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CONTROL SOLUTIONS WITH HARDWARE-IN-THE-LOOP AND SCADA SYSTEM FOR DRUM-BOILER TURBINE PROCESS IN THERMAL POWER PLANTS

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Conducător ştiinţific: prof.univ.dr.ing. Gheorghe-Daniel ANDREESCU
Referenţi ştiinţifici: prof.univ.dr.ing. Gheorghe LAZEA
prof.univ.dr.ing. Dan POPESCU
prof.univ.dr.ing. Ioan SILEA

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PREFACE

The present work is dedicated to designing, testing and implementing several suitable control strategies for natural circulation boiler processes with associated turbine in thermal power plants. The implementation makes use of modern and fundamental features like Hardware-in-the-loop and Real-Time having as final result an industrial thermal power plant platform for control strategy testing and also operator training.

Outline of the thesis

The thesis is organized in 6 chapters and approaches 4 major issues in thermal power plants:
i) Modeling of boiler-turbine units, fitting the model to a real thermal power plant;
ii) Design, implement and test control solutions (3 feedback cascade control & multivariable decoupled gain-scheduled control) for thermal power plants;
iii) Provide 2 test platforms for control solutions using real-time with hardware-in-the-loop and industrial technology from Siemens and National Instruments;
iv) Provide the necessary know-how for integrating the control solutions in the existing SCADA system and give an important insight in wireless control on process actuators.

The 1st Chapter shows some projections and statistics on main fuels used for power generation from a global to a European and national level. Also starting points about thermal power plants and modern test systems are introduced. State-of-the-art is presented at the beginning of each chapter.

The 2nd Chapter presents the designed SCADA system for COLTERM thermal power plant south of Timisoara in terms of hardware and software, functionality and utilization, as an integration platform for automatic control strategies.

The 3rd Chapter begins by presenting a temperature control system application, under Labview environment, as an introduction to automatic control of slow dynamics processes. Following, a review is presented with pros and cons on boiler turbine models, ranging from low order models to high order, complex models. Both models were fitted for a real thermal power plant, and are integrated into applications. The issue of attenuating the shrink and swell minimum phase phenomena, by using and comparing simple PI laws with gain-scheduled 3 feedback cascade PI control structures is presented as the 1st control solution.

This 4th Chapter presents the 2nd control solution employing a centralized multivariable gain-scheduled decoupled control for a boiler-turbine system. Unlike the cascade control solution, the present multivariable control solution deals with model interaction reduction based on decoupled control.

The 5th Chapter starts by introducing as application, key building blocks for designing an industrial automation system with Siemens equipment and software. The main purpose lies in implementing, comparing and validating test platforms for control solution for thermal power plants with HIL and RT applied on an actual complex structure.

The 6th Chapter summarizes the main contributions of this work.

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The present thesis is not a stand-alone work but more a combination of beautiful minds working together as one, towards the final goal.

Firstly, I would like to express my gratitude to my supervisor Prof.dr.eng. Gheorghe-Daniel ANDREESCU for his support, availability, patience, for the numerous constructive discussion - technical and less technical, his constant positive attitude and encouragement and the overall invaluable guidance during the Ph.D. program. Prof. Andreescu, it is always a pleasure to work with you.

I wish to thank Prof.dr.eng. Nicolae MUNTEAN for the trust he has given me in industrial automation projects and academic performance, for his support and priceless advice, and for walking along me when I took my first steps as an engineer. All this couldn't have been possible without your help.

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Timişoara, Februarie 2012 Mihai IACOB

Mihai IACOB

Control Solutions with Hardware-In-The-Loop and SCADA System for Drum-Boiler Turbine Process in Thermal Power Plants

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Keywords: Boiler-turbine models, Cascade control, Hardware-in-the-loop, Multivariable decoupled control, SCADA, Shrink and swell, Thermal power plant

The main results of the thesis are the following:

- Develop a SCADA platform (hardware and software) for integrating automatic control: designed and implemented SCADA system for COLTERM thermal power plant South of Timisoara.
- Give an important head-start for control and simulator implementation using SCADA platform based on applications employing world-wide National Instruments and Siemens Automation technologies.
- Mathematical models for thermal power plants having as core three fitted models (low-order model, complex physical law based model, interpretation model).
- Design, implement and test two control strategies (3 feedback PI cascade control, multivariable gain-scheduled decoupled control) with integration capability in the centralized SCADA system.
- Design and implement two platforms for control solution testing using modern concepts like hardware-in-the-loop and real-time with industrial targets.
- Conduct a risk analysis of a wireless control scenario on process actuators in SCADA system when cables and busses are not a feasible solution.

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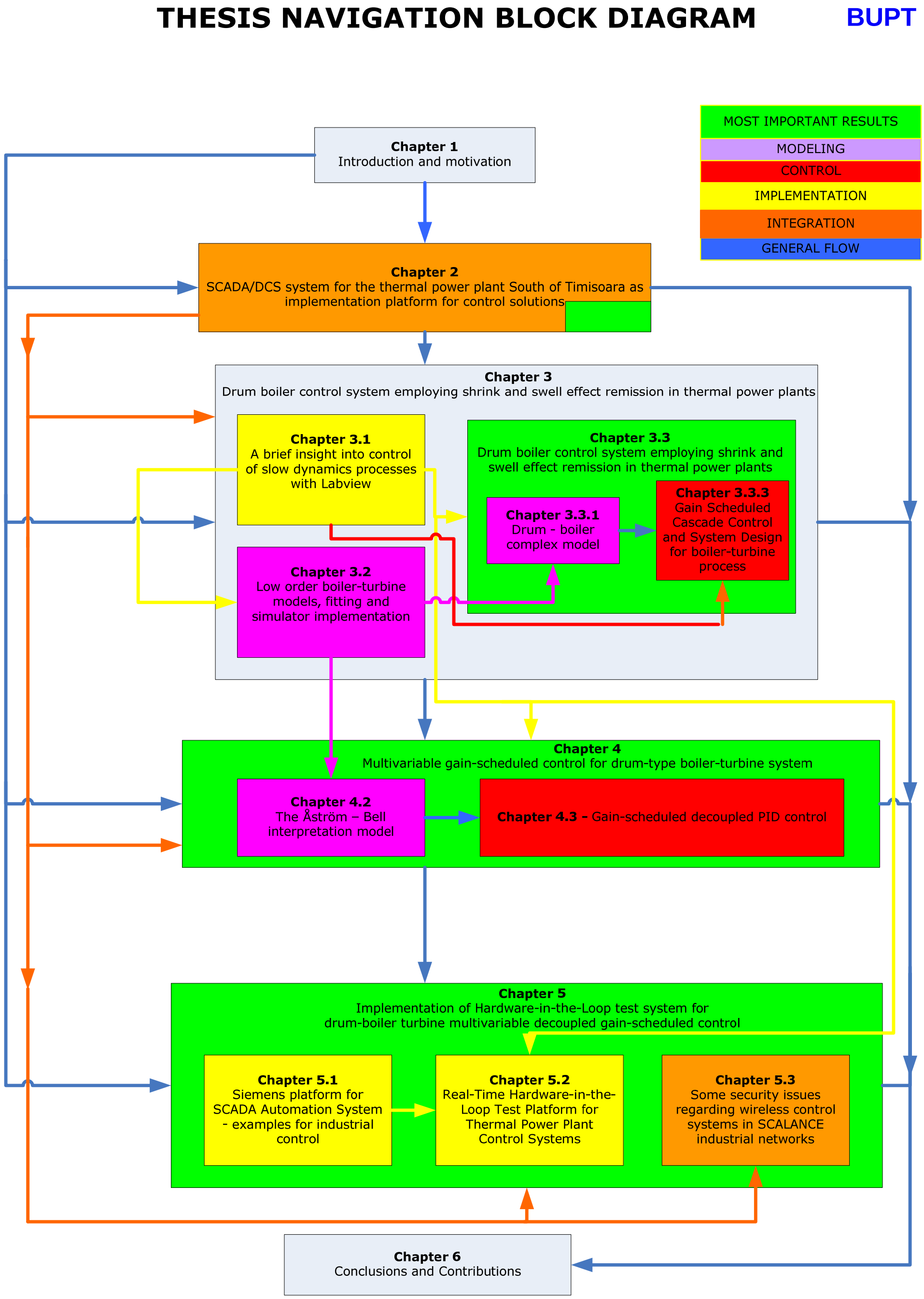
THESIS NAVIGATION BLOCK DIAGRAM



NOMENCLATOR

Abbreviations

Symbol	Name
DCS	Distributed control system
HIL	Hardware-in-the-loop
HMI	Human machine interface
OPC Server	Ole for process control server
PCS7	Process control system 7
PI	Proportional integral
PLC	Programmable logic controller
SCADA	Supervisory control and data acquisition
SUT	System under test
RT	Real-time

Symbols

Symbol	Name	Measuring Unit
α_r	Steam quality	
α_v	Steam volume ratio	
β	Empirical Parameter	
A_d	Wet area of drum	[m^2]
C_p	Specific heat of metal	[J/kg.K]
E	Electric Power	[MW]
E_i	Input Power	[kW]
E_o	Output Power	[kW]
H	Energy storage	[kW.s]
h	Enthalpy	[J/kg]
K_V	Valve coefficient	
L	Water level	[m]
m	Mass	[kg]
P	Drum pressure	[MPa]
P_T	Throttle pressure	[MPa]
q	Mass flow rate	[kg/s]
Q	Fuel heat power	[kW]
t	Temperature	[$^\circ$C]
t_s	Saturation temperature of steam	[$^\circ$C]
u	Internal Energy	[J/kg]
V^o	Volume at equilibrium	[m^3]
υ	Specific volume	[m^3/kg]

Subscripts

Symbol	Name
cd	Condensation
d	Drum
dc	Downcommer
e	Evaporation
f	Fuel
fs	Fluid (water and steam)
fw	Feedwater
r	Riser
s	Steam
sd	Steam in drum
t	Total
w	water
wd	Water in drum
wt	Total water

1. INTRODUCTION AND MOTIVATION BUPT

1.1. Global Energy Trends

Energy demand worldwide continues to increase, particularly in the United States and emerging economies, such as China, India and even Romania. On the basis of present policies, global energy demand will be more than 50% higher in 2030 than today, with energy related greenhouse gas emissions around 55% higher [1.1].

Low carbon emission fuels have lately played an important role in helping energy production, but unfortunately, it is clear that ***coal, oil and gas*** will play a significant part in meeting the world's energy needs for the foreseeable future, resulting in necessary and mandatory power plant improvements for reducing their emissions and rising their efficiency.

Global primary energy demand in the reference scenario [1.1] of the International Energy Agency (IEA) is projected to increase by 52% from 2003 to 2030, reaching 16.3 billion tons of oil equivalent (toe) (Fig.1.1.).

The role of ***biomass and waste***, much of which is used in traditional ways in developing countries, will decline slightly during the projection period. Their share of world primary energy demand will fall from 11% in 2003 to 10% in 2030, as they are replaced by modern commercial fuels. In absolute terms, the consumption of traditional biomass in developing countries will continue to grow. The use of biomass and waste will increase in power generation.

Other renewables, a group that includes geothermal, solar, wind, tidal and wave energy is expected to grow faster than any other energy source, at an average rate of 6.2% per year. However, they will still contribute marginally to meeting

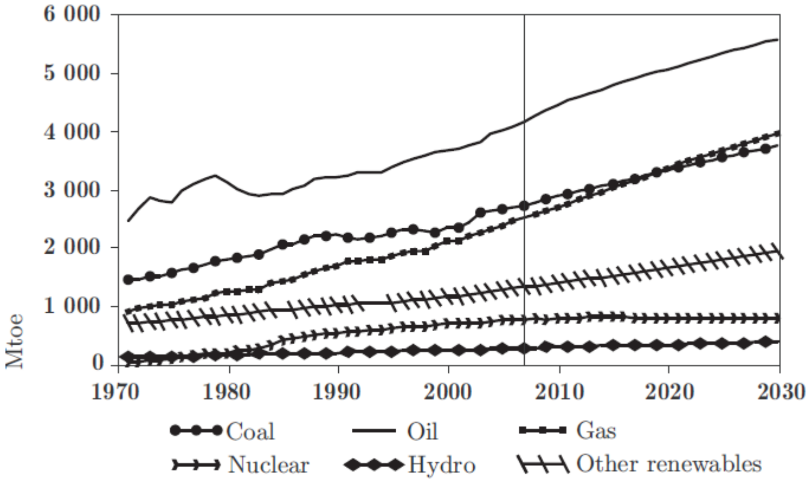


Fig.1.1.World primary energy demand by fuel in the reference scenario [1]

global energy demand in 2030. Their share in primary demand will grow from 0.5% in 2003 to 1.7% in 2030.Most of the increase in the use of renewable will be in the power sector [1.2].

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Green fuels (e.g. algae fuel) are predicted to be the future of energy production, but nowadays, in order to reduce emissions many countries apply for co-firing plants. A mixture of coal and biomass is a good example of such a unit.

From the economic point of view, this might be a better solution than to build a new power plant from scratch. This fact does not mean that the efficiency of the plant will be necessary improved, however it will reduce the pollution factors.

1.2. Energy outlook in Romania

Romania has significant fossil fuel and hydroelectric resources: It has crude oil reserves of about 1.4 billion barrels, proven natural gas reserves estimated at 335 Gm3, estimated coal reserves of 3.98 billion short tons. Most of these reserves are lignite and sub-bituminous coal. The total hydroelectric power potential is about 40 TWh per year of which 12 TWh per year has already been developed. Domestic production supplies 70% of the primary energy demand.

Production of Electricity according to energy sources in Romania, as compared to other countries in Central and Eastern Europe and the European Union is presented in (Fig.1.2). The analysis was carried out in 2005. It can be seen that Romania and not only is highly dependent of fossil fuel power generation, making thermal power plants indispensable for the time being. As a prediction horizon, it is estimated that green energy will embrace an increase by the year 2015 (Fig.1.3), but the actual load is still to be supported mainly by fossil fuel generation units.

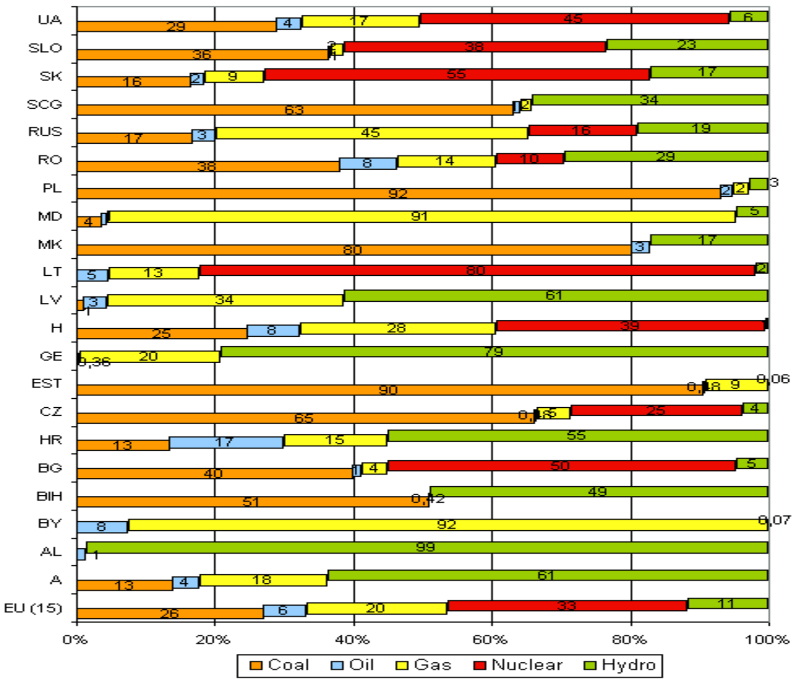

Fig.1.2. Energy production of states in Europe [1.3]

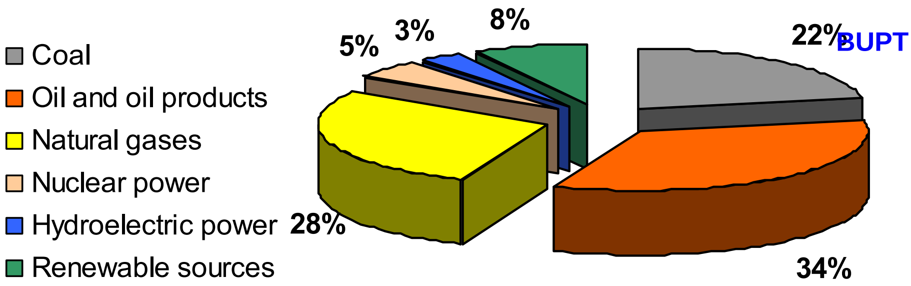

Fig.1.3.Energy projection for the year 2015

1.3. Steam thermal power plants and their efficiency

In the last century the primary way of producing electric energy was by burning fossil fuels or by means of nuclear fission reaction. The ***basic concept*** is to produce high pressure steam which is fed to a turbine unit in order to drive the turbine shaft into electric power generation. The mechanism of producing steam is called a water-steam cycle: water is heated to steam, it expands in a turbine, cools, and eventually is compressed again. Energy is added to the steam during compression and heating, and drawn from it during expansion and cooling, the expansion step leading to the production of electrical power. The driving mechanism behind the generation of electricity is the expansion of steam in the turbine.

We may observe from (Fig.1.4) that to produce steam, we burn fuel in a furnace. Via a series of heat exchangers (economizer, evaporator, superheater) the heat from combustion warms the water into superheated steam, which is passed to the turbine. There the steam is allowed to expand, which causes the turbine shaft to turn. This drives the electrical generator.

All power plants and users of electricity form a framework referred to as the electrical grid. The power of the electrical grid in Europe oscillates at a frequency of 50 Hz. If the demand for electricity exceeds the power supply by the power plants, the frequency drops. To raise the frequency back to the nominal 50 Hz, a power plant must produce more electricity, which is directly influenced by the output torque of the turbine. The output torque is proportional to the steam flow through the turbine [1.4].

From the generation point of view we will concentrate mainly on ***pulverized fuel plants in cogeneration with gas***. The energy released during the combustion contains energy that can be converted in work up to a certain extent ('exergy'). The remaining part cannot physically be converted into work, and is known as 'anergy'. The heat of combustion is transferred with over ***90% efficiency*** to water in the boiler of a power station to produce steam. The higher the pressure and temperature of steam, results in more exergy, i.e. the part of the energy in the steam that is able to perform work. The total efficiency of conversion is governed by the laws of physics, and depends on the ratios of steam pressure and temperature at the input and output of the turbine. Low temperatures at the output, through cooling in the condenser, lead to higher efficiencies. This effect is further enlarged through direct cooling, for example using sea-water [1.2].

We will focus mainly on the thermal power plant South of Timisoara, Romania, which is also a cogeneration plant (coal and gas). As functioning parameters, this is a small scale thermal power-plant with a generation capacity of

16 MW. The plant employs three steam boilers (as generation units), each of them having the steam pressure up to 20 Bar, 33 kg/s steam flow, and a maximum 10 MW generation capacity working with one boiler. Before analyzing the different control solutions for the actual plant and how to integrate them, we propose to describe the existing systems.

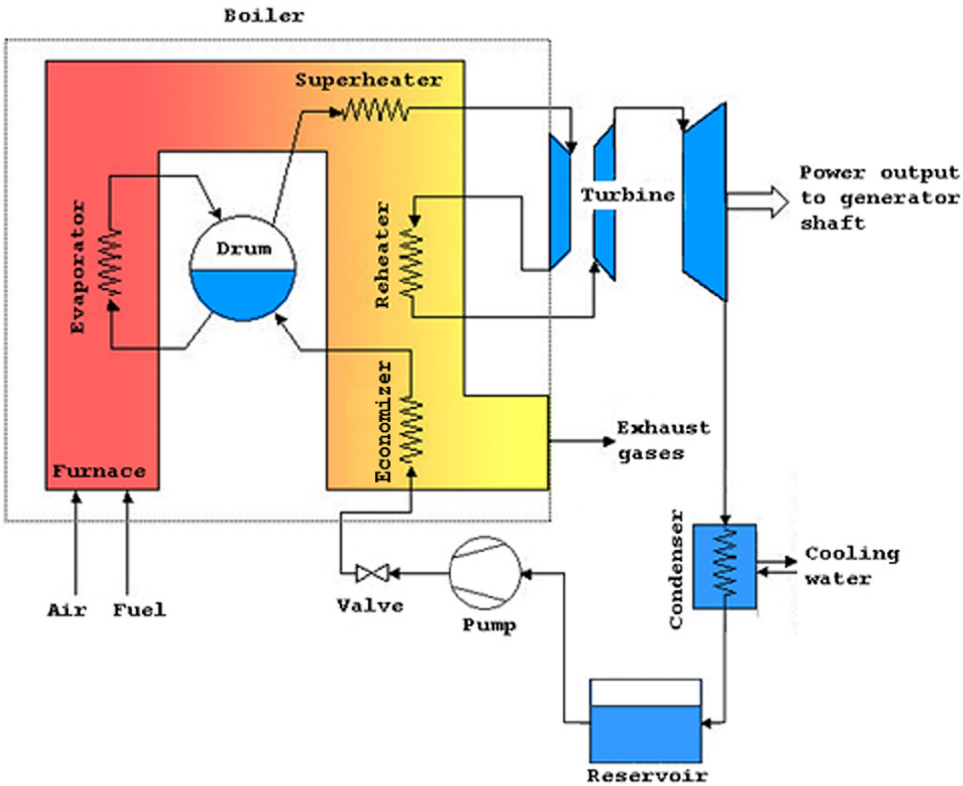

Fig.1.4.General thermal power plant structure [1.4]

1.4. Hardware-in-the-loop (HIL) as control strategy test platform

Industrial control applications tend to grow in size and complexity and require sophisticated test methods. One of these methods is Hardware-in-the-loop (HIL), an approach that has been introduced by the aerospace and defense industries in the 1950s [1.5]. In the past decade, the tremendous advances of semiconductor industry, the subsequent easy accessibility of powerful computing resource and the decreasing prices of simulation hardware led to further adoption of HIL simulation to domains like industrial control applications or automotive systems [1.6].

The ability to design and to automatically test real processes with HIL will reduce development cycle, increase efficiency, improve reliability, safety and quality and help prevent costly and dangerous failures of these systems for a large number of applications. Unnecessary and expensive testing on the real plant is avoided with this approach as most problems are identified and solved in the HIL phase

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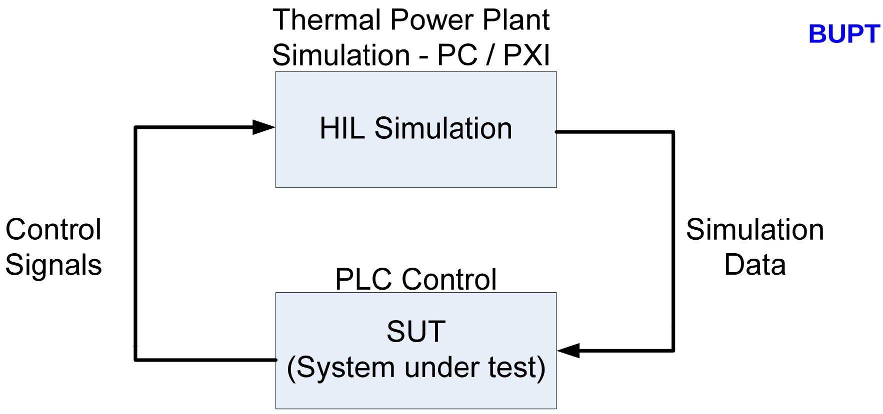

Fig.1.5.General HIL-SUT structure for thermal power plant system

conducted in the laboratory where the controller exists as hardware and the process exists as a software model running in real-time [1.7].

Hardware-in-the-loop is a concept based on splitting a system into two components: the simulation component and the control component, i.e., system under test – SUT (Fig.1.5). HIL uses a simulation of processes integrated in a physical device, and the real-time controller for automatic control. One of the advantages of this solution is that it is not needed to use the real process in order to test and validate a wide range of plant control strategies. Moreover, control is implemented on the real target, providing valuable knowledge for tangible industrial automation problems that engineers might face during controller design.

The control algorithm can be initially coded in high-level programming languages and then compiled and downloaded to a dedicated processor. Final engineering of the power plant control strategy is extremely costly while traditional software-only simulation [1.8]-[1.12], which is necessary to help the engineers optimize the system architecture, component choices and the system performance in terms of efficiency, power density, cost and lifetime, is often insufficient to exactly capture the control dynamics.

One way to bridge the gap between simulation and final system construction is real-time hardware-in-the-loop (RT-HIL) testing [1.13], [1.14]. This solution increases the realism of the simulation and provides access to hardware features currently not available in the software-only simulation. It also reduces the risk of discovering any dangerous error in the very last stage of the on-the-field testing and assembling [1.15].

Transposing this concept on the present thesis, the ***thermal power plant simulation*** runs in the ***HIL Simulation unit***, which is represented by a PC and PXI-RT unit, and the ***control strategy proposed*** for the plant runs in the ***System under test unit***, which is represented by a PLC.

1.5. The thesis

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The ***main objectives*** of the thesis are:

i) To provide the *know-how* for successfully designing, *integrating and upgrading control strategies* in real thermal power plant systems.

ii) To provide a Hardware-in-the-Loop *real-time simulators* for rapid control strategy testing/validation/integration and also dispatcher training for improved thermal power plant process control.

These *main objectives are achieved* in terms of:

- SCADA platform (hardware and software) for integrating automatic control: designed SCADA system for COLTERM thermal power plant south of Timisoara, SCADA system functionality and utilization – *Chapter 2*.
- Head-start for control and simulator implementation using SCADA platform, based on applications employing world-wide National Instruments and Siemens Automation technology - *Chapters 3 & 5*.
- Process based approach of thermal power plants having as core three developed models (low-order model, complex physical law based model, interpretation model-approximation model)– *Chapters 3 & 4*.
- Design, implementation and test two control strategies (PI cascade control, multivariable decoupled control) with integration capability in the centralized SCADA system – *Chapters 3 & 4*.
- Two test stand platforms for implementations of control paradigms testing using modern concepts like hardware-in-the-loop and real-time with industrial targets – *Chapter 5*.
- Risk analysis of a wireless control scenario on process actuators when cables and busses are not a feasible solution – *Chapter 5*.

Over the years many theories for MIMO control design have been introduced and implemented successfully on a range of systems. In power plant control, however, the use of multi-SISO loops for low-level controllers such as drum level and pressure control is still commonplace. The reasons for this are partially cost, and partially an unwillingness to implement complex and new technology. Additionally, current multi-SISO structures are relatively easy to switch to manual mode in the event of an emergency [1.4].

The overall work is focused on providing and analyzing ***control system solutions*** for thermal power plants, with particular interest in the thermal power plant South of Timisoara, Romania. Two main control strategies are developed, based on i) simple PI control laws and cascade gain-scheduled control (multi SISO structure) and ii) multivariable adaptive centralized decoupled control paradigms (MIMO control). These solutions are applied on non-linear drum-boiler-turbine models.

In our research we came a cross a wide variety of ***models***, from low-order models to highly non-linear complex models. An analysis of which model is best suited for implementation relative to control structures and model accuracy, is carried out presenting the pros and cons. The models were adapted to fit the real thermal power plant South of Timisoara by constructive and functioning parameters.

The final system is provided with a ***Hardware-in-the-Loop*** implementation with the main advantages of rapid developing of complex control strategies, implemented on an industrial Real-time (RT) PLC without the real process, but using a ***Real-time*** time simulation of the plant. The RT implementation and HIL method are *one of the key features* of the present dissertation (thesis).

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The HIL-RT system is compared to common simulation techniques, with an accent placed on the synchronization issues between control and simulation RT equipments. The HIL method adds realism to the applications, thus providing an important insight into complex control integration on real time industrial targets i.e., PLCs. Moreover it reduces downtimes in control integration and assures a test stand for control strategy analysis before going to the real process, helping in discovering faults and issues in an early stage of the control engineering process.

Using HIL and RT concepts, the control algorithms are validated for the real thermal power plant process, needing only some fine tuning.

Control system performances are discussed for each of the control solutions.

Taking into account that the control strategies that are proposed work on a Siemens centralized controller and the situation where the worm Stuxnet invaded the Iran Uranium Facilities a couple of years ago, some security problems regarding an eventual situation of a *tele-control using wireless networks* are also investigated.

The ***purpose*** of this thesis is to offer concrete, reliable and easy to implement solutions, on industrial targets, for advanced improved control of a boiler-turbine-unit in a thermal power plant, under a HIL and RT test concepts. Moreover a couple of simulators are provided for dispatcher training and for analysis of thermal power plant process transients with manual/automatic shift, with real-time capability.

The ***present thesis*** provides the know-how, based on practical applications, for choosing, designing and implementing the appropriate control structures in thermal power plants along with modern test methods like Hardware-in-the-Loop and Real-Time using world-wide Siemens Automation and National Instruments technologies.

During the research period the author has published, in the thesis domain, 11 papers, from which 9 papers in international recognized databases: 3 in ISI Proceeding, 5 in IEEE Xplore and 1 book chapter in CRC Press, Taylor & Francis group on Amazon.

[1.1] IEA. World Energy Outlook 2005, 2005.

[1.2] Hans Van Putten, “Integrated Modelling for Improving the Design and Operation of Steam Power Plants with a Focus on Increasing Their Efficiency”, Ph.D Thesis, 2008.

[1.3] EAST-GSR, "Analysis of the local situations in the Eastern European partner countries", Romania, 2005.

[1.4] Eric Wictor, “Multivariable Feed Water Control for an Electrical Power Plant MSc Thesis, Technical University of Delft, Netherlands, March 2007.

[1.5] S. Nabi, M. Balike, J. Allen, and K. Rzemien, “An overview of hardware-in-the-loop testing systems at Visteon,” SAE technical paper series, SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001 USA, March 2004.

[1.6] M. Schlager, W. Elmenreich, and I. Wenzel, ”Interface design for hardware-in-the-loop simulation,” in Proc. IEEE Symposium on Industrial Informatics (ISIE 2006), Montreal, Canada, pp. 1554-1559, July 2006.

[1.7] Oncu, S., Guvenc, L. Ersolmaz, S. Ozturk, E. Kilic, N. and Sinal, “Steer-by-wire control of a light commercial vehicle using a Hardware-in-the-loop test setup”, SAE Paper, 2007-01-4198.

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[1.8] R. M. Nelms, B. W. Evans, and L. L. Grigsby, "Simulation of AC spacecraft power systems", IEEE Transactions on Industrial Electronics, Vol.36, No.3, pp.398-402, Aug. 1989

[1.9] R. M. Nelms, and L. L. Grigsby, "Simulation of DC spacecraft power systems", IEEE Transactions on Aerospace and Electronic Systems, Vol.25, No.1, pp. 90–956, Jan. 1989.

[1.10] J. R. Lee, B. H. Cho, S. J. Kim, F. C. Lee, "Modeling and simulation of spacecraft power systems", IEEE Transactions on Aerospace and Electronic Systems, Vol.24, No.3, pp. 295 – 304, May 1988.

[1.11] G. Colombo, U. Grasselli, A. Deluca, A. Spizzichino, "Satellite power system simulation", Acta Astronautica, Vol.40, No.1, pp.41-49, 1997.

[1.12] W. Billerbeck and Gilbert Lewis Jr., "Spacecraft power system studies using Pspice", Proc. 36th Intersociety Energy Conversion Engineering Conference, Vol.1, pp.1-18, 2001.

[1.13] Seungkyu, O., Hyoungsoo, K. and Jinhee, J., "Proposals for improvement of AFS system using HIL and SIL simulation", ICROSSICE International Joint Conference, Fukuoka International Congress Center, Japan, pp. 555-559, August 2009.

[1.14] Wenzel, T. A., Burnham, K. J. Williams, R. A. and Blundell, "Closed-loop driver/vehicle model for automotive control". System Engineering, 2005. ICSEng 2005. 18th International Conference, Las Vegas, USA, pp. 46-51, Aug. 2005.

[1.15] Zhenhua, J., Roger A. D., Rodrigo L., Hernan F., "Hardware-in-the-Loop testing of digital power controllers", Applied Power Electronics Conference and Exposition, APEC '06. 21st Annual IEEE, pp. 901-906, March 2006.

2. SCADA/DCS SYSTEM FOR THE THERMAL POWER PLANT SOUTH OF TIMISOARA AS IMPLEMENTATION PLATFORM FOR CONTROL SOLUTION

The present chapter presents the designed SCADA system for COLTERM thermal power plant south of Timisoara in terms of hardware and software, functionality and utilization, as an integration platform for automatic control strategies which are to be discussed in *Chapters 3 & 4*.

Modern process control systems are used in industrial automation for flexibility, modularity and reliability, employing state of the art technology based on three concepts: Distributed Control System (DCS), Programmable Logic Controller (PLC) and Supervisory Control and Data Acquisition (SCADA).The present chapter describes a SCADA/DCS system that the author developed and implemented at the thermal power plant South of Timisoara, Romania for preparing the power plant to accept automatic control solutions.

2.1. Background

Continuous innovation guarantees sustained market success for machines and plants. The innovation steps become easier if one can exploit previous investments for machine generations. In today's automation world, the requirements are high and complex. Each new system has to be better, more reliable, more flexible, more user friendly than the ones before it.

New software technologies have also emerged due to integration needs of machines, control and monitoring instruments, field equipment in easy-to-use visualization environments and web-based applications: PCS7 – Siemens, CX-Supervisor – Omron, Genesis 32 – ICONIX, Labview – National Instruments. All these merged concepts and modules can have as result a successful, and fully functional SCADA, DCS or PLC system. In today's process/factory automation these concepts are merged resulting in a robust and reliable automation project.

Programmable Logic **Controls** (PLCs) are used for system control. As need to monitor and control more devices in the plant grew, the PLCs are distributed and the systems became more intelligent and smaller in size.

In a ***distributed control system*** (DCS), the data acquisition and control functions are performed by a number of distributed microprocessor-based units situated near the controlled devices or by instruments from which data is gathered. DCSs have evolved into systems providing very sophisticated analog control capability.

SCADA has been around as long as there have been control systems. The first SCADA systems utilized data acquisition by means of meter panels, lights and strip chart recorders; the operators manually manipulated various control knobs, exercising supervisory control [2.1], [2.2]. The term **supervisory control** is associated with (i) the process industries, where it manages the activities of a number of integrated operation units to achieve certain economic objectives for process; and with (ii) the discrete manufacturing automation, where it coordinates the activities of several interacting pieces of equipment in manufacturing cells or systems [2.3].

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Process automation makes use not only of SCADA concept but also of DCS and PLC.

The advantages of process control systems using SCADA, DCS and PLC, all together are:

- Industrial computers can record and store a very large amount of data;
- Data can be displayed in any way at user demands;
- Thousands of intelligent sensors over a wide area can be connected to system;
- The operator can incorporate real data simulations into the system;
- Many types of data can be collected by PLCs;
- Data can be viewed from anywhere, not just on site;
- Existing plant infra-structure can be used;
- Redundancy can be applied at the required levels;
- Distributed profiles DCS with hot swapping (if needed) can be used for unreachable locations (by wire);
- Open systems in comparison to traditional static ones;
- Communications and telemetry are improved.

The standardized concepts make the project foundation developed to improve monitoring, energy and material saving, to assure a superior scalability and remote command execution. The old equipments is replaced with PLCs, servers, modern approaches regarding network equipments and topologies and flexible monitoring stations. Remote actions and uninterrupted monitoring are possible due to redundant servers and web-based applications via OPC and web server.

2.2. Thermal power plant problem definition

Every existing plant, no matter the case, needs monitoring and control, either by means of hardwired relays, either by modern electronic components, capable of replacing older systems. This is also the case at the Thermal Power Plant South of Timisoara. Historically, the old plant informatics system was engineered in 1990 by ISPE Bucharest. The equipments delivered at that time were put out of production many years ago. The old process control system was put in function in 1993, a software upgrade being developed in 2002. The desire for a new SCADA system has emerged from the following drawbacks:

- Poor reliability and maintenance.
- Process computers DAS 900 (Data Acquisition System) can no longer be maintained in function due to lack of spare parts and obsolete ARCNET network technology.
- SICONIX pseudo-SCADA software engineered by ISPE Bucharest is a closed system, making impossible the integration and communication with new SCADA system in the plant.
- Inability of interfacing and transmitting parameters to the energetic group installed in the SICONIX monitoring system.
- Need of releasing/removing the cable routes with a standard industrial field data bus.
- Long acquisition times and lack of protection circuits against electromagnetic disturbances.
- Not able to execute commands on field elements and no web-based capability available.
- No redundancy at any level.

