CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Electrical Engineering
Department of Control Engineering

Monitoring and control system for the TOTEM project

Master Thesis

Study Program: Cybernetics and measurements

Branch of study: Control engineering

Thesis advisor: Doc. Ing. Václav Vacek CSc.

Bc. Michal Vitek

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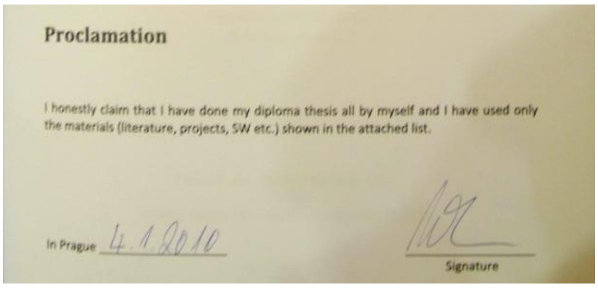

Proclamation

I honestly claim that I have done my diploma thesis all by myself and I have used only the materials (literature, projects, SW etc.) shown in the attached list.

In Prague 4.1.2010

Signature

České vysoké učení technické v Praze
Fakulta elektrotechnická

Katedra řídicí techniky

ZADÁNÍ DIPLOMOVÉ PRÁCE

Student: **Bc. Michal Vítek**

Studijní program: Elektrotechnika a informatika (magisterský), strukturovaný
Obor: Kybernetika a měření, blok KM1 - Řídicí technika

Název tématu: **Monitorovací a řídicí systém pro projekt TOTEM**

Pokyny pro vypracování:

V rámci diplomové práce navrhněte řešení pro monitorovací a řídicí systém chladicího okruhu pro projekt TOTEM, který je situovaný na LHC v CERNu.
Identifikujte základní dynamické parametry chladicího okruhu a navrhněte regulaci pomocí akčních členů instalace. Vypracujte alespoň dvě varianty řešení a porovnejte je.
Navrhněte jednoduchý okruh pro ověření funkčnosti monitorovacího a řídicího systému.
Řídicí systém a jeho vzdálenou správu koncipujte jako "otevřený", tak aby mohl komunikovat i s dalšími paralelními systémy.

Seznam odborné literatury:

Dodá vedoucí práce

Vedoucí: Doc. Václav Vacek Ing., CSc.

Platnost zadání: do konce letního semestru 2009/10

prof. Ing. Michael Šebek, DrSc.
vedoucí katedry

doc. Ing. Boris Šimák, CSc.
děkan

V Praze dne 27. 2. 2009

Abstract. This diploma thesis describes a project of automation of experimental cooling plant within the TOTEM project constructed in CERN, Geneva. The project is dedicated to all components of control system – from hardware and communication protocol selection to high-level control application development. Selection, commissioning and evaluation of hardware action elements are supplied along with cost comparison of individual solutions. Final SCADA application is designed in PVSS II, which controls the cooling plant via transducers and action elements. ELMB boards connected over the CAN buses with control SCADA system are used for sensor readout and action element positioning.

Abstrakt. Tato diplomová práce popisuje projekt automatizace experimentálního chladícího okruhu pro projekt TOTEM konstruovaný ve středisku CERN v Ženevě. Během projektu byly vybrány všechny komponenty řídicího systému, počínaje hardwarem a komunikačními protokoly a konče vývojem řídicí aplikace nejvyšší úrovně. Práce detailně mapuje několik možných hardwarových řešení, jejich výběr, zkoušky, vyhodnocení. V úvahu byly brány technické i ekonomické faktory. Výsledná řídicí SCADA aplikace vytvořená v systému PVSS II umožňuje řízení chladícího okruhu pomocí senzorů a akčních členů. K odečtu hodnot a generování řídicích signálů jsou použity moduly ELMB připojené přes sběrnice CAN k řídicímu SCADA systému.

Table of content

1. Introduction

The design of control system for experimental plant is complicated process which takes many steps and each requires prudential approach. The first issue is to analyze controlled process from the response time, hazards and safety operation point of view. The second step is to propose plant layout with action elements and measuring transducers. The third is to choose convenient hardware components and data acquisition and control software which presents data to operator.

The limitations of the design result from the system specifications, applicable technology, available finance and operation requirements. The demands on a modern control system serve as motivation for an innovative approach. The final solution then arises from a compromise between natural restraints of the controlled application, requirements on the control system and available resources.

This diploma thesis describes the construction of control system for the future upgrade of the TOTEM Experiment. This control structure will be also used for the experimental cooling plant, which is used during the commissioning of TOTEM Roman Pots sub-detectors. During the construction process, the applicable data collection system was implemented, hardware resources were selected and verification tests of operation were carried out.

1.1. TOTEM Experiment

TOTEM (TOTal Elastic and diffractive cross section Measurement) is one of the projects built at the international laboratory for nuclear research, CERN. TOTEM is focused on the precise measurement of the proton-proton interaction cross section and on the in-depth study of the proton structure. The study of such physical processes is complementary to other general-purpose programs of the Large Hadron Collider (LHC). The detail description of the experiment can be found in (1).

The TOTEM experiment comprises three main sub detectors – Roman Pots (RPs) consisting of particular silicon detectors and two particle tracking telescopes (T1 and T2). All of the three sub-detectors are designed to detect charged particles emitted by the proton-proton collisions at LHC interaction point 5 (IP5) next to the CMS project. The layout of the TOTEM experiment can be seen on the Figure 1 adopted from (2).

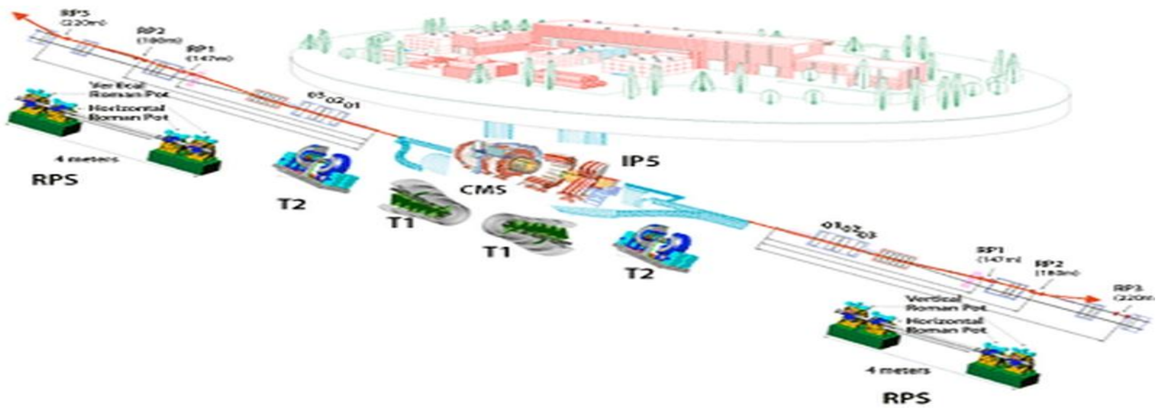

Figure 1 – TOTEM Experiment layout, adopted from (2)

Roman Pots (see (3)) are detectors using an experimental technique introduced in the early 1970s in Rome based on the detection of very forward protons in movable beam insertions. That is why they are called “Roman”. Detectors are placed inside vacuum vessels, called pots, and moved into the primary vacuum during the operation of the detector. The total number of RPs will be twenty-four (groups of six pieces mounted in four different sectors). In the time this document was prepared the RPs were still partly in the production phase and only twelve RPs were in place mounted in two stations placed at 217.3 [m] distance from IP5 in both directions. The extension of the detector (maximum distance between the stations parts) inside the LHC is 434.6 [m]. The twelve remaining RPs, which are still in the production process, shall be commissioned at the CERN Prévessin site at the beam testing area before the final installation to the LHC.

1.2. TOTEM Detector control system

The TOTEM detector control system (TOTEM DCS), also called Big.Brother, was developed at CERN between the years 2006 and 2009 by a doctoral student Fernando Lucas Rodriguez. The system was designed to control all components of the TOTEM project - three sub-detectors (Roman Pots, T1 and T2), environmental monitors, high voltage and low voltage power and cooling plants. The detail description of a system can be found in (4).

The TOTEM DCS was implemented in the PVSS II SCADA system. The software functionalities required for tasks related to the control and monitoring of the TOTEM project were split into modules of PVSS code. Those modules can be easily combined to create desired control application. These modules are distributed in a form of a JCOP framework package, see (5), called TOTEM DCS. This type of distribution allows easy remote installation and eventual updates.

The TOTEM DCS is using a tree architecture where each branch represents one sub-detector and its supporting components. The structure of one branch representing the Roman Pots sub-detector and its accessories are depicted in Figure 2 adopted from (6).

The high level control is provided by six servers (two per sub-detector) named from TOTEM-DCS-01 to TOTEM-DCS-06. Two cooperating computers manage each sub-detector. The first one is in charge of the communication with the low-level controllers, finite state machine and data-base server; the second provides user interface to the connected users. OPC servers and drivers for the communication mediate the communication with the low-level controllers over field-buses. The programmable logic computers (PLCs) and embedded local monitors are used as low-level controllers.

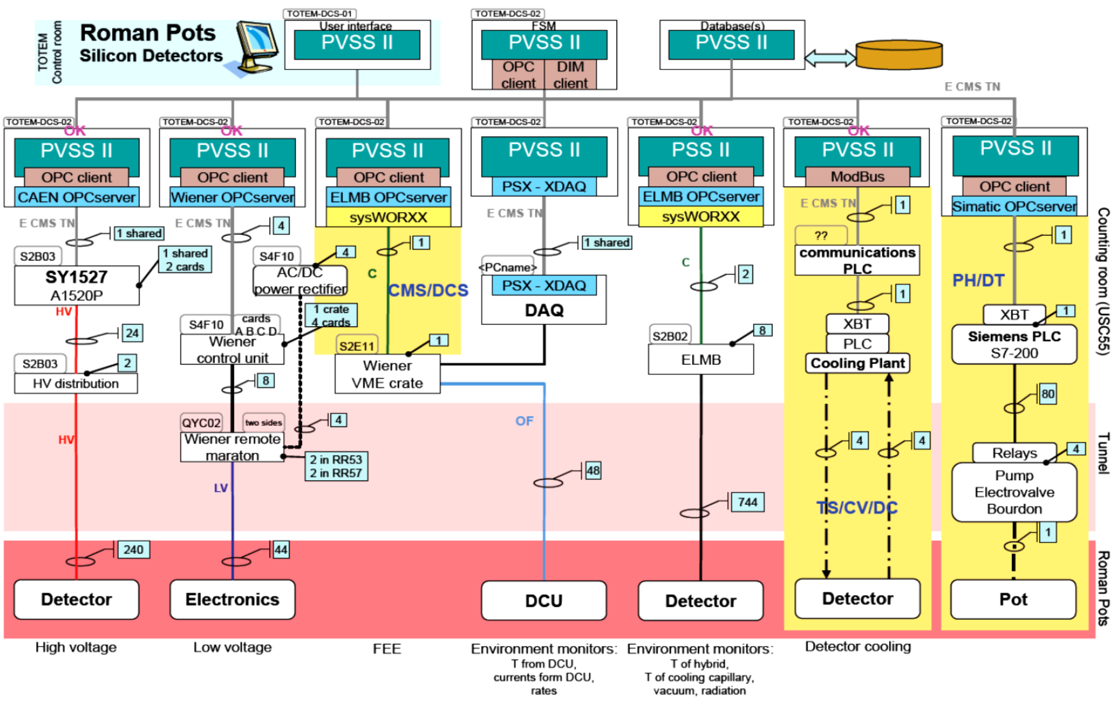

Figure 2 – Schematic of a Roman Pots control system, adopted from (6)

1.3. TOTEM cooling plant

The cooling is a significant part of many industrial processes and it should be understood as an important element in the heat management. This section describes the cooling plant built in the service cavern at the inter section point 5 (IP5) of the LHC for the TOTEM project.

1.3.1. Demands on the cooling plant

Roman Pots sub-detectors require for operation temperatures in range below 0 [°C]. The RPs are generating up to the 800 [W] of the heat in total and the targeted set-point temperature of the RP inner electronics during the operation is around -20 [°C]. Each RPs station can be operated independently on the others and its heat load may vary over the full scale (0-100%) depending on the RPs state. Thus the sectors must be split to the separately controlled cooling loops to enable maintaining environment in each sector and the cooling plant must be able to keep the cooling system stable even if the heat generated by the RPs electronics is zero.

1.3.2. Cooling principle

The two stage evaporative cooling system was selected for the Roman Pots cooling. During the cooling process, the pre-chilled refrigerant is supplied under the high pressure in the liquid state into the capillary located inside the RP volume. The pressure drop introduced post-capillary causes evaporation of the coolant, thus cooling along the evaporator. The cooling was designed as a two phase, because of the cooling mediums main disadvantage - low heat transfer coefficient (comparing to water). Chilled liquid refrigerant has reduced enthalpy and therefore can absorb more heat during the evaporation.

1.3.3. Cooling medium

The selected coolant is fluorocarbon C_3F_8 that is described in section 2.5.2. It was chosen because of its characteristics: electrically insulator, non-flammable, non-toxic and stable after the irradiation.

1.3.4. Cooling plant layout

The Roman Pots are located in the highly irradiated area in the LHC tunnel. Thus, all control elements of the cooling plant are located in the IP5 service cavern which is always accessible - even when the LHC is operational. The plant has four separate cooling loops that lead to the sectors with RPs. Two capped inputs and outputs are prepared for the future upgrades and one line with dummy load heaters.

1.3.5. Cooling process description

The liquid refrigerant is stored in the water-cooled tank, which also serves as a condenser. During the run, the coolant is under high pressure brought to the distribution rack where the pipe splits to four separate loops.

A manually operated TESCOM pressure regulator sets the pressure in each loop and pressure sensors measure the inlet pressures of the loops. The nominal flow of the refrigerant through each of the cooling lines is 10 [g/s].

The liquid coolant then enters into the capillaries housed in the RPs mounted in the loop where it evaporates. The vapor is exhausted from the loops through a TESCOM back-pressure regulators by a pair of compressors connected in parallel. The set-point of the TESCOM back-pressure regulators needs to be adjusted manually.

The compressors power depends on the amount of the coolant circulating through the cooling loops. The line with the dummy load is used to maintain cooling plant stable when the flow of the coolant through the normal cooling lines is less than 8 [g/s]. The simplified schematic of the cooling plant depicted in Figure 3.

1.3.6. Existing cooling plant control system

Stable cooling process is essential for safe operation of the Roman Pots sub-detectors. Thus, the TOTEM cooling plant requires a reliable control and monitoring system that would prevent damage of the cooled RPs and the cooling plant itself. The main requirements for the control system (CS) regarding the cooling are: start up and shut down of the cooling process, adjusting the cooling parameters (inlet pressure and outlet back-pressure of the coolant) and monitoring the RPs environment (temperatures and vacuum pressure).

The CS is based on the two SIEMENS S7-200 PLC low-level controllers. The first one serves for controlling and monitoring the cooling process. The second one is in charge of the vacuum system. The status of the operation is communicated to the high level control via the SIEMENS Communication PLC, which doesn't have access to the action elements. Thus they are protected against the unwanted access from the outer systems. The high level control is built in the PVSS II supervisory software that is communicating with low-level controllers over the Simatic OPC server. The high level controller is included in the TOTEM DCS hierarchy.

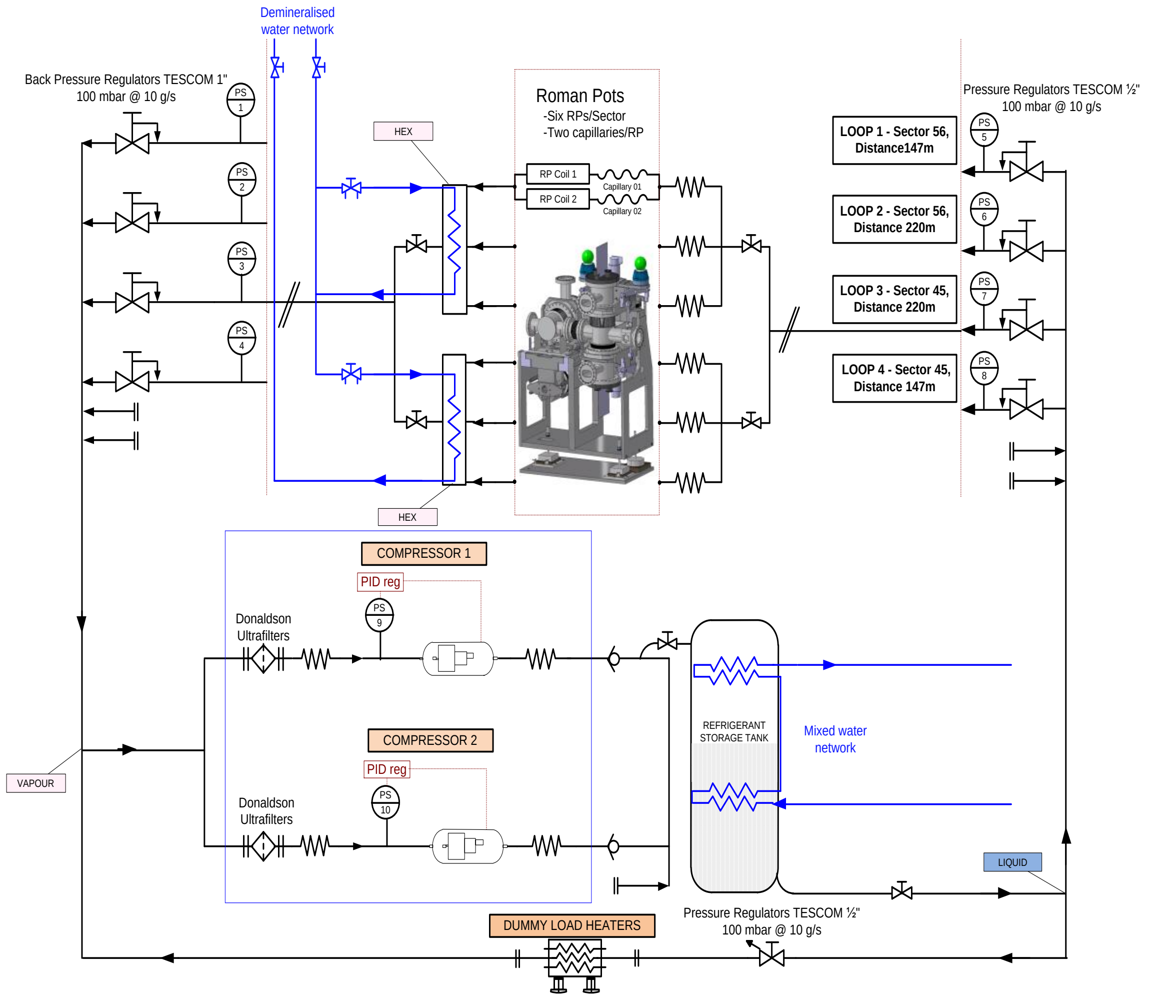

Figure 3 – TOTEM cooling plant scheme

The CS can separately control cooling process in four cooling loops. Each cooling loop can alter between three different states. The states and conditions corresponding to them are described in the list below.

- ON State: The electromagnetic valves on the liquid side and on the vapor side that holds the liquid in the tank are open. The valves at the beginning and at the end of the cooling loop are open.
- OFF State: The electromagnetic valve on the liquid side of the cooling loop is closed. The coolant is being recuperated from the loop into the tank.
- LOCKED State: The electromagnetic valves on the liquid side and on the vapor side of the cooling loop are closed. The cooling loop is ready for the maintenance.

The parameters of the cooling – pressure of the coolant passing to the cooling loop and the pressure of the vapor leaving the cooling loop (back-pressure) – can be adjusted by a set of manually operated TESCOM pressure and back-pressure regulators. For such operation, presence of service personnel is required.

1.4. The goals of the thesis

The TOTEM cooling plant described in section 1.3 is going to be upgraded to system that allows remote control of its all cooling parameters. The plan is to replace the manually operated action elements (pressure and back-pressure regulators).

The Roman Pot sub-detector is a unique device that is located in an area with a very difficult access and almost no possibility for repairs during the LHC operation. Therefore only reliable and proven solutions can be used for the construction of any of its sections, including the cooling plant. On the other hand, the component selection is limited by the budget restraints, that is why the chosen solution must be affordable.

The thesis aims to collect necessary information and software resources that could be used for the selection of the most appropriate solutions. The list of all tasks is according to the specifications:

A. To propose two low cost hardware solutions for the automated pressure regulation of the inlet liquid coolant pressure in the TOTEM cooling plant cooling loops.
B. To propose two low cost hardware solutions for the automated back-pressure regulation of the outlet vapor coolant pressure in the TOTEM cooling plant cooling loops.

C. To carry out performance tests of the most promising solutions on a real system.

D. To develop software solution for the control of the modified cooling plant that would be compatible with the current control system of the plant and with the control system of the TOTEM project.

2. Theoretical background

This chapter reviews important concepts, processes and devices that are referred in other parts of this document. Detail description of the issues can be found in the cited documents.

2.1. Industrial control system

Industrial control system (ICS) is a group of control subsystems that are currently use in the industrial control – supervisory control and data acquisition (SCADA), distributed control systems (DCSs) and programmable logic controllers (PLCs). ICSs are used typically used in industries such as water, oil and gas, power plants or data processing. Scheme of the industrial control system is depicted in Figure 4.

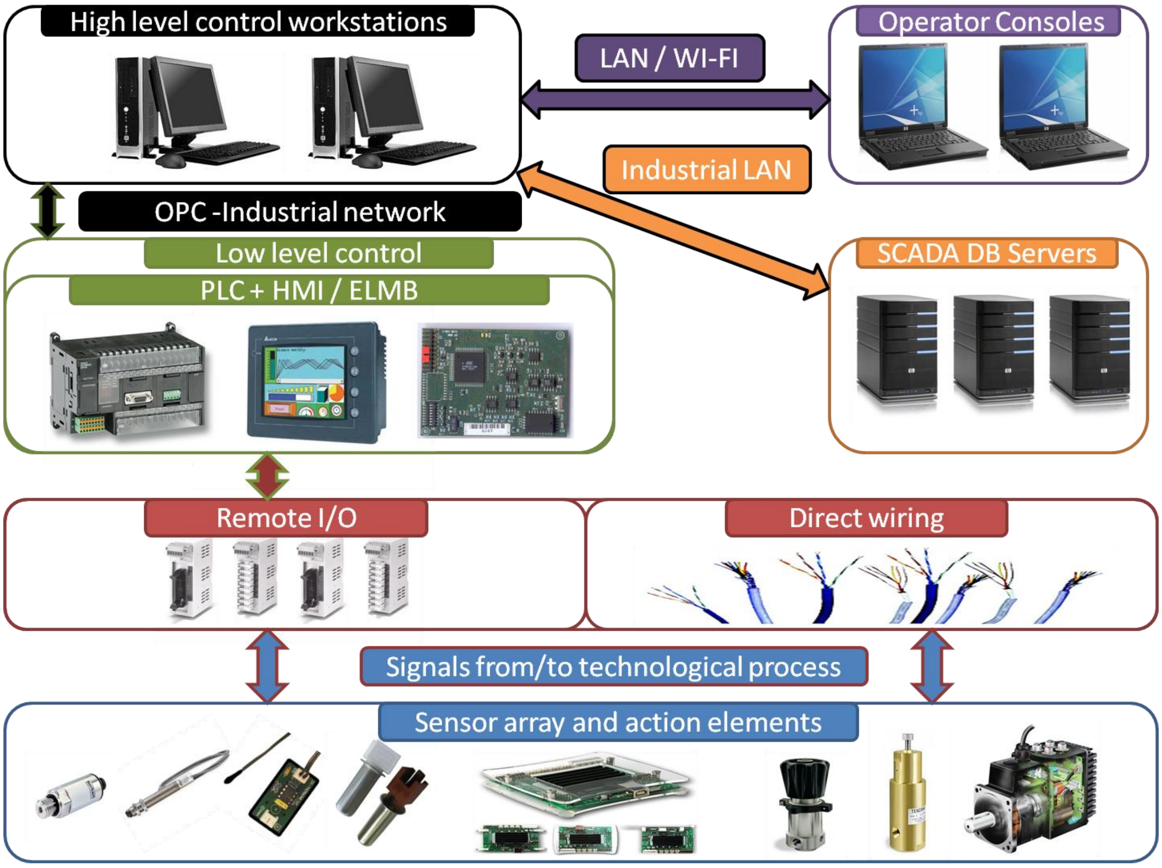

Figure 4 – Industrial control system schematic

2.1.1. Distributed control system

Distributed control system architecture decentralizes the sub-control elements along the whole industrial installation. DCS setup gives control system robustness, expandability and flexibility. As drawbacks stand more complicated networking and higher requirements on the financial resources comparing to the centralized control. In the design of the DCS are as sub-control elements usually used input/output (I/O) programmable modules capable of communication via standard industrial communication protocol (CAN Open, Profi-Bus, Industrial Ethernet, Lon Works, etc.). The module receives information from the input elements in the process (sensors) and transmits instructions to the output elements in the field. Module can serve as a local controller and it is still connected to the central data collector through the field-bus. The central controller is connected to the human machine interface (HMI) or to the operator consoles. DCS data collector can also use a SCADA system for the connection to the physical equipment. In this thesis the DCS is considered as a layout of the hardware components and SCADA as a software framework that provides functionality for the DCS.

2.1.2.Supervisory control and data acquisition system

SCADA refers to a system that collects data from various sensors at a factory, plant or in other remote locations and then transmits this data to a central computer, which then manages and processes this information. It can be also seen as a system with many data elements called data points. Points can be either hard or soft. A hard data point can be an actual monitor/sensor; a soft point can be seen as an application or software calculation. Data elements from hard and soft points are recorded and logged in the data-base (DB) to create a time stamp or history. SCADA is usually operated through HMI that provides easy access to the system and to the collected data. The design of the access depends on the particular system and on its purpose (access to large potentially dangerous systems needs to be well secured). Data maintained by SCADA is also being used for determination of the current state or for the forecast of the future states of the system. This knowledge can be used for the modeling of the controlled process finite state machine (FSM). Software implementation of SCADA can be found in multiple well known software packages (e.g. Honeywell EXPERION, ETM PVSS II, Siemens Simatic STEP7, etc.).

2.1.3.Human Machine Interface

A SCADA system usually includes a user interface called Human Machine Interface (HMI) or Graphical User Interface (GUI). The HMI is location where data is processed and presented to be viewed and monitored by a human operator. HMI's are an easy way to standardize the facilitation of monitoring multiple low-level controllers (LLCs) such as PLC, ELMBs or other programmable controllers. LLCs usually run a pre-programmed process and monitoring each of them individually can be difficult, because they can be spread out over the whole site. Because LLC historically had no standardized method to display or present data to an operator, the SCADA system communicates with them throughout the industrial network and processes information that is then easily disseminated by the HMI. The HMI can also be linked to a SCADA data-base and it can use data from the technological process to provide graphs on trends, logistic info, schematics for a specific sensor or machine or even make troubleshooting guides accessible. HMIs are usually built in the SCADA software, which provides functionality how to visualize data to operator and which collects batch operator actions.

2.1.4.Finite state machine

A finite state machine (FSM) is a model of system behavior composed of a finite number of states, transitions between those states, and actions. In industry, optimized FSM is used, which states for the machine with the minimum number of states. The design of the FSM is usually done by graphical diagrams that display all possible states and state transition conditions. The FSM transition logic between states is shown on the Figure 5.

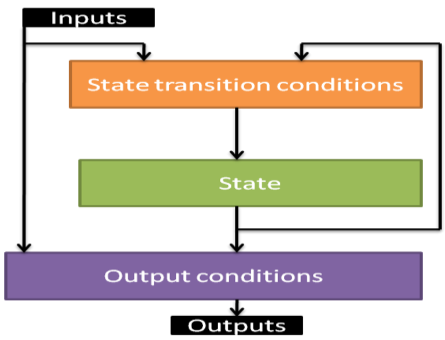

Figure 5 – FSM logic

2.2. High level control

A high level control (HLC) stands on the top of the control hierarchy. The HLC has information about the global state of the controlled systems and through the low-level controllers can access to its any part. The HLC is usually realized by an interconnected industrial computers or PC workstations running the SCADA software.

2.3. Low-level controller

A low-level controller (LLC) is a front-end controller used in the technological process. The controller is in direct touch with the action elements and it communicates gathered information to the higher levels of the control hierarchy. Typical example of the LLC is programmable logic controller (PLC) or embedded local monitor board unit (ELMB).

2.3.1.Programmable logic controller

A programmable logic controller (PLC) is a digital computer used for automation of various industrial processes. The PLC is designed for multiple inputs and output arrangements, extended temperature ranges, immunity to electrical noise, and resistance to vibration and impact. Programs to control machine operation are typically stored in battery-backed or non-volatile memory. The programming is usually done in the ladder logic and/or Petri nets, the program then runs in sequences. The programs are evaluated in cycles – scan times. Typical scan time for PLC is in range from 5 milliseconds (e.g. Honeywell c300) to hundreds milliseconds (depending on the PLC hardware setup and on the complexity of the program).

PLC may need to interact with people for the purpose of configuration, alarm reporting or everyday control. Therefore, a HMI is usually employed when the level available of the graphical user interface depends on the actual PLC hardware setup (LED output/text messages/complex GUI available from the remotely connected computer). The I/O ability of the PLC depends on its hardware configuration and it can be usually modified or expanded if needed through I/O modules. Nowadays there are available extension modules for all standard I/O digital and analog ranges. The PLCs are produced by many vendors – Siemens, Honeywell, WAGO, etc.

2.4. CAN Open communication protocol

CAN Open is a communication protocol defined by the CAN in Automation (CiA) organization. The detailed description of the protocol can be found at (7). The CAN Open standard implements the seventh layer of the OSI/ISO communication model, the application layer. The interoperability of devices from different manufacturers is also granted by standardization of the following items.

The communication profile

It defines the communication between devices connected to the bus. The communication model implements the master-slave and also the slave-slave communications. At least one master device must be connected to the CAN Open bus to perform the start-up and initial operations.

The Device Profile Specifications

It specifies the specific behavior for different types of devices such that the basic network operation is secured.

Object Dictionary

The object dictionary is a data-base with an ordered collection of objects containing the description of the device and its network behavior. The object dictionary is not stored directly in the CAN Open nodes but it is provided in the form of an electronic data-sheet.

Standardized communication objects

Two object types are defined:

- Process data objects -broadcasted and unconfirmed messages with high priority used for real-time transfer. This type of communication is usually used for the control commands because they are immediately propagated to the controlled device.
- Service data objects - confirmed messages used in the peer-to-peer communication between two nodes. The messages have low priority and they are transmitted in the time of bus low-level occupancy.

Standardized Network Management

The network management defines the possible states of the nodes, master node competences, supervision over the bus and the start-up procedure. The master node handles the transition of the slave nodes between the possible states: initialization, pre-operational, operational and stopped. After the boot up sequence the device enters in pre-operational state. The two mechanisms for the network supervision are implemented – node guarding and life guarding (only one can be active).

Standardized systems services for synchronous operation of the network

The network master can query values of the input channels by sending a SYNC command to the bus.

2.5. Evaporative Cooling

Evaporative cooling is a physical phenomenon in which evaporation of a liquid into environment cools a surrounding area or objects. The cooling is usually realized by a heat engine that works according to the first thermo-dynamical law under which it is possible to change the internal heat energy or work. Heat engine must also respect the second thermo dynamical low according to which is not possible full heat conversion. Evaporative cooling can be used in many applications from the cooling of civil buildings to cryogenic applications.

2.5.1. Two stage evaporative cooling

Two-stage evaporative cooling improves the standard evaporative cooling and brings advantage of working with the coolant in ambient temperatures during most of the cooling cycle for the industrial systems. In the first stage warm coolant is pre-cooled indirectly (by passing through a heat exchanger that is cooled by different cooling circuit - water, evaporation on the outside etc.). In the second stage (direct stage), the pre-cooled coolant passes to the evaporator. The media pressure reduces here sharply - it is reduced by capillaries or the volume of the evaporator is bigger than the pipelines in the previous parts of the cooling circuit. The boiling temperature of cooling media changes together with the pressure therefore the coolant starts evaporating – cooling the surrounding area. The vapor is usually drained from the evaporator by a compressor in to the condenser where it is compressed to a pressure which corresponds to the boiling temperature higher than the ambient temperature. Excess heat that arises during this process is released into the environment.

2.5.2. Octafluoropropan

Octafluoropropan C_3F_8 (R218) is a chemical compound used in the refrigeration industry as a coolant or a component in refrigeration mixtures. Besides, it is used in the production of semiconductors such as etching material. The R218 is suitable for usage in the evaporative cooling systems because it is dielectric, radiation resistant, nontoxic and stable. The boundary between the liquid and vapor state is shown on the pressure-enthalpy diagram depicted on Figure 6, adopted from (8). More information about this topic can be found at (9).

