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Automation of Industrial Dual Fuel Water Heating Boiler on the example of Iru Powerplant

Master's thesis

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Tööstusliku kahekütuselise veeküttekatla automatiseerimine Iru elektrijaama näitel

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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.

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Abstract

The control system of an industrial water heating boiler, which can operate on two distinct types of fuel, poses challenges in terms of safety and environmental standards. Natural Gas and Diesel require different air-fuel mixtures to maximize utilization of the combustion products. Regardless, the paper focuses on the automation and control system of the dual-fuel boiler, with a discussion on the IEC 61508 standard and its influence on the control system design. The main control system of the boiler is governed by safety logic, which means that burner operation is restricted based on safety conditions. Safety conditions are triggered to halt hazardous burner operations and prevent accidents. The project's objective is to successfully integrate various systems to renovate the dual-fuel water heating boiler for further use.

The paper delves into the details of how the control system can meet these requirements while highlighting specific cases that require careful execution. As an example, upholding powerplant SIL level with certified devices and carefully constructed logic and maintaining proper fuel mixture.

This thesis is written in English and is 47 pages long, including 6 chapters, 23 figures and 8 tables.

Annotatsioon

Tööstusliku kahekütuselise veeküttekatla automatiseerimine Iru elektrijaama näitel

Tööstusliku veesoojenduskatla, mis võib töötada kahel erineval kütuseliigil, juhtimissüsteemiga kaasnevad ohutus- ja keskkonnanormide osas erilised väljakutsed. Maagaas ja diisel nõuavad erinevaid õhk-kütusesegusid, et põlemissaadusi maksimaalselt ära kasutada. Sellest vaatamata keskendutakse käesolevas dokumendis kahe kütusega katla automatiseerimis- ja juhtimissüsteemile ning arutletakse standardi IEC 61508 ja selle mõju üle juhtimissüsteemi projekteerimisele. Katla peamist juhtimissüsteemi reguleerib ohutusloogika, mis tähendab, et põleti tööd piiratakse ohutustingimuste alusel. Ohutustingimused käivituvad, et peatada ohtlik põleti töö ja vältida õnnetusi. Projekti eesmärk on edukalt integreerida erinevad süsteemid, et renoveerida kahe kütusega veeküttekatel edasiseks kasutamiseks.

Dokumendis süvenetakse üksikasjadesse, kuidas juhtimissüsteem suudab neid nõudeid täita, tuues samal ajal välja konkreetsed juhtumid, mis nõuavad hoolikat teostamist. Näiteks elektrijaama SIL-taseme säilitamine sertifitseeritud seadmete ja loogika abil ning õige kütusesegu säilitamine.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 47 leheküljel, 6 peatükki, 23 joonist, 8 tabelit.

List of abbreviations and terms

CHP	Combined Heat Powerplant
CO	Carbon Oxide
DCS	Distributed Control System
FIF	Fuel Input Factor
HFO	Heavy Fuel Oil
HIMatrix	Safety-related Controller system
I/O	Input / Output
LFO	Light Fuel Oil
LNG	Liquefied Natural Gas
MPC	Model Predictive Controller
MW	Megawatts
NO	Nitrogen Oxide
PFD	Probability of Failure on Demand
PID	Proportional-Integral Derivative
PLC	Programmable Logic Controller
PLU	Programmable Logic Unit
SafeEDR	SafeEthernet UDP integration
SafeEthernet	a protocol for transmitting safety-related data up to SIL 4
SIL	Safety Integrity Level
SO	Sulfur oxide
SRS	Safety Related System

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1 Introduction

Control systems are essential in many industries, providing autonomous process observation and regulation of processes, thereby eliminating the need for human intervention. Proactive process control plays a critical role in ensuring safe operation and preventing hazardous conditions. In instances where strict safety requirements are in place, Safety Related Systems are employed to oversee specific aspects of the process. The automation facilitated by control systems delivers consistent and reliable performance and reduces variability and errors associated with manual operation, improving operational efficiency, reduces downtime, and lowers operational costs, ultimately leading to better profitability. One of the key features is adaptability to changing operating conditions and fluctuations in demand or environmental factors, enabling the maintenance of optimal performance levels. Another advantage is the ability to remotely monitor processes, especially in DCS-based systems, in real-time from a centralized location, providing factory personnel with increased operational flexibility.

Furthermore, control systems aid in ensuring compliance with industry regulations and standards by accurately monitoring and documenting process parameters. It is crucial to design control systems with compliance considerations in mind, considering relevant industry regulations and standards, because control systems operate within the confines of their design and hardware limitations. The control process generates substantial amounts of data, serving as an asset for continuous improvement, and enabling process optimization through data analysis and feedback mechanisms. By harnessing this data, alternative control methods can be developed to improve efficiency.

This paper focuses on providing information about the project, the scope of the project, and the author's contributions to the project.

1.1 Project significance

The project's significance lies in bringing the Boiler control system up to modern control and environmental standards through the introduction of flexible burner power control and modernization of the existing control system and by delivering improvements to Safety Related System. Reduction of NO_x emissions through Flue Gas recirculation is one of the key parts of the project. The project development has taken quite a bit of time since the initial start date of the project, however, changes had to be made to account for problems encountered during the testing/commissioning phase.

1.2 Task Specification

The primary challenge in automating the dual fuel water heating boiler is moving the current automation system from outdated hardware to up-to-date modern hardware, all the while adding new features and fixing drawbacks from the old system.

Upgrading the system requires additional work because it contains working logic and devices slated to be re-used. For power plant operation, the boiler's automation must adhere to IEC 61508 standards and use hardware compatible with SIL 3-level, meaning that safety hardware should be confined to the Safety System, otherwise, that decreases SIL level beyond minimal for the powerplant operation. SIL level is based upon the idea of the Probability of Failure on Demand values. For the SIL 3-level, those values are the following: Low demand mode of operation: $> 10^{-4}\ to\ < 10^{-3}$; High demand mode of operation: $> 10^{-8}\ to\ < 10^{-7}$. A more in-depth discussion of this topic will be in the SIL level determination heading.

Overarching project goals:

- Flexible Control System for low-power output boiler
    - Small-step heat output control for individual burners
- Achieving low NO_x emissions
    - Flue Gas Recirculation
- Dual Fuel usage
    - Fuel Supply System for Natural Gas (LNG)
    - Fuel Supply System for the Diesel Fuel (LFO)
        - Diesel Fuel preconditioning
- Safety Related Burner Management System

Personal project Goals:

- Understanding the background requirements of industrial water heating boiler automation
- Fuel Usage and Importance of Fuel Mixture
    - Fuel/Air Mixture (Higher Air content for Diesel Fuel)
- How Safety Integrity Level influences hardware choices
    - Different controller usage
    - Controller certification
    - Monitoring device Certification

1.3 Scope

The paper primarily emphasizes the automation of the dual-fuel water heating boiler and the essential background knowledge necessary for its successful integration into the control system. While the document may not explicitly elaborate on this deeper aspect of boiler automation, the inherent complexity and importance of boiler operations underscore the significance of meticulous adherence to all automation requirements.

Boiler automation requirements encompass a myriad of factors, ranging from temperature regulation and fuel management to pressure control and emergency shutdown procedures. Each requirement is intrinsically linked to the safe and efficient operation of the boiler system. Neglecting any of these requirements can have far-reaching consequences, jeopardizing not only operational efficiency but also posing serious risks to personnel safety and asset integrity.

The focus of the work on the interconnection of requirements underscores the holistic approach necessary for effective boiler automation. The integration of these requirements is not merely a checklist exercise, but a meticulous orchestration aimed at ensuring seamless operation and optimal performance.

By weaving together the various automation requirements, the control system can effectively govern the in-depth dynamics of the boiler operation.

Furthermore, the document highlights the paramount importance of aligning the implementation of automation requirements with the safety system. The safety system serves as the linchpin in safeguarding the boiler's operation against potential hazards and mitigating risks to personnel and equipment. Therefore, the control system must operate in symbiosis with the safety system.

By working in tandem with the safety system, the control system can uphold the overarching goal of maintaining safe and reliable boiler operations. This collaborative approach mitigates the risk of interference between systems, thereby bolstering operational integrity and minimizing the likelihood of accidents or malfunctions. Consequently, adherence to all boiler automation requirements, coupled with seamless integration with the safety system, is indispensable for ensuring the safe, efficient, and sustainable operation of the dual-fuel water heating boiler.

1.4 Motivation behind the project

The author's motivation for undertaking the project stems from a desire to gain a comprehensive understanding of the intricacies involved in automating an industrial water heating boiler. Coming from a background in embedded programming, where the focus tends to be more on software development rather than physical processes, the author recognizes the importance of bridging the gap between theoretical knowledge and practical application in the realm of boiler automation.

By delving into the details of how automation is achieved in the context of an industrial water heating boiler, the author aims to enhance their proficiency in designing and implementing suitable control systems. Understanding the physical processes underlying boiler operation provides invaluable insights into the nuances of system dynamics, enabling the author to devise more effective automation strategies tailored to specific operational requirements.

From the perspective of the customer, automation of the boiler represents more than just a technical upgrade—it is a strategic investment with multifaceted benefits. Primarily, automation aligns boiler operations with environmental emissions requirements, ensuring compliance with regulatory standards and mitigating the ecological footprint of industrial activities. By modernizing both the boiler and its associated control system, the customer gains the flexibility to adapt to evolving regulatory frameworks and environmental mandates, thus future-proofing their operations against regulatory uncertainties.

Moreover, the modernization of the boiler and control system translates into operational advantages beyond regulatory compliance. Upgrading to state-of-the-art hardware enhances the efficiency, reliability, and safety of boiler operations, thereby minimizing downtime and maximizing productivity. The availability of up-to-date hardware facilitates easier maintenance and replacement procedures, reducing operational disruptions and enhancing overall system resilience.

In essence, the project serves as a catalyst for knowledge acquisition and skill enhancement, empowering the author to navigate the intricacies of boiler automation with confidence and proficiency. Simultaneously, from the customer's perspective, the automation initiative represents a strategic investment aimed at enhancing operational efficiency, ensuring regulatory compliance, and future-proofing boiler operations against evolving technological and environmental landscapes.

2 Literature review

To begin with, let's examine the process of regulating an Industrial water heating boiler by controlling the output of each burner in precise increments of a few MW. Following that, we will explore strategies to minimize NO_x emissions and incorporate the use of dual fuel in the system. Last, but certainly not least, we will address the Safety Related System.

2.1 Flexible Control

The intermittent, fluctuating, and random nature of renewable energy power generation poses significant challenges to the security, stability, and economic operation of the power grid. [1] As the proportion of renewable energy in the power system increases, the basic support power supply may become insufficient, leading to a lack of deployment capacity across different times and seasons. This can result in continuous peak operation pressure and affect the balance and stability of the power system.

In response to these challenges, traditional thermal power units are undergoing performance improvements and flexibility transformation. Furthermore, the application of energy storage technology has provided practical solutions for thermal power units to engage in "peak-shaving and valley-filling" activities. Peak-shaving and valley-filling refer to the use of energy storage technology to address the fluctuating electricity demand throughout the day. During peak hours, when electricity demand is high, the stored energy is used to "shave" or lessen the peak load on the power grid, thereby reducing strain on the system. Conversely, during off-peak hours, excess energy is stored, effectively "filling" the energy "valleys" by capturing and storing the surplus electricity for later use. This method helps in stabilizing the grid, balancing the energy supply and demand, and enhancing the overall efficiency and reliability of the power system. It's important to find the right balance, as an excessive configuration of energy storage can not only reduce the installed scale of supporting power supplies such as thermal power units but also impact the economic operation of the power system.

The flexible adjustment ability of thermal power units in combination with energy storage has become crucial to ensure the security and stable operation of the power system, but flexible power output of the Industrial Water heating boiler requires finding optimal conditions for operating as can be understood from following paper [2], proposing a simple and cost-effective solution for optimizing small-scale biomass boilers.

It emphasizes achieving optimal operation conditions with maximal effect on the overall function of the controlled device, introducing an extreme-seeking algorithm for achieving optimal operating conditions, particularly in combustion devices such as biomass-fired boilers. The proposed algorithm involves changing the quantity of combustion air and evaluating its impact on fuel consumption and CO_2 emission, ultimately aiming to minimize fuel consumption.

To expand more on the optimization of the operating conditions, we can look further. Study [3] confirms the successful enhancement of the CHP plant's peak shaving capabilities through the proposed dry/wet state automatic conversion control scheme.

The concept of "dry/wet state" refers to the varying conditions of the working fluid within a once-through boiler in a combined heat and power plant. This distinction is crucial for the efficient and flexible operation of the plant, especially in achieving deep peak shaving under full operating conditions. The dry/wet state conversion control scheme is designed to address and optimize the transition between these two states of the working fluid. In the "dry" state, the working fluid within the boiler exists as steam due to the higher load, while in the "wet" state, the working fluid exists as a steam-water mixture in response to lower loads. Efficient and smooth transitions between these states are vital for maintaining operational stability, reducing energy costs, and minimizing harmful emissions.