Regarding these limitations, some problems are taken into account as specific requirements for the new design:

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- The power supplies feeding the sensors must have separate connectivity of the protection earth and null wires in order to attenuate electromagnetic disturbances;
- Keep a close evidence of events and actions;
- Have a well defined set of rules based on a selection key (manual/remote concept), not to allow two operators to command the same equipment at the same time;
- Real-time capability with upon-change display regarding I/O;
- Design the web-based system in such a way that the monitoring and command tasks are distributed according to the needs of each operator;

The solution for the new SCADA system of CET Sud Timisoara (Fig.2.1) is a web-based process control and monitoring application that uses the following devices:

- A PLC with I/O modules as master station, with a central rack and 3 expansion racks, which is capable of collecting and processing data from 3 plant boilers and heating stations (Fig.2.2). Another function is to execute command algorithms for pumps and valves. ***This is a centralized station.***
- Two distributed slaves, which acquire data from long distant sensors and control execution elements, where direct cable connection with the centralized PLC is not possible. Data is acquired via Profibus Distribute

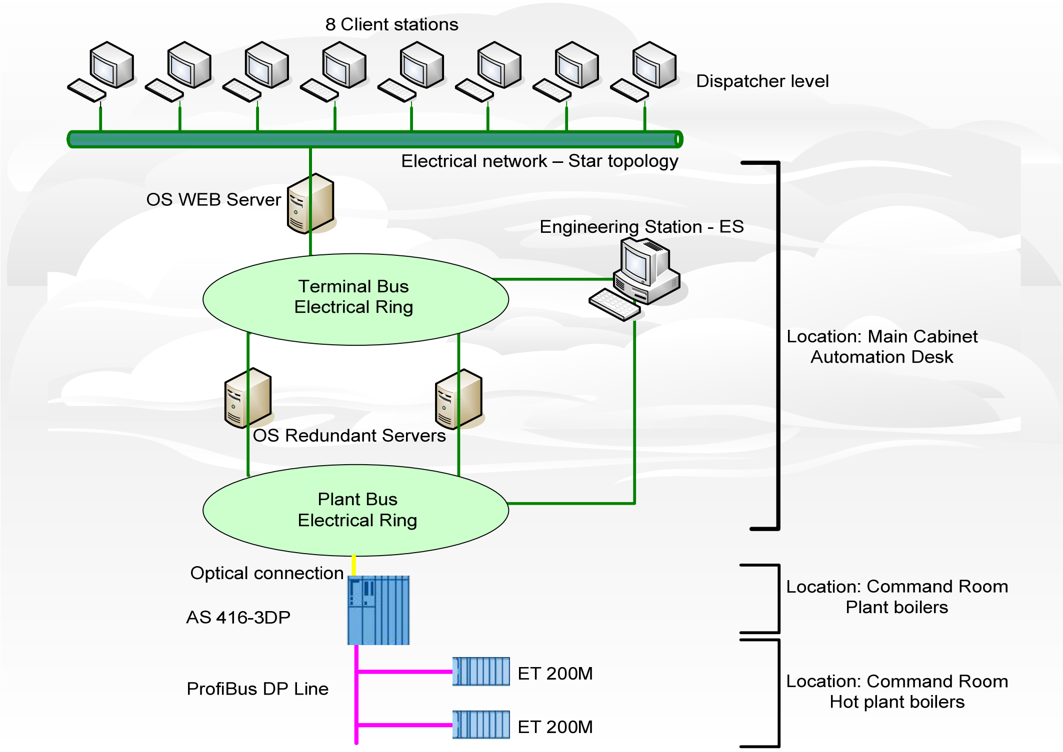

Fig.2.1. SCADA System architecture for the thermal power plant south of Timisoara

Periphery (DP).

- Two OS servers, which work in a redundant regime for data transport and synoptic implementation of the plant areas. The functionality principle is: “Synchronization after server comes back on-line”. The servers also record data, contain the evolution trends for a week, alarms and events. All these data are available for clients via OS web-server.
- An OS web-server capable to publish reports, synoptic images, dynamics, process values and commands to clients.
- Eight Human Machine Interface (HMIs), clients for centralized process control and monitoring of the plant. Maintenance is also possible here by displaying the servers and PLC status.
- An engineering system (ES) used for programming, downloading the server and PLC configurations and PLC programs. Furthermore, diagnostics, I/O checkout and simulation are executed on the ES.
- Four switches used for two communication busses: plant bus (PB) and terminal bus (TB) to design two Industrial Ethernet redundant rings (Fig.2.3) [2.4].
- Several 4-20 mA to 4-20 mA converters for signal filtering and disturbance attenuations.

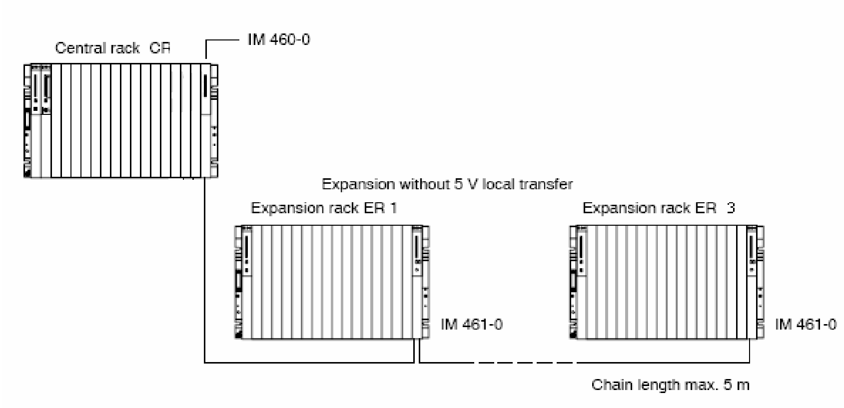

Fig.2.2. PLC central rack & expansion rack structure

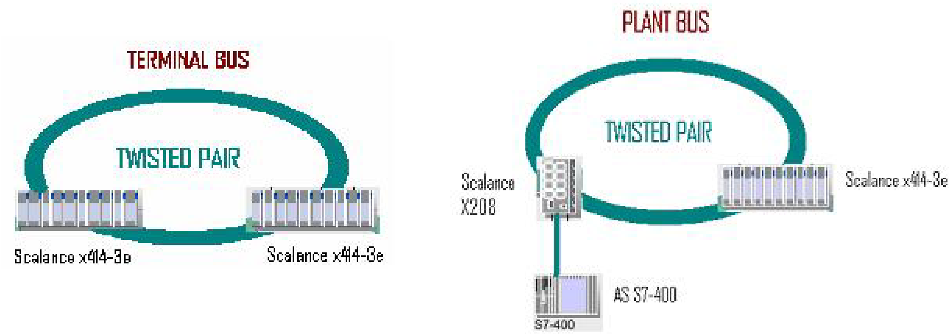

Fig.2.3. Electric ring networks Plant Bus (PB) & Terminal Bus (TB)

2.3. Application architecture

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All web-based applications are centered on the N-Tier architecture, which is a client-server architecture combined with layer architecture [2.5]. The architecture for our application has field components (PLCs, sensors), two OS application servers with databases, an engineering system (ES), a web-server and 8 clients.

According to this structure, the clients correspond to the **Presentation tier,** which helps to translate the information from EBCDIc and ASCII into audio, video and images.

The ***Application tier*** is associated with the web-server, which deals with the client requests and acts as an intermediater between the OS servers and clients.

The ***Database tier*** contains the database management system that processes all persistent data. The OS server and the OS redundant server work for this tier.

The ***Field Tier*** deals with the distributed modules, PLC and sensors and has the task of acquiring and processing data [2.6].

Data from hot heating plant boilers are acquired by distributed modules. Data from heating plant boilers and plant boilers are acquired by the main cabinet, which contains the CPU and expansion racks. The processor with 3 Profibus interfaces contains on his racks, modules for the acquisition of binary and analog inputs like the distributed modules. The difference is that the distributed stations only take data without processing it, but the ***Automation System*** (AS) does.

The communication is made via ***SIMATIC Profibus DP***, which is a field bus with baud rate up to 12 Mbit/s based on the RS-485 standard with 1 km maximum length. The two electric ring networks (Fig.2.3) allow the Servers and the Engineering System (ES) to exchange data with each other and with the AS. The flexibility of these networks is obvious when the engineers run diagnostics, execute signal test or download. The PB uses ***SIMATIC Industrial Ethernet*,** ISO protocol (MAC Based) and the TB uses TCP/IP. The networks employ X414-3E and X208 switches, which exchange data at 1000 Mbit/s.

2.4. How it’s made

The first step is to design the system architecture and to establish the hardware emplacement. The second step is to choose the appropriate modules for processing and acquiring data. And the final step, programming and configuring the equipment. The system monitors 737 binary inputs, 324 analog inputs and commands 10 binary outputs (4 valves and 2 pumps). Also reserve modules of 20% resources are taken into account.

2.4.1. Plant bus level – Hardware configuration

At the **Plant Bus level** (PB)**,** the automation system contains a central controller (CC) placed in the universal rack UR1, another 3 expansion units (EU) placed in the expansion racks (ER1).Communicatio is established via send/receive interface modules IM460-0 and IM461-0 always used together (Fig.2.2). The send modules (send IMs) are inserted in the CC, while the corresponding receive modules (receive IMs) are plugged into the series-connected EU [2.7].

Dew to the lack of voltage transfer between the IMs, each EU needs separate power supply. The hardware rack specifications are:

- **Rack 0** contains Power Supply (PS) 24Vdc/20A; CPU (3 Profibus and 2 Industrial Ethernet interfaces), communication processor for Industrial Ethernet CP, 3 Digital Input modules 32xDI of 24Vdc, 8 Analog Input modules 8xAI with 13Bit resolution and the send/receive module.
- **Rack 1** contains one PS 24Vdc/10A; 6 modules 32xDI of 24Vdc, 6 modules 16xAI of 16Bit resolution, 2 modules 8xAI of 13Bit resolution and a receive module.
- **Rack 2** contains PS 24Vdc/10A; 5 modules 32xDI of 24Vdc, 10 modules 8xAI of 13Bit resolution and a receive module.
- **Rack 3** contains PS 24Vdc/10A; 5 modules 32xDI of 24Vdc, 10 modules 8xAI of 13Bit resolution and a receive module.

The distributed stations communicate with the AS via Profibus 1.5Mb/s with a distributed profile. The first station contains 3 modules 32xDI of 24Vdc and 4 modules 8xAI of 13Bit resolution. The second station contains 1 module 32xDI of 24Vdc and 1 Digital Output module 32xDO of 24Vdc/0.5A. The 8xAI module has the measuring type of 4-20mA / 2 wire; the 16xAI module has 4 wire on 4-20mA. Analog modules also have wire-break signaling capability; a "configuration in run" (CIR) is also possible (if needed). CIR supports hot swapping by adding/removing new slaves and modules and making new parameter settings for inserted modules [2.8].

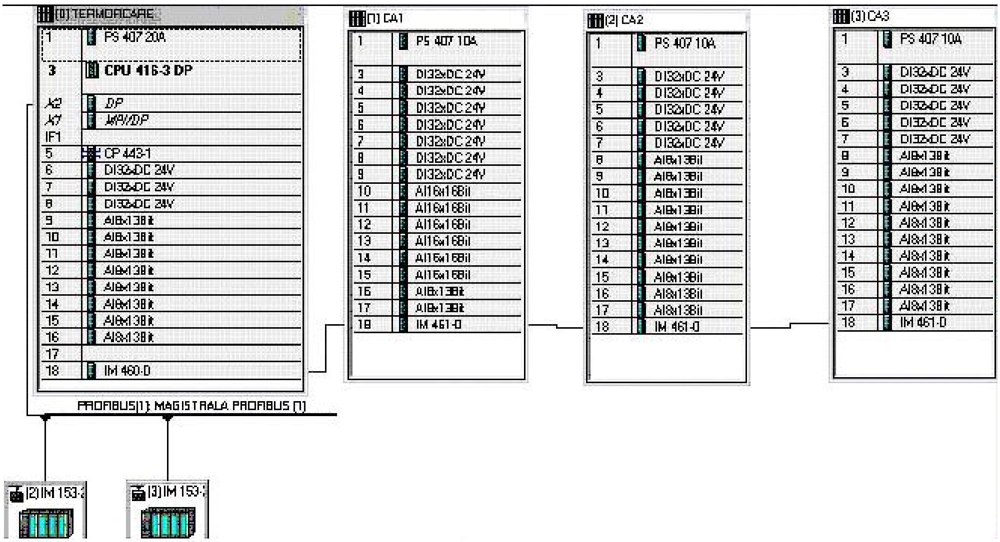

Fig.2.4. Hardware Configuration of the system with HWConfig tool in Step7 software

Using EU is a cost effective solution in comparison with distributed profiles (DCS). On the other hand, if the signals pass long distances in the plant, the slave solution used with the CIR capability is the best one. The tool used to define the connections, communications and configurations on all levels is "HWConfig" (Fig.2.4) from the PCS7 software by Siemens.

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2.4.2. Plant bus level – PCS7 software

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The PLC programming is made with PCS7 software package, which has the following main tools: Continuous Function Chart (CFC) and Sequential Function Chart (SFC). In PCS7, these high-level languages have replaced the classic ladder diagram (LAD), S7Graph, function-block diagram (FBD), that were used to build process control applications. The overall plant process is described by continuous processes. For this purpose CFC charts are used and implicitly the CFC Editor of PCS7 [2.9]. CFC uses predefined blocks that are stored in the Master Data Library, for signaling, scaling process values and build command and control algorithms.
In CFC, before working with signals, we must pass them through channel drivers.

The flow for **signaling** procedure, e.g., the produced heating energy (Fig.2.5) is the following:

- Identify the signal address from the AI module.
- Pass the values to virtual channels by connecting their address to the "value" signal. The channels are called "CH_AI" and are standard CFC blocks. Scale the values by giving them upper and lower limits through the "VHRANGE" and "VLRANGE" parameters. Hysteresis can also be applied on the "CH_AI" block.
- Get the values from the output of the CH_AI block, put them in a comparator "CMP_R". If the value goes into overflow then substitute the value with "0" by connecting the output of "CMP_R" to the "SUBS_ON" signal. By activating this signal, the output of the "CH_AI" block will get the value from the "SUBS_V" parameter. Underflow situations are eliminated in the same manner.
- Add the values and place them to a measure and monitoring "MEAS_MON" block.

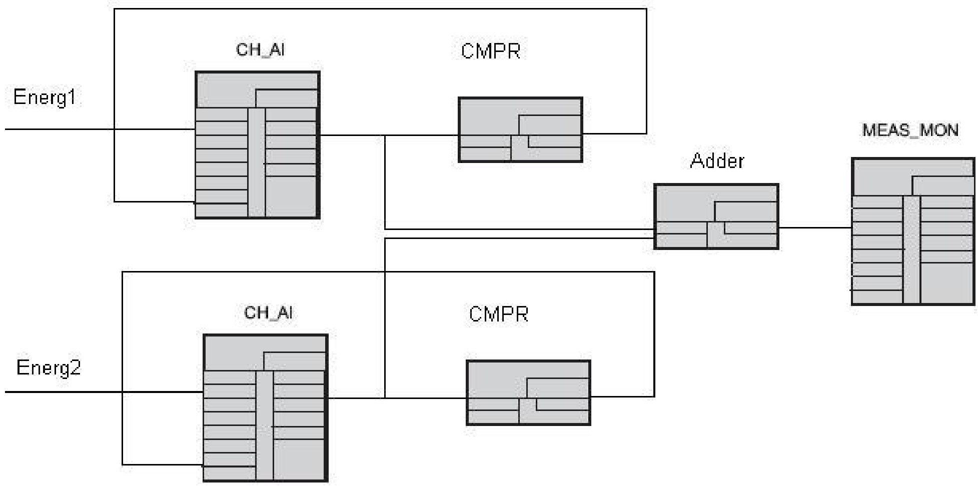

Fig.2.5.Continuous function chart (CFC) logic for signaling heat energy production

Define on this block, the alarm and warning limits for the scaled value. When executing the "Create/Update block icon" function, an interface for the operator is created on the associated process picture.

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The "***Val_Mot***" block is a dedicated CFC for controlling motor driven valves. The valve command algorithm is implemented:

Signalization:
FB_OPEN= RB & not (LB)
FB_CLOSED=LB & not (RB)
Commands:
OPEN= MS & D & not (SK)
CLOSE=MS & not (D) & not (SK)

RB	Right boundary
LB	Left boundary
MS	Motor start
D	Direction
SK	Selection key

There is a time control mechanism for the valve opening/closing. If the time passes then the valve disables itself. The block can be used again only if the error is acknowledged. A stop in an intermediate position is also possible: not (RB) & not (LB) & not (SK). If SK is activated then the valve blocks itself. Linking the input signal SK at "Link_Man" and "Liop_Sel" valve signals, we switch and activate from operator control to interconnected inputs – manual control. By this fact, the possibility of simultaneous commands from the clients and from the buttons in the command rooms is eliminated. There are 4 valves controlled with instances of this block.

The "***MOTOR***" is a CFC block, which starts/stops the pumps. It is used to control motors by means of a control signal ON/OFF. The motor speed feedback-signal (on/off) can be monitored optionally by means of a contactor relay. Various inputs are available for controlling the motor. They are implemented in a concrete hierarchical relationship to each other and to the motor states. In particular, the locking, the feedback monitoring and the motor circuit breaker influence the control signal "QSTART". A SK is also implemented on the block.

In order to test the blocks to work properly, they are downloaded in PLC under simulation mode. By activating "Test Mode on/off" function, we can execute tests and diagnostics directly on PLC. The channel drivers (analog or binary) have a "SIM_ON" signal, which activates the "SIM_V" parameter, so that the driver outputs its value. All the programming, testing and diagnostics are made on the ES.

2.4.3. Terminal Bus level – Servers

At the ***Terminal Bus*** level, there are the redundant OS Servers and the Web Server. The OS Servers are the main components of the SCADA system. Each server or station, with an OS indicative, is configured with a *WinCC Application*. The redundant OS Server contains a "standby" WinCC applications and the Web Server a client application. WinCC is the integrated software in PCS7 that permits SCADA operations.

A. Terminal Bus-Database Tier-OS Redundant Servers

They hold 34 synoptic main images, which are arranged in a hierarchical mode depending on the area they belong to. Each WinCC application contains it's own station project. Each station project is a SCADA environment. The synoptic images are created in "Graphics Designer" and have to be placed in a hierarchical architecture. The tool that allows this operation is "Picture tree manager", where to each picture a container is assigned (Fig.2.6). Picture-container assignment can also be done directly in the "Plant View" in the Simatic Manager.

Secondary images, which are not associated with the plant areas, hold and display evolution charts of the process values for one week. Other secondary pictures have the functions of showing synthesized tables with all the process values on the associated areas.

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Evolution charts are created in "Tag Logging" editor in the server's WinCC application, which archives the process values to be able to display their history. The acquisition time and the archive period has to be assigned for each process value.

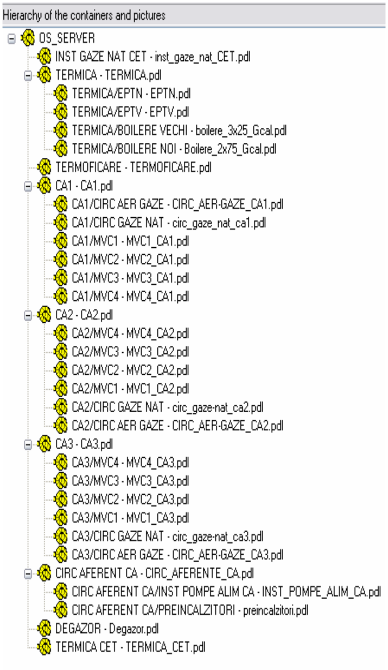

Fig.2.6.Hierarchy structure of synoptic images

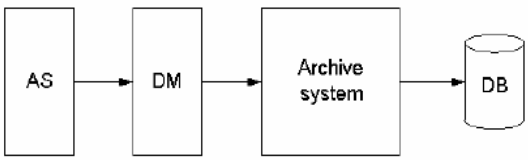

Fig.2.7.Server archiving principle

The archiving system processes runtime tags stored in the runtime database and after, writes them in the archiving database. Archived values can be exported in Excel. The following sequences are executed (Fig.2.7.):

- Automation System (AS) saves the process values, which are sent to the WinCC application through communication drivers;
- Data manager (DM) processes the values and returns them to the archiving system through process tags;
- Archive system processes the acquired values (depends on the archive configuration);
- Runtime database (DB) saves the process values, which are going to be archived.

The synoptic images are created with the "Graphics Designer" tool. Here, the user interface with the process is created. Different type of dynamics can be added to each property of every object from the library either by dynamic dialogs, C or VBS scripts and tags. Different C scripts are written for signaling the functioning state of equipments in the field, e.g., coal and gas burners.

Reference of C functions:

GetTagBit(bit_name) reads bit and returns a boolean value;
SetTagBit(bit_name) sets a bit and returns a boolean value;

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The interface of CFC blocks for command and monitoring are placed on the associated area images by activating the "Create Update block/icon" function. The alarms are automatically generated by the "MEAS_MON" CFC block, in association with the limits defined on it. The operator interface for "MEAS_MON" provides: value vizualization, alarm redefinition, acknowledgement, dinamic scaling and 5 minutes evolution charts.

The OS Servers run in redundant regime. They are configured with the "Redundancy" editor from WinCC. The main server and the redundant server (Standby) have WinCC applications. The servers exchange data through COM1 RS-232 interface. The servers monitor each other in runtime to allow preventive acknowledge of partner failure. This fact assures the clients of uninterrupted control. During fault, the active server will continue archiving all messages and process data for the WinCC project. After the failed server comes back on-line, the contents of messages and user archives will automaticly be copied to the warm returned server. This operation fills the data gaps of the server. This action is called "Syncronization after server comes back on-line". This type of redundancy is called "Hot standby system" because the spare system is operated in synchronization with the active system. The structure can be considered as a parallel redundancy.

The process reliability for such structures can be determined using the following equations [2.8]:

$$R_P = 1 - Q_A * Q_B \quad (2.1)$$

$$R_P = R_A + R_B - R_A * R_B \quad (2.2)$$

where Q_i is the system unreliability: $Q_i = P(X_i)$ is the probability of unit failure; R_A and R_B are the reliabilities of the two servers; R_p is the overall process reliability.

The process pictures are published to the OS Web Server from the OS Server and further to the clients. There will be two publications, one on the OS Server and other on the OS Web-Server. "Web navigator" is the WinCC tool used for this action.

B. Terminal Bus and Local Network – Application and Presentation Tier – OS Web Server and Clients

Within a PCS7 OS multiple station system, the PCS7 OS Web server is an OS client with PCS7 OS Web server functionality. An OS client, which is configured as a PCS7 OS Web server, can no longer be used as an operating station (OS client) within the PCS7 system.

A PCS7 OS Web client accesses the project data provided on the PCS7 OS Web server via Intranet or Internet using a web browser [2.11], so the process can be operated and monitored. The setup of Web Clients can be done by accessing the Web Server by remote operations. It is important to review the number of licenses. In our current system 9 clients can simultaneously access the Web Server.

These lients are ordinary stations called week clients, due to web browser connectivity and have no WinCC project.

User monitoring and command rights are configured via "User administrator" tool on the Web Server. All servers run on Windows 2003 Server operating system.

C. PCS7 programming software architecture

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The main concepts of industrial automation PLC, DCS and SCADA are implemented here through Siemens PCS7, composed of two main tools WinCC and Step7. PCS7 comes with new development tools and facilities:

- new editors CFC and SFC with libraries;
- different views:
  - Plant View - for configuring the plant hierarchy and associating programming blocks with plant areas. Here the OS project contains the picture and the AS project the programming block.
  - Process Object view shows details for the individual object;
  - Component View shows the physical location where the objects are (e.g. CFC in the PLC and process pictures on the OS Servers).

The system is built around a multi-project architecture. There are two main projects, one for the AS and one for the Oss, in order to allow distributed engineering. Finally each of the objects in a project are downloaded to their targets. The targets are recognized by means of connections, configured with "NetPro" tool in Simatic Manager and proper physical configuration of each of them.

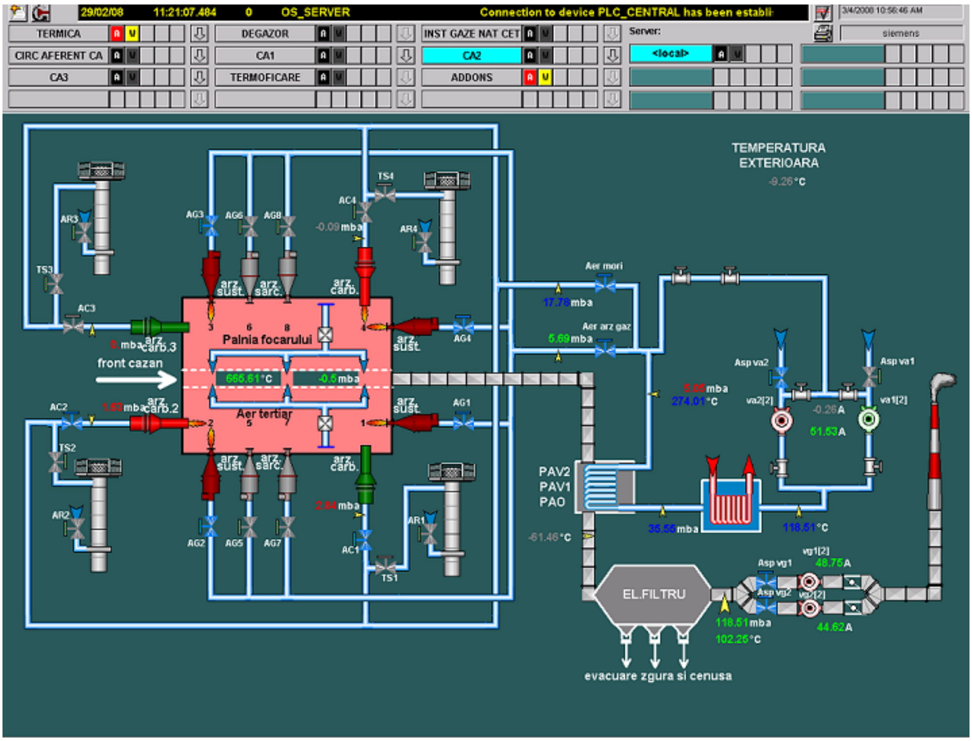

Fig.2.8.SCADA system synoptic image Air – Gas Circuit for steam boiler 2

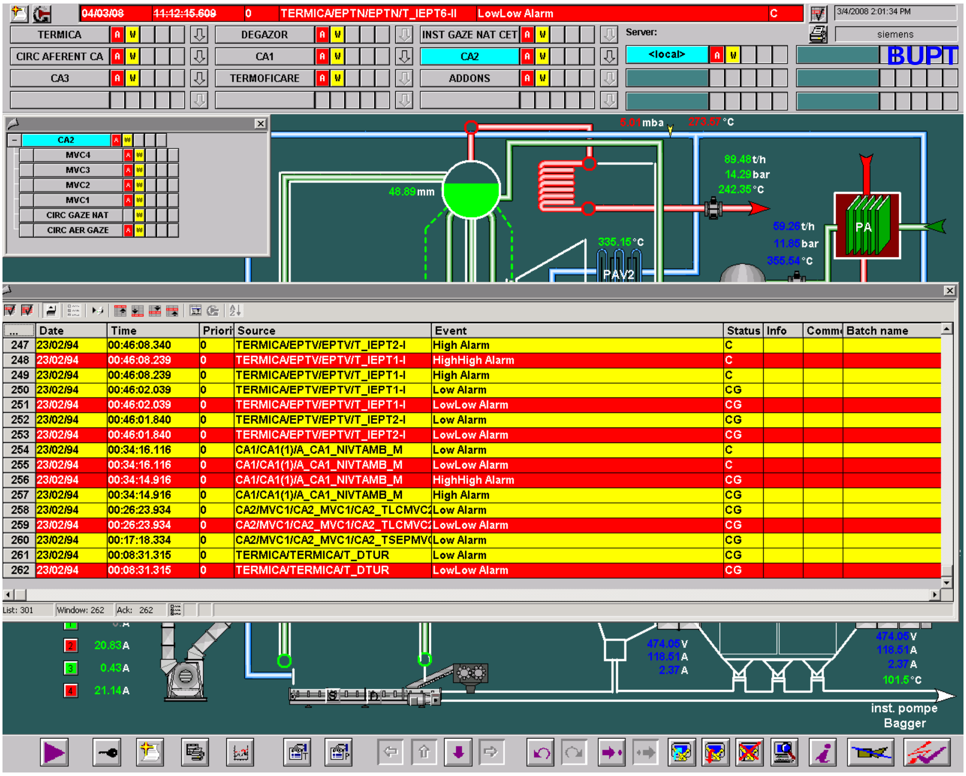

Fig.2.9.Example of PCS7 alarm system

2.5. Conclusion

As ***relevance to the thesis***, the present chapter presents the designed SCADA system application for COLTERM thermal power plant south of Timisoara in terms of hardware and software, functionality and utilization, as an *integration platform for automatic control strategies which are to be discussed in Chapters 3 & 4.*

This application presents the design and implementation of a SCADA system for a thermal power plant (CET) South of Timisoara, meant to supervise and control field distributed electric devices using Siemens software and equipment. Remote actions and uninterrupted monitoring are possible due to redundant servers and web-based applications via OPC server and web server. The new system has replaced the old existing SCADA and it is currently in use and fully functional.

The system has the following advantages:

- Remote and safe operation and monitoring from anywhere in the world.
- Suggestive synoptic images (Fig.2.8).
- Evolution charts for one week.
- Archives and easy to interpret alarm system (Fig.2.9).
- Physical features: flexibility, scalability and powerful modular structure, all these characteristics leading to a reliable and robust system.

- Improved dispatcher reaction by centralizing the monitoring of the plant with a user-based concept, showing real-time data, trends and synoptic images and executing commands from the operator stations.

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All this leads to a decrease in transient and dead times. Overall, operators are less prone to errors and with the help of the "event manager", it is possible to analyze previous actions in order to improve plant sequences.

In this stage, the SCADA automation system infrastructure for the thermal power plant South of Timisoara is ready to accept different control strategies.

Relevant author published work to the present chapter is represented by papers [1] indexed in ISI Proceedings, IEEE Explore, SCOPUS; and [2] in CRC Press - Taylor & Francis Group on Amazon.

[2.1] D. Bailey and E. Wright, "Practical SCADA for Industry", Newnes Elsevier, 2003.

[2.2] S.A. Boyer, "SCADA: Supervisory Control and Data Acquisition", 3rd Edition, ISA, 2004.

[2.3] M. P. Groover, Automation, Production Systems, and Computer- Integrated Manufacturing, 3rd Ed., Pearson Education Inc., Prentice Hall, 2008.

[2.4] www.automation.siemens.com/bilddb/index.asp?lang=en.

[2.5] R. Chartier, "Application architecture: an n-tier approach", http://www.15seconds.com/issue/011023.htm.

[2.6] O. Chelai, "A web-based application for water pressure control", in Proc. 8th International Conference on Technical Informatics CONTI 2008, Timisoara, Romania, vol. 1, pp. 139-142, June 2008,

[2.7] Siemens, PCS7 Manual Collection 2007 – "Automation System S7-400 Module Specifications",2007.

[2.8] Siemens, PCS7 Manual Collection 2007 - "Engineering system", 2007.

[2.9] Siemens, PCS7 Manual Collection 2007 -"Getting started Part 1", 2007.

[2.10] V. Tipsuwanporn and J. Rodkamtui, "Fault tolerant control system in critical process based on Ethernet network", in Proc. 2006 IEEE Conference on Robotics, Automation and Mechatronics, Bangkok, pp. 1-4, June 2006.

[2.11] Siemens, PCS7 Manual Collection 2007 – "PCS 7 OS Web Option".

3. DRUM BOILER CONTROL SYSTEM EMPLOYING SHRINK AND SWELL EFFECT REMISSION IN THERMAL POWER PLANTS

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The present chapter begins by presenting a temperature control system application, under Labview environment, as an introduction to the development medium and to automatic control of slow dynamics processes. Following, a review is presented with pros and cons on boiler turbine models, ranging from low order models to high order, complex knowledge based models. Both models were fitted for a real thermal power plant, were validated by open loop tests and static functioning points and are integrated into applications. The models are presented through two applications. The issue of attenuating the shrink and swell minimum phase phenomena, by using and comparing simple PI laws with gain-scheduled cascade PI control structures is illustrated towards the end of the chapter. Results are presented in a comparative form with discussions.

3.1. A brief insight into control of slow dynamics processes with Labview

This chapter presents a SCADA (Supervisory control and data acquisition) system for monitoring and control of a thermal process by using ADAM 6024 acquisition module and LabView Software. The link between the process and the PC stations is established by using DeviceXplore OPC server. Here the data (in/out) is defined, scaled and ready for processing. The HMI (Human machine interface) has the task to acquire data from the OPC Server, execute the required control algorithms and provide real time capability. The software used for these tasks is LabView 8.6.

The behavior of the system is studied on a laboratory process, ***gradually introducing key building blocks for the present thesis***, which are used for control and implementation. These features are:

- Labview graphical language programming software for modeling and control (Chapters 3 - 5).
- Ziegler – Nichols open loop tuning method for cascade gain-scheduled control of the boiler-turbine process (Chapter 3).
- OPC Server as a transition environment between hardware-in-the-loop linked systems (Chapters 5).
- Important insight in controlling slow dynamics processes (Chapter 3, 4).

The advantages of these systems consist in the simplicity of the programming language, the possibility to control the system through internet via OPC Server, the possibility to use data from/to text file and system evolution data being stored on the HMI.

3.1.1. Description of an application for temperature control

The application studied is a thermal process for monitoring and controlling temperature. These tasks are implemented with LabView8.6 on the human-machine interface which in this case is a PC. The control of temperature is made by a PI controller.

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ADAM 6024 module is used as a I/O controller. Through one analog channel the data from the process is acquired and send to the software developed in LabVIEW. By an analog output channel the values that come from the PI controller are sent as command values to the process. The transfer of data from ADAM 6024 to the thermal process is dint by a Temperature Conditioner and Amplifier module.

The data transfer between the computer and the ADAM 6024 module makes use of Ethernet bus. ADAM-6024 modules feature a 10/100 Mbps Ethernet chip and support industrial Modbus/TCP protocols over TCP/IP for data connection. ADAM-6000 also supports UDP protocol over Ethernet networking [3.1].

3.1.2. Presentation of hardware system configuration

The elements which form the hardware system are presented below:

- The ADAM-6024 Ethernet-based data acquisition and control modules provide I/O, data acquisitions, and networking in one module to build a cost effective, distributed monitoring and control solution for a wide variety of applications. Through standard Ethernet networking, ADAM-6024 retrieves I/O values from sensors, and can publish them as a real-time I/O values to networking nodes via LAN, Intranet, or Internet. With Ethernet enabled technology, ADAM-6000 series modules build up a cost-effective DA&C system for Building Automation, Environmental Monitoring, Facility Management and eManufacturing applications. This module has 6 analog inputs, 2 analog outputs, 2 digital inputs and to digital outputs. All the channels can receive current in range of 0-20 mA and voltage between 0-10 V for outputs and -10 - +10 V for inputs. The ranges used are 0-10 V input and output.
- Temperature Conditioner and Amplifier module used for realizing the circuit for measuring temperature with a thermocouple and for transforming the command value from DC voltage to AC voltage necessary for turning on the heating. On this module are also the clamp for power supply of the heater and cooler, an on/off shifter for the cooler and the clamp for thermocouple which makes the connection between the process and this module.
- PUT – 1 – Thermal Process features thermal actuators: two electrical resistances (2 x 50W, 24VAC) and a fan (170 MC/h, 24DC, 4.5W). In the temperature unit, the process takes place on an aluminum plate. For the application with ADAM 6024 the thermocouple is supplied. The unit also includes a mercury thermometer which is used to provide the reference temperature.
- Power supplies in number of three one for ADAM 6024 in DC, one for heating in AC and one for fan in DC.
- Computer for running the control program.
- Cables to connect all the elements described above.

Fig 3.1 shows the diagram of hardware configuration.

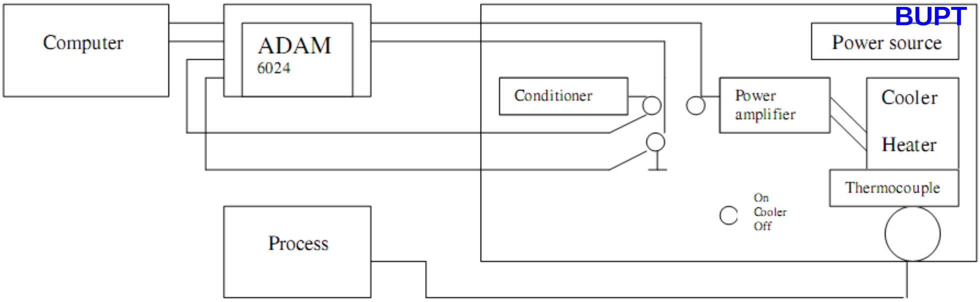

Fig 3.1. Hardware diagram for temperature control system

The following paragraph presents the interconnection method:

- The ADAM 6024 module must be connected with the computer by Ethernet and all the power supplies set at the necessary voltage;
- One input of the ADAM 6024 must be connected to the conditioner; one output must be connected to the power amplifier from the same module;
- All clamps for power supply connected to the sources needed and the thermocouple connected to the clamp marked on the temperature conditioner and amplifier module;

After all these steps have been completed the thermocouple measures the temperature in the process. The temperature reading is sent to one input of the ADAM 6024 from the temperature conditioner and amplifier module. This value is introduced in the PI from the software and the value given by the controller is sent back to the process through the output of the ADAM 6024. As a result the temperature remains constant at the desired value.

3.1.3. Labview software application

The control of the process is implemented with LabVIEW8.6. LabVIEW has a lot of virtual instruments developed by national instruments to make the programming work easier. It also has the possibility to communicate with a lot of devices by having drivers for almost all communication protocols [3.2].