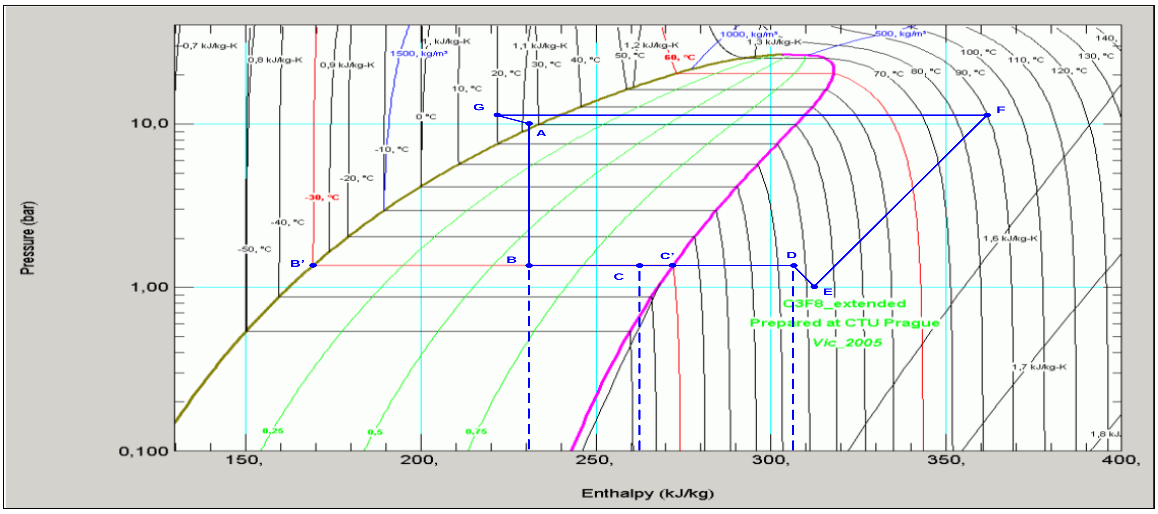

Figure 6 – Octafluoropropan pressure – enthalpy diagram, adopted from (8)

3. Control system components selection

This section describes the selection of the technologies and hardware components that can be used for the cooling plant. The whole system was prepared as modular and scalable. It must not only work with TOTEM cooling plant, but also with the testing cooling plant. From this restrain arises the need for architecture that would be fail safe but also easily adjustable, hardware independent and compatible with already used monitoring systems. The design of the control system was also influenced by the information adopted from (10).

The software part of the control systems has to be capable of handling readout of the cooling plant sensor array that consists from approximately 80 individual analog sensors and control of at least 10 action elements. The price is not essential for the selection of the software package, but product available with CERN license is preferred.

The main limitation during the selection of the hardware components were the price of the components (components should be low-cost) and their reliability – the repairs are difficult during the cooling plant operation.

During the components selection two paths were considered:

- Use similar software and hardware technologies to the ones of CMS and other LHC experiments and modify them if necessary.
- Utilize completely different technologies and provide a compatible communication interface.

At least two possibilities corresponding to this philosophy were on every decision-making level judged to determine the most appropriate solution.

3.1. SCADA software products comparison

The goal of the SCADA products comparison was the selection of the most suitable software package for the implementation of the cooling plant control system. The comparison was done on a set of software products for industrial applications that are commonly known whose license was available. The tested products were Honeywell Experion and ETM PVSS 2.

Analyzed parameters used for the selection of the software were:

- Hardware requirements.
- Scalability.
- Connectivity with the OPC server.
- Data storage system.

3.1.1.Experion

Experion is a commercial SCADA system produced by the American company with international scope and a broad range of business activities.

3.1.1.1. Experion architecture

Experion SCADA is a server based solution consisting of components depicted in Figure 7. All hardware controllers and external data sources communicate with Experion server over LAN via TCP/IP protocol. The SCADA engine runs in Windows 2003 server environment only. There is supported a server redundancy option, with server A and server B as a hot standby back up pair. There can be a grid of up to 20 servers mutually communicating together. All data from all servers can be accessed by up to 40 simultaneously connected client stations, which can visualize or access data from all servers in the grid.

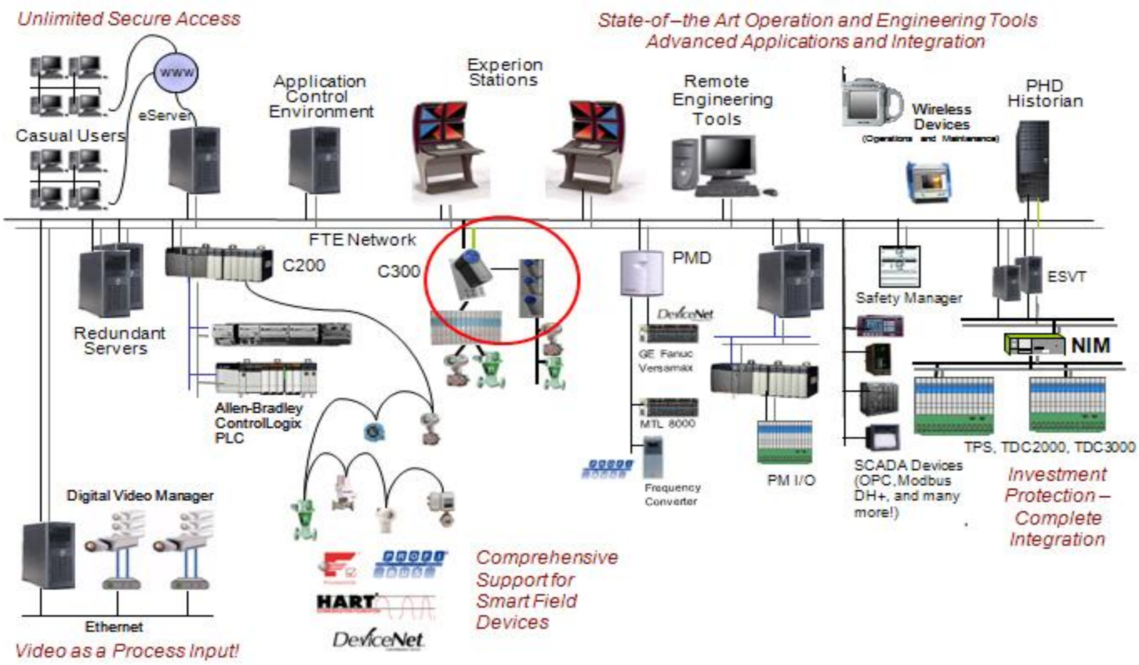

Figure 7 - Experion based control system architecture

3.1.1.2. Experion server Data structure

There are several data-bases running on each Experion server. Their structure is depicted in Figure 8.

For process data coming from field via I/O channels there is a separate data-base called ERDB, which contains definition of all I/O instruments list, all controller list, mirror of program downloaded into C300 controllers and also all data loaded and read from the field.

For process data coming over communication - OPC communication, Modbus communication – there is data-base RTDB, which contains up to 65000 data containers for points. Each measurement or communication channel definition takes one point in this data-base.

Finally, for maintenance of access rights there exists EMDB (Enterprise Model DB), which contains map of all servers, which are communicating together, list of all stations in the system, organization structure of all the plant, alarm definitions and user access and control rights. This data-base is located only on one server in whole system and it is shared by all servers in the plant.

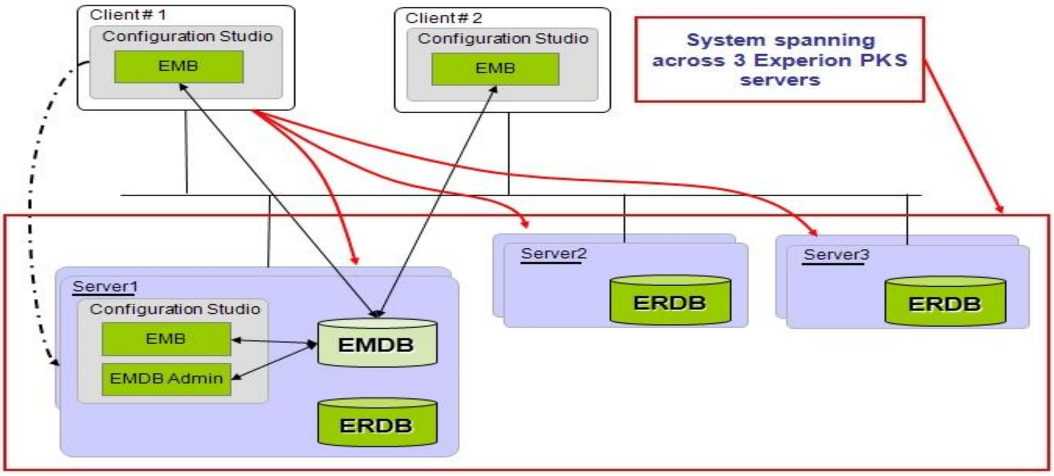

Figure 8 – Experion data-bases structure overview

3.1.1.3. History collection

All points and parameters, even operator commands can be archive stored. Operator commands and alarms are stored asynchronously and server has live FIFO list of 100 000 events, which occurred recently in the system. For all process values, historization can be defined, but fastest update rate for history is only 5 seconds.

3.1.1.4. PLCs used by Honeywell

Field devices – measurement instruments or actuators - are typically accessed through Industrial controller of C200/C300 series. More recent is C300 series controller, which can seamlessly communicate with multiple platform actuators of HART, FIELDBUS or PROFIBUS standard. C300 provides to the SCADA system the fast update rate between 500 [ms] and for special applications also a fast version with 5 ms scan rate is available. Special feature of C300 is guaranteed scan time and load estimate priory to operation. All prescribed operations and IO channels are served in the scan time in deterministic order.

3.1.1.5. I/O Cards

Honeywell delivers the controller C300 with proprietary I/O cards of AI, AO, DI and DO type. C300 controller and all I/O modules have the option to be redundant, which provides a smooth failover in case of hardware failure. The AI and AO card reads out data in 4-20 [mA] HART format. Up to 64 I/O cards can be attached to C300 on two I/O links (Honeywell proprietary bus for I/O readout). Fieldbus devices are communicating with C300 over TCP/IP via FIM4 module, which can serve up to 64 FIELDBUS devices on 4 branches.

3.1.1.6. Simulation of C300 controller as a framework for process evaluation

In those cases, when no direct field interaction is required and only evaluation of sequence or logic control is required, there exists a C300 simulation option. A special PC with Honeywell dedicated software would run an application which behaves and processes data like C300 controller. Such option can be successfully used, when you need to control process over communicated channel. The embedded function for PID control available in C300 can process input signal and generate output, all alarming and history can be configured via same approach as for hardwired I/O channel. Greatest advantage is that a developed program can be transferred into real C300 processor without extra workaround. From server point of view, there is no difference between simulation and real C300.

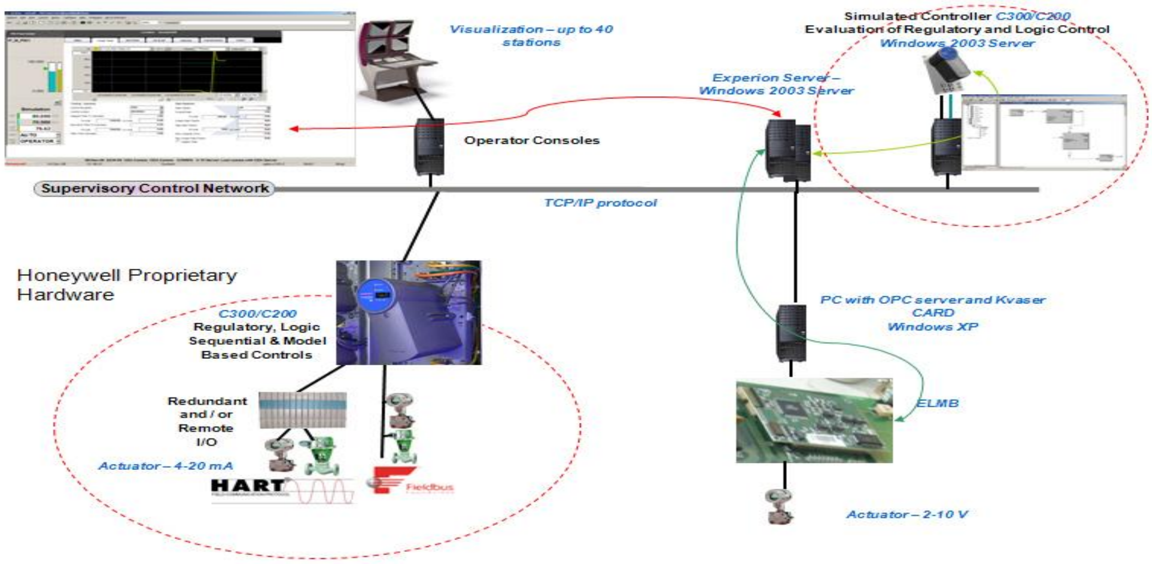

Figure 9 – Experion connection to the low-level controllers

3.1.1.7. Connection of devices over OPC

In case that different than Honeywell hardware is going to be used, there exists an option that Experion server can communicate with this hardware over OPC of Modbus. For such purposes there exists a retouched data-base in Experion, which maintains this communication, called RTDB (Real Time Data-base). Each server is able to read/write up to 65000 points with defined sampling rate from 2 s. A special software component in Experion server, called OPC integrator provides transfer of values between points in RTDB and remote OPC server. In the Figure 9, the goal is to read out and evaluate process values coming from CAN bus standard device. For such purpose, there must be a computer server with CAN Open OPC server running, which would publish values from field. The OPC integrator would mirror these values from OPC server into points on the server or in the simulated C300. In the C300, the collected real time data is compared with alarm limits and also control action is derived. Embedded functions for PID control or even blocks for singe loop model predictive controls will generate the output signal, which is transfer via OPC back into field. Typical response time of this solution is around 5 seconds (3 seconds takes OPC transfer + 2 seconds takes value processing) and sampling rate is around 2 seconds (one direction time for OPC).

3.1.1.8. Hardware requirements

At least one computer is necessary for the Experion based control system. The computer must be a rack server manufactured by DELL company (e.g. DELL PowerEdge 2970), because only such computers are supported by Honeywell company. The demands on hardware are growing, when the C300 simulation or OPC server is necessary, detail requirements are enlisted in the Table 1. The price of the DELL rack server is approximately 12000 CHF and the price of the desktop computer is 1100 CHF (based on price list from (11)).

Table 1 – Experion hardware requirements

Computer usage	Operational system	Computer type	HDD space	OM Size
Experion server	Windows 2003 server	DELL 2970	30 [GB]	3 [GB]
C300 simulation	Windows 2003 server	DELL 2970	30 [GB]	3 [GB]
OPC server	Windows XP	Vostro 220	5 [GB]	1 [GB]

3.1.2.Process Visualization and Control System

A SCADA system named PVSS II (meaning Process Visualization and Control System II) produced by the Austrian company ETM, see (12).

PVSS was chosen by all LHC experiments as the supervisory system of the corresponding DCS systems and it is now recommended as a CERN – wide SCADA system. The main properties for which it was selected are:

- Scalability - it can work with systems of any size (it has no limitation in the number of connected devices).
- Versatility - it can be expanded with modules written in the C++ and its inner scripting language (Control Programming Language) has also C++ syntax.
- Built-in support of the networking over TPC/IP.
- Low hardware requirements – it can run on any computer with Windows XP.
- Easy access to internal variables.

3.1.2.1. PVSS system architecture

The PVSS SCADA system is composed from central components – blocks - organized in four layer hierarchy, see Figure 10. The first - lowest - layer consists from drivers that are provides the direct contact with the field devices. Data historization (data-base manager) and reaction on the communicated events (event manager) are located in the second layer. The C++ programs and Control Programming Language scripts can be lunched in the third layer. The top layer is reserved for the user interfaces.

Each PVSS II system has always one event manager and one data-base manager. It can have multiple drivers (connected to the hardware), running scripts or user interfaces. Each of these items can run on a separate processor if required.

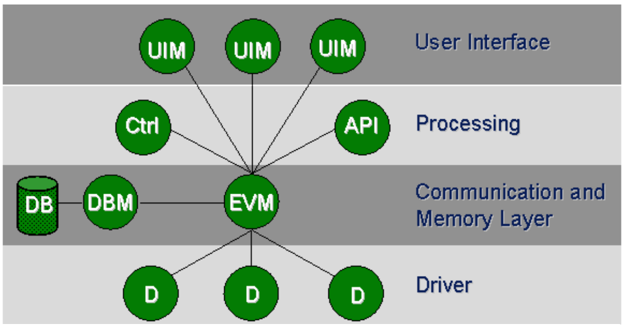

Figure 10 – PVSS system hierarchy, adopted from (13)

Several PVSS II systems can be connected together to enhance the capabilities and offered resources and to distribute the load, see Figure 11. A system can be spread over several PCs or more than one system can be run on one PC. This design makes PVSS II highly scalable and allows independent development of control system subparts.

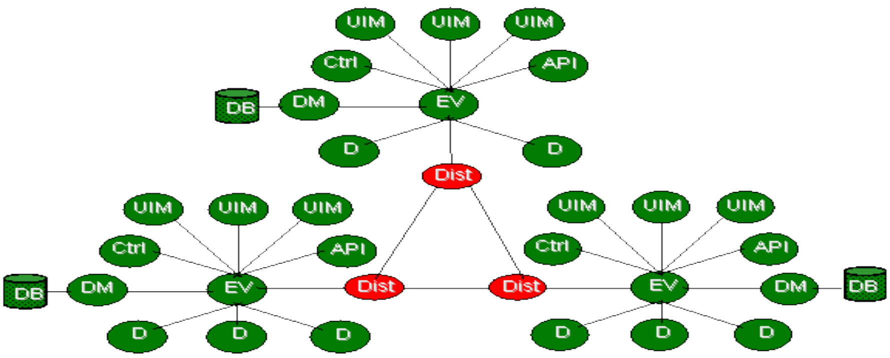

Figure 11 – PVSS distribution of the system components, adopted from (13)

3.1.2.2. Data organization

All data (parameters, variables, communicated values, etc.) are organized into the structural units called Data Points, see Figure 12. The data points have tree hierarchy consisting from any data types (numbers, text strings, etc.). Each data point stored on a PVSS machine must have locally unique name (two data points can have same name but they must be stored in different systems).

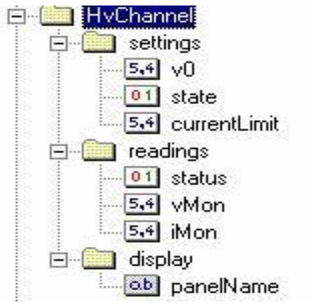

Figure 12 – Example of the PVSS data point structure, adopted from (13)

3.1.2.3. History collection

The system of the data archiving can be specified for each data point. The data can be stored asynchronously after the value in the data point changes, synchronously with any synchronization time or in combination. The data can be stored locally in the SQL based data-base built in the PVSS, or they can be communicated to the external data-base (e.g. Oracle data-base).

3.1.2.4. Connection of devices over OPC

The PVSS have built in support for connection with OPC server, which can run on the same computer as the PVSS system. After the server is configured in the PVSS and lunched the communication is automatically established by PVSS OPC client. The values from OPC server are then copied into corresponding data points and vice versa. The PVSS offers also the simulator of the OPC server that can be used for the testing purposes. The PVSS system architecture is not limited in the number of connectable devices over OPC – the only limitation is given by used hardware.

3.1.2.5. Hardware requirements

The PVSS II system runs on Windows and Linux and one can mix both operating systems even within a single PVSS II system. Thus the only requirement on the computer is the ability to run any Windows (e.g. Microsoft Windows XP) or Linux system (e.g. Ubuntu 9.0) and to have enough free hard disk space for the PVSS installation – 2 [GB].

3.1.3.SCADA system selection conclusion

Both evaluated SCADA system are very powerful and usable as a control systems for the TOTEM cooling plant. The basic functionality of both systems is almost the same, but the Experion system moreover offers a complete solution for control system including PLC, action elements and tools for the PID control. The PVSS is on the other hand more scalable and resources requiring solution with wide support at CERN.

The PVSS II was after considering all available information selected as the most suitable SCADA system for the cooling plant control system. The main reasons for the selection are:

- Lower hardware requirements.

  (Experion requires DELL rack server with Microsoft Windows 2003, PVSS can be on the other hand started on any computer with Windows or Linux operation system)

- Higher scalability and easier redundancy.

  (PVSS systems can create any architecture with built in communication over the LAN, thus the final system can be easily modified and any redundancy can be added.)

- CERN – wide usage and support of the PVSS II.

3.2. High level control PC environment selection

The high level control (HLC) PC is considered as a powerful computer capable to keep running the selected SCADA HMI software in real-time, managing communication with the low-level controller and provide data management (archiving or transfer data to an external DB server). For PVSS II, the hardware demands are not so extensive. Modest application can run on laptop PC with Windows XP or Linux as operation system. These requirements can be met by almost any computer from the category of medium-price or high-price computers equipped with additional modules extending its communication abilities.

The computer for the TOTEM control system was selected based on these criteria:

- Support by CERN support center.
- Price of the computer.
- Computer mobility (weight and size) of the computer.
- Computer performance.

The evaluated batch of computers was composed from desktop computer iMac – see 3.2.2, and from Elite Book 2530p portable computer - see 3.2.1.

The iMac has better hardware parameters (performance) and it is slightly cheaper than the Elite Book. On the other hand, it is not supported by the CENR support department, it can´t be bought in the CERN stores, its size and weight is six times bigger than at the Elite Book PC and it can't be used directly with the supplied operational system.

Thus the Elite Book PC was chosen as the as the server computer for the high level control SCADA system.

3.2.1.HP Elite Book 2530p

The Elite Book 2530p (see Figure 13) is laptop capable of running SCADA PVSS II. The model is compatible with the CERN official distribution of Microsoft Windows XP (NICE Windows) and it is also supported by CERN IT department. The price in the CERN store is 1834.CHF. The hardware parameters of the laptop are enlisted in Table 2.

Figure 13 – HP Elite Book 2530p

Table 2 – Elite Book 2530p parameters

Property	Value
Weight	2.2 [Kg]
Processor	Intel Core 2 Duo, 1.86 [GHz]
Hard disk	120 [GB], 5400 [rotations/min]
Operational Memory	2 [GB], DDR2, 800 [MHz]
Dimensions	282 x 215 x 25 [mm]

3.2.2.Apple iMac

The iMac computer (see Figure 14) is a desktop computer with all components integrated in a screen. It is designed for use with the operational system Mac OS, but it can be also used with Linux based operational system.

Figure 14 – iMac computer

The computer is not offered in CERN store, thus it is not officially supported by the CERN IT department. It is used at the CERN experiments in the control rooms as an operator console therefore there are some experience with its usage and there also exist support from the Apple company. The price for the computer with all accessories is 1600 CHF. The hardware parameters of the iMac are enlisted in Table 3.

Table 3 – iMac parameters

Property	Value
Weight	13.8 [Kg]
Processor	Intel Core 2 Duo, 3.06 [GHz]
Hard disk	1000 [GB], 7200 [rotations/min]
Operational Memory	4 [GB], DDR2, 1066 [MHz]
Dimensions	517 x 650 x 207 [mm]

3.3. Low-level controller selection

This section describes the considered low-level controllers usable for the TOTEM cooling plant and their evaluation.

3.3.1.Embed local monitor board

Embed local monitor board (ELMB) is a radiation proof (up to 5 [Gy]) and magnetic proof (up to 1.5 [T]) module designed for monitoring of multiple I/O channels, see Table 4. ELMB can be used for measurement of process variables or as a low-level controller of action elements. The detail description of the device can be found in (14).

The main processor is ATmega128L housed on a piggy board called ELMB 128. The ELMB128 is equipped with a multiplexed 64-channel ADC with 16-bit resolution that can be addressed from the CAN Open OPC server without dedicated programming. The board is plugged onto a general-purpose motherboard (ELMB Motherboard), which adapts the I/O signals. Communication with hardware devices (sensors, motors…) is made through a set of digital and analog ports, communication with the high level control runs over the CAN bus using the CAN Open communication protocol.

3.3.1.1. Module management

ELMB module is controlled by inner firmware, which can be fully reprogrammed - adapted for a specific task. Restoration of the initial settings is done by the reset button (hard reset) or by CAN Open reset message (soft reset). The module itself does not provide any HMI and all diagnostics must be done by the high level control devices via the CAN Open messages.

Table 4 – ELMB I/O features

Property	Value
A/D Converter – resolution	16 [bit]
Number of analog inputs	64 lines
D/A Converter - resolution	external (see 3.3.1.3), 12 [bit]
Number of analog outputs	64 with 4 external D/A converters
Maximum output analog voltage	30 [V] DC with external power supply
Number of digital inputs and outputs	18 bi-directional and 8 input-only lines

3.3.1.2. I/O features

Up to 64 analog differential channels, up to 26 digital inputs and up to 18 digital outputs are provided for measurement and control of the technological process (see Table 4). Analog input channels enable unipolar and bipolar measurements in the range of 25 [mV], 55 [mV], 100 [mV], 1 [V], 2.5 [V] and 5 [V]. The sampling frequency of the A/D converter shared by all channels can be set in range from 1.8 to 100 [Hz] (the frequency 100 [Hz] is unreliable and not recommended by the manufacturers). Result of the analog measurement process is stored in the ELMB EEPROM as a 16 [bit] value. Samples can be filtered and/or utilized by ELBM firmware program. The processed samples are communicated through CAN bus after the CAN synchronization message or after required set of samples is collected. The maximum usable frequency for the synchronization message is 1 [Hz] (when the ELMB sampling frequency is set to 100 [Hz]).

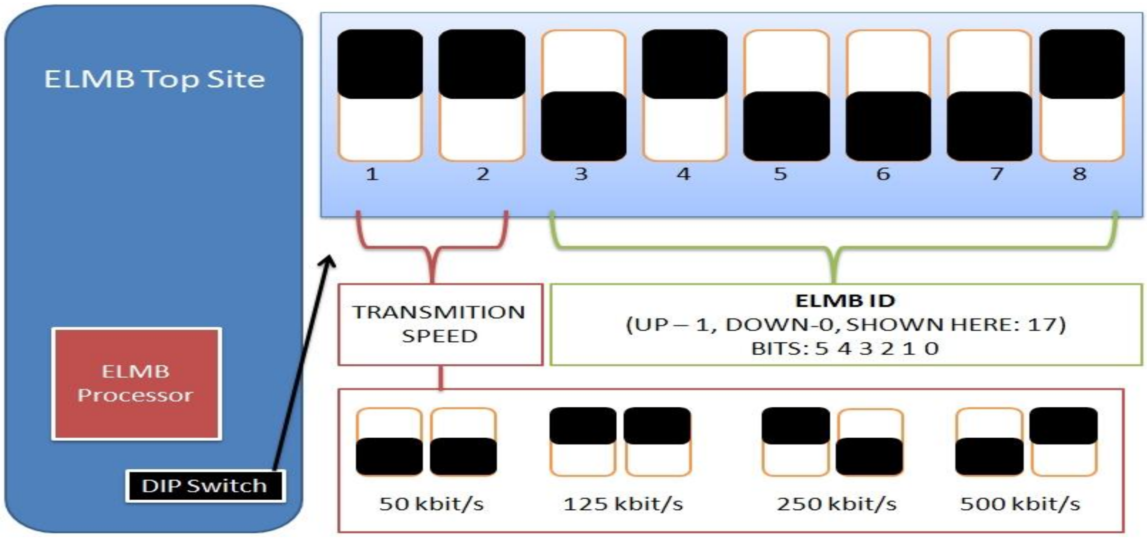

Figure 15 – Embedded local monitor board DIP switch

3.3.1.3. *ELMB Digital to Analog Converter*

ELMB does not contain D/A converter. Analog output signal has to be created by separated ELMB Digital -to-Analog Converter (ELMB-DAC). The standard ELMB software supports up to four ELMB-DACs connected in chain, thus providing in total sixty four 12-[bit] analog output channels.

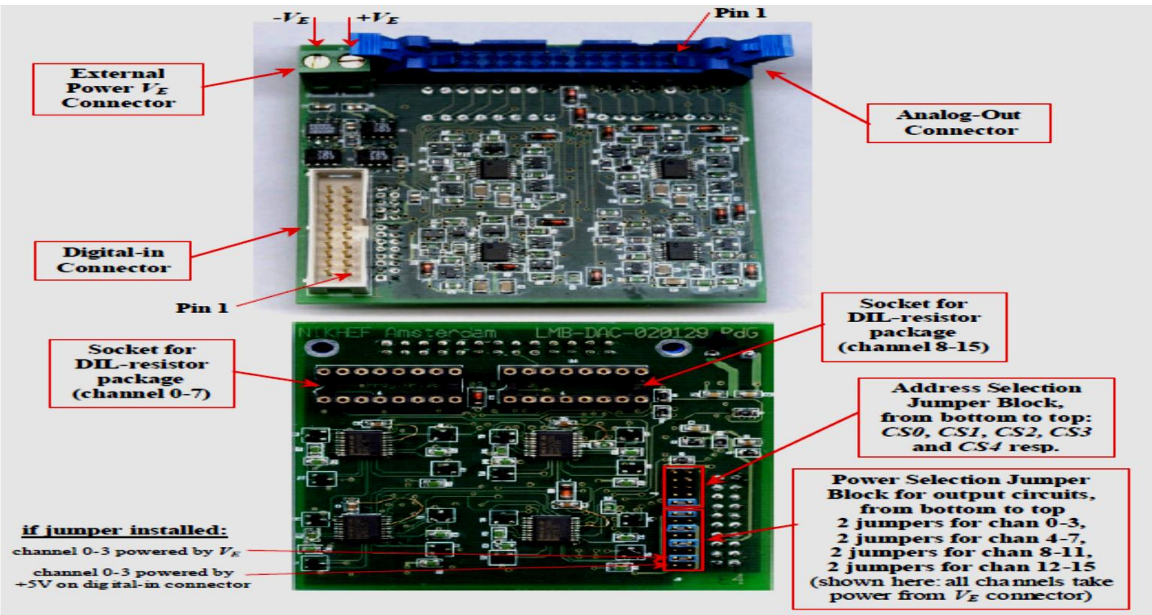

Figure 16 – Embedded local monitor board digital to analog converter, adopted from (15)

The ELMB-DAC is communicating with its surrounding via the digital-in connector and analog-out connector. The ELMB-DACs digital-in connector connects directly to the 20 pin J8 connector of the ELMB motherboard. All ELMB-DACs connectors are located at the front of the converter, see Figure 16 adopted from (15).

The ELMB-DAC can generate maximal output voltage 3 [V] DC when it is powered only by the ELMB. External voltage power supply V_e (from 5 to 30 [V]) of ELMB DAC output circuits is required to provide stable wide range output. The output can be either current (0-20 [mA]) or voltage (0-(V_e-2.2) [V]). The converter output can be controlled in the whole range with the resolution 4096. The size of the output is further in this document referred in AO units, which correspond to the resolution (e.g. ELMB DAC channel set-point 1024 [AO units] means that 5 [mA] current signal will be generated on the channel output).

The type of the powering is set on the bottom side of the ELMB-DAC by jumpers as well as the output type which can be switched by additional resistor plugged in the DIL socket. The accuracy of the converter's output is in range 0.1%-1% of the FS, depending on the quality of parts used during the production. The detail description of the ELMB-DAC can be found in (15).

3.3.1.4. Communication

Communication with the neighborhood of the ELMB module runs on the CAN bus with the super structural communication protocol CAN Open (for details see (7)). One CAN bus branch can contain up to 64 ELMB modules (nodes). Each module must have a unique identification address (ID) in the range 0-63. A DIP switch situated on the front side of the ELMB 128 module is used for the setup of the ID and of the data transmission speed. Speed can be set in range from 50 to 500 [Kbit/s]. ID setting possibilities and the data transmission speed settings are depicted in the Figure 15. Speed of the communication influences the maximum length of the bus (500 [Kbit/s] – max. length 130 [m]; 50 [Kbit/s] – max. length 1.3 [Km]).

3.3.1.5. PID Framework

The ELMB PID application framework firmware is a CAN Open embedded application running on a setup consisting from ELMB and ELMB DAC module. It can run up to four independent PID controllers simultaneously. The following information about the framework was adopted from (16).

The framework provides all interaction with ADC and DAC hardware, the timing of the PID controllers and the CAN Open communication. Before use, the framework needs to be fully adapted for the particular application – user has to program control algorithm and adjust the configuration. Configuration and control of the PID controllers is provided by the application's CAN Open object dictionary, which contains entries for all the parameters and data. The configuration parameters can be stored permanently in the on-board non-volatile memory.

Because ELMB has no internal scan, each PID controller has an associated countdown counter, which is initialized according to the controller's setup. The sequence starts to perform the iteration of the associated PID controller when a counter reaches zero. An internal clock with a frequency of 5 [Hz] is used to time the start of the iterations.

Once the PID controllers are configured and running, ELMB-PID basically runs autonomously and only transmits CAN Open messages in case of an error. Each PID controller can be also set in monitor mode. In the monitoring mode the PID-controller sends after the iteration a message containing the acquired ADC input value and a message with the calculated DAC output value. The monitoring mode can be used for the monitoring of the PID work by the high level controller. The PID algorithm can be active anytime, but the CAN messages can be transmitted only when the ELMB is in the operational state.

