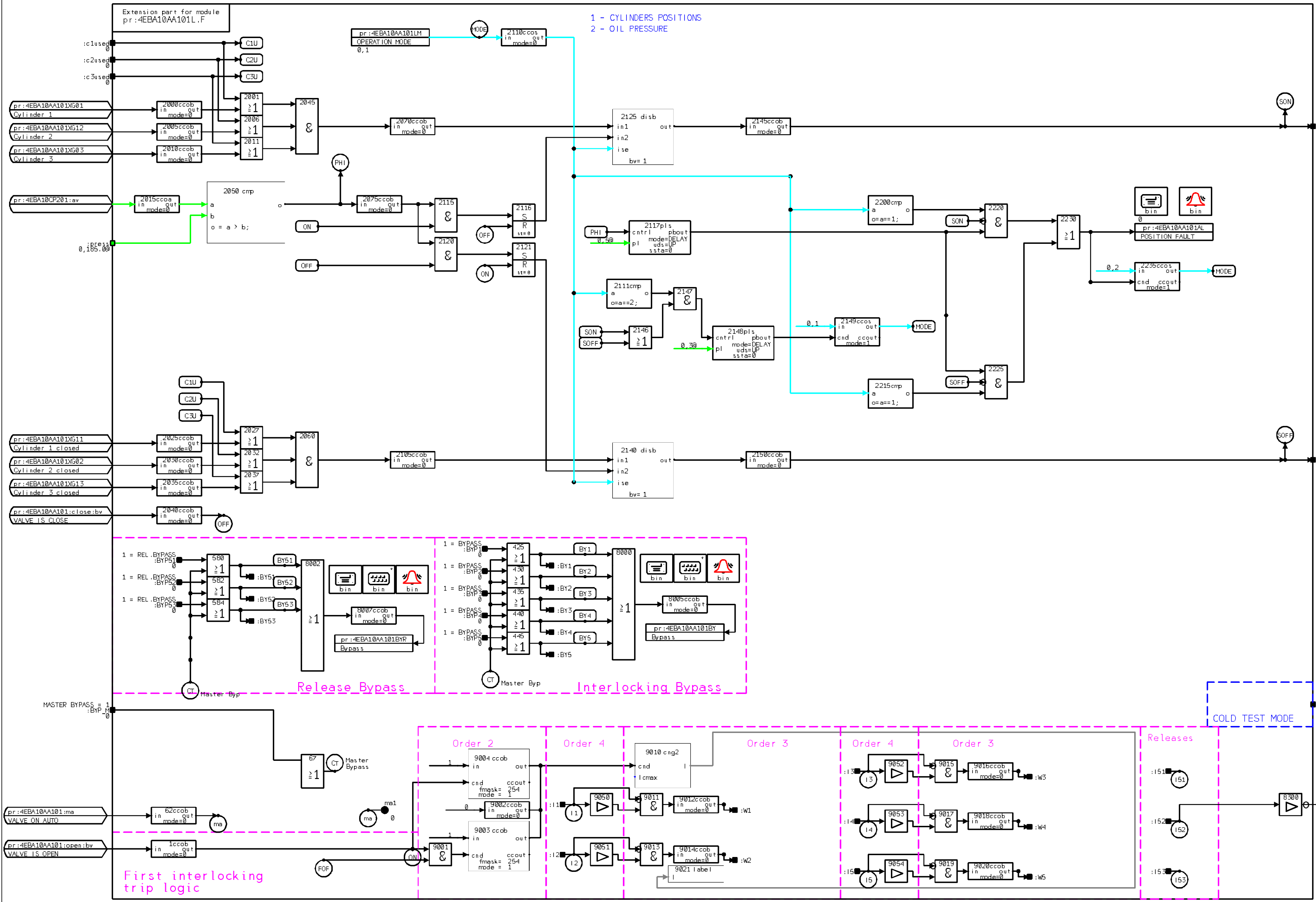
TO AUTO
pr:4EBA10AA101YB01
OPEN
pr:4EBA10AA101YB02
CLOSE
MANUAL
:M
4EBA10AA101
AUTO
:A
4EBA10AA101
AUTO OPEN
:AOP
4EBA10AA101
AUTO CLOSE
:ACL
4EBA10AA101
LOCAL
:L
No references
Local CLOSE
:LCL
No references
Local OPEN
:LOP
No references
M/L ALLOWED
:DLC
No references
L/M ALLOWED
:LDC
No references
pr:4EBA10AP501:ins
HYDROSTATION 1 RUNNING
pr:4EBA01AA101
CONNECTION VALVES
pr:4EBA20AP501:ins
HYDROSTATION 2 RUNNING
:INT51_2
:INT52_2
:INT53_2
:_AND51_1
:_AND53_1
:_OR51
RELEASE LOGIC
RELEASE OPEN
:ROP
4EBA10AA101
RELEASE CLOSE
:RCL
4EBA10AA101
pr:4ECA10AF101:ins
CONVEYOR STATUS
pr:4EBA10AF901:ins
LEVELING ROLL
pr:4ECA10CL101
CONV NIVOO
:INT1
:INT2
:INT3
:INT4
:INT5
To Interlocking page
Order 1
MODE DEPENDED INTELOCKING
FORCE CLOSE
:FCL
FORCE STOP
:FST
4EBA10AA101
FORCE OPEN
:FOP
4EBA10AA101
SAFETY INTERLOCK
:E6
No references
M/A ALLOWED
:MAC
4EBA10AA101
A/M ALLOWED
:AMC
4EBA10AA101
Design Members:
IL:VL5ELm
Application version: TRESLIB 2.0
Module version: 1.1
Planner
11-05-01 12:00
IL_VL5L
Modification
15-03-05 10:25
dna
Customer
Department Rapla
4EBA
Tag
4EBA10AA101L
Loop name
Storehouse conveyor 1
Page 1 / 2

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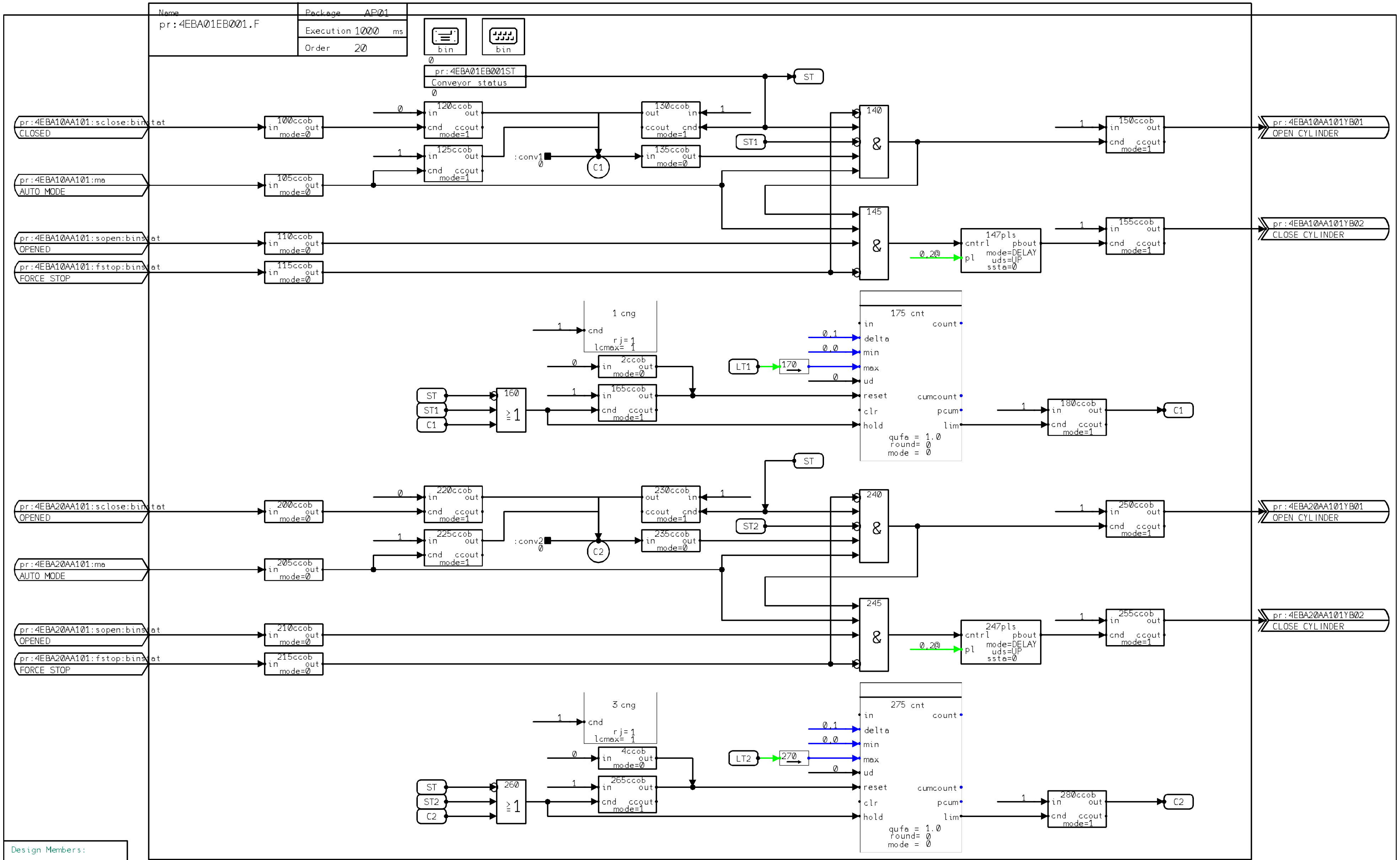
| Modification 15-03-05 10:25 | dna | | | | |