We have grazed the concept of optimal combustion conditions and minimizing emissions, but what emissions and combustion conditions should we look for when designing a boiler control scheme?

2.2 Low NO_x emissions

Automation of industrial water heating boilers encapsulates various fields of scientific research to increase the efficiency of fuel burning. Combust product recirculation yields the best efficiency gains. But understanding where efficiency gains come from takes looking back at the diverse research. The first thing to start is fuel and combustion characteristics.

2.2.1 Fuel and Combustion product mixtures.

Research [4] suggests that attaining the most cost-efficient fuel combination for industrial power plants requires minimizing the utilization of natural gas while maximizing the consumption of blast furnaces and coke gases.
The finding suggests that relying less on natural gas as a primary energy source and instead utilizing secondary resources like blast furnaces and coke gases can lead to significant cost savings. By reducing the reliance on natural gas, which is commonly associated with higher costs, industrial power plants can mitigate financial expenses without compromising their capacity for heat and electricity production.

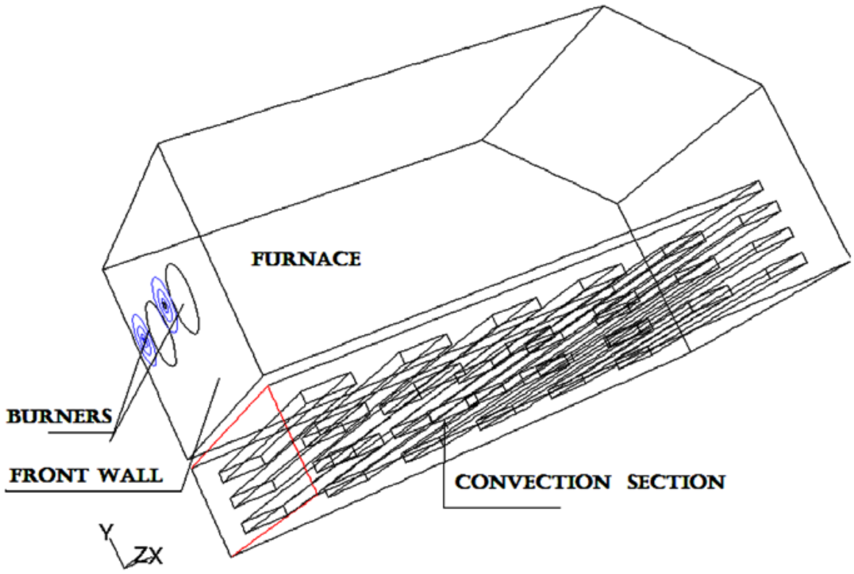
The research results showed that the best option, corresponding to the minimum energy costs is determined by the minimum use of purchased fuel and the maximum consumption of secondary in forms of combustion products.

Balancing fuel with other byproducts is not the only thing that matters for maximizing industrial water heating boiler efficiency. We also must look at how consistent airflow and temperature affect the combustion process.

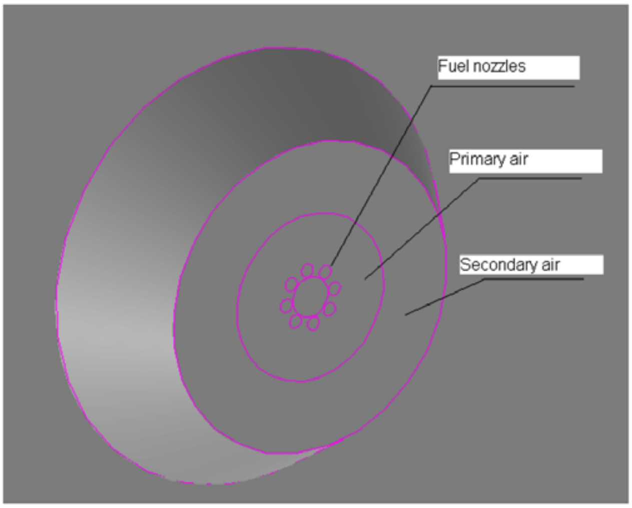
2.2.2 Pollution minimalization

Furnace's average temperature and NO concentration decrease as the excess air factor (A/F ratio) increases for a given air mass flow rate. When the fuel mass flow rate is fixed, increasing the excess air factor results in a maximum thermal NO concentration at the boiler exit at a ratio of 1.2. The combustion air temperature has a significant impact on the furnace and exhaust temperatures, as well as NO concentration.

As the combustion air temperature increases, the furnace temperature and NO concentration increase sharply. However, the exhaust temperature shows a minimum value at a combustion air temperature of 500 °C. The results also indicate that the swirl angle of the combustion air affects the temperature and NO concentration. Higher swirl angles result in increased furnace maximum temperature and increased thermal NO concentrations at the boiler exit. However, NO concentration at the boiler exit exhibits a minimum value at around a swirl angle of 45°. [5]



a. Furnace and convection section



b. View of the burner.

Figure 1 Configuration of the boiler. [5]

Achieving the desirable swirl angle in industrial furnace design requires careful consideration of various factors. Designers can optimize the geometry of flow passages, utilize inlet modifications such as swirl vanes, introduce tangential injection of fluid, and employ vortex generators to control and manipulate the swirl angle. These strategies enable the precise tuning of the swirl to achieve efficient combustion and minimize NO_x concentration. By integrating these methods into the design process, engineers can optimize industrial furnace performance while meeting environmental objectives.

In our case, low NO_x concentration is achieved through oxygen deficiency for the first high-temperature combustion and secondary low-temperature combustion with peripheral air. Oxygen deficiency is achieved through the recirculation of the flue gases.

Natural Gas was mentioned in almost all of the previously discussed papers, but what about using diesel fuel as the main fuel source for the automation of industrial water heating boilers?

2.3 Dual Fuel

From the study [6] we can understand that using a dual-fuel engine operating on LNG instead of a diesel engine operating on HFO can lead to significant reductions in emissions. Specifically, there is a reduction of about 30.1% in CO_2 emissions, 81.44% in NO_x emissions, and 96.94% in SO_x emissions.

The use of LNG as a fuel offers several advantages. It has lower sulphur content, resulting in reduced SO_x emissions. It also produces lower pollutant emissions, such as NOx and particulate matter, compared to diesel fuel. Additionally, LNG has a lower carbon content, leading to potential reductions in CO_2 emissions.

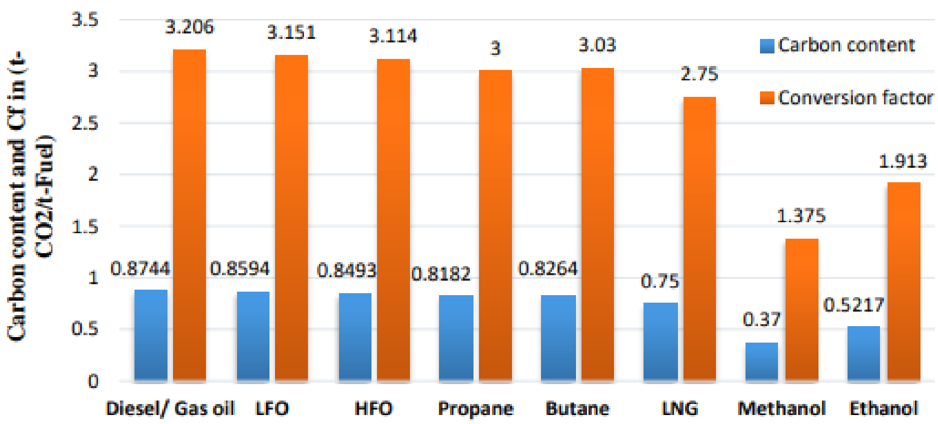


Figure 2 Conversion factors and carbon content for marine fuels. [6]

Conversion factor indicates correlation between tons of fuel burned and tons of CO_2 produced for main engines and auxiliary engines.

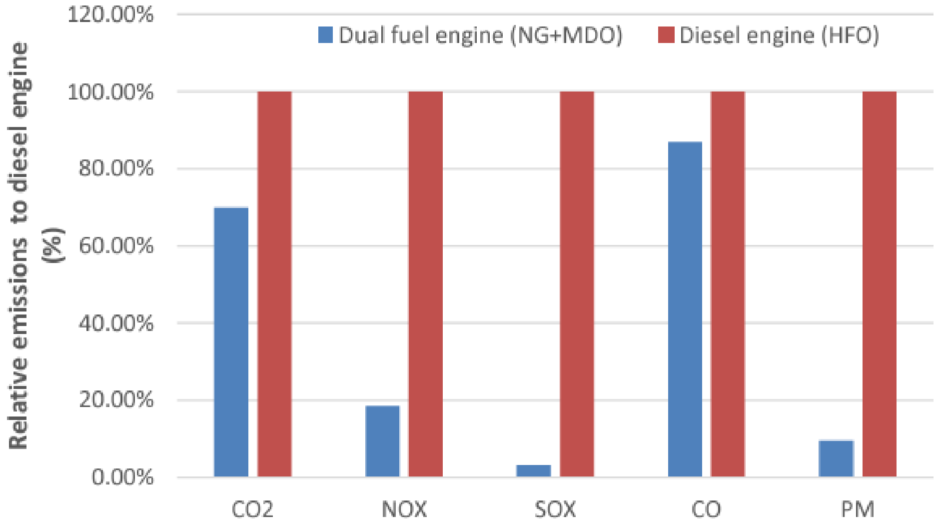


Figure 3 Relative emissions of dual fuel engine and diesel engine for the case study. [6]

In the cases where the transition from diesel fuel to the dual-fuel solution is desirable, there exists a procedure [7] for converting diesel engines to dual-fuel engines, including modifications to the fuel injection system, combustion chamber, and control systems. The conversion to a dual-fuel engine involves modifications to the fuel injection system, air-to-fuel ratio, and compression ratio of the engine.

Now we understand the rationale behind the preference for liquid natural gas over diesel fuel in operating the water boiler. Nevertheless, diesel fuel holds significance as an alternative fuel option in cases where there is no supply of LNG or when the prices of LNG are excessively high to be economically feasible. This webpage [8] offers insights into the historical trends of LNG and diesel prices.

We have gained insight into several key aspects of industrial water heating boiler fuel selection and usage. At the same time, it is vital to regulate and supervise the combustion process in order to avoid potential dangers. Further progress requires examining safety standards and considerations.

2.4 Safety Related System

Industrial water boiler safety is an essential aspect of boiler operation since it must be promptly shut down in the event of an emergency to mitigate risks to power plant personnel. However, what are the foundations of the safety requirements for industrial water boilers?

2.4.1 Standards

IEC 61508 is an international standard that applies to electrical, electronic, and programmable electronic safety-related systems. Articles highlights the concept of reliable control and its application in control system design under device failures. It states that reliable control can contribute to system safety design according to IEC 61508 by achieving safety functions in a control system. [9]

On the other hand, the IEC 61511 is aimed at users and integrators who are involved in the utilization of system components developed in accordance with the IEC 61508. This standard is structured into three parts, covering the general framework, definitions, system software/hardware requirements, guidelines, and hazard and risk analysis.

System integrators and end users should follow risk reductions in the same way as safety system designers. The management of functional safety and life cycle approach is particularly important, encompassing activities such as organization, resources, documentation, qualification of personnel, risk estimation and management, planning, implementation, supervision, judgment, and assessment. Functional safety management aims to avoid faults throughout the specification, design, development, production, and operation stages, requiring the determination of management and technical activities, assignment of responsibilities, control of performance, planning of verification and validation, and documentation of test results. [10]

To understand more about safety and how safety integrity levels are formed we will look at how risks can be determined and assessed within the automation industry.

2.4.2 Risk analysis.

The analysis activity is comprised of three basic areas of data gathering [11]: limits of the analysis, hazard identification, and risk estimation. Important factors to consider are the life phases of the machinery, limits of the machinery, reasonably foreseeable uses or states of the machinery, and the anticipated roll and level of training, experience, or ability of the future users.

Risk estimation involves evaluating the consequences and likelihood of each hazard, establishing parameter estimates consistently related to representative integer values, and considering the severity of a hazard based on the consequences. The occurrence of harm is evaluated based on the frequency and duration of exposure, the probability of a hazardous event, human-machine interaction, and the probability of avoiding or limiting the harm.

Table 1 Severity and Consequences [11]

Severity value (Se)	**Consequences**
4	Death, losing an eye or limb
3	Permanent loss of finger or toe
2	Reversible injury requiring medical attention
1	Reversible injury requiring first aid

The risk evaluation activity follows the analysis activity and involves arranging the risk estimation data to determine if the level of acceptable risk has been achieved. It evaluates the risk related to the identified hazard in terms of the consequences of adverse effects and the likelihood of occurrence of adverse effects.