The program in LabVIEW has to different parts the front panel, where the graphics and the instruments for data control and indicators are placed, and the block diagram where the program is constructed by inserting the needed existing blocks and connecting them by wires in a suitable way.

This application reads data from OPC server under a tag format. The OPC reads the raw data from AI0 (analog input 0-10 VDC) from the ADAM module and converts it by scaling, in temperature tag. This temperature is read with LabVIEW and then is placed as process variable at the input of the controller. The set point is adjusted by the user as well as the PID constants. The PI controller draws off at the output a variable which is written to another tag from the OPC server. This tag is set to write data to the AO1 (analog output 0-10VDC) of the ADAM 6024. The data received from LabVIEW is temperature and it must be scaled to become a voltage in order to command the next step of the process. The operation described above cycles to maintain the temperature at the desired value.

3.1.3.1. Front panel of the application

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The front panel of the application is the human machine interface. It presents the data acquisitioned in a graphical form, contains all the buttons that can start or stop different parts of the application and contains all the virtual instruments which correspond to the variables from the block diagrams. Here you can also find the instruments which show the data obtained after executing some parts of the program in order to help users to verify if the application is working properly.

The front panel from this application is shown in the Fig 3.2. It contains two charts (one presenting the data read from the process and the second one the evolution of the controller), 3 buttons (stop the three main parts of the program) and one switch (stops data to be written on the tag of the OPC server).

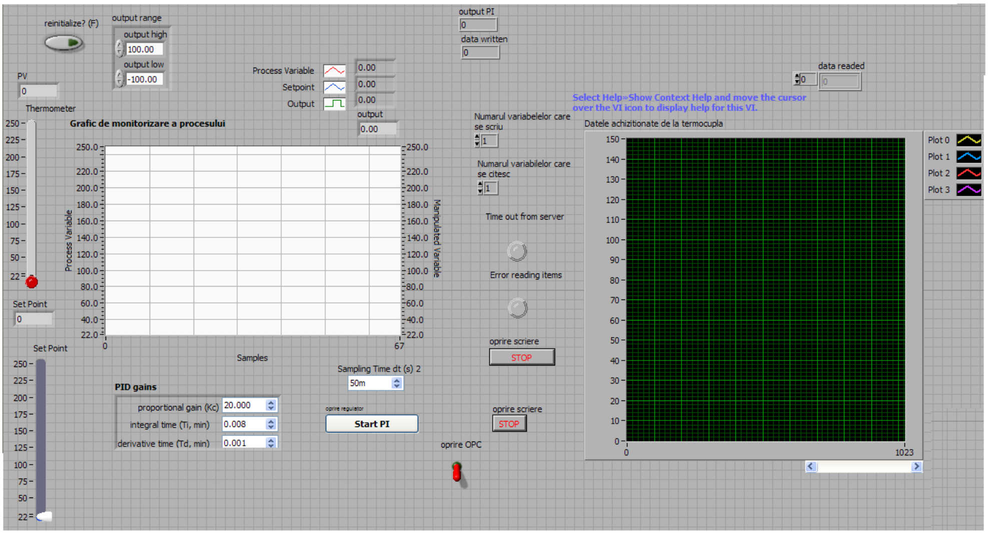

Fig 3.2. Front panel of the software application for temperature control system

3.1.3.2. Block diagram of the control program

This is the part of the LabVIEW code where the program for control and monitoring is developed. The structure of the program is presented in Appendix 1.

The graphical language code reads the data, by using data-socket communication for TCP/IP protocol, from the selected tag of the OPC server. The process is controlled by computing a command by the PI controller and again by using data-socket communication, the command value is written in a tag to the OPC Server, which sends it to an output of the ADAM module, thus controlling the process.

3.1.4. Experimental results

To maintain the temperature at a desired value it is necessary to calculate the constants for the controller. The chosen method for control is the PI controller, because the thermal process is a slow process with dead-time. To determine the gain and the integral time the Ziegler - Nichols method was used for step response of the system in open loop process. The formulas for calculating the constants of the controller are:

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$$KP = \frac{0.9 \cdot T}{K \cdot T_m}, \frac{KP}{KI} = 3.3 \cdot T_m \qquad (3.1)$$

where: K-gain, T_m-dead time, T-time constant. The constants obtained after measuring the step response and the controller gains are presented in table.3.1.

Temp. [°C]	K	T_m	T	KP	KP/KI
30	2.3	0.3	0.9	1.173	0.99
50	1.25	2	3	1.08	6.6
80	0.61	0.1	0.5	7.36	1.66
125	0.45	0.05	0.3	12	1

Table 3.1. Ziegler-Nichols open loop parameters and PI controller gains

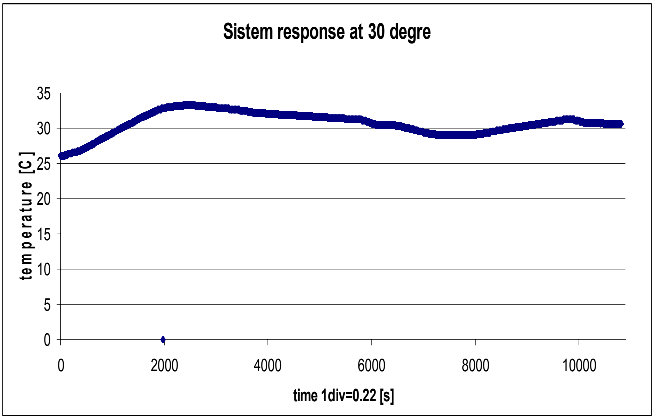

Fig 3.3. System response for step reference from 25 °C to 30 °C

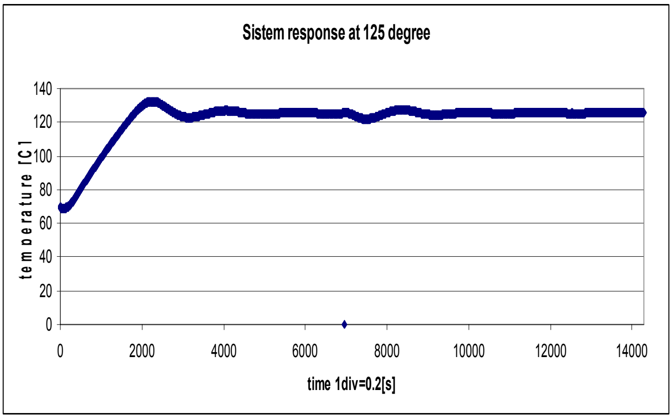

Fig 3.4. System response for step reference from 70 °C to 120 °C

The experimental results present a good response of the temperature process. The temperature is maintained satisfactory at the desired value.

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It can be seen that the accuracy of maintaining the value of temperature at set point is acceptable. The system presents some oscillations but the value of the overshoot is only of 3 degrees Fig 3.3.

In Fig 3.4 the controller maintains the temperature at the desired set point accurately. The overshoot is of 7 degrees.

The differences that appear between the two graphs are because of the PID gain values. The two possibilities for setting the controller gains are: in the first case Fig 3.3 the overshoot has a low value and the temperature oscillates all the time; in the second case Fig 3.4 the overshoot is high but the system doesn't oscillate almost at all. On these considerations the constants of the controller are selected in concordance with the need of the application.

3.1.5. Conclusions for section 3.1

This chapter presents a monitoring and control system of a thermal process by using ADAM 6024 acquisition module and LabView Software.

The behavior of the system is studied on a laboratory process, ***gradually introducing key building blocks for the present thesis***, which will be used for control and implementation in the following thesis chapters:

- Labview graphical language programming software which is the main tool (environment) for developing of models and control strategies in the present thesis (Chapters 3 - 5).
- Ziegler – Nichols open loop tuning method for cascade adaptive control of the boiler-turbine process (Chapter 3.3).
- OPC Server as a transition environment between hardware-in-the-loop linked systems (Chapters 5).
- Important insight in controlling 1st order + dead time systems (Chapters 3.3, 4).

The advantages of these systems consist in the simplicity of the programming language, the possibility to control the system through internet via OPC Server, real time capability, the possibility to use data from/to text file and system evolution data being stored on the HMI.

3.2. Low order boiler-turbine models, fitting and simulator implementation

The present chapter introduces low-order boiler turbine models, as a first step in modeling and control of boiler-turbine processes, and presents a critical analysis of these models.

The chapter deals with an open loop dispatcher training simulator implemented in Labview for Colterm heating power plant in Timisoara, Romania. The system employs real-time capability, graphical user interface (GUI), uninterrupted operator interaction, having as background a low order boiler-turbine model for dynamic simulation. The operator manually controls the fuel charge on each of the three boilers, the turbine valve position and the steam to consumers in order to anticipate parameter evolution on each of the boiler units and on the power generated by the turbine.

Subsequently parts of the low-order boiler-turbine model are used in Chapter 3.3 for model extension. The real – time implementation from the present chapter provides an important background in Chapter 5 for HIL systems while the modeled low-order process itself gives a good head-start in thermal process understanding for Chapter 3.3 and Chapter 4.

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3.2.1. Low order boiler-turbine models

The data problems and the need for accurate low order models representing boiler dynamics is not new [3.3]. Every model has to be adapted in parameter and architectural terms for each cogeneration plant. There are a couple of ways of constructing such a model either by use of first principle of mass, energy and volume balance or by using simplified models. The system responses are similar and can be considered as equally valid in some situations as presented in [3.4].

A suitable boiler model for the long term dynamics simulation of a power system must accurately represent the main unit outputs as well as capturing some of the relevant internal variables [3.5]. The outputs monitored are the power generated by the turbine and the throttle pressure, and as variables the steam flow, generated steam and drum pressure.

Concerning the heating power plant in Timisoara the overall modeled system is divided into three 49t/h coal fired boilers having the capacity of producing 100t/h steam at pressures up to 20 bars. These units use the steam for the internal and external consumers and to generate electric power by passing the superheated steam to a 16 MW turbine. The boilers are small cogeneration units compared to the ones described in [3.4] due to their double functionality.

The present chapter also presents how to put a LabView virtual instrument (VI) – "the simulator", into a real time application, although this is done only for test purpose. The concept is then to be used in Chapter 5.

The difference between running in real-time under a real-time operating system (RTOS) - in LabVIEW, or using a general purpose operating system (i.e. Windows - GPOS), is that the RTOS assures determinism by executing the simulator as a time critical priority program on the real-time target (hardware) leaving the interface to be executed by the host (i.e. PC, touch screen).

On the other hand, ***low order boiler models present major drawbacks***:

- No information whatsoever about water dynamics, hence no automatic control possibility on the loop.
- No information regarding distribution of steam and water in the riser and down-comer.
- No information linked to steam quality, steam volume ration and other important internal parameters.
- The shrink and swell dynamic, is not implemented in order to be compensated.
- In order to perfectly fit the model to a thermal power plant, tests need to be carried out at the real site, thing which is not always possible.

General schematic of the plant is presented in Fig 3.5. The water entering the water walls of the boilers is transformed into steam due to heat transfer from the furnace to the pipes metal. The steam is gathered in a drum which sends it to a super heater for transforming wet steam to saturated steam. After leaving the boiler unit the steam is sent to a turbine which generates electric power.

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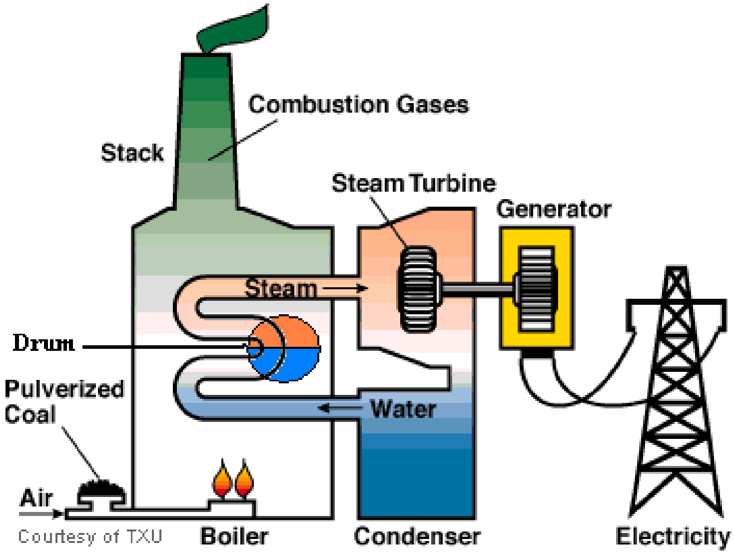

Fig 3.5. Overview of boiler-turbine generator unit

Several boiler models were proposed for different types of generating units, some having as a starting point the low order model presented in Fig 3.6 from [3.6].

The turbine valve is used to control the steam pressure (P_T) and steam flow (S_F) at the turbine inlet. The net steam flow (SN) is the difference between the generated steam (S_G) and S_F. The drum pressure (P_D) is proportional to the integral of the net steam flow to the storage volume (C_B), which gives the ***energy balance relation***:

$$C_B \frac{d\Delta P_D}{dt} = \Delta S_G - \Delta S_F \tag{3.2}$$

P_T which is the steam inlet to turbine [3.7] is the difference between drum pressure and the pressure drop on the super heater (P_{SH}). The drop in steam pressure from the drum to turbine is represented as the square of the steam flow rate (S_F), while Ksh denotes the friction coefficient of the super heater tubes [3.7]. The main non-linear characteristics of the system and are illustrated in relation (3.3 – 3.5):

$$P_D - P_T = K_{SH} S_F^{\,2} \tag{3.3}$$

where:

$$S_F = \mu P_T \tag{3.4}$$

and

$$P_{SH} = K_{SH} S_F^{\,2} \tag{3.5}$$

The fuel dynamics is modeled using dead time element with the time constant Td of the fuel, in series with a first order element with time constant Tf for the heat to reach the water inside the water walls. The fuel dynamics is limited (HLM=49 t/h) by physical constrain.

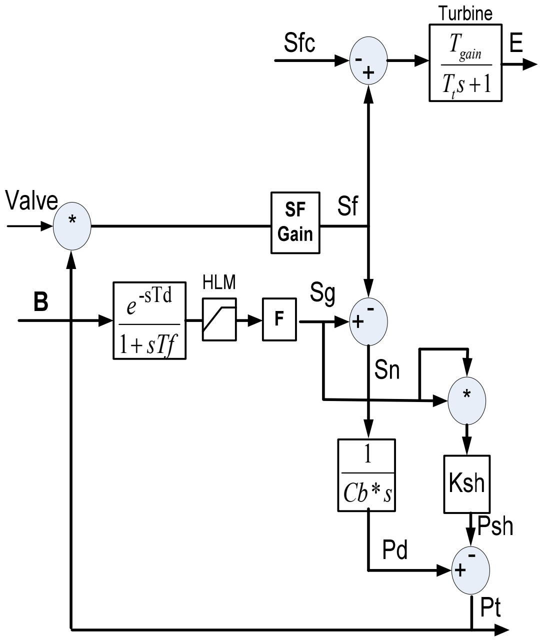

Fig 3.6. Low order model of boiler - turbine system [3.6]

Parameter	Description
Cb	Boiler storage constant
B [t/h]	Fuel flow rate
ep	Pressure deviation
F	Fuel gain
HLM	Steam generation high limit
Ksh	Super heater drop friction coefficient
Pd [bar]	Drum pressure
Pref [bar]	Throttle pressure reference
Psh [bar]	Pressure drop from drum to throttle on super heater
Pt [bar]	Throttle pressure
Sg [t/h]	Steam generation
Sf [t/h]	Turbine steam flow
Sfc [t/h]	Steam to consumers
Sn [t/h]	Net steam flow into drum
Td [s]	Fuel time delay
Tf [s]	Fuel and water wall time constant
T_{gain}	Turbine gain
T_t [s]	Turbine time constant
Valve	Valve position

Table 3.2. – Parameter description

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The model proposed in this paper for implementing the open loop simulator is based on the one from figure 2 in [3.8]. The boiler-turbine unit can be modeled as a MIMO 2x2 system [3.9] having the following inputs and outputs:

- Inputs: Valve – [0% - 100%] and B - fuel demand 0[t/h] – 49[t/h].
- Outputs: PT [bar] - throttle pressure and SF [t/h] - steam flow.

Implementation with the graphical language codes in Labview for the boiler system, the turbine and the overall simulator is presented in Appendix 2.

3.2.2. Fitting the model for thermal power plant south of Timisoara

Model coefficients can be calculated by using the methods described in [3.6] and [3.8], by conducting two tests on the real plant:

- 1st test, by modifying the throttle valve position with about 10% for determining the boiler storage constant (CB).
- 2nd test, by making a step change in fuel demand for determining the fuel dynamics TD and TF coefficients.

Unfortunately this test couldn't be carried out for the desired range of steps.

Only a step in steam valve position corresponding to a 2% opening and closing could be executed. The pressure stabilizes after about 2 minutes with a difference of 0.2 from 13.5 to 13.3 [bar], Fig 3.7. From this test the boiler constant C_B can be estimated at about 146 seconds.

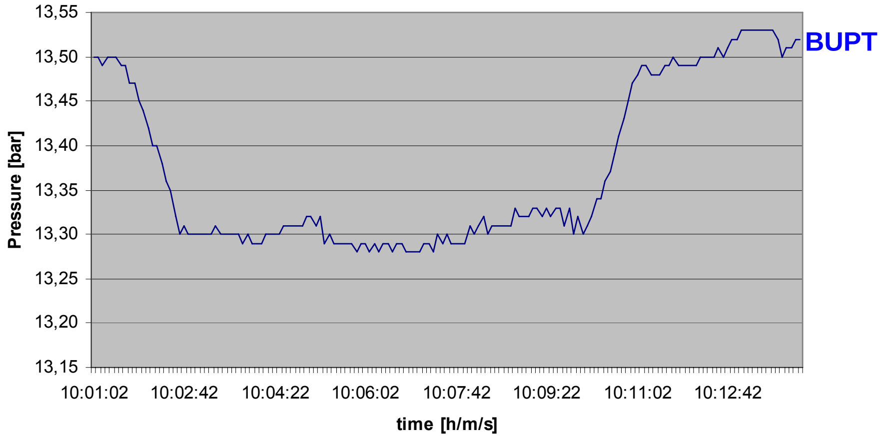

Fig 3.7. Pressure (PT) response to 2% step change in valve position

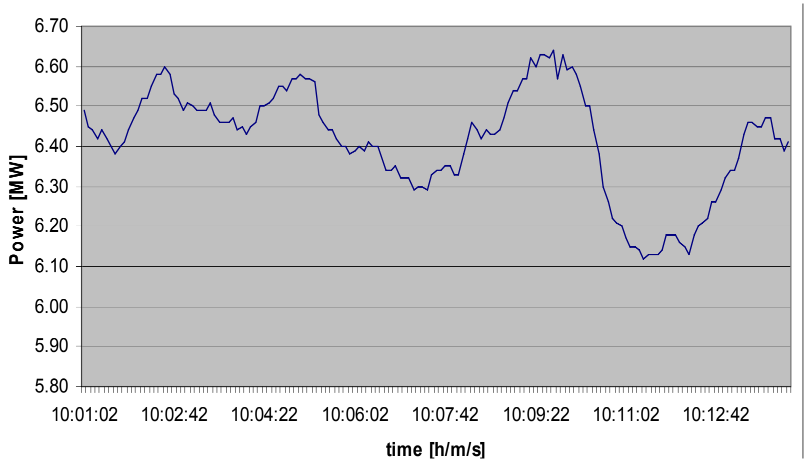

Fig 3.8. Steam flow (SF) response to 2% step change in valve position

Usually boiler constants range from 140s to 180s, depending of the type of fuel used: coal, gas, oil, cogeneration (gas + coal) and so on.

A precise estimation would require to record and analyze the steam flow rate as described in section 3.1 from reference [3.6]. Regarding the small amplitude of the step in valve position, due to the lack of automatic control loop on the fuel flow rate, the steam flow data is hard to analyze due to disturbances as presented in Fig 3.8 and Fig 3.9. Coefficients for evaluating the fuel time delay TD and the fuel and water wall time constant TF are approximately the same for coal plus gas fired boiler as for coal fired boilers, so were taken from [3.6], the values being presented in table 3.3.

In order to model the turbine, the generated power is analyzed, Fig 3.9, in the present scenario with steam valve step. It is observed that the generated power follows closely, almost instantaneously the steam flow rate, which is the input for the turbine model (see appendix 2).

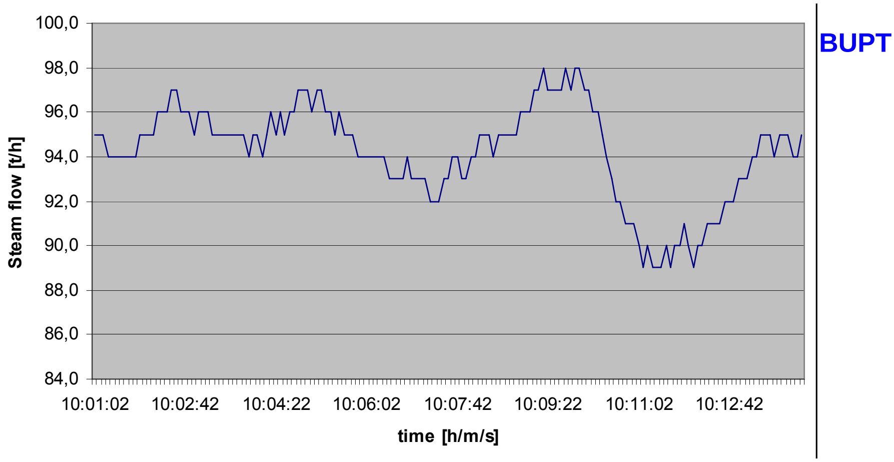

Fig 3.9. Generated power (E) response to 2% step change in valve position

The turbine is then approximated with a 1[st] order plus gain element where the steam flow gain SF and the turbine time constant T plus gain are presented in table 2.3.

For the boilers of the thermal power plant at Timisoara the parameters were identified as follows:

TD	TF	C_B	F	SF gain	T_t	T_{gain}	K_{SH}
4	14	146	1.998	0.1	2	0.068	0.000138

Table 3.3 – Boiler – turbine coefficients

The coefficients above apply to all of the three boilers thanks to the same architecture and performance.

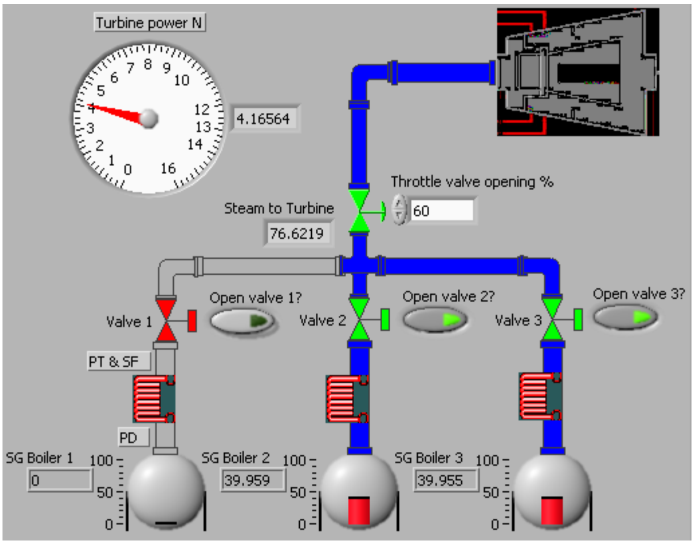

Fig 3.10. Simulator interface for 3 boiler-turbine system

The steam from the boilers is collected on a common pipe and sent to a 16 MW turbine inlet. Each boiler needs a valve in order to balance the steam on the common steam pipe as in Fig 3.10, which also represents the graphical user interface.

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At the real site the problem is that this valves are open/close types and do not allow positioning in order to control the throttle pressure. This is a major inconvenience because until the boiler reaches the pressure in the throttle pipe the afferent valve cannot be opened and all the steam is either lost in the atmosphere or given to consumers.

3.2.3. Real-time implementation of the simulator for low-order model of boilers and turbine system

Real-time option of the simulation model is very important because it adds realism by allowing the operator to act on the system while the simulation is executing. Otherwise the simulation would run very fast, taking into account the current processor computing capability. Real – time capability can be implemented by choosing to run only the main simulation loop presented in Appendix 2, Fig.2C, on an RT target with an RTOS assuring determinism to the process. The principle is presented Fig 3.11.

Using the Real time communication wizard three VI's are created: time critical loop (TCL) which contains the simulation, normal priority loop (NPL) which contains the communication protocols through RT FIFO's and calls the TCL and the host loop which contains the GUI Appendix 2, Fig.2D.

The NPL is downloaded to the RT hardware PCI 7041/6024E and the host loop runs on the PC. The RTOS provides determinism which is the characteristic of a system that describes how consistently it responds to external events or performs operations within a given time limit [3.10]-[3.14].

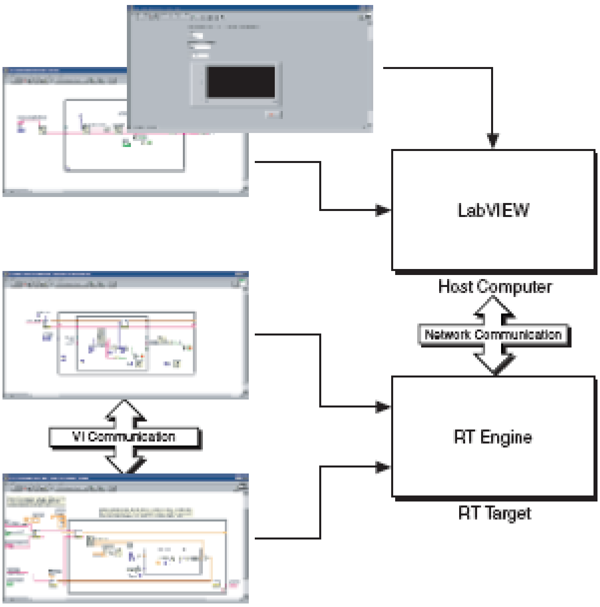

Fig 3.11. Real-time implementation principle for thermal power plant simulator [3.10]

3.2.4. Simulation results

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Several tests were done on the simulator to verify the accuracy of the dynamics of the model. Each test was executed starting from the desired operating point. Some results were compared to the real data from the power plant in a similar maneuver in order to validate the model.

A. Test 1 – Step in valve position 70% - 72%

The first test employs validation of the model while executing a similar test on the valve position as the one on the real power plant. The stationary point has the following parameters: Boiler firing rate B=47.5 t/h; PT=13.5 bar; SF=94.7 t/h; Valve 1=open; Turbine power E=6.44 MW; Throttle valve=70%.

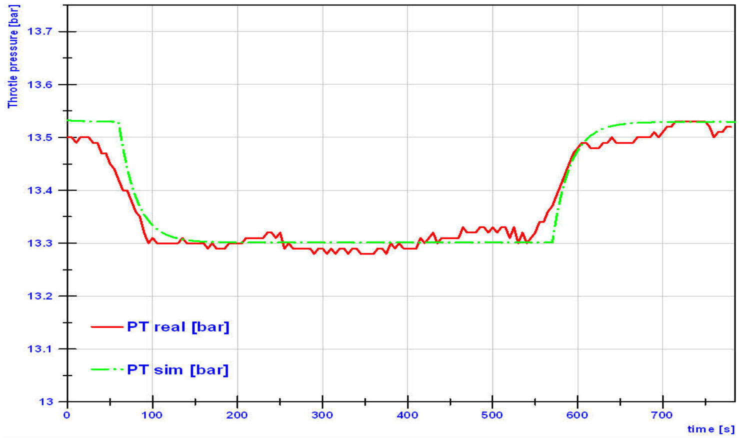

Fig 3.12. Pressure (PT) response to step change in valve position 70%-72% at t=60s, and 72%-70% at t=570s

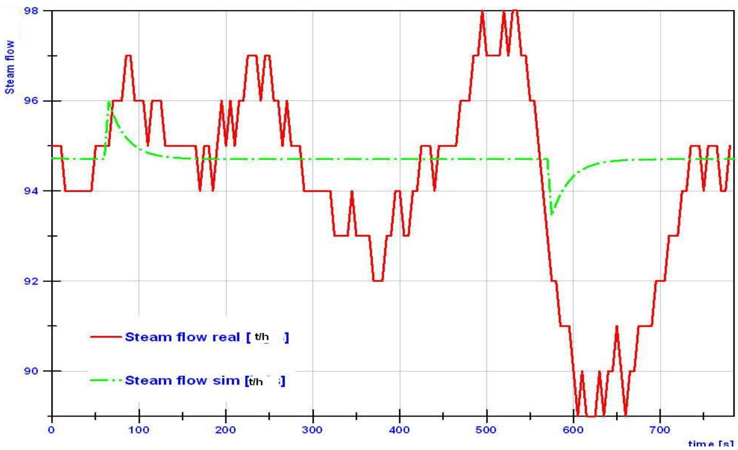

Fig 3.13. Steam flow (SF) response to step change in valve position 70%-72% at t=60s, and 72%-70% at t=570s

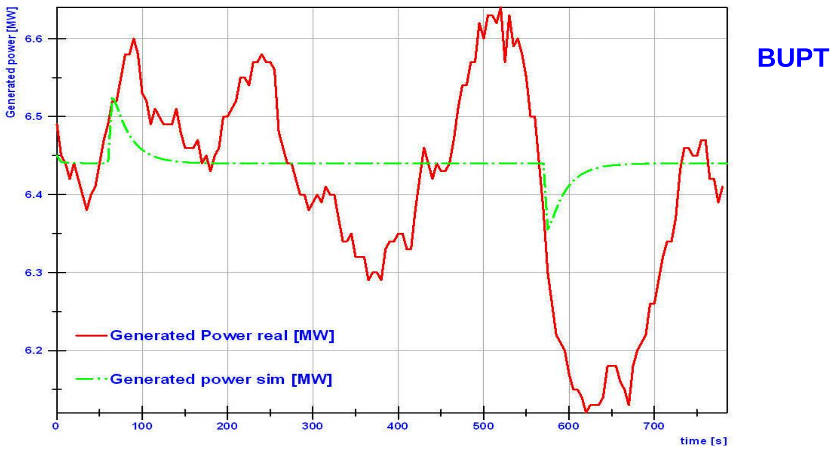

Fig 3.14. Generated power (E) response to step change in valve position 70%-72% at t=60s, and 72%-70% at t=570s

At t=60s a step change in throttle valve position is made from 70% to 72 %. The throttle pressure is up to 10% lower than drum pressure due to pressure drop on the super heater. The pressure drops due to throttle valve opening Fig 3.12. A spike is detected at turbine power and steam flow Fig 3.13 and Fig 3.14, because of the instant excess of steam, but gradually the speed of the fluid decreases due to the pressure drop, thus the steam flow returns to its former value. At t=570s the steam valve closes, the same phenomena being detected but, this time inverted.

In order to verify the fitting of the model, a comparison is made between the simulated and real data from the thermal power plant.

By analyzing this data, it results that the model is well fitted and corresponds to the behavior of the real thermal power plant though many oscillation due to disturbances are present and make parameter fitting difficult.

B. Test 2 – Step in fuel flow rate (B) 32 t/h -29 t/h & step in steam to consumers corresponding to 15 t/h

Modification at the load of the boiler and steam to consumers makes the subject of the next test.

Other operating points are chosen:

Boiler 1 operating point: PT=8.74 bar; B=29 t/h; SF=58 t/h; Valve1=open;

Boiler 2 operating point: PT=9.7 bar; B=32 t/h; SF=64t/h; Valve2=open;

Throttle Valve=70%; E=8.74 MW – generated by two boilers at close pressure operating points

For boiler two, a step change in its firing rate is made at t=100s, from 32 t/h to 29 t/h. A pressure and steam flow drop is recorded Fig 3.15 and Fig 3.16. The power output of the turbine also decreases from 8.74 MW to 7.9 MW Fig 3.17.

The results presented in this chapter are intuitive for dispatchers in order to estimate boiler responses at various operating points and plant maneuvers. Further expansions can be made to the simulator by estimating more accurately the responses of the plant by executing literature presented dynamic test rather than static test or by using equation based models.

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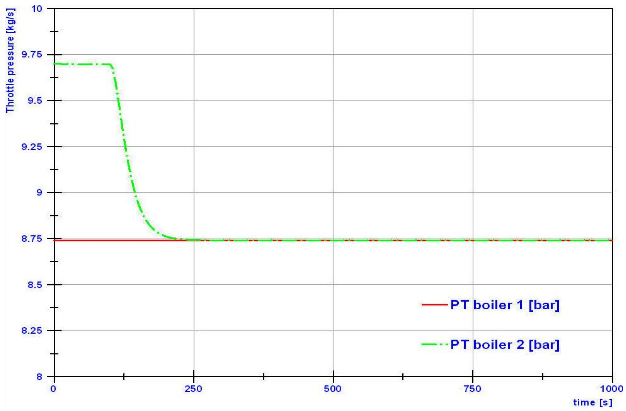

Fig 3.15. Pressure (PT1, PT2) response for boiler 1 – red & boiler 2 – green for step at t=100s in firing rate (B) 32t/h – 29 t/h at boiler 2

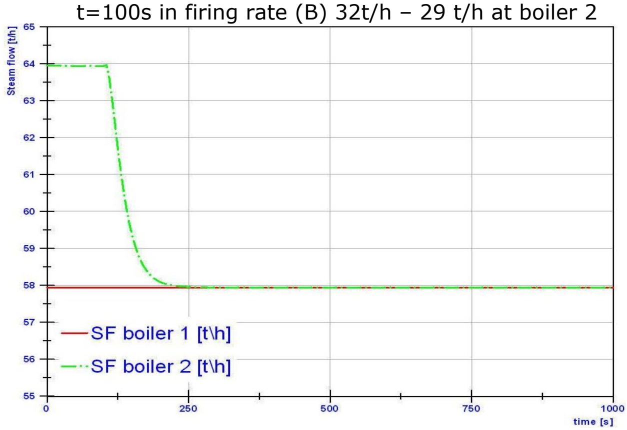

Fig 3.16. Steam flow response for boiler 1 – red & boiler 2 – green for step at t=100s in firing rate (B) 32t/h – 29 t/h at boiler 2

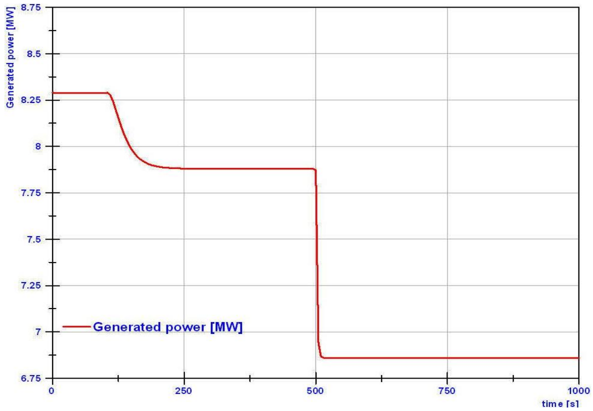

Fig 3.17. Generated power (E) response for step at t=100s in firing rate (B) 32t/h – 29 t/h and step at t=500s in steam flow rate to consumers (SFc)– 15 t/h

At t=500s steam from the common collector pipe is sent to consumers, meaning that SFc=15 t/h. The power of the turbine decreases due to less steam at the inlet. This actually acts as a constant disturbance to the 3 boiler system commanded by a manual maneuver from the steam to consumers valve.

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The first power decrease results from the drop in firing rate, while the second decrease is due to 15 t/h of steam sent to the internal/external consumers.

3.2.5. Conclusions for Section 3.2

Low order boiler models have been widely used in literature for estimating industrial furnaces and generation units thanks to their simplicity. Such models are not perfect and might not always match exactly the responses of the real plant. In this chapter is presented a simulator capable to be switched in real time, based on data recorded on the actual plant. The functionality of this simulator can be found in dispatcher training for operating the boilers and to determine where improvements are needed by analyzing times during transient response and parameter values at various operating point.

Relevance to the thesis of this chapter can be found in:

- Presenting and fitting boiler turbine models to a real thermal power plant – COLTERM thermal power plant South of Timisoara.
- Give a head-start in understanding the complex thermal power plant processes by providing an important insight in process functionality, by using a simple, low-order representation.
- Critical analysis low-order boiler-turbine models, by means of accuracy/difficulty with pros and cons.
- Presenting the usefulness of a real-time implementation in Labview of the simulator, with the major advantage of giving the operator time to react to simulated process responses.
- Provide a thermal power plant simulator in real-time for dispatcher training in order to observe parameter transients and execute manual maneuvers.

3.3. Drum boiler control system employing shrink and swell effect remission in thermal power plants

This present chapter develops a control system for a drum-boiler unit, which employs a three feedback cascade control (water level, steam flow, feed-water) versus a single feedback control for the water level loop, in order to attenuate the non-minimum phase shrink-and-swell effect. The overall control structure includes a heat flux control loop for throttle pressure stabilization. Gain scheduling technique is added to improve system responses at various operating points. The process is built around the Åström-Bell non-linear complex drum-boiler model fitted for a real 16 MW thermal power plant. The model is extended with actuators, super-heater and turbine dynamics. The implementation is carried out in Labview, employing a graphical user interface (GUI) for friendly man machine interaction with selection of manual/automatic mode. The simulation results are focused on manual/automatic control operation with satisfactory response behaviors.