Page 2 / 2




metso

| Planner | dna | Customer | Department | Tag | Loop name |
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| Modification 15-02-03 14:17 | dna | | | | |

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Extension part
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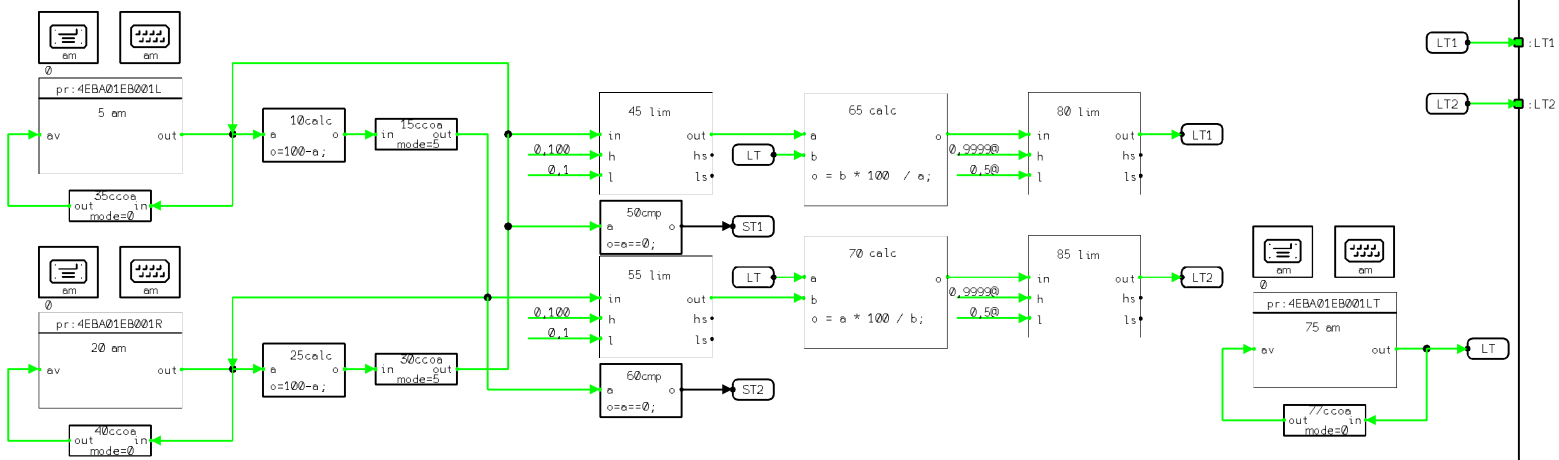
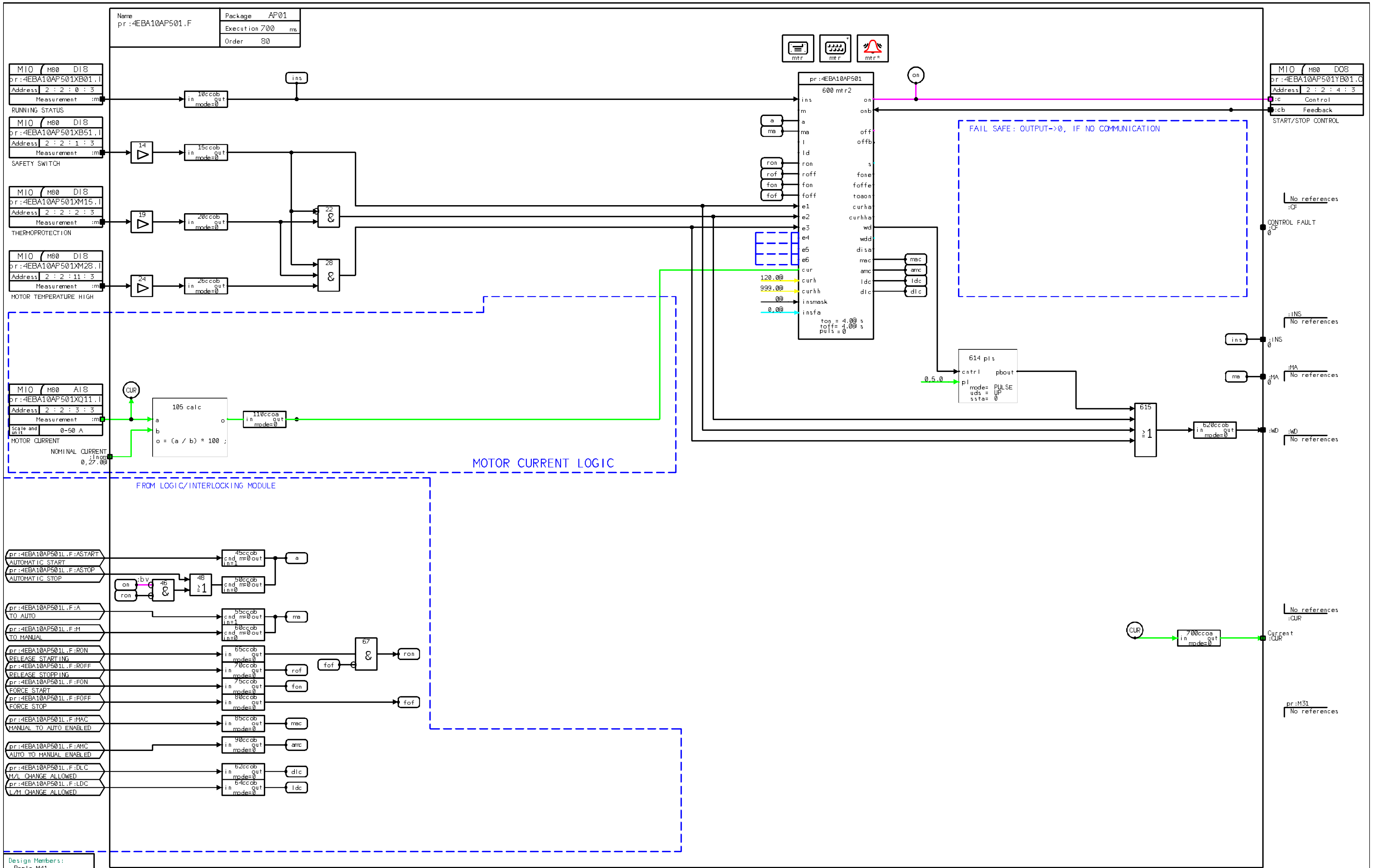



Page 2 / 2

| Planner 14-11-06 17:54 | dna | Customer | Department Rapla 4EBA | Tag 4EBA01EB001 | Loop name KONVEIERITE LOOGIKA |
|---|---|---|---|---|---|
| Modification 15-02-03 14:17 | dna | | | | |

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Application version: TRESLIB 2.0 Module version: 1.5