Table 2 Risk Evaluation Matrix (Format example) [11]

Severity Se	**Probability of harm**				
	3 - 4	5 - 7	8 - 10	11 - 13	14 - 15
4	SIL 2	SIL 2	SIL 2	SIL 3	SIL 3
3		B(OM)	SIL 1	SIL 2	SIL 3
2			B(OM)	SIL 2	SIL 2
1				B(OM)	SIL 1

B(OM) - de-minimus risk level

2.4.3 SIL level determination

Safety Integrity Level values are defined for different operation modes based on the calculated Probability of Failure on Demand (PFD) values. The PFD values, ranging from 10^{-1} to 10^{-5}, are associated with four different SIL levels, as outlined in the following table. The PFD value represents the likelihood of a failure occurring when a safety function is required, while the SIL value indicates the quality of a safety system. A smaller PFD value corresponds to a reduced probability of a dangerous failure. It is emphasized that no system can be entirely free from errors, and hence, a 100% guarantee for identifying all failures within a system is not feasible.

Table 3 SIL level classification [12]

Safety Integrity Level	**Low demand mode of operation** T_i = 2 years T_i = 10 years	**High demand or continuous mode of operation** T_i = 1 month or T_i = 2 months or T_i = 6 months or T_i = 1 year
1	$> 10^{-2}\ to\ < 10^{-1}$	$> 10^{-6}\ to\ < 10^{-5}$
2	$> 10^{-3}\ to\ < 10^{-2}$	$> 10^{-7}\ to\ < 10^{-6}$
3	$> 10^{-4}\ to\ < 10^{-3}$	$> 10^{-8}\ to\ < 10^{-7}$
4	$> 10^{-5}\ to\ < 10^{-4}$	$> 10^{-9}\ to\ < 10^{-8}$

To fulfil the safety integrity level requirements, which are requested from a safety related system, limits of probabilities of failures are stated in the international standard IEC / EN 61508. The developer or manufacturers can calculate the probabilities of failure for its safety related system and can provide a mathematical proof that the developed safety related systems meet the required probability of failure limits. [12]
An alternative way to determine SIL levels can be read in this article [13].

A good way to understand SIL levels is through their use cases. SIL level 3 is important for us as we are trying to upgrade the automation of the industrial water heating boiler within the power plant. On the other hand, SIL level 4 is widely used in the railway networks.

More about compliance with safety standards IEC61508 and IEC61511 can be read about in this paper [14], researching the Probability of Failure on demand for a complex Safety Instrumented System in the Oil & Gas application.

Safety is a crucial factor in the automation of industrial water heating boilers due to the potential to cause harm and jeopardize lives. The automation system must operate with a reliable safety system, in which safety logic serves as the foundation.

2.4.4 DCS and Safety System relation

The complete implementation of the boiler automation system, considering a safety system, is often overlooked, yet some papers [15] demonstrate configurations for this specific scenario. Paper focuses on the main protection system of a thermal power unit, specifically the boiler and turbine main protection, within the context of a DCS control system, highlighting the potential for signal distortion during transmission, leading to protection malfunction or refusal of action, thereby impacting the stable operation of the generator-turbine. To address this, proposals have been made to implement a new control method for main protection, emphasizing the use of SIL3 safety level rating to enhance the safety and reliability of the entire main protection system and ensure stable operation of the turbine unit.

SIL concept is a key focus, particularly regarding its significance in evaluating safety system functionality in the thermal power industry, advocating for the application of SIL3 safety level in coal-fired power plant main protection control to ensure stable and safe operation of the steam turbine generator unit. Underscoring the importance of SIL3 in enhancing the probability of system security functions and abiding by the design requirements of safety functions within the thermal power industry.

The "Hardware and Software" section of the paper will cover the discussion on safety hardware choices. Nevertheless, it is important to provide a brief overview of the HIMA HIMatrix family of devices, which was selected to meet the requirements of the Safety Related System hardware. We used a compact system that was mounted on the DIN rails as Valmet's hardware is DIN rail mountable as well, more about the system can be read here [16].

2.5 Previously used control scheme

Iru Powerplant's second watering heating boiler previously used an MPC control scheme, however, the heat output of the burners considerably changed from 116 MW to 66MW. Previous MPC models cannot be used due to power differences, a new model needs to be identified, but this is not in the scope of either this paper or the overall project. It is still relevant to understand what was done beforehand.

The PID control algorithm has a problem controlling industrial water heating boilers with the main control loop focusing on the output temperature. Due to the time delay between the fuel-burning process and heat transfer from the furnace to the water, the PID controller's integration time is set longer than the measurement delay to avoid permanent overshoot. This results in a slow reaction to setpoint changes and disturbances.

The Model Predictive Controller uses a model to predict the behavior of a process and generate manipulated process inputs to minimize deviations of process outputs from a setpoint. The controller uses receding horizons for prediction and control, with the first value of the control horizon applied now and existing estimations discarded in the next time instance. A cost function is used to penalize output deviations from the setpoint, and changes of the input vector can also be penalized to control process dynamics. One notable property of MPC is its ability to obey constraints, allowing for the limitation of output, input, and input changes. This property is particularly useful for considering physical limitations, such as tank levels or valve opening/closing limits.

Constraints are defined in the form of linear inequalities using matrices of constraint parameters. Assessing effectiveness of MPC in a virtual environment using real data.

The results indicated that, even when the identified model was centered around a different operating point than the actual process, the MPC demonstrated approximately 10% better performance compared to a PID controller. [17]

Model Predictive is effective in controlling processes throughout their entire operational range. The implementation of unconstrained MPC is noted as straightforward, yet it fails to consider the physical limitations of the process, leading to potentially inadequate control actions in certain circumstances. [18]

2.6 Conclusions based on the literature review.

The conclusions drawn from the literature review underscore the multifaceted nature of comprehending the automation of industrial water heating boilers. The assortment of information collected from various sources highlights the interplay between safety-related systems and Control Systems and underscores the importance of fuel combustion expertise in the automation domain. While engineers may not possess exhaustive knowledge across all relevant fields, a fundamental understanding of the underlying principles is indispensable for developing a comprehensive control system.

The examination of existing literature demonstrates that the successful automation of industrial water heating boilers requires expertise in various fields, such as mechanical engineering, thermodynamics, fluid dynamics, control theory, and environmental regulations. Each of these disciplines provides valuable insights into different aspects of boiler automation, ranging from the physical processes that govern heat transfer and combustion to the regulatory frameworks that govern emissions control and safety standards. One of the key highlights is the significance of understanding the fundamental principles that govern boiler operation and automation. While automation engineers may not possess extensive knowledge in all related areas, a basic understanding of essential concepts and principles enables them to develop improved control strategies and anticipate potential challenges. This comprehensive approach facilitates the development of control systems that enhance boiler efficiency, while also ensuring compliance with regulations and safety protocols.

To successfully tackle the complexities of boiler automation and guarantee safe, productive, and environmentally friendly operations, automation engineers need to gather and utilize knowledge from various fields. This approach allows for the identification of correlations between different criteria and the establishment of logical connections that need to be put into practice. It is important to understand that each requirement cannot be evaluated independently, as the bigger picture may not be fully grasped. Once the entire picture is comprehended, we execute the automation project. Before delving into that, let's briefly review the historical background of water heating boiler automation.

3 Project Overview

After understanding various intricacies of boiler automation**,** we will transition to the actual task at hand and take a quick overview of second industrial water heating boiler changelog.

3.1 Control system before renovation.

The control system before the renovation did not possess the necessary hardware and software to incorporate flue gas recirculation to reduce NO_x emissions, which is essential for enhancing the efficiency of the combustion process by fully consuming the fuel. Additionally, due to the increasingly stringent environmental regulations, modifications in the control system were imperative to improve efficiency and comply with the operating requirements. Consequently, alterations were made to both the gas and diesel components of the system, although the implementation of the diesel part underwent a complete transformation to accommodate the new fuel delivery system. The transition from PLU cards-based Safety Related System to HIMA-based Safety Related system also occurred in this timeframe.

3.2 Gas Control System Alterations

The Boiler Gas Fuel Control System has undergone several enhancements to improve efficiency and safety. A new Gas Fuel Flowmeter has been integrated to provide accurate measurement of gas flow rates.

Discrete relays with low and high pressure setpoints have been implemented to closely monitor gas pressure levels, ensuring optimal operation and safety through the SRS mechanism. Additionally, the Fast-Acting Valves within the SRS system have been replaced. Pneumatic adjustable valves have been introduced to precisely regulate gas flow to the peripheral part of the burner, allowing for finer control and optimization of combustion processes. These upgrades collectively contribute to a more reliable and efficient operation of the Boiler Gas Fuel Control System.

3.3 Diesel Control System Alterations

Numerous modifications have been implemented in the Diesel Control System to boost its effectiveness and functionality. There are now two pumps, the Main and Reserve Booster Pumps have been implemented to guarantee consistent and dependable fuel delivery. The addition of a Ring Pressure Regulator Valve further improves control over fuel pressure, optimizing combustion processes and preconditioning the diesel fuel.
The incorporation of new Fast-Acting Diesel Valves in the SRS system allows for quick and precise regulation of diesel flow in case of emergency, enhancing overall system dependability. To further enhance control mechanisms, a Pneumatic adjustable Valve has been introduced to manage diesel flow to peripheral burner components, ensuring optimal performance. The last thing to note is that Fast-Acting Compressed Air Valves in the SRS system for diesel fuel and nozzle-blow down system.

3.4 Difference between PLCs and DCS based solutions.

As the Boiler Control System mostly works within the confines of the Distributed Control System, it would make sense to point out a couple of differences between DCS and PLC-based solutions.

Distributed Control System and PLC are both utilized in industrial processes to control and monitor operations, but they differ in several aspects. Regarding architecture, DCS is designed with multiple independent controllers spread throughout a facility, enabling communication among themselves and with central operator stations. On the other hand, PLC systems usually adopt a centralized architecture, relying on a single controller or a limited number of controllers to execute logic and manage devices (Cross-controller communication in a PLC system is configurable but at the cost of more engineering work).
In terms of scalability, DCS offers greater flexibility as it allows for easy expansion by adding more control units or I/O modules as needed. However, expanding PLC systems might involve more intricate programming and wiring. Control philosophy also sets them apart. DCS is commonly employed in continuous or batch processes due to its ability to handle complex control strategies and tightly integrate control loops. PLC systems, in contrast, are frequently utilized in discrete manufacturing processes, such as assembly lines or packaging, where simple on/off control or sequencing logic is sufficient.

There is a difference in cost. DCS systems tend to be more expensive due to their complexity and the need for redundant components to ensure high reliability. PLC systems, however, are often more cost-effective for smaller-scale applications or projects with simpler control requirements. At the same time, certified SRS PLCs are expensive, so these are not used as process controllers, but as safety controllers with for example DCS that does not have a SIL level certification.

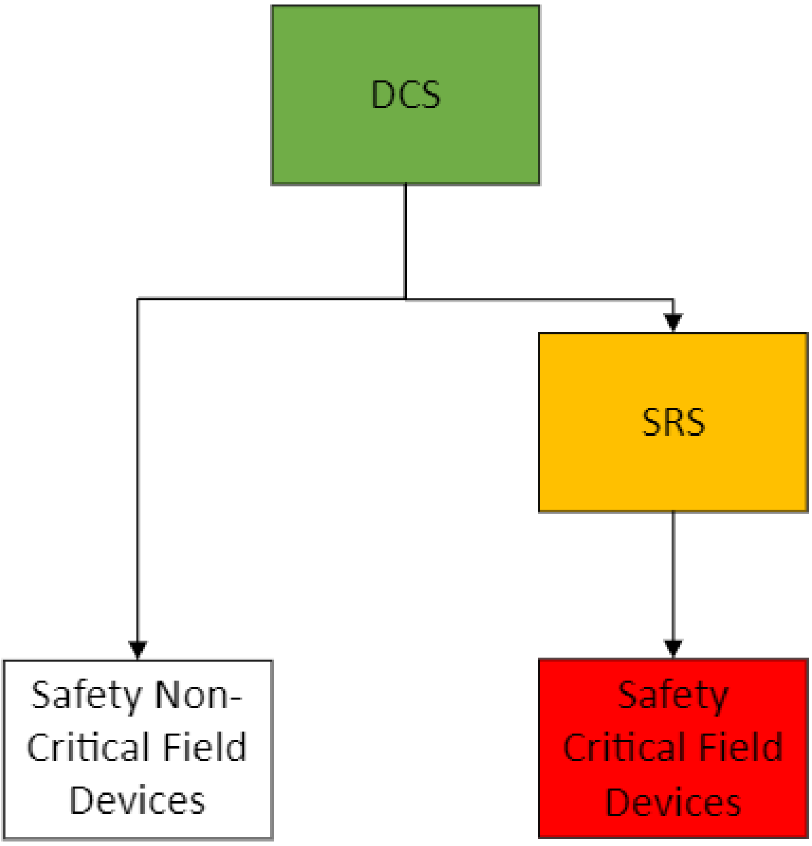


Figure 4 System Communication and Device allocation.

3.5 Boiler Control Diagrams

In this part we are going to discuss the usage of the control diagram and the first of many control diagrams that will be discussed further in Parts of the Process.