The main advantage of the ELMB PID is the autonomy of the regulation - ELMB controls the process even without connection to the higher level controller. The disadvantages of the ELMB PID are inability to use ELMB to measure process variables, necessity of using the live guarding protocol instead of the node guarding protocol (while node guarding is normally used at the CENR projects.) and the limited number of controllers.

3.3.1.6. Solution cost

The price for one ELMB module with standard motherboard is 400 CHF. If the module is used only for the readout of the analog sensors, than the price is 6.25 CHF per analog input channel. The price for one ELMB DAC that would extend ELMB with 16 analog outputs is roughly 280 CHF, which means 17.5 CHF per analog output. The price is based on the prices of the parts and estimated price of the work in year 2007, because in the time this diploma was written there was no serial production of ELMB DAC.

3.3.2.Siemens S7 300 based system

Siemens Company offers wide spectrum of the universal control systems and components for the industrial automation, measurements and regulation. Following information about Siemens PLCs was adopted from (17) and (18).

Users have at their hands optimal control elements for every task, from simple to large with broad communication possibilities. PLCs are delivered with differently powerful processor units. Siemens modular PLCs are optimized for strictly control algorithms. They are robust and they operate in the specific harsh environmental conditions without problems. They show high resistance against the vibrations.

The operation temperatures of the PLCs are in the range from -25 [°C] to 60 [°C]. PLC can be flexibly adjusted and extended with variety of modules. Modular PLC can be also used in the redundant, fault tolerant applications or in fail-safe systems. Power supply of the PLC can be chosen in wide range of the AC or DC voltage.

Typical representatives of the modular PLCs are series S7-300 - see Figure 17 adopted from (18), which computing abilities were recently upgraded. The local operator panel is provided by LED display shows multiple text lines.

3.3.2.1. Communication

S7 300 PLCs communicate with the high level SCADA servers over the Profibus net or through the expansion module over the industrial Ethernet. It is necessary use of additional modules for the communication with the analog devices or sensors. Standard AI module of the 6ES7 331-7KF series has 8 inputs capable of reading voltage, current or resistivity input. The input range for the voltage can be set for the bipolar reading in the range between 50 [mV] and 10 [V], for the current is the range from the -20 to 20 [mA], the resistivity can be measured up to the 6000 [Ohm]. Each module can measure in one of AI ranges. To measure high voltage and resistivity, two modules are necessary.

Precision of the measurement is between 0.5% and 1% depending on the input type and I/O module series. Maximum sampling frequency (for standard I/O module) of the input is 1000 [KHz] which is sufficient for most of the technical applications.

3.3.2.2. Functions

The processing unit of PLC contains the instructions that control the plant. Those instructions are executed sequentially, once per scan cycle. The main program is also referred to as OB1. Aside the main program function blocs can be used. These optional elements of the program are executed only when called: by the main program, by an interrupt routine, or by another subroutine. Subroutines are useful in cases when it is necessary to execute a function repeatedly. Variety of the functions, including the PID control, can be programmed and stored into PLC that can then run without high level supervision. For the program, one of the supported programming languages is used, such as lather diagram or Petri nets. The programming environment is the Simatic Step 7 software package contains a simulator that can be used during the program debugging.

Figure 17 – Siemens S300, adopted from (18)

Aside the programmable functions it is possible to extend the PLC capabilities with hardware function modules. Those modules can be typically used for the program commissioning and testing without using the real program.

3.3.2.3. *Solution cost*

According to the Siemens catalogue 2009, PLC prices start at the 400 CHF per CPU unit. Prices of the expansion modules differ due to the type – average price is 150 CHF per module. Thus, the cheapest setup that would provide required number of the analog and digital I/O would cost 1300 CHF.

3.3.3.WAGO I/O System

WAGO is a Czech company that offers complex solution for the automation called WAGO-I/O-SYSTEM. The following information was adopted from (19) and (20).

WAGO-I/O-SYSTEM offers a flexible I/O solution. With support for over 16 fieldbus/network protocols, PLCs and slave couplers it offers good versatility. Expanding I/O modules of the PLCs are available in over 200 different combinations, thus the system can be adjusted according to any requirements. The example of a WAGO system is depicted in Figure 18, adopted from (20).

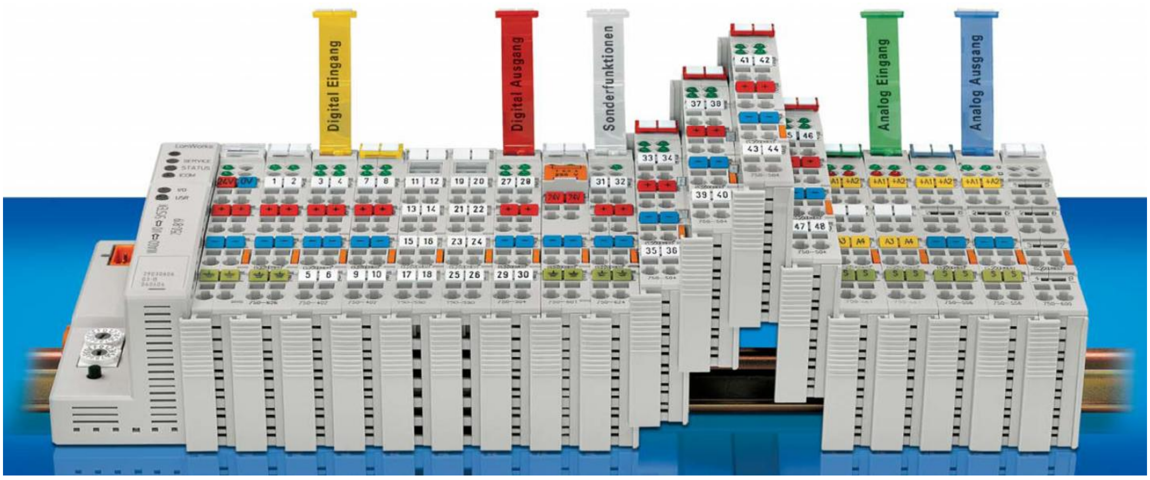

Figure 18 - WAGO system overview, adopted from (20)

The AS-Interface removes need of user's knowledge of bus systems or communication protocols, device configuration or vendor specific configuration. Comparing to other solutions the cost of the wiring is reduced by 25%, Also requirements on the space for the cabling are reduced. System is fully modular and easily expandable – after physical connection of the module and adjustment of the addressing the system is ready for use. Distribution of the control elements over the facility can be done within a range of 100 [m] (300 [m] with repeaters), the devices are topology independent and they do not use bus terminators. As a controller is used AS Interface Master, that supports up to 62 slave modules. Master module is fully programmable with a WAGO PRO Programming tool, using one of the supported programming languages (IL, LL, FBD, ST, FC and CFC). The length of the scan cycle is between 0.3 and 10 [ms]. In addition there are available hardware function modules providing special functions.

3.3.3.1. WAGO Communication interface

The communication between the WAGO module setup and the high level control SCADA system can run on the wide specter of the field buses and protocol thanks to the non-programmable field bus couplers or programmable couplers. The couplers support many industrial standards such as Profibus, CAN Open, Ethernet or Device Net. The I/O system can communicate with the technological process through expansion I/O modules when one module could have up to 8 channels. Modules allow analog bipolar voltage measurements (from -10 to 10 [V]), current measurements (from 0 to 20 [mA]) and wide range of the resistivity measurements. Whole system can monitor over 400 process variables. Sampling frequency of a channel is in range from 20 [Hz] to 5000 [KHz] depending on the module type.

3.3.3.2. Solution cost

Average price for a single WAGO I/O module is 180 CHF, price for a non-programmable gateway coupler is 250 CHF, and therefore the price of a whole WAGO I/O system depends on the final configuration. Estimated price of e setup capable measuring 80 process variables with 10 analog outputs would be 2250 CHF.

3.3.4. Hardware selection conclusion

The system based on two ELMB units with one ELMB DAC was selected as a low-level controller for the TOTEM cooling plant. The price for the whole setup, which is radiation hard, magnetic field resistant and fully supported by CERN, is 1080 CHF.

ELMB is compatible with CAN Open communication protocol and all registers can be accessed via CAN Open OPC server.

This ELMB based system is weaker in the speed of the operation, available communication interfaces (only CAN Open) or inner program adjustability. But these objectives do not have such big weight in the decision making process.

3.4. Action elements selection

This section introduces action elements that, which were selected as convenient for automation of the cooling plant described in section 1.3.

3.4.1.Pressure regulation

The pressure regulators function is to match the pressure of the media flowing through the regulator to the set-point. The regulator consists from three parts – restriction element, loading element and measuring element.

The restriction element of a regulator is valve that is in direct contact with a regulated media. Thus it must be materially compatible. The valve position regulates the flow of media and thus a pressure (pressure is inversely proportional to the valve opening). The valve construction must be capable of regulating flow (globe valve, butterfly valve, poppet valve, etc.).

The loading element (also called actuator) applies a force on a restriction element in order to vary him. The most common means used as a loading element are a weight, a hand jack, a spring or a diaphragm actuator.

The measuring element provides the feedback from the regulated process. It is usually connected to control logic, which according to its readings, actuates the force applied by a loading element on a restriction element. The pressure regulators can be divided into two groups according to the location of the measuring element. Pressure Regulators (PR) with measuring element placed after the restriction element and Back-Pressure Regulators (BPR) with the measuring element located before the restriction element.

3.4.2.Valve throughout characteristics

The most important parameter for the selection of the suitable valve (restriction element) is K_v (the flow-rate in [m^3/h] at defined temperature. This creates pressure drop of one bar across a valve orifice), that expresses the capacity of the valve. Some valves have indicated a parameter C_v (the flow-rate in [gallon/minute] at defined temperature, which creates pressure drop of one [pound/inch^2]) which is an American equivalent to K_v.

Other feature to reflect is cavitation. Cavitation is a formation of vapor bubbles of a flowing liquid in a region where the pressure of the liquid falls below its vapor pressure, which creates shock waves that have destructive effect on a valve. This significantly reduces its life-time. It is necessary to choose a valve with multi-stage pressure reduction to decrease the cavitation risk.

3.4.3. Calculation of the desired valve K_v factor

The K_v required from valve placed on a cooling loop described in section 1.3.5 was calculated separately for a liquid according to Equation [3.4-1] and for a vapor according to Equation [3.4-2]. The used parameters are enlisted in Table 5.

$$Kv = \frac{Q}{100}\sqrt{\frac{\rho}{\Delta p}}\left[\frac{m^3}{h}\right] \qquad [3.4\text{-}1]$$

$$Kv = \frac{Qm}{100}\sqrt{\frac{vx}{\Delta p}}\left[\frac{m^3}{h}\right] \qquad [3.4\text{-}2]$$

The resulting rounded K_v which already includes additional safety margin 20% is for both cases (liquid and vapor) 0.015 [m^3/h] (the results were rounded to the nearest thousandth).

Table 5 – Variables used for a Kv calculation

Variable	Description
Q	Flow rate in operating condition
ρ	Medium density in operating condition
Δp	Required pressure drop on the valve
Q_m	Mass flow in operating conditions

v	Specific volume of steam at temperature of vapor measured before the valve, and half the pressure measured before the valve
x	Proportionate weight volume of saturated steam to wet steam

3.4.4.Selected models

There are many different types of regulators and control valves for the pressure regulation on the market. Thus, only low cost solutions from three well-known companies (Honeywell, Emerson and TESCOM) were picked for further testing. The solutions selected for the regulation of the liquid pressure are:

- TESCOM Dome-loaded pressure regulator (restriction element), U/p converter (actuator) and ELMB with DAC (measuring element).
- TESCOM Dome-loaded pressure regulator (restriction element), I/p converter (actuator) and ELMB with DAC (measuring element).
- Honeywell control valve (restriction element), Honeywell linear motor controlled by voltage (actuator) and ELMB with DAC (measuring element).
- Emerson control valve (restriction element), Emerson linear motor controlled by voltage (actuator) and ELMB with DAC (measuring element).

The solutions selected for the regulation of the vapor back-pressure are:

- TESCOM Dome-loaded back-pressure regulator (restriction element), U/p converter (actuator) and ELMB with DAC (measuring element).
- TESCOM Dome-loaded back-pressure regulator (restriction element), I/p converter (actuator) and ELMB with DAC (measuring element).

All these solutions are in detail described and discussed in chapter 7.

3.5. Selected control system components

The components selected for the control system determine its final form. The high level control will be realized by PVSS II SCADA system running on the HP Elite Book 2530. The implementation of the cooling plant into the PVSS is described in section 6.4. The ELMB units with ELMB DAC were selected as low cost low-level controllers that serve as a front-end hardware device.

Figure 19 gives an overview on all the selected building blocks and illustrates how the control system works. Inside the local SCADA system is foreseen a hierarchical structure based on the functionality of the devices following a device oriented approach. Such a hierarchical structure helps the operator in tracing of problems, as all relevant for a cooling plant can be seen in one glance. The highest control structure level depictured in Figure 19 is optional and its implementation is not described in this paper.

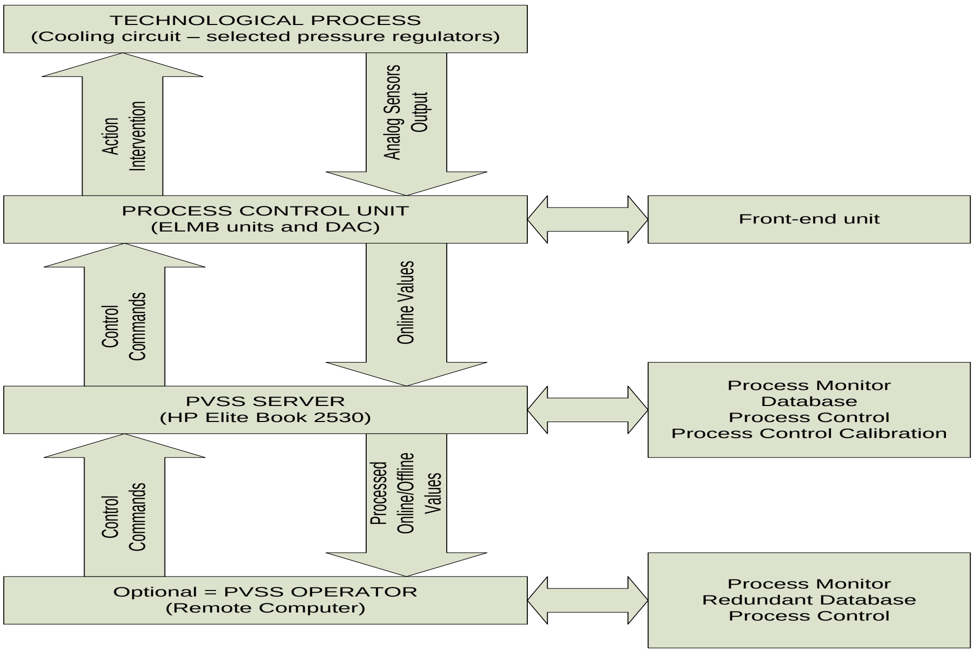

Figure 19 – Control system structure overview

4. C4 - Control system framework

This chapter of the diploma thesis describes the main software components developed according to the requirements that emerged from the control system design proposed in the chapter 3.

The C4 components are combined into one software package called C4 framework that consists from a pack of functions organized in libraries and from a set of PVSS II panels.

The library – panel structure makes the C4 highly modular and ready for the integration with other systems.

The name C4 was chosen because the package provides tools that can be used to configure, calibrate, contemplate and control a technological process. All panels and libraries that were created are stored on the CD inserted to this document in the directory C4.

4.1. Control framework functionality

C4 framework (C4F) is a control system environment for easy parameterization of the distributed control of the industrial systems. C4F is programmed in the PVSS II version 3.6 and it is compatible with the newest PVSS II version 3.8. The C4F aims to be used as an extension of the TOTEM DCS (see chapter 1.2) and the environment for the commissioning of newly designed control system hardware components.

The primary function of the C4F is to provide tools for an overall control and monitoring of the connected components. The only requirements on the controlled system is usage of low-level controllers that are compatible with the OPC standards and that are able to communicate over one of the standard industrial field buses. The C4F respects and implements the architecture of the modern distributed control systems.

C4F system is in charge of the overall control and monitoring of the data-taking process with possibility to overhand that responsibility (e.g. to external data-base) if needed. Part of the system's functions is able to operate outside data-taking periods when it can act as the master of the active components. The C4F major task is to provide tools for:

- Setup and calibration of the controlled system.

- Central supervision of all connected elements.
- Graphical user interfaces.
- Data storage management.
- Communication with external systems.

4.2. Requirements

Minimum hardware and software requirements demanded for the C4F run are:

- Work station with at least 5 [GB] of free space on the hard disk drive (HDD), 1 [GB] of the operational memory and processor with performance on the level of Intel Pentium 4 or higher. Such computer was chosen in section 3.2.
- Interface for communication over the required industrial bus (e.g. National Instruments card NI PXI-8513 or CAN Kvaser communication card).
- Installed PVSS II version 3.6, service pack 1 or higher.
- Project created in the PVSS II.
- JCOP framework (version 3.2 and higher) and its components CORE and ELMB installed in the PVSS project.

4.3. Main panel

The C4F main panel (C4Fmp) is a main C4F screen, which is initiated together with the PVSS project. Some of the C4F scripts are directly connected to this panel. Thus, the panel normal closing procedures were redirected and the C4FC can only be closed by a *CLOSE* button so the unintended closure is limited. The panel itself is divided into six main sections and each of them with different function.

The Figure 20 depicts the main panel sections:

- Section 1 contains the *CLOSE* button of the C4F and elements of the C4F access management (see section 4.9).
- Section 2 contains the navigation drop-down menu with elements organized in the tree architecture. The content of this field is automatically updated with currently stored user-made visualizations and files with graph templates.
- Section 3 provides information about the currently active sensor alarms and control over their filtering in *Small Alarm Screen*.

- Section 4 contains panels with information about all active objects registered in the C4F. The panels are organized in an object with three tabs. They are described in chapter 4.5.
- Section 5 is a place where all panels, visualizations and graphs launched in the C4F are displayed. Individual items are organized into tabs which automatically resize according to the size of an active element.
- Section 6 contains second navigation bar, which is redundant considering the navigation of Section 2. The sub-elements are ordered in different order according to the most frequently used items on the top.

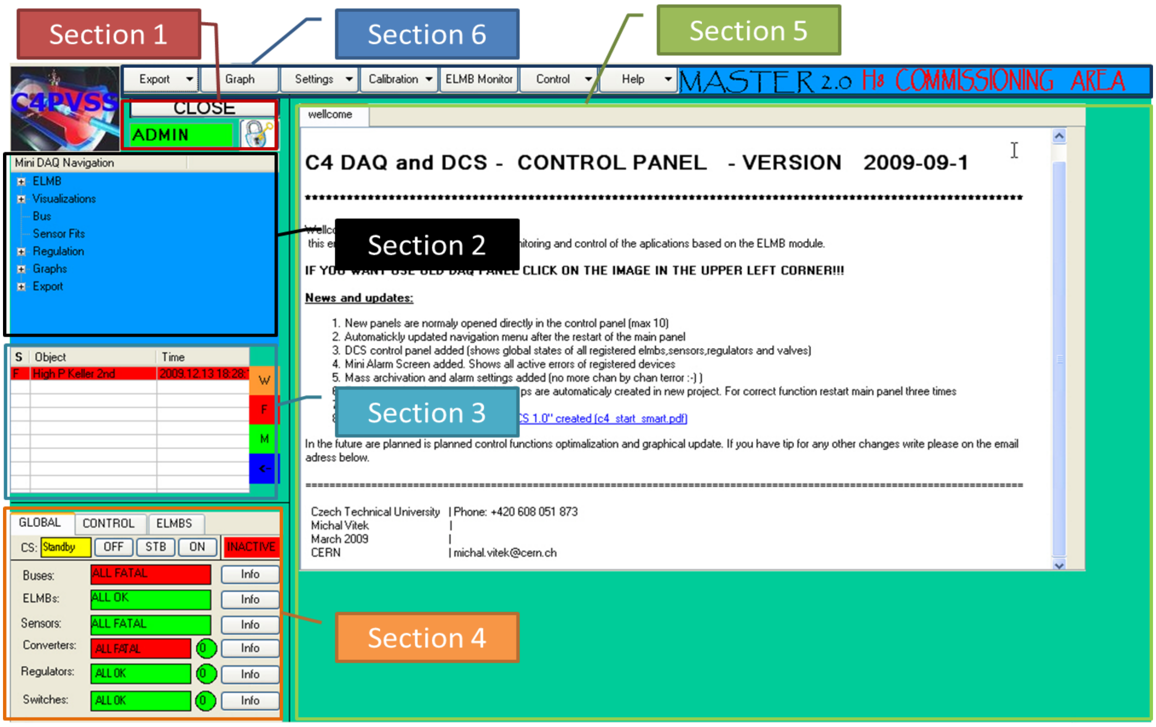

Figure 20 – C4F Main panel overview

4.4. Control panel

The C4F control panel (C4Fcp) is an object housed by C4Fmp. It is composed by three tabs named *GLOBAL*, *CONTROL* and *ELMBs* depicted in Figure 21. The panel serves for the monitoring and control of all active C4F objects.

The *GLOBAL* tab is the main tab of the control panel. It is initially active and it combines overview of states, statuses and control buttons of all active C4F objects, field buses, sensors and ELMBs. The relevant information is expressed by texts and colors that correspond to the C4F implementation of the finite state machine described in section 4.8. Changes are propagated to the tab immediately after the monitored data changes.

The *CONTROL* tab displays detail information about all C4F objects. All registered objects are enlisted in the table – each row represents one object. The objects are loaded into the table after the start of the control panel. The refresh button in the upper right corner of the tab reloads the information, thus the changes in the registered objects propagate.

The *ELMBs* tab serves for the monitoring and control of all ELMB units registered in the C4F. The units are organized in a table, in which rows are representing ELMB units. The table displays state of the ELMBs and all eventual errors registered by the PVSS. With the selection box and button under the table all registered units can be brought to desired state by one mouse click.

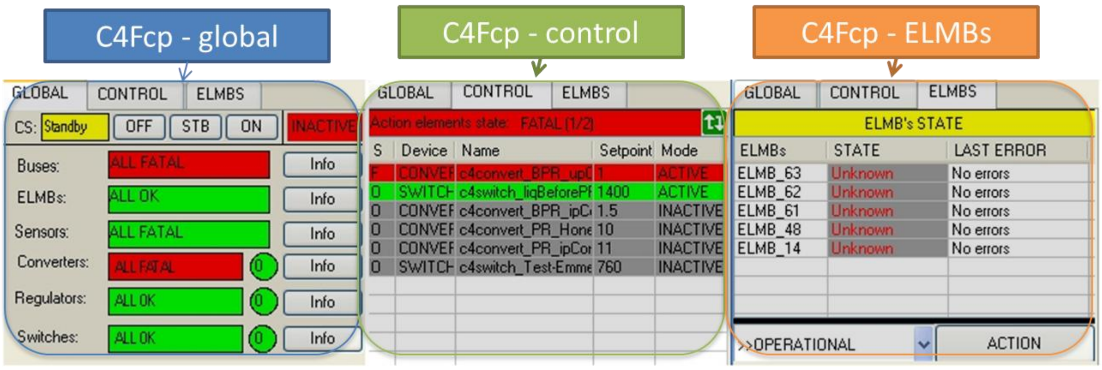

Figure 21 – C4F Control panel tabs

4.5. Objects in PVSS

The objects implemented in the C4 framework were designed as the instruments applicable to the general management of the industrial system with DAC-ELMB converter. Objects were designed with various automatic control options ranging from none to complete. Description of the control algorithms can be found at the devices descriptions. The data of the registered objects are stored in the data point structure of the master PVSS projects.

The control commands of the C4F objects usable for the monitoring of their state and for adjusting their parameters are implemented in several PVSS panels accessible from the C4F Control panel.

4.5.1. Switch object

The C4F Switch (C4FS) is an object designed for the simple generating of the logical signals. The C4F switch has three different set-points, each for a different C4F state. The set-points have to be set to the C4F switch in the ELMB AO units – no conversion is available. All parameters necessary for the registration of the C4FS are enlisted in Table 6. The C4FSs data are stored in data points associated in the data point group called *c4switches* that is stored in the high level control server computer data-base. The C4F panel prepared for the C4FS management (see Figure 22) is called *dcs_valveManager.pnl* and it is located in the *panels/objects* subdirectory of the PVSS project.

Table 6 – C4F Switch parameters

Name	Set-point: On	Set-point: Stand-by	Set-point: Off	ELMB AO	Active
Text	[AO units]	[AO units]	[AO units]	DP address	[Boolean]

The created C4FS objects that have their Active parameter set to TRUE are directly connected to the C4F state and they propagate the corresponding set-point to the ELMB AO.

Figure 22 – C4F Switch manager

The C4FS objects are then periodically checking the value of their ELMB AO. If the set-point and the output value doesn't match their status is changed to FATAL, otherwise the status is set to OK. If the C4FS object active parameter is set to FALSE, the value of the ELMB OA output is ignored and the status is set to OK.

4.5.2. Converter object

The C4F Converter (C4FC) is an object designed for the usage with converters of physical quantities controlled by an analog voltage or current signal. The C4FC has three different set-points, each for a different C4F state. The set-points set to the C4FC have to be desired outputs of the connected converter. All parameters necessary for the registration of the C4FC are enlisted in Table 7.

Table 7 – C4F Converter parameters

C4FC Parameter	Parameter type
Name	Text
Set-point: On	[regulator output units]
Set-point: Stand-by	[regulator output units]
Set-point: Off	[regulator output units]
Output (ELMB AO)	Data point address
Reference (ELMB AI)	Data point address
A coefficient	Real number
B coefficient	Real number
Minimal step	Real number
Maximum	Real number
Minimum	Real number
Overstep	Boolean
Maximal difference	Real number
Regulation	Boolean
Active	Boolean

The C4FCs data is stored in data points associated in the data point group called *c4convers* that is stored in the high level controller data-base. The C4F panel prepared for the C4FC management (see Figure 23) is called *dcs_converterManager.pn* and it is located in the PVSS Project subdirectory *panels/objects*.

The created C4FC objects, which have their Active parameter set to TRUE, are directly connected to the C4F state and they propagate the corresponding set-point to the ELMB AO. The value of the ELMB AO is set according to the equation [4-1], where *y* is ELMB AO, A and B are C4FC parameters and *x* is C4FC set-point.

$$y = Ax + B \qquad [4\text{-}1]$$

The C4FC objects are then periodically checking the input value of the ELMB AI they are registered to and if necessary take action. The procedure differs depending on what value that is stored in the C4FC parameter Regulation. The procedures are described in sections 4.5.2.1 and 4.5.2.2. If the C4FC object active parameter is set to FALSE, the values read from the ELMB OA and ELMB AI are ignored and the C4FC status is set to OK.

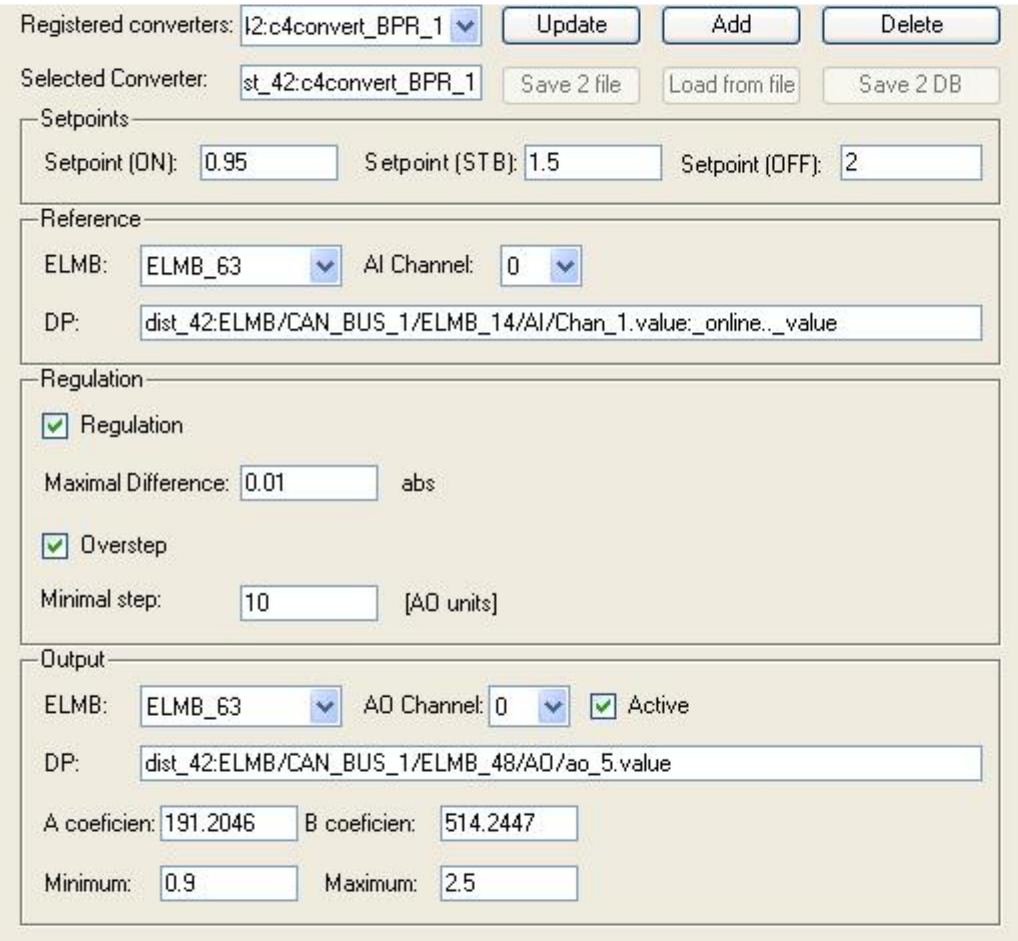

Figure 23 – C4F Converter manager

4.5.2.1. C4FC object control algorithm with regulation parameter TRUE

The C4FC uses the range control to calculate new ELMB AO output. This type of regulation is used for minimized regulated components stress, which increases devices lifetime. The regulator proportional part is for the C4FC constantly set to 0.25 to minimize potentially unwanted overshoot. The regulation algorithm is described below and the regulation scheme is shown on Figure 24.

Algorithm:

1) It is calculated the difference between the set-point and the converter output (DIFF).
2) If the DIFF is outside that dead-band (± Maximal difference C4FC parameter), then the status of the C4FC is set to FATAL LOW or FATAL HIGH depending on the DIFF negativity or positivity and the regulation process continues by point 3. Otherwise, the status is set to OK and regulation process continues by point 1.
3) The DIFF is multiplied by the P regulator constant, the new values is named DIFFP.
4) The DIFFP is adapted to meet the terms of the equations [4-2], where Minimum, Maximum, A and B are the C4FC parameters and *x* is current ELMB AO set-point.

$$Minimum \leq (x - B)/A + DIFFP \leq Maximum \qquad [4\text{-}2]$$

5) The new set-point for the ELMB AO is then calculated according to equation [4-3], where *y* is ELMB AO set-point (EAOSP), A and B are C4FC parameters, *x* is DIFFP and *z* is current ELMB AO set-point.

$$y = Ax + B + z \qquad [4\text{-}3]$$

   If the C4FC AO parameter Overstep is set to TRUE then the regulation algorithm continues with point 6, otherwise it continues with point 7.

6) If the absolute difference between the EAOSP and current ELMB AO set-point is lower than C4FC parameter Minimal step then the value calculated according to

the equation [4-4] is applied as an ELMB AO set-point. Then the algorithm waits 100 [ms].

$$ELMB\ AO = EAOSP + \left(\frac{-DIFF}{abs(DIFF)}\right) * Minimal\ step \qquad [4\text{-}4]$$

7) The EAOSP is applied as an ELMB AO set-point. Then the algorithm continues with point 1.

4.5.2.2. C4FC object control algorithm with regulation parameter FALSE

The C4FC doesn't adjust the ELMB AO set-point out of the registered set-points under any circumstances. The potential deviations are indicated according to the following steps.

1) It is calculated the difference between the set-point and the converter output (DIFF).
2) If the DIFF is outside that dead-band (± Maximal difference C4FC parameter), then the status of the C4FC is set to FATAL LOW or FATAL HIGH depending on the DIFF negativity or positivity and the process continues by point 3. Otherwise, the status is set to OK and regulation process continues by point 1.
3) The ELMB AO is adjusted to the value calculated according to the equation [4-1] if it differs from it. The potential adjustment is indicated by a message in the PVSS II, project console. The message has a form "C4DCS: *C4FC Name* adjusted to value *applied set-point".*

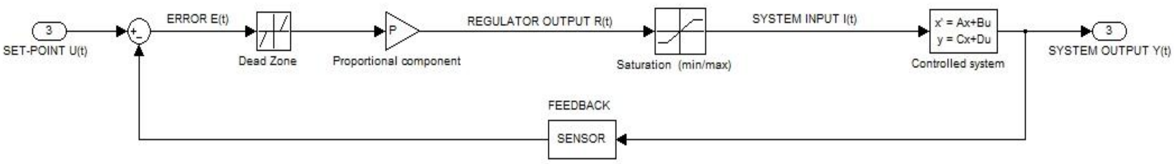

Figure 24 – C4FC Regulation scheme

4.5.3. Regulator object

The C4F Regulator (C4FR) is an object designed for the P, PS, PD or PSD regulation of a technological process with an actuator controlled by an analog voltage or current signal. The C4FR offers three different set-points, each for a different C4F state. The set-points set to the C4FR have to be desired values measured by a sensor monitoring controlled physical quantity. All parameters necessary for the registration of the C4FR are enlisted in Table 8.