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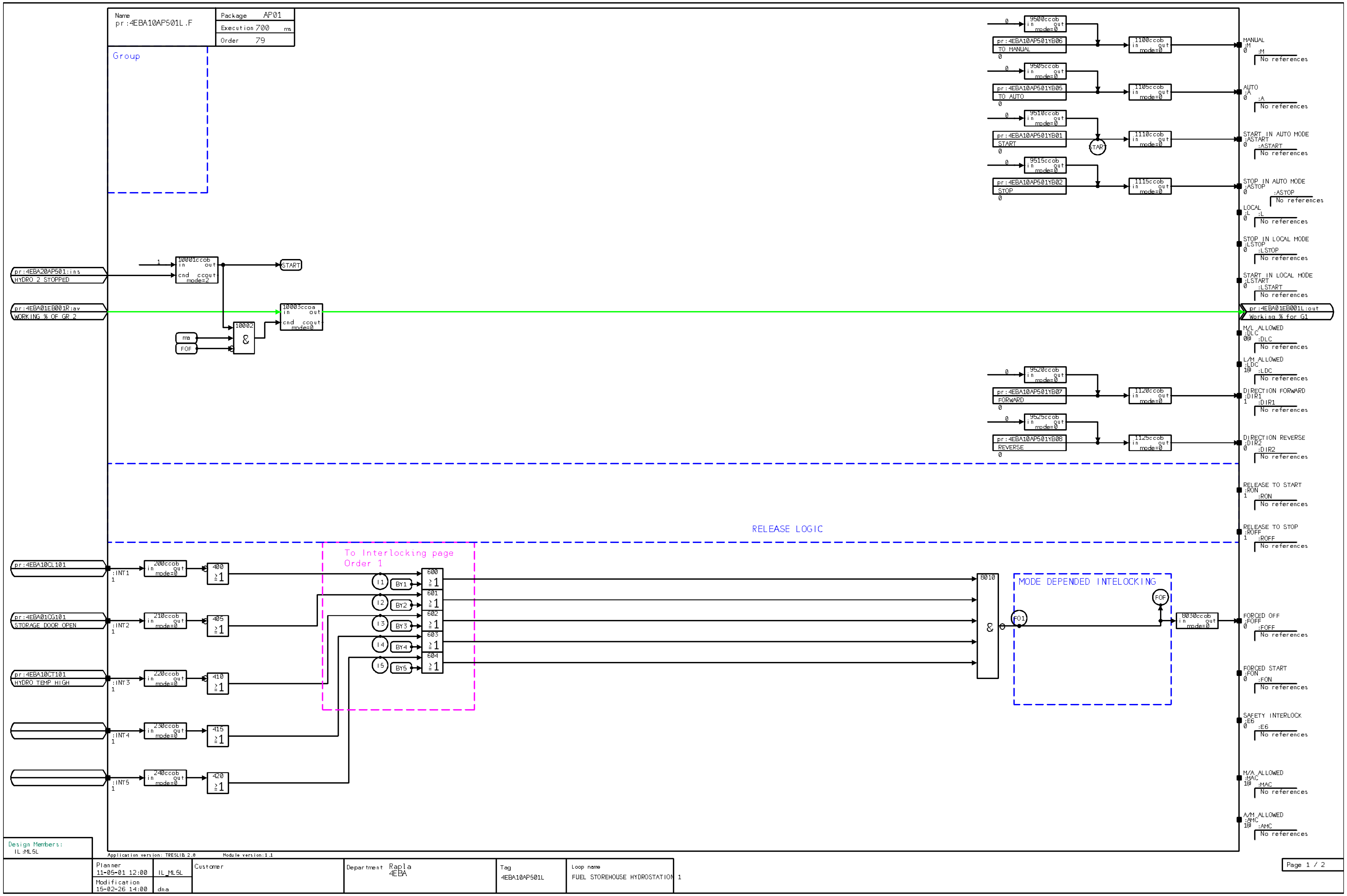
|---|---|---|---|---|---|---|
| Modification | 15-03-10 15:13 | dna | | | | |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Group
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HYDRO 2 STOPPED
pr:4EBA01EB001R:av
WORKING % OF GR 2
START
ma
FOF
pr:4EBA10AP501YB06
TO MANUAL
pr:4EBA10AP501YB05
TO AUTO
pr:4EBA10AP501YB01
START
pr:4EBA10AP501YB02
STOP
pr:4EBA10AP501YB07
FORWARD
pr:4EBA10AP501YB08
REVERSE
MANUAL
AUTO
START IN AUTO MODE
STOP IN AUTO MODE
LOCAL
STOP IN LOCAL MODE
START IN LOCAL MODE
pr:4EBA01EB001L:out
Working % for G1
M/L ALLOWED
L/M ALLOWED
DIRECTION FORWARD
DIRECTION REVERSE
RELEASE TO START
RELEASE TO STOP
FORCED OFF
FORCED START
SAFETY INTERLOCK
M/A ALLOWED
A/M ALLOWED
No references
RELEASE LOGIC
pr:4EBA10CL101
pr:4EBA01CG101
STORAGE DOOR OPEN
pr:4EBA10CT101
HYDRO TEMP HIGH
To Interlocking page
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Application version: TRESLIB 2.0
Module version: 1.1
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IL_ML5L
Modification
15-02-26 14:00
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Customer
Department Rapla
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Tag
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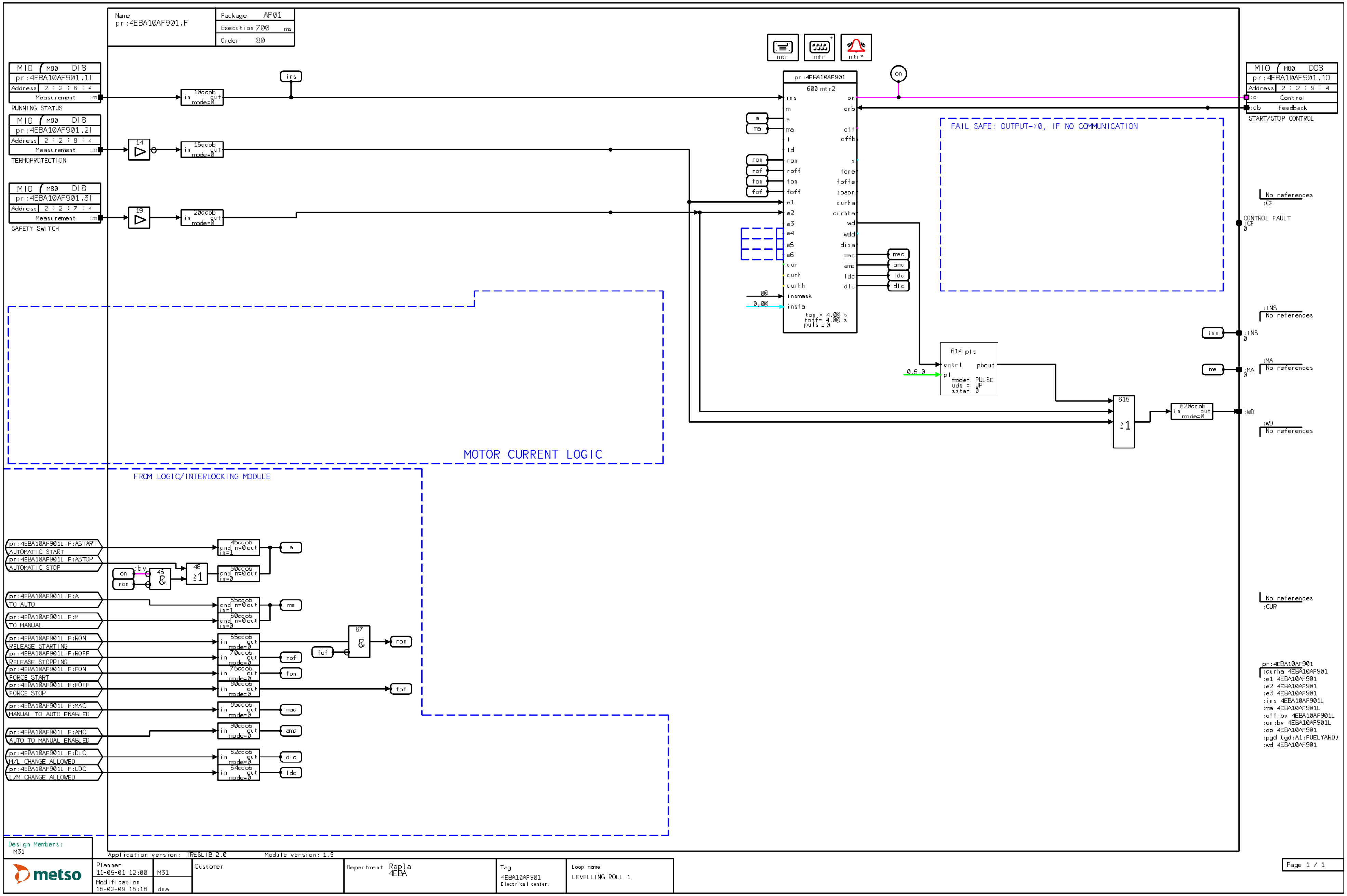
Loop name
FUEL STOREHOUSE HYDROSTATION 1
Page 1 / 2