3.5.1 Control Diagram description.

Control diagrams, also called control flow diagrams or control system diagrams, serve as visual depictions used in automation. Their purpose is to illustrate the systematic progression of control signals and processes within a given system. These diagrams are of utmost importance in the design, analysis, and resolution of issues in control systems across a range of fields, including industrial automation, robotics, and process control. Below is an overview of their key application:

The creation of control systems involves the use of control diagrams, which function as detailed plans. These diagrams aided us in visualizing the complete framework of the control system, encompassing the different elements and their interconnectedness. Through the graphical representation of control logic and signal flow, engineers can verify that the system will function according to its intended purpose.

3.5.2 Water heating boiler control diagram

Let us examine the boiler control diagram, which serves as an effective means to illustrate the extent of work carried out during the renovation process. Although not extensively detailed, this diagram encompasses a wide range of devices. It outlines the devices that require control and the measurements obtained for monitoring these devices.

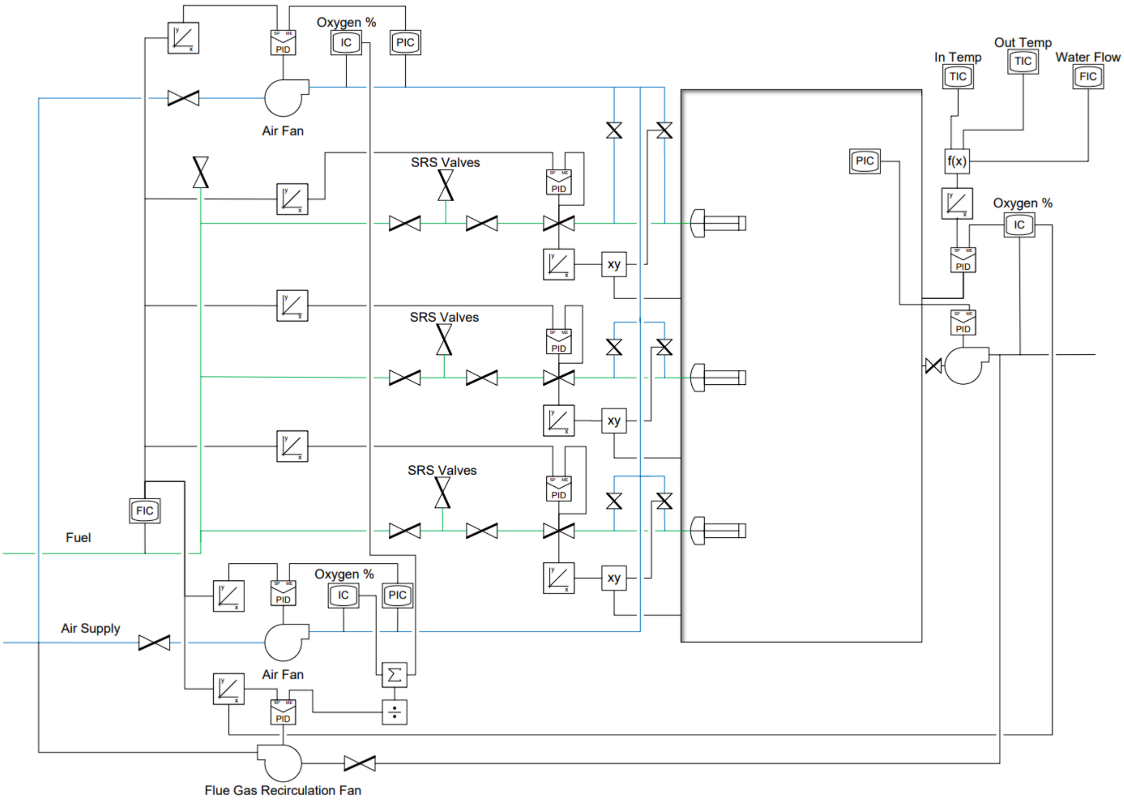


Figure 5 Simplified Boiler Control Diagram

Even though the number of controlled devices is high, a lot of functionality was re-used along the way, as each burner has the same setup and both air supply lines function in the same manner.

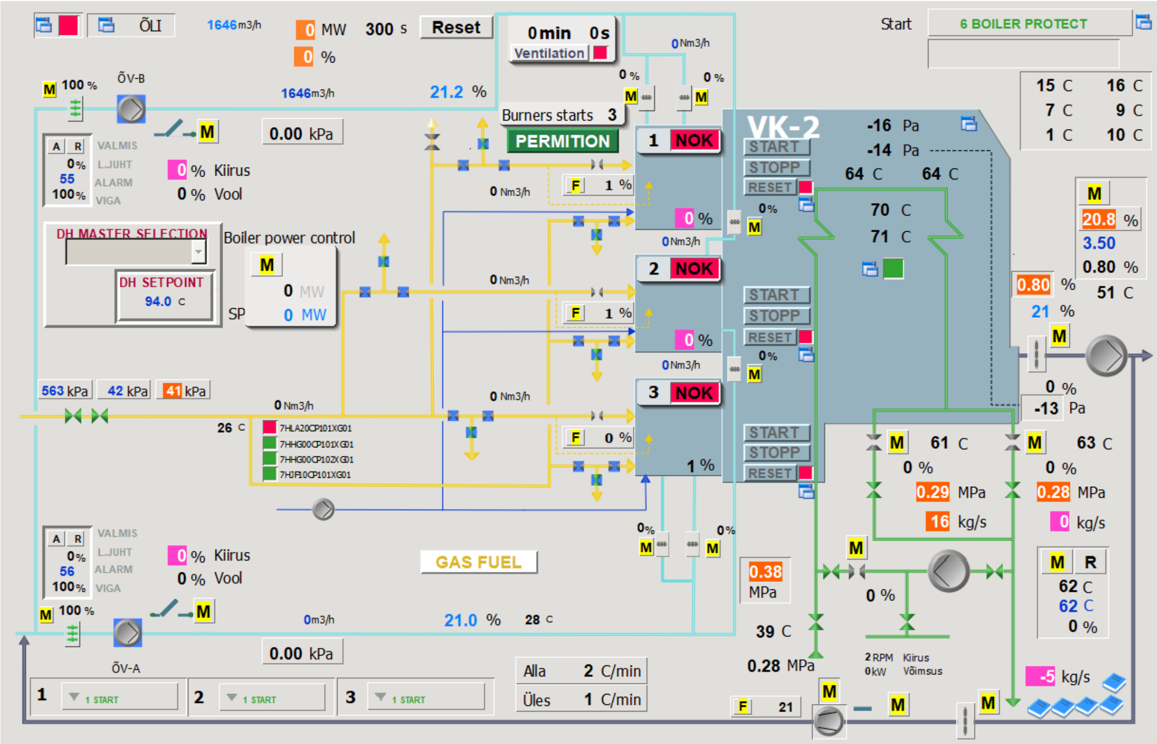


Figure 6 Operator Display for Natural Gas

After taking a quick overview we can transition into an in-depth description of the requirements and their implementation. As previously discussed, the interconnection of the requirements is one of the key parts of this paper.

4 Requirements interdependencies

Every requirement cannot be assessed in isolation as the implementation of the requirement needs to be assigned to either the DCS control system or to the Safety system. DCS Control System and Safety Control System have different principles in mind when taking control logic into consideration. DCS control system can operate without a few sensors functioning. SRS logic, however, requires every sensor to send data to the system to prevent any potentially hazardous situation. This means the SRS system will shut down the operation of the sensor-assigned area in case of a malfunction.

But before evaluating the impact of every requirement we must put them in writing in some way, shape, or form. One such way is using a user story format. [19]

Table 4 User story template

Title	**Story**	**Acceptance Criteria**
Self-representing name of the task	As I [user] I want [functionality] So that [benefit]	Given [how the things begin] When [action taken] Then [outcome of taking action]

Engineer as a persona represents automation and logic tasks to be performed for the system to be ready to operate.

The operator as a persona represents visualization-based tasks so the system can be monitored and diagnosed.

Table 5 Boiler Automation requirements as user stories

Title	Story	Acceptance Criteria
Oxygen % monitoring	As an Engineer, I want to monitor incoming and outgoing oxygen % so that I can balance the amount of oxygen from two fuel lines and monitor the burning process.	Given the installed oxygen sensors and working data logging when the boiler is operational then the incoming and outgoing oxygen % can be monitored.
Flue gas recirculation	As an Engineer, I want to recirculate the combustion products so that I can achieve lower NO_x emissions by achieving complete combustion.	Given the required hardware and logic for the flue gas recirculation when it is physically implemented then lower NO_x emission numbers can be achieved.
Dynamic airflow setpoint setting for flue gas recirculation	As an Engineer, I want to dynamically set a setpoint to the flue gas recirculation fan so that I can balance the number of flue gases based on the input fuel and oxygen.	Given the implemented oxygen % monitoring and fuel flowmeters installation when the boiler is operating then the amount of flue gases going back to the combustion chamber can be adjusted.
Diesel fuel circulation system	As an Engineer, I want to circulate diesel fuel in the ring so that I can precondition fuel for usage and keep it at a constant viscosity.	Given the constant circulation of the input diesel fuel and working fuel pumping system when fuel system is active then fuel can be preconditioned for use.
Constant diesel fuel pressure	As an Engineer, I want to monitor diesel fuel pressure so that I can achieve a constant flow rate to the burners.	Given the diesel fuel pressure monitoring and implemented PID controller when pressure regulation is needed then constant flow rate can be maintained.
Burner diesel fuel pressure monitoring	As an Engineer, I want to monitor the pressure in the diesel fuel pipes so that I can shut down the burner in case of overpressure.	Given the pressure sensor monitoring and implemented shutdown sequence when overpressure occurs then the burner shutdown sequence can initiate.

Individual burner valve monitoring	As an Engineer, I want to monitor valves assigned to the individual burner so that I can have individual burner running status and monitor the start-up sequence.	Given the individual burner valve monitoring and implemented start-up sequence when burner is operational then burner status monitoring can be achieved.
Valve position monitoring for boiler ventilation	As an Engineer, I want to monitor the position of the fuel, ignition, and air valves so that I can identify when boiler ventilation is possible.	Given the implementation of the valve position monitoring when the positional data is being constantly read, then Ventilation can only be performed during ideal circumstances.
Burner fuel mixture monitoring	As an Engineer, I want to monitor the fuel mixture so that I can achieve a proper fuel combustion process.	Given the implementation of the fuel-mixture monitoring by fuel and air valve position monitoring when the boiler is operational then the combustion process can be monitored.
Dynamic position setpoints for fuel and air valves for burner load control	As an Engineer, I want to dynamically allocate setpoints to the fuel and air valves so that I can achieve burner load regulation.	Given the implementation of the fuel mixture monitoring and setpoint curve when the boiler is operating then the individual burner load can be adjusted.
Operator Display Safety Condition Monitoring	As an Operator I want to see statuses of the safety conditions on the operator screen so that I can knowingly take decision to take further actions	Given the implemented mimics and working communication with safety system when boiler is operating then the safety conditions can be monitored by operator
Operator Display Device Status Monitoring	As an Operator, I want to see the status of all hardware important in the operation of the boiler, so that I can monitor the process. (Running statuses of Fans, Valve Positions, Burner Main/Igniter Flame)	Given the implementation of hardware device mimics and working communication from the field when electricity is applied then device statuses can be monitored.

User stories provide us with a way to put requirements into clear and concise sentences that can be broken down into simpler requirements that automation engineers should implement. User stories are usually written by the end users of the system but in our case, it is an explanatory intermediate step before outlining proper requirements.

However, not all the requirements can be easily described by user stories. Safety requirements take the form of a table that outlines which devices should be shut down in case of sensor malfunction or deliberate connection break. This form of describing safety requirements is called a safety matrix.

For the sake of easier understanding the table will be presented in simplified form as listing all the conditions and outcomes are unnecessary.

Table 6 Simplified Safety Matrix

	Movement of all valves into the pre-determined safe condition for the shutdown of the burner	**Closure of the valves associated with the natural gas fuel and opening of the venting lines.**	**Closure of the valves associated with the diesel fuel**
Common interlock	x		
Natural Gas Interlock		x	
Diesel Fuel Interlock			x

When a common interlock is inactive, it causes the shutdown of the entire operation of the burner by moving valves into a pre-determined safe condition. Depending on the purpose of the valves, they can be either opened or closed.

A malfunction of the gas interlock causes only the valves associated with the gas fuel burning part to move into their safety condition.

Diesel interlock only governs the operation of the diesel burning system and all valves are closed upon this condition.

4.1 Functional and non-functional requirements

To make requirements clearer we will separate them into functional and non-functional requirements. Functional requirements describe the specific features and functionalities that a system must provide. They outline what the system should do in terms of input, processing, and output. Non-functional requirements specify the qualities or attributes that the system must have, but they do not describe specific behaviors. They address aspects such as performance, reliability, usability.

Table 7 Functional requirements

ID	Description
FR-001	A functional diesel fuel pumping system must be established to ensure continuous circulation of input diesel fuel for preconditioning.
FR-002	The diesel fuel pressure in the ring will be continuously monitored by the system. To ensure a consistent flow rate to the burners, the implementation of a Pressure-controlling PID controller is necessary.
FR-003	The pressure in diesel pipes coming to the burner will be continuously monitored by the system. If an overpressure situation occurs, the system will activate a sequence to shut down the burner.
FR-004	The system shall include valve position monitoring for fuel, ignition, and air valves.
FR-005	Ventilation shall be possible only during predetermined circumstances based on valve position monitoring.
FR-006	The system shall monitor valve positions assigned to individual burners.
FR-007	The system shall provide information on individual burner running status and startup sequence using valve monitoring.