Table 8 – C4F Regulator parameters

C4FR Parameter	Parameter type
Name	Text
Set-point: On	[regulator output units]
Set-point: Stand-by	[regulator output units]
Set-point: Off	[regulator output units]
Output (ELMB AO)	Data point address
Reference (ELMB AI)	Data point address
P coefficient	Real number
S coefficient	Real number
D coefficient	Real number
Sampling time	Real number
Initial condition	Real number
A coefficient	Real number
B coefficient	Real number
Minimal step	Real number
Maximum	Real number
Minimum	Real number
Overstep	Boolean

Maximal difference	Real number
Regulation	Boolean
Active	Boolean

The C4FRs data is stored in data points associated in the data point group called *c4regs* that is stored in the high level control server computer data-base. The C4F panel, depicted in Figure 25, prepared for the C4FR management is called *dcs_regulatorManager.pn* and is located in the PVSS Project subdirectory *panels/objects*.

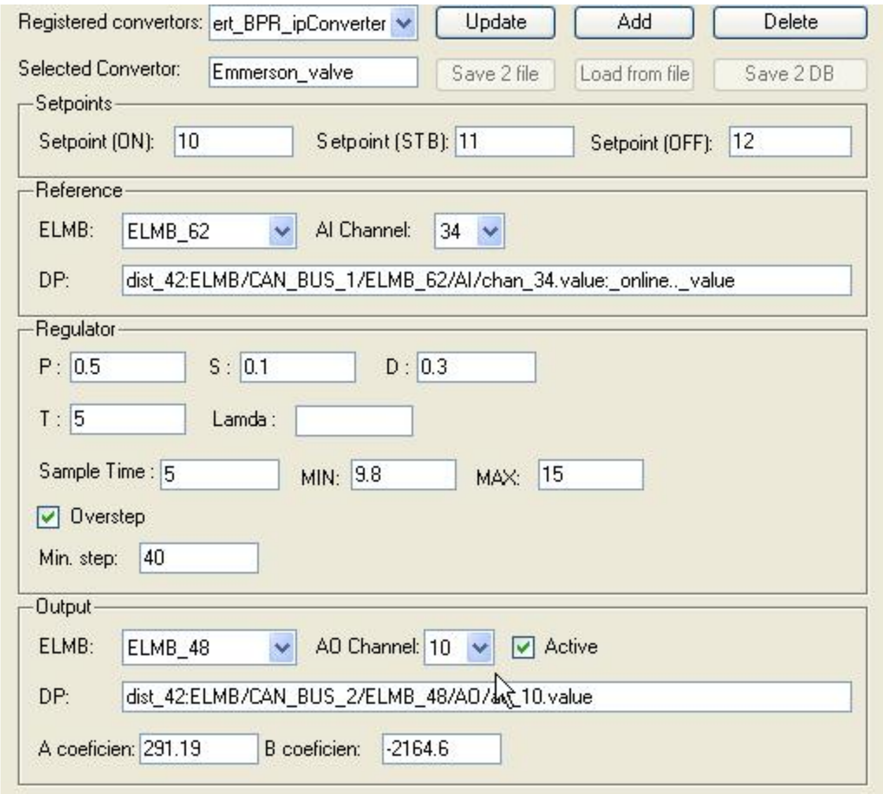

Figure 25 - C4F Regulator manager

The C4FR regulation algorithm, described below, corresponds to the regulation scheme depicted in Figure 26. The regulation is done synchronously with the frequency corresponding to the *Sampling time* parameter of the C4F regulator.

Algorithm:

1) It is calculated the difference between the set-point and the regulator output (*DIFF*).

2) If the *DIFF* is outside that dead-band (± Maximal difference C4FR parameter), then the status of the C4FR is set to LOW or HIGH depending on the *DIFF* negativity or positivity and the regulation process continues by point 3. Otherwise the status is set to OK and regulation process continues by point 1.
3) The proportional, summative and derivative parts are calculated from the *DIFF*, *P*, *S*, *D* and *Initial condition* parameters of the regulator. The new value is named *DIFFPID*.
4) The *DIFFPID* is adapted to meet the terms of the Equations [4-2], where *Minimum*, *Maximum*, *A* and *B* are the C4FR parameters,*x* is current ELMB AO set-point and *DIFFPID* is *DIFFP*.
5) The new set-point for the ELMB AO is then calculated according to equation [4-3], where is ELMB AO set-point (*EAOSP*), *A* and *B* are C4FR parameters, is *DIFFPID* and is current ELMB AO set-point.

   If the C4FR parameter *Overstep* is set to TRUE then the regulation algorithm continues with step 6, otherwise it continues with point 7.
6) If the absolute difference between the *EAOSP* and current ELMB AO set-point is lower than C4FR parameter *Minimal step* then the value calculated according to the Equation [4-4] is applied as an ELMB AO set-point. Then the algorithm waits 100 [ms].
7) The EAOSP is applied as an ELMB AO set-point. The algorithm then continues with point 1.

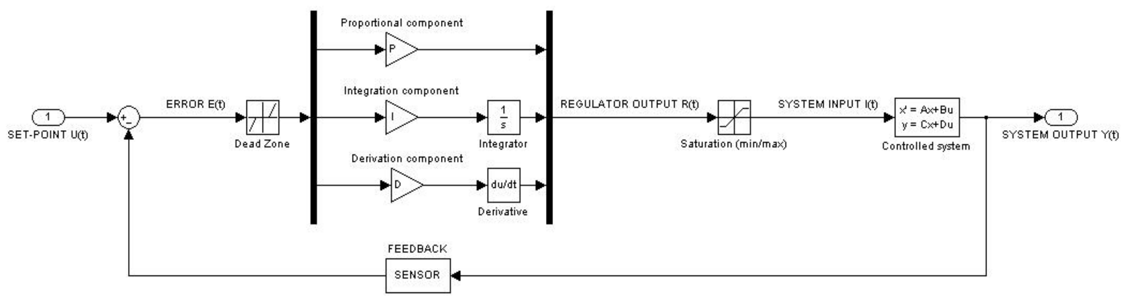

Figure 26 - C4FR Regulation scheme

4.6. Data management, archiving and synchronization

The C4F uses four different ways for storing data (SQL data-base, csv, xml and data points), when each method has different utilization.

4.6.1. Standard archiving

Sensors historical data are by default stored in an internal PVSS SQL based archive housed by the high level control server. The parameters including the data-base parameters, archiving frequency, dead-band smoothing, etc. can be adjusted using the original panels of the JCOP framework.

4.6.2. Newly developed panel for archiving definition

The second option is to use C4F panel named *dataExportManager.pnl* can be used. The C4F panel is based on the JCOP panel, but it in addition allows mass-parameterization. Thus, if necessary, archive can be set for multiple sensors in one time, which saves time during the parameterization of large systems.

4.6.3. Export of archived values

The data from the SQL data-base can be exported into the *csv* (comma-separated values) file format using the C4F panel named *dataExportManager.pnl* (see Figure 27) that can be started directly from the C4Fmp navigation menu (see 4.3). The list of data-base items selected for the export can be stored on the local disk of a high level controller. The advantage of the csv format is easy portability and compatibility with most commonly used office software suits.

The XML (Extensible Mark-up Language) file format was in limited way implemented in the C4F for the storage of its internal settings and it is also used for the synchronization between different PVSS projects (see 4.6.4).

The PVSS data points hold the information about all objects registered in the C4F and about the state of the control system. The data points are partly created automatically during the C4F installation and partly during the registration of the devices. The data stored in the data points are necessary only for the server computer (high level controller) thus they are not included in the data export used for the synchronization of the C4F. They can be exported or imported into the PVSS project using the standard tools of the JCOP framework.

4.6.4.Synchronization

The C4F can be synchronizing by simply copying new data into the PVSS project and overwriting all existing files. The C4F settings, panels, scripts and other important data necessary for the synchronization can be exported into a directory created automatically in the directory *export* of the PVSS project. The export can be started and customized by a commands initialized from the C4Fmp navigation menu (*Export->Synchronization Export*). The created project can be then copied into another PVSS project in which is then synchronized or installed the C4F. The synchronized C4F needs to be restarted so the applied changes propagate to its state.

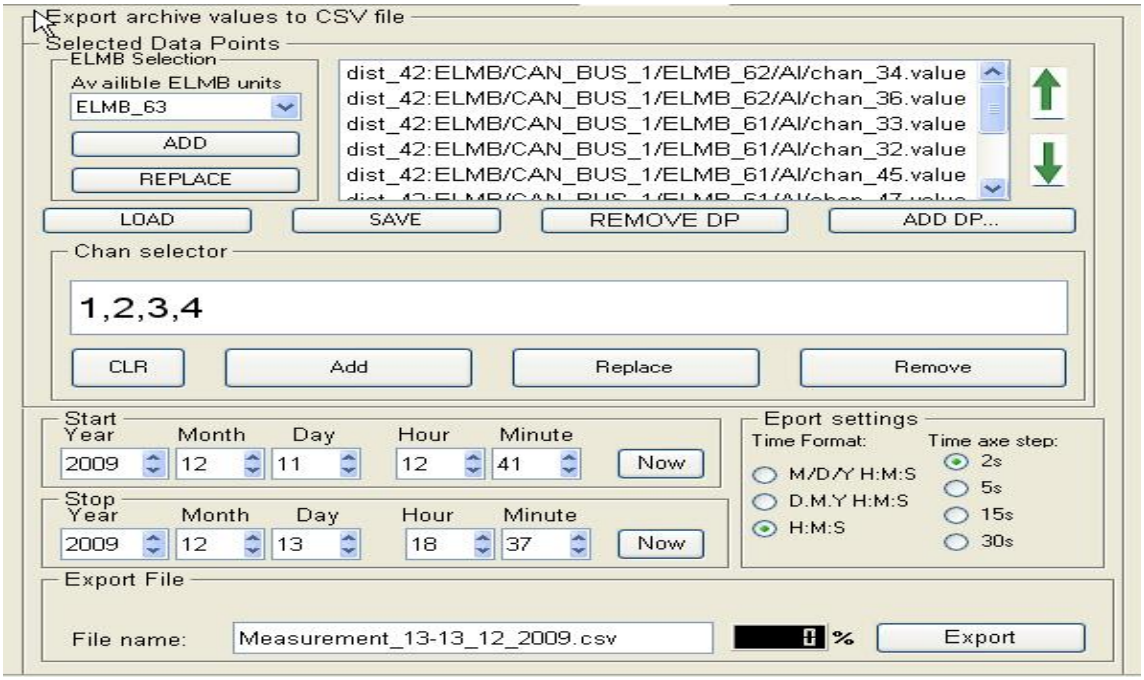

Figure 27 – C4F data export panel

4.7. Alarms handling

The PVSS and JCOP framework provides wide support for the alarm handling. The multiple alarm levels can be associated with each data point. The PVSS event manager notifies all objects that listen to the data point alarm immediately after the alarm conditions are met.

The panel depicted in Figure 28 was created to allow mass parameterization of the sensor alarms. Alarms can be from this panel defined for any number of data points in one step. The panel also allows storing list of data points for which the alarms are then monitored by the C4F. The list of the monitored alarms doesn't have to correspond with the data point list with defined alarms.

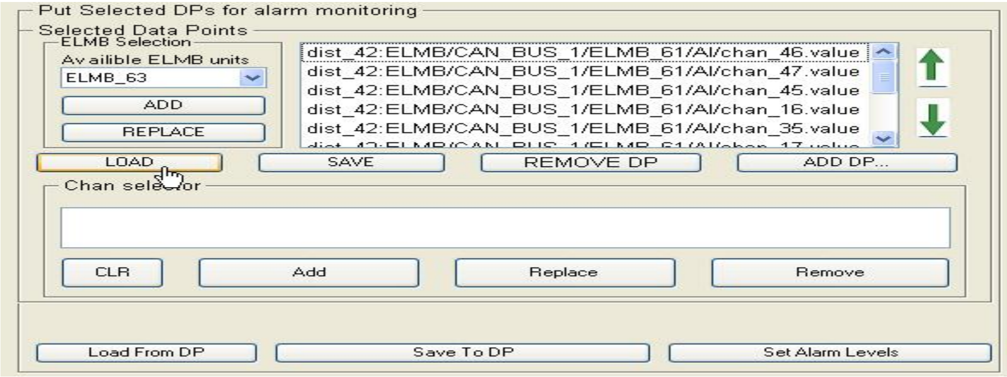

Figure 28 – C4F Alarm manager

4.7.1.Mini Alarm Screen

The active monitored alarms are displayed in Mini Alarm Screen (MAS) housed by C4F main panel at Section 3 depicted in Figure 20. The MAS displays alarms in a table where each row represents one alarm - see Figure 29. The type of the alarm is indicated by background color and letter in the column S.

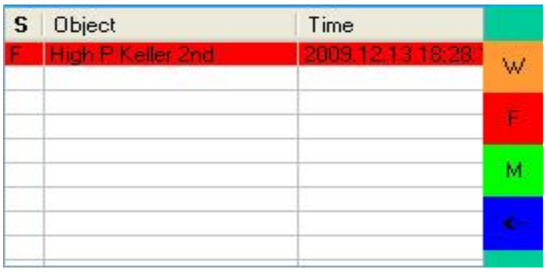

Figure 29 – Mini Alarm Screen

The MAS recognizes three different alarm states – WARNING, FATAL and MASKED. Monitoring of each alarm state can be activated or deactivated by buttons located next to the table with alarms. The buttons are available only for the logged C4F user. The MAS is refreshed every time the alarm filtering is changed.

4.8. Finite State Machine tree

The motivation for implementation of the Finite State Machine tree (FSM) into the C4 was to provide the user with an overview of all system resources at one place. The graphical user interface (GUI) of the controlled system usually provides operator a topological overview of the plant. The FSM comprises devices to groups according to their type, calculates their state and status, and calculates the state and status of the groups. The implemented groups correspond with objects available in the C4 framework (CAN buses, ELMB units, sensors, switches, converters and regulators). This section of diploma thesis describes the implemented procedures, states and transition conditions of the implemented FSM.

4.8.1. State hierarchy

The states of the C4 FSM are organized into the tree structure and work in two directions – as a commands send from the tree high level nodes to all connected branches, and as a state indicators calculated according to the defined criteria. The states of the elements are calculated from the states of the elements in the lower levels of the tree and vice versa. Thus the command from the top node can propagate to all elements in the connected branches and also the state of the top node can be changed from the low-levels of the tree. The C4 FSM States tree is depicted in Figure 30.

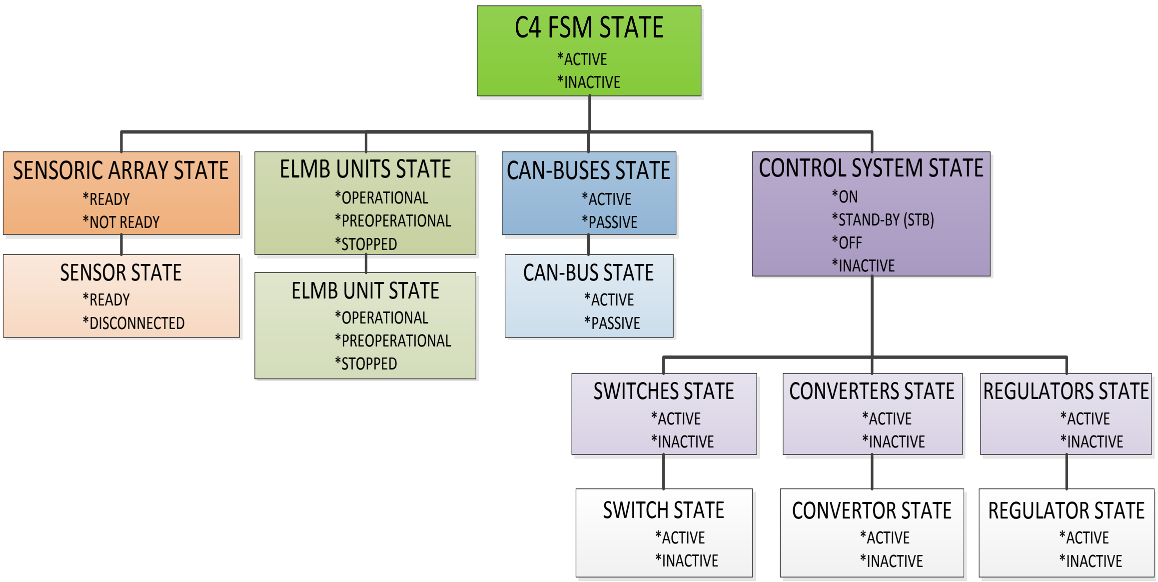

Figure 30 – C4 FSM States tree

4.8.1.1. C4 FSM STATE

The top node of the C4 FSM States tree is global state called C4 FSM STATE. The state is calculated from the SENSORIC ARRAY STATE, ELMB UNITS STATE, CAN-BUS STATE and CONTROL SYSTEM STATE. The C4 FSM STATE is top or root node in the tree hierarchy and therefore STATE command can be applied to it.

The current state is in the C4F indicated at the C4 Control panel, tab Global – see Figure 21. The button referring to this node is located in the upper right corner. The button label corresponds to the actual state as well as its background color. The state of the node can be changed (FSM STATE command can be send to the subordinate nodes) by clicking on this button (ADMIN privileges are required). The state value is stored in the C4 Global data point named FSM_state. The available states of the node with the transition conditions are enlisted in Table 9.

Table 9 – C4 FSM node states

State	Transition conditions	Associated color
ACTIVE	• SENSORIC ARRAY STATE is READY • ELMB UNITS STATE is OPERATIONAL • CAN-BUS STATE is ACTIVE • CONTROL SYSTEM STATE is ON, STAND-BY or OFF	green
INACTIVE	• SENSORIC ARRAY STATE is NOT READY • ELMB UNITS STATE is PREOPERATIONAL or STOPPED • CAN-BUS STATE is PASSIVE • CONTROL SYSTEM STATE is INACTIVE	red

4.8.1.2. SENSORIC ARRAY STATE

The SENSORIC ARRAY STATE is a node whose state corresponds to a summary state of all sensors whose alarms are registered in C4 ALARMS. The sensors are passive elements and can't be controlled, therefore there this node doesn't reacts on the FSM STATE commands and it also doesn't transmit the commands to the subordinate nodes. The state of this node is not displayed in the current version of the C4 Control panel. The available states of the node are enlisted in Table 10.

Table 10 – C4F SENSORIC ARRAY node states

State	Transition conditions	Associated color
READY	• SENSOR STATEs corresponding to the sensors registered in C4 ALARMS are all READY	green
NOT READY	• SENSOR STATEs corresponding to the sensors registered in C4 ALARMS are all READY	red

4.8.1.3. SENSOR STATE

The SENSOR STATE is a node on the lowest level of the C4 FSM STATE hierarchy whose state corresponds directly to the state of the sensor physically connected to the readout system and registered in the C4 ALARMS. The sensors are passive elements and can't be controlled; therefore this node doesn't react on the FSM STATE commands. The state of this node is displayed in the current version of the C4 Control panel by a background color of all fields displaying the signal from the corresponding sensor (typically in the GUIs). The available states of the node are enlisted in Table 11.

Table 11 - C4F SENSOR node states

State	Transition conditions	Associated color
READY	• flag in the data point corresponding to the ELMB input channel on which the sensor is registered is set to value CONNECTED	green
DISCONNECTED	• flag in the data point corresponding to the ELMB input channel on which the sensor is registered is set to value DISCONNECTED	grey

4.8.1.4. ELMB UNITS STATE

The ELMB UNITS STATE is a node whose state corresponds to a summary state of all ELMB units registered in the C4F data-base. The state of this node is not displayed in the current version of the C4F control panel. The available states of the node are enlisted in Table 12.

Table 12 - C4F ELMB UNITS node states

State	Transition conditions	Associated color
OPERATIONAL	• ELMB UNIT STATEs corresponding to the ELMB unit registered in C4 are all OPERATIONAL	green
PREOPERATIONAL	• ELMB UNIT STATEs corresponding to the ELMB unit registered in C4 are all PREOPERATIONAL	orange
STOPPED	• ELMB UNIT STATEs corresponding to the ELMB unit registered in C4 are all STOPPED	red

4.8.1.5. ELMB UNIT STATE

The ELMB UNITS STATE is a node on the lowest level of the C4 FSM STATE hierarchy whose state corresponds directly to the state of the ELMB unit physically connected to the readout system and registered in the C4. The state of this node is not displayed in the current version of the C4 Control panel. The available states of the node are enlisted in Table 13.

Table 13 - C4F ELMB UNIT node states

State	Transition conditions	Associated color
OPERATIONAL	• flag in the data point corresponding to the ELMB unit registered in C4 is set to value OPERATIONAL	green
PREOPERATIONAL	• flag in the data point corresponding to the ELMB unit registered in C4 is set to value PREOPERATIONAL	orange
STOPPED	• flag in the data point corresponding to the ELMB unit registered in C4 is set to value STOPPED	red

4.8.1.6. CAN-BUSES STATE

The CAN-BUSES STATE is a node whose state corresponds to a summary state of all CAN buses registered in the C4F data-base. The node is passive therefore it can´t transfer commands to the subordinate nodes. The state of this node is not displayed in the current version of the C4F control panel. The available states of the node are enlisted in Table 14.

Table 14 - C4F CAN-BUSES node states

State	Transition conditions	Associated color
ACTIVE	• CAN-BUS STATEs corresponding to the CAN buses unit registered in C4 are all ACTIVE	green
PASSIVE	• CAN-BUS STATEs corresponding to the CAN buses unit registered in C4 are all PASSIVE	red

4.8.1.7. CAN-BUS STATE

CAN-BUS STATE is a node on the lowest level of the C4 FSM STATE hierarchy whose state corresponds directly to the state of the CAN bus physically connected inside the monitored system. The state of this node is not displayed in the current version of the C4F control panel. The available states of the node are enlisted in Table 15.

Table 15 - C4F CAN-BUS node states

State	Transition conditions	Associated color
ACTIVE	• flag in the data point corresponding to the CAN bus registered in C4 is ACTIVE	green
PASSIVE	• flag in the data point corresponding to the CAN bus registered in C4 is PASSIVE	red

4.8.1.8. CONTROL SYSTEM STATE and C4F Objects STATE

CONTROL SYSTEM STATE is a node whose state corresponds to a summary state of all C4F objects. The CONTROL SYSTEM STATE node doesn't monitor the states of the subordinate nodes and it can be only changed by the control buttons located in the C4F control panel.

The node has four possible states described in Table 16. The state INACTIVE is common for all subordinate nodes, but states ON,STB and OFF are in the subordinate nodes represented as ACTIVE state (this approach is applied when the STATE command is send to the lower nodes).

Table 16 - C4F CONTROL SYSTEM node states

State	Transition conditions	Associated color
ACTIVE	• CAN-BUS STATEs corresponding to the CAN buses unit registered in C4 are all ACTIVE	green
PASSIVE	• CAN-BUS STATEs corresponding to the CAN buses unit registered in C4 are all PASSIVE	red

The states of the C4F objects (switches, converters and regulators) are all the same, and they are described in Table 17. The objects states have two level hierarchy – the top level node state of each object is determined as a summary of its subordinate nodes (e.g. state of the C4F switches is ACTIVE in case all switches registered in the C4F).

Table 17 – C4F Objects node states

State	Transition conditions	Associated color
ACTIVE	• State of the corresponding C4F object (or all subordinate C4F objects) is ACTIVE. The state is used during the regulation process.	green
PASSIVE	• State of the corresponding C4F object (or all subordinate C4F objects) is PASSIVE. The state is used during the regulation process.	red

4.8.2.Status hierarchy

C4F FSM implements statuses tree hierarchy of all objects that can be registered in the C4F, see Figure 31. The statuses are described in Table 18. The statuses are determined from the lower levels of the tree and they then propagate to the top level node called C4 FSM STATUS. The statuses are indicated in the C4F main panel, control panel and other C4F subordinate panels by text messages and their background colors.

The nodes on the lower level correspond directly to the status of devices registered in the C4F and physically connected to the system. The nodes in the higher levels of the hierarchy are summary nodes using majority logic. The algorithm is described below.

Algorithm

1) If the status of any subordinate node changes, then the numbers of subordinate nodes in sub-statuses are calculated.
2) The sub-state with the higher number is set as a state of the node. If there is more sub-statuses with the same number, then the status that is more dangerous for the system is selected – this approach is used every time for top level node C4FSM STATUS.
3) The status information is then complemented by number of subordinate nodes in the determined status that is added after the name of the status (e.g. READY (5/9)).

   In case all subordinate nodes are in the same status, then instead of the numbers is parameter ALL added before the name of the status (e.g. ALL READY).

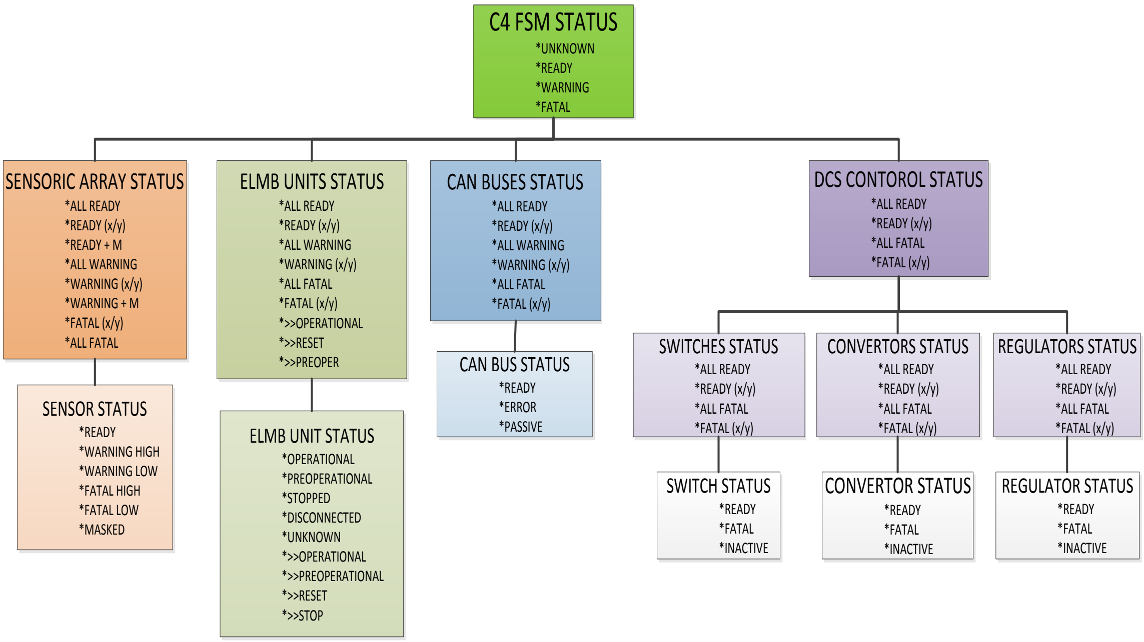

Figure 31 – C4F FSM Status tree

Table 18 – C4F statuses description

STATUS	DESCRIPTION	COLOR
READY	The status indicates that there are no known problems connected with the node. The status is in the GUI indicated by text READY or OK.	green
READY + M	This status is specific for the SENSORIC ARRAY node. It has the same properties as the READY status, but it in addition indicates that some statuses of the subordinate nodes have status MASKED	green
WARNING	The status indicates small problems of the node that could potentially endanger the node. The problems should be solved during next maintenance.	yellow
WARNING + M	This status is specific for the SENSORIC ARRAY node. It has the same properties as the WARNING status, but it in addition indicates that some statuses of the subordinate nodes have status MASKED	yellow
FATAL	The status indicates problems that present great danger for the node. The problems must be solved immediately.	red
ERROR	The status indicates problems that may interrupt correct function of the node. The problems may not be dangerous for the node, but they may cause problems during the data monitoring in the C4F.	red
PASSIVE	The status indicates no response of the corresponding node.	red
INACTIVE	The status is virtually set in the C4F and it means that the status of the node is not monitored.	grey
UNKNOWN	The status means that the majority logic was not able to gather enough data to determine the node status.	grey
>>>OPERATIONAL	This is specific status of the ELMB connected nodes. It indicates that the ELMB is in the transition between states. When the transition is finished the status is updated to one of the standard ones.	purple

>>>PREOPER	This is specific status of the ELMB connected nodes. It indicates that the ELMB is in the transition between states. When the transition is finished the status is updated to one of the standard ones.	purple
>>>RESET	This is specific status of the ELMB connected nodes. It indicates that the ELMB is in the transition between states. When the transition is finished the status is updated to one of the standard ones.	purple

4.9. Access control

Communication techniques based on the Internet will be offered for remote maintenance and surveillance of the controlled system. This implies security risk. Therefore an access control mechanism is putted in place in order to prevent any damage or other disturbance caused by such incidents.

The C4F system utilizes standard encryption and authentication techniques if necessary. The access control is needed for user to be allowed perform certain actions depending on his expertise. For instance an user which is only allowed to monitor the system (an observer) do not need any authentication, while an expert which is allowed to change all key settings needs to be logged-in into the system.

The C4F is ready for the integration with SQL data-base containing the user access data and roles. For the testing purposes were created only two built in users called OBSERVER and ADMIN that are described in Table 19. The currently active user is indicated by a text message in the C4F main panel.

Table 19 – C4F Users descriptions

User	Description
OBSERVER	The OBSERVER is user that is logged in after the start of the system and which does not have any administrating rights in the C4F. The control elements placed in the GUI of a C4F control panel and all subordinate panels are disabled, available are only function necessary for the data monitoring, archiving and export.
ADMIN	The ADMIN is user that needs to log-in to the C4F system. The password is stored in the C4F locally in the C4F data point structure and can be easily adjusted by a logged user. Even the password is not protected by an encryption (such system can´t be used in real application) the mechanism can be effectively used to prevent less skilled users from performing unwanted actions during training.

4.10. C4F Installation

The C4F files are distributed in an archive file. The C4F installation procedure is described in the following steps. The C4F is after the installation ready for usage with administrator password set to *pass.*

1) Extract the archive in the PVSS project directory.
2) Start the project and open its console.
3) Add to the console new item with parameter *–p control_panel2.pnl* and, set *Turn on always* setting.
4) Restart the newly added item three times.
5) Restart the PVSS project.

5. H8 Experimental cooling circuit

The experimental cooling circuit (ECC) located at H8 in Bldg. 887 in CERN Prévessin was designed to provide flexible and maximally adjustable cooling potential for the TOTEM Roman Pot testing and commissioning. The cooling plant was assembled and it is operated by specialists under the auspices of the Physics Department of the CTU in Prague. The ECC design is in many ways equivalent to the design of the cooling plant used at IP 5 for the Roman Pots cooling that is described at section 1.3.

5.1. Cooling plant topology

The ECC is located on the concrete platform at CERN Prévessin site, building 887, sector 168. The whole ECC installation takes around 20 [m^2] and its main elements are located on three separate places. The whole layout is depicted in Figure 32.