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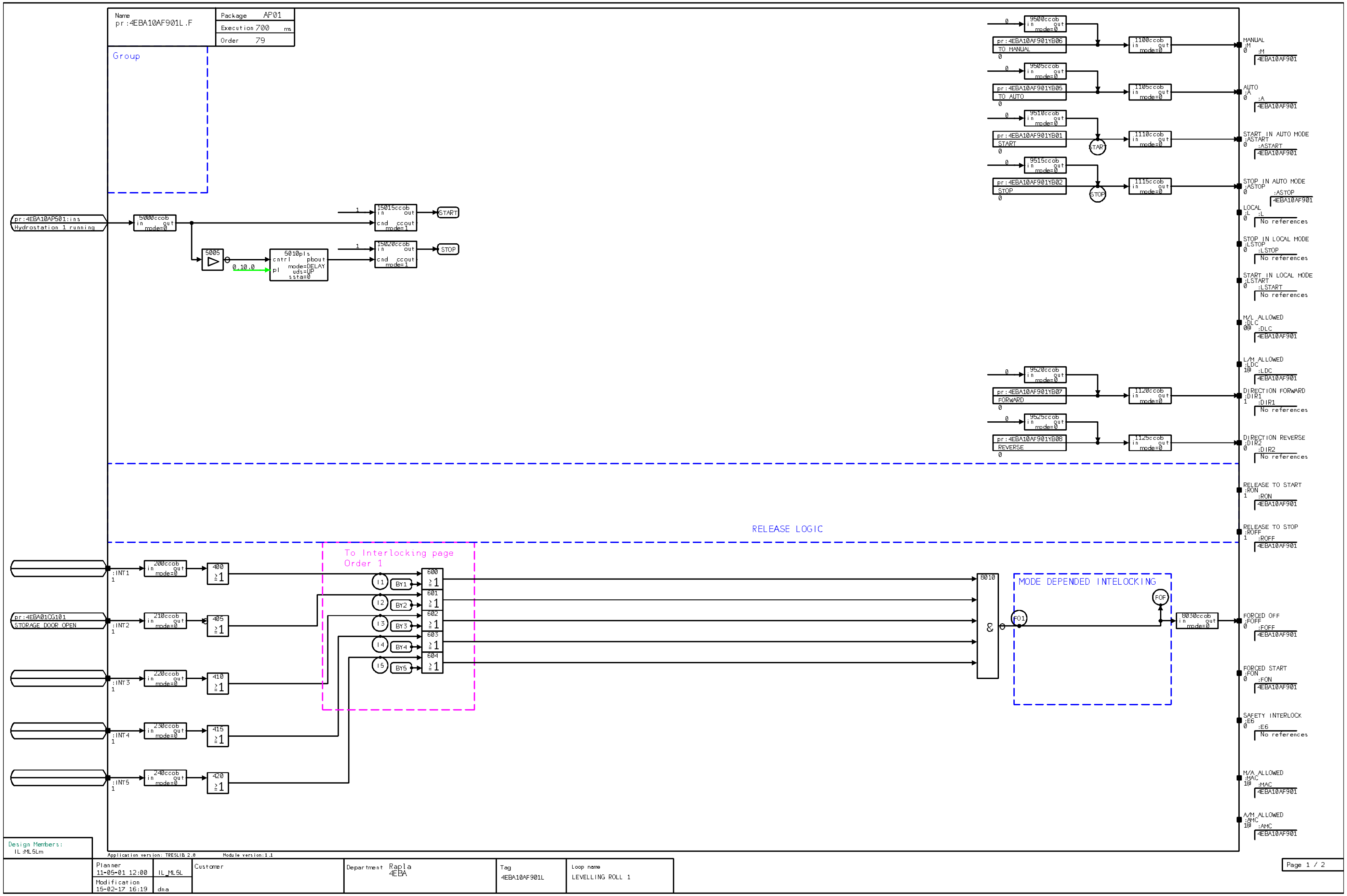
RUNNING STATUS
MIO M80 DI8 pr:4EBA10AF901.2I Address 2 : 2 : 8 : 4 Measurement
TERMOPROTECTION
MIO M80 DI8 pr:4EBA10AF901.3I Address 2 : 2 : 7 : 4 Measurement
SAFETY SWITCH
MIO M80 DO8 pr:4EBA10AF901.1O Address 2 : 2 : 9 : 4 Control Feedback
START/STOP CONTROL
pr:4EBA10AF901
600 mtr2
FAIL SAFE: OUTPUT->0, IF NO COMMUNICATION
CONTROL FAULT
No references
614 pls
615
620ccob
MOTOR CURRENT LOGIC
FROM LOGIC/INTERLOCKING MODULE
pr:4EBA10AF901L.F:ASTART AUTOMATIC START
pr:4EBA10AF901L.F:ASTOP AUTOMATIC STOP
pr:4EBA10AF901L.F:A TO AUTO
pr:4EBA10AF901L.F:M TO MANUAL
pr:4EBA10AF901L.F:RON RELEASE STARTING
pr:4EBA10AF901L.F:ROFF RELEASE STOPPING
pr:4EBA10AF901L.F:FON FORCE START
pr:4EBA10AF901L.F:FOFF FORCE STOP
pr:4EBA10AF901L.F:MAC MANUAL TO AUTO ENABLED
pr:4EBA10AF901L.F:AMC AUTO TO MANUAL ENABLED
pr:4EBA10AF901L.F:DLC M/L CHANGE ALLOWED
pr:4EBA10AF901L.F:LDC L/M CHANGE ALLOWED
pr:4EBA10AF901
:curha 4EBA10AF901
:e1 4EBA10AF901
:e2 4EBA10AF901
:e3 4EBA10AF901
:ins 4EBA10AF901L
:ma 4EBA10AF901L
:off:bv 4EBA10AF901L
:on:bv 4EBA10AF901L
:op 4EBA10AF901
:pgd (gd:A1:FUELYARD)
:wd 4EBA10AF901
Design Members: M31
Application version: TRESLIB 2.0
Module version: 1.5
metso
Planner 11-05-01 12:00 M31
Modification 15-02-09 15:18 dna
Customer
Department Rapla 4EBA
Tag 4EBA10AF901 Electrical center:
Loop name LEVELLING ROLL 1
Page 1 / 1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Execution 700 ms
Order 79
Group
pr:4EBA10AP501:ins Hydrostation 1 running
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pr:4EBA10AF901YB05 TO AUTO
pr:4EBA10AF901YB01 START
pr:4EBA10AF901YB02 STOP
pr:4EBA10AF901YB07 FORWARD
pr:4EBA10AF901YB08 REVERSE
MANUAL :M
AUTO :A
START IN AUTO MODE :ASTART
STOP IN AUTO MODE :ASTOP
LOCAL :L
STOP IN LOCAL MODE :LSTOP
START IN LOCAL MODE :LSTART
M/L ALLOWED :DLC
L/M ALLOWED :LDC
DIRECTION FORWARD :DIR1
DIRECTION REVERSE :DIR2
RELEASE TO START :RON
RELEASE TO STOP :ROFF
FORCED OFF :FOFF
FORCED START :FON
SAFETY INTERLOCK :E6
M/A ALLOWED :MAC
A/M ALLOWED :AMC
4EBA10AF901
No references
RELEASE LOGIC
To Interlocking page Order 1
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:INT1
:INT2
:INT3
:INT4
:INT5
Design Members: IL:ML5Lm
Application version: TRESLIB 2.0
Module version: 1.1
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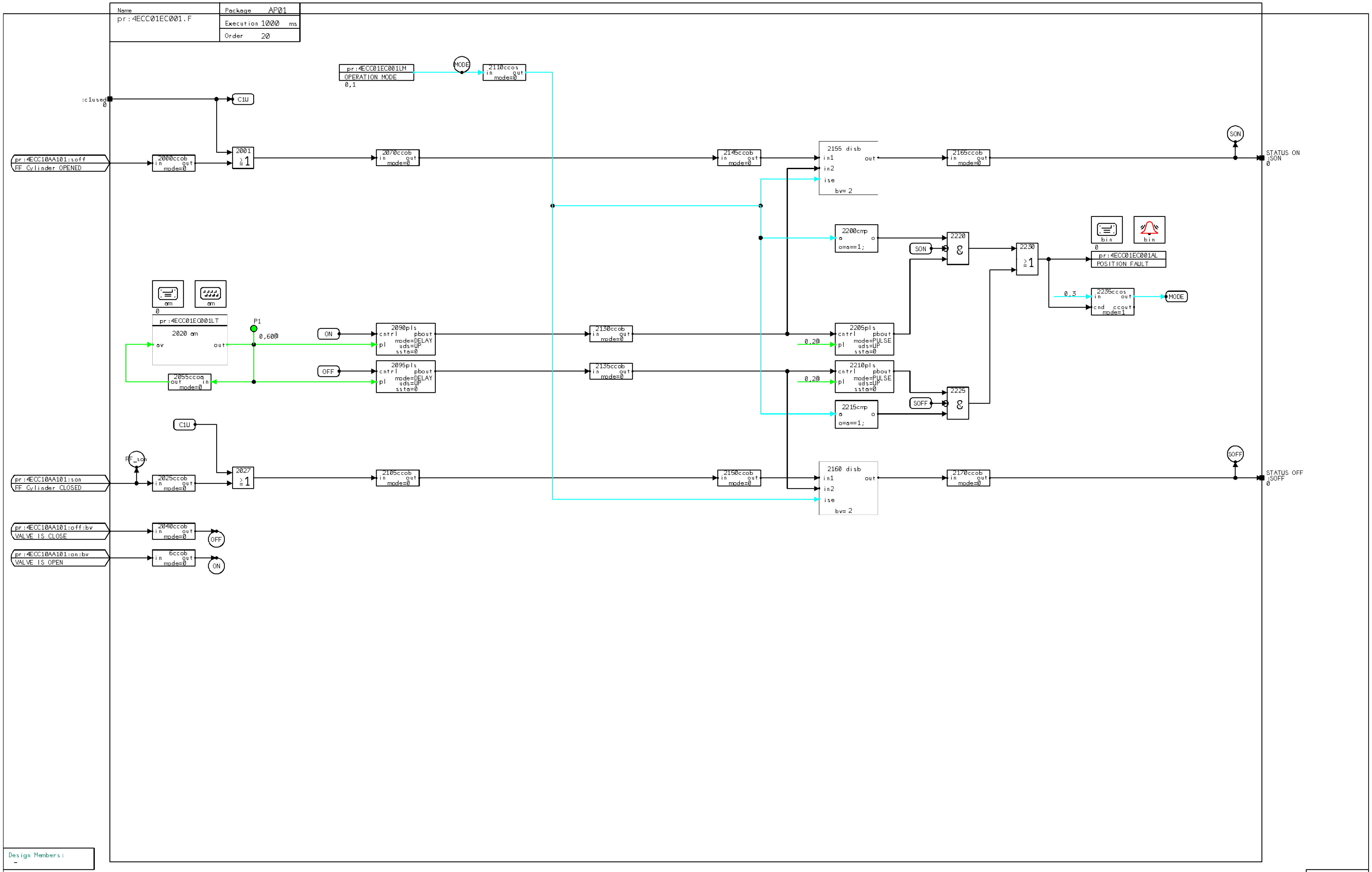
Modification 15-02-17 16:19 dna
Customer
Department Rapla 4EBA
Tag 4EBA10AF901L
Loop name LEVELLING ROLL 1
Page 1 / 2