FR-008	The system shall provide burner load control through dynamic position setpoint allocation to the fuel and air valves.
FR-009	The system shall support flue gas recirculation to achieve lower NOx emissions.
FR-010	The inclusion of oxygen sensors in the system is necessary to monitor the levels of incoming and outgoing oxygen percentage to control the burning process.
FR-011	The system shall provide the dynamic amount of flue gases flow back into the combustion chamber by monitoring the amount of incoming fuel and incoming oxygen percentage.
FR-012	The system shall facilitate communication with the safety system for real-time safety condition monitoring by the operator.
FR-013	The system shall facilitate communication with the safety system for real-time safety condition monitoring by the operator.
FR-014	The safety system shall accept commands from DCS to open/close the valves, but only if the safety interlock allows for this to happen.
FR-015	The system shall implement mimics for displaying safety conditions on the operator screen.
FR-016	The fuel mixture monitoring feature must be provided by the system to guarantee complete combustion.

Table 8 Non-Functional requirements

ID	Description
NFR-001	Safety Related System shall function per SIL level 3, with the following failure probabilities: Low demand mode of operation: $> \ 10^{-4}\ to\ <\ 10^{-3}$ High demand mode of operation: $> \ 10^{-8}\ to\ <\ 10^{-7}$
NFR-002	Safety Related Systems should operate within the time constraints set in the initial design. When the signal from the device disappears for more than three or five seconds (depending on the device) affiliated interlock should activate to prevent the process from running unmonitored.
NFR-003	The system shall provide clear and easily understandable status information. The system is required to offer status information that is clear and easily comprehensible. The green colour of the device indicates that it is in an active running state or that valves are open. On the other hand, the grey colour signifies that the device is inactive and ready for operation. Lastly, the red colour indicates an active fault or interlock status, signifying that a specific function is not in a ready state.
NFR-004	Performance shall not degrade when scaling up the number of monitored parameters. Logging of the multiple parameters should be possible, so the operational efficiency of the boiler can be evaluated.
NFR-005	The design of the system should prioritize ease of maintenance, accompanied by comprehensive documentation for troubleshooting and updates. Every device must operate per the provided documentation, leaving no operating principles undocumented. Furthermore, additional troubleshooting mimics should be made available to diagnose any connection issues that may arise between the DCS and SRS systems.
NFR-006	The system shall provide real-time monitoring with low latency. Operators will have process-related information displayed as soon as a measurement update occurs.

4.2 Hardware and software

The project necessitated the integration of specialized hardware to establish a robust safety system that complied with the requirements of SIL level 3 or higher. Addressing this critical aspect, we opted for the HIMatrix F35 controller [20], renowned for its reliability for industrial safety applications. In addition to this controller, we utilized extra I/O modules connected via the SafeEthernet [21] protocol, ensuring seamless integration. DCS Control System was also connected to the HIMatrix controller using a separately configured SafeEDR link to be able to send open/close command signals to the fast-acting valves and monitor various safety conditions.

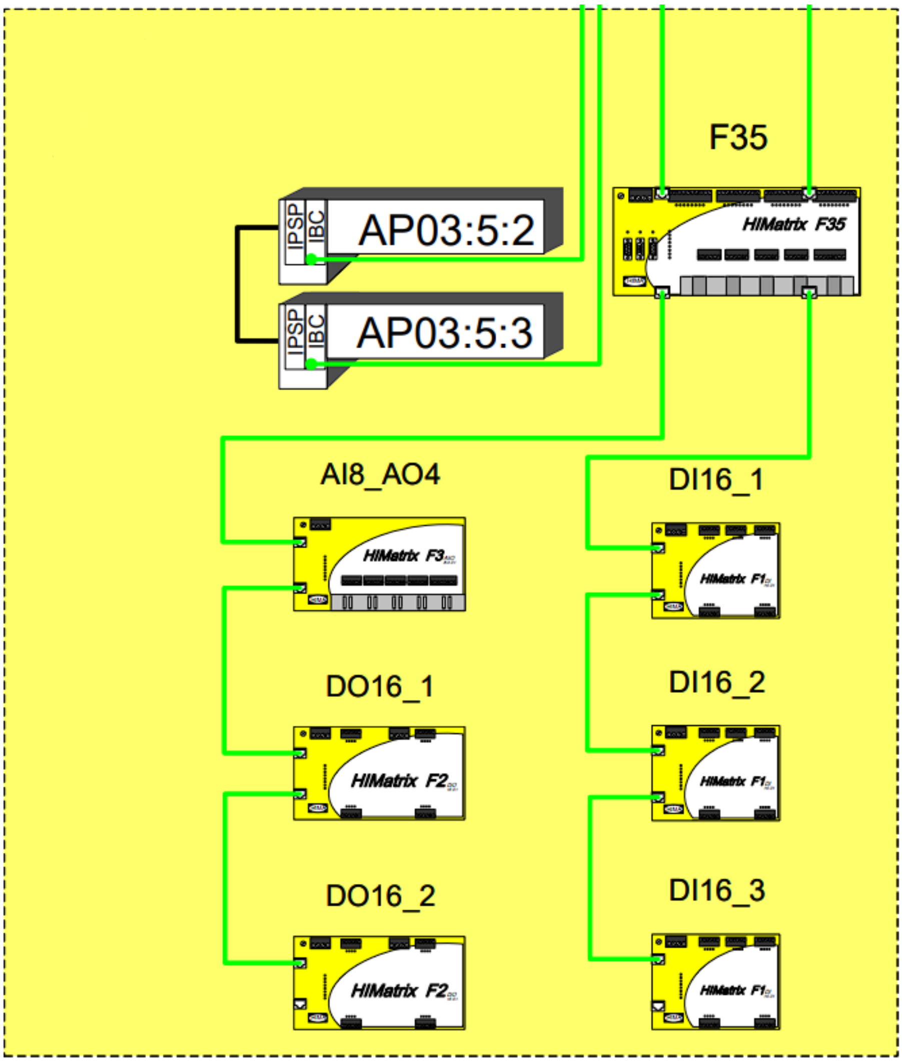


Figure 7 Controller and Modules connections.

HIMatrix F35 controller has an integrated four-port switch. Two connections are used for I/O modules. Two other ports are redundant connections to two MOXA switches to communicate on the same network as the rest of the powerplant controllers. Valmet I/O in this cabinet is connected to the ACN RT G5 controllers.

There are other options available apart from the SafeEDR protocol, as mentioned in this paper [22]. However, in this particular implementation, there was no need to explore these alternatives since all the safety system hardware was supplied by HIMA, and the Valmet DCS system seamlessly communicated with the HIMatrix controller using SafeEDR.

Every element of the safety system, ranging from sensors to actuators, was directly linked to either the HIMatrix F35 controller or the supplementary I/O modules [23] [24] [25]. This meticulous arrangement guaranteed straight communication pathways, essential for swift and precise response mechanisms in critical situations. Cabinet assembly for this project can be seen in Figure 22 Water Heating Boiler 2 Cabinet Front.

The adoption of this specialized hardware prompted a significant overhaul of the project's software framework. Many functions had to be either reconfigured or developed from scratch to accommodate the intricacies of the new hardware components. This marked our second deployment of SafeEDR, underscoring its reliability and effectiveness in facilitating seamless communication between the safety system and the overarching DCS control system.

While delineating distinctions between software and hardware components may seem redundant, it is paramount to recognize their symbiotic relationship. Indeed, the synergy between hardware and software is indispensable, as both components are integral to the cohesive functioning of the boiler control system. Without their harmonious integration, the attainment of the project's predefined functional objectives would remain elusive. Thus, by acknowledging and optimizing this interdependence, we ensured the comprehensive efficacy and resilience of the implemented safety measures within the boiler control system.

5 Parts of the Process

Transitioning from requirements conveyed through words to requirements conveyed through visual representations, we will utilize control diagrams. These diagrams are readily comprehensible to individuals operating within the automation sector and were already tackled in previous parts.

5.1.1 Water Heating Boiler Load Control

To fully maximize the boiler capacity using the same burners, it is necessary to divide the Boiler Load Setpoint among three separate control loops. Each loop will independently monitor the Fuel/Air ratios and adjust (open/close) valves based on changes in the desired mixture ratio to achieve optimal results.

Burner Run statuses are discrete signals formed from the position of the fast-acting fuel valves to determine the working status of a burner and calculate power distribution to that burner. Load Setpoint in this control case, is the value from 0% (0 MW) to 100% (66MW). Each burner can only take 33% of the Load Setpoint.

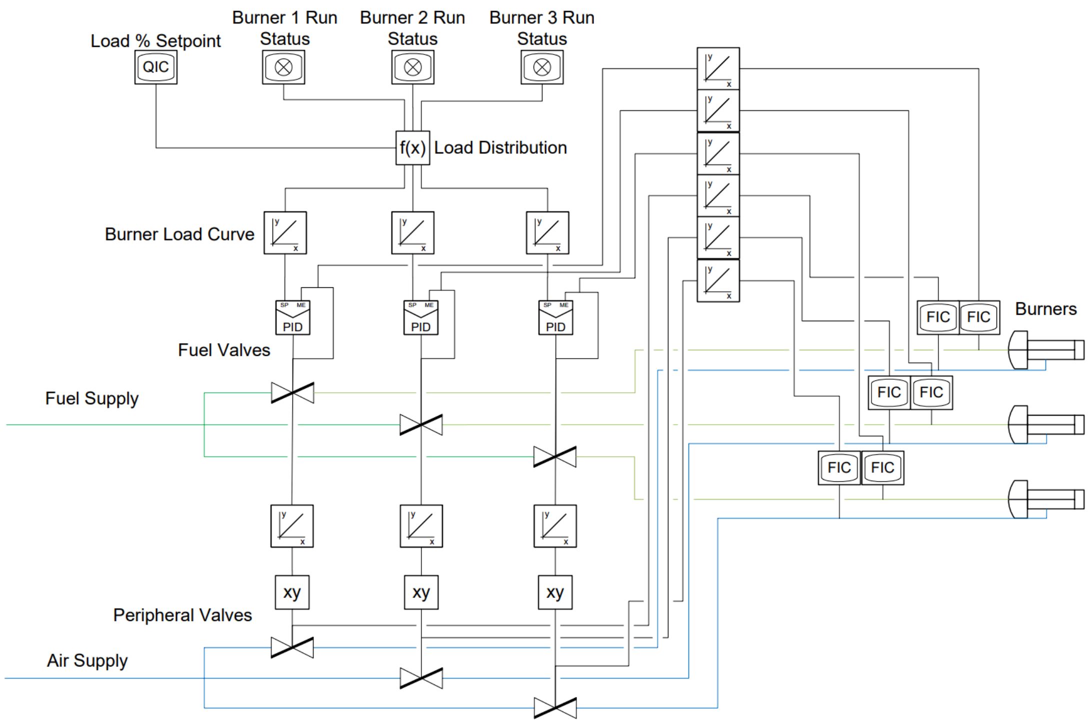


Figure 8 Boiler Load Distribution Control Diagram

Load Setpoint then gets translated into positional data for the valves using a linear curve and gets fed into PID controllers. Fuel/Air mixtures are different for gas and diesel fuel; however, overall load distribution and fuel mixture control principles are the same for both fuels.