There are many mathematical models of boiler-turbine units in literature. Simple low order models e.g., *the model presented in Chapter 3.2*, were extensively studied for simulation and control [3.6] - [3.8]. Several simulation software were developed for the long term simulation of power system transients. For brevity purposes, most of them have tended to use simple low order models to represent the slow boiler dynamics which become significant over the longer time frames. An analysis carried out by M.E. Flynn and M.J. O'Malley in [3.5] point out the disadvantages of such models and which are presented in the following paragraph.

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Linear small perturbation models were also used in this same direction and purpose [3.15]-[3.19]. Other low order models have been developed [3.6],[3.20],[3.21]. In [3.6] the inaccuracy due to imprecise representation of the dynamics involved was quantified and it was found that the model parameters had only a small influence on the overall boiler dynamics. The low order model developed in [3.16] is only valid for small deviations from the nominal operating conditions and the parameters depend on the operating point of the plant. In any event, all of these oversimplified models fail to address the issue of plant protection [3.22].

Moreover most of these low-order models are restricted to power and pressure modeling, *as presented in Chapter 3.2*, without providing valuable information on boiler water dynamics and important density driven parameters. More detailed models range from complex knowledge based models to experimental ones derived from special plant tests. In the middle of this range are so-called 'interpretation' models [3.23], [3.24], which are complex enough to capture the key dynamics and in the same time have good control design features [3.25]. These boiler models must also have a fundamental approach on physical laws which is also the present case.

Such a model which merges the complexity of physical laws with plant data is the Åström and Bell drum-boiler model, developed in [3.27].

The boiler-turbine control systems are usually applied on the models developed by Åström and Bell, e.g. in [3.26], [3.27]. The models very well capture the shrink-and-swell effect used for control design and provides useful information for thermal power plant operators and dispatchers in order to anticipate transient responses for specific outputs and internal parameter variations.

The cascade control has its origins in [3.28] and presents a good solution for control optimization and disturbance rejection. The inner loop handles quick loads and rejection of disturbances, while the outer loop deals with process stabilization. As a result, the cascade control architecture has become one of the most important and popular control architectures and has found great applications in industrial process control, such as power plants [3.29], chemical plants [3.30], and so on [3.31]. Many thermal power plants all over the world use cascade control for water level, which is also the solution chosen in the present case.

The cost of thermal power plant operation is mainly based on the fuel consumption. For optimization reasons, the power generation must follow, as close as possible, the power load demand. This condition might be an issue due to the shrink-and-swell phenomena, which appears when a drop of pressure in the drum is detected.

Due to the phenomena of minimum phase behavior, the controller tends to initially react with an inverse command relative to what the process would really need, so the control system must be able to handle this effect [3.32].

The key features of the present chapter are:

- Model and extend a complicated nonlinear problem with fluid multiphase partial differential equations into a manageable and controllable solution.
- Developing and implementing a gain-scheduled cascade control system for a drum-boiler model with GUI.
- Reduce the shrink-and-swell effect.
- Perform a case study and extend a complex 4th order state-space non-linear coupled drum-boiler model.

- Adapting the model to a real thermal power plant including simulation facilities for dispatcher/operator training.
- Simulation results in manual/automatic control operation with satisfactory response behaviors of three feedback control versus single feedback control, for the water level in a wide range of plant operating points.

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3.3.1. Drum - boiler complex model

The basic schematic of a drum boiler unit is presented in Fig 3.18. Heat fed to the risers causes the water to boil, thus producing steam. The steam, due to gravity forces, rises in the drum, causing circulation through the downcomer-riser system. From the energetic point of view, water and heat are provided to the boiler and steam is taken out. Steam is also present below the liquid level, which causes an undesired effect called the shrink-and-swell phenomenon.

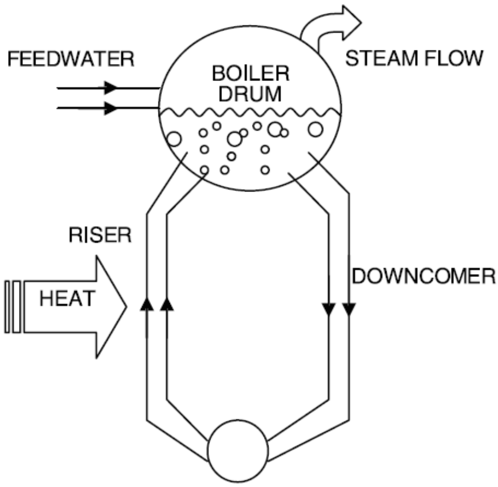

Fig 3.18. General drum-boiler schematic.

3.3.1.1. Shrink and swell effect

If there is a necessity in power demand, more steam needs to be provided to turbine by opening the turbine valve. This causes a sudden drop of pressure in the drum, allowing the steam bubbles under the liquid to expand in volume and therefore increase the water level. The phenomenon is called the swell effect. On the other hand, taking into account the mass balance of the boiler, it is expected that the water level decreases because the steam leaves the system. Eventually, the water level decreases with delay, if the feed-water flow is kept constant [3.32], [3.33]. The shrink effect is the opposite of the swell effect. This phenomenon takes place when steam demand is reduced. Following the same principle, the pressure rises, causing the vapor bubbles to shrink, resulting in a water level drop. Eventually, the water level rises if the feed-water flow is kept constant.

The combined phenomenon is called shrink-and-swell and presents a challenge to water level control due to its non- minimum phase behavior.

3.3.1.2. Åström-Bell drum-boiler complex model

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The chosen drum-boiler model is the one presented in Åström-Bell [3.27]. The model is developed by using overall mass and energy balance equations of the boiler system (3.6 – 3.8). The behavior of the drum level is obtained by accounting for the distribution of steam and water in the system.

Global mass balance equation:

$$\frac{d}{dt}[\rho_s V_{st} + \rho_v V_{wt}] = q_f - q_s \tag{3.6}$$

Global energy balance equation:

$$\frac{d}{dt}[\rho_s V_{st} u_s + \rho_v V_{wt} u_w + m_t C_p t_m] = Q + q_f h_f - q_s h_s \tag{3.7}$$

Volume balance equation:

$$V_t = V_{st} + V_{wt} \tag{3.8}$$

In this stage we need to make manipulations on the global energy balance equation, by expressing the internal energy u as follows: $u = h - \frac{P}{\rho}$ in order to obtain a density-pressure-enthalpy driven relation:

$$\frac{d}{dt}[\rho_s h_s V_{st} + \rho_w h_w V_{wt} - PV_t + m_t C_p t_m] = Q + q_f h_f - q_s h_s \tag{3.9}$$

Applying continuity expressions for mass flow rates of steam and water, (3.10), (3.11), and accounting for the fact that the total volume V_t is constant, thus providing a relation for V_{st} (3.13) from (3.8), a second order model is obtained (3.14). The fluid multiphase partial differential equations will be extracted from quadratic function representations of drum pressure P, for the parameters h_s, h_w, ρ_s, ρ_w and t_s at the end of this chapter.

Continuity relation for mass flow rate of steam:

$$\frac{d}{dt}\rho_s V_{st} = \dot{m}_{st} = V_{st}\frac{\partial \rho_s}{\partial p}\frac{dp}{dt} \tag{3.10}$$

Continuity relation for mass flow rate of water:

$$\frac{d}{dt}\rho_w V_{wt} = \dot{m}_{wt} = V_{wt}\frac{\partial \rho_w}{\partial p}\frac{dp}{dt} \tag{3.11}$$

The metal temperature t_m and the saturation temperature of steam t_s are strongly correlated, and both react, almost the same at changes in pressure, which allows the following substitution in the model (3.12): $t_m = t_s$.

Continuity relation for saturation temperature of steam:

$$\frac{d}{dt} m_t C_p t_m = m_t C_p \frac{dt_s}{dt} = m_t C_p \frac{\partial t_s}{\partial p} \frac{dp}{dt} \qquad (3.12)$$

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Total volume of steam expression:

$$V_{st} = V_t - V_{wt} \qquad (3.13)$$

The resulting model:

$$\begin{cases} e_{11} \dfrac{dV_{wt}}{dt} + e_{12} \dfrac{dp}{dt} = q_f - q_s \\ e_{21} \dfrac{dV_{wt}}{dt} + e_{22} \dfrac{dp}{dt} = Q + q_f h_f - q_s h_s \end{cases} \qquad (3.14)$$

where the e_{ij} coefficients are expressed by relations (3.15):

$$\begin{cases} e_{11} = \rho_w - \rho_s \\ e_{12} = V_{wt} \dfrac{\partial \rho_w}{\partial p} + V_{st} \dfrac{\partial \rho_s}{\partial p} \\ e_{21} = \rho_w h_w - \rho_s h_s \\ e_{22} = V_{wt} \left(h_w \dfrac{\partial \rho_w}{\partial p} + \rho_w \dfrac{\partial \rho_w}{\partial p} \right) + V_{st} \left(h_s \dfrac{\partial \rho_s}{\partial p} + \rho_s \dfrac{\partial \rho_s}{\partial p} \right) - V_t m_t C_p \dfrac{\partial t_s}{\partial p} \end{cases} \qquad (3.15)$$

In this stage a second order state space model has been developed, having as inputs: q_s - steam flow rate, Q – energy heat flux and q_f – feed water flow rate. As states, the total water volume - V_{wt} and the drum pressure P, are chosen. The present model is well formulated in the case of representing the state variable responses as feedback to input steps, on the other hand it provides no information about the water level inside the drum, in order to observe the shrink and swell effect. For this, the distribution of steam and water in the boiler system is needed.

In order to describe the drum level it is necessary to provide information about the quantity of steam present in the system. This is observed if the average volume fraction is introduced $\overline{a_V}$ as function of steam quality a_r, in relation (3.16).

$$\overline{a_v} = \frac{\rho_w}{\rho_w - \rho_s} \left[1 - \frac{\rho_s}{(\rho_w - \rho_s) a_r} \ln \left(1 + \frac{\rho_w - \rho_s}{\rho_s} a_r \right) \right] \qquad (3.16)$$

The transfer of mass and energy between steam and water by condensation and evaporation is a key element in the model. When modeling the phases separately the transfer must be accounted for explicitly. This can be avoided by writing joint balance equations for water and steam [3.27], (3.17) and (3.18).

Global mass balance for the risers:

$$\frac{d}{dt} \left[\rho_s \overline{a_v} V_r + \rho_w (1 - \overline{a_v}) V_r \right] = q_{dc} - q_r \qquad (3.17)$$

Global energy balance for the risers:

$$\frac{d}{dt}\left[\rho_s h_s \overline{a_v} V_r + \rho_w h_w (1-\overline{a_v}) V_r - P V_r + m_r C_p t_s\right] = Q + q_{dc} h_w - \left(a_r h_c + h_w\right) q_r \tag{3.18}$$

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where q_r is the total mass flow rate out of the risers, q_{dc} is the total mass flow rate which enters the risers and h_c is the condensation enthalpy.

In order to obtain a 3rd state equation, algebraic manipulations were done on equations (3.17) and (3.18). By multiplying relation (3.17) with $-\left(a_r h_c + h_w\right)$ and adding to relation (3.18) gives (3.19):

$$\begin{gathered}\frac{d}{dt}\left(\rho_s h_s \overline{a_v} V_r\right) - (h_w + a_r h_c)\frac{d}{dt}(\rho_s \overline{a_v} V_r) + \frac{d}{dt}[\rho_w h_w (1-\overline{a_v}) V_r] \\ -(h_w + a_r h_c)\frac{d}{dt}\left[\rho_w (1-\overline{a_v}) V_r\right] - V_r \frac{dP}{dt} + m_r C_p \frac{dt_s}{dt} = Q - a_r h_c q_{dc}\end{gathered} \tag{3.19}$$

where the total mass flow rate which enters the risers, also called downcomer flow rate q_{dc} and the condensation enthalpy are represented by relations (3.20) and (3.21):

$$q_{dc} = \sqrt{\frac{2\rho_w A_{dc}\left(\rho_w - \rho_s\right) g \overline{a_v} V_r}{K}} \tag{3.20}$$

$$h_c = h_s - h_w \tag{3.21}$$

where g is the gravitational acceleration, K is a dimensionless friction coefficient and A_{dc} is the downcomer pipe's area.

By introducing continuity expressions like the ones presented in relations (3.10 – 3.11) for the differential terms of equation (3.19) the 3rd state equation is illustrated in relation (3.22). The 3rd state variable is chosen as the dimensionless parameter steam quality a_r .

$$e_{32}\frac{dp}{dt} + e_{33}\frac{d\alpha_r}{dt} = Q - \alpha_r h_c q_{dc} \tag{3.22}$$

where the e_{32} and e_{33} coefficients are expressed by relation (3.23):

$$\begin{gathered}e_{32} = \left(\rho_w \frac{\partial h_w}{\partial p} + \alpha_r h_c \frac{\partial \rho_w}{\partial p}\right)(1-\alpha_v)V_r + \left((1-\alpha_r)h_c \frac{\partial \rho_s}{\partial p} + \rho_s \frac{\partial h_s}{\partial p}\right)\alpha_v V_r \\ +(\rho_s + (\rho_w - \rho_s)\alpha_r) h_c V_r \frac{\partial \alpha_v}{\partial p} - V_r + m_r C_p \frac{\partial t_s}{\partial p} \\ e_{33} = ((1-\alpha_r)\rho_s + \alpha_r \rho_w) h_c V_r \frac{\partial \alpha_v}{\partial \alpha_r}\end{gathered} \tag{3.23}$$

The partial derivates of the *steam volume fraction with pressure and mass fraction* are obtained from relation (3.16) and are presented below:

$$\frac{\partial \overline{a_v}}{\partial P} = \frac{1}{(\rho_v - \rho_s)^2}\left(\rho_w \frac{\partial \rho_s}{\partial P} - \rho_s \frac{\partial \rho_w}{\partial P}\right) *$$

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$$* \left[1 + \frac{\rho_w}{\rho_s}\frac{1}{1+\eta} - \frac{\rho_s + \rho_w}{\eta \rho_s}\ln(1+\eta)\right] \qquad (3.24)$$

$$\frac{\partial \overline{a_v}}{\partial a_r} = \frac{\rho_w}{\eta \rho_s}\left[\frac{1}{\eta}\ln(1+\eta) - \frac{1}{1+\eta}\right]$$

where $\eta = \frac{a_r(\rho_w - \rho_s)}{\rho_s}$ is used only as a notation.

The 4th state relation, in order to have a complete description of the physical phenomena in the drum, comes from the mass balance of the steam under the liquid level. In order to obtain this relation it is needed to account for the fact that a boiler model is a very complicated system in terms of geometry. There are many riser tubes, downcomer tubes, separation columns, safety valves, 2 drums and so on, and the only way is to apply a basic separation mechanism between steam and water by stating separate volumes: V_{sd} for steam and V_{wt} for water. In relation (3.25) V_{sd} is the 4th state variable for the model.

Mass balance relation for steam under the liquid:

$$\frac{d}{dt}(\rho_s V_{sd}) = a_r q_r - q_{sd} - q_{cd} \qquad (3.25)$$

where q_r is the flow rate out of the riser, q_{sd} is the steam flow rate through the liquid surface and q_{cd} is the condensation flow under the liquid level.

In order to compute the 4th state equation a_r is needed from the 3rd state equation and the values for the mass flow. We will state and discuss each mass flow relation from equation (3.25).

Condensation flow under the liquid level q_{cd}:

$$q_{cd} = \frac{h_w - h_f}{h_c} q_f + \frac{1}{h_c}\left[\rho_s V_{sd}\frac{dh_s}{dt} + \rho_w V_{wd}\frac{dh_w}{dt} - (V_{sd} + V_{wd})\frac{dP}{dt} + m_d C_p \frac{dt_s}{dt}\right] \qquad (3.26)$$

By applying the continuity relation to equation (3.26) gives (3.27) which is used for state equation 4.

$$q_{cd} = \frac{h_w - h_f}{h_c} q_f + \frac{1}{h_c}\left[\rho_s V_{sd}\frac{\partial h_s}{\partial P} + \rho_w V_{wd}\frac{\partial h_w}{\partial P} - V_{sd} - V_{wd} + m_d C_p \frac{\partial t_s}{\partial P}\right]\frac{dP}{dt} \qquad (3.27)$$

Steam flow rate through the liquid surface in the drum q_{sd}:

$$q_{sd} = \frac{\rho_s}{T_d}(V_{sd} - V_{sd}^0) + a_r q_{dc} + a_r \beta (q_{dc} - q_r) \qquad (3.28)$$

where V_{sd}^0 is the volume of steam in the drum when hypothetically there is no condensation of steam, T_D is the residence time of the steam in the drum and β is an empirical parameter.

If the state variables P and a_r are known, from equation (3.17), we can compute the total mass flow rate out of the risers q_r:

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$$\begin{aligned} q_r &= q_{dc} - \frac{d}{dt}(\rho_w \overline{a_v} V_r) - \frac{d}{dt}[\rho_w (1-\overline{a_v}) V_r] \\ &= q_{dc} - V_r \frac{d}{dt}\left[\rho_w(1-\overline{a_v}) + \rho_s \overline{a_v}\right] \\ &= q_{dc} - V_r \frac{d}{dt}\left[\rho_w - \overline{a_v}(\rho_w - \rho_s)\right] \end{aligned} \tag{3.29}$$

Further computations are necessary in order to obtain a calculable expression for q_r. We will split the term $\frac{d}{dt}\left[\rho_w(1-\overline{a_v}) + \rho_s \overline{a_v}\right]$ into 2 partial differentials $\sigma_1 and \sigma_2$ as follows.

$$\begin{aligned} \sigma_1 &= \frac{\partial}{\partial P}\left[\rho_w - \overline{a_v}(\rho_w - \rho_s)\right]\frac{dP}{dt} \\ &= \left(\frac{\partial \rho_w}{\partial P} - \overline{a_v}\frac{\partial \rho_w}{\partial P} + \overline{a_v}\frac{\partial \rho_s}{\partial P} + \frac{\partial \overline{a_v}}{\partial P}\right)\frac{dP}{dt} \\ &= \left(\frac{\partial \rho_w}{\partial P}(1-\overline{a_v}) + \overline{a_v}\frac{\partial \rho_s}{\partial P} + \frac{\partial \overline{a_v}}{\partial P}\right)\frac{dP}{dt} \end{aligned} \tag{3.30}$$

$$\begin{aligned} \sigma_2 &= \frac{\partial}{\partial a_r}\left[\rho_w - \overline{a_v}(\rho_w - \rho_s)\right]\frac{da_r}{dt} \\ &= -(\rho_w - \rho_s)\frac{\partial \overline{a_v}}{\partial a_r}\frac{da_r}{dt} \end{aligned} \tag{3.31}$$

Introducing $\sigma_1 and \sigma_2$ in the final form of (3.29) a final expression is obtained for the total mass flow rate out of the risers q_r:

$$q_r = q_{dc} - V_r\left(\frac{\partial \rho_w}{\partial P}(1-\overline{a_v}) + \overline{a_v}\frac{\partial \rho_s}{\partial P} + \frac{\partial \overline{a_v}}{\partial P}\right)\frac{dP}{dt} + V_r(\rho_w - \rho_s)\frac{\partial \overline{a_v}}{\partial a_r}\frac{da_r}{dt} \tag{3.32}$$

By introducing the expressions (3.27), (3.29) and (3.32) into (3.25) the 4th and final state equation is obtained, having as state parameter the volume of steam under the liquid level V_{sd}:

$$e_{42}\frac{dp}{dt} + e_{43}\frac{d\alpha_r}{dt} + e_{44}\frac{dV_{sd}}{dt} = \frac{\rho_s}{T_d}(V_{sd}^0 - V_{sd}) + \frac{h_f - h_w}{h_c} q_f \tag{3.33}$$

where the e_{42}, e_{43} and e_{44} coefficients are expressed by relation (3.34):

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$$e_{42} = V_{sd}\frac{\partial \rho_s}{\partial p} + \frac{1}{h_c}\left(\rho_s V_{sd}\frac{\partial h_s}{\partial p} + \rho_w V_{wd}\frac{\partial h_w}{\partial p} - V_{sd} - V_{wd} + m_d C_p \frac{\partial t_s}{\partial p}\right)$$
$$+\alpha_r(1+\beta)V_r\left(\alpha_v\frac{\partial \rho_s}{\partial p} + (1-\alpha_v)\frac{\partial \rho_w}{\partial p} + (\rho_s - \rho_w)\frac{\partial \alpha_v}{\partial p}\right) \tag{3.34}$$
$$e_{43} = \alpha_r(1+\beta)(\rho_s - \rho_w)V_r\frac{\partial \alpha_v}{\partial \alpha_r}$$
$$e_{44} = \rho_s$$

In this modeling phase an expression for the water level L can be stated:

$$L = L_w + L_s = \frac{V_{wd} + V_{sd}}{A_d} \tag{3.35}$$

The water level represent a combination of water amount dynamics l_w and amount of steam in the drum l_s. A_d represents the wet surface of the drum at the operating level. The volume of water in the drum is represented by expression (3.36), which introduced in (3.35) gives the final level output equation (3.37).

Volume of water in drum:

$$V_{wd} = V_{wt} - V_{dc} - (1 - \overline{a_v})V_r \tag{3.36}$$

Water level expression:

$$L = \frac{V_{wt} - V_{dc} - (1 - \overline{a_v})V_r + V_{sd}}{A_d} \tag{3.37}$$

The complete model is presented in relations (3.38) and the model coefficients in relation (3.39).

Drum-boiler model:

$$\begin{cases} e_{11}\dfrac{dV_{wt}}{dt} + e_{12}\dfrac{dp}{dt} = q_f - q_s \\ e_{21}\dfrac{dV_{wt}}{dt} + e_{22}\dfrac{dp}{dt} = Q + q_f h_f - q_s h_s \\ e_{32}\dfrac{dp}{dt} + e_{33}\dfrac{d\alpha_r}{dt} = Q - \alpha_r h_c q_{dc} \\ e_{42}\dfrac{dp}{dt} + e_{43}\dfrac{d\alpha_r}{dt} + e_{44}\dfrac{dV_{sd}}{dt} = \dfrac{\rho_s}{T_d}(V_{sd}^0 - V_{sd}) + \dfrac{h_f - h_w}{h_c}q_f \end{cases} \tag{3.38}$$

Drum-boiler e_{ij} model coefficients:

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$$\begin{cases}
e_{11} = \rho_w - \rho_s \\
e_{12} = V_{wt}\dfrac{\partial \rho_w}{\partial p} + V_{st}\dfrac{\partial \rho_s}{\partial p} \\
e_{21} = \rho_w h_w - \rho_s h_s \\
e_{22} = V_{wt}\left(h_w \dfrac{\partial \rho_w}{\partial p} + \rho_w \dfrac{\partial \rho_w}{\partial p}\right) + V_{st}\left(h_s \dfrac{\partial \rho_s}{\partial p} + \rho_s \dfrac{\partial \rho_s}{\partial p}\right) - V_t m_t C_p \dfrac{\partial t_s}{\partial p} \\
e_{32} = \left(\rho_w \dfrac{\partial h_w}{\partial p} + \alpha_r h_c \dfrac{\partial \rho_w}{\partial p}\right)(1-\alpha_v)V_r + \left((1-\alpha_r)h_c \dfrac{\partial \rho_s}{\partial p} + \rho_s \dfrac{\partial h_s}{\partial p}\right)\alpha_v V_r \\
+(\rho_s + (\rho_w - \rho_s)\alpha_r)h_c V_r \dfrac{\partial \alpha_v}{\partial \alpha_r} - V_r + m_r C_p \dfrac{\partial t_s}{\partial p} \\
e_{33} = ((1-\alpha_r)\rho_s + \alpha_r \rho_w)h_c V_r \dfrac{\partial \alpha_v}{\partial \alpha_r} \\
e_{42} = V_{sd}\dfrac{\partial \rho_s}{\partial p} + \dfrac{1}{h_c}\left(\rho_s V_{sd}\dfrac{\partial h_s}{\partial p} + \rho_w V_{wd}\dfrac{\partial h_w}{\partial p} - V_{sd} - V_{wd} + m_d C_p \dfrac{\partial t_s}{\partial p}\right) \\
+\alpha_r(1+\beta)V_r\left(\alpha_v \dfrac{\partial \rho_s}{\partial p} + (1-\alpha_v)\dfrac{\partial \rho_w}{\partial p} + (\rho_s - \rho_w)\dfrac{\partial \alpha_v}{\partial p}\right) \\
e_{43} = \alpha_r(1+\beta)(\rho_s - \rho_w)V_r \dfrac{\partial \alpha_v}{\partial \alpha_r} \\
e_{44} = \rho_s
\end{cases} \tag{3.39}$$

The system inputs are: the heat flow rate Q, the feed water flow rate q_f, and the steam flow rate q_s. The system outputs are the pressure P and the water level L. Most simulation softwares work with state space equations; hence a state-space model was derived, with the following parameters chosen as states: drum pressure P, total volume of water V_{wt}, steam quality a_r and volume of steam in drum V_{sd}.

$$\begin{cases}
\dot{x}_2 = u_1 \dfrac{h_f e_{12} - e_{22}}{e_{21}e_{12} - e_{11}e_{22}} + u_2 \dfrac{e_{12}}{e_{21}e_{12} - e_{11}e_{22}} + u_3 \dfrac{e_{22} + h_s e_{12}}{e_{21}e_{12} - e_{11}e_{22}} \\
\dot{x}_1 = -\dfrac{e_{11}}{e_{22}}\dot{x}_2 + \dfrac{u_1}{e_{12}} - \dfrac{u_3}{e_{12}} \\
\dot{x}_3 = -\dfrac{e_{32}}{e_{33}}\dot{x}_1 + \dfrac{u_2}{e_{33}} - x_3 \dfrac{h_c q_{dc}}{e_{33}} \\
\dot{x}_4 = -\dfrac{e_{42}}{e_{44}}\dot{x}_1 - \dfrac{e_{43}}{e_{44}}\dot{x}_3 + \dfrac{\rho_s}{T_d e_{44}}(x_4^0 - x_4) + \dfrac{h_f - h_w}{h_c e_{44}}u_1 \\
y_1 = x_1 \\
y_2 = \dfrac{x_4 + V_{wd}}{A_d}
\end{cases} \tag{3.40}$$

where e_{ij} coefficients are presented in (3.39).

Inputs, Outputs, States

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Input vector: $[u_1\ u_2\ u_3]^T = [\ q_f\ \ Q\ \ q_s]^T$

State vector: $[x_1\ x_2\ x_3\ x_4]^T = [P\ V_{wt}\ \alpha_r\ V_{sd}]^T$

Output vector: $[y_1\ y_2]^T = [P\ L]^T$

For evaluation of $h_s, h_w, \rho_s, \rho_w, \frac{\partial \rho_s}{\partial P}, \frac{\partial \rho_w}{\partial P}, \frac{\partial h_s}{\partial P}, \frac{\partial h_w}{\partial P}, t_s and \frac{\partial t_s}{\partial P}$ at the saturation pressure P, the following quadratic approximations from [3.33] have been used:

$$
\begin{aligned}
&h_s=a_{01}+[a_{11} + a_{21}(P-10)](P- 10)\\
&\rho_S=a_{02}+[a_{12} + a_{22}(P-10)](P-10)\\
&h_w=a_{03}+[a_{13} + a_{23}(P-10)](P-10)\\
&\rho_W=a_{04}+[a_{14} + a_{24}(P-10)](P-10)\\
&t_s=a_{05}+[a_{15} + a_{25}(P-10)](P-10)\\
&h_{fw}=h_w+[a_{06} + a_{16}(P-10)](t_{fw}- t_s)\\
&h_c = h_s - h_w
\end{aligned}
\tag{3.41}
$$

The a_{ij} coefficients are presented in Appendix 3, chapter 1. The partial differential equations are easily calculated from (3.41).

In conclusion the Åström and Bell model for a boiler system is presented in (3.40) with the associated coefficient presented in (3.39).

3.3.1.3. Adapting and Extending the Åström - Bell Model

A) Adapting the model

The major advantage of the Åström - Bell drum-boiler model is that it can be easily adapted to any type of plant, by knowing some constructive and functioning parameters. In the present case, for the thermal power plant Timisoara South, these parameters are: V_d=31.4m^3, m_t=18000kg, m_r=16000kg, m_d=2000kg, β=0.3, K=25, T_d=12s, V_{dc}=11.41m^3, V_r=15m^3, A_d=20m^2, A_{dc}=1.36m^2, C_p=650J/Kg and t_{fw}=104°C.

The volumes and areas were computed from the geometry of the boiler. The metal masses were estimated. Feed-water temperature is considered constant at t_{fw}= 104 °C and so the specific heat of metal C_p = 650 J/Kg because of very little variation. Due to lack of data availability, some parameters were hard to find and were kept from the original model (V_{sd}^0, Td, K, β).

The masses, volumes and areas were calculated and approximated from plant blue prints and handbooks.

The operating points were adapted quiescently according to the real operating points at the thermal power plant site.

Overall, the model was successfully validated in various static operating points presented in Table 3.4.

Table 3.4 – Static operating points of the thermal power plant South of Timisoara

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FP	q_f[kg/s]	*Q*[W]	K_v[%]	*P* [Mpa]	*Pow*[MW]
50%	13.08	3.02e7	60	1.2	3.8
75%	23.76	5.48e7	100	1.39	5.48
90%	28.45	6.58e7	100	1.82	8.2
100%	31.53	7.31e7	100	2.13	9.15

B) Extending the Model

The extended model adds the following elements:

- The feed-water valve was modeled as a 1^{st} order element with a time constant of 10s.
- The fuel valve (heat flux) was modeled as 1^{st} order plus delay element with time constant of 45s and delay of 4s.
- The steam valve was modeled as 1st order element with a time constant of 12s. By modeling the steam valve, the mass of steam becomes an output for the overall system.
- By modeling the pressure drop on the super-heater, the throttle pressure P_T becomes a control parameter for the fuel loop. Frequently P_T is represented as a difference between the drum pressure P and the pressure drop on the superheater where K_{SH} = 0.00057 and is the superheater friction coefficient, by using a modified form of Bernoulli's law. The relation is presented in equation (3.42).

$$P_T = P - K_{SH} q_s^{1.5} \tag{3.42}$$

- Throttle pressure can actually be estimated as being 5% to 10% of the drum pressure. Then q_s can be computed, and by multiply the relation with the valve coefficient K_v relation (3.43) is obtained, where K_v is a normalized position of valve actuator and acts as an input and q_s is an output for the model. The present approach was studied in Chapter 3.2, with a low-order boiler model.

$$q_s = K_v * \left[(P - P_T) * \frac{1}{K_{SH}} \right]^{0.66} \tag{3.43}$$

- The turbine is modeled as a 1^{st} order system also presented in Chapter 3.2, permitting visualization of the power output.

The extended model allows operation and visualization of a broader range of parameters.

After extension, the model is described by the following relations relative to the turbine generated power (E) and steam flow (q_s):

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$$\begin{cases} \dot{x}_2 = u_1 \dfrac{h_f e_{12} - e_{22}}{e_{21}e_{12} - e_{11}e_{22}} + u_2 \dfrac{e_{12}}{e_{21}e_{12} - e_{11}e_{22}} + q_s(u_3)\dfrac{e_{22} + h_s e_{12}}{e_{21}e_{12} - e_{11}e_{22}} \\ \dot{x}_1 = -\dfrac{e_{11}}{e_{22}}\dot{x}_2 + \dfrac{u_1}{e_{12}} - \dfrac{q_s(u_3)}{e_{12}} \\ \dot{x}_3 = -\dfrac{e_{32}}{e_{33}}\dot{x}_1 + \dfrac{u_2}{e_{33}} - x_3\dfrac{h_c q_{dc}}{e_{33}} \\ \dot{x}_4 = -\dfrac{e_{42}}{e_{44}}\dot{x}_1 - \dfrac{e_{43}}{e_{44}}\dot{x}_3 + \dfrac{\rho_s}{T_d e_{44}}(x_4^0 - x_4) + \dfrac{h_f - h_w}{h_c e_{44}}u_1 \\ \dot{x}_5 = -\dfrac{1}{T_{gain}}x_5 + q_s(u_3)\dfrac{T_t}{T_{gain}} \end{cases} \tag{3.44}$$

and output relations:

$$\begin{cases} y_1 = x_1 \\ y_2 = x_5 \\ y_3 = \dfrac{x_4 + V_{wd}}{A_d} \end{cases} \tag{3.45}$$

where the new vectors are:

Input vector: $[u_1\ u_2\ u_3]^T = [\ q_f\ \ Q\ \ K_V]^T$

State vector: $[x_1\ x_2\ \ x_3\ \ x_4\ x_5]^T = [P\ V_{wt}\ \ \alpha_r\ \ V_{sd}\ E]^T$

Output vector: $[y_1\ \ y_2\ \ y_3]^T = [P\ E\ L]^T$

The turbine model was presented in Chapter 3.2, Fig 3.6, and E [MW] represents the electric power generated by the turbine-generator system.

3.3.1.4. Computational block diagram for extended Åström and Bell boiler-turbine model

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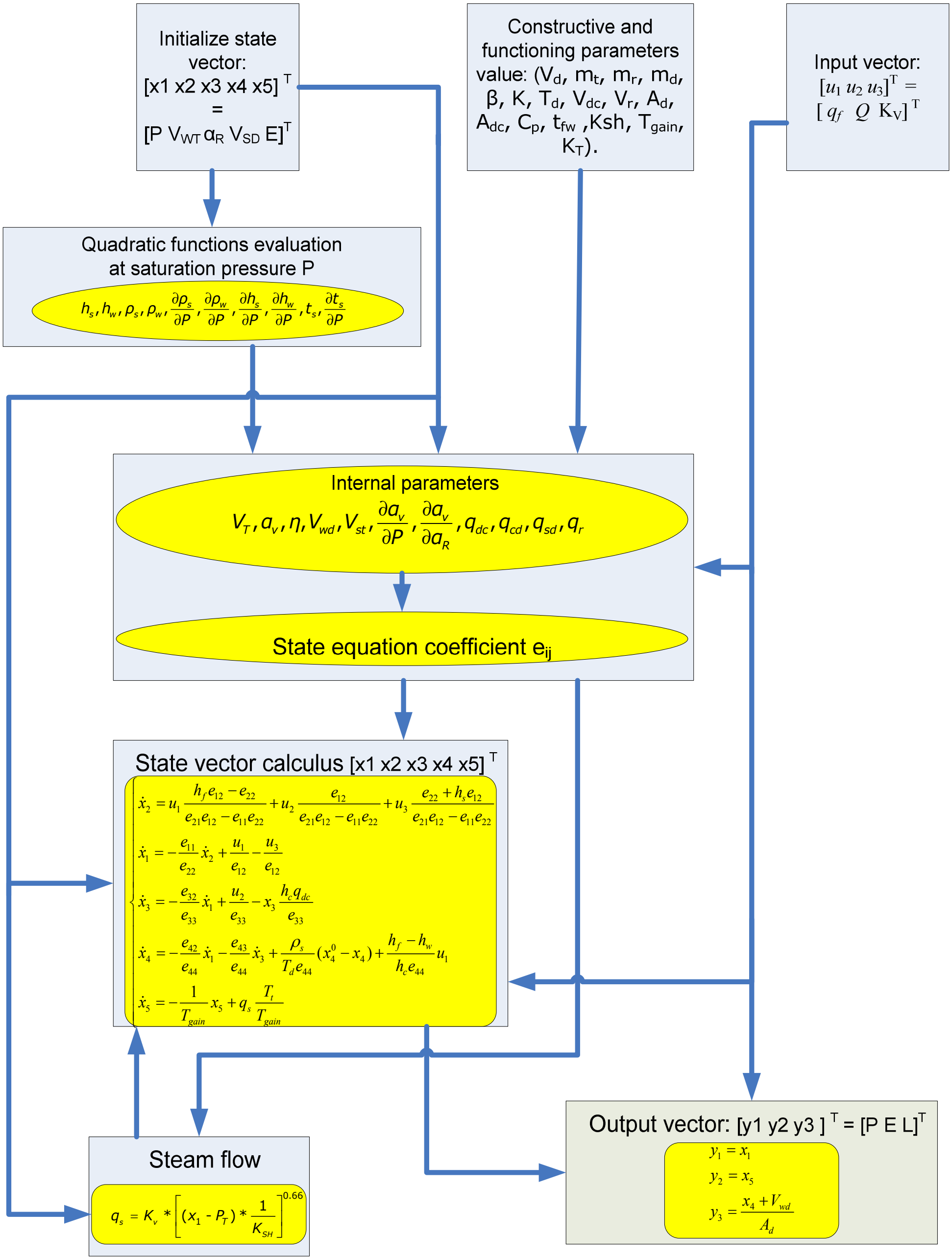

Fig 3.19. Computational block diagram of the boiler-turbine extended model

3.3.2. Gain-scheduled control and system design for boiler-turbine process

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3.3.2.1. Gain scheduled control for shrink and swell effect remission

The adopted control strategy is the three feedback control compared with single feedback control for water level loop. A heat flux control-loop has been added in order to maintain a constant pressure to turbine. The drum-boiler control system is presented in Fig 3.20 and is implemented in Labview.