# APPENDIX 3 – FUEL FEEDING FROM MINI-SILO APPLICATION

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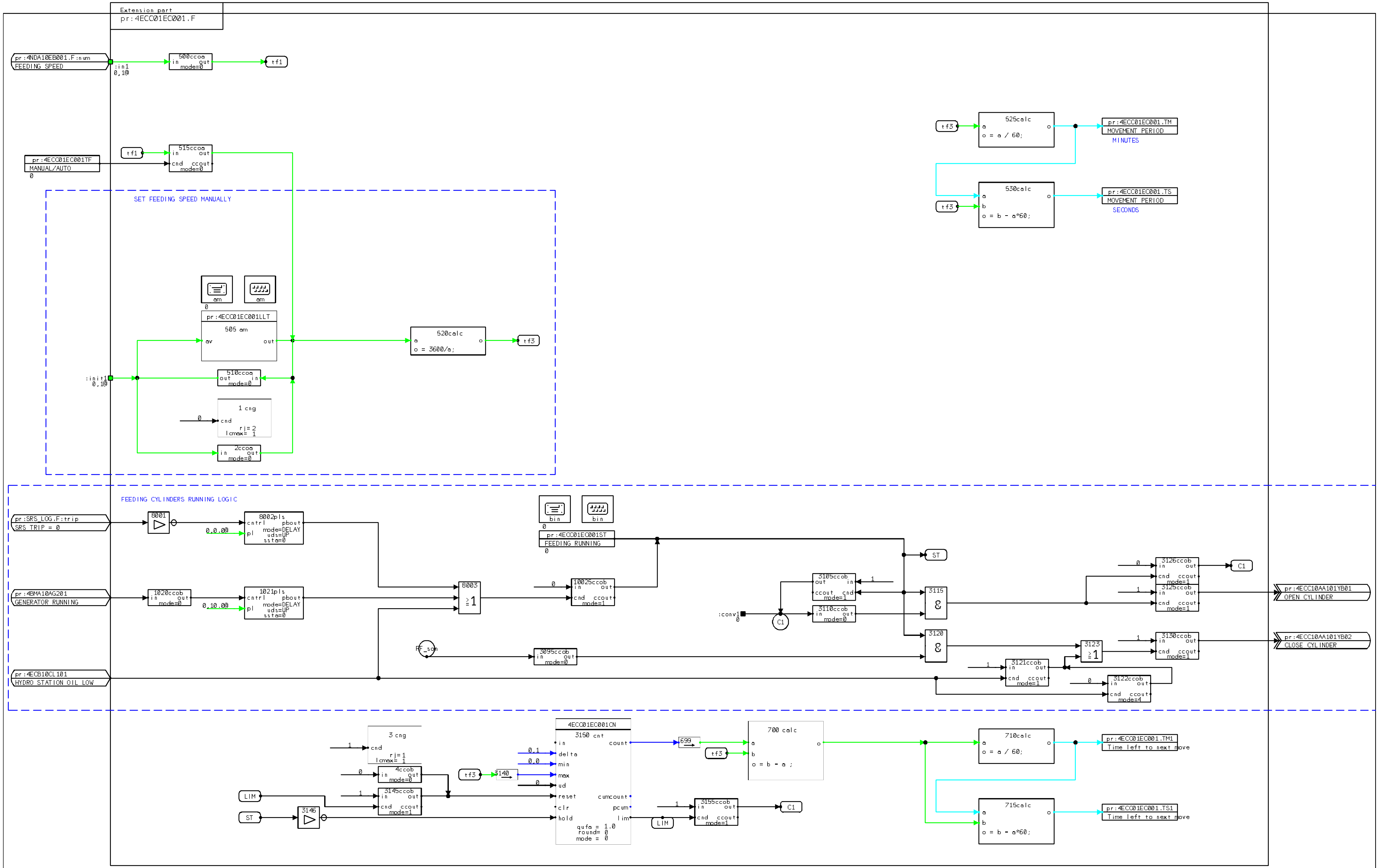
| Modification 15-03-03 10:47 | dna | | | | |