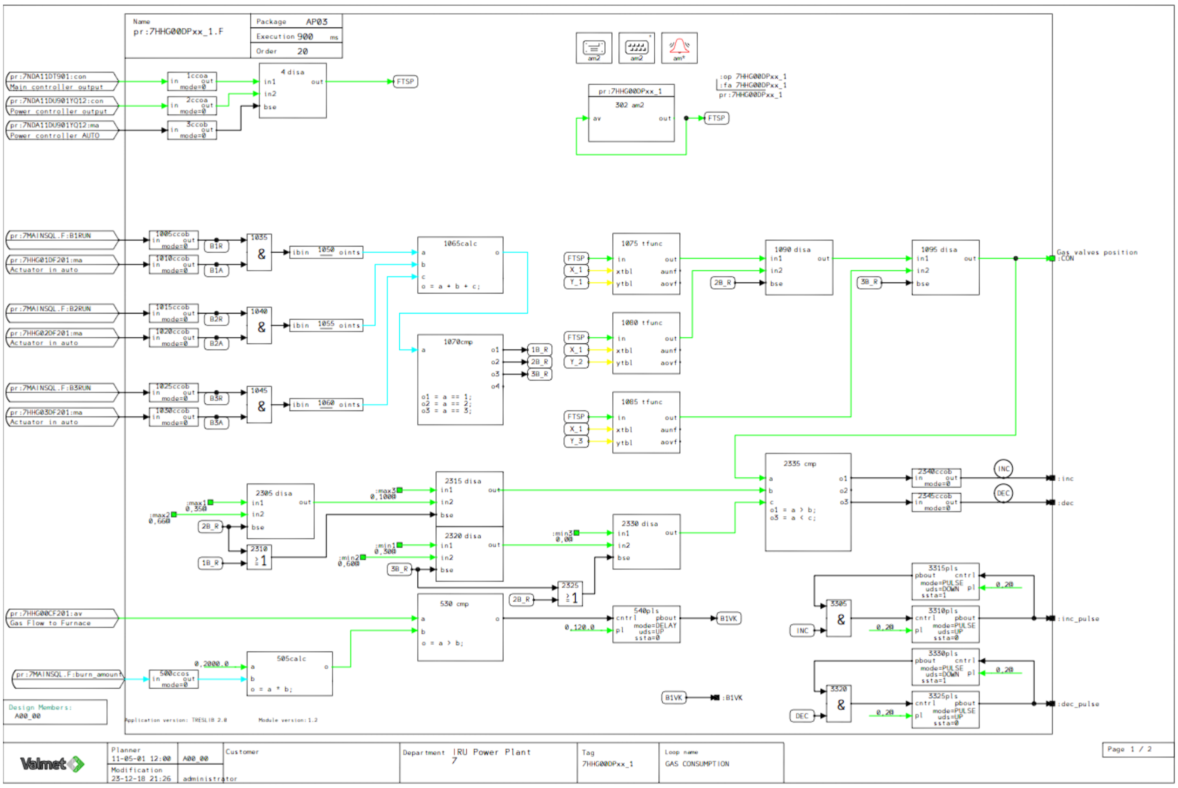


Figure 9 Boiler Load Distribution Functional Block Diagram

The actual Functional Block diagram for Load Distribution is a bit more complex than the control diagram would lead you to believe, as it includes logic used in the start-up sequence of the boiler.

5.1.2 Burner Interlock Safety Logic

The Burner Safety logic operates by continuously monitoring all the relevant signals. If any of the signals are no longer present or become inactive, this indicates an unsafe condition, causing the burner to halt its operation (The time delay before this occurs is determined by the type of safety condition. Flame sensors have an internal delay mechanism), and the valves will revert to a pre-established safe position.

Green indicates currently active signals in a safe state. Red indicates inactive signals in an unsafe state.

The interlock of only one burner will be examined as an example, every boiler's burner has an identical power output of 22 MW and the same valve setup, resulting in a matching interlock for each burner.

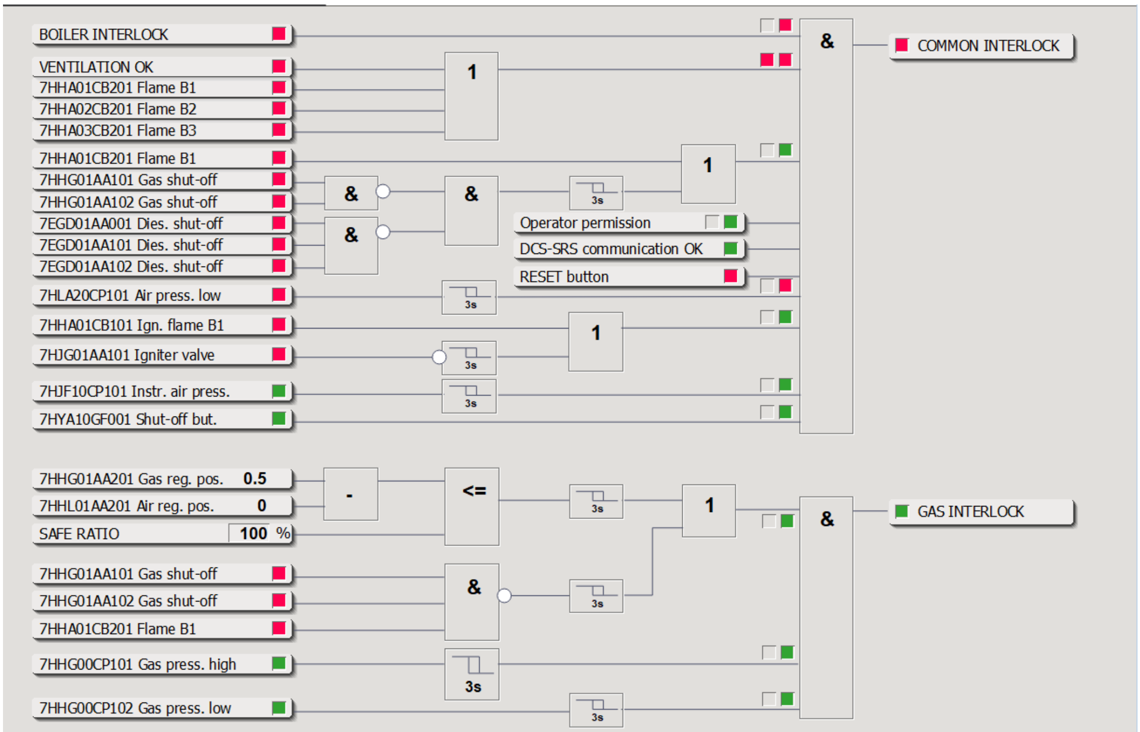


Figure 10 Operator Display for Burner Interlock

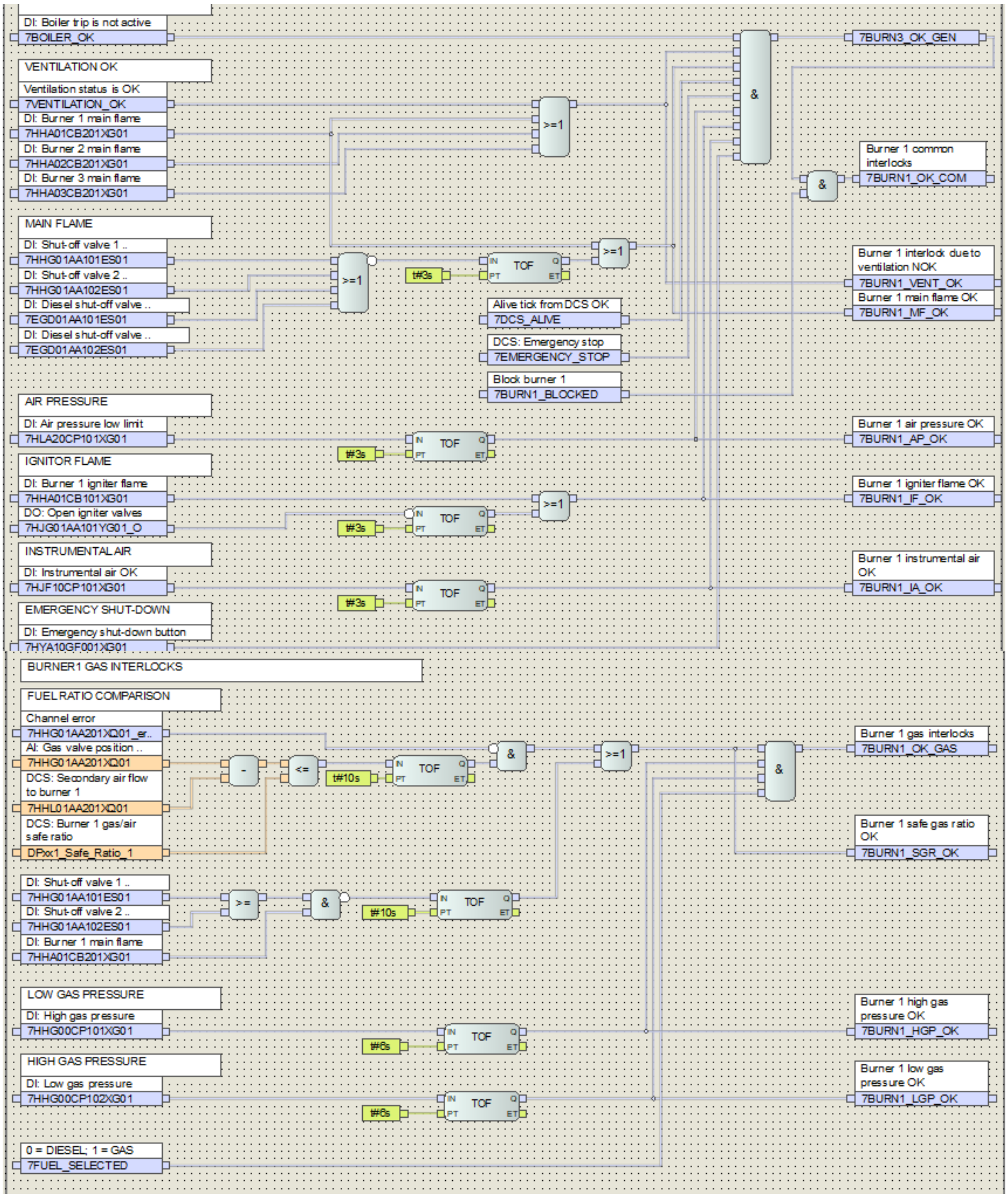


Figure 11 SilWorX project Burner Interlock

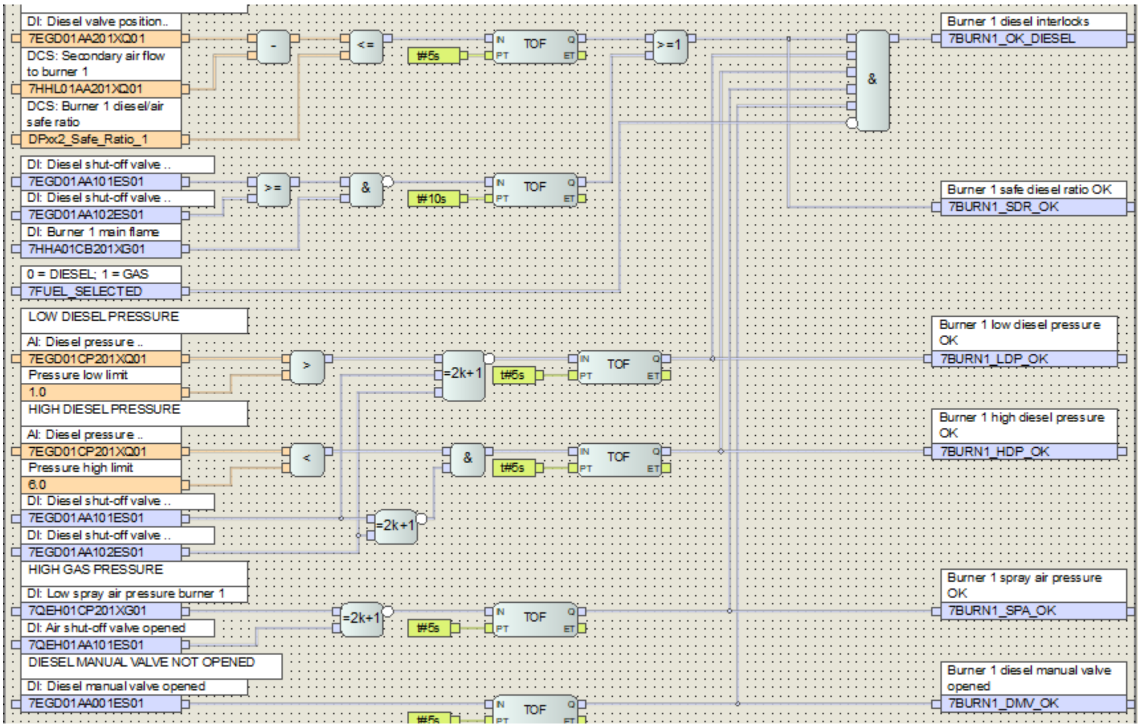


Figure 12 SilWorX project Burner Interlock continuation.

SilWorX and DCS Operator Display logical diagrams look similar, however as those are two completely different systems, we need a separate representation of safety logic inside the DCS system. All the safety logic runs on the HIMatrix controller, but DCS receives data through a configured SafeEDR connection.

5.1.3 Diesel Fuel Supply

As outlined earlier in the requirements diesel fuel has its very own supply system to regulate pressure and diesel flow to the burners. Two pumps and an adjustable valve keep the pressure inside a ring at the setpoint level. The current setpoint level is 9 bars.

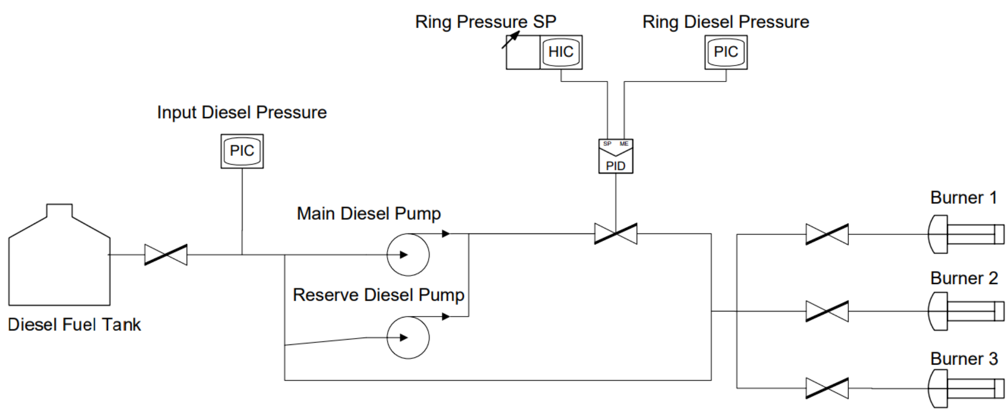


Figure 13 Ring Diesel Pressure Control Diagram

Only one diesel pump works at the time, the second one is the backup solution when the first one is undertaking maintenance or has broken down. The start of the diesel fuel supply system is the first step to starting boiler operation on diesel fuel. Diesel pumps cannot be started before manual booster pumps are started; this condition is monitored by a pressure sensor before the circulation ring.