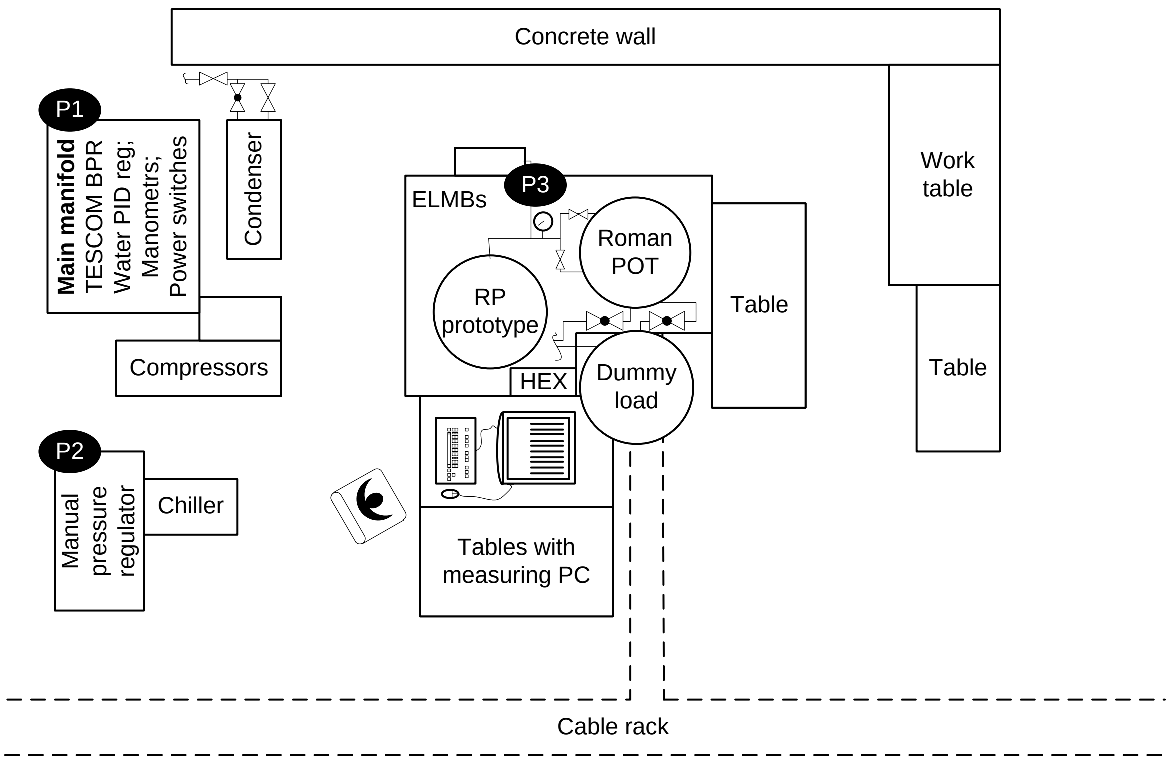

Figure 32 – H8 Cooling circuit layout

5.2. The Coolant management

The ECC is using a C_3F_8 as a medium for the first phase of the evaporative cooling. The liquid refrigerant is stored in the condenser when the cooling circuit is not active. The total capacity of the condenser is around 7 [Kg] of the C_3F_8 and for the stable cooling is required at least 50% of the maximum capacity. The coolant must be separated from the outer environment all the time because it changes its behavior when it is contaminated.

5.3. The Cooling process description

The ECC was built for the cooling of one RP during its commissioning, however it is capable of cooling three independent heat loads located on three separate cooling lines, when only one line is required for stable cooling. The simplified scheme of the ECC is depicted in Figure 33.

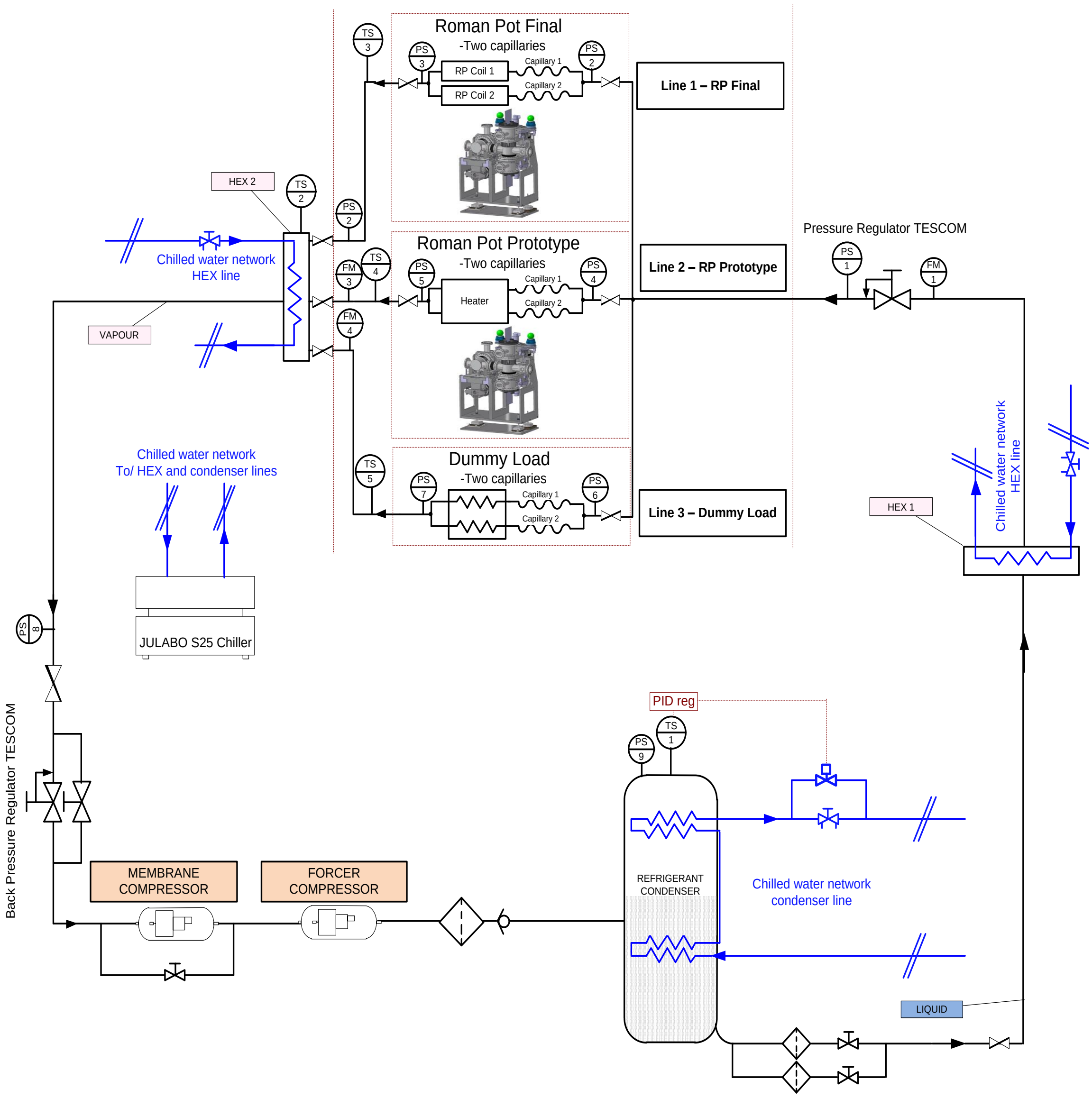

Figure 33 – H8 Cooling circuit schematic

The cooling process in the ECC is started when the coolant is released from the condenser into the liquid line pipes. The coolant must be heated on 37 [°C] (which corresponds to approximately 10 [bar_a] of the condenser pressure) before the start to maintain stable liquid flow. The coolant is after the ECC start led through the copper pipes with 6 [mm] diameter from the condenser through two parallel filters into the first heat exchanger (HEX 1). The temperature of the refrigerant is in the exchanger adjusted by chilled water (see Figure 33, Chiller water network: HEX line) to 17 [°C], because chilled liquid C_3F_8 has reduced enthalpy and therefore can absorb more heat during the evaporation.

The coolant flows from the HEX 1 to the manually operated TESCOM pressure regulator (MTPR). The MTPR can adjust the inlet pressure to the cooled areas in range from 8 to 13 [bar_a] as is required for the operation of the ECC. The pipeline splits into three independent lines after the MTPR. Each line can be closed or opened by a manual valve. The heat from the power loads is in each line removed during the coolant evaporation process around the capillaries. The lines are named according to their purpose.

- RP Final line

-the line is connected to the RP that is in the commissioning process. Two capillaries are placed in the inner volume of the RP. The required flow of the coolant through the line during the commissioning is in range from 1 to 1.8 [g/s].

- RP Prototype line

-the line leads to the prototype of the RP that was used for the testing of the RP cooling design. The capillaries in the RP Prototype are similar to the capillaries in the RP. Heaters placed after the capillaries are simulating the power load of the RP electronics.

- Dummy Load line

-Dummy Load line is designed for maintaining the ECC operation when neither RP nor RP Prototype lines are operated. Evaporation takes place on pair of capillaries when the temperature of the evaporated vapor is modified by heater placed after the capillaries. The flow through the line is in range from 0.8 to 1.4 [g/s].

The vapor from operated lines is brought through pipes to the HEX 2. The pipelines must be thermally insulated to prevent water condensation. The vapor is heated up by chilled water (Chiller water network: HEX line) to the temperature around 17 [°C] in the HEX. The three lines combine into one 8 [mm] vapor line in the HEX 2. The vapor line then leads to the TESCOM dome loaded back pressure regulator (TBPR). The TBPR could be used for adjustment of the ECC coolant back-pressure (the back-pressure determines the temperature in the cooled areas). The operation range of the back-pressure during the ECC run is from the atmospheric pressure to 2.5 [bar_a]. The by-pass around the TBPR is used only when all refrigerant needs to be recuperated from the ECC pipelines into the condenser. Two compressors (forcer compressor and membrane compressor) connected in series are located after the TBPR. They drain the coolant vapor of the circuit into the condenser. The additional heat is passed to the refrigerant during the process, therefore the condenser temperature is regulated by the flow of chilled water (Chiller water network: Condenser line) on 37 [°C].

5.4. Nitrogen distribution network

The ECC installation is connected to two separate sources of nitrogen.

5.4.1. Medium pressure nitrogen network

The first nitrogen source is a nitrogen distribution network of building H8. The maximum achievable pressure in this network is 10 [bar_a]. The network is depictured in Figure 35.The nitrogen is led through 8 [mm] plastic pipes from the source to the ECC where splits into three lines.

The pressure in the lines can be adjusted by the reduction valve (maximal pressure is 10 [bar_a]) located near the MTPR. The schematic of the distribution network is depictured in Figure 35.

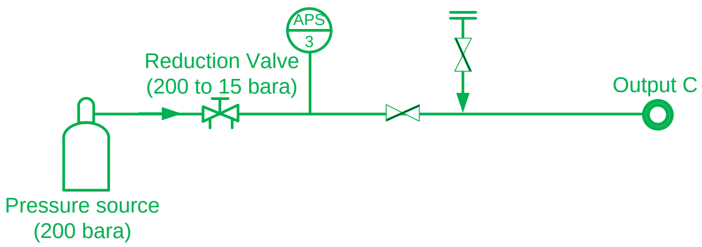

Figure 34 – ECC High pressure network

The pressure in line B and in the caped line is monitored by mechanical pressure sensor which is in the figure labeled APS 1. The pressure in the line A is adjusted by reduction valve (nominal set-point is 5 [bar_a]) and monitored by mechanical pressure sensor labeled APS 2.

5.4.2.High pressure nitrogen network

The second network with the high pressure nitrogen is available in ECC. The source of the nitrogen is pressure cylinder, the maximum achievable pressure is 200 [bar_a]. The cylinder is to the network pipelines connected through reducing manometers that allows the regulation of the output pressure. The schematic of the network is depicted in Figure 34.

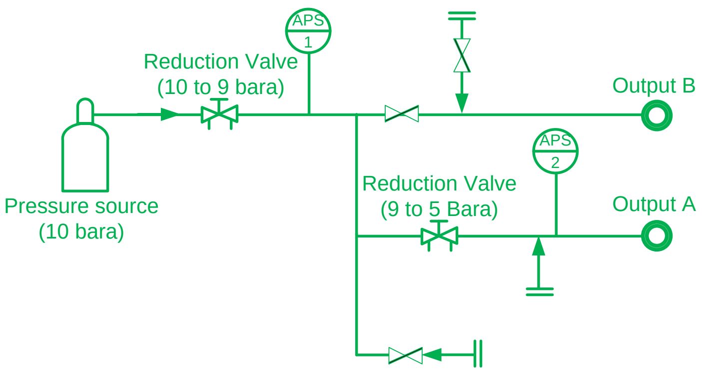

Figure 35 – ECC Medium pressure nitrogen network

5.5. Data acquisition system

The state of the ECC is monitored by a sensor array composed from many temperature sensors (TSs), pressure sensors (PSs) and flow-meters (FMs). The output signals of the sensors are via ELMB units communicated to the ECC HLC. The detail description of the system is in chapter 6 of this paper.

6. H8 Experimental cooling circuit control system

This section of the diploma thesis describes the old DAQ system used together with the ECC and the process of its replacement with the new control system based on the framework described in chapter 4. The old DAQ was left in place as a backup for the emergency situations until the new control system proves that is reliable and stable.

New hardware components necessary for the functioning of the control system were installed together with the framework. It was decided not to modify the existing setup and to install new components separately to avoid unintended interference.

6.1. Control system initial state description

6.1.1. Software configuration

The control system of the DAQ was originally designed only for the monitoring of the sensors placed along the ECC. The high level control (HLC) was realized by the PVSS project programmed in the PVSS II version 3.0, OPC server and the data-base running on a desktop computer. The coding of the project didn't allow upgrade to the newer version of the PVSS or the implementation into the C4 framework. The DAQ was providing a simple GUI displaying the values obtained from the technological process, trends and state of the low-level controllers.

6.1.2. Read out system hardware configuration

The front end units providing the communication between the HLC and sensors were three ELMB units connected to one CAN bus branch. The communication between the HLC and ELMBs was running over the CAN bus with the National Instruments/USB card used as an interface. The definitions of the ELMB units, connected sensors and calibration constants were stored in the OPC server configuration file. The file was generated or updated through a Microsoft office Excel 2003 sheet and associated macros.

6.1.3.Archiving setup

The process variables data were asynchronously smoothing archived without on the HLC. The DAQ allowed the user to export the data from the data-base into the Excel file using a supplement for the Excel and set of templates.

The detail description of the DAQ system can be found in (21), (22) and (23).

Table 20 – ECC Power requirements

Devices	Voltage	Connectable in parallel	Nominal power consumption
ELMB	12 [V] DC	No	35 [mA]
ELMB DAC	26 [V] DC	No	20 [mA]/channel
Electromagnetic valves	24 [V] DC	Yes	400 [mA]
Pressure transducer	24 [V] DC	Yes	300 [mA]
Electromechanical valve	24 [V] AC	Yes	500 [mA]

6.2. Power supply upgrade

The demands on the electricity supply are significantly increased due to hardware configuration changes made on the ECC. The ECC original power supply setup consisted from two laboratory power supplies with five adjustable voltage outputs. All of the outputs were used to power installed sensors, ELMB units and CAN bus. Thus new power supplies (PSs) were installed.

The known requirements of the newly installed hardware together with needs of the hardware described in section 7.4 are enlisted in Table 20.

The stabilized 230 [V] AC/12 [V] DC supply, manufacture by TATAREK company, was installed as a power supply for the ELMB units. The maxim output current of a supply is 500 [mA] and the price was 16 CHF. The power supply box (see 6.2.1) was constructed as a power supply for electromechanical valves.

The rest of the devices is powered by new laboratory power supply with two adjustable voltage outputs installed in sector P3 of the ECC (see Figure 32). The power supply is placed next to the power supplies of the original control system – see Figure 37.

6.2.1.Power supply box

The purpose of the power supply box (PSB) that was built for the ECC power supply system is to provide stable 24 [V] AC output. The box meets safety standards during the operation, it is resistant to impact and electrical outputs are protected against short-circuit conductors.

Figure 36 - MCF/B19624F transformer

The composition of the PSB is based on the grey polycarbonate junction box with dimensions 150 x 175 x 80 (A [mm] x B [mm] x H [mm]), see Figure 36. The transformer of 230 [V] AC to 24 [V] AC, type MCF/B19624F TRAFO, with two voltage outputs is housed inside the box. Each output is limited to 50 [VA]; in total, the transformer can provide 100 [VA]. The transformer is connected to the box by two sheet-metal L profiles and set of 8 screws. The gaps between the transformer and the box are filled with ARMAFLEX insulation to minimize the impact of possible vibrations on the coupling in the PSB. The input and output power sockets are located on the front side of the PSB, see Figure 38. The input 230 [V] AC voltage is led to the transformer through the standard three pin device power socket. The voltage outputs of the transformer are through the fuses connected to the circle plastic connector with four pins as an output that are compatible with BURNDY 2.56 [mm] pin connectors. The inside of the PSB is secured by set of four plastic safety screws located on the top of the box. The total price of the parts used on the PCB was 55 CHF (the summation is based on the prices in the CERN store catalogue and FARNELL company price list).

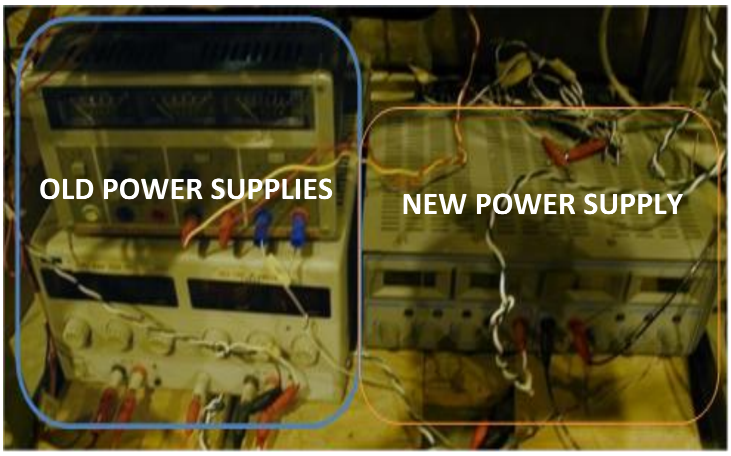

Figure 37 – Power supply installation

The PSB resistance was tested after its assembly. First test consisted from the fall of the PSB from 100 [cm] to the concrete ground. The height was selected concerning the place where the PCB will be located in the final installation. No damage was found on the outer packaging or on the internal connections after the test. The voltage outputs were shorted during the second test. The fuses were broken but the transformer stayed untouched.

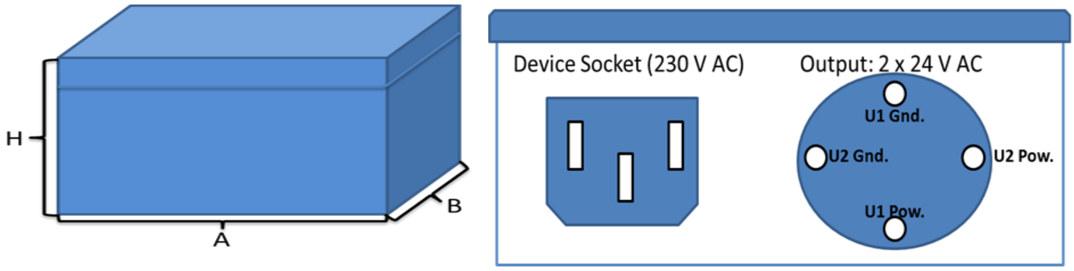

Figure 38 – Power supply box schematic

6.3. Low-level control system upgrade

The low-level control system of the ECC was expanded with two ELMB units and one ELMB DAC according to the decision made in chapter 3.3. The ELMBs are designated as low-level controllers providing the communication between the high level control SCADA system and newly installed ECC hardware components. The first ELMB named *ELMB_48*, connected with the ELMB DAC, is used for generating of the control signals. The second ELMB named *ELMB_14* provides readout from the newly installed sensors and feedback readings of applied control signals.

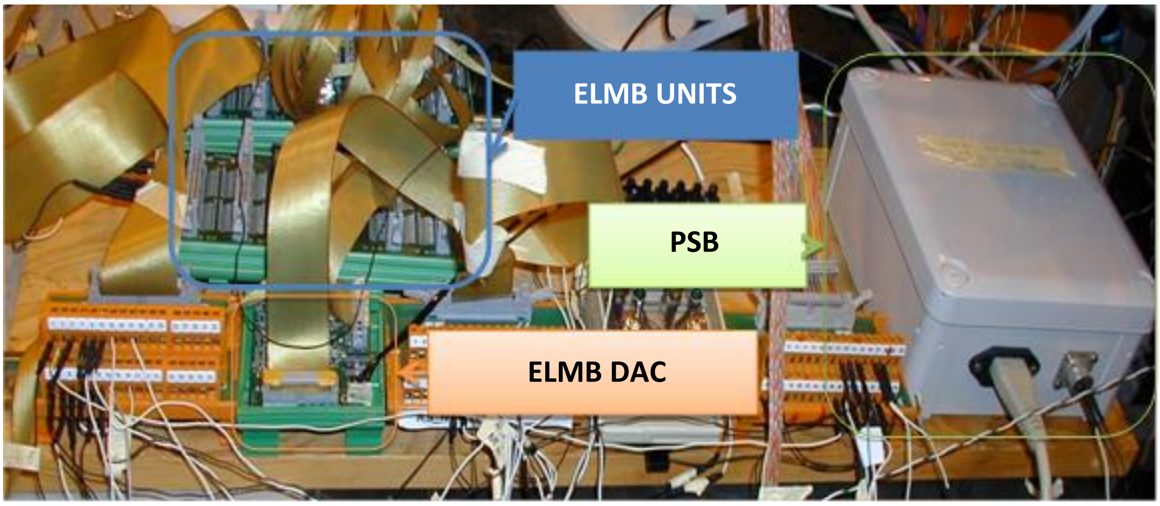

Figure 39 – ELMB installation overview

The ELMB units were together with the ELMB DAC mounted on DIN rail placed on wooden platform. The platform also houses the PSB described in section 6.2.1 and bus-bars for the interconnections with the wires leading from the ECC – see installation overview depicted in Figure 39.

The new ELMB units are connected with the PVSS SCADA server (selected in section 3.2) through the CAN bus cable. The cable is connected to both ELMBs on one side and to the National Instruments CAN card inserted in the server on the other side.

The electricity is for the ELMBs and for the ELMB DAC provided by the power supply system described in section 6.2.

6.3.1.ELMB units setup

The ELMB units were configured before the installation. Their configuration was adjusted by their DIP switches and in their framework to be compatible with the already installed ELMB units. The IDs of new ELMBs are 14 and 48. The configuration parameters of all installed ELMBs are enlisted in Table 21.

Table 21 – Configuration parameters of ECC ELMB units

ELMB name	ID	AD Range	Auto-start	Communication speed	CAN Bus
ELMB_14	14	100 mV	1 (TRUE)	125000 Baud/s	CAN_BUS_1
ELMB_61	61	100 mV	1 (TRUE)	125000 Baud/s	CAN_BUS_1
ELMB_62	62	100 mV	1 (TRUE)	125000 Baud/s	CAN_BUS_1
ELMB_63	63	100 mV	1 (TRUE)	125000 Baud/s	CAN_BUS_1
ELMB_48	48	100 mV	1 (TRUE)	125000 Baud/s	CAN_BUS_2

6.3.2.ELMB field bus connection

The ELMB units are connected to the HLC server through two CAN bus chains. The ELMBs that were used in previous DAQ system are connected to the CAN bus chain named in the SCADA system CAN_BUS_1. The new ELMBs are connected to second CAN bus named CAN_BUS_2. The scheme of the connection is depictured in Figure 39.

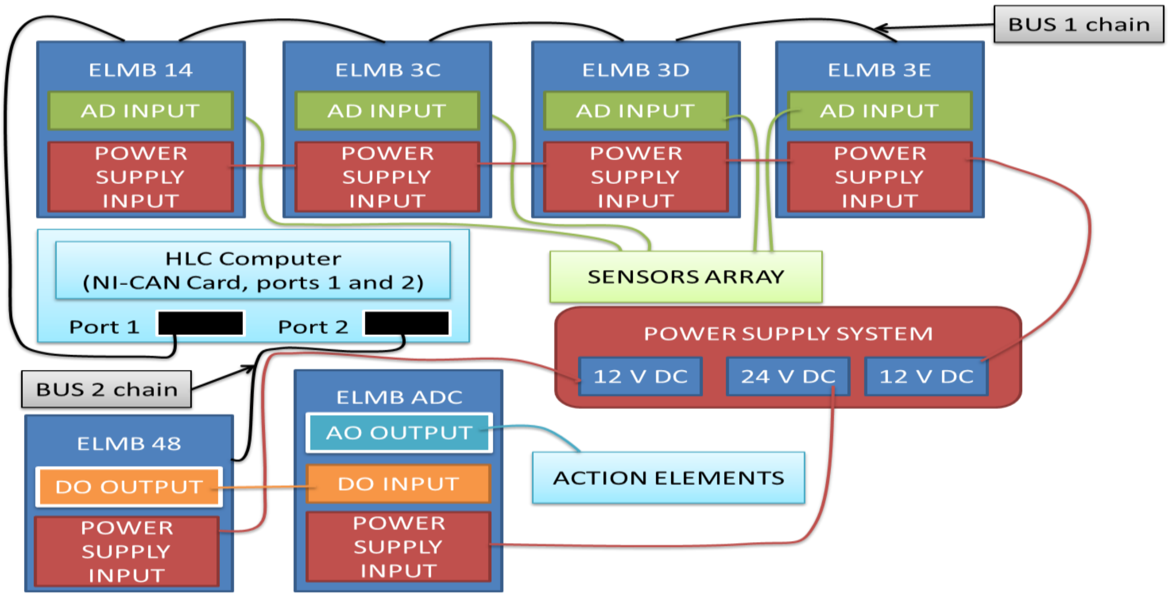

Figure 40 – ECC ELMB Connection overview

The CAN bus chains are in the SCAD system described in section 6.4 with parameters listed in Table 22.

Table 22 – ECC CAN Buses parameters

Registered bus	Interface type	Interface port	Communication speed	NMT command
CAN_BUS_1	NI-CAN	1	125000 Bit/s	1 (Start)
CAN_BUS_2	NI-CAN	2	125000 Bit/s	1 (Start)

6.4. ECC PVSS SCADA system with C4F

The high level of the ECC monitoring and control system was according to section 3.1 implemented in the ETM PVSS II SCADA system. The C4 framework described in chapter 4 was used for the parameterization of ECC hardware elements.

6.4.1. ECC PVSS project

The PVSS II, version 3.6 was installed on the computer selected in section 3.2. Distributed PVSS project called *TOTEM_Prevessin_HLC* with the system number 42 (identification number of the PVSS project) was then created. The JCOP framework version 4.0.0, with components CORE, AI and ELMB, was installed in the PVSS project. The last installed component was C4F framework. The project is stored on the CD inserted to this thesis - see APPENDIX A.

6.4.2. Signal definitions

Different types of sensors with different outputs are used and therefore it is necessary to measure voltage (from 0.05 [mV] to 10 [V]) and resistivity (from 10 [Ohm] to 100 [KOhm]) on wide ranges. The total number of monitored sensors exceeds sixty and it is rising because of the continuous works on the ECC over last three years.

The detail list of signals with defined alarm trip points is stated in the APPENDIX B. The list of all signals is in the OPC configuration file stored on the CD attached to this thesis.

6.4.3. Data archive settings

The data from signals listed in section 6.4.2 are stored on the computer that is running the HLC. The relative dead band 0.01% is used to minimize the size of the data-base. This means that the signal output is stored asynchronously on difference between two following read outs. The PVSS archive manager named ARCH000 manages the data storage.

6.4.4. Graphical user interface

The PVSS II, JCOP framework and C4F framework offer many ways how to display data. These options however ignore the layout of the monitored system and they are more device oriented (e.g. values read by the ELBM are shown). Thus, PVSS panels and trends respecting the layout of the ECC were prepared.

The panels are composed from easily parameterizable objects displaying online information of ELMB AI channel and objects showing information about C4F objects. The panels are stored in the directory *panels/visualizations* located in the PVSS project main directory. They are accessible from the C4 main panel navigation menu, which is automatically updated according to content of this directory. Examples of those panels with overview of ECC and Roman Pot are depictured in Figure 41 and in Figure 42.

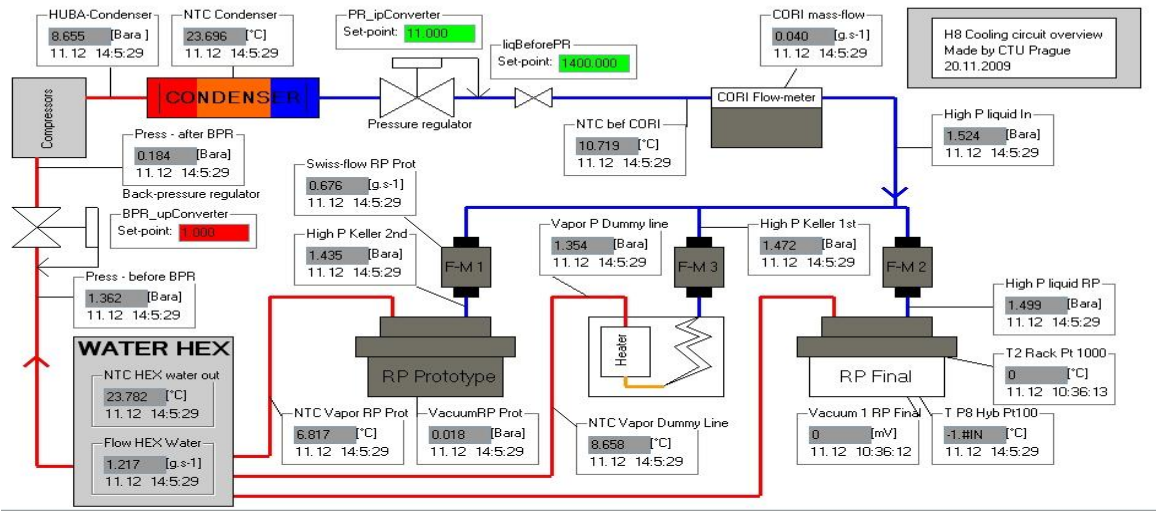

Figure 41 - ECC Overview GUI

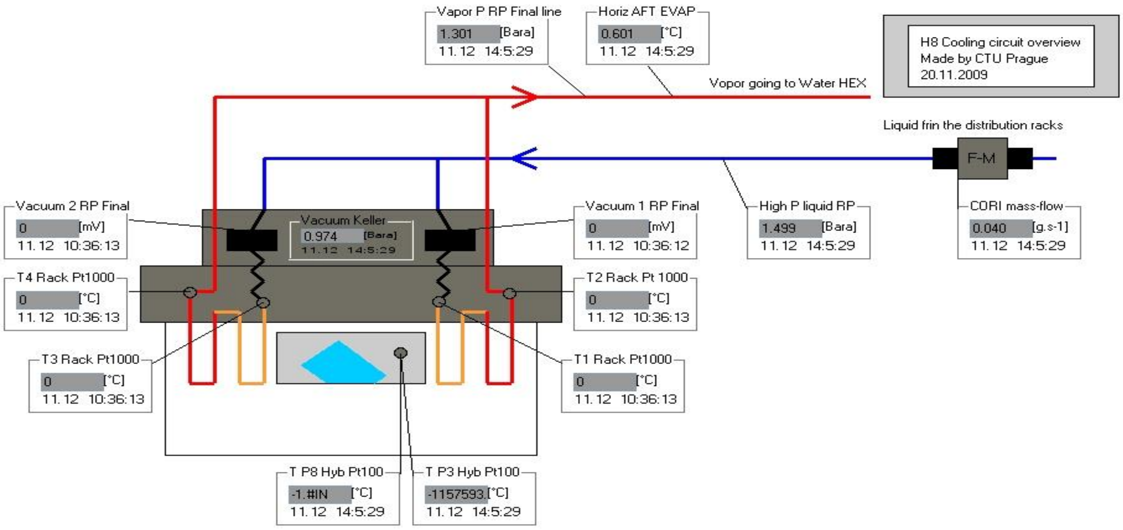

Figure 42 – ECC Roman Pot overview GUI

The trends were prepared in form of data point lists compatible with the C4F trending system. The C4F is capable of displaying up to 16 curves (each corresponding to one data point). Prepared data point lists are composed from data points that refer to similar physical devices (low pressure transducers, high pressure transducers and temperatures). The lists are stored in the directory *source* located in the PVSS project main directory.

6.4.5.Communication settings

The PVSS project was created as distributed, thus it can use TCP/IP network to interconnect with remote computers. The following code was inserted into the project configuration file, so it can communicate with other computers used for the remote monitoring of the ECC.

```
[dist]

maxBcmBufferSize = 120000

bcmBufferLimitTimeout = 120

distPeer = “ctu-siemens” 242

distPeer = “ctu-ibm” 342

distPeer = “mistr-listr.cern.ch” 442

distPeer = “listr.cern.ch” 942
```

7. Verification of the control system components

This section of the diploma thesis describes the verification process of the action elements for the pressure regulation selected for the construction of the control system in section 3.4. The verification was performed on the experimental cooling circuit ECC described in chapter 5 with the modification of the control system described in the chapter 6.

7.1. Goals of the verification

The verification principle was designed to accomplish three objectives.

- First, was to ensure that the selected action elements are compatible with the ECC hardware.
- Second, verification checked which elements were capable of fulfilling their purpose. In other words, it confirmed which of the elements can be used for the regulation of the pressure and/or back-pressure.
- Third, verification confirmed if the action elements can work together with the whole control system.

The result of the verification process is summarized in section 7.7.3.

7.2. Evaluation criteria

The assessment of the suitability of individual devices for control of the selected cooling system was implemented on the following criteria.

- Possibility and intensity of connection to a control system.
- Control precision (length of the step response, the size of overshoot, deviation from the requested value).
- Long-term stability of the controlled variable.
- Fail-safe behavior.
- Price of the solution.

The settings of the devices in the control system were individually tuned for each device to achieve its best behavior.

The components were evaluated separately in two groups according to their destination. The equipment, which can be used to control pressure and back-pressure, was assessed in both groups. The groups are described in section 7.3.

7.3. Tested setups

The selected components were combined into setups and split into two groups. Some of the components were present in both groups. The component characteristics are described in section 7.4.