Page 1 / 2




metso

| Planner | | Customer | Department | Tag | Loop name |
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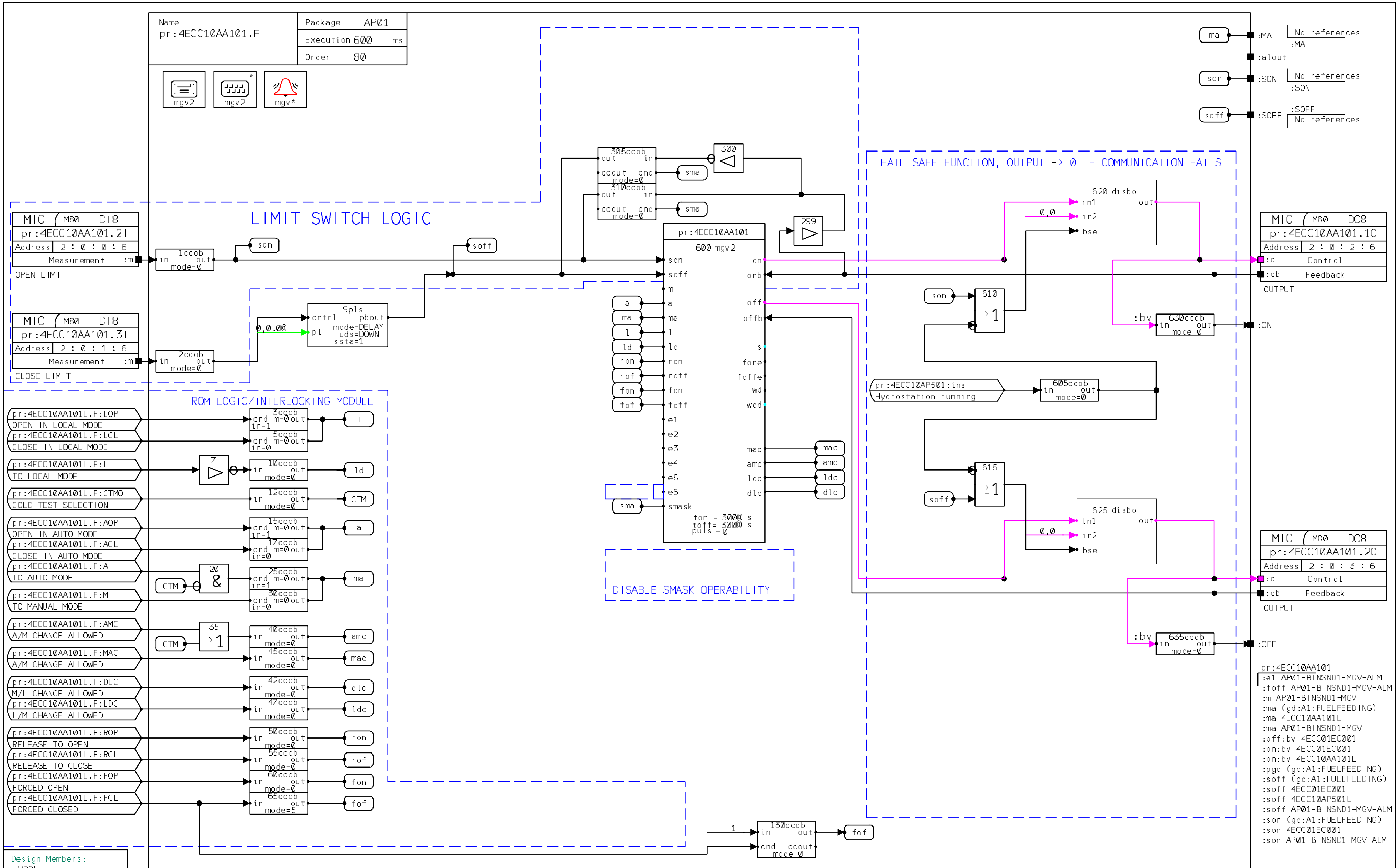
| Modification 15-03-03 10:47 | dna | | | | |

Page 2 / 2

Name pr:4ECC10AA101.F

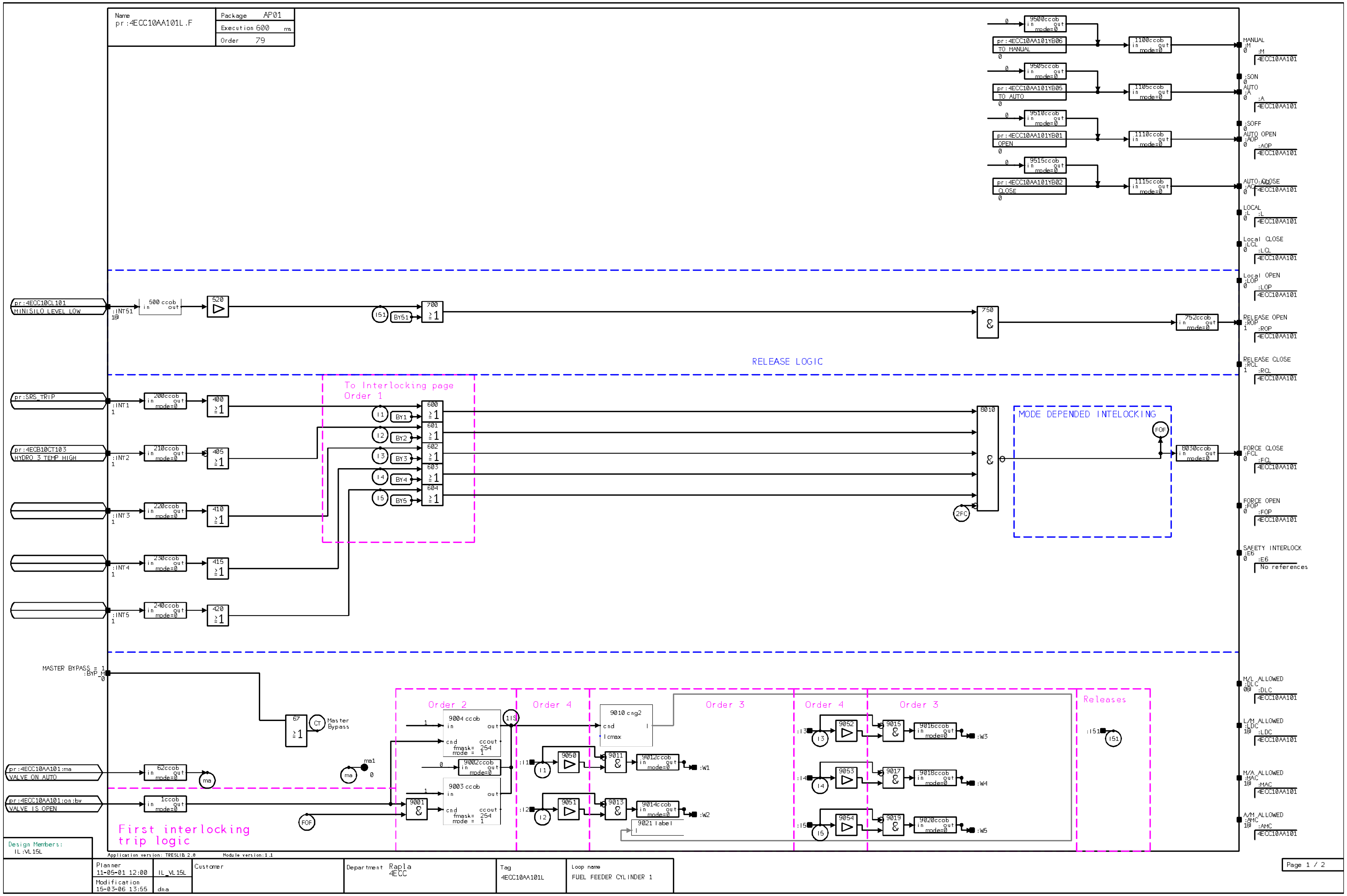
Package AP01 | Execution 600 ms | Order 80




Design Members: V22Lm

Application version: TRESLIB 2.0 Module version: 1.0

| | | | | | |
|---|---|---|---|---|---|
| metso | Planner 98-09-23 12:45 V22Lm / Modification 15-03-05 17:51 dna | Customer | Department Rapla 4ECC | Tag 4ECC10AA101 | Loop name FUEL FEEDER CYLINDER 1 |