Here you can see the Operator Display for the Second Boiler to operate on diesel fuel. Diesel Fuel operations incorporate mostly the same devices as previously discussed. With the addition of Nozzle Blow Down using the compressed air.

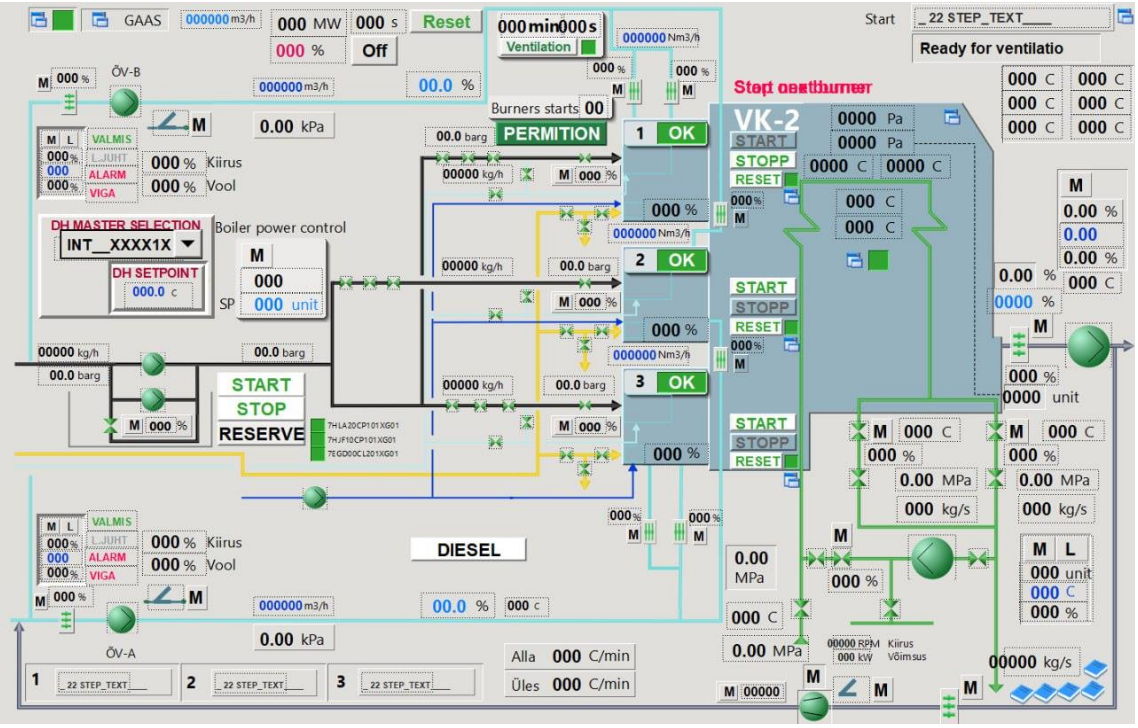


Figure 14 Operator Display for Diesel Fuel

5.1.4 Flue Gas Recirculation

Flue Gas Recirculation is one of the important parts of the process to reduce NO_x emissions and requires careful control of the fan to achieve suitable results. Fan setpoint differs when functioning on diesel fuel or gas fuel to achieve desired airflow. The average of both Input Oxygen % measurements is taken, as there are two possible paths air can take to reach the burners.

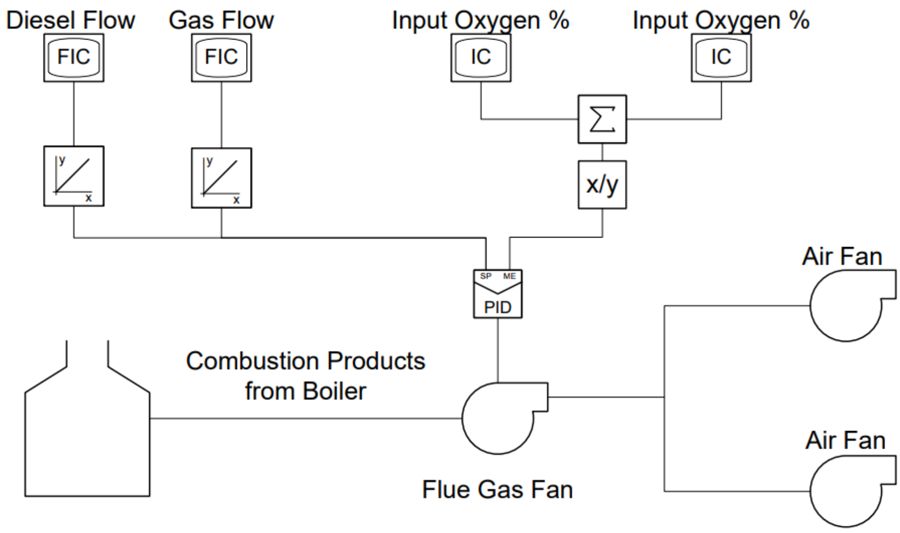


Figure 15 Flue Gas Recirculation Control Diagram

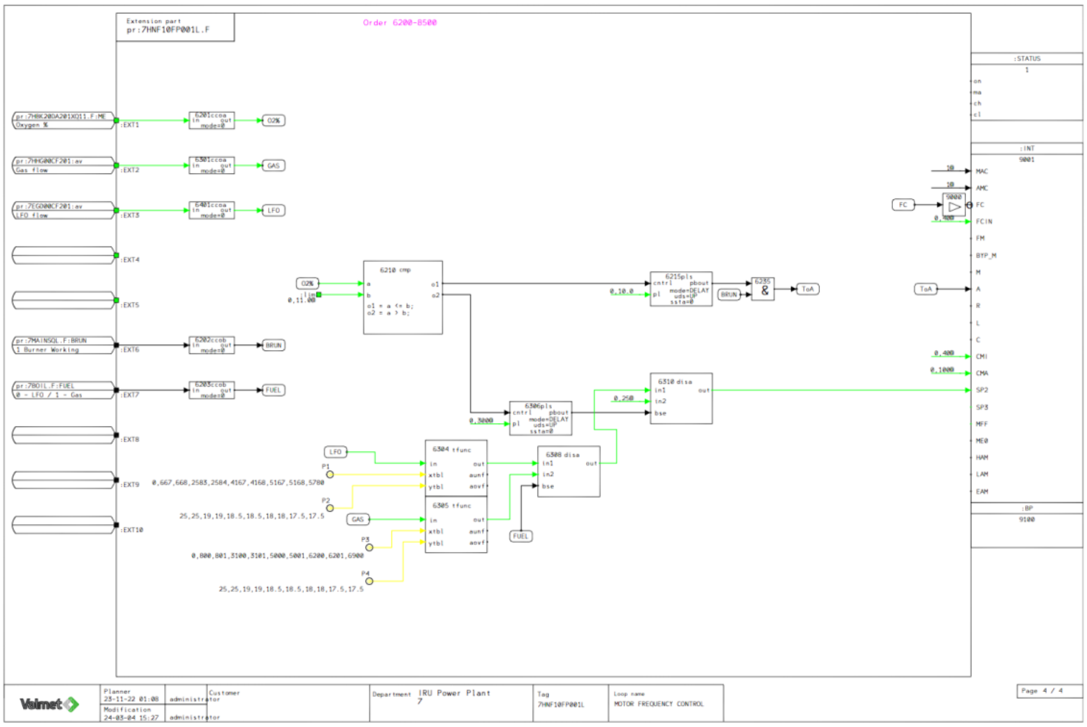


Figure 16 Flue Gas Recirculation Functional Block Diagram Logic

Besides automatic operation logic, the fan controller has a condition to be turned into manual operation mode, based on the amount of oxygen leaving the combustion chambers of the boiler.

5.1.5 Boiler Start-up Sequence

The boiler Start-up sequence by itself warrants a comprehensive overview describing the step-by-step process of preparing an Industrial Water heating boiler for functioning, but to avoid shifting focus too much from giving the overall picture, we are going to look at only a couple of parts of the boiler start-up sequence, without tackling the whole thing.

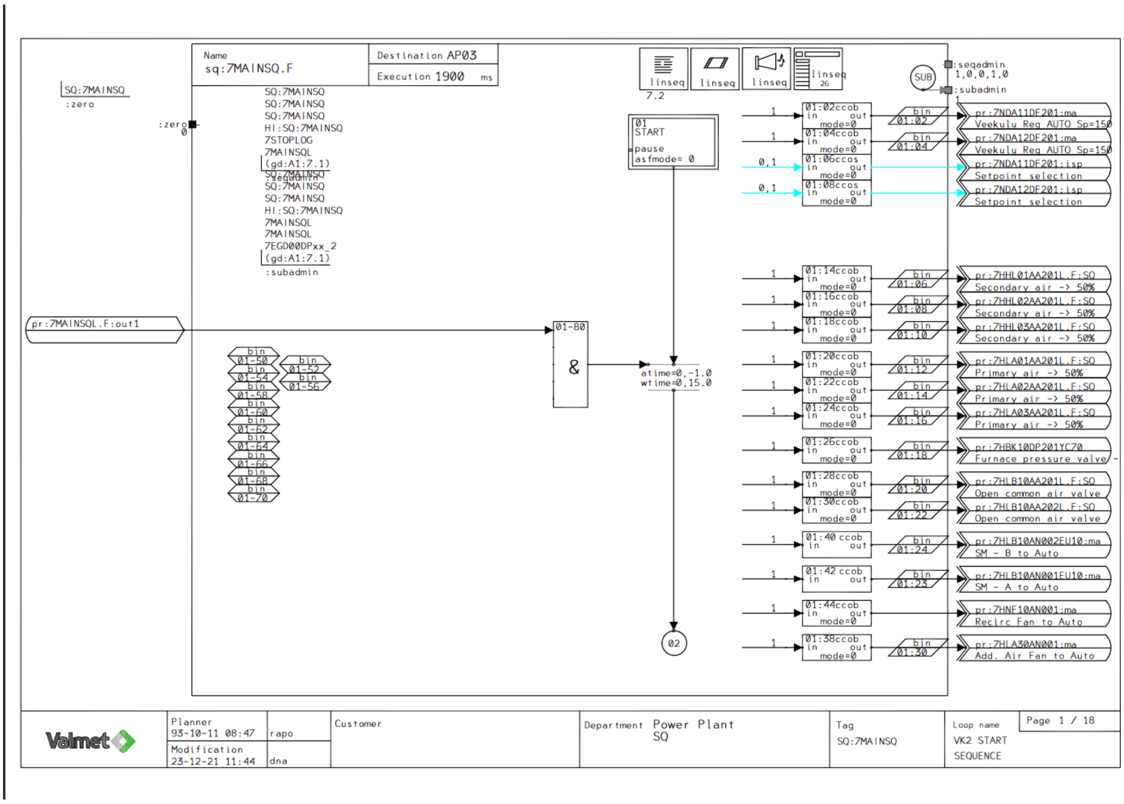


Figure 17 Boiler Start-up Sequence Step 1

In the first step of the boiler start-up sequence, we set burner air valves to the starting positions, open air valves before air fans, and set multiple device function modes to automatic. PID controllers for the air circulation are set to remote mode.

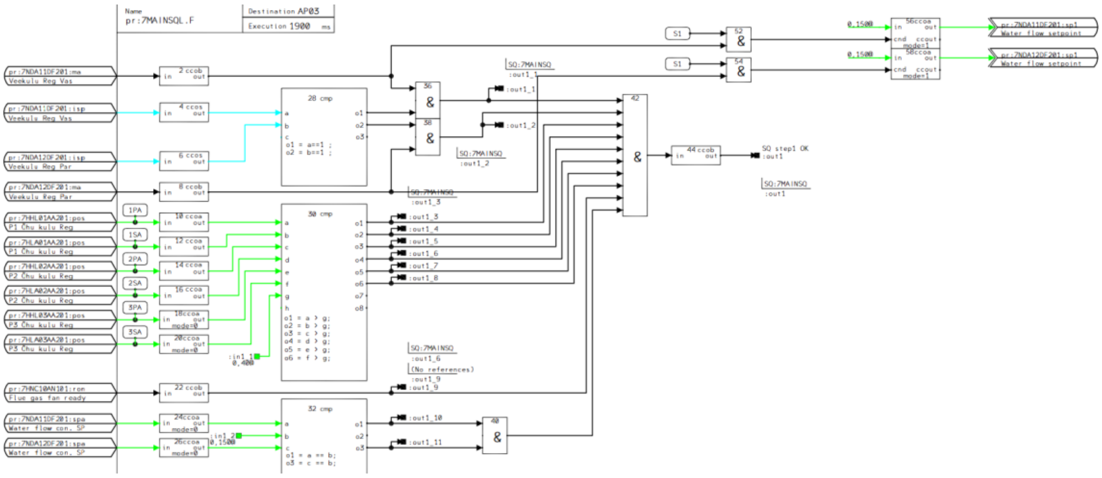


Figure 18 Boiler Start-up Sequence Step 1 Completion control

At the same time, we have a separate program monitoring that every command given in the sequence is fulfilled before we can progress to the next sequence step. The next four steps of the sequence start the devices with automatic operation mode applied. Step six is the general Boiler Protection step that only proceeds when the boiler interlock is in a safe state. Step seven is the ventilation step, where all air valves are completely open. Step eight is more interesting, regulating the set point for the vacuum inside the furnace, depending on the number of currently running burners.