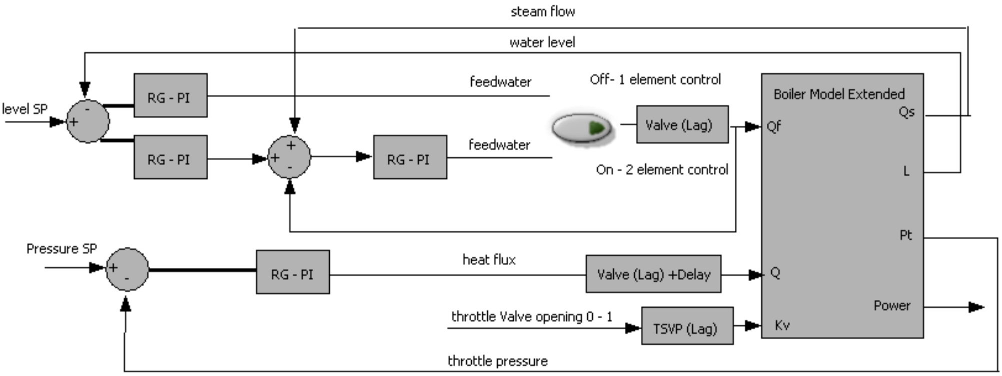

Fig 3.20. Drum-boiler control systems implemented in Labview for shrink and swell effect remission (1 feedback and 3 feedback control).

- The single element control is a simple PI feedback loop on water level and presents serious drawbacks when fast loads are required.
- The three feedback control consists in a two loop cascade control: i) a fast acting internal loop on the valve actuator for feed-water, and ii) a slower external loop for water level. In order to add predictability to fast changing loads, which results in the remission of the shrink-and-swell effect, steam flow is added as a feed-forward correction to the internal loop. The rule of thumb for adopting a cascade control strategy is that the outer process is at least 5 times slower than the inner process. The cascade control must be tuned with the following procedure. The outer loop is switched to manual mode and the inner loop is tuned, then, the inner loop is placed in automatic control mode and the outer loop is tuned [3.34]. The inner loop is tuned without the feed-forward loop, only with the water valve model using Ziegler-Nichols method and some fine tuning. Then, the inner loop is switched to accept the setpoint from the outer loop in automatic mode. Now, the outer controller must be in manual mode in order to apply a step signal to the process to be able to obtain the controller gains,also taking into account the feed-forward loop, again with Ziegler-Nichols and some fine tuning. Step by step the controllers, starting from the inner loop are switched from manual to automatic mode, taking good care that for both controllers (inner & outer) the setpoints match the process feedback values (PVs).
- The pressure control loop operates on the heat flux. It is essentially a simple PI loop which keeps turbine pressure at the desired value.

Thermal power plants have a wide range of operating points, resulting in performance loses if only one set of gains are provided to controllers. By using gain-scheduling technique, system responses are considerably improved.

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To compare system performances of both control strategies (three feedback control versus single feedback control), there is the possibility to switch between them. The access is given to controller gains if gain-scheduling mode is not active.

The control gains for gain-scheduling were found using Ziegler-Nichols method. In order to find the best gains for different operating points, some trial and error fine tuning where done.

Table 3.5 – Controller gains at various steam flow values

q_S [kg/s]	Heat flux loop		Outer controller level loop	
	Kp	Ti [min]	Kp	Ti [min]
0-14	$3*10^7$	4	2	0.3
15-20	$3.5*10^7$	4	2	0.15
21-34	$4*10^7$	3	3	0.1

The gains for the inner loop do not need scheduling due to the simple valve simple 1st order model: Kp=10 and Ti [min] = 0.03.

3.3.2.2. System Design in Labview

The "G" language (graphical programming language of Labview) is chosen for implementation. The backbone consists in a flat sequence structure with two frames Fig 3.21.

The 1st frame initializes the system by selecting one from the four manual operating points, and sends values to the non-linear state-space model for integrator initial conditions in the 2nd frame.

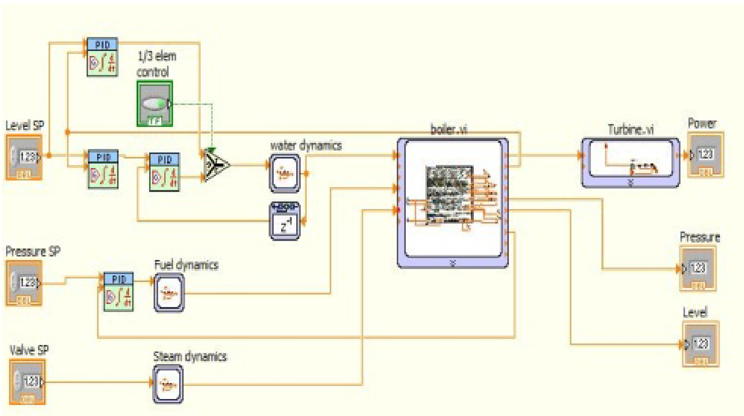

Fig 3.21. Boiler-turbine simulator design backbone in Labview

The 2nd frame contains a simulation loop, which runs the ODE Solver. The boiler and turbine are modeled as separate subsystems. The boiler subsystem contains a formula node, which is very similar to the C language. The complete code is presented in Appendix 3, point 2.

The communication and data transition between 1st and 2nd frame are carried out through local variables.

Firstly, the system starts in manual mode (one of the four operating points). It is possible to switch to automatic mode by selecting level or/and pressure control button and if two feedback or three feedback control is preferred. The system also allows access to controller gains if gain scheduling is not active and access to the inner control gains for calibration.

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The full simulation loop "G" code can be found in Appendix 4.

3.3.3. Simulation Results

In order to validate the functionality and the drum-boiler dynamic model, four tests were done: two in manual mode (open loop) and two in automatic mode (closed loop).

3.3.3.1. Tests in manual mode (open loop)

A. Test 1 - Step change in heat flux – manual

For the first validation test, a step change in heat flux was applied, corresponding to 0.5 MW power demand Fig 3.22.

The drum level is actually a mixture of competing dynamics illustrated by the volume of steam and water, represented by the level output relation 2.37. The volume of steam in the drum increases due to the heat flux step, thus converting more water to steam. There is also a small increase in the condensation flow, but only for a short time and for a small thermal power plant this doesn't affect to much the total water volume due to the small operating pressure. In large scale power plants, which operate at high pressures, the total water volume increases at first due to the condensation flow, but eventually, will decrease due to the amount of water converted to steam. The swell effect is caused by the volume of steam which has a rapid increase at first and is illustrated in Fig 3.22.

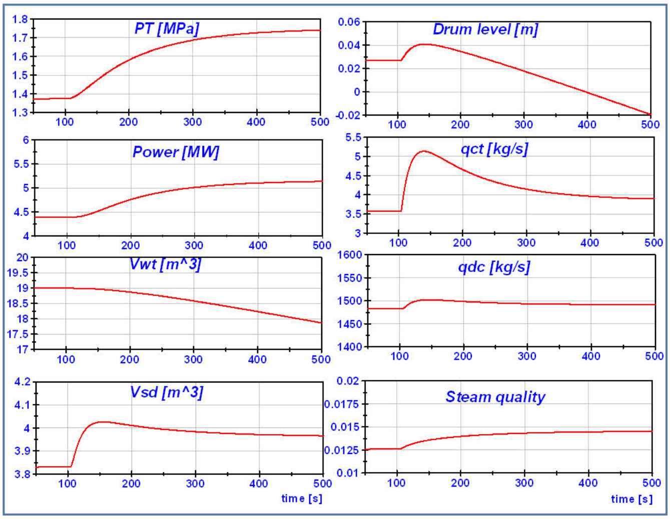

Fig 3.22. Responses to a step change of heat flux coresponding to 0.5 MW, in open loop: pressure, power, water volume, steam volume, drum level, condensation flow, downcommer flow rate, steam quality.

B. Test 2 – Step change in throttle valve position – manual

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The second validation test consists of modifying the throttle valve position (10%), corresponding to 4 kg/s steam flow rate Fig 3.23.

This scenario is actually only a disturbance in the overall system and was executed to emphasize the shrink and swell effect which appears whenever a change in steam flow demand occurs. Opening the valve results in a rapid increase in steam flow, thus generated power, but this is only momentarily as the pressure drops. The speed of the vapor increases but the pressure simultaneously decreases. This is caused by the energy conservation law of Bernoulli, having as effect the behavior of the steam flow and subsequently the behavior of the generated power by the turbine presented in Fig 3.23. In a real power plant operation, the steam valve and the heat flux are set together in order to meet the power load demand.

This inverse response to a sudden load increase is dynamic swell.

Dynamic shrink is also observed when a sudden load decrease occurs. However, the dynamic shrink phenomenon does not disrupt the natural convection circulation of the boiler as completely as the dynamic swell effect [3.35]. The shrink effect can be observed if the throttle valve closes e.g. 70% to 60%.

The shrink-and-swell effect causes the water level to behave as a non-minimum phase system if feed water flow is kept constant.

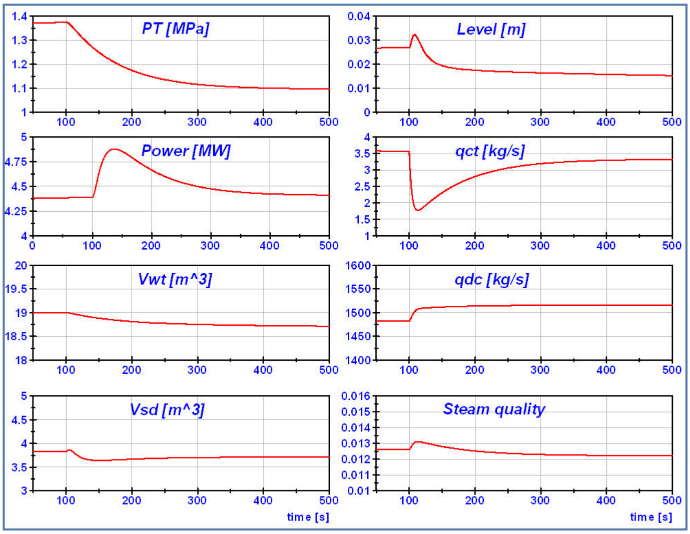

Fig 3.23. Response to a step change of throttle valve position (10%) in open loop: pressure, power, water volume, steam volume, drum level, condensation flow, downcommer flow rate, steam quality.

Tests were executed at 50% boiler load.

3.3.3.2. Tests in automatic mode (closed loop)

The following tests are conducted with automatic control, by comparing single feedback with three feedback control, for water level, with pressure loop and gain scheduling active. The shrink and swell effect in automatic mode manifests due to the delay in the boiler firing rate, leaving as dominant dynamics, at first, the steam valve. The firing rate cannot increase fast enough to match the steam demand resulting in a temporary increase in drum level.

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The key feature of this control is to keep water level and pressure in admissible ranges and to increase the generated power when steam rushes out of the drum. This situation is common at fast turbine loads.

Two tests were conducted at 50% load and at 90% load in automatic mode.

C. Test 3 – Step change valve position – 50% load – automatic control

In Fig 3.24 pressure, power and level responses are compared in the case of one feedback control and three feedback control for 4kg/s step in steam flow rate (15% valve opening) at 50% boiler load. The cascade control improves the settling time of the water level, and reduces the swell effect, though it slightly has larger overshoot. The level settling time, presents improved characteristic. In Fig 3.25. the controller commands on the feed water flow and heat flux are presented. The swell effect is shown. Using 1 feedback control the command decreases, due to the swell effect and after a period of time increases. By using 3 feedback control, the feed-forward steam loop adds predictability to the control structure and deals better and faster with disturbances acting on the inner loop.

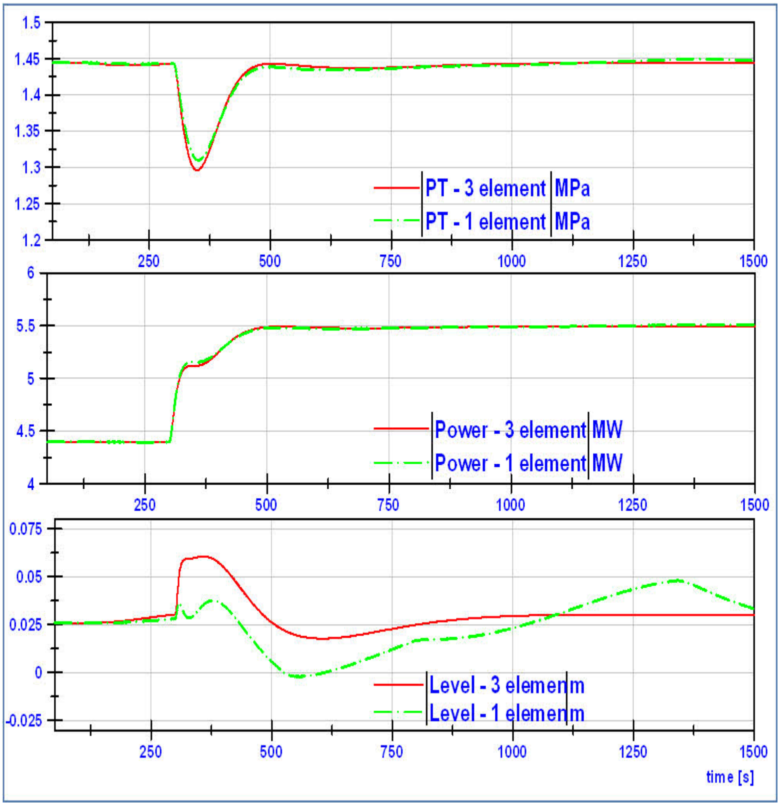

Fig 3.24. Pressure, power and level responses at 50% boiler load at step change in valve position 60% - 75%.

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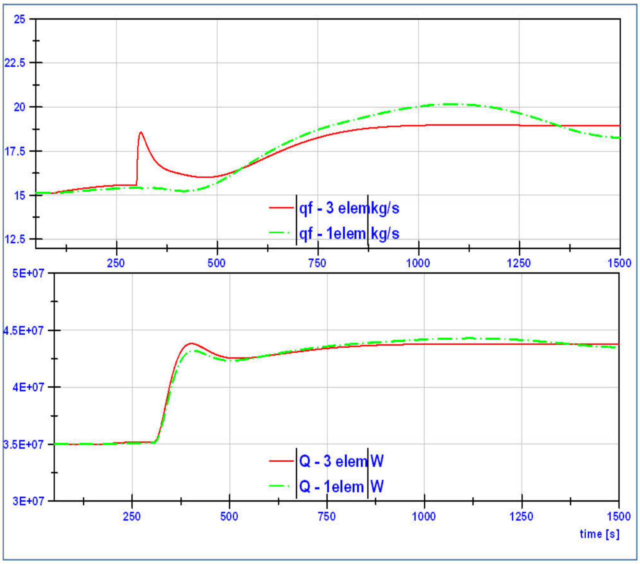

Fig 3.25. Controller commands on feed-water and heat flux at 50% boiler load at step change in valve position 60% - 75%.

D. Test 4 – Step change valve position – 90% load – automatic control

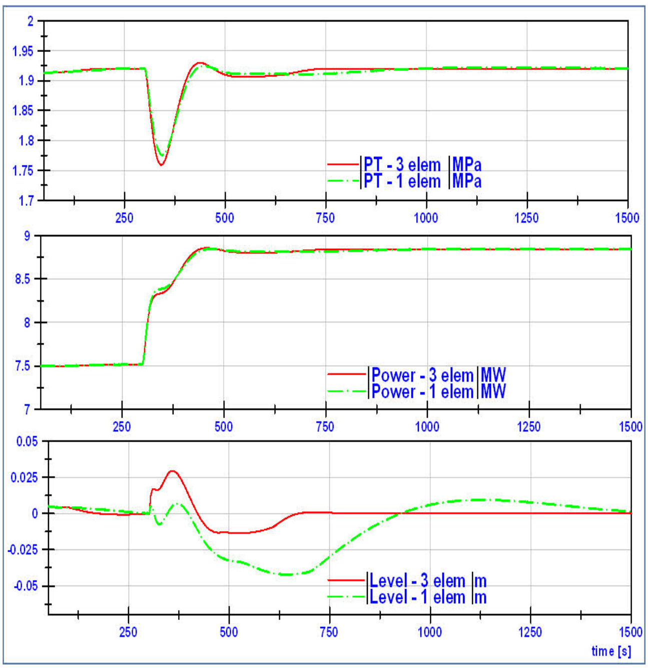

Fig 3.26. Pressure, power and level responses at 90% boiler load at step change in valve position 85% - 100%.

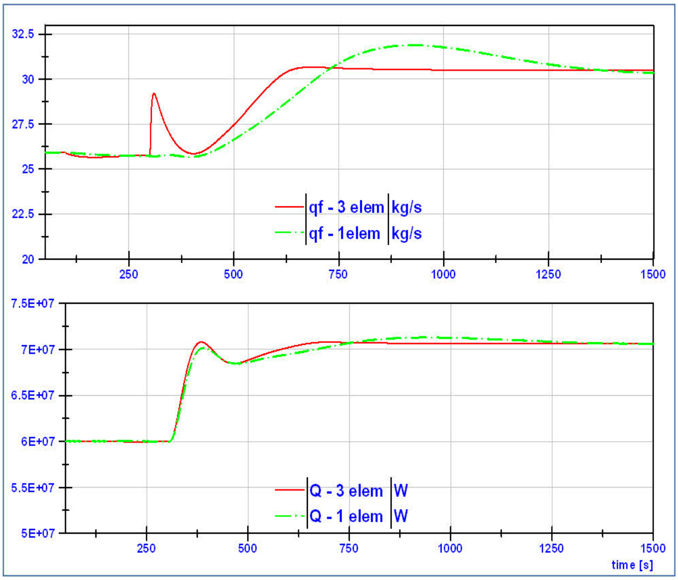

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Fig 3.27. Controller commands on feed-water and heat flux at 90% boiler load at step change in valve position 85% - 100%.

In Fig 3.26 and Fig 3.27, the same scenario is presented but at 90% load.

At high loads, it is observed that three feedbacks control presents significant improvement over single feedback control.

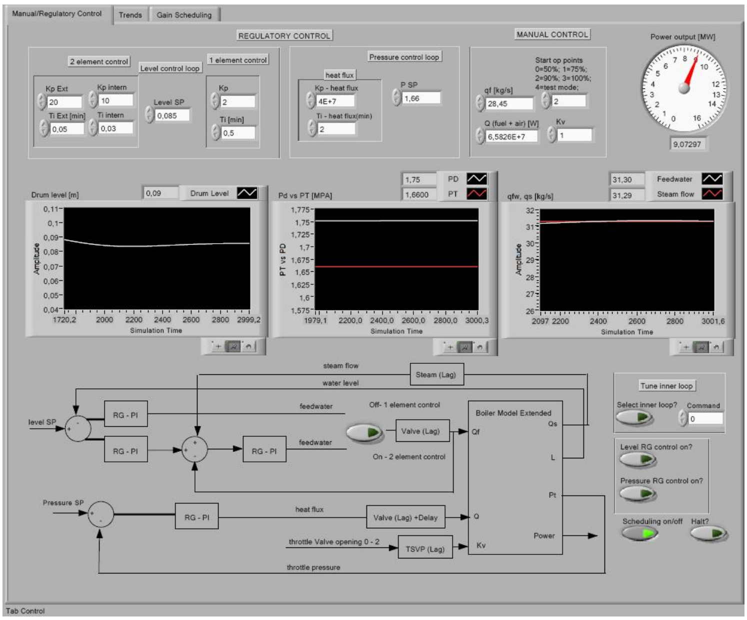

Fig 3.28. Graphical user interface for human machine interaction

A GUI was developed Fig 3.28 to facilitate the human-machine interaction. Operators start the simulation in one of the four operating points. They have the possibility to make manual or automatic maneuvers by switching one of the control buttons. By modifying the setting points, they can observe transient and stationary process responses.

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In addition, details about the internal model parameters can be found in the second tab “Trends”.

3.4. Conclusions

This chapter develops and tests by simulation a drum-boiler-turbine system with automatic control for water level and throttle pressure. The turbine model, superheater relation and boiler turbine functioning principle are gradually introduced in Chapter 3.2 along with a real-time implementation scenario needed for an industrial simulator. Some simple control features, regarding controller tuning and response to processes with slow dynamics under automatic control are presented in Chapter 3.1.

All in all, the previous chapters are illustrated in order to use process concepts, controller design/tuning and present the method for integrating the boiler turbine simulator into and industrial real-time application for Chapter 3.3.

The key features of the present chapter are:

- Perform a case study model and extend a complex 4^{th} order state-space non-linear coupled drum-boiler model.
- Fit the complex model to a real thermal power plant Colterm, Timisoara, with suitable simulation results in open loop mode and provide an insight into shrink and swell phenomena behavior.
- Implement a gain-scheduled cascade control system with a feed-forward loop, adding predictability in anticipating the boiler load changes subsequently the variation of the drum level, for a drum-boiler model with GUI.
- Reduce the shrink-and-swell effect and improve output responses.
- Provide simulation results in manual/automatic control operation with satisfactory response behaviors for three feedback control versus single feedback control for water level, in a wide range of plant operating points.
- Provide a simulator for control strategy testing and also dispatcher/operator training at the thermal power plant South of Timisoara, Romania.

Relevant author published work to the present chapter is represented by papers [5] and [10] indexed in IEEE Explore, SCOPUS; and [6] at a local Symposium.

[3.1] ADAM – 6000 Series User Manual, Ethernet – Based data acquisition and control modules, 2008.
[3.2] LabVIEW User Manual, National Instruments, Austin, 1998.
[3.3] F.P. Demello. F.P. Emad, “Boiler Pressure Control Configuration", IEEE Winter Power Meet., N.Y., Feb. 1967.
[3.4] F.P. de Mello, “Boiler models for system dynamic performance studies” IEEE Transactions on Power Systems, Vol.6, No. 1, Feb 1991.

BUPT

[3.5] M. E. Flynn and M. J. 0' Malley, "A drum boiler model for long term power system dynamic simulation," IEEE Transactions on Power Systems, Vol. 14, No. 1, Feb. 1999.

[3.6] E. Cheres, "Small and medium size drum boiler models suitable for long term dynamic response", IEEE Transactions on Energy Conversion, Vol.5, No. 4, Dec. 1990.

[3.7] C. S. Chen, Senior Member, IEEE, Y. D. Lee, C. T. Hsu, Member, IEEE, and C. K. Chen, "Transient response of an incinerator plant by considering boiler model with dynamic steam" IEEE Transactions on power systems, vol. 23, no. 1, Feb. 2008.

[3.8] Wen Tan, Fang Fang, Liang Tian, Caifen Fu, JizhenLiu, "Linear control of a boiler-turbine unit: Analysis and design", pp. 189-197, ISA Transactions 47, 2008.

[3.9] Wen Tan,* Jizhen Liu, Fang Fang, Yanqiao Chen, "Tuning of PID controllers for boiler-turbine units", ISA Transactions 43, pp.571–583, 2004.

[3.10] National Instruments, "Real-time module user manual".

[3.11] National Instruments, "Selecting Your LabVIEW™ Real-Time Deployment Platform".

[3.12] National Instruments, "LabVIEWTM Control Design Toolkit User Manual", September 2004 Edition, Part Number 371057B-01.

[3.13] National Instruments, "LabVIEW TM Simulation Module User manual", April 2004 Edition, Part Number 371013A-01.

[3.14] Mihaela Lascu, "Advanced Programming Techniques in LabView", Politehnica Timisoara Masthead, 2007.

[3.15] Schulz R.P., Brower AS., Cleveland C.M., Gentile T.J., Mosteller H.W., Piwko R.J., Turner A.E., Winkelman J.R., "Long Term Power System Dynamics, Phase III Vol. 1: Analysis Of Capability To Simulate Disturbances", EPRIEL983, Vol. 1 RP 764-2, Final report May 1982.

[3.16] Herget C.J., Park C.U., "Parameter identification and verification of low order boiler models", IEEE Trans. on Power Apparatus and Systems, Vol. PAS 95 No. 4, pp 1153-1 158, 1976.

[3.17] Åström K., Eklund K., "A simplified non-linear model of a drum boiler-turbine unit", International Journal of Control, Vol. 16, No. 1, pp145-169, 1972.

[3.18] Anderson P. M., 'Modelling thermal power plants for dynamic stability studies", Cyclone Copy Centre, Ames, Iowa, 1974.

[3.19] EPRI Research project 1469-1, 'Long Term System Dynamics Simulation methods', Final Report, EL 3894, February 1985.

[3.20] Hemmaplardh K., Cate E.G., Hammond R.A., Sackett S.A., "Applications of dynamic models in dispatcher training simulator and in other system dynamic performance studies", IEEE Trans. Power Apparatus and Systems, Vol. PAS-104, No. 6, pp. 1349-1355, 1985.

[3.21] Malachi Y., Winokur M., Kottick D, "Long term simulation of the Israel Power system dynamic response, a case study" IEE 3rd International Conference on Power Systems Monitoring and Control, pp. 62-67, 1990.

[3.22] Kundur P., Morched AX, Kar P.K., Rogers G.J., Morison G.K., "Long Term Dynamics Simulation: Modelling Requirements", EPRI EL6627 RP 2473-22, final report December 1989.

[3.23] C. Maffezzoni, "Boiler-turbine dynamics in power-plant control," Control Engineering Practice, vol. 5, no. 3, pp. 301–312, Mar. 1997.

[3.24] N. W. Rees and C. X. Lu, "Some thoughts on the advanced control of electrical power plants," Transaction of the Institute of Measurement and Control, vol. 24, no. 2, pp. 87–106, 2002.

[3.25] C. X. Lu, N. W. Rees, and S. C. Donaldson, "The use of the Åström-Bell model for the design of drum level controllers in power plant boilers," in Proc.16th IFAC World Congress, vol. 16, part 1, Jul. 2005.

[3.26] R. D. Bell and K. J. Åström, "Dynamic Models For Boiler-Turbine-Alternator Units: Data Logs And Parameter Estimation For A 160 MW Unit," Report TFRT-3192, Lund Inst. Technol., Lund, Sweden, 1987.

[3.27] K. J. Åström and R. D. Bell, "Drum-boiler dynamics," Automatica, vol. 36, no. 3, pp. 363–378, 2000.

[3.28] R. G. Franks and C. W. Worley, "Quantitative analysis of cascade control," Ind. Eng. Chem., vol. 48, no. 6, pp. 1074–1079, 1956.

[3.29] M. Xu, S.-Y. Li, and W.-J. Cai, "Cascade generalized predictive control strategy for boiler drum level," ISA Transactions, vol. 44, no. 3, pp. 399–411, Jul. 2005.

[3.30] T. M. Teo, S. Lakshminarayanan, and G. P. Rangaiah, "Performance assessment of cascade control systems," J. Inst. Eng., vol. 45, no. 6, pp. 27–38, 2005.

[3.31] C. Huang, Y. Bai, and X. Liu, "H-Infinity state feedback control for a class of networked cascade control systems with uncertain delay," IEEE Transactions on Industrial Informatics, vol. 6, no. 1, pp. 62–72, Feb. 2010.

[3.32] A. H. Fawnizu and N. W. Rees, "Overcoming the shrink-and-swell effect in water level control strategy on industrial boiler-drum," in Proc. 16th International Conference on System Engineering (ICSE'03), vol. 3, no. 2, pp. 10–15, Sep. 2003.

[3.33] K. J. Åström and R. D. Bell, "Simple drum-boiler models," in Proc. IFAC Int. Symposium on Power Systems, Modelling and Control Applications, Brussels, Belgium, pp. 123–127, 1988.

[3.34] K. Åström and T. Hagglund, "PID Controllers: Theory, Design and Tunning" 2nd Edition, 1995.

[3.35] http://www.controlguru.com/wp/p48.html, practical process control e-textbook, Dynamic Shrink/Swell and Boiler Level Control.

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4. MULTIVARIABLE GAIN-SCHEDULED CONTROL FOR A DRUM-TYPE BOILER-TURBINE SYSTEM

This chapter presents the 2nd control solution employing a centralized multivariable gain-scheduled decoupled control for a boiler-turbine system. Unlike the cascade control solution presented in Chapter 3.3, the present multivariable control solution deals with model interaction reduction based on decoupled control.

The boiler-turbine mathematical model is a 3x3 nonlinear strongly-coupled MIMO system with hard constraints. The proposed control strategy employs decoupling technique, controller reduction, gain scheduling with dynamic model linearization, and adaptive PID control with filtered updated gains and anti-windup to improve system response quality. A more detailed approach on implementation and technology together with real time constraint programming method is presented in Chapter 5.

4.1. Background

A boiler-turbine system provides high pressure steam to drive the turbine in thermal electric power generation. The purpose of the boiler-turbine control system is to meet electric power load-demands in order to maintain the pressure and water level in the drum within acceptable ranges. In Fig 4.1 the main components of a thermal power plant are illustrated.

The boiler-turbine model is a 3x3 MIMO nonlinear strongly-coupled system [3.17]. By applying simulation techniques, such systems can provide both useful

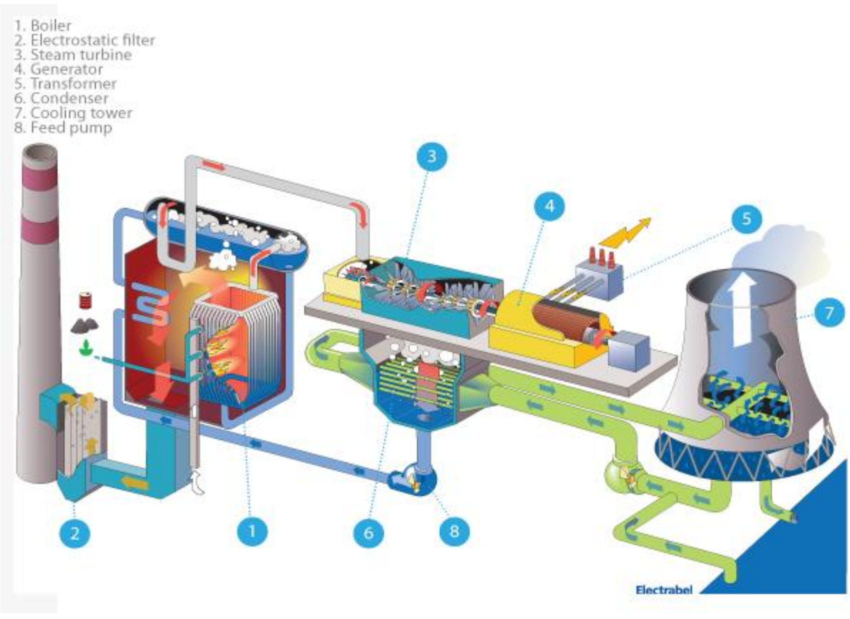

Fig 4.1. General structure of a thermal power plant [4.1].

information for thermal power plant operators and dispatchers in order to anticipate transient responses for specific inputs or parameter variations, and on the other hand, to test and analyze complex control strategies.

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The methods to control boiler-turbine systems are often chosen based on process interaction levels. If there are low interactions between channels, a diagonal controller (decentralized control) is frequently used. Alternatively, when interactions are significant (our case), a full matrix controller (centralized control) is advisable [4.2].

In recent years, many researchers have paid attention to the control of boiler-turbine units using different control methodology such as: i) robust control (zero tracking error), with difficulties in dealing with input constraints, ii) genetic algorithm based-control (large overshoot), iii) fuzzy control, iv) non-linear control, and so on [4.3].

In this chapter, the model originated in [3.17] is developed and adapted to fit the thermal power plant of South Timisoara, Romania. The multivariable centralized control is improved by using a gain-scheduling technique through dynamic model linearization.

The main contributions of this chapter consist in: i)simulating and adapting a boiler turbine model in order to fit a real power plant, ii) developing a gain-scheduled multivariable control with dynamic linearization and iii)provide an important insight into boiler-turbine transient parameter responses subjected to complex control strategies.

4.2. The Åström – Bell interpretation model

The most important overall dynamics of such a complex system was very well captured by a 160 MW, oil fired drum-type boiler-turbine-generator unit in a third order multi-input multi-output nonlinear model by Bell and Åström in [4.4]. The model represents the boiler unit P16 and the turbine unit G16 at Oresundsverket in Malmo, Sweden, and has been an active research topic for the last 3 decades. It can be considered the best simple model currently available for simulation of the overall dynamics of a fossil - fueled power unit.

The modeling core appeared in Åström and Eklund [3.17] and [4.5], which modeled the electric power output and drum pressure by a 2nd order nonlinear model. Later, in Bell and Åström [4.6] the model was extended to a 7th order for anticipation of the increase in water level. Also, actuator dynamics for the fuel, feedwater and throttle control valves were included. In Bell and Åström [3.26] two versions of the model were proposed, the main issue being the integration of evaporation rate concept by Morton and Price in [4.7] which simplified the drum level prediction and the model reduced back to the 3rd order. In [4.4] the results of a comparative study among several low order models were presented, where the 3rd order model performed satisfactorily. A little later, in [4.8] the modeling of the drum water level was supported in physical first principles without increasing the model order. The final model is presented in [4.9], [4.10]where the drum boiler part of the model was restated and increased to 4th order to account more precisely for the shrink and swell effect in the drum water level which was described in Chapter 3.3.

The best model chosen for decupled control is the 3rd order model due to the satisfactory dynamic description of process signals and its feasibility regarding control properties.

4.2.1. Analytical modeling

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The model which will be derived represents a 3x3 state space coupled non-linear model which has as inputs normalized positions of valve actuators that control: u1 - the mass flow rate of fuel, u2 - the steam to turbine, and u3 - the feed water to drum [4.11] and as outputs y1 - the drum steam pressure P [kg/cm^2], y2 - the megawatt power output E [MW] and y3 - the water level deviation L [m].

We will start by defining the ***global energy balance equations***, which states that the variation of energy stored in the boiler components is the difference between the output and input energy, illustrated in the differential (4.1):

$$\frac{dH}{dt} = E_i - E_0 \tag{4.1}$$

In this stage it is needed to account for an expression of the parameters in relation (4.1).

Experimental data were used in order to find proper expressions for H, E_0 and E_i. It is assumed that the temperatures for the feedwater, steam and the iron components (downcommers, risers, drums) of the boiler are kept constant. The parameter which has powerful transients is the pressure, meaning that this is also a key variable for the energy of the boiler. ***The energy storage H*** is then approximated as a linear distribution of pressure in the boiler (4.2):

$$H = H(P) = aP + b \tag{4.2}$$

The input power E_i is given mainly by the feedwater flow – u1 and the fuel flow - u2, if we consider that the boiler efficiency is constant and that the air flow to the boiler burners is optimum. The expression for P_i is also a linear distribution of the 2 input parameters stated in (4.3):

$$E_i = a_1 u_1 - a_2 u_3 \tag{4.3}$$

where a_1 and a_2 are constants to be determined in order to fit the model to a real thermal power plant.

The output power E_0 must be a function of the steam flow q_s and if the pressure drop on the superheater is neglected then the relation is (4.4):

$$E_0 = b_1 q_s \Delta h + b_2 \tag{4.4}$$

where Δh is the enthalpy drop on the turbine and b_1 and b_2 are fitting constants.

In order to have a computational relation it is needed to state the expressions for Δh and q_s. For the steam flow it is possible to use the expression presented in chapters 3.2 and 3.3 under the analytical form: $q_s = b_3 u_2 \sqrt{\Delta P}$ taking into account the gauge reading in figure 10 of [3.17].

But if we neglect the pressure drop on the superheater it is also possible to choose an equally valid linear distribution under the form of relation (4.5) described in [4.5]:

$$q_s = b_3 u_2 P \tag{4.5}$$

For the enthalpy drop across the turbine relation (4.6) is used:

$$\Delta h = b_4 P_i^r \qquad (4.6)$$

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where P_i is the input pressure to the turbine and if we neglect the pressure drop on the superheater the following relation is valid: P_i=P. Parameter $r = \frac{1}{8}$ is approximated in conformity with [3.17].

In this modeling phase we can give an expression for the output power E_0. By introducing equations (4.5) and (4.6) in (4.4) the relation for the output power is stated in (4.7):

$$E_0 = \alpha_4(u_2 P^{\frac{9}{8}} + \alpha_5) \qquad (4.7)$$

By introducing relations (4.3) and (4.7) in (4.1) and by accounting for the expression of the stored energy H in (4.2) the equation system illustrated in (4.8) is obtained:

$$\begin{cases} \dfrac{dH}{dt} = a_1 u_1 - a_2 u_3 - \alpha_4(u_2 P^{\frac{9}{8}} + \alpha_5) \\ \dfrac{dH}{dt} = a\dfrac{dP}{dt} \end{cases} \qquad (4.8)$$

The final form of the 1st state equation is given in (4.9):

$$\begin{cases} \dfrac{dP}{dt} = -\alpha_1 u_2 P^{\frac{9}{8}} + \alpha_2 u_1 - \alpha_3 u_3 \\ E_0 = \alpha_4(u_2 P^{\frac{9}{8}} + \alpha_5) \end{cases} \qquad (4.9)$$

where $\alpha_1 = \frac{\alpha_4}{a}, \alpha_2 = \frac{a_1}{a}, \alpha_3 = \frac{a_2}{a}$ are normalized coefficients and $\alpha_5 = 0$, determined from the experimental data.