Name pr:4ECC10AA101L.F
Package AP01
Execution 600 ms
Order 79
MANUAL
AUTO
AUTO OPEN
AUTO CLOSE
LOCAL
Local CLOSE
Local OPEN
RELEASE OPEN
RELEASE CLOSE
FORCE CLOSE
FORCE OPEN
SAFETY INTERLOCK
No references
M/L ALLOWED
L/M ALLOWED
M/A ALLOWED
A/M ALLOWED
RELEASE LOGIC
MODE DEPENDED INTELOCKING
To Interlocking page Order 1
pr:4ECC10CL101 MINISILO LEVEL LOW
pr:SRS_TRIP
pr:4ECB10CT103 HYDRO 3 TEMP HIGH
MASTER BYPASS
Master Bypass
pr:4ECC10AA101:ma VALVE ON AUTO
pr:4ECC10AA101:on:bv VALVE IS OPEN
First interlocking trip logic
Order 2
Order 4
Order 3
Releases
Design Members: IL:VL15L
Application version: TRESLIB 2.0
Module version:1.1
Planner 11-05-01 12:00 IL_VL15L
Modification 15-03-06 13:55 dna
Customer
Department Rapla 4ECC
Tag 4ECC10AA101L
Loop name FUEL FEEDER CYLINDER 1
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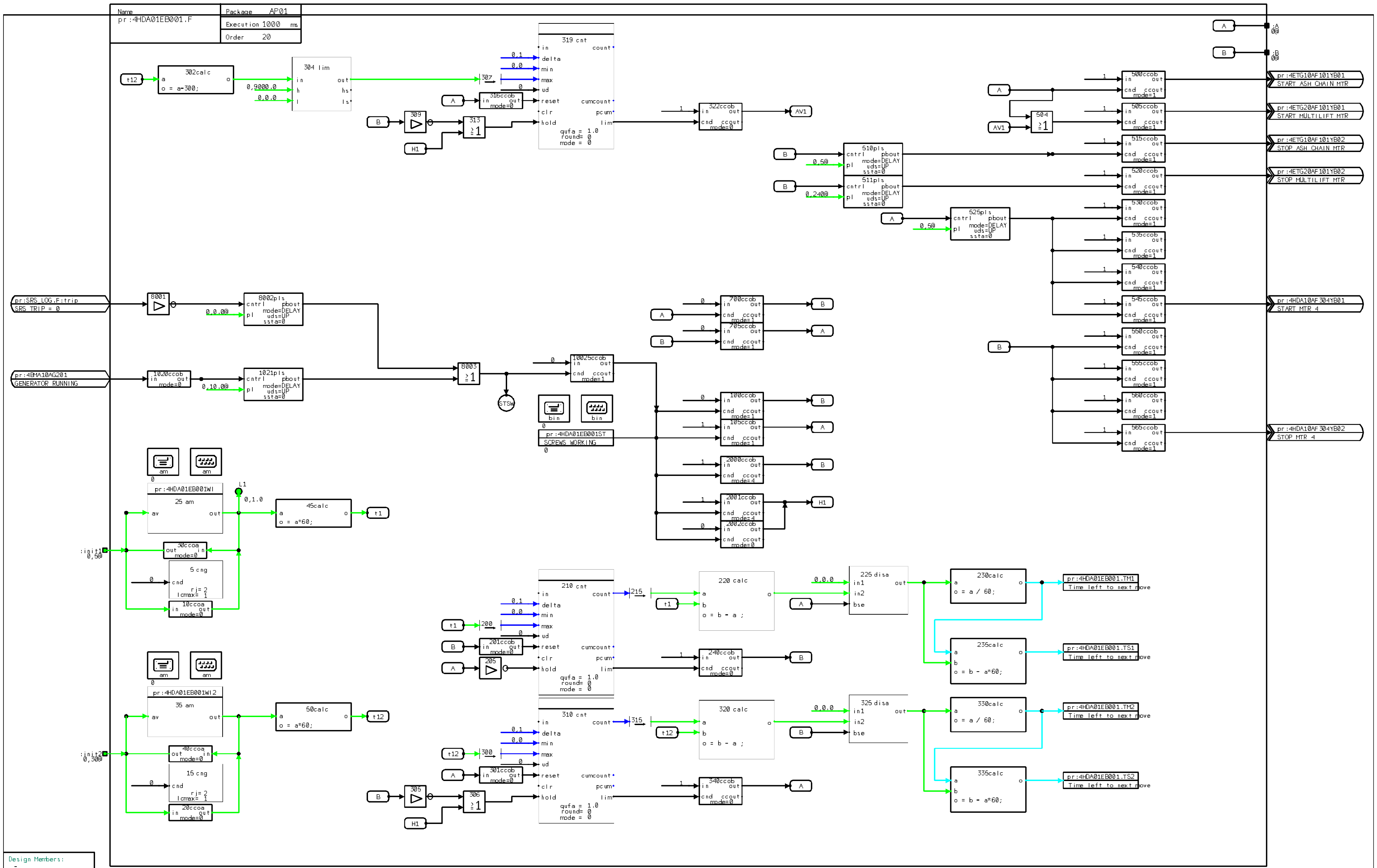
# APPENDIX 4 – ASH DISPOSAL APPLICATION




Design Members:

metso

| Planner | | Customer | Department | Tag | Loop name |
|---|---|---|---|---|---|
| 14-11-19 15:15 | dna | | Rapla 4HDA | 4HDA01EB001 | ASH CONVEYOR WORKING LOGIC |
| Modification 15-03-05 16:47 | dna | | | | |

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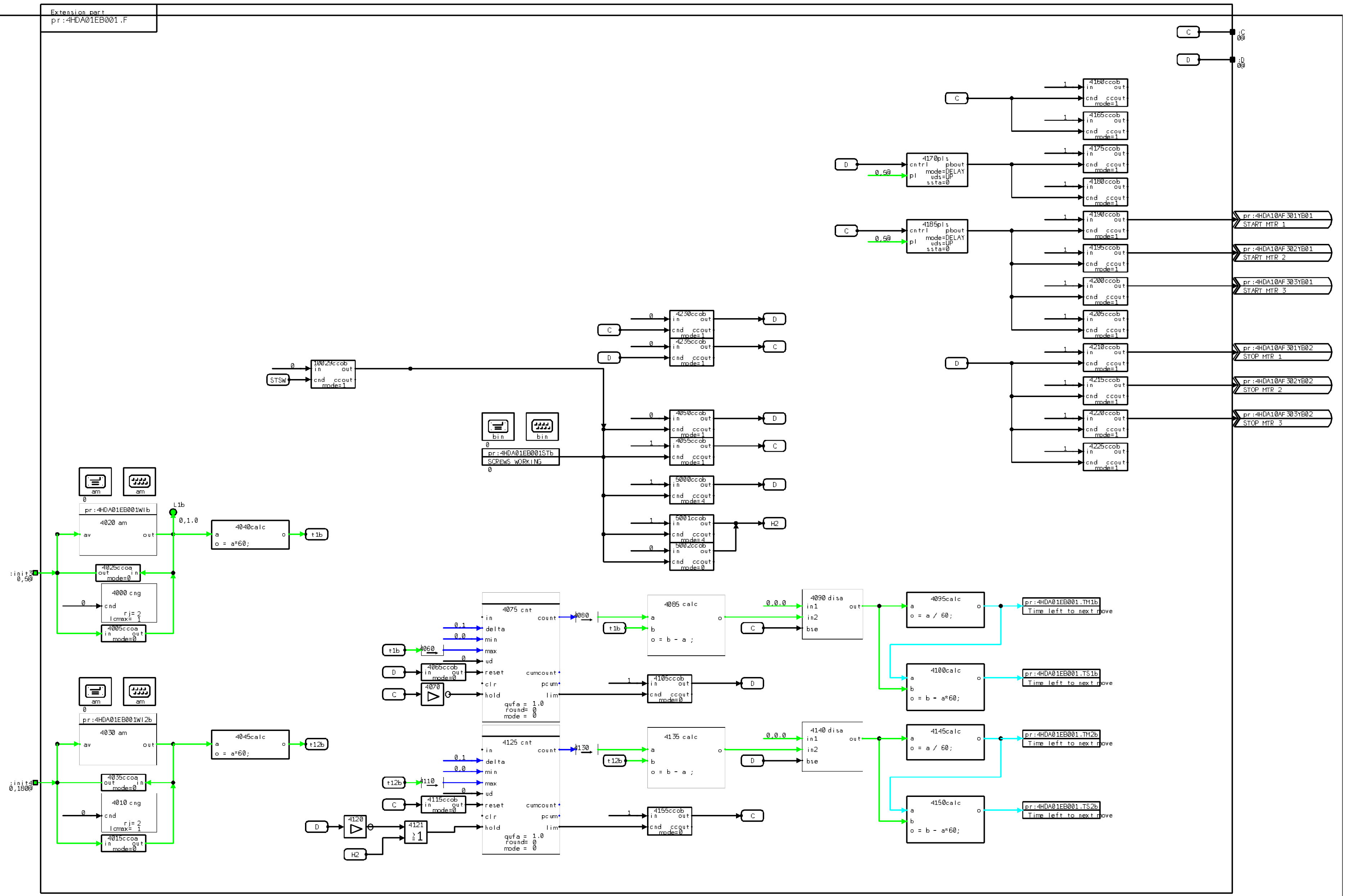