First group consisted from setups assigned for the liquid coolant pressure regulation in the cooling loop of the plant described in section 1.3. The testing of this group was performed on the main liquid line of the cooling circuit described in chapter 5. The first group component setups were:

- TESCOM Dome-loaded pressure regulator with Joumatic U/p converter.
- TESCOM Dome-loaded pressure regulator with Marsh Bellofram I/p converter.
- Honeywell control valve with Honeywell linear actuator.
- Emerson control valve with Emerson linear.

The second group components were dedicated for the coolant vapor back-pressure regulation in the outlet of the cooling loop. The group was tested on the main vapor line described in chapter 5.

- TESCOM Dome-loaded back-pressure regulator with Joumatic U/p converter.
- TESCOM Dome-loaded back-pressure regulator with Marsh Bellofram I/p converter.

7.4. Components characteristics

The characteristics of components selected for the verification are described in this chapter. The descriptions emerged as a combination of information from manufacture data sheets and data gathered from tests and measurements.

7.4.1.TESCOM Dome loaded pressure regulator

The TESCOM Pressure regulator (TPR), model 44-2211-242, is mechanical pressure regulators. The tested TPR was in the dome-loaded version, which means that the set-point of the back-pressure is given by the referential pressure brought to the regulator. Thus the further tests of the TPR were performed in combination with one of the tested control signal/pressure converters. The converter served as the regulator actuator.

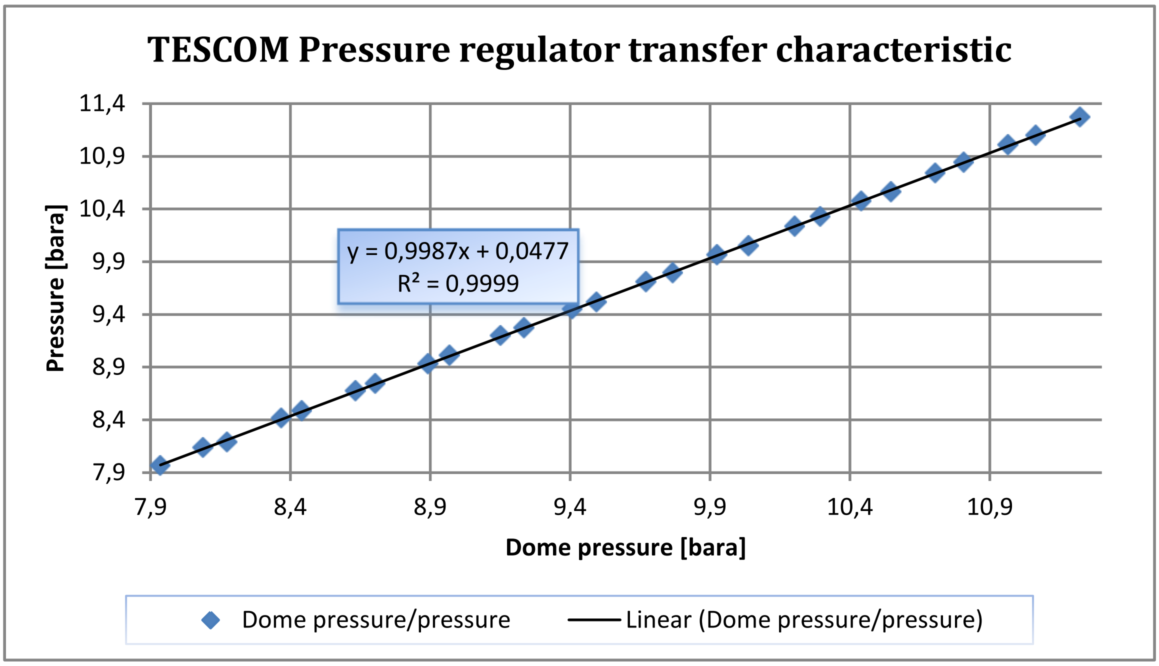

Figure 43 – TESCOM Pressure regulator - transfer characteristic

The dome-pressure and the pressure after the pressure regulator should be in the ideal case the same. The mechanical losses in the regulator may cause that the pressure is lower than the dome pressure. Thus, the transfer characteristics between the dome pressure and pressure was carried out, see Figure 43.The parameters of the TPR given by the factory are listed in the Table 23. The price of the regulator was 643 CHF.

Table 23 – TESCOM Pressure regulator characteristics

Model Number	Working area	Maximal inlet pressure	C_v	Precisions
26-23-00-28-208	0.1-35 [bar_a]	350 [bar_a]	0.6	0.5 % FS

7.4.2. TESCOM Dome loaded back pressure regulator

The TESCOM Back pressure regulator (TBPR), model 26-23-00-28-208, was chosen as a representative of mechanical back-pressure regulators. The tested TBPR was in the dome-loaded version, which means that the set-point of the back-pressure is given by the referential pressure brought to the regulator. The regulator was therefore tested only in combination with one of the tested control signal/pressure converters. The controller features stated by the manufacturer are listed in Table 24. The price of the regulator was 643 CHF.

Table 24 – TESCOM Back-pressure regulator characteristics

Model Number	Working area	Maximal inlet pressure	C_v	Precisions
26-23-00-28-208	0.1-3.5 [bar_a]	35 [bar_a]	0.6	0.5 % FS

The dome pressure and the back-pressure should be for the ideal back-pressure regulator the same, but they may differ because of the mechanical losses in practice. Thus, the conversion characteristic between the dome pressure and the back-pressure was carried out - see Figure 44. The conversion ration that arises from the measurements was later used during the calculation of the control signal for the tested converter (control signal/pressure).

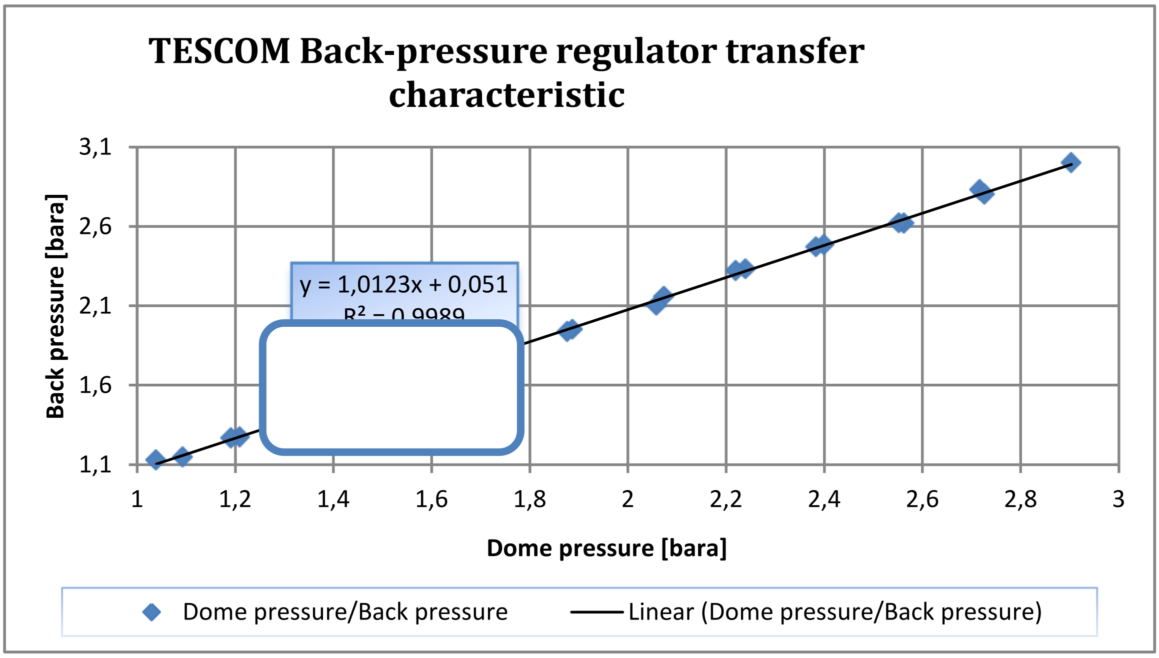

Figure 44 – TESCOM Back-pressure regulator – transfer characteristic

7.4.3.Marsh Bellofram 3220 I/p converter

Marsh-Bellofram 3220 I/p (MBIPC) is an electro-pneumatic servo-pressure controller with two solenoid valves for the industrial process automation manufactured by the Marsh-Bellofram company. The transducers dimensions are 55x55x88 [mm] (width x depth x height) and it has multiple wholes 8 [mm] threaded wholes that could be used for the mounting. The converter is depictured in Figure 45.

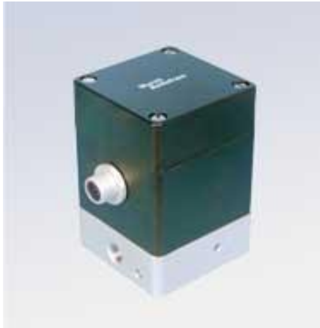

Figure 45 – MBIPC Overview

The MBIPC has three 1/8“connectors labeled S, O and E. The pressure source has to be connected to the port S, the pressure output has to be connected to the port O and the pressure is released from the system through the port E (to this port can be also connected the vacuum pump if necessary).

The MBIPC maximum output pressure is 16 [bar_a] while for the correct function is required a pressure source with 100-110% output of the required nominal pressure. The output pressure is monitored by the internal pressure sensor and the accuracy of the output is in range ±0.5% of the full scale (±80 [mbar]).

MBIPC is powered by the 24 [V] DC power supply, the control signal is current from range 4-20 [mA] (4 [mA] refers to 0 [bar_a] outlet pressure) and it has 0-10 [V] DC output signal as a feed-back from the internal pressure sensor.

The standard price of MBIPC with a M12 cable, which is necessary for the electrical connection, was in year 2009 332 CHF.

7.4.3.1. Conversion ratio analysis and calibration

The analysis of the Bellofram I/p converter conversion ratio was done in two steps.

First step was the MBIPC calibration on the output pressure range from 1.1 to 3.8 [bar_a] with a constant source pressure 5 [bar_a]. The aim was to calibrate MBIPC in the working area of vapor back-pressure regulation. The set-point of the DAC channel was varied from 750 to 1250 AO units with a step of 50 units and the corresponding current output of the DAC was monitored by precise Keithley 2000 multi-meter. The output pressure of the converter was read from the pressure sensor with precision ±25 [$mbar_a$]. The procedure was done in the raising and in the decreasing direction. The monitored values were recorded 15 seconds after the change of the set-point. The resulting conversion functions are depicted in Figure 46, Figure 47 and Figure 48. The functions are linear but they show that the MBIPC has an average hysteresis 59 [mbar] (min 49 [mbar]; max 79 [mbar]). The fit function - Equation [7.4-1] - was later used for the calculations of the set-point for the ELMB DAC during the back-pressure regulation tests.

Low pressure fit function

$$y = 184.32x - 530.64, \quad [7.4\text{-}1]$$

where *y* is calculated AO set-point and *x* is requested output pressure.

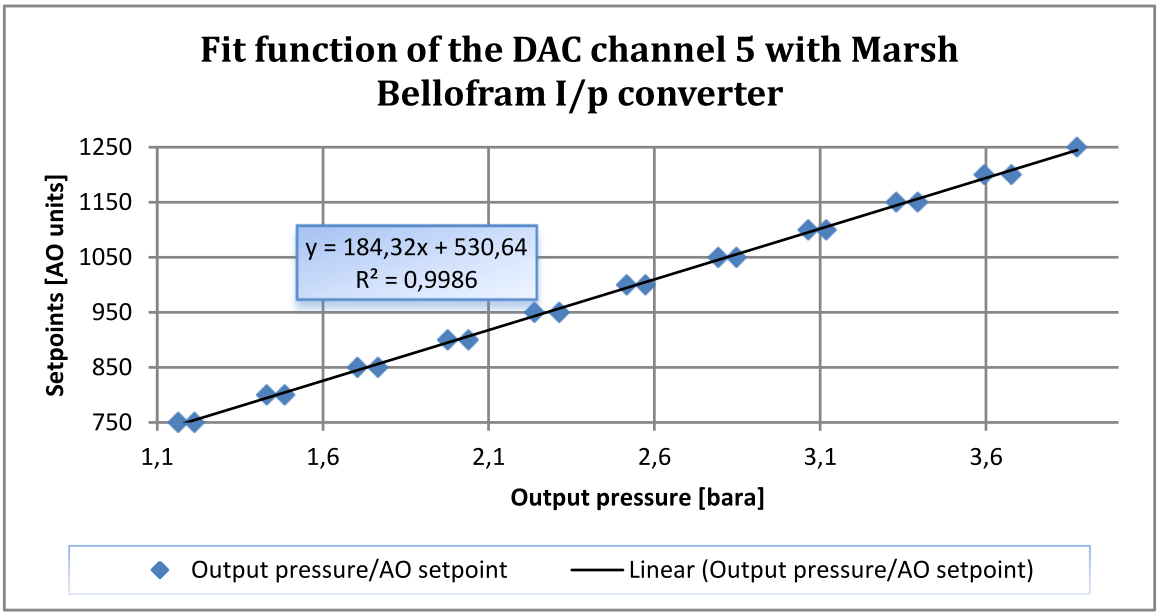

Figure 46 – MBIPC fit function p/AO – low pressure

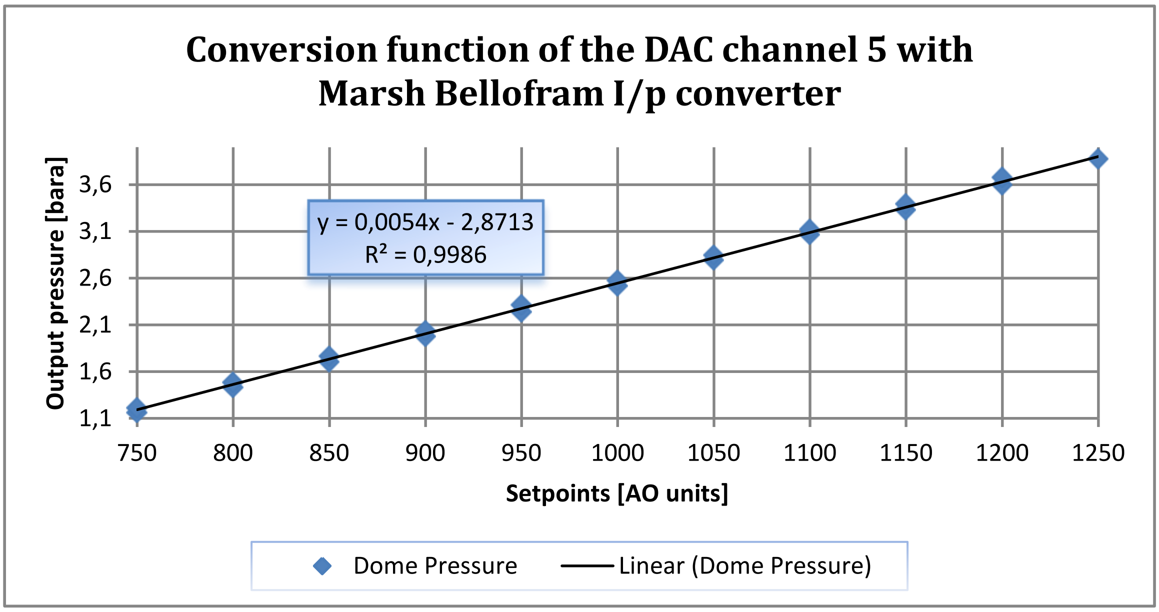

Figure 47 – MBIPC Conversion function AO units/p – low pressure

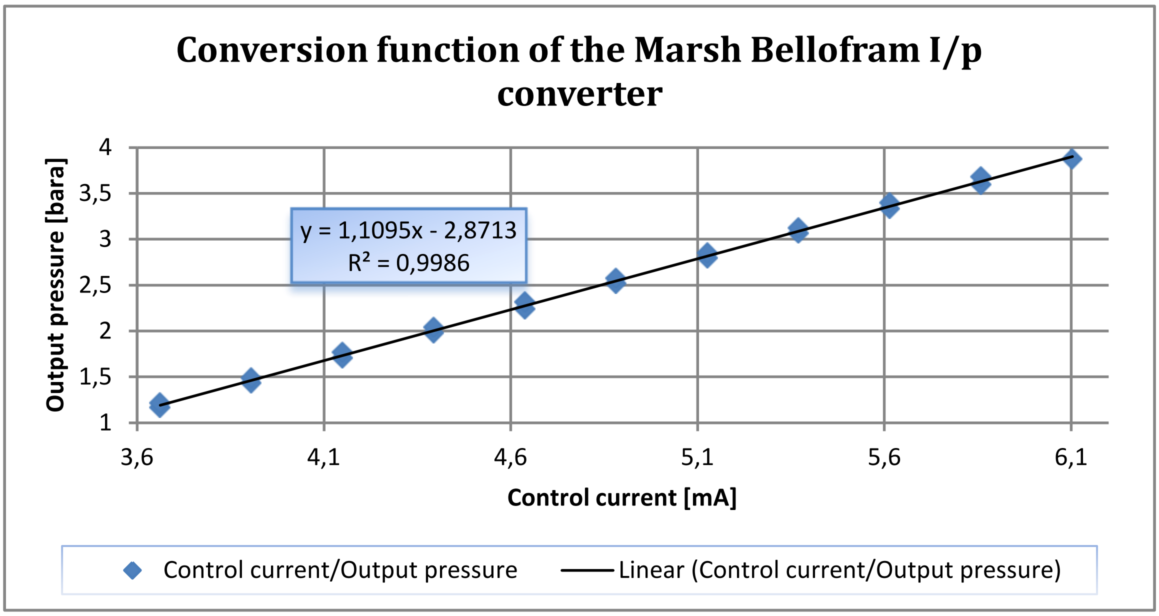

Figure 48 – MBIPC Conversion function I/p – low pressure

Second step was the MBIPC calibration on the output pressure range from 8 to 11 [bar_a] with a constant source pressure 14 [bar_a]. It aimed to calibrate MBIPC in the working area of liquid pressure regulation. The set-point of the ELMB DAC channel was varied from 2200 to 2800 AO units with a step of 50 units and the corresponding current output was monitored. The output pressure was monitored by sensor with precision ±50 [$mbar_a$]. The retrieved characteristics are depictured in Figure 49, Figure 50 and Figure 51. The fit function - Equation [7.4-2] - was later used for the calculations of the set-point for the ELMB DAC during the pressure regulation tests.

High pressure fit function

$$y = 184.32x - 530.64, \qquad [7.4\text{-}2]$$

where *y* is calculated AO set-point and *x* is requested output pressure (the variables in following fit functions have the same or similar meaning).

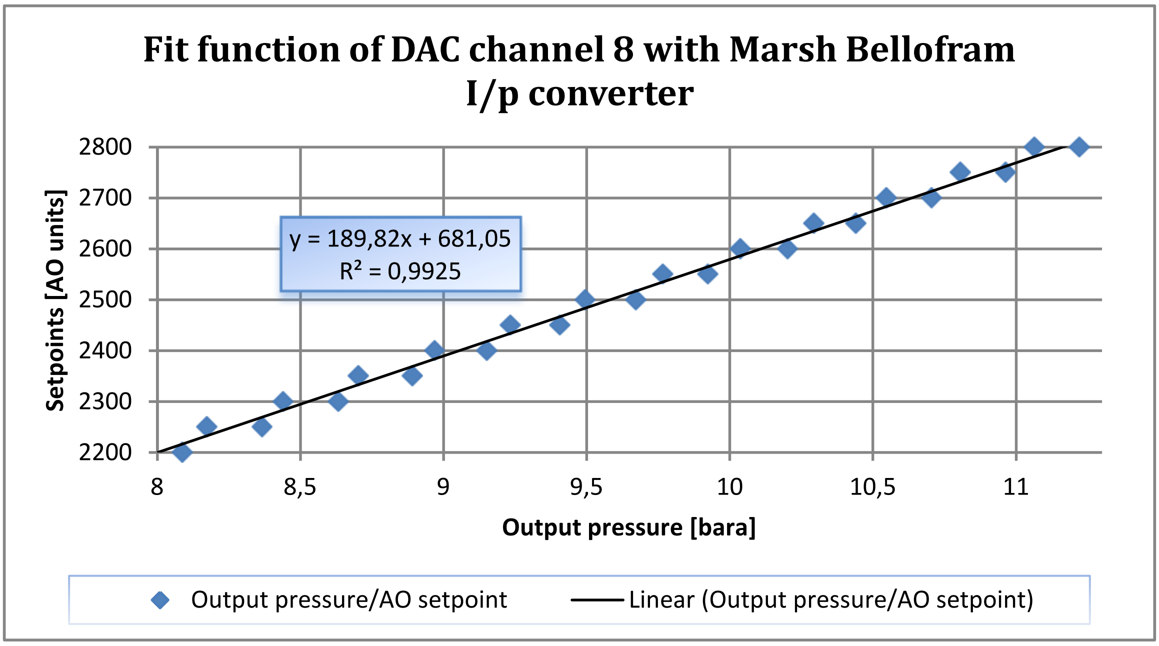

Figure 49 – MBIPC Fit function p/AO – high pressure

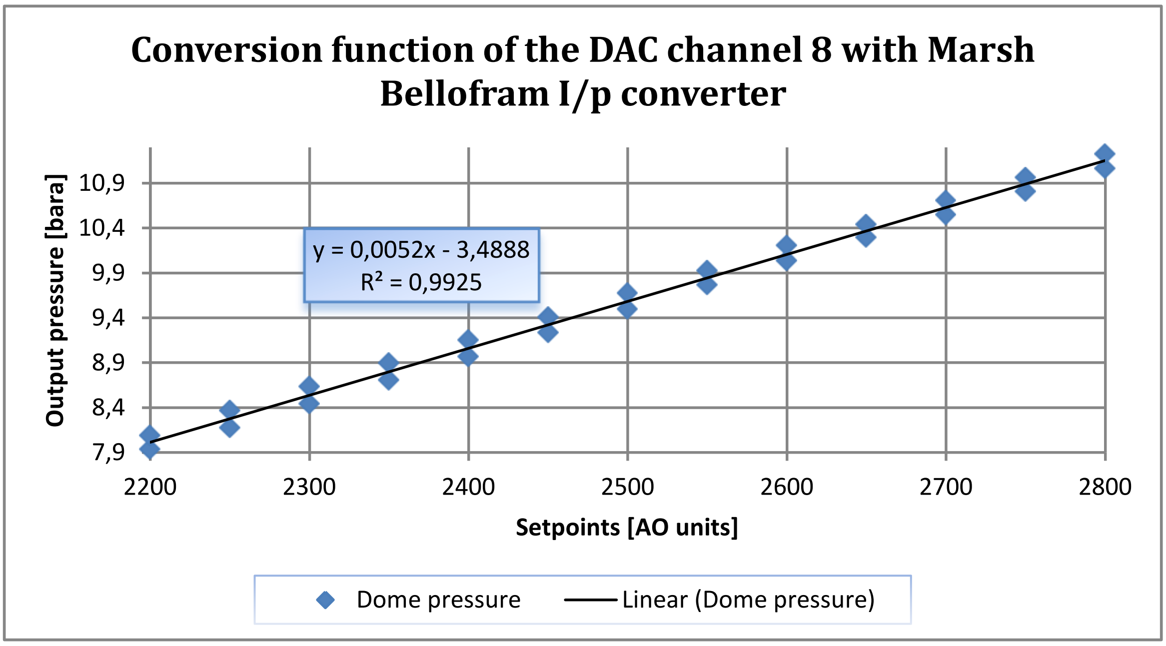

Figure 50 - MBIPC Conversion function AO units/p – high pressure

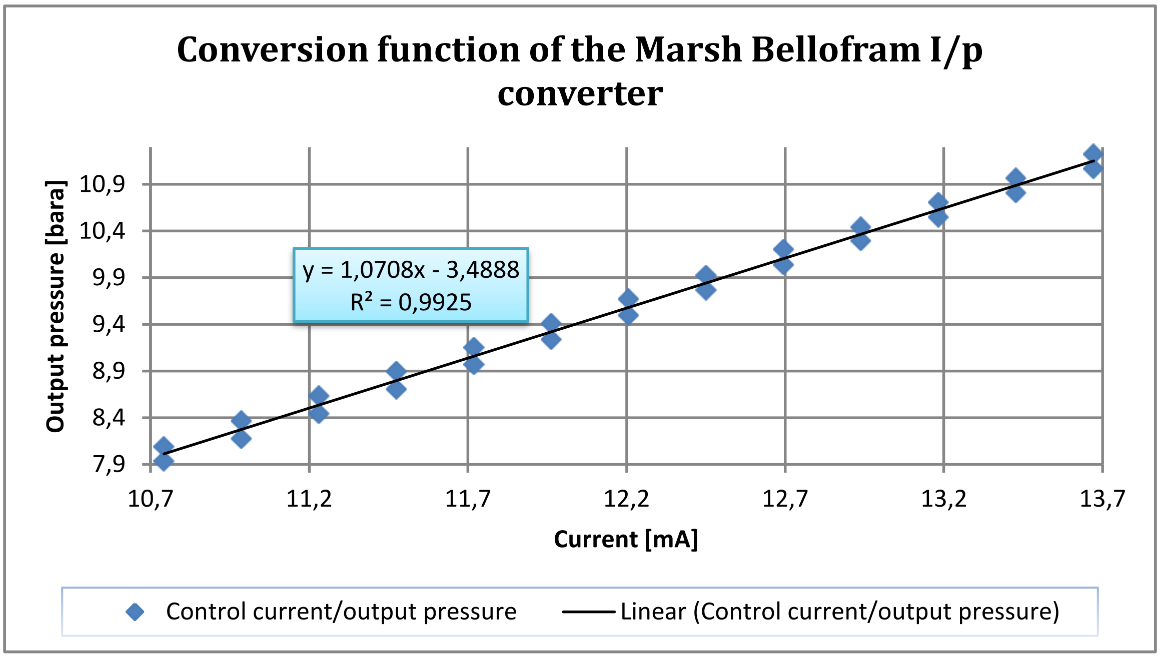

Figure 51 - MBIPC Conversion function I/p – high pressure

7.4.4.Joumatic SentronicD U/p converter

Joumatic Sentronic[D] U/p converter (SUPC) is a 3-way proportional valve with electrical control designed for the pressure regulation in the industrial systems. The inner control electronic of the SUPC is capable of the PID regulation of the output pressure, when the factory settings of the regulation can be adjusted by specialized software provided by the Joumatic Company. The converter is depictured in Figure 52.

Figure 52 – SUPC Overview

The SUPC has three 1/8"G screwed holes labeled 1, 2 and 3. The holes serve as I/O of the working media. The pressure source has to be connected to the port 1, the pressure output has to be connected to the port 2 and the pressure is released through the port 3 (to this port should be also connected the vacuum pump or sound silencer).

The maximum output pressure of the SUPC is 6 [bar_a] and for its correct function is required the pressure source with 100-110% output of the required.

The standard price of a SUPC with cable necessary for the electrical connection was in year 2009 according to manufacturer 945 CHF

7.4.4.1. Conversion ratio analysis and calibration

The SUPC was calibrated together with the ELMB DAC channel 5 (see 7.6.2) that was generating its voltage control signal. The channel was calibrated in range from 1000 to 2100 [AO units], which was expected to correspond with SUPC working range. The channel conversion characteristic is depictured in Figure 53.

The SUPC was calibrated in range from 1.1 to 2.8 [bar_a] with a constant source pressure 5 [bar_a]. The set-point of the DAC channel was varied from 1000 to 2100 [AO units] with a step of 100 units and the corresponding voltage output of the DAC was monitored by precise Keithley 2000 multi-meter. The pressure sensor with precision ±25 [mbara] read the output pressure of the converter. The procedure was performed in the raising and in the decreasing direction. The monitored values were recorded 15 seconds after the change of the pressure set-point. The resulting conversion functions are depicted in Figure 53, Figure 55 and Figure 55.

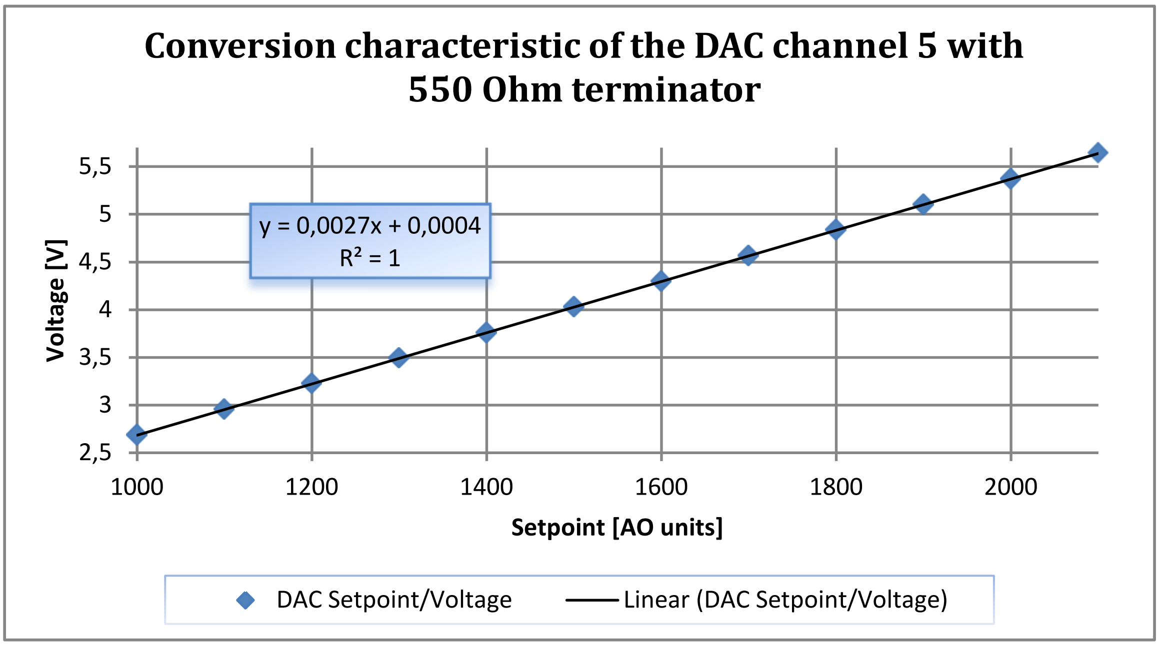

Figure 53 – ELMB DAC Channel 5 conversion characteristic

The fit function - Equation [7.4-3] - was later used for the calculations of the set-point for the ELMB DAC during the back-pressure regulation tests.

Fit function

$$y = 586.11x + 350.79 \qquad [7.4\text{-}3]$$

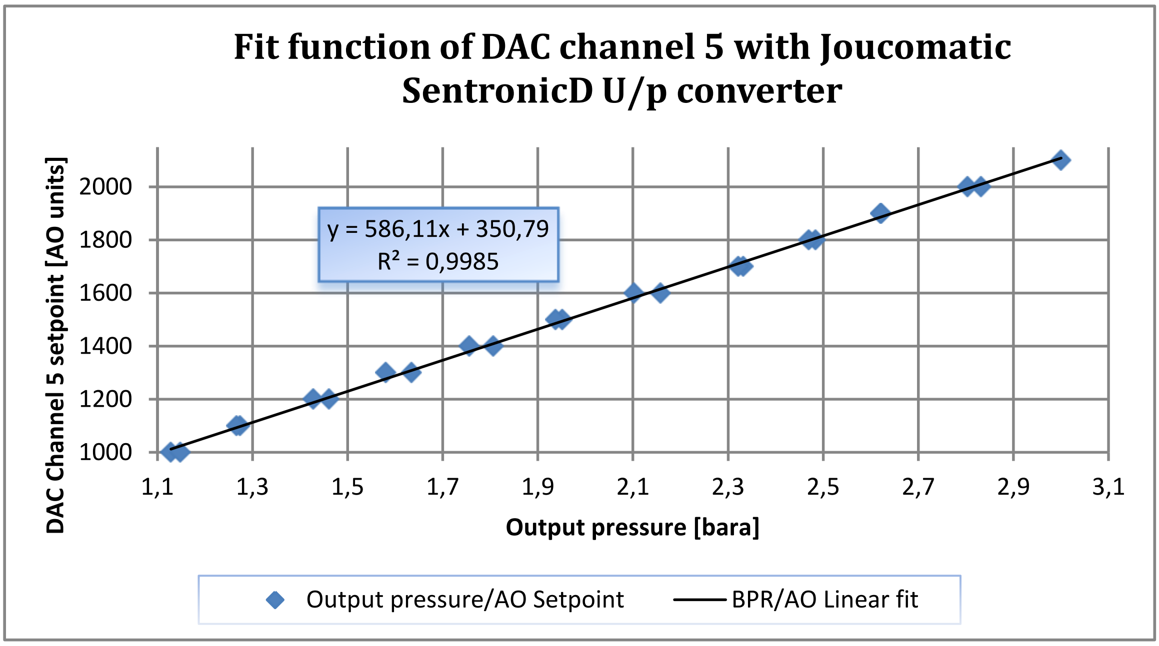

Figure 54 - SUPC Fit function p/AO

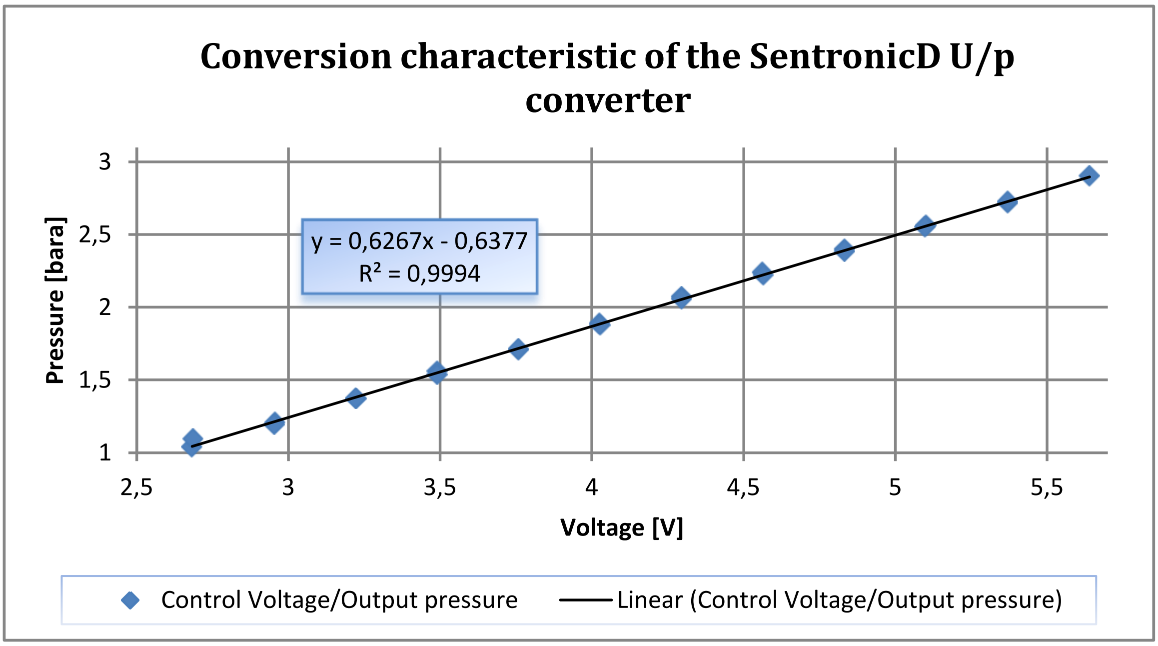

Figure 55 – SUPC Conversion characteristic U/p

7.4.5. Emerson Little-Scotty valve with Belimo electric actuator

Little-Scotty 24000 control valve is a restriction element intended for the pressure, flow or temperature regulation. The valve is from the category of the low cost solutions for the pressure regulation. The parameters of the valve retrieved from its manufacturer are listed in Table 25.