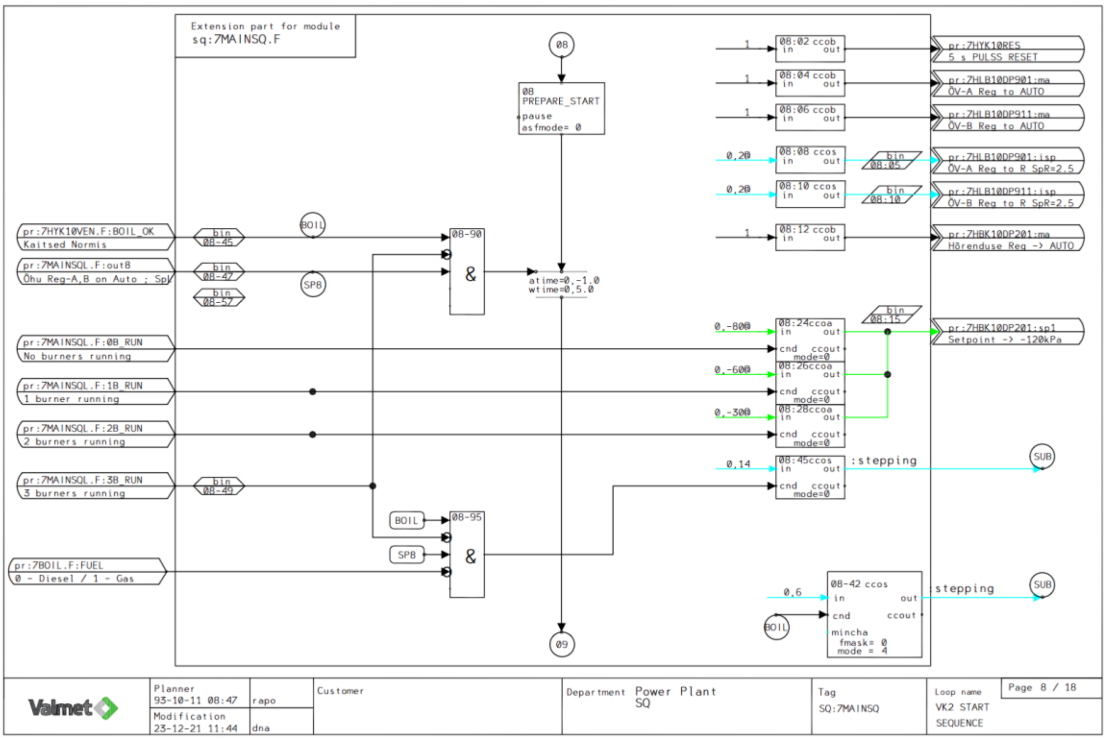


Figure 19 Boiler Start-up Sequence Step 8

The start-up sequence in total has 18 steps, eight of those steps are identical for the LNG and LFO fuels. After these initial eight steps, the process diverges into either the LNG or LFO branch based on the fuel selected on the operator display. Both branches follow a similar structure until a specific step where the operator can manually select the burner to start. The last four steps of each branch operate in a loop.

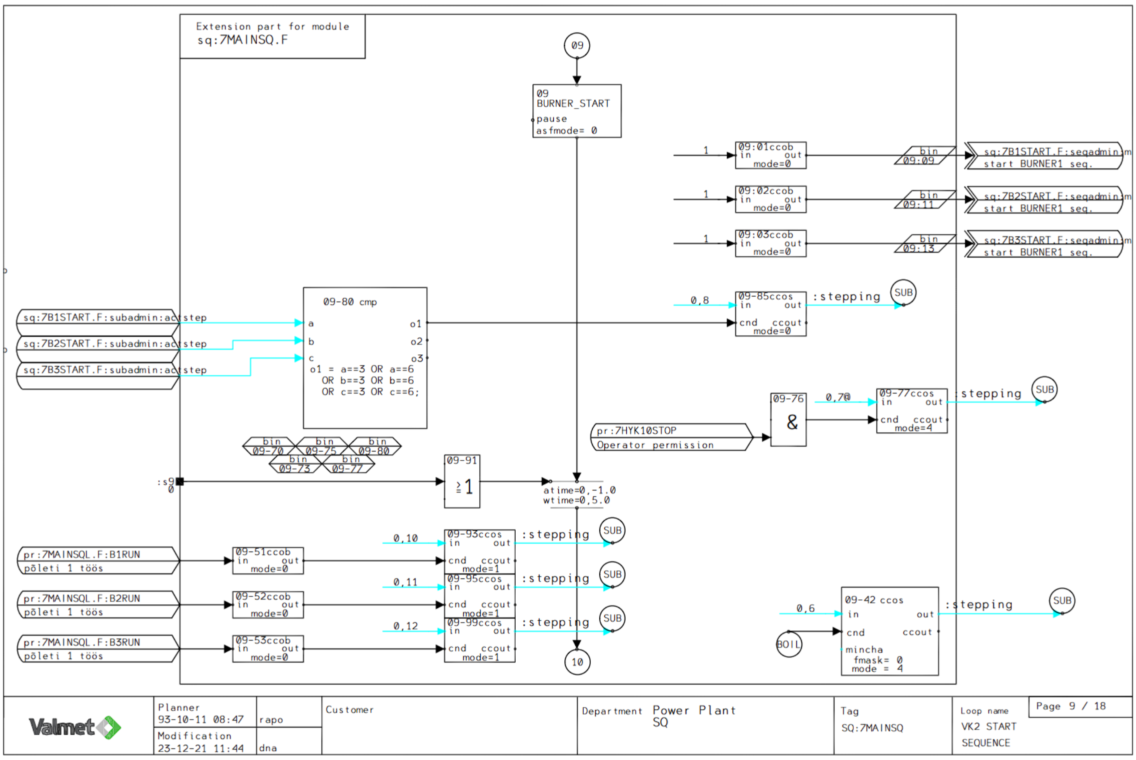


Figure 20 Boiler Start-up Sequence Step 9

After the preferred burner has been chosen for the start-up, the main start-up sequence transitions to the selected boiler start-up sequence.

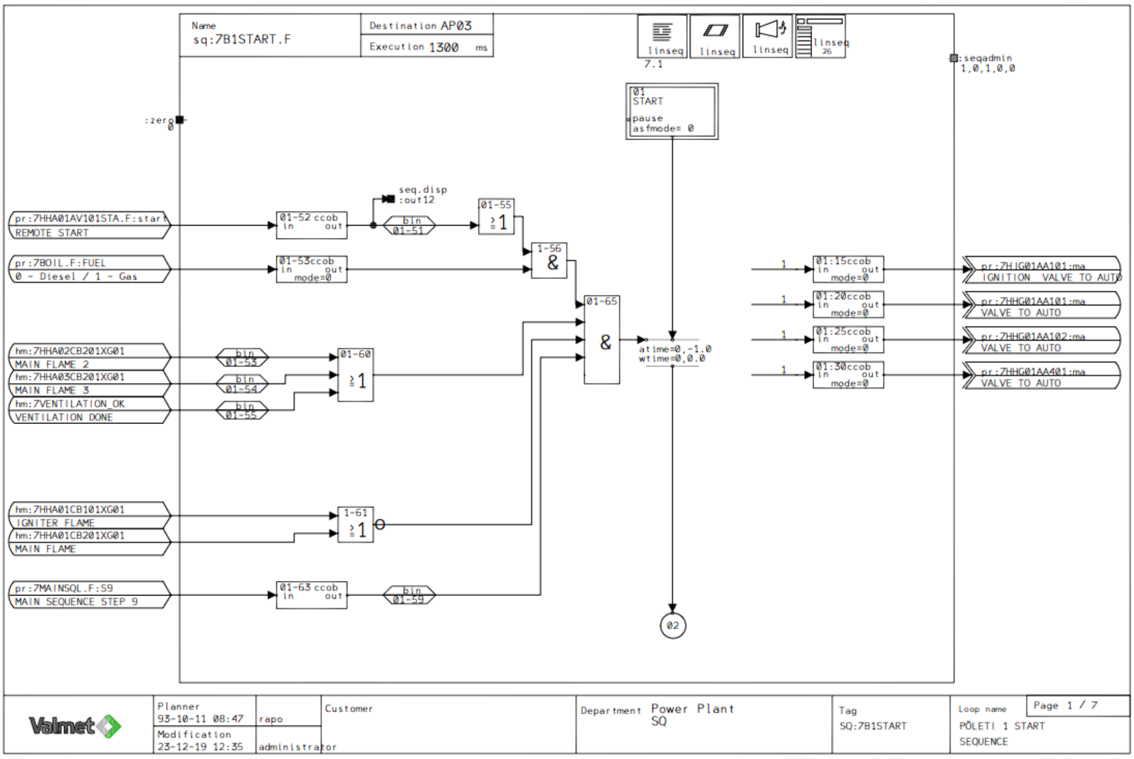


Figure 21 Burner Start-up Sequence

The burner start-up sequence communicates directly with the HIMatrix controller to send commands to open valves and monitor various conditions. The burner interlock structure was previously outlined in the Burner Interlock Safety Logic.

After the burner start-up sequence is finished, control is handed back to the main sequence to start managing the power output of the burner and prepare for the start of the next burners. The main sequence functions until all three burners of the boiler are in operating condition.

6 Summary

This section of the document includes conclusions and analysis of the work done during the writing of the thesis and implementation of the project.

6.1 Conclusions

Early assessments indicate that the project has the potential to enhance the long-term reliability of the dual-fuel water heating boiler system by using more up-to-date safety hardware with refined safety logic. Previously used Programmable Logic Unit cards were cumbersome to debug, as you could not see what exactly was going on the card and only worked with logical inputs and outputs of the particular card.

New enhanced communication between the safety system and the DCS control system allows for easy monitoring of the conditions of the safety matrix. Operators can easily understand what conditions cause the system to be in an inoperable state by looking at the operator's display mimics.

The author has acquired extensive expertise in the implementation of automation for industrial water heating boilers. As an automation engineer in this project, the author has done:

- evaluated technical requirements.
- analysed safety requirements.
- created process control applications.
- created safety-related applications.
- intersystem communication setup

After the project is finished, the collection of running system data allows for a more in-depth analysis of operational efficiency and stability. Ongoing trials and fine-tuning efforts are still underway, making it difficult to provide any definitive statements at this stage. However, it is certainly more straightforward to use.

6.2 Steps after project completion

After completing the project, the subsequent steps are critical to ensure the continued effectiveness and refinement of the automated system for the industrial water heating boiler. Initially, comprehensive data must be gathered on various performance indicators, encompassing energy consumption, combustion efficiency, temperature control precision, and the functionality of safety features. This data forms the foundation for evaluating the system's overall effectiveness, providing insights into its operational strengths, and identifying areas for improvement.

Subsequently, employing advanced data analytics techniques [26] becomes imperative to unearth opportunities for future development and fine-tune the system for optimal performance. Through rigorous analysis of the collected data, patterns, correlations, and inefficiencies can be identified, enabling a deeper understanding of the system's behaviour. Root cause analysis is conducted to pinpoint underlying factors contributing to deviations from desired performance metrics, facilitating targeted adjustments and refinements. Predictive modelling aids in forecasting future performance trends, allowing proactive measures to be taken to mitigate potential issues before they escalate.

Continuous monitoring is established to track the impact of implemented changes and gather feedback from operational experiences. This iterative process fosters a culture of continuous improvement, where insights from ongoing evaluations inform adjustments and refinements to the automated system. Documentation of findings, adjustments, and recommendations ensures knowledge retention and facilitates informed decision-making. Additionally, training sessions are provided to operators and maintenance personnel to equip them with the necessary skills to effectively operate and maintain the system. By diligently following these post-project steps, stakeholders can uphold the efficiency, reliability, and safety of the automated system, ensuring its continued alignment with operational goals and regulatory requirements.

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Appendix 2 – Additional figures

Figure 22 Water Heating Boiler 2 Cabinet Front

Figure 23 Water Heating Boiler 2 Cabinet Back