The second state equation is given by the dynamics of the turbine-generator system. In steady state the generator energy output E is proportional to the output power E_0. But under these conditions we must account for an energy loss of the entire boiler-turbine-generator system through the condenser. By stating a linear distribution of the steam flow under the form of relation (4.10), with c_2 as the energy drop parameter and some mathematical manipulations, the generated energy can be formulated.

$$q_s = (c_1 u_2 - c_2)P \qquad (3.10)$$

By equating (4.6) and (4.10) into (4.4) the relation for the produced energy can be stated under the analytical form presented in (4.11):

$$E = (\alpha_6 u_2 - \alpha_7)P^{\frac{9}{8}} + \alpha_8 \qquad (4.11)$$

where: $\alpha_6 = c_1 b_1 b_4, \alpha_7 = c_2 b_1 b_4 and \alpha_8 = b_2$. In order to obtain the dynamics of the turbine-generator and the 2nd state equation a differential manipulation is done on (4.11):

$$\frac{dE}{dt} = \frac{(\alpha_6 u_2 - \alpha_7)P^{\frac{9}{8}} + \alpha_8 - E}{h} \qquad (4.12)$$

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where h=0.1s is the ODE Solver step.

The 3rd state equation comes from stating the water level deviation L in the drum (3.14), by accounting for the total volume of water and steam V_w in the drum of the boiler below the reference level.

$$L = d_1 V_w + d_2 \qquad (4.14)$$

where d_1 and d_2 are parameters to be estimated from drum dimensions. The volume of water in the drum V_w is actually a mixture of dynamics: the total volume of water in the drum V_{wa} and the amount of evaporated water V_e. The total volume of water in the drum V_{wa} can be expressed as functions of feetwater flow rate q_{fw}, steam flow rate q_s and the specific volume of water υ_w at a specific operating point. Also the total volume of water can be expressed as relation (4.15):

$$V_{wa} = \upsilon_w V_t \rho_{fs} \qquad (4.15)$$

The 3rd state equation is then stated in relation (4.16):

$$\frac{d\upsilon_w V_t \rho_{fs}}{dt} = (q_{fw} - q_s)\,\upsilon_w \iff \frac{d\rho_f}{dt} = \frac{(q_{fw} - q_s)}{V_t} \qquad (4.16)$$

where ρ_{fs} is the fluid density (water and steam).

The final analytical model is presented in relation (4.17) by linking the 3 state equations from (4.8), (4.12) and (4.16):

$$\begin{cases} \frac{dP}{dt} = -\alpha_1 u_2 P^{\frac{9}{8}} + \alpha_2 u_1 - \alpha_3 u_3 \\ \frac{dE}{dt} = \frac{(\alpha_6 u_2 - \alpha_7)P^{\frac{9}{8}} + \alpha_8 - E}{h} \\ \frac{d\rho_f}{dt} = \frac{(q_{fw} - q_s)}{V_t} \\ y_1 = P \\ y_2 = E \\ y_3 = L \end{cases} \qquad (4.17)$$

Most of the parameters illustrated in relation (4.17) are not expressed so a mathematical exploitation is needed:

- The mass flow rate of fuel, steam and feedwater:

$$\begin{aligned} q_f &= K_{f0} u_1 \\ q_s &= (c_1 u_2 - c_2)P \\ q_{fw} &= K_{fw} u_3 \end{aligned} \qquad (4.18)$$

where K_{f0} is the fuel flow constant and K_{fw} is the water flow constant.

- The fuel heat power:

$$Q = K_{f1} q_f + K_{f2} \quad (4.19)$$

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where K_{f1} is the proportional constant and K_{f2} is the bias constant of fuel heat power.

- The evaporation mass flow rate:

$$q_e = \frac{K_b Q - r_1 q_{fw} + K_{mass} q_s}{1 + K_{mass}} \quad (4.20)$$

where K_b=reciprocal of latent heat vaporization, r_1= loss of fuel energy used for evaporation per unit mass of feedwater entering and K_{mass}= additional mass of steam evaporated per unit mass lost from the system.

- The steam density :

$$\rho_s = K_{s1} P + K_{s2} \quad (4.21)$$

where K_{s1} is the proportional constant and K_{s2} is the bias constant.

- Steam quality:

$$\alpha_r = \frac{\dfrac{1}{\rho_{fs}} - \upsilon_w}{\dfrac{1}{\rho_s} - \upsilon_w} \quad (4.22)$$

where ρ_s is the steam density.

- Amount of evaporated water:

$$V_e = \frac{T_s \upsilon_f q_e}{A} \quad (4.23)$$

where υ_f is the specific volume of saturated water at 322 deg C, A is the wet area of the drum and T_s is the fall of boiler water mass per unit increase in evaporation rate.

In this stage we are able to define ***the complete analytical model*** of the boiler-turbine-generator system described by non-linear coupled 3x3 MIMO model:

$$\begin{cases} \dfrac{dx_1}{dt} = -\alpha_1 u_2 x_1^{\frac{9}{8}} + \alpha_2 u_1 - \alpha_3 u_3 \\ \dfrac{dx_2}{dt} = \dfrac{(\alpha_6 u_2 - \alpha_7) x_1^{\frac{9}{8}} + \alpha_8 - x_2}{h} \\ \dfrac{dx_3}{dt} = \dfrac{K_{fw} u_3 - (c_1 u_2 - c_2) x_1}{V_t} \\ y_1 = x_1 \\ y_2 = x_2 \\ y_3 = d_1 \left[\upsilon_w V_t x_3 + \dfrac{T_s \upsilon_f q_e(u_1, u_2, u_3, x_1)}{A} \right] + d_2 \left(\alpha_r(x_1, x_3) \right) \end{cases} \quad (4.24)$$

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where for y_3, $d_2 = a\alpha_r + b$ and d_1, a and b are constants to be determined and, $\alpha_r(x_1, x_3)$ is given by (4.22), (4.21) and $q_e(u_1, u_2, u_3, x_1)$ is given by (4.20), (4.19), (4.18).

The state vector is: $[x1\ x2\ x3]^T = [P\ E\ \rho_{fs}]^T$

The output vector is $[y1\ y2\ y3]^T = [P, E, L]^T$ .In the water level (L), as algebraic components appear: the steam quality α_r and the evaporation rate q_e [kg/s].

The input vector is $[u1\ u2\ u3]^T$ which represent normalized positions of valve actuators that control: u1 - the mass flow rate of fuel, u2 - the steam to turbine, and u3 - the feed water to drum.

A full model variable/parameter description can be found below in table 4.1:

Table 4.1 – Model variable description

Variables and parameters	Description	Measuring unit
u1	Fuel valve position	p.u.
u2	Throttle valve position	p.u.
u3	Feedwater valve position	p.u.
E	Electric power output	MW
P	Steam pressure	Kg/cm^2
L	Drum level	m
ρ_{fs}	Fluid density (steam, water)	Kg/m^3
q_f	Fuel mass flow rate	Kg/s
q_s	Steam mass flow rate	Kg/s
q_{fw}	Feedwater mass flow rate	Kg/s
ρ_s	Steam density	Kg/m^3
α_r	Steam quality	Dimensionless
q_e	Evaporation mass flow rate	Kg/s

4.2.2. Fitting the analytical model for thermal power plant south of Timisoara

The model is adapted to fit a small coal and gas fired thermal power plant South of Timisoara, Romania at 16 MW generation capability, 32.69 kg/s steam flow and a maximum pressure of 20 bar, *using static functioning points*. The model is a 3x3 MIMO nonlinear strongly-coupled system, with wide-range simulation efficiency, given by the state equations (3.24).

In order to fit the model properly it is needed find the coefficient for the model in concordance with the static functioning points.

- *Fuel flow, steam flow and feedwater flow* coefficient:

The maximum amount of coal which can be fed to the boiler is 43.400 [kg/h] = 12.05 [kg/s] = K_{f0} (4.25). The maximum amount of steam produced at 100% operating point is 100 [t/h] = 32.69 [kg/s] at 100% load so the c1 and c2 coefficients were identified as in (4.26). The maximum amount of water fed to the boiler is equal to the mass flow rate of steam and is Kfw = 32.69 [kg/s] (4.27).

$$q_f = 12.05 u_1 \tag{4.25}$$

$$q_s = (1.9765u_2 - 0.19)\,x_1 \tag{4.26}$$

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$$q_{fw} = 32.69u_3 \tag{4.27}$$

- *Fuel heat flow rate* coefficients were approximated as follows K_{f1}=4398.34 [KW*s/Kg] and K_{f2}=-10000 [KW], and the heat flux relation is presented below.

$$Q = 4398{,}34q_f - 10.000 \tag{4.28}$$

- The coefficients for the *evaporation mass flow rate* are: K_b=0.0008 [kg/kJ], r_1=0.08912 and K_{mass}=3.46608.

$$q_e=(1.533*u_2-0.124)x_1+95.4u_1-0.653u_3-18 \tag{4.29}$$

- The *steam density* coefficients K_{s1}=0.497 [cm^2/m^3] and K_{s2}=0.15 [kg/m^3], were approximated from steam tables.

$$\rho_s = 0.497x_1 + 0.15 \tag{4.30}$$

- The *quality of steam* numerical relation is presented in (4.31), where the specific volume of water $\upsilon_w = 0.0011$ at t=160 [degC]:

$$\alpha_r = \frac{\dfrac{1}{x_3} - 0.0011}{\dfrac{1}{0.497x_1 + 0.15} - 0.0011} \tag{4.31}$$

- In order to obtain the water level relation some constructive and functioning constants of the boiler-turbine-generator system are summarized in table 4.2:

Table 4.2 – Constructive parameter description

Parameter	Value	Units	Description
V_t	57,81	m^3	Total volume of the downcommer – riser - drum
T_s	350	s*m^2	Fall of boiler water mass per unit increase in evaporation rate
υ_f	0.0015	m^3/kg	Specific volume of saturated water at 322 degC
A	20	m^2	Wet area of the drum

By fitting and estimating the parameters $\alpha_1 = 0.0285, \alpha_2 = 0.9, \alpha_3 = 0.15$ and $\alpha_6 = 0.507, \alpha_7 = 0.16, \alpha_8 = 0$ from relations (4.25-4.31) and by equating these relations in expression (4.24) gives boiler-turbine-generator fitted numerical model:

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$$\begin{cases} \dot{x}_1 = -0.0285 u_2 x_1^{\frac{9}{8}} + 0.9 u_1 - 0.15 u_3 \\ \dot{x}_2 = \dfrac{(0.5074 u_2 - 0.16) x_1^{\frac{9}{8}} - x_2}{0.1} \\ \dot{x}_3 = \dfrac{32.69 u_3 - (1.9765 u_2 - 0.19) x_1}{57.81} \\ y_1 = x_1 \\ y_2 = x_2 \\ y_3 = 0.05(0.0636 x_3 + 60 \alpha_r + 0.019 q_e - 31.2) \end{cases} \tag{4.32}$$

where:

$$\alpha_r = \frac{(1 - 0.0011 x_3)(0.497 x_1 + 0.15)}{x_3 (1 - 0.000546 x_1)} \tag{4.33}$$

$$q_e = 95.4 u_1 - 0.653 u_3 + (1.533 u_2 - 0.124) x_1 - 18 \tag{4.34}$$

The state variables are: x_1 - the drum steam pressure *P* [Bar], x_2 - the generated power *E* [MW] and x_3 - the water fluid density in drum ρ_{fs} [kg/m^3]. The three outputs y_1, y_2, y_3 are respectively: the drum steam pressure x_1, the megawatt power output x_2 and the water level deviation *L* in [m]. In the water level, as algebraic components appear: the steam quality α_r (4.33) and the evaporation rate q_e [kg/s] (4.34). The three inputs are normalized positions of valve actuators that control: u_1 - the mass flow rate of fuel, u_2 - the steam to turbine, and u_3 - the feed water to drum in [kg/s]. The rates of change of the three valve actuators are illustrated in relations (4.35):

$$\begin{aligned} -0.07 \le \frac{du_1}{dt} \le 0.07 \\ -0.02 \le \frac{du_2}{dt} \le 0.02 \\ -0.05 \le \frac{du_3}{dt} \le 0.05 \end{aligned} \tag{4.35}$$

The static functioning points around which the model is fitted, experimentally determined, are presented in the table below:

Table 4.3 – Static functioning points

F.P.	Fuel valve u1	Throttle valve u2	Feedwater valve u3	Pressure P [bar] y1	Power E[MW] y2	Fluid density ρ_{fs} [kg/m^3] y3
50%	50%	62%	48%	15.22	3.31	450
64%	64%	73%	62.6%	16.34	4.9	450
71%	71%	100%	73%	13.46	6.47	450
90%	90%	100%	91%	16.63	8.21	450
100%	100%	100%	100%	18.3	9.14	450

4.2.3. Dynamic linearization of the fitted model

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The present chapter deals with the periodic linearization of the thermal power plant model in various operating points and provides a transfer function representation in order to be able to provide the optimum controller gains for the centralized control strategy.

In this phase, the non-linear dynamics of the boiler-turbine-generator system is provided by a state – space representation, generally described by the set of equations presented in (4.36).

$$\begin{cases} \dot{x} = f(x,u) = Ax + Bu \\ y = g(x,u) = Cx + Du \end{cases} \tag{4.36}$$

where $x = [x_1\ x_2\ x_3]^T = [P\ E\ \rho_{fs}]^T$ is the state vector, $y = [y_1\ y_2\ y_3]^T = [P\ E\ L]^T$ is the output vector and $u = [u_1\ u_2\ u_3]$ is the input vector.

The non-linear model is linearized around the following operating points $y_0 = (y_{10}\ y_{20}\ y_{30})$, $x_0 = (x_{10}\ x_{20}\ x_{30})$, $u_0 = (u_{10}\ u_{20}\ u_{30})$ using reduced Taylor series, and extended to dynamic linearization in order to prepare the adaptive gains for the multivariable control. The linear state-space model is obtained by defining the linear matrixes in a Jacobian representation as in relations (4.37):

$$A = \left.\frac{\partial f}{\partial x}\right|_{x_0,u_0} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \frac{\partial f_1}{\partial x_3} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \frac{\partial f_2}{\partial x_3} \\ \frac{\partial f_3}{\partial x_1} & \frac{\partial f_3}{\partial x_2} & \frac{\partial f_3}{\partial x_3} \end{bmatrix}; \quad B = \left.\frac{\partial f}{\partial u}\right|_{x_0,u_0} = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \frac{\partial f_1}{\partial u_2} & \frac{\partial f_1}{\partial u_3} \\ \frac{\partial f_2}{\partial u_1} & \frac{\partial f_2}{\partial u_2} & \frac{\partial f_2}{\partial u_3} \\ \frac{\partial f_3}{\partial u_1} & \frac{\partial f_3}{\partial u_2} & \frac{\partial f_3}{\partial u_3} \end{bmatrix} \tag{4.37a}$$

$$C = \left.\frac{\partial g}{\partial x}\right|_{x_0,u_0} = \begin{bmatrix} \frac{\partial g_1}{\partial x_1} & \frac{\partial g_1}{\partial x_2} & \frac{\partial g_1}{\partial x_3} \\ \frac{\partial g_2}{\partial x_1} & \frac{\partial g_2}{\partial x_2} & \frac{\partial g_2}{\partial x_3} \\ \frac{\partial g_3}{\partial x_1} & \frac{\partial g_3}{\partial x_2} & \frac{\partial g_3}{\partial x_3} \end{bmatrix}; \quad D = \left.\frac{\partial g}{\partial u}\right|_{x_0,u_0} = \begin{bmatrix} \frac{\partial g_1}{\partial u_1} & \frac{\partial g_1}{\partial u_2} & \frac{\partial g_1}{\partial u_3} \\ \frac{\partial g_2}{\partial u_1} & \frac{\partial g_2}{\partial u_2} & \frac{\partial g_2}{\partial u_3} \\ \frac{\partial g_3}{\partial u_1} & \frac{\partial g_3}{\partial u_2} & \frac{\partial g_3}{\partial u_3} \end{bmatrix} \tag{4.37b}$$

The linear state space model has then the following representation:

$$\begin{cases} \Delta\dot{x} = A\Delta x + B\Delta u \\ \Delta y = C\Delta x + D\Delta u \end{cases} \tag{4.39}$$

where $\Delta y = y - y_0$ and similarly for Δu and Δx.

The state-space linear model has the following matrixes:

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$$A=\begin{pmatrix} -0.032u_{20}x_{10}^{\frac{1}{8}} & 0 & 0 \\ (5.71u_{20}-1.8)\,x_{10}^{\frac{1}{8}} & -10 & 0 \\ 0.0032-0.034u_{20} & 0 & 0 \end{pmatrix} \quad B=\begin{pmatrix} 0.9 & -0.0285x_{10}^{\frac{9}{8}} & -0.15 \\ 0 & 5.074x_{10}^{\frac{9}{8}} & 0 \\ 0 & -0.0341x_{10} & 0.0565 \end{pmatrix} \qquad (4.39a,b)$$

$$C=\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 3\frac{\partial\alpha_r}{\partial x_{10}}+0.0096\frac{\partial q_e}{\partial x_{10}} & 0 & 0.0318+3\frac{\partial\alpha_r}{\partial x_{30}} \end{pmatrix} \qquad (4.39c)$$

$$D=\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1.81 & 0.00147x_{10} & -0.000626 \end{pmatrix} \qquad (4.39d)$$

An example is shown in Fig 4.2, Fig 4.3 and Fig 4.4 for the drum pressure, generated power and water level, at a discrete step of h = 0.1s. Every 2s, the new functioning point is updated and the linearization is carried out around the new point y_0. In order to get back on the non-linear curve, a correction is applied for each adaptation step by subtracting the previous output difference at every 2s. The linear graph is obtained by applying the following relation:

$$y(k)=\Delta y(k)+y_0(k)-\Delta y(k-1) \qquad (4.40)$$

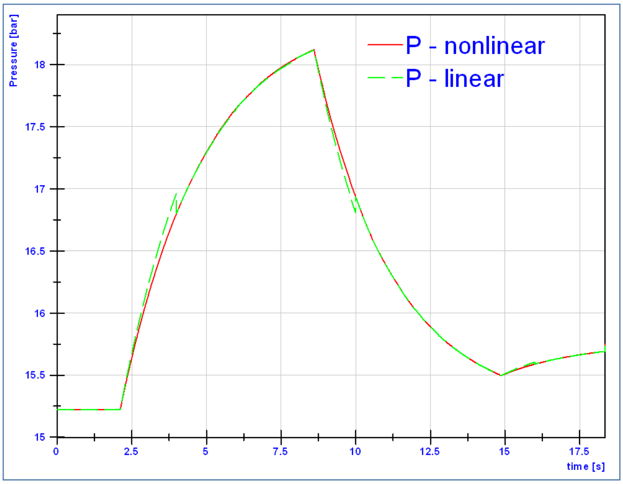

Fig 4.2. Pressure (y1) responses with dynamic linearization.

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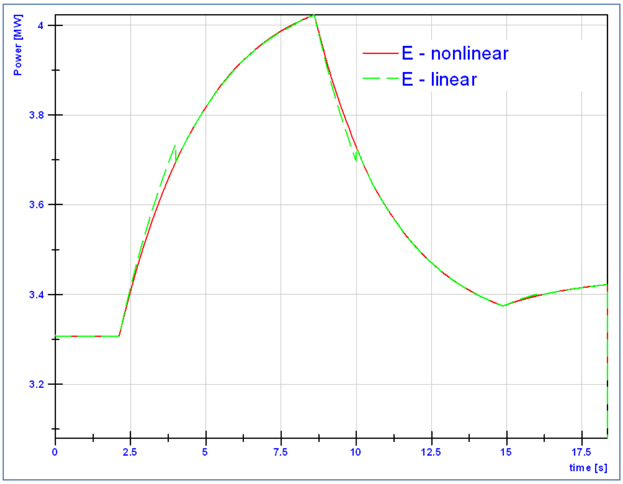

Fig 4.3. Power (y2) responses of dynamic linearization.

Fig 4.4. Water level (y3) responses of dynamic linearization.

The linearization of pressure and power works very well. It is tempting however to consider that the approximation for the water level is not good enough, but if we consider the differences between the models on the level scale, it can be seen that these are very small < 1% of the total range (-0.5 to 0.5).

After linearization, the new MIMO matrixes A, B, C, and D are found. In order to obtain the model into a MIMO transfer function form G(s), a translation is necessary using the Laplace transformation (4.41).

$$Y(s) = [C(sI - A)^{-1} B + D]U(s) = G(s)U(s) \tag{4.41}$$

The coefficients of the transfer function matrix are adapted every 30s. An example of the model is presented in Fig 4.5 for 50% boiler load.

$$\begin{bmatrix} \dfrac{0.9}{s+0.041} & \dfrac{-0.771}{s+0.041} & \dfrac{-0.15}{s+0.041} \\ \dfrac{4.267}{s^2+10.041s+0.41} & \dfrac{137.24s+1.99}{s^2+10.041s+0.41} & \dfrac{-0.711}{s^2+10.041s+0.41} \\ \dfrac{1.81s^2+0.077s-0.0008}{s^2+0.041s} & \dfrac{0.275s^2-0.0116s-0.0002}{s^2+0.041s} & \dfrac{-0.0006s^2+0.017s-0.0009}{s^2+0.041s} \end{bmatrix}$$

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Fig 4.5. Linear transfer function matrix of the model in the case of 50% boiler load.

It is known from Chapter 3.3, where the shrink and swell effect was discussed, that the water level dynamics present a non-minimum phase phenomena. This was observed in the boiler responses and in the controller commands and known from process experience, though no transfer function model could be derived, due to the complexity of the model, resulting in difficulties in designing a complex control strategy. Now, it can be observed that row three of the transfer function matrix in Fig 4.5, contain positive zeros, resulting in a minimum phase behavior, associated to water level output.

The transfer matrix is used to design the centralized adaptive control by decoupling.

4.3. Gain-scheduled decoupled PID control

One important control system target is the ability to compensate, as accurate as possible, the loop interactions over a wide range of operating points. In order to achieve this performance a decoupled centralized control strategy was adopted Fig 4.6. The centralized control strategy was adopted in implementation due to the real centralized control architecture with Siemens S7400 controller at the thermal power plant south of Timisoara, presented in Chapter 2.

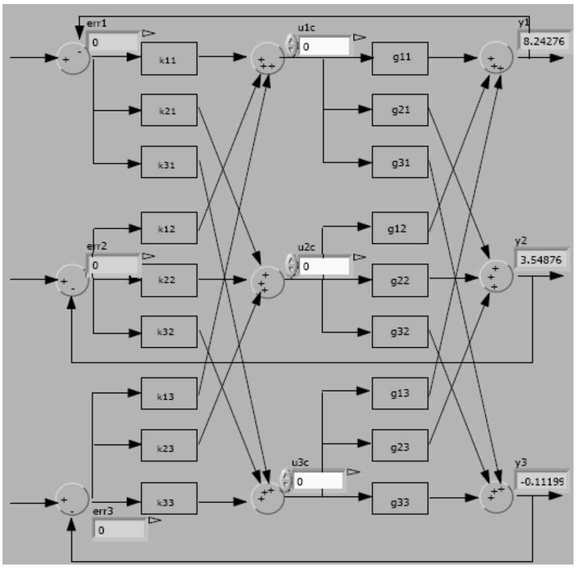

Fig 4.6. Proposed system using decoupling control method.

4.3.1. PID analytical decoupling

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Analytical decoupling, control tuning methods and control reduction methods for multivariable systems are intensively discussed in [4.2]-[4.3], [4.12]-[4.13] , so some of the tedious calculus details are omitted for brevity.

The fundamental idea is to find a control matrix K(s) so that the closed-loop system $\frac{G(s)K(s)}{[I+G(s)K(s)]}$ is decoupled. This is done if the open loop matrix L(s) has a diagonal form (4.42).

$$L(s) = G(s)K(s) = \begin{bmatrix} l_1(s) & 0 & 0 \\ 0 & l_2(s) & 0 \\ 0 & 0 & l_3(s) \end{bmatrix} \tag{4.42}$$

If gain-scheduled control is desired for the system, then it is needed to state the transfer matrix G(s) in an analytical form (4.43). In order to ease this process the author makes use of the transfer function form presented in Fig 4.5. Several functioning points of the plant were tested and the linear transfer matrix G(s) maintains the form, but not the coefficients, of the transfer functions due to the dynamic linearization mechanism. The coefficients change every 30s if the model is engaged in a transient regime.

$$G(s) = \begin{pmatrix} \frac{a_1}{s+a_2} & \frac{b_1}{s+a_2} & \frac{c_1}{s+a_2} \\ \frac{d_1}{(s+a_2)(s+a_3)} & \frac{e_1 s + e_2}{(s+a_2)(s+a_3)} & \frac{f_1}{(s+a_2)(s+a_3)} \\ \frac{g_1 s^2 + g_2 s + g_3}{s(s+a_2)} & \frac{h_1 s^2 + h_2 s + h_3}{s(s+a_2)} & \frac{i_1 s^2 + i_2 s + i_3}{s(s+a_2)} \end{pmatrix} \tag{4.43}$$

For obtaining the controller transfer matrix it is needed to extract K(s) from (4.42) to obtain the matrix of the nine ideal controllers:

$$K(s) = G(s)^{-1} L(s) = \begin{pmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ K_{31} & K_{32} & K_{33} \end{pmatrix} =$$

$$\frac{1}{|G|} \begin{pmatrix} G^{11} l_1 & G^{21} l_2 & G^{31} l_3 \\ G^{12} l_1 & G^{22} l_2 & G^{32} l_3 \\ G^{13} l_1 & G^{23} l_2 & G^{33} l_3 \end{pmatrix} = \begin{pmatrix} \tilde{g}_{11}^{-1} l_1 & \tilde{g}_{21}^{-1} l_2 & \tilde{g}_{31}^{-1} l_3 \\ \tilde{g}_{12}^{-1} l_1 & \tilde{g}_{22}^{-1} l_2 & \tilde{g}_{32}^{-1} l_3 \\ \tilde{g}_{13}^{-1} l_1 & \tilde{g}_{23}^{-1} l_2 & \tilde{g}_{33}^{-1} l_3 \end{pmatrix} \tag{4.44}$$

where: $\tilde{g}_{ij}(s) = \frac{|G(s)|}{G^{ij}(s).}$.

The forms of the equations in (4.44) are computed for carrying out controller reduction to a PI form.

As long as the plant pressure, power and water level dynamics are known, the control matrix (4.44) can be determined. In this case, the open loop matrix (4.42) and the control reduction are decided with methods described in [4.2].

4.3.2. Finding the open loop matrix $L(s)$

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In this particular scenario, where the model was fitted, it is needed to find the appropriate and desired open loop dynamics for the pressure, power and water level. As stated in [4.3], the closed loop system must be stable and without steady-state errors in case of set-point change and fast shifting loads. This means that the open loop transfer function must contain an integrator, resulting in a general expression for $l_i(s)$ (4.45):

$$l_i(s) = k_i \overline{l_i(s)} \frac{1}{s} \tag{4.45}$$

Since the corresponding processes of $l_1(s)$ *and* $l_2(s)$ do not have any non – minimum phase zeros and no unstable poles, their closed loop transfer functions are 1st order systems, with imposed time constants T_1=18s for pressure and T_2=50s for power. The generic relation is illustrated in (4.46):

$$h_i(s) = \frac{\frac{k_i}{s}}{1 + \frac{k_i}{s}} = \frac{1}{T_i s + 1} \tag{4.46}$$

where k_1=0.055, k_2=0.02 experimentally determined and $\overline{l_i(s)} = 1$ for i=1,2.

In this stage the MIMO process model derived in (4.43) shows a 2nd order relation in 3rd row, with poles in s=0. For obtaining a stable closed loop transfer function $\overline{l_3(s)} = \frac{s + z_i}{s}$ is chosen [4.3], thus obtaining a closed loop transfer function with a structure of a second order element characterized by the undamped natural frequency ω_n and damping factor δ (4.47):

$$h_i(s) = \frac{k_i \frac{s + z_i}{s^2}}{1 + k_i \frac{s + z_i}{s^2}} = \frac{k_i(s + z_i)}{s^2 + k_i s + k_i z_i} \tag{4.47}$$

where $\omega_n = \sqrt{k_i z_i}$ and $\delta = \sqrt{\frac{k_i}{4z_i}} = 1$ (critical damping), resulting that $k_i = 4z_i \Rightarrow \omega_n = 2z_i$. If z_3=0.01 is chosen, then the natural frequency is $\omega_n = 0.02$ and k_3=0.04 [4.2].

The open loop transfer matrix has the form presented in relation (4.48):

$$L(s) = \begin{pmatrix} l_1 = \frac{0.055}{s} & 0 & 0 \\ 0 & l_2 = \frac{0.02}{s} & 0 \\ 0 & 0 & l_3 = \frac{0.0004(100s + 1)}{s^2} \end{pmatrix} \tag{4.48}$$

4.3.3. Controller reduction method

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In order to obtain dynamic controller gains it is necessary to compute relation (4.44). The matrix controller's transfer functions are complicated and very hard to implement on industrial targets, e.g. PLCs as it is desired towards the end of this dissertation. To be able to do this it is needed to obtain a common form for the controllers, for example PID forms. This chapter makes use of the reduction methods, respectively model reduction to the inverse simplified expression $\tilde{g}_{ji}$ presented in [4.2] to obtain a PI control matrix.

The PI controller form is presented in relation (4.49):

$$K_{ij} = \frac{K_i}{s}(K_{Pij}s + K_{Iij}) \tag{4.49}$$

The controller form that is obtained from relation (4.44) is:

$$K_{ij}(s) = k_i[\tilde{g}_{ji}(s)]^{-1}\frac{1}{s} \tag{4.50}$$

where:

$$\tilde{g}_{ji}(s) = \frac{|G(s)|}{G^{ij}(s)} = \frac{\tilde{b}_{ij}(s)}{\tilde{a}_{ij}(s)}\left[\bar{l}_i(s)\right]^{-1} \cong \frac{\beta_0}{\alpha_{1Kij}s + \alpha_{0Kij}}. \tag{4.51}$$

Then if the approximation in (4.51) is introduced into (4.50), the gains for the corresponding controller are: $K_{Pij} = k_i\frac{\alpha_{1Kij}}{\beta_0}; K_{Iij} = k_i\frac{\alpha_{0Kij}}{\beta_0}$.

4.3.4. Complete controller gain calculus example

Following, we will present an example for computing controller gains and reducing controller K_{11} to a PI form. The remaining controller transfer functions and gains result in the same manner as presented for K_{11}. A complete calculus for controller gains is presented in Appendix 5, where the coefficients are extracted from relation (4.43).

Relation (4.44) states that it is needed to compute $G^{-1}(s) = \frac{G^*(s)}{|G(s)|}$. On the other hand equation (4.51) shows that for the proposed controller's reduction method only the steady state component from the determinant |G(s)| is needed, so we can omit showing the full determinant transfer function.

The approximated determinant transfer function with associated steady state term β_0 is presented in relation (4.52):

$$|G(s)| \cong \frac{a_1e_2i_3 + d_1c_1h_3 + b_1f_1g_3 - c_1e_2g_3 - f_1a_1h_3 - b_1d_1i_3}{s(s+10)(s+a_2)^3} = \frac{\beta_0}{s(s+10)(s+a_2)^3} \tag{4.52}$$

The next step is to compute the transfer function from position "G^{11}" from the $G^*(s)$ matrix. The relation is presented in (4.53):

$$G_{11}(s) = \frac{(e_1 s + e_2)(i_1 s^2 + i_2 s + i_3) - (h_1 s^2 + h_2 s + h_3) f_1}{s(s+10)(s+a_2)^2} \tag{4.53}$$

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By equating (4.52) and (4.53) into (4.51) and reducing the high order zeros, we obtain $\tilde{g}_{11}(s)$:

$$\begin{aligned} \tilde{g}_{11}(s) &= \frac{\beta_0}{(s+a_2)[s(i_3 e_1 + e_2 i_2 - f_1 h_2) + e_2 i_3 - f_1 h_3]} \bar{l}_1(s) \\ &\cong \frac{\beta_0}{s[a_2(e_2 i_3 - f_1 h_3)(i_3 e_1 + e_2 i_2 - f_1 h_2)] + a_2(e_2 i_3 - f_1 h_3)} \\ &= \frac{\beta_0}{\alpha_{1K11} s + \alpha_{0K11}} \end{aligned} \tag{4.54}$$

where $\bar{l}_1(s) = 1$.

Then from (4.50) we can deduce the PI controller transfer function:

$$K_{PI11}(s) = \frac{K_1 \alpha_{1K11}}{\beta_0} + \frac{K_1 \alpha_{0K11}}{\beta_0} \frac{1}{s} \tag{4.55}$$

It is important to analyze the magnitude bode characteristic of the theoretical designed controller and the reduced controller, to determine if the approximation was executed correctly.

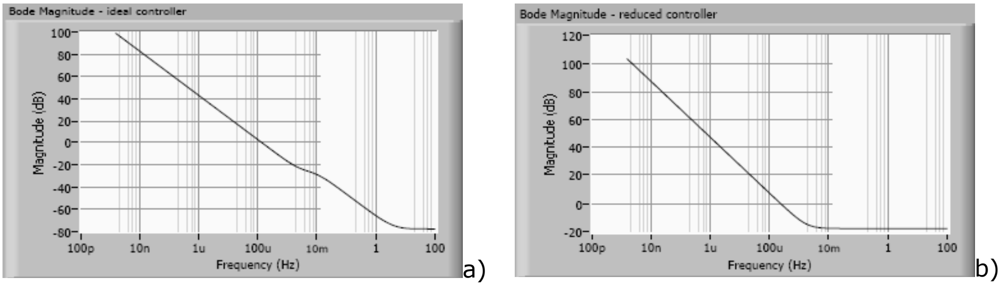

Fig 4.7. Bode characteristics for a) theoretical designed controller and b) reduced PI controller.

The frequency responses of the two controllers are similar at low frequencies, but different at high frequencies, resulting in equal performance at low frequencies. This is actually what we are looking for, considering that slow processes are associated with low frequencies and rapid dynamics with high frequencies. Furthermore high frequencies manifest at the beginning of the system response, low frequencies taking the upper hand while the process reaches steady state. It is observed that the integrator character is maintained for zero error tracking and disturbance rejection.

The step size of the ode solver is chosen at h=0.1s due to the biggest system time constant which is T=18.2s. Tests were done with h=0.5s and the process works equally well. If the execution of the simulation loop is carried out slower, then the process becomes unstable. This is because the controller response becomes too slow for the dynamics of the process. The controllers in the simulation are designed in continuous time.

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4.3.5. Gain-scheduling and anti wind-up mechanism

In order to achieve gain scheduling and make the control matrix adaptive, the transfer functions from the process matrix are represented in a literary form as in (4.43). Many of the coefficients appear several times, which eases the calculus. The determinant is computed in the same manner followed by K(s) and PI reduction.

As the process operating points are updated at every 30s, the controller gains are changed. The new gains are shifted smoothly in order to achieve bump-less behavior for the control. For this reason, the updated gains use 1st order low pass filters, applied to the coefficient arrays K_P and K_I of the PI controllers. The filtering is done in LabView in the same simulation loop as the linearization and gain calculus.

$$H(s) = \frac{1}{4s+1} \tag{4.56}$$

A controller gain table is presented on the next page for operating points at different pressures (table 4.4).

Table 4.4 – Controller gains at various pressure operating points

Pressure [bar]		Controller Gains								
		K11	K12	K13	K21	K22	K23	K31	K32	K33
10	Ki	0.00089674	0.00154489	0.00371867	-0.00085961	0.00282421	0	0.00066837	0.00178016	0.02231204
	Kp	0.15259261	0.15631939	0.74884177	-0.10157603	0.3340067	0	-0.0365615	0.05220738	4.49305063
15	Ki	0.0014831	0.00153114	0.00372401	-0.00123851	0.0018426	0	0.00060178	0.00169766	0.02234406
	Kp	0.1256425	0.1095496	0.63951316	-0.10966127	0.16333416	0	-0.0723601	-0.0065657	3.83707895
17	Ki	0.00172542	0.00152681	0.00372655	-0.00181756	0.00160377	0	0.00051807	0.00167168	0.02235933
	Kp	0.10639942	0.08115063	0.57138095	-0.12750978	0.11267232	0	-0.0975776	-0.03924381	3.4282857
19	Ki	0.00188171	0.00152434	0.00372696	-0.00210484	0.00148044	0	0.00046682	0.00165688	0.02236174
	Kp	0.09845277	0.06979652	0.54399638	-0.13216716	0.09310778	0	-0.1091971	-0.05222991	3.26397826

It is difficult to operate a thermal power plant using a fixed set of controller gains due to the numerous situation in which the process can be at different moments of time. The improved responses of the decoupled control with gain-scheduled technique are observed in section 4.4 of the present chapter, manifested mainly on the water level. For a large scale thermal power plant, e.g. P=200 bar maximum operating pressure, gain scheduling becomes essential due to the large setpoint differences e.g. 20-40 bar.

For example, the variations of controller gains for K_{11} and K_{12} for the operating pressure functioning point in table 4.4 are illustrated in Fig 4.9 and Fig 4.10.

Considering the constraints of the actuator models, an anti-windup strategy is implemented (Fig 4.8).