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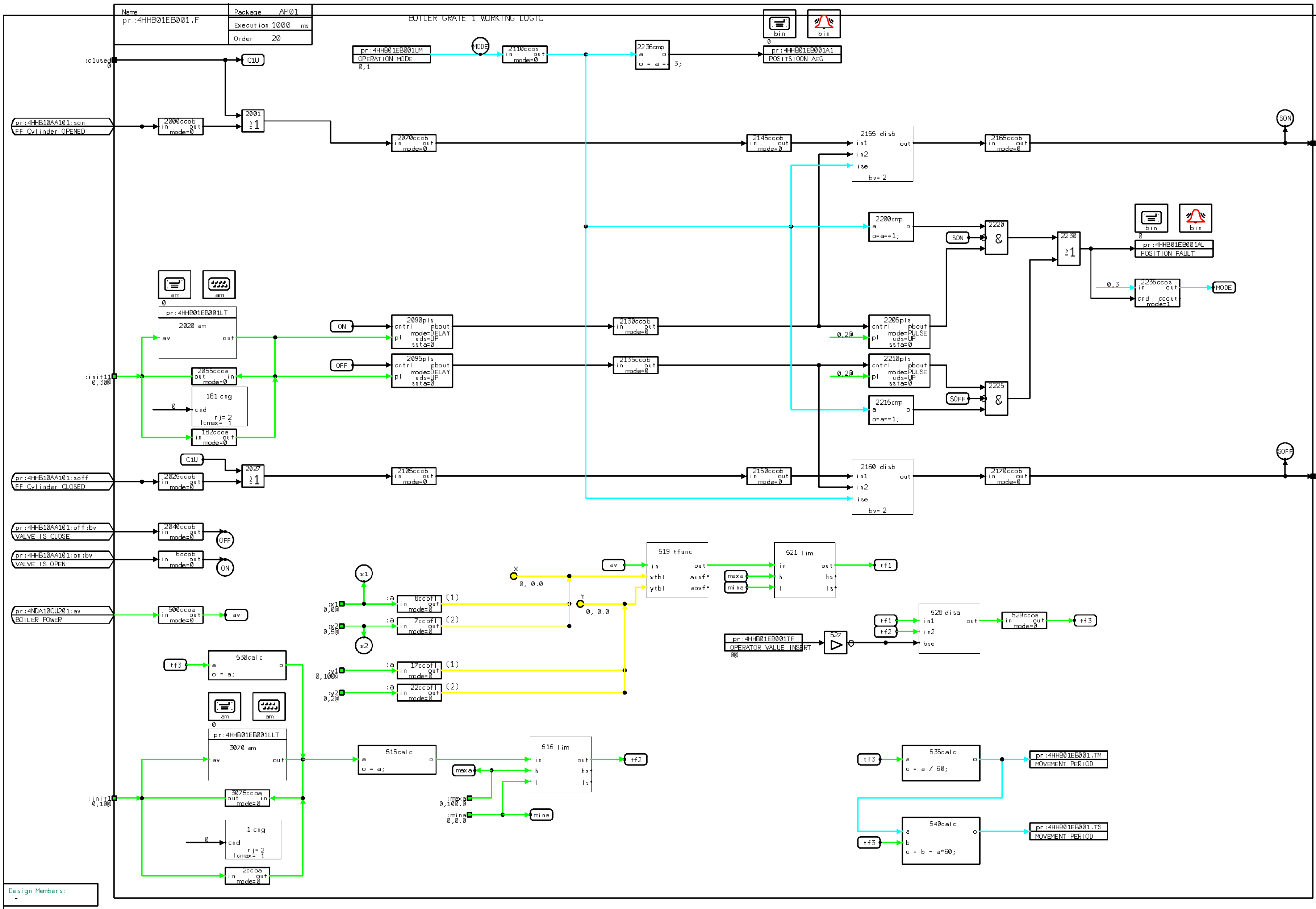
| Planner | Customer | Department | Rapla | Tag | Loop name |
|---|---|---|---|---|---|
| 14-11-19 15:15 dna | | | 4HDA | 4HDA01EB001 | ASH CONVEYOR WORKING LOGIC |
| Modification 15-03-05 16:47 dna | | | | | |

# APPENDIX 5 – GRATE CONTROL APPLICATION




Design Members:
-

metso

| Planner 14-11-17 15:24 | dna | Customer | Department Rapla 4HHB | Tag 4HHB01EB001 | Loop name GRATE LOGIC |
|---|---|---|---|---|---|
| Modification 15-04-02 15:12 | dna | | | | |

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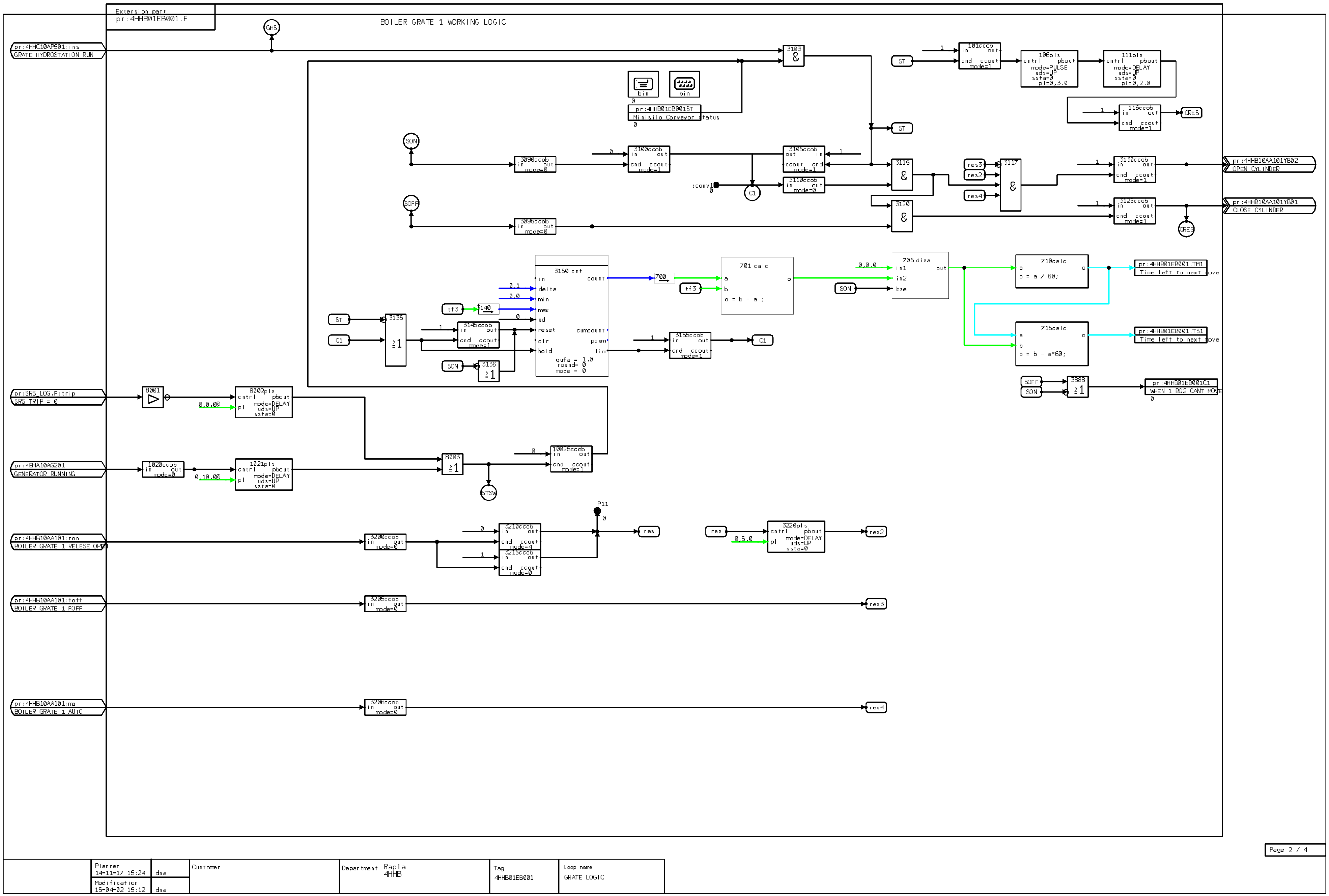
Extension part
pr:4HHB01EB001.F
BOILER GRATE 1 WORKING LOGIC
pr:4HHC10AP501:ins
GRATE HYDROSTATION RUN
pr:SRS_LOG.F:trip
SRS TRIP = 0
pr:4BMA10AG201
GENERATOR RUNNING
pr:4HHB10AA101:ron
BOILER GRATE 1 RELESE OPEN
pr:4HHB10AA101:foff
BOILER GRATE 1 FOFF
pr:4HHB10AA101:ma
BOILER GRATE 1 AUTO
pr:4HHB10AA101YB02
OPEN CYLINDER
pr:4HHB10AA101YB01
CLOSE CYLINDER
pr:4HHB01EB001.TM1
Time left to next move
pr:4HHB01EB001.TS1
Time left to next move
pr:4HHB01EB001C1
WHEN 1 BG2 CANT MOVE
pr:4HHB01EB001ST
Minisilo Conveyor status
701 calc
o = b - a ;
710calc
o = a / 60;
715calc
o = b - a*60;
705 disa
3150 cnt
qufa = 1.0
round= 0
mode = 0
106pls
mode=PULSE
111pls
mode=DELAY
8002pls
1021pls
3220pls
Page 2 / 4
Planner
14-11-17 15:24
dna
Modification
15-04-02 15:12
dna
Customer
Department Rapla
4HHB
Tag
4HHB01EB001
Loop name
GRATE LOGIC