The Belimo electric actuator is a linear motor compatible with the Little-Scotty control valve. The motor is housed in the plastic cover that serves as a protection against the surrounding environment. The actuator is controlled by current signal between the 4 and 20 [mA] and it is supplied by the 24 [V] AC. The received set-point is indicated by the feedback voltage signal in range from 0 to 10 [V] DC. The actuator is in case of power failure automatically brought to position where the connected valve is closed.

Figure 56 – LSBA Overview

Table 25 – Little Scotty characteristics

Flow direction	Characteristics	End connectors	Material	Seat ring	Kv
Flow to open	Linear	½" NPT	Cast bronze	Nitronic 60	0.02

The Little-Scotty control valve and Belimo actuator (LSBA) are supplied by the Emerson Company as a compact solution for the automated regulation of the pressure. The LSBA has fail-save protection, which needs standard power supply and control signal for its function.

7.4.5.1. Conversion ratio analysis and calibration

The LSBA was calibrated on in range of output pressures from 9.8 to 11.2 [bar_a]. The range was narrower because part of the ECC work area (pressures smaller then 10 [bar_a]) is located on the margins of the valve work zone. In this area, is valve transfer function is strongly nonlinear. Therefore it was not possible to include those data in the calibration fit. The LSBA conversion function and fit function, which was used in the C4F based control system, are depictured in Figure 57 and Figure 58.

The fit function - Equation [7.4-4] - was later used for the calculations of the set-point for the ELMB DAC during the pressure regulation tests.

Fit function

$$y = 291.19x - 2164.6 \qquad [7.4\text{-}4]$$

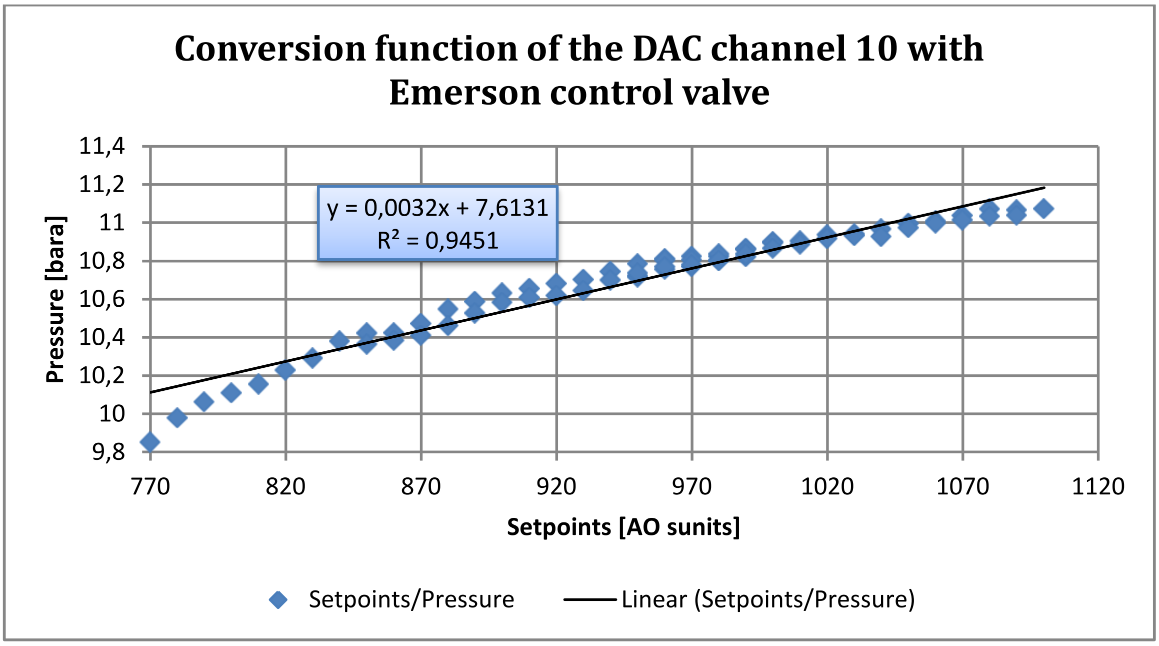

Figure 57 – LSBA conversion characteristic AO Units/p

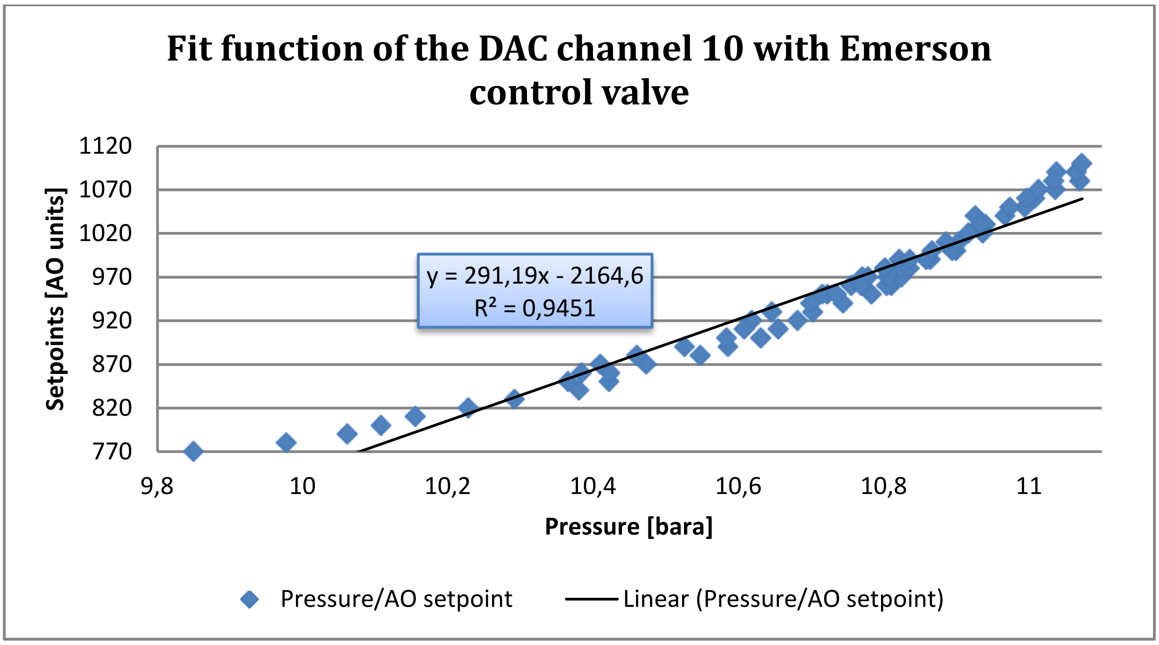

Figure 58 – LSBA fit function p/AO Units

7.4.6. Honeywell V5832 valve with MT010-N electric actuator

The Honeywell V5832 control valve (see Figure 45) is a low cost valve designed for the regulation of the water flow in the heat management systems. Its material allows usage of the valve with the coolant described in section 1.3.3. The parameters of the valve are listed in Table 26.

Figure 59 – Honeywell valve

The MT010-N electric actuator is a linear motor usable with the V5832 valve as an actuator. The motor is powered by 24 [V] AC and the control signal of the actuator is voltage between 0 and 10 [V] DC. The actuator logic can be modified by two mechanical switches housed under the plastic cover of the motor. The actuator stays in the lastly set position in case of a power failure (no fail-safe action is taken). The set composed from the Honeywell V5832 valve and MT010-N electric actuator will be further referred as HVMN.

Table 26 – Honeywell V5832 characteristics

Flow direction	Characteristics	End connectors	Material	Kv
Flow to open	Linear	½" G	Bronze	0.16

7.4.6.1. Conversion ratio analysis and calibration

The ECC work area is according to HVMN K_v placed in first 5% from the FS. The HVMN characteristic in this area is strongly nonlinear. Thus, it was not possible to measure conversion or fit characteristic. The fit function was determined from two set-points on the ECC working area edges (7.5 [bar_a] and 13 [bar_a]).

Fit function

$$y = 17.143x + 421 \quad [7.4\text{-}5]$$

7.5. Hardware connections

This section describes all physical connections between the tested devices and ECC including connection to the supporting structure, electrical wiring, and in some cases connection to the nitrogen distribution network.

7.5.1.MBIPC installation

7.5.1.1. Pressure regulation setup

MBIPC (see 7.4.3) was bolted to the back side of ECC secondary manifold (see P2 described in 5.1) using two M8 bolts screwed into the bottom of the transmitter for the pressure regulation tests. It was subsequently connected to a supply 24 [V] DC voltage, led from the ECC PSS described in section 6.2.

Control signal input of the MBIPC was connected to the channel 8 of the ELMB DAC described in chapter 6.3. All electrical interconnections were made on the M12 - six wire cable that was connected to the MBIPC input socket.

The last step of the installation was the connection of the MBIPC to the high pressure nitrogen network – port C described in section 5.4. The MBIPC output nitrogen port was connected to the TESCOM Pressure regulator (see 7.4.1). The output pressure was monitored by pressure transducer.

The simplified scheme of the MBIPC connection to the ECC is depictured in Figure 60.

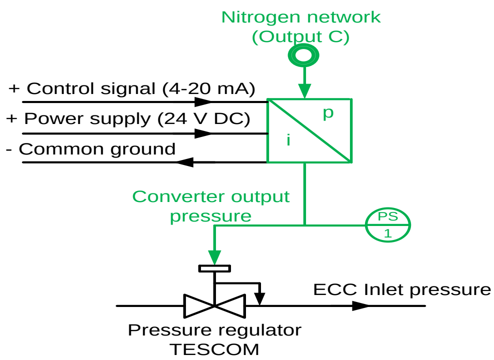

Figure 60 – MBIPC connections schematic A

7.5.1.2. Back-pressure regulation setup

MBIPC was for the back-pressure regulation tests bolted to the front side of ECC main iron manifold (see P1 described in 5.1) using two M8 bolts screwed into the bottom of the transmitter.

Control signal input of the MBIPC was connected to the channel 5 of the ELMB DAC.

MBIPC nitrogen input was connected to the medium pressure nitrogen network – port A described in section 5.4. The MBIPC nitrogen output was then connected to the TESCOM back-pressure regulator (see 7.4.2). The rest of the connections was the same as the pressure regulation connections.

The simplified scheme of the MBIPC connection to the ECC is depictured in Figure 61.

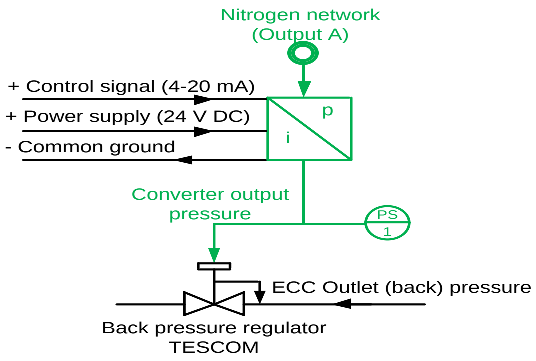

Figure 61 - MBIPC connections schematic B

7.5.2.SUPC installation

SUPC (see 7.4.4) was bolted to the main iron ECC manifold in which was firstly drilled new hole, because the distance between mounts on the SUPC and on the MBIPC, which was mounted there before, does not match.

MBIPC was then connected through the 5-wire M12 connector to 24 [V] DC power supply and to the 0-10 [V] DC control signal (DAC channel 8 terminated by 550 [Ohm] resistor). The output voltage of the DAC channel was in feed-back connected to the *ELMB_14*, analogue input 4.

The medium pressure nitrogen was connected to SUPC port 1 from the ECC nitrogen network – port A (see Figure 35). The simplified scheme of the SUPC connected to the ECC on the Figure 62.

7.5.3.TPR installation

TPR (see 7.4.1) was connected through SWAGELOK 6 [mm] fittings to the ECC cooling liquid line. The regulator was in addition screwed with one bolt to the ECC secondary manifold at sector P2 depictured in Figure 32. The TPR dome nitrogen input was later connected to the output of MBIPC.

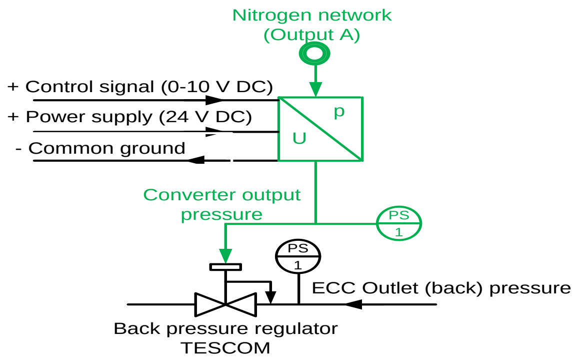

Figure 62 – SUPC Connection schematic

7.5.4.TBPR installation

TBPR (see 7.4.2) was connected through SWAGELOK 8 [mm] fittings to the ECC cooling vapor line. The regulator was screwed with one bolt to the ECC main manifold at sector P1 depictured in Figure 32. The TPR dome nitrogen input was later connected to the output of MBIPC and later to the SUPC output.

7.5.5.LSBA installation

LSBA (see 7.4.5) was connected to the ECC cooling liquid line through ½"/6 [mm] SWAGELOK fittings. The threads were sealed with Teflon tape to prevent leakage.

The whole LSBA was placed on top of P2 secondary manifold described in section 5.1.The LSBA actuator was connected to a supply 24 [V] AC voltage, led from the ECC PSB described in chapter 6.2.1. Control signal input of the LSBA was connected directly to the channel 10 of the ELMB DAC through twisted pair wire. The control signal and the power supply were using the same grounding wire.

7.5.6.HVMN installation

HVMN (see 7.4.6) was connected to the ECC cooling liquid line through ½"/6 [mm] SWAGELOK fittings. The threads were sealed with Teflon tape to prevent leakage. The HVMN actuator was connected to a supply 24 [V] AC voltage, led from the ECC PSB described in chapter 6.2.1. Control signal input of the HVMN was connected to the channel 4 of the ELMB DAC over the 550 [Ohm] terminating resistor. The control signal and the power supply were using the same grounding wire.

7.6. Connection to the C4 control system

This section describes how the tested devices/setups controlled by an electrical signal were registered in the C4F based control system (ECC PVSS system described in section 6.4). The devices were not used simultaneously and thus some of their settings overlap. Two different settings were used for the devices used for the both – pressure and back-pressure regulation tests.

7.6.1. MBIPC settings in C4F

The MBIPC was registered in the ECC control system as a C4 device C4FC. The initial settings of the converter for the pressure regulation and for the back-pressure regulation are enlisted in Table 27. The parameters were altered during the device testing.

Table 27 – MBIPC parameters in C4F

Parameter	Back-pressure regulation parameters	Pressure regulation parameters
Converter Name	C4Converter:Bellofram_BPR	C4Converter:Bellofram_PR
Active	TRUE	TRUE
Set-point Off	1.265 [bar_a]	9 [bar_a]
Set-point Stand-by	1.569 [bar_a]	10 [bar_a]
Set-point On	2.06 [bar_a]	11 [bar_a]
AO Output channel	ELMB_48, AO Channel 5	ELMB_48, AO Channel 8
Feed-back channel	ELMB_14, AI Channel 3	ELMB_14, AI Channel 4
Regulation	TRUE	TRUE
Minimum step	5 AO Units	5 AO Units
Over-step	FALSE	FALSE
Minimum	0.9 [bar_a]	7.8 [bar_a]
Maximum	4 [bar_a]	13 [bar_a]

7.6.2.SUPC settings in C4F

The SUPC was registered in the ECC control system as a C4 device C4FC. The initial settings of the converter are listed in Table 28. During the later tests were some of the parameters altered.

Table 28 - SUPC parameters in C4F

Parameter	Back-pressure regulation parameters
Converter Name	C4Converter:Joumatic_BPR
Active	TRUE
Set-point Off	1.2 [bar_a]
Set-point Stand-by	1.5 [bar_a]
Set-point On	2.0 [bar_a]
AO Output channel	ELMB_48, AO Channel 5
Feed-back channel	ELMB_14, AI Channel 3
Regulation	TRUE
Minimum step	3 AO Units
Over-step	TRUE
Minimum	0.9 [bar_a]
Maximum	4 [bar_a]

7.6.3.LSBA settings in C4F

The LSBA was registered in the ECC control system as a C4FR. The settings of the regulator are listed in Table 29. The P, S and D parameters of the regulator raised from the measurements of the valve characteristics connected to the ECC system (The PID regulator design – its parameters – was calculated using Ziegler-Nichols procedure, see (24)).

Table 29 - LSBA parameters in C4F

Parameter	Back-pressure regulation parameters
Regulator Name	C4Regulator:Emerson_PR
Active	TRUE
Set-point Off	10 [bar_a]
Set-point Stand-by	10.5 [bar_a]
Set-point On	11 [bar_a]
AO Output channel	ELMB_48, AO Channel 10
Feed-back channel	ELMB_14, AI Channel 6
P	0.8
S	0.22
D	0.35
T	1
Minimum step	25 AO Units
Over-step	TRUE
Minimum	9.7[bar_a]
Maximum	13 [bar_a]

7.6.4.HVMN settings in C4F

The HVMN was registered in the ECC control system as a C4 device C4FC. The initial settings of the converter are listed in Table 30. During the later tests were some of the parameters altered.

Table 30 - HVMN parameters in C4F

Parameter	Back-pressure regulation parameters
Converter Name	C4Converter: Honeywell_PR
Active	TRUE
Set-point Off	11 [bar_a]
Set-point Stand-by	10.5 [bar_a]
Set-point On	10.8 [bar_a]
AO Output channel	ELMB_48, AO Channel 4
Feed-back channel	ELMB_14, AI Channel 7
Regulation	TRUE
Minimum step	20 AO Units
Over-step	TRUE
Minimum	10 [bar_a]
Maximum	13 [bar_a]

7.7. Measured regulation characteristics

This section describes the results of the pressure regulation probation. The two tests were performed with all examined setups – the stability test (ability to maintain pressure in given bend) and the reaction on step in the requested set-point.

7.7.1.Pressure regulation - tests

The tasks for setups tested in the pressure regulation were:

- To maintain pressure on given level (with maximal dead-band 110 [mbar] – 1% FS) for 5 minutes.
- To regulate pressure according any requested set-point picked in range from 8 to 11 [bar_a].

7.7.1.1. TESCOM Dome loaded pressure regulator with Marsh Bellofram 3220 I/p converter

The TPR with MBIPC was first setup tested to control the pressure. The MBIPC was registered in the C4 control system as a C4FC with active regulation, see 7.6.

The stability test of the output pressure was performed with given setup. The monitored pressure did not leave 60 [mbar] wide dead–band in five minutes, thus the setup passed the test.

The steps of the set-point were performed in the expected work area (9 – 11 [bar_a]) with active proportional regulation and dead-band ±16 [mbar]. The overshoot and stabilization time were analyzed on the transient characteristics. The summarization of the results is listed in Table 31 and the examples of the characteristics are depictured in Figure 63 and Figure 64.

Table 31 – TPR with MBIPC Tests summary

Initial set-point [bara]	Terminal set-point [bara]	Stabilization time [s]	Overshoot [mbar]	Overshoot [%]
9	10	86	29	2.9
9	11	97	37	3.36
10	9	160	22	2.44
10	11	82	31	2.82
11	10	151	26	2.6
11	9	172	19	2.11

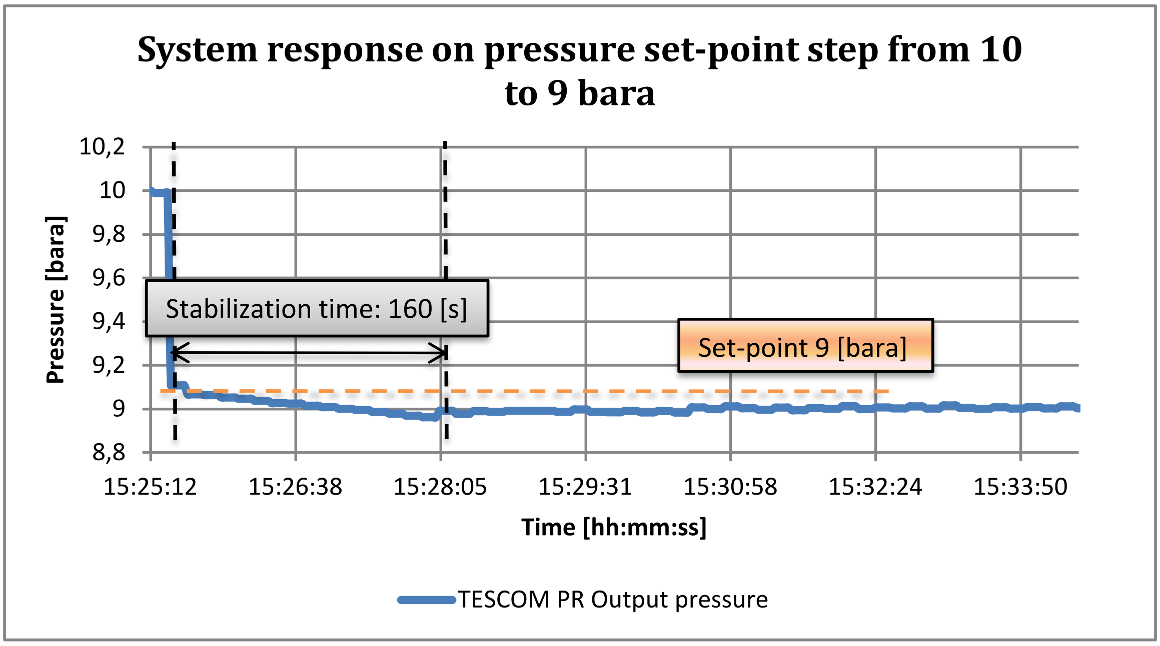

Figure 64 - TESCOM PR with Marsh Bellofram converter, step from 10 to 9 bara

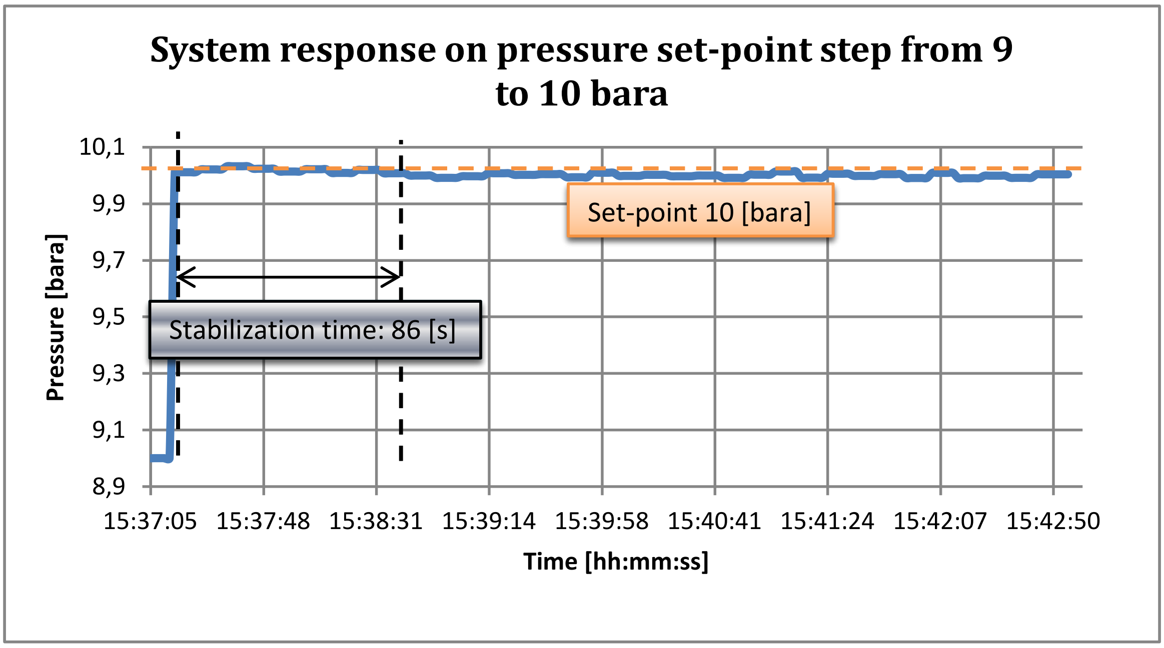

Figure 63- TESCOM PR with Marsh Bellofram converter, step from 9 to 10 bara

7.7.1.2. Emerson Little-Scotty control valve with Belimo actuator

The LSBA was second setup tested to control the pressure. The LSBA was registered in the C4 control system as a C4FR with parameters enlisted in Table 29 - LSBA parameters in C4F.

The stability test of the output pressure was performed with given setup. The monitored pressure did not leave 60 [mbar] wide dead–band in five minutes, thus the setup passed the test.

Table 32 – LSBA Tests summary

Initial set-point [bara]	Terminal set-point [bara]	Stabilization time [s]	Overshoot [mbar]	Overshoot [%]
9	10	Immeasurable	Immeasurable	Immeasurable
9	11	Immeasurable	Immeasurable	Immeasurable
10.34	10.542	8	18	1.7
10.34	11.22	10	16	1.6
11.22	10.542	11	22	2
11.22	10.34	12	21	2

The steps of the set-point were performed in the work area from 9 to 11 [bar_a] with PID regulation and dead-band ±35 [mbar]. The pressures below 10 [bar_a] were not reachable, because of the nonlinearity of the control valve conversion characteristics in that area, see Figure 57 – LSBA conversion characteristic AO Units/p. The overshoot and stabilization time were analyzed on the transient characteristics.

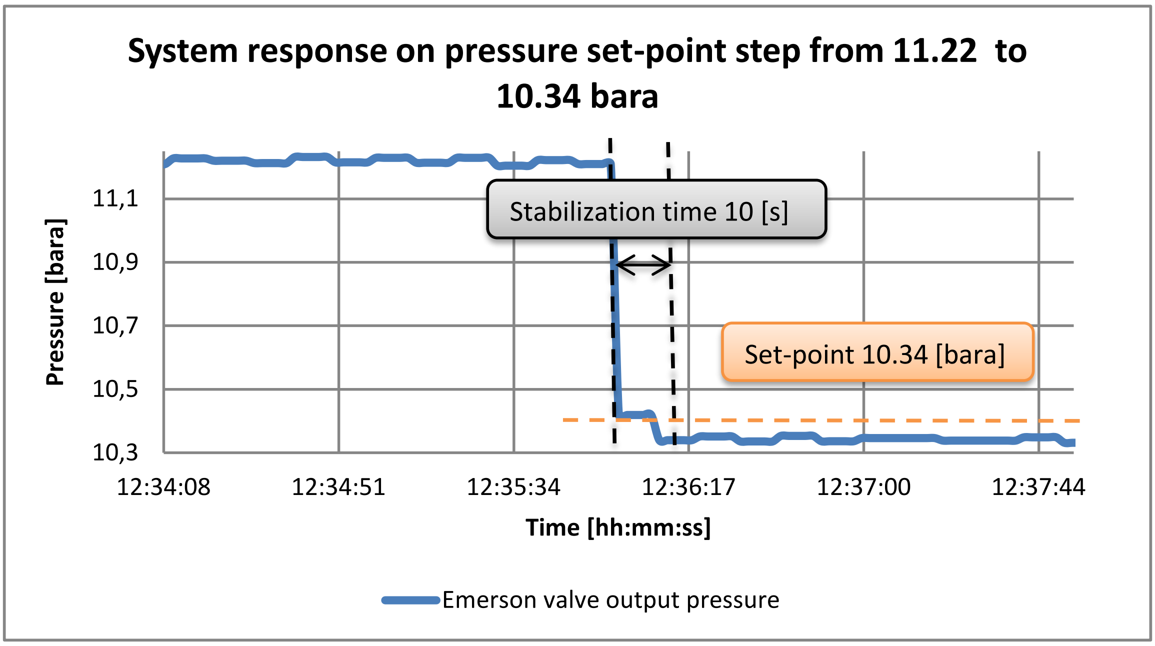

Figure 65 – LSBA Setup, step from 11.22 to 10.34 bara

The summarization of the results is listed in Table 32 and the examples of the characteristics are depictured in Figure 65 and Figure 66.

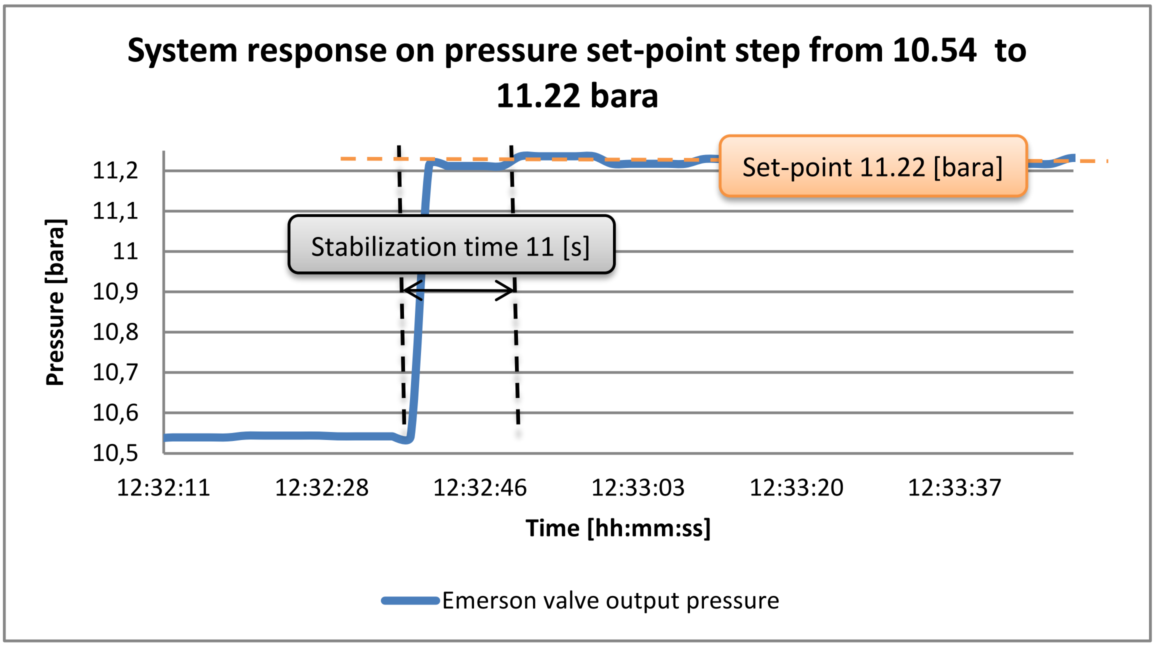

Figure 66– LSBA Setup, step from 10.54 to 11.22 bara

7.7.1.3. Honeywell V5832 valve with MT010-N actuator

The HVMN was last setup tested for pressure regulation. The HVMN was registered in the C4 control system as a C4FC with active regulation, see 7.6. It was not tested with a PID regulation algorithm, because it was not able to measure reliable dynamic characteristics necessary for the regulation identification.