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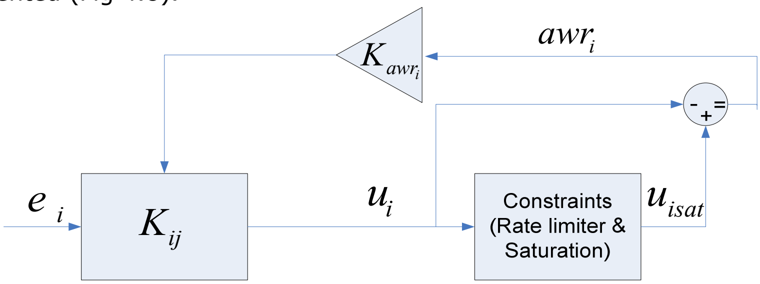

Fig 4.8. Anti-windup structure using rate limiter and saturation constraints.

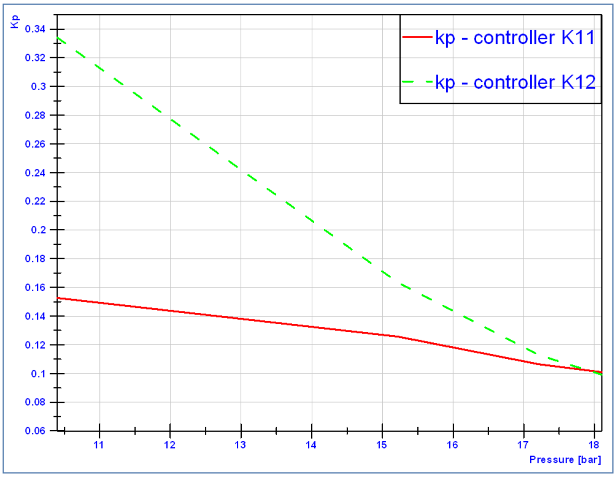

Fig 4.9. Kp controller gains as function of pressure operating points in table 4.4: Kp11 solid line (red), Kp12 dashed-dotted (green).

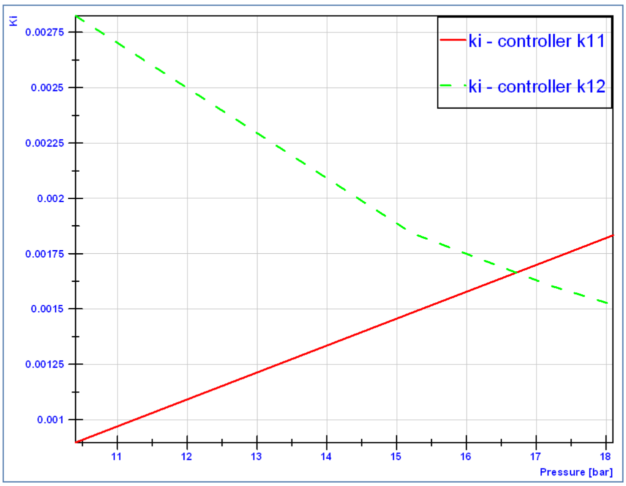

Fig 4.10. Ki controller gains as function of pressure operating points in table 4.4: Ki11 solid line (red), Ki12 dashed-dotted (green).

4.4. Test results

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In this section, the performance of the proposed control and the level of decoupling are analyzed.

In figures Fig 4.11-Fig 4.14, two simultaneous setpoint changes are done on the drum pressure and power output, in order to analyze the performance of the proposed adaptive control. At t = 100s the pressure is increased from 15.22 to 17.22 [bar] and the power from 3.31 to 6.31 [MW]. The system quickly reaches the pressure and power demand. The gain-scheduled technique slightly improves the system responses.

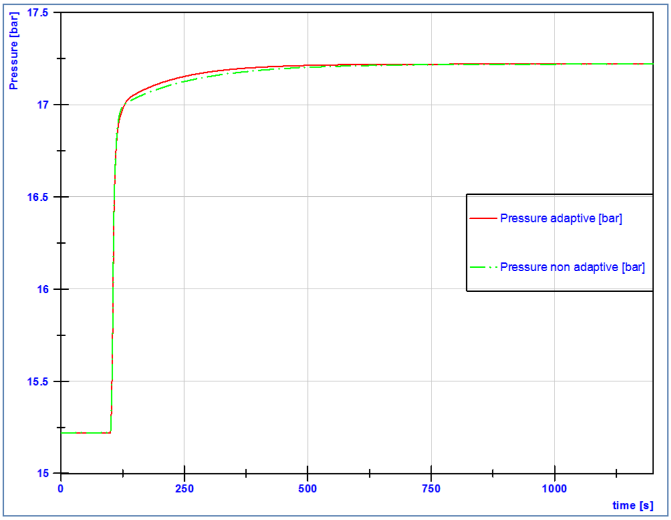

Fig 4.11. Pressure responses for simultaneous setpoint changes to a near operating point in pressure and power: adaptive solid line (red), non adaptive dashed-dotted line (green).

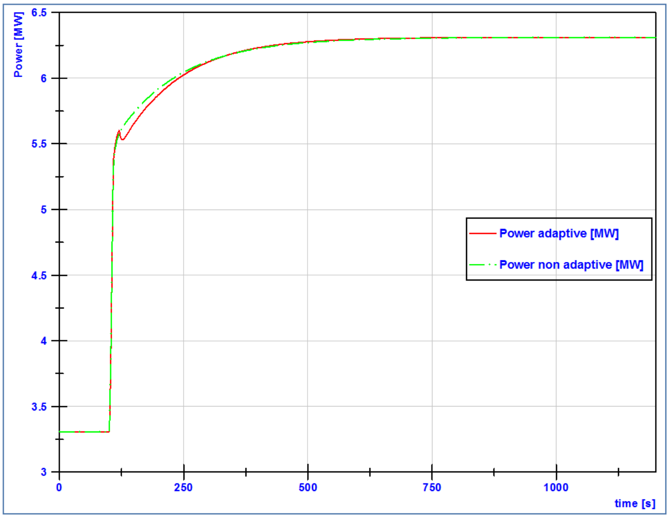

Fig 4.12. Power responses for simultaneous setpoint changes to a near operating point in pressure and power: adaptive solid line (red), non adaptive dashed-dotted line (green).

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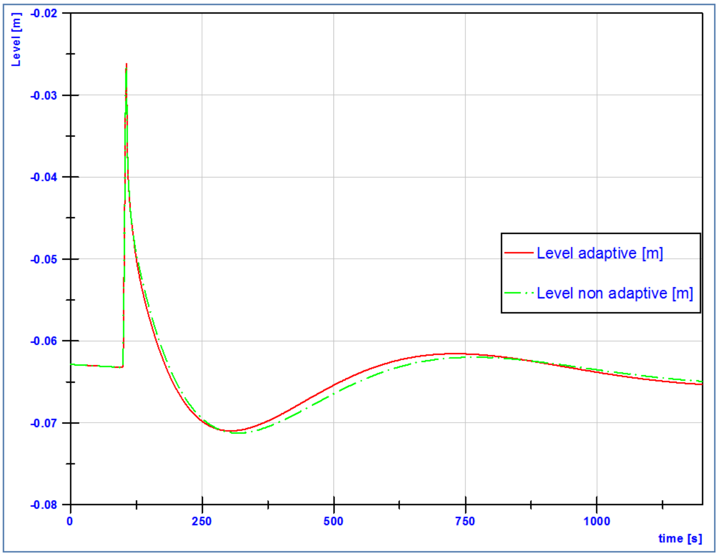

Fig 4.13. Water level responses for simultaneous setpoint changes to a near operating point in pressure and power: adaptive solid line (red), non adaptive dashed-dotted line (green).

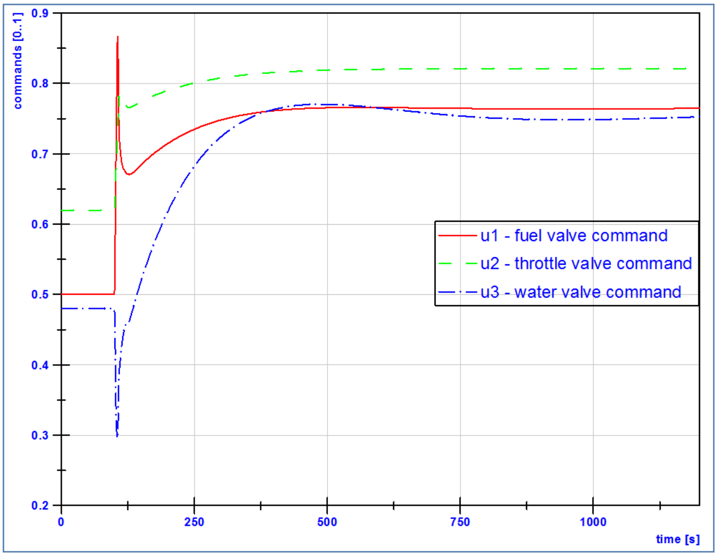

Fig 4.14. Controller commands with gain-scheduling for simultaneous setpoint changes to a near operating point in pressure and power.

The pressure reaches a little faster the desired operating point while the water level presents a slightly smaller oscillation and settles faster.

The gain-scheduled technique by dynamic model linearization is not yet justified due to the small improvements in system responses.

The decoupling level reached is satisfactory with no overshoot and a good settling time for pressure and power.

The water level remains within acceptable ranges < 3.5% of the total scale. The spike is caused by the opening of the turbine valve which acts directly on the boiler pressure. This disturbance causes the water level to rise due to the non-minimum phase phenomena, the shrink-and-swell effect discussed in chapter 3.

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The controller commands do not differ significantly so for brevity a comparison with the gain scheduled strategy is omitted.

Next, the author presents a similar test scenario where the pressure and power receive simultaneous setpoints to a far operating point: P=10.4 to 18.5 [bar] and E=3.31 to 8.5 [MW]. System responses and controller commands are illustrated in figures Fig 4.15 - Fig 4.18.

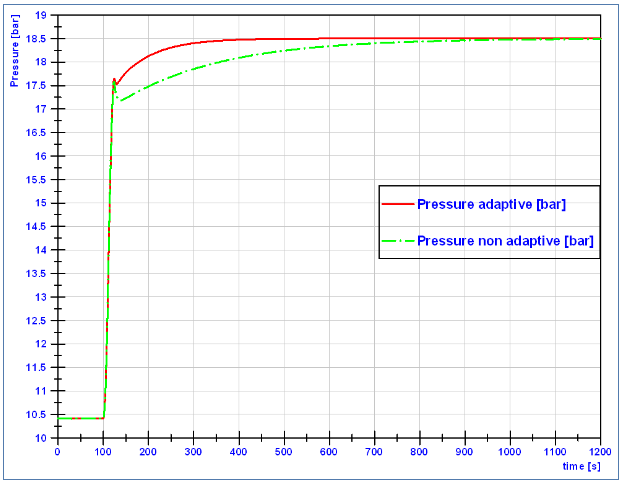

Fig 4.15. Pressure responses for simultaneous setpoint changes to a far operating point in pressure and power: adaptive solid line (red), non adaptive dashed-dotted line (green).

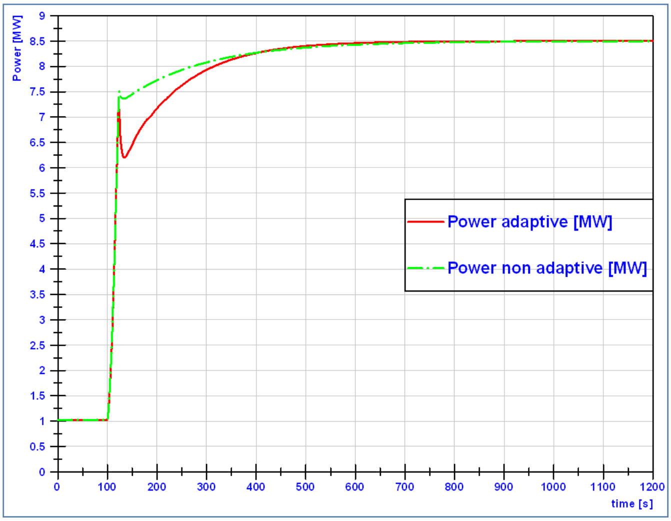

Fig 4.16. Power responses for simultaneous setpoint changes to a far operating point in pressure and power: adaptive solid line (red), non adaptive dashed-dotted line (green).

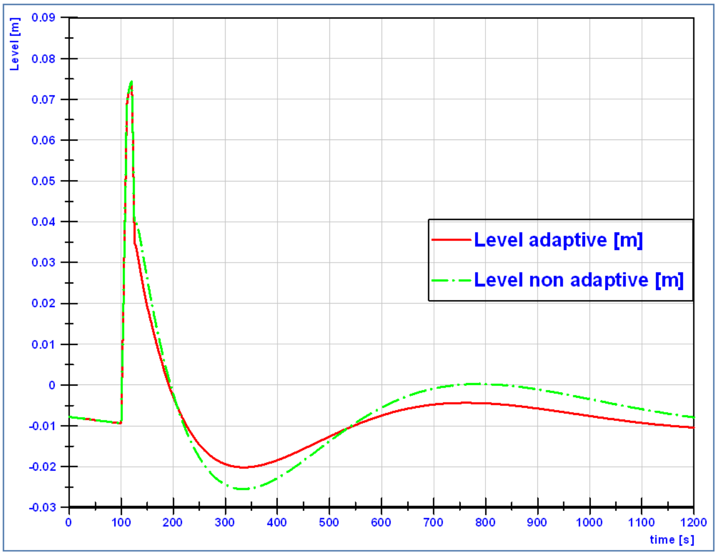

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Fig 4.17. Water level responses for simultaneous setpoint changes to a far operating point in pressure and power: adaptive solid line (red), non adaptive dashed-dotted line (green).

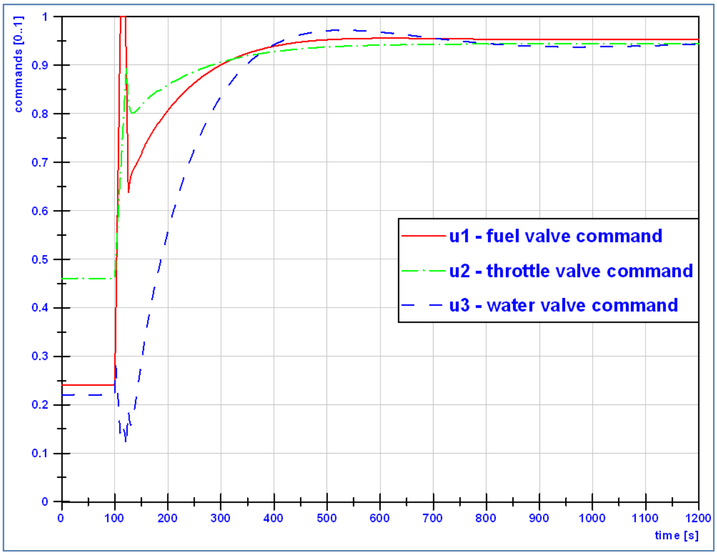

Fig 4.18. Controller commands with gain scheduling for simultaneous setpoint changes to a far operating point in pressure and power.

The throttle pressure reaches faster the desired operating point with the proposed gain scheduled technique. The pressure response with fixed controller gains reaches the desired value only at about t=900s.

The generated power shows a small spike at about t=120s with gain-scheduling. However it reaches fast enough the power response waveform with fixed controller gains at t=350s.

For safety reasons, in a boiler system it is important to keep the water level inside the drum as constant as possible. Taking into account the responses presented in Fig 4.17, the gain scheduled multivariable decoupled control shows a good improvement in water level settling time and oscillation amplitude, < 9% of the total scale. Fig 4.19 shows the importance of the 1st order low pass filters applied on the controller gains. The test is done on a power demand. Undesired "bumps" appear over the transient regime.

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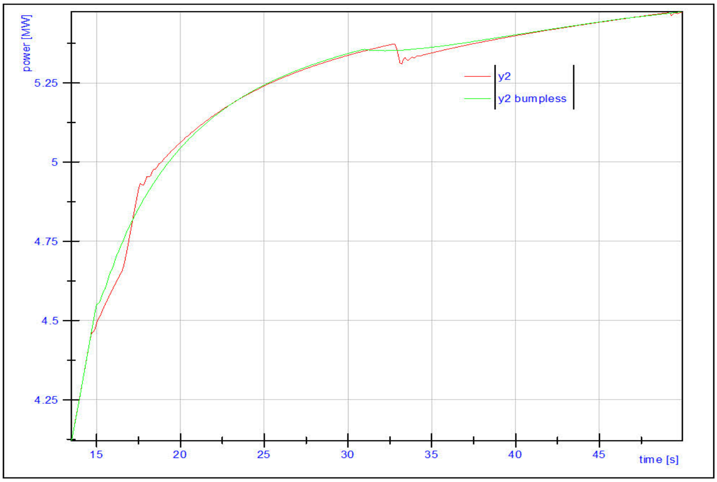

Fig 4.19. Generated Power (y2) response with filtered and non filtered scheduled controller gains.

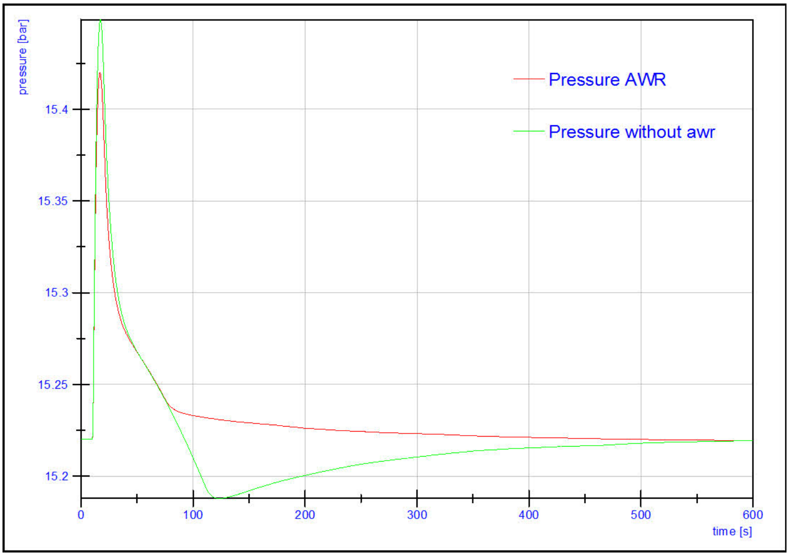

Fig 4.20. Pressure response to water level deviation with (red) and without (green) anti wind-up.

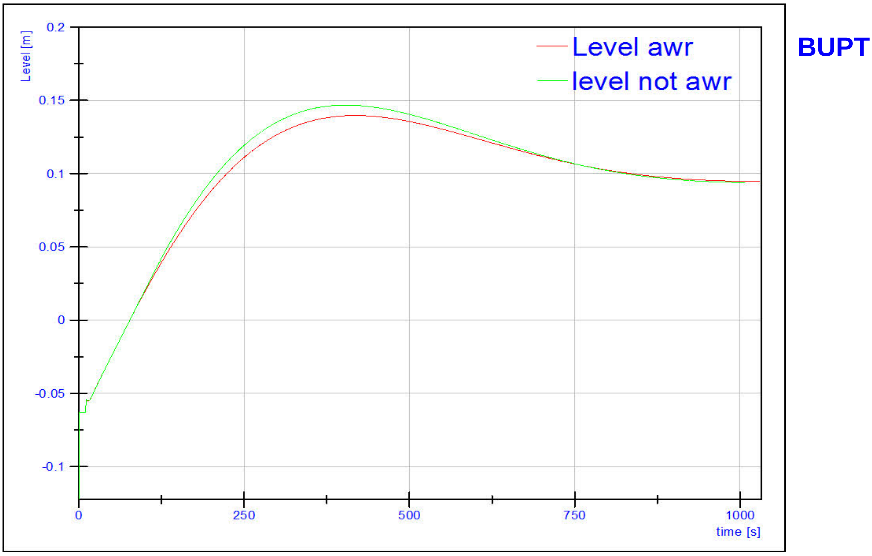

Fig 4.21. Water level step with (red) and without (green) anti wind-up.

The anti-windup technique also improves system responses. Fig 4.20 illustrates the pressure response to water level step from -0.063 to 0.1m with & without anti-windup. This has a major effect over the pressure and turbine power.

In order to fully test the functionality of the decoupled control system a sequential setpoint test was done at 50% boiler load. At t=100s the pressure demand is increased from 15.22 to 17.22 [bar]. Then at t=400s the power demand is increased from 3.31 to 6.31 [MW].

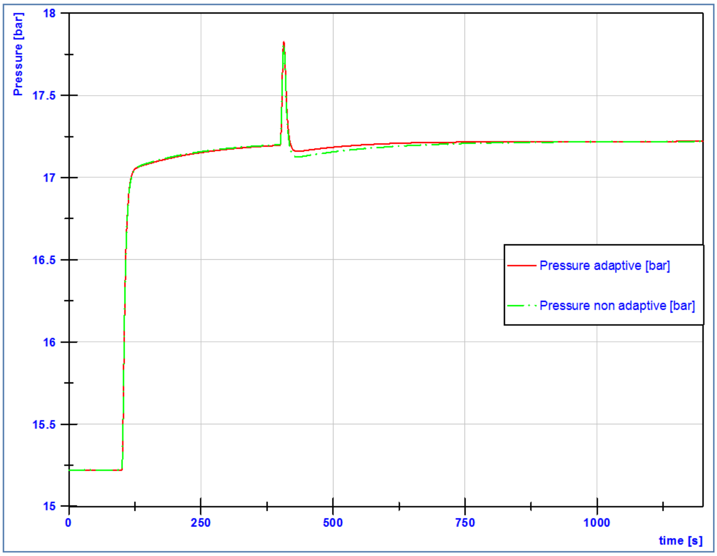

Fig 4.22. Decoupled control performance: Pressure responses to sequential setpoints: adaptive solid line (red), non adaptive dashed dotted line (green).

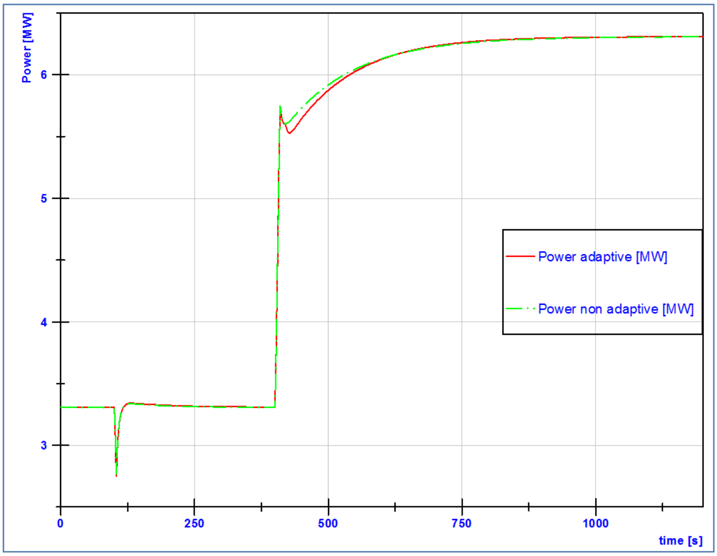

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Fig 4.23. Decoupled control performance: Power responses to sequential setpoints: adaptive solid line (red), non adaptive dashed dotted line (green).

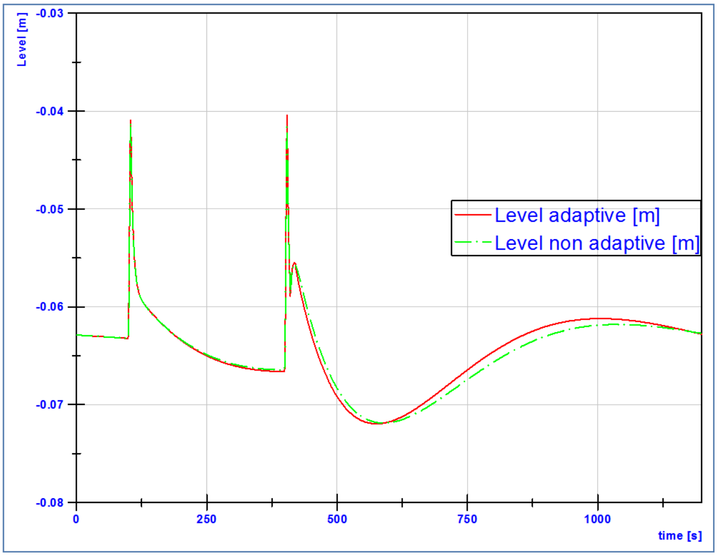

Fig 4.24. Decoupled control performance: Water level responses to sequential setpoints: adaptive solid line (red), non adaptive dashed dotted line (green).

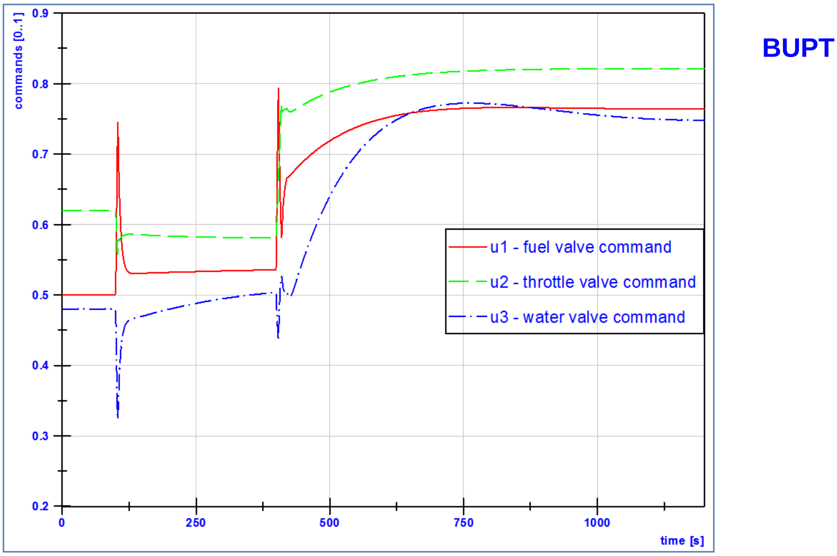

Fig 4.25. Decoupled control performance: Controller commands for sequential setpoints: adaptive scenario.

The decoupler has a satisfactory behavior, though some interactions are still present due to precision loss in calculus of the linear model and controller reduction.

For this test the author focuses mainly on the decoupler performance rather than the gain-scheduled technique performance, due to the small setpoint step.

Results are presented above in figures Fig 4.22 - Fig 4.25.

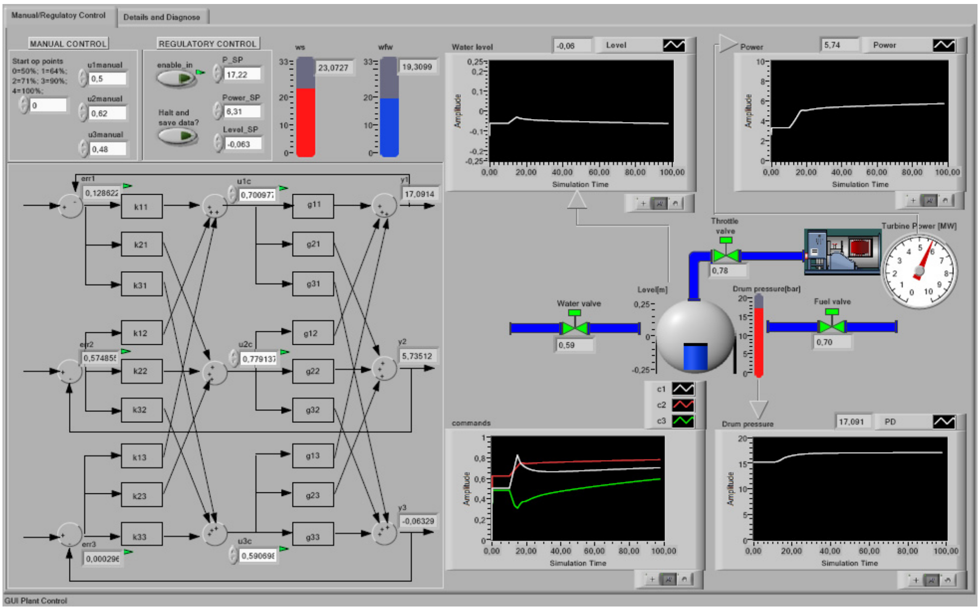

Fig 4.26. Graphical user interface (GUI) for boiler-turbine unit with decupled control

A GUI is developed, Fig 4.26, to facilitate the human-machine interaction. The simulator can start in one of the four operating points. There is the possibility to execute manual or automatic maneuvers. By modifying the set points (automatic), or directly the valve openings (manual) one can observe transient and stationary process responses.

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The system was implemented in Labview with the idea of providing a thermal power plant simulator, more specific a steam boiler with turbine simulator for the operators at the thermal power plant South of Timisoara, Romania.

A soft real-time and hard-real time constraints simulator implementation on industrial targets under hardware-in-the-loop concept will be presented in chapter 4.

4.5. Conclusions

This chapter presents the 2nd control solution employing a centralized multivariable gain-scheduled decoupled control for a boiler-turbine system. Unlike the cascade control solution presented in Chapter 3.3, the present multivariable control solution deals with model interaction reduction based on decoupled control.

A multivariable decoupled centralized control method is chosen with good performances in transient responses for controlling a boiler-turbine unit. The control strategy is improved by gain-scheduling technique based on dynamic model linearization. Due to hard input constraints, adaptive PID control with anti-windup is designed. To eliminate undesired bumps in system responses, when adaptive controller gains are shifted, the updated PI controller gains are filtered.

The ***main contributions*** of this chapter consist on:

- Implementing and fitting a 3x3 MIMO boiler-turbine interpretation model to the real thermal power plant South of Timisoara.
- Developing, testing and validating a gain-scheduled decoupled control by using dynamic linearization, controller order reduction and anti wind-up for process interaction compensation and system response improvement.
- Provide a functional simulator in manual/automatic mode for the presented control strategy testing and open loop process responses with graphical user interface (GUI) in Labview.

Relevant author published work to the present chapter is represented by paper [7] indexed in IEEE Explore and SCOPUS.

[4.1] http://www.orcycle.be/index.php/en/orctheorie

[4.2] F. Morilla, F. Vazquez, and J. Garrido, "Centralized PID control by decoupling for TITO processes," in Proc. 13th IEEE Int. Conf. on Emerging Technologies and Factory Automation (EFTA 2008), Hamburg, Germany, pp. 1318–1325, Sep. 2008.

[4.3] J. Garrido, F. Morilla, and F. Vazquez, "Centralized PID control by decoupling of a boiler-turbine unit," in Proc. European Control Conf. (ECC'09), Budapest, Hungary, pp. 4007–4012, Aug. 2009.

[4.4] Bell, R.D. and K.J. Astrom. "Simplified Models of Boiler-Turbine Units". Report LUTFD2/(TFRT-3191)/1-52/(1987). Lund Institute of Technology, Sweden, 1987.

[4.5] Astrom, K.J. and K. Eklund. "A simple non-linear drum boiler model". International Journal of Control. Vol. 22, No. 5, pp. 739-740, 1975.

[4.6] Bell, R.D. and K.J. Astrom. "A simple drum level model". Report LUTFD2/(TFRT-7163)/1-029/(1979). Lund Institute of Technology, Sweden, 1979.

[4.7] Morton, A.J. and P.H. Price. "The controllability of steam output, pressure and water level in drum boilers". Proceedings Institution of Mechanical Engineers. pp. [75-84], 1977.

[4.8] Astrom, K.J. and R.D. Bell. "A nonlinear model for steam generation processes". Proceedings IFAC 12th Triennial World Congress. Sydney, Australia. pp. 649-652, 1993.

[4.9] Bell, R.D. and K.J. Astrom. "A fourth order non-linear model for drum-boiler dynamics". Proceedings IFAC 13th Triennial World Congress. San Francisco, USA. pp. 31-36, 1996.

[4.10] Raul Garduno-Ramirez, "Overall Intelligent Hybrid Control System for a Fossil-Fuel Power Unit", Thesis in Electrical Engineering, The Pennsylvania State University, Department of Electrical Engineering, 2000.

[4.11] Un-Chul Moon and Kwang Y. Lee, "Step-response model development for dynamic matrix control of a drum-type boiler-turbine system," IEEE Trans. on Energy Convers., vol. 24, no. 2, pp. 423–430, June 2009.

[4.12] S. Skogestad, "Simple analytic rules for model reduction and PID controller tuning," Journal of Process Control, vol. 13, no. 4, pp. 291–309, June 2003.

[4.13] T. Liu, W. Zhang, and F. Gao, "Analytical decoupling control strategy using a unity feedback control structure for MIMO processes with time delays," Journal of Process Control, vol. 17, no. 2, pp. 173–186, Feb. 2007.

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5. IMPLEMENTATION OF HARDWARE-IN-THE-LOOP TEST SYSTEM FOR DRUM-BOILER TURBINE MULTIVARIABLE DECOUPLED GAIN-SCHEDULED CONTROL

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The present chapter starts by introducing key building blocks for designing an industrial automation system, based on world-widely used process equipment and software in ***Chapter 5.1***. This comes from the need of integrating fully simulated control scenarios into industrial real-time targets. Real plants are controlled with PLCs and employ a wide variety of topologies, industrial busses, sensors, actuators, process servers, process software and process specific problems regarding implementation and engineering. For this purpose the Siemens totally integrated automation (TIA) concept is introduced for providing an important insight into implementation of complex control strategies on industrial targets. A practical applications set in Supervisory Control and Data Acquisition (SCADA) is presented for introducing the technology used for implementation of the decoupled multivariable gain-scheduled boiler-turbine control system. The studied SCADA system is described in terms of architecture, process interfaces, functionality, and application development facilities. These concepts are implemented on an integrated automation system with distributed periphery using TIA Democase from Siemens. The applications show the main SCADA elements by developing a system to control an induction motor, which can be either a valve or a pump, in interlocked manual/automatic mode, with touch-screen Human Machine Interface (HMI). The system employs industrial busses like ProfiBus and Industrial Ethernet. The SCADA system also shows trends, alarms, motor frequency and automatic sequence of motor speed profile. This is useful due to actuator control problems i.e. valve actuators for steam, water and heat flux which may arise in the control system design phase.

Chapter 5.2 deals with hard and soft real-time (RT) conditions implementation of hardware-in-the-loop (HIL) systems for testing of control strategies in thermal power plants. The used model is the 3x3 non-linear strongly coupled system adapted to fit a real thermal power plant of 16 MW presented in Chapter 4.

The main purpose of this work lies in implementing, comparing and validating proposed HIL methods over classic simulation methods applied on an actual complex structure, rather then analyzing control system performance (which was studied in Chapter 4).

Three implementation systems (control and model) are developed and compared by testing, i.e., 1) ***fully simulated system*** using Labview running on a PC under a general purpose operating system; 2) ***non-real-time*** or ***soft real-time constraint HIL*** system with OPC server; 3) ***complete real-time*** or ***with hard real-time constraints HIL deterministic system***. The purposes of the present work are: to reduce downtimes in control system design and to determine which test platform is best suited in terms of accuracy, cost and efficiency for control system testing in thermal power plants. The three systems make use in implementation of the same nonlinear boiler-turbine model with decoupled multivariable adaptive control in order to provide precise comparative results.

Test scenarios:

- For the ***1st test scenario*** the boiler-turbine model and control are developed in Labview and both run on a PC (fully simulated).
- The ***2nd test scenario*** presents a soft real-time constraints HIL system where the model runs on the PC, under a general purpose operating system and the control on a real-time target, a Siemens S7-300 PLC. Data exchange between parties is provided by an OLE for process control server (OPC Server) at the software level, and by an Industrial Ethernet bus at the physical level. Synchronization between PLC and PC (which does not have a real time operating system) was a challenge.
- The ***3rd test scenario*** shows a hard real-time constraints HIL system (RT HIL system), where the model runs on a National Instruments PXI-8106 real-time platform and the control on the same PLC as in test scenario number 2. The communication between the PXI - PLC is realized by decoding the S7 Industrial Ethernet protocol in Labview.

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Comparative results on the three systems are illustrated towards the end of the present chapter, the HIL-RT system presenting a slightly better accuracy and performance in transient regimes.

Chapter 5.3 show some tests regarding applications of tele-control strategies by means of industrial wireless networks with concentrated concerns over security with Siemens Scalance wireless routers. These final tests were done in the case of a wireless ProfiNet system on remote actuators, where cabled relays or busses cannot be mounted due to lack of accessibility, distance issues or high electromagnetic disturbances on busses or wires.

5.1. Siemens platform for SCADA Automation System - examples for industrial control

SCADA systems became popular to arise the efficient monitoring and control of distributed remote equipments. Today SCADA systems include operator-level software applications for viewing, supervising and troubleshooting local machines and process activities. Powerful software technologies are used for controlling and monitoring equipments in easy-to-use web-based applications, e.g., platforms: PCS7, WinCC SCADA, WinCC Flexible – Siemens, CX-Supervisor – Omron, Genesis 32 – ICONIX 0 [5.1].

The term supervisory control is associated with (i) the process industries, where it manages the activities of a number of integrated operation units to achieve certain economic objectives for process; and with (ii) the discrete manufacturing automation, where it coordinates the activities of several interacting pieces of equipment in a manufacturing cells or systems, such as a machines interconnected group by a material handling system [5.2].

SCADA encompasses the collecting of information transferring to the central site, carrying out any necessary analysis and control, and then displaying that information on a number of operator screens or displays. The required control actions are then conveyed back to the process [5.3].