The stability test of the output pressure was performed with given setup. The monitored pressure did not leave 60 [mbar] wide dead–band in five minutes, thus the setup passed the test.

The steps of the set-point were performed in the expected work area (9 – 11 [bar_a]) with active proportional regulation and dead-band ±60 [mbar]. The nonlinearity of the control valve caused that the set-points from 8.5 to 10.5 [bar_a] were not reachable. The system reaction (oscillations) on such set-point is depicted in Figure 67. The response on the set-points on the edges of the work area was fast (10 [s]) and reliable, see Figure 68.

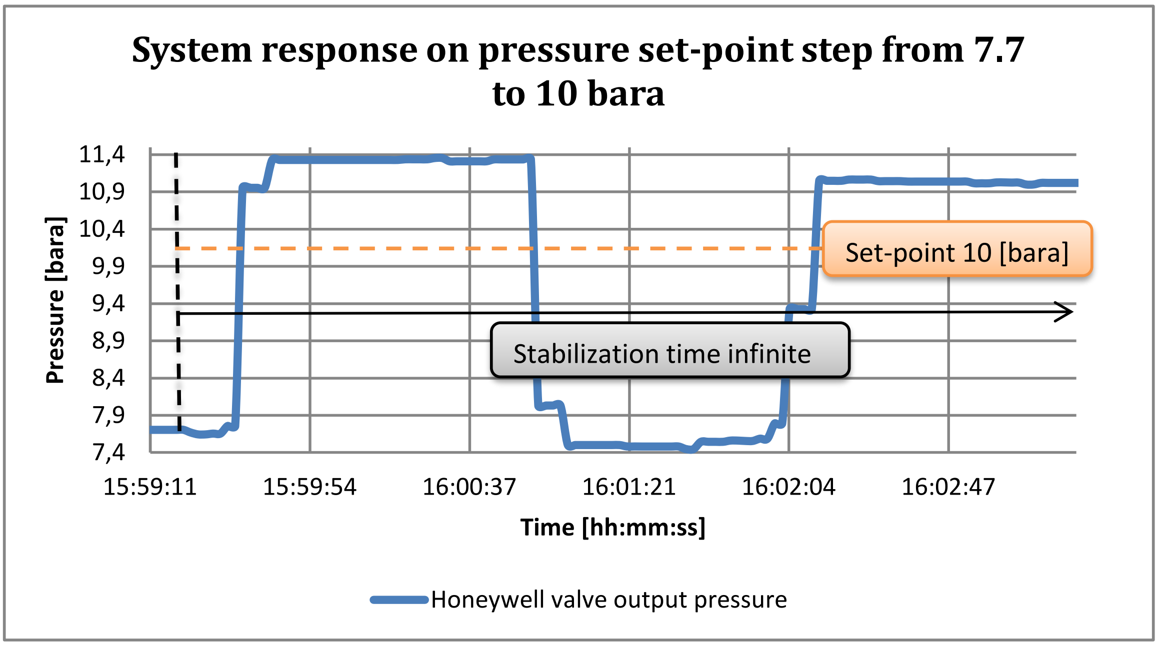

Figure 67 - HVMN Setup, step from 7.7 to 10 bara

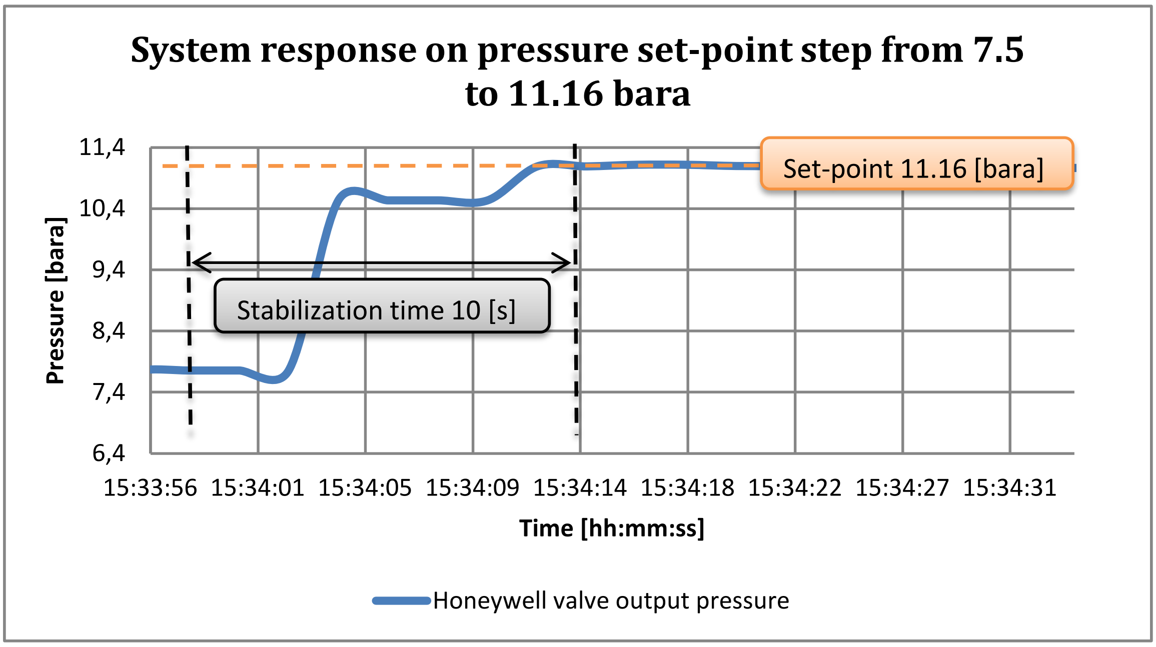

Figure 68 - HVMN Setup, step from 7.5 to 11.16 bara

7.7.2.Back-pressure regulation - tests

The goals for setups tested in the pressure regulation were:

- To maintain pressure on given level (with maximal dead-band 20 [mbar] – 1% FS) for 5 minutes.
- To regulate back-pressure according any requested set-point picked in range from 1 to 2 [bar_a].

7.7.2.1. TESCOM Dome loaded back-pressure regulator with Marsh Bellofram converter

The output stability of the setup composed from TBPR and MBIPC was tested in two stages. In both stages, the ECC back-pressure set-point was set to 1.5 [bar_a] and then was monitored the TBPR dome pressure and the ECC back pressure.

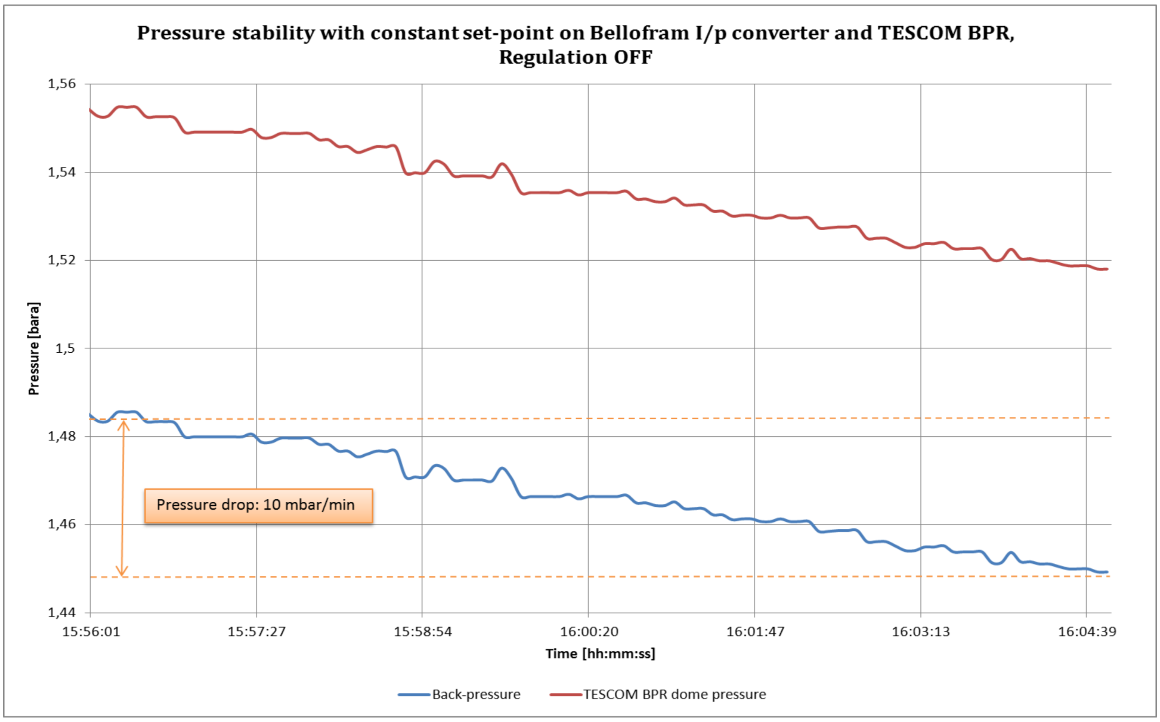

Figure 69 – Pressure stability test – TESCOM pressure regulator with Marsh Bellofram converter, regulation OFF

In the first stage, the MBIPC was registered in the C4 control system as a C4FC with inactive regulation, see 7.6. The result of the first stage test is depicted in Figure 69. During the first stage, the setup did not pass the stability test, because it showed average negative rate 10 [mbar/min] and was not able to maintain requested set-point.

In the second stage, the MBIPC was registered in the C4 control system as a C4FC with active regulation proportional regulation. The dead zone was set to ±10 [mbar]. Narrower band could not be used because of the MBIPC distinctive ability and feed-back pressure sensor output signal stability. Over 95% of measured values were in the dead band and the maximum error towards the set-point was 12 [mbar] during the second stage, see Figure 70. The setting from the first stage was abandoned because of the under-precise outcomes and unstable pressure output.

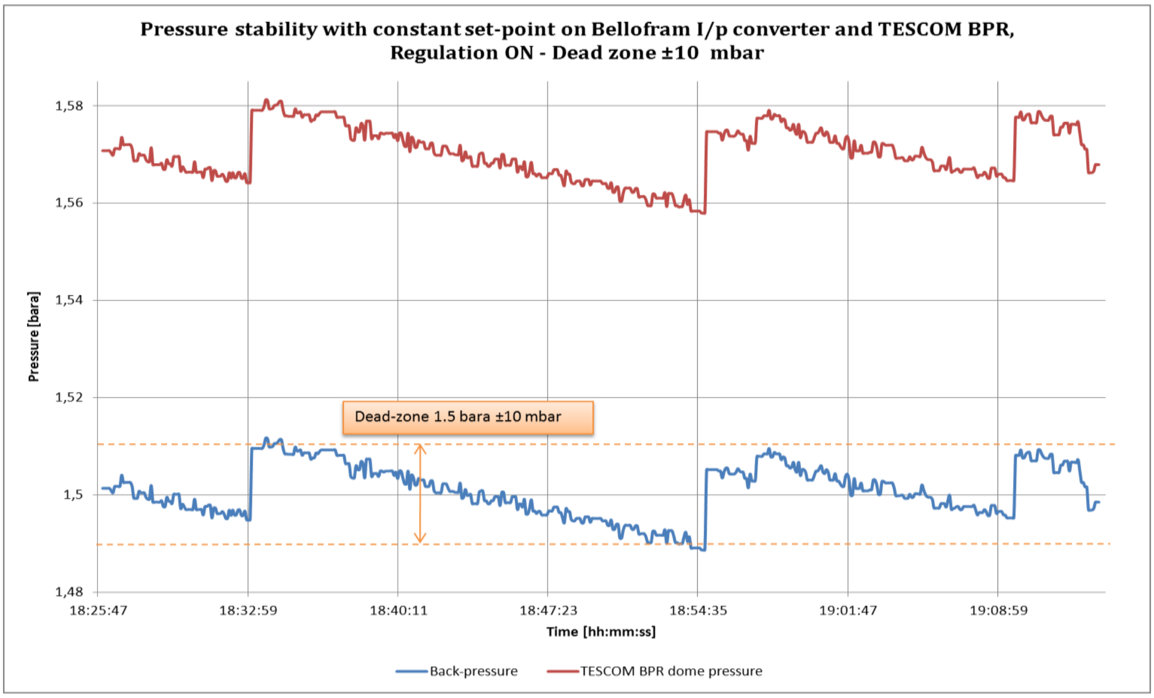

Figure 70 – Pressure stability test – TESCOM pressure regulator with Marsh Bellofram converter, regulation ON

The steps of the set-point were performed in the expected work area (1 – 2 [Bar_a]) with a proportional regulation and dead-band ±16 [mbar]. The overshoot and stabilization time were analyzed on the transient characteristics. The output was considered stable when it reached the dead band and stayed in it for at least 30 seconds. The steps were made from lower to higher pressures and vice versa. The results of the test are listed in Table 33 and examples of transient characteristics are on Figure 71 and Figure 72. The stabilization time is almost 40% longer in jumping from higher to lower values then vice versa due to the instability of the output pressure. The applied regulation technique helped to reduce the back pressure error more then 10 times comparing to the error expected due to a conversion characteristics and parameters of the devices used in the test.

Table 33 – TESCOM Back-pressure regulator with Marsh Bellofram converter summary

Initial set-point [bara]	Terminal set-point [bara]	Stabilization time [s]	Overshoot [mbar]	Overshoot [%]
1.265	2.06	110	37	1.79
1.567	2.06	105	40	2.55
2.06	1.265	158	37	2.92
2.06	1.567	165	40	2.55

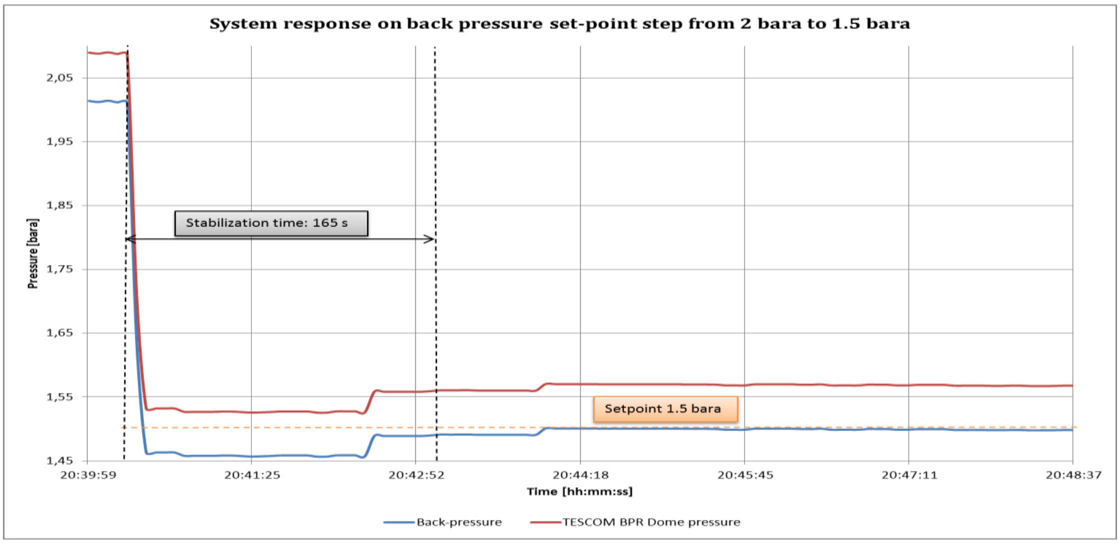

Figure 72 - TESCOM BPR with Marsh Bellofram converter, step from 2 to 1.5 bara

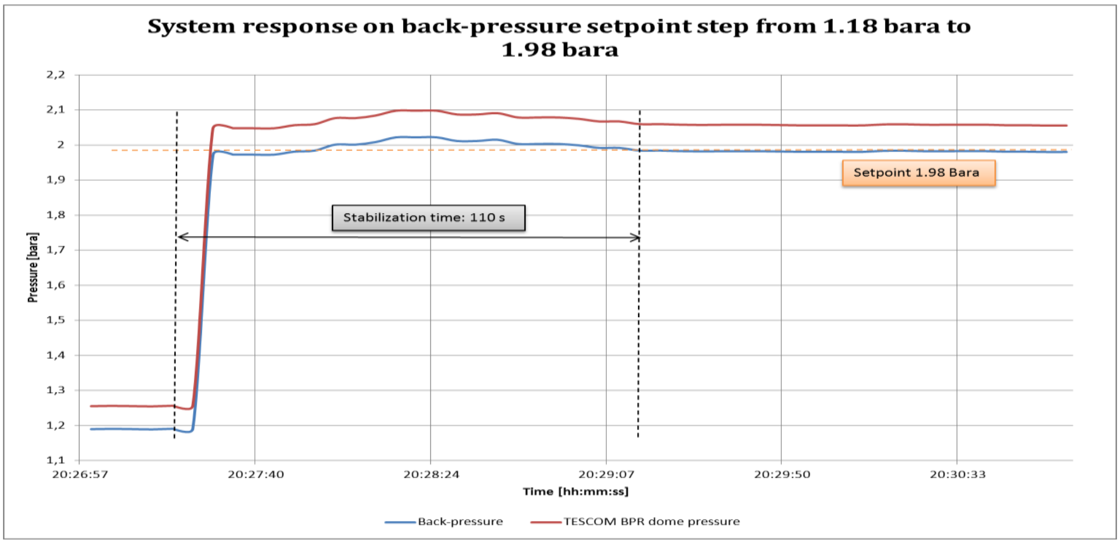

Figure 71 - TESCOM BPR with Marsh Bellofram converter, step from 1.18 to 1.98 bara

7.7.2.2. TESCOM Dome loaded back-pressure regulator with Joumatic Sentronic^{D} converter

The TPR with SUPC was the second setup tested to control the back-pressure. The SUPC was registered in the C4 control system as a C4FC with active regulation, see 7.6.

The output stability of the setup was tested and no deviations from the requested value were found. The internal Joumatic controller that is compensating most of the errors influencing the dome pressure causes such behavior. The selected dead-band for the pressure regulation tests (testing of the reaction on step) was ±16 [mbar]. Examples of the step responses are depictured in Figure 73 and in Figure 74. The results are summarized in Table 34.

Table 34 - TESCOM BPR with Joumatic converter pressure regulation test summary

Initial set-point [bara]	Terminal set-point [bara]	Stabilization time [s]	Overshoot [mbar]	Overshoot [%]
1.045	2.01	131	100	5
1.5	1.045	100	52	5.2
1.5	2.01	103	49	2.5
2.01	1.045	135	86	8.6

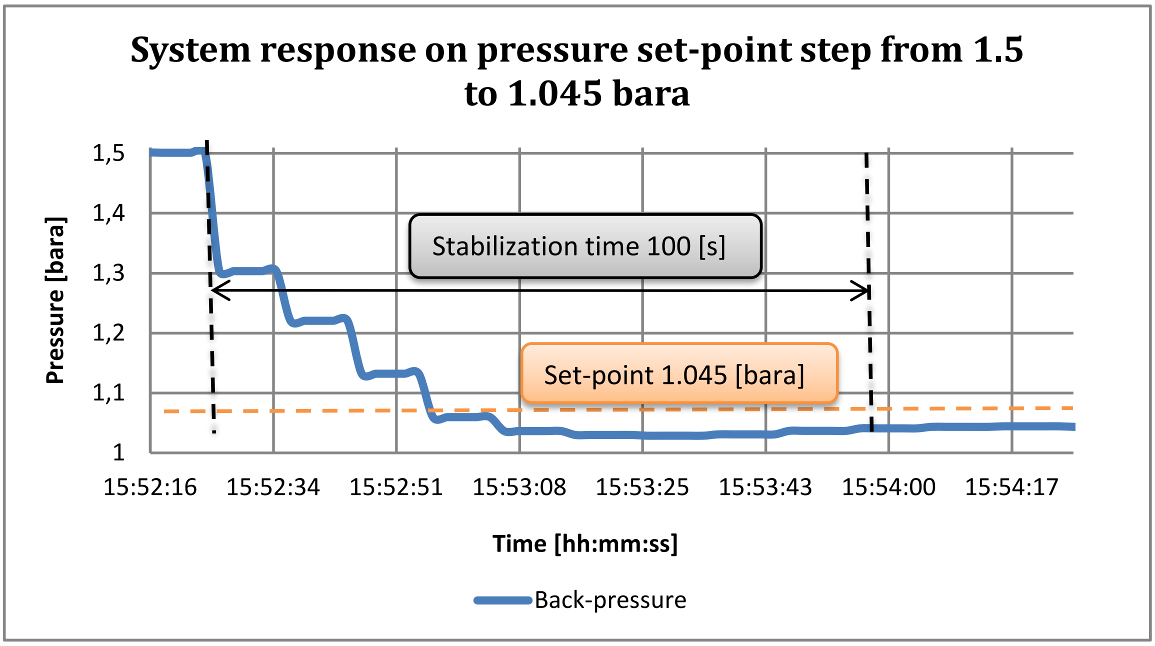

Figure 73 - TESCOM BPR with SUPC, step from 1.5 to 1.045 bara

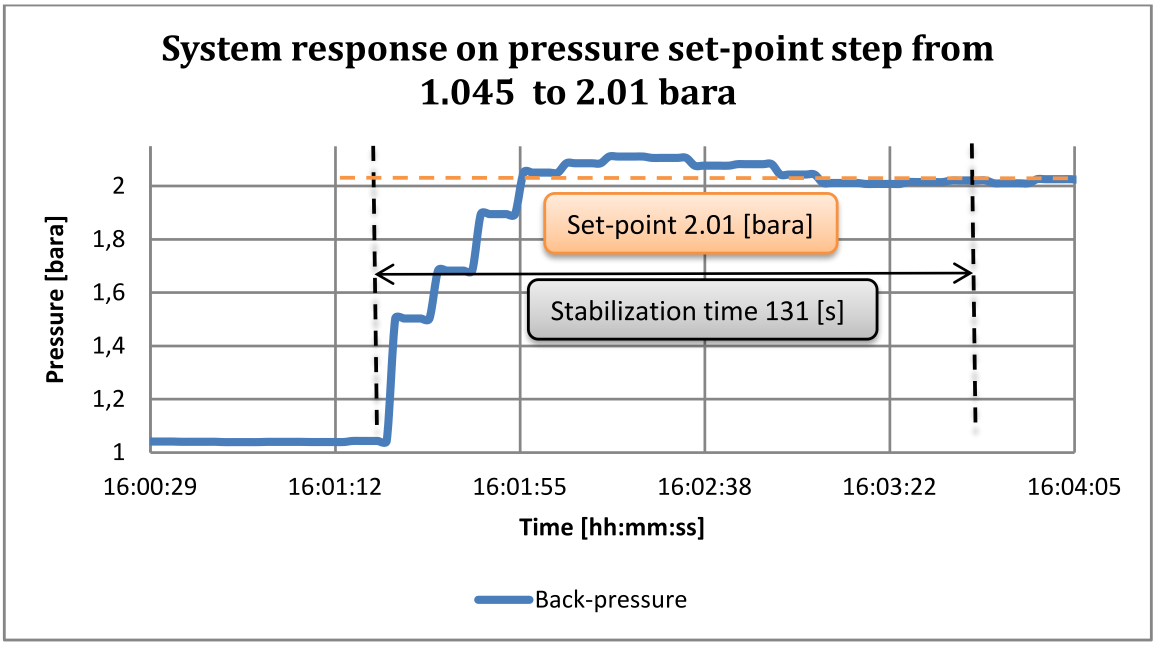

Figure 74 - TESCOM BPR with SUPC, step from 1.045 to 2.01 bara

7.7.3.Test results analysis

Three different setups were used for the pressure regulation of the liquid coolant in the ECC cooling loop. The only setup capable of regulating the pressure in FS was the TPR with MBIPC, which was therefore selected as the most suitable for the regulation. The setups with the control valves (HVMN and LSBA) have much faster response, but they were not able to regulate the pressure in required scale. This was caused by their nonlinear characteristics in the requested working range.

Two setups based on the TBPR and control signal/pressure converter (SUPC and MBIPC) were used for the regulation of the back-pressure of the vapor coolant in the ECC cooling loop. Both setups are usable to regulate the back-pressure in the requested working area. The setup with the MBIPC was selected as the best option, because it offers the best ratio between regulation characteristic and price (the price of the SUPC is almost three times higher than the price of the MBIPC).

8. Conclusion

The main objectives of this diploma introduced in chapter 1.4 were successfully completed. Each section in this chapter is dedicated to one of the thesis goals.

8.1. Automated pressure regulation

Three low cost solutions for automated pressure regulation were tested. First of them was a setup consisting of a Small Honeywell linear valve assembled with electromechanical actuator. The second one was Emerson control valve with electromechanical Belimo actuator. The last one was a setup composed from TESCOM dome loaded pressure regulator with Marsh Bellofram I/p converter. From three proposed solution, the third one appeared to be the most convenient for the further utilization. Detailed setup description is and performance tests are described in chapter 7. The test summary is presented in Table 35 - Pressure regulation summary.

Table 35 - Pressure regulation summary

Setup	Setup price	Stability test	Regulation
TPR with MBIPC	975 CHF	OK, dead-band 16 [mbara]	OK, in full scale
LSBA	725 CHF	OK, dead-band 60 [mbara]	OK, limited work area
HVMN	150 CHF	OK, dead-band 60 [mbara]	FAILED

8.2. Automated back-pressure regulation

Two low cost solutions for automated back pressure regulation were tested. First of them was a setup consisting of TESCOM back-pressure regulator and Marsh-Bellofram I/p converter. The other one was TESCOM back-pressure regulator and Joumatic U/p converter. From two proposed solution, the first one appeared to be more convenient for further usage offering the best ration between regulation quality and cost. Detail setups description is also mentioned in sections 7 and performance tests results are summarized in Table 36.

Table 36 – Back-pressure regulation summary

Setup	Setup price	Stability test	Regulation
TBPR with MBIPC	975 CHF	OK, dead-band 16 [mbara]	OK, in full scale
TBPR with SUPC	1588 CHF	OK, dead-band 6 [mbara]	OK, in full scale

8.3. Performance tests

The TOTEM cooling circuit described in section 1.3 was analyzed and several options for the pressure regulation were selected due to its characteristics in section 3.5. Those options were later tested together with the designed control system components on the experimental cooling circuit described in chapter 5.Real tests were performed as it is mentioned in chapter 7. From the test evaluation (see section 7.7.3), it is clear that proposed solutions are convenient for experimental plant automation.

8.4. Control system software implementation

The chapter 3 discusses usable building blocks of the control systems and recommends the most suitable solutions. The suggested control system should use ETM PVSS II installed on the HP Elite Book 2530p as a SCADA system. The modular C4 control framework was prepared for the implementation of the control system of the cooling plant – (see 4).

The low-level control can be then realized by a set of two ELMB units and one ELMB DAC. The total price for such solution would be 1050 CHF excluding the price of the PVSS software.

8.5. Total costs of suitable upgrade solution

The total costs of one cooling loop automation are listed in sections 8.1 and 8.2. The total costs on the automation of the cooling plant, which is described in 1.3, are calculated as the sum of the cost of automation of four loops, low-level controllers' price and the cost of SCADA system modification. The calculation overview is given in Table 37.

Table 37 – Total costs summary

Component	Standard list price in year 2009
Pressure regulation (recommended option)	4*975 CHF
Back-pressure regulation (recommended option)	4*975 CHF
Low-level ELMB modules	1050 CHF
High level SCADA system	1834 CHF excluding the PVSS price
Total costs	**10684 CH**

8.6. Further step proposition

This diploma offers an overview of the recommended solutions for the automation of the cooling plant. The solutions, once selected, were intensely tested. However, the performed tests were not aimed to the long-term behavior of the components and to the usage of the advanced regulation techniques. Therefore, in the next step the test that would provide such information should be carried out.

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Table of used symbols and abbreviations

Abbreviation	Clarification
AC	Alternating Current
ADC	Analog to Digital Converter
AI	Analog Input
AI	Analog Input
ALICE	A Large Ion Collider Experiment
AO	Analog Output
ATLAS	A Toroidal LHC ApparatuS
BPR	Back-Pressure Regulator
C4F	C4 Framework
C4FC	C4F Converter
C4Fcp	C4F control panel
C4Fmp	C4F main panel
C4FR	C4F Regulator
C4FS	C4F Switch
CAN	Controller Area Network
CAN	Controller Area Network
CERN	The European Organization for Nuclear Research
CHF	Swiss franc
CiA	CAN in Automation

CS	Control System
DAC	Digital to Analog Converter
DAQ	Data AcQuisition system
DB	Data-base
DC	Direct Current
DCS	Distributed Control System
DI	Digital Input
DIFF	DIfference between the set-point and signal From the reFerence sensor
DIFFP	DIFF multiplied by Proportional compound of the P regulator
DIL	Dual in-line package
DIP	Dual In-line Package
DO	Digital Output
EAOSP	Set-point of the ELMB analog output channel
ECC	Experimental Cooling Circuit
EEPROM	Electronically Erasable Programmable Read-Only Memory
ELMB	Embedded Local Monitor 128 with motherBoard
ELMB DAC	ELMB Digital to Analog Converter
FIFO	First In First Out
FM	Flow Meter
FS	Full Scale
FSM	Finite State Machine

GUI	Graphical User Interface
HDD	Hard Disk Drive
HEX	Heat EXchanger
HLC	High Level Control
HMI	Human Machine Interface
HVMN	Honeywell valve with MT010-N actuator
I/O	Input/Output
ICS	Industrial Control System
ID	ELMB IDentification address
IP	Internet Protocol
ISO	International Organization for Standardization
LAN	Local Area Network
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty
LLC	Low-Level Controller
LSBA	Little-Scotty valve with Belimo actuator
MBIPC	Marsh-Bellofram 3210 current to pressure converter
NIC-HEF	Nationaal Instituut Voor Subatomaire Fysica
NTC	Negative Temperature Coefficient
OLE	Object Linking and Embedding
OM	Operational Memory

OPC	OLE for Process Control
OSI	Open System Interconnection
PID	Proportional-Integral-Derivative
PLC	Programmable Logic Controller
PR	Pressure Regulator
PS	Pressure Sensor
PSB	Power Supply Box
PSS	Power Supply System
PVSS	Process Visualization and Control System
RP	Roman Pot
RTDB	Real Time Data-base
SCADA	Supervisory Control And Data Acquisition
SUPC	JOUMATIC Sentronic^{D} voltage to pressure converter
TBPR	TESCOM Dome-loaded Back-Pressure Regulator
TCP	Transmission Control Protocol
TOTEM	TOTal Elastic and diffractive cross section Measurement
TOTEM-DCS	TOTEM Detector Control System
TPR	TESCOM Dome-loaded Pressure Regulator
TS	Temperature Sensor

List of figures

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APPENDIX

A. Inserted CD content

Text	Text of this diploma thesis in *docx* and *pdf* format
C4	Files of the C4 framework
TOTEM_Prevessin_HLC	Control project of the ECC cooling circuit
OPC	OPC configuration file of the ECC cooling circuit

B. H8 Signal data-base

ELMB	AI Channel	Description	FATAL LOW	WARNING LOW	/ARNING HIG	FATAL HIGH
61	47	Press - After BPR	0,2	0,3	0,8	1,1
61	46	Press - Before BPR	0,8	0,9	2,1	2,3
61	45	Huba-Condenser	9	10	12	13
61	35	CORI mass-flow	1,5	2	5	5,5
61	16	NTC Condenser	25	28	40	45
61	17	NTC bef CORI	12	15	25	30
61	33	High P Keller 2nd	9	10	12	13
61	32	High P Keller 1st	9	10	12	13
61	58	NTC Vapor Prot	-10	-15	-32	-35
61	42	Vacuum Keller	-0,01	-0,005	0,01	0,02
61	28	NTC HEX water out	10	12	25	30
62	34	High P liquid In	8	9	11	13
62	38	Swiss-flow RP Prot	1,1	1,3	2,1	2,3
62	36	High P liquid RP	9	10	12	13
62	33	Vapor P Dummy Line	0,8	0,9	2,1	2,3
62	18	NTC Vapor Dummy	-10	-15	-32	-35
62	37	Vapor P RP	0,8	0,9	2.1	2.1
62	48	T P8 Hyb Pt100	-10	-15	-30	-35
62	9	T2 Rack Pt1000	-10	-15	-30	-35
62	16	Horiz AFT EVAP	-10	-15	-32	-35
62	8	T1 Rack Pt1000	-10	-15	-32	-35
62	50	T P3 Hyb Pt100	-10	-15	-32	-35
62	10	T3 Rack Pt1000	-10	-15	-32	-35
62	11	T4 Rack Pt1000	-10	-15	-32	-35
63	0	Vacuum 1 RP Final	-0,01	0	15	20
63	1	Vacuum 2 RP Final	-0,01	0	15	20