Control and supervision tasks of industrial plants are distributed over wide areas, and are characterized by many sensing and actuation points (in order of hundreds or even thousands of units) as in petrol chemical plants, paper factories, newspaper rotary printing presses, plants for extraction and bottling of alimentary

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juices, energy monitoring, etc. They require the use of sophisticated automation schemes that must be able to grant access to production data and field distributed variables at large distances, and from various levels of factory automation (field, control, supervision, etc.) [5.4].

Programmable Logic Controls (PLCs) are used for system control. As need to monitor and control more devices in the plant grew, the PLCs are distributed and the systems became more intelligent and smaller in size.

In a distributed control system (DCS), the data acquisition and control functions are performed by a number of distributed microprocessor-based units situated near to controlled devices or by instruments from which data are gathered. DCS have evolved into systems providing very sophisticated analog control capability [2.1].

SCADA, PLC and DCS are three types of control systems. Nowadays, there are systems that incorporate all these concepts in one integrated automation system.

Totally Integrated Automation (TIA) is the foundation to implement industry specific automation solutions that are coordinated with individual requirements, combining increased productivity with a high level of investment security [5.5]. TIA is the unique basis offered by Siemens for uniform and customized automation in all sectors of the production, process and hybrid industries. TIA offers uniform automation technology on one single platform for all applications of process automation, starting with input logistics, covering production or primary processes as well as secondary processes, up to output logistics.

The present chapter introduces theoretical and practical concepts regarding SCADA, illustrated and implemented on an integrated automation system TIA from Siemens.

Terminology, concepts, principles, procedures, computations, and communication protocols used in the control field programming are studied. The programming of the human machine interface (HMI), to present process data to a human operator, is another subject of interest.

During these applications, besides analyzing theoretical concepts, several applications will be developed. The final and most important application refers to control of an induction motor associated with a frequency inverter, in manual or automatic mode. The manual control mode is equivalent to predefine frequencies and logic programming. This is done by means of telegrams which are transmitted to the frequency inverter. In the automatic control mode a specific sequence is run (sequential discrete control).

The present chapter has the following ***Siemens automation technology*** used in ***experimental implementation solutions of the thesis***:

- Presents 7 applications which give an important head-start in integrating the multivariable control strategy (Chapter 4) into the existent Centralized SCADA Siemens System at the thermal power plant South of Timisoara.
- Presents how to program the frequency inverters for control of asynchronous machines of the valve and pump actuators for steam, water, and heat flux in boiler-turbine control.
- Present means of programming (continuous and sequential programming) for Siemens industrial controllers.
- Presents how to develop a graphical user interface for friendly human-machine interactions (HMI).
- Presents a safety scenario by using a proximity sensor.

All these features present a solid background for the multivariable decoupled control implementation (Chapter 4) and also for the cascade control for shrink and swell effect remission implementation (Chapter 3.3).

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5.1.1. Practical applications for SCADA systems using TIA democase

Using the equipment from Siemens SCADA – TIA Democase, process engineers can acquire the know-how to develop real functional applications.

The development platform for applications is STEP 7, which is the standard software package used for configuring and programming SIMATIC programmable logic controllers. The standard package includes a series of valuable tools like: Symbol Editor, NETpro, SIMATIC Manager, Hardware Configuration, Programming Standardized Languages (Ladder Logic (LAD), S7Graph, STL, SCL, FBD) and Hardware Diagnostics.

To create an automation solution with STEP 7, there are a series of basic tasks:

- Plan your controller;
- Design the program structure;
- Create a project structure;
- Configure hardware;
- Configure networks & communication connections;
- Define symbols;
- Create the program;
- Configure operator control and monitoring variables;
- Download programs to the programmable controller;
- Test programs;
- Monitor operation, diagnose hardware;
- Document the application.

A project contains all programs and data for the entire automation tasks. It is an object structure, under which other STEP 7 objects will be organized [5.6]. This project can contain several hardware stations, networks or several programs that are used in one or several CPUs.

Following these steps, through practical examples, process engineers may learn to use the equipment and program it, and the final result will be an application for controlling an induction motor. Each application has the following structure: purpose, theoretical topics, workflow, questions and references.

The application are divided into eight sections: A) General description of SCADA - Totally Integrated Automation Democase, B) Hardware configuration and programming languages, C) Programming and commissioning for frequency inverter SINAMICS G120, D) Manual control for frequency inverter, E) Automatic control for frequency inverter, F) Integration of manual and automatic control modes for frequency inverter, G) Introduction to WinCC Flexible SCADA platform, H) Programming elements in WinCC Flexible.

5.1.1.1. General Description of SCADA - TIA Democase

The aim of this section is to present the SCADA system with its components. SCADA - TIA Democase from Siemens Fig 5.1 is an integrated automation system for digital control of electric drives with distributed peripheral [5.7]. It can be used for a wide range of applications with variable speed drives, like: pumps, fans or conveyor belt, etc. This subject covers applications to plant and mechanical engineering, as well as manufacturing technology and process engineering. BUPT

The main TIA Democase integrated components are:

- S7-300 PLC that controls ET200S;
- ET200S consists on: communication interface module IM 151-3, Motor starter DS1e-xH, proximity sensor Opto Bero;
- Sinamics G120 frequency inverter;
- Induction motor connected via PROFIBUS;
- Human Machine Interface (HMI) panel MP 277 connected via industrial Ethernet.

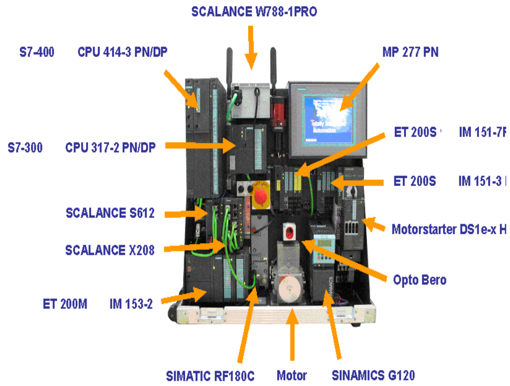

Fig 5.1. SCADA – TIA Democase setup

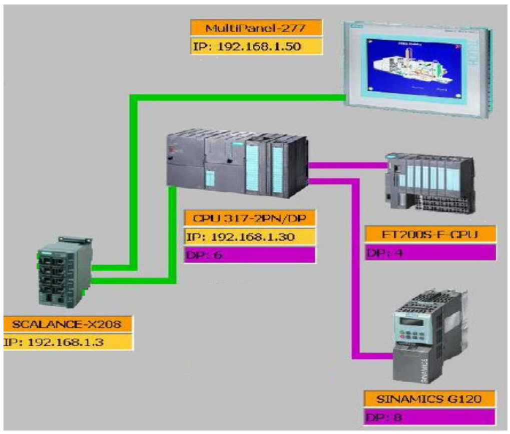

Fig 5.2. Selected components for SCADA applications from Fig 5.1

The motor is controlled manually with predefined frequencies, and automatically by sequence.

5.1.1.2. Hardware Configuration and Programming Languages

This section presents concepts on how to configure the hardware, the communication connections and some programming elements. In Fig 5.2 are presented the used components for the application.

Hardware Configuration Fig 5.3 is a tool used to configure and assign parameters to the hardware of an automation project. In a station window, the racks, modules, distributed I/O (DP) racks can be arranged. Each rack has a configuration table associated, in which a specific number of modules can be inserted, just like a real rack. In the configuration table, an address is assigned automatically to each module.

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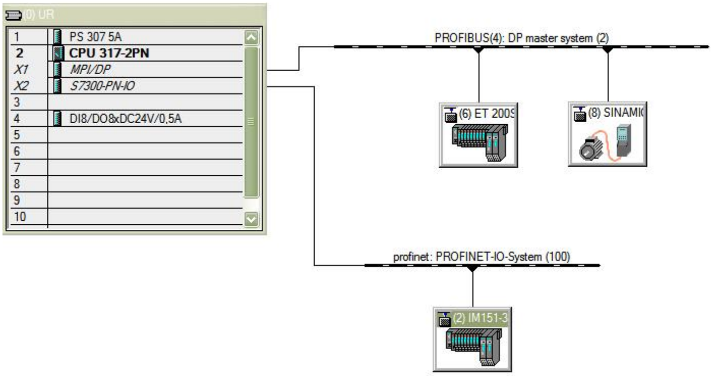
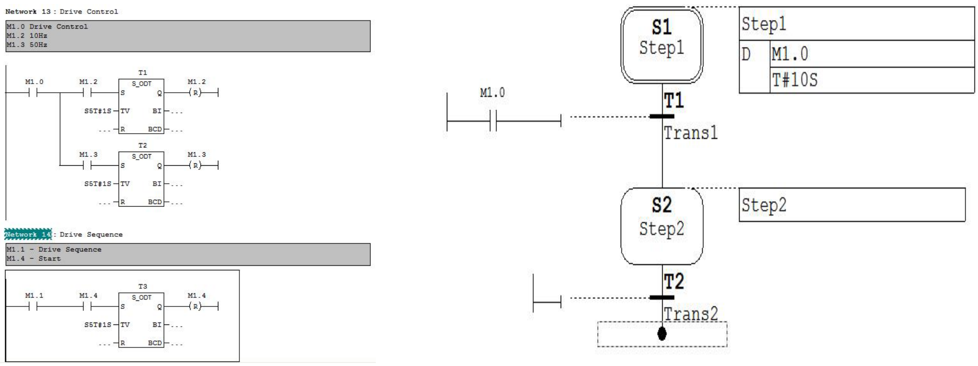


Fig 5.3. Hardware configuration of the system from Fig 5.2.

The following programming languages are used. The graphic programming language Ladder Logic (LAD) is based on the representation of circuit diagrams for programming the PLCs [5.8] . LAD will be used to design the control logic for the manual drive control. S7Graph [5.9] is used to implement the automatic drive control. The logic backbone is presented in Fig 5.4 a, b.



a) b)

Fig 5.4. a) Manual selection of frequency inverter logic in LAD and b) Automatic speed profile frequency inverter logic in SFC.

5.1.1.3. Programming and Commissioning for Frequency Inverter SINAMICS G120

The inverter is parameterized to be adapted to motor for optimal operation and protection. This is realized using one of the following operator units:

- Keyboard and display unit (Operator Panel) that is snapped onto the inverter;

- Software (STARTER commissioning tool) that allows the inverter to be parameterized and controlled by a PC.

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Fig 5.5. Control and status words of the frequency inverter command

Although inverters can be parameterized for very specific applications, many standard applications can be configured by means of just a few parameters [5.10].

The specific telegrams with 2 control words and 2 status words are developed and presented in Fig 5.5.

5.1.1.4. Manual Control for Frequency Inverter

The aim of this section is to implement the manual drive control for the frequency inverter. The manual operating mode for the motor assumes the following:

- Start the motor at preset frequency (10, 25 and 50 Hz);
- Stop the motor.

The three-phase induction motor is controlled by the inverter. The motor starter will protect and switch any three-phase loads. The ensemble formed by ET200S (Direct starter), inverter and motor have to be programmed. For programming the inverter, telegrams will be sent to it Fig 5.6. In the hardware configuration for SINAMICS G120, the standard telegram 1 was selected.
Ladder logic LAD is used for programming the manual drive control.

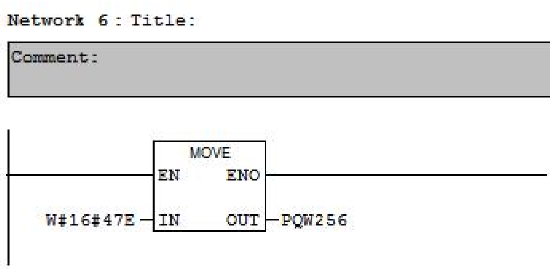

Fig 5.6. Sending control word 1 to Sinamics G120 inverter

5.1.1.5. Automatic Control for Frequency Inverter

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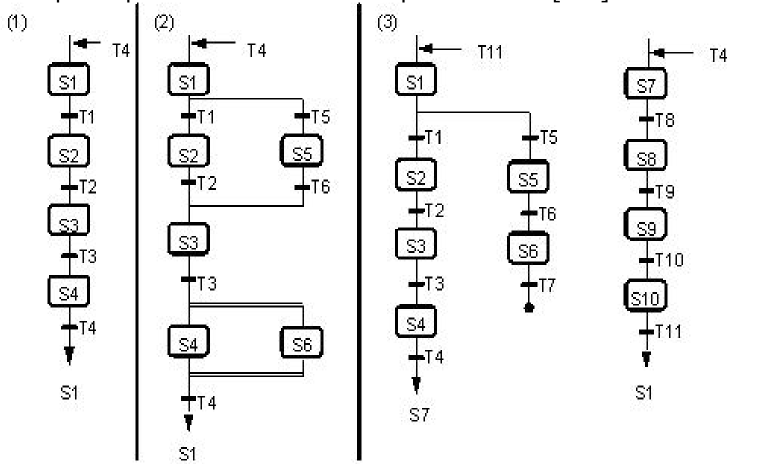
This section main scope is the implementation of automatic control of the frequency inverter used for controlling the induction motor. The automatic control consists in a sequence of steps executed in a defined order.

A sequencer consists of a series of steps and transitions that are activated in a fixed order depending on the step enabling conditions. A sequencer is always executed starting with an initial step, or several initial steps located at any position in the sequencer. As long as the actions of a step are being executed, this step is active. If several steps are being executed at the same time, they are all active steps. An active step is exited when the transition following this step is satisfied. The next step following the satisfied transition becomes active.

At the end of a sequencer, there is a jump to any step in this sequencer or to another sequencer (this allows cyclic operation of sequencer) or a branch stop. The sequence of steps stops when the branch stop is reached [5.9].



(1) S7 Graph FB with a linear sequencer
(2) S7 Graph FB with a sequencer with an alternative and simultaneous
(3) S7 Graph FB with two sequencers

Fig 5.7. Sequencer types in S7 Graph

In Fig 5.7 are presented a few usual sequencer types in S7 Graph: linear sequencer, alternative and simultaneous sequencer and parallel sequencer.

The following sequences are designed:

- Step 1 – Run at 10Hz,
- Step 2 – Hold for 10s 10Hz,
- Step 3 – Run at 25Hz,
- Step 4 – Hold for 10s 25 Hz,
- Step 5 – Slow down to 10 Hz,
- Step 6 – Hold for 10s 10Hz,
- Step 7 – Ramp up to 50Hz,
- Step 8 – Hold 50Hz for 10s,
- Step 9 – Reverse rotation sense to -50Hz,
- Step 10 – Hold -50Hz for 10s,
- Step 11 – Slow down to 0 Hz,
- Step 12 – Stop.

5.1.1.6. Integration of Manual and Automatic Control Modes for Frequency Inverter

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This section presents the integration of the two inverter functioning modes Fig 5.8. The integration means to bring together the two control modes into one system, and ensuring that they function together as a system.

In this case, there are a series of conditions to consider:

- The switching between the two subsystems (operating modes of the inverter) is possible at any time;
- A force stop is available in each subsystem, when the inverter brings the motor in its initial state.

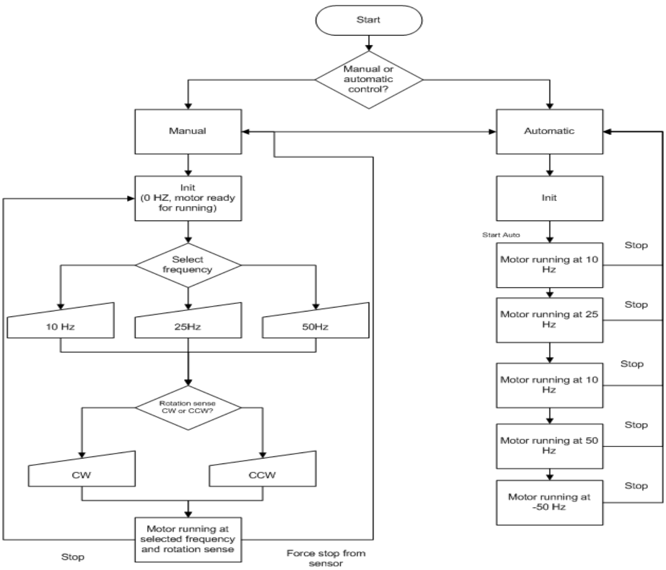

Fig 5.8. Flowchart of the Manual and Automatic control modes of the frequency inverter

Only in the manual control mode, the proximity sensor is on. When the IQ-Sense module detects an object, the motor is stopped and the motor starter is disabled (contactor off). In this case, an initialization is necessary to start running again the application [5.11].

5.1.1.7. Introduction to SCADA Platform (WinCC Flexible)

This section introduces WinCC Flexible - the software for programming the human machine interface (HMI) in SCADA applications.

The HMI provides the transparency needed between the operator, who works in environments where the processes are becoming more complex, and the machine. The HMI system represents the interface between man (operator) and process (machine/plant). There is an interface between the operator and WinCC flexible (at HMI device) and an interface between WinCC flexible and controller. The controller is the actual unit that controls the process.

An HMI system assumes the following tasks:

- Process visualization: the process is visualized on the HMI device. The screen on the HMI device is dynamically updated. This is based on process transitions.

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- Operator control of the process: the operator can control the process by means of a graphical user interface (GUI), e.g., the operator can preset reference values for the controls or start a motor.
- Displaying alarms: critical process states automatically trigger an alarm, for example, when the set point value is exceeded.
- Archiving process values and alarms: the HMI system can log alarms and process values. This feature allows to log process sequences and to retrieve previous production data.
- Process values and alarms logging: the HMI system can output alarms and process value reports. This allows printing out production data at the end of a shift, for example.
- Process and machine parameter management: the HMI system can store the parameters of processes and machines in recipes. For example, these parameters can be downloaded in one pass from HMI device to PLC to change over the product version for production [5.12].

A full automation solution not only involves a HMI system such the WinCC-Flexible, but also additional components, e.g. controller, process bus and periphery. Process tags provide the link for communication between the controller and HMI system. Without the advantage of the Totally Integrated Automation, each tag would have to be defined twice: once for the controller and once for the HMI system. The elements necessary for programming the HMI are: tags, screens (objects used on the screens), alarms, trends and special objects.

5.1.1.8. Programming Elements in WinCC Flexible

This section presents some special objects used in WinCC Flexible: trend view, gauge, alarms, scripting [5.13] and the finalization of the main application.

The trend view is a dynamic display object. It is meant for the graphical representation of tag values from the current process or from an archive in form of trends. The Trend view can display actual process data or data from a log continuously when it is supported by the HMI device.

The gauge is a dynamic display object. It displays analog numerical values using a pointer.

The main tasks of the alarm system are:

- Visualization on the HMI: report events or states that occur in the plant or process. A state is reported as soon as it occurs.
- Reporting: Alarm events are output to a printer.
- Logging: Alarm results are saved for further editing and evaluation.

WinCC flexible provides predefined system functions for common configuration task. They can be used to perform many tasks in Runtime and need no programming skills to do so. Runtime scripting is used to solve more complex problems.

The workflow for this application is the following:

- Create a script to convert the frequency value from hexadecimal to decimal, and associate the value to an internal tag.
- Insert into the manual drive control a gauge for the frequency value Fig 5.9.

- Create a screen for automatic drive control Fig 5.10.
- Create a trend view to monitor the frequency value in a separate screen Fig 5.11.
- Create two analog alarms: one for the frequency being below 25 Hz and another one for the frequency being above 45 Hz.
- Create discrete alarms to notify when the frequency is at 10 Hz, 25 Hz and 50 Hz.
- Create a screen for the alarm view Fig 5.12.
- Insert buttons in both operating modes for trend view and alarms.
- Finalize the application.

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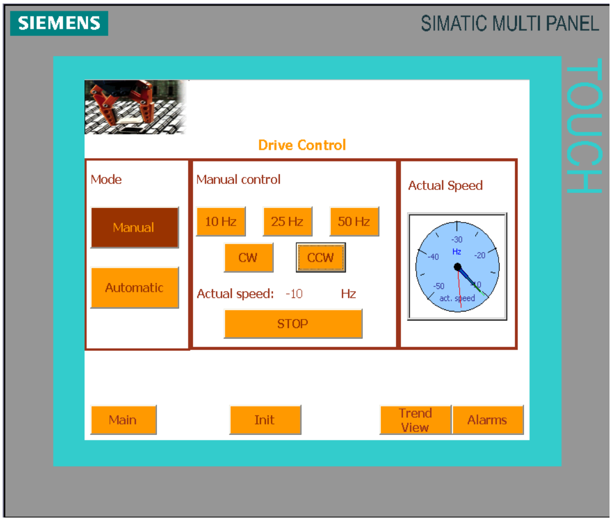

Fig 5.9. Manual drive control mode for frequency inverter.

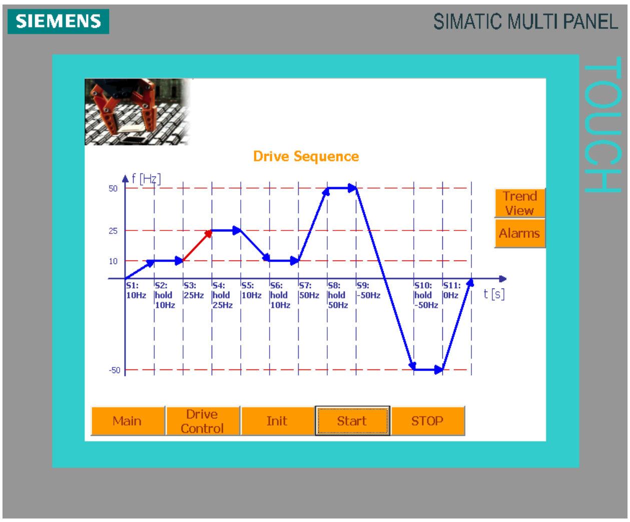

Fig 5.10. Automatic (sequential) drive control mode – reference sequence for frequency inverter.

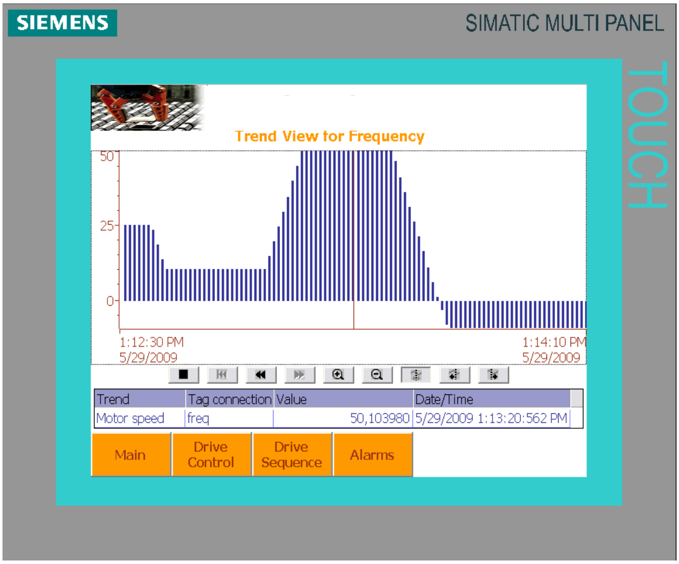

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Fig 5.11. Trend view for inverter frequency.

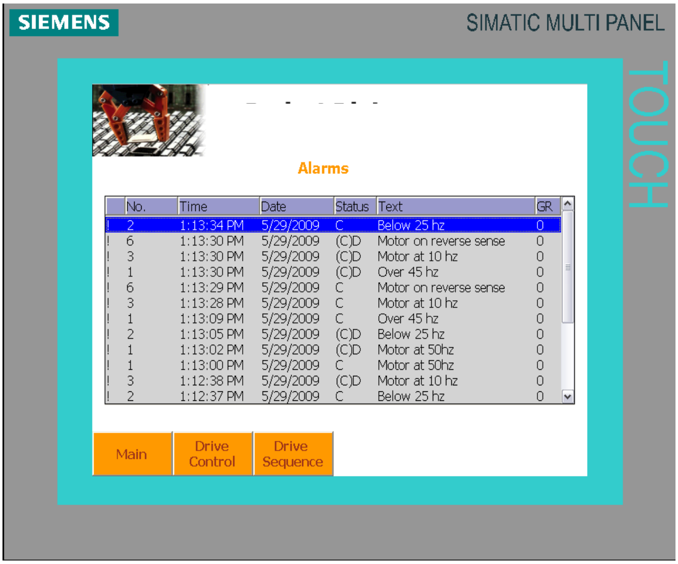

Fig 5.12. Alarms system.

5.1.2. Conclusions for section 5.1

This chapter deals with theoretical and practical concepts in Supervisory Control and Data Acquisition (SCADA) systems. The work package is focused to gradually develop applications using an integrated automation system from Siemens - Totally Integrated Automation Democase with distributed peripheral employing Profibus and Ethernet communications. The final application is targeted to control an induction motor with associated frequency inverter, in interlocked manual/automatic mode, with touch-screen, human machine interface (HMI) to provide interaction with the motor speed and to show variables, trends and alarms. The start/stop, manual/automatic control modes are frequently used in pump, valves and fan control.

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The application was divided into eight sections with specific activities, progressively developed as a good example of an automation problem solved following the basic steps necessary for an accurate industrial solution. It includes the hardware configuration and programming languages, STEP 7 standard software package for SIMATIC PLCs and WinCC Flexible SCADA platform.

One of the SCADA application goals is to help develop skills necessary to design and analyze professional automatic control systems in process, plant and manufacturing technology engineering.

The concepts and software technologies used to develop the present application can be reused to write many other similar control/supervisory applications.

The present chapter deals with ***Siemens automation technology*** used for ***experimental implementation solutions of the thesis.*** Useful features for the thesis are presented below:

- Presents 7 applications which give an important head-start in:
  - Integrating the multivariable control strategy (Chapter 4) or the cascade control (Chapter 3) into a Centralized SCADA ystem, like the one at the thermal power plant South of Timisoara, using state-of-the-art hardware and software Siemens technology.
  - Designing and implementing control strategy test platforms for industrial processes.
- Presents how to program frequency inverters for control of asynchronous machines of the valve and pump actuators for steam, water, and heat flux.
- Presents means of programming (continuous and sequential programming) for Siemens industrial control targets.
- Presents how to develop a graphical user interface for friendly human-machine interactions (HMI).
- Presents a safety scenario by using a proximity sensor

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5.2. Real-Time Hardware-in-the-Loop test platform for thermal power plant control systems

Technological advance in computer technologies enable one to create a fully functional instrument consisting on a computer, a data acquisition card (DAQ) and a specialized program. As processes became more complex, the need for dedicated hardware and software that can accept continuous rising constraints became natural. During the recent years, it has become apparent that creating useful and economical measurement devices can be a natural tendency [5.14].

Industrial control applications also tend to grow in size and complexity and require sophisticated test methods. Such a method is hardware-in-the-loop (HIL). HIL is a concept that has been introduced by the aerospace and defense industries in the 1950s [5.15]. In the past decade, the tremendous advances of semiconductor industry, the subsequent easy accessibility of powerful computing resource and the decreasing prices of simulation hardware led to further adoption of HIL simulation to domains like industrial control applications or automotive systems [5.16].

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Hardware-in-the-loop is a concept based on splitting a system into two components: the simulation component and the control component, i.e., system under test – SUT Fig 5.13.

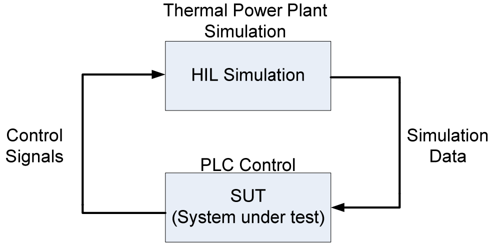

Fig 5.13. General HIL system description

Real-time (RT) constraints also present a challenge in test systems, determinism being the key feature in obtaining accurate responses and controller commands. Such systems usually exist in automation (e.g. PLCs) following the classic control principle where the controller waits for the process responses to compute the new commands.

The definition of the RT mode according to the ANSI norm is presented in [5.17]. This definition points out two main sub-modes that differ in terms of the time limitations for the working system [5.18]:

- *Hard real-time* (HRT), where time limits imposed by the designer and/or equipment are strict, and under no circumstances can be contravened;
- *Soft real-time* (SRT), where the limits are not so strict and sometimes, violation of the rules is acceptable.

Following the RT and HIL concepts, *two systems were developed for decoupled gain-scheduled control strategy testing* on a boiler-turbine model. The two systems use ***HRT (PXI-PLC)*** and ***SRT (PC-OPC-PLC)*** time limits under a ***HIL concept***. The third system, which is a ***fully PC simulated process with associated control***, is also analyzed.

The ability to design and to automatically test real processes with HIL and RT will reduce development cycle, increase efficiency, improve reliability, safety and quality and help prevent costly and dangerous failures of these systems for a large number of applications

The present chapter deals with implementation of three types of systems for drum-boiler turbine model and control. The performances of the three systems are analyzed in terms of usefulness, accuracy and cost/efficiency for providing a complex test platform for control strategies in thermal power plants using modern principles like Hardware-in-the-Loop and Real-Time.

The advantages of using HIL systems with RT are presented in comparison with a fully simulated scenario. All three systems are described in terms of architecture, communication, control and modeling logic implementation and comparative response results.

5.2.1. Fully simulated system implementation on PC – Test Platform 1

The present chapter illustrates the implementation of the fully simulated scenario associated to the boiler-turbine model and control. The simulation is carried out in Labview, under the graphical programming language, called “G” language.

The simulator backbone consists in a flat sequence structure with 3 frames.

- The 1st frame initializes the simulator by selecting one of the four manual operating points, and sends values to the 2nd frame for the non-linear state-space model integrators. which contains a simulation
- The 2nd frame contains a simulation loop incorporating the non-linear state-space model, the control subsystem with anti wind-up and the dynamic linearization subsystem. The link between subsystems is made with local variables. Also selection between manual and automatic mode is implemented in the present frame.
- The 3rd frame deals only with data acquisition to files.

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The complete “G” code is presented in Appendix 6, where the backbone is illustrated in Fig.6A., while the sub virtual instruments (SubVis) and simulation subsystems are presented in figures Fig.6B. – Fig.6D.

5.2.2. Hardware-in-the-loop (HIL) PLC-OPC-PC system with soft real-time constraints (SRT) – Test Platform 2

In this chapter, HIL key features are described regarding the simulator implementation in Labview, communication with the shared variable engine and OPC Server, PLC control design and synchronization.

In the HIL method, the system is implemented in two separate sections: i) the process model simulated on PC also known as ***HIL Simulation*** and ii) the control algorithms on real-time control target (PLC) also known as ***System Under Test (SUT)***. The basic principle is presented in Fig 5.14 .

The simulation runs in a PC with Labview platform employing: the plant, a graphical user interface and several other subsystems. The simulation model provides all the process signals that are supplied to the controller through an Industrial Ethernet bus [5.19].

The communication between the PC and PLC is done by one of the most recent industrial data exchange protocols, the OPC [5.20], [5.21]. The key OPC feature is that is able to convert address based variables (PLC) to tag/shared variables (Labview simulation - shared variable engine).

The control is implemented in a S7 315F-2PN/DP PLC, using source code list (SCL) and ladder diagram (LAD) programming tools, integrated in Step7 software from Siemens.

HIL technique was adopted because in addition there are centralized Siemens controllers in the real plant. It is desired that, before performing the operations on the real plant, a simulated (manual/automatic) maneuver with the new control strategy to be carried out, thus providing valuable comparative information for operators. Moreover, testing the functionality of this control type on PLC systems can provide a good insight in implementing “non-classical” control methods on industrial real-time control targets.

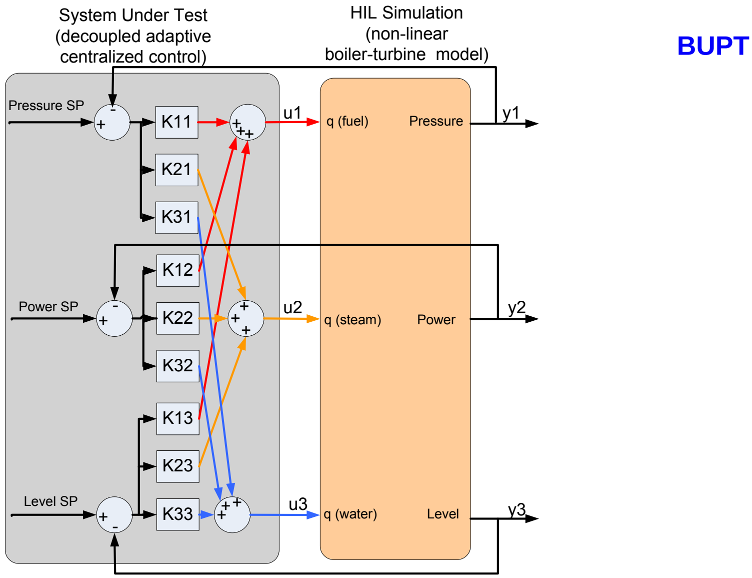

Fig 5.14. Implementation HIL-SRT principle: i) SUT – centralized adaptive decoupled control and ii) HIL Simulation – non-linear boiler turbine model

The HIL-SRT system schematic with associated hardware and software is presented in Fig 5.15.

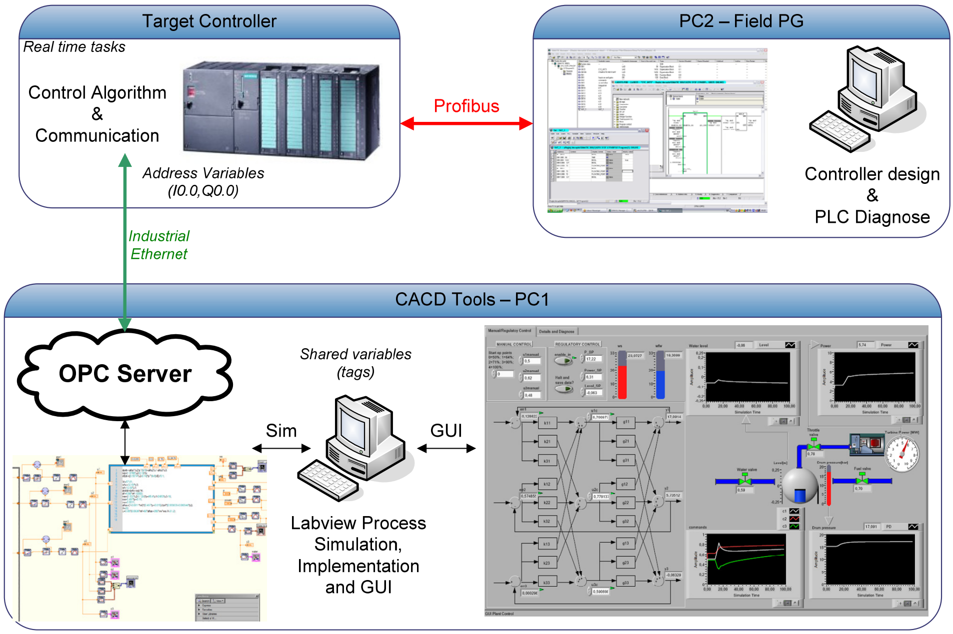

Fig 5.15. General implementation schematics of HIL and SUT

From the software point of view: i) ***PC1 contains the HIL simulation*** with graphical user interface (GUI) implemented in "G" language of Labview and the OPC Server ii) the PLC contains ***SUT*** with the Step7 code with the control algorithm and iii) PC2 is an industrial field oriented computer with Profibus interface and contains the Step7 programming software which employs developing, monitoring, diagnosing and testing the control code.

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System data flow implies that the HIL simulation computes the processing variables and the new controller gains and sends them to the OPC Server. The OPC Server translates Labview Simulator tag/shared variables to PLC address-based variables and sends them to the controller. The PLC updates its variable table, computes the control commands and sends them again for conversion to the OPC Server creating a cycle. Each of the components (Simulation, OPC Server and PLC) uses bidirectional data communication.

5.2.2.1. HIL simulation

The HIL simulation "G" code is similar with the one presented in Appendix 6, for the fully simulated scenario Fig 5.16, though some important differences do exist:

- The control code no longer runs on the PC, but on the PLC.
- The OPC server deals with data transfer between HIL and SUT through the shared variable engine. Local variable engine is still used for transition between loops.
- Some level of synchronization is needed between the OPC Server and HIL.

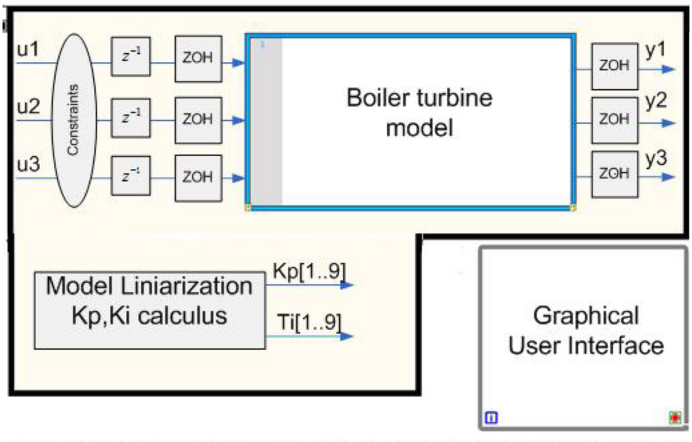

Fig 5.16. General description of HIL simulation block

HIL simulation contains the non-linear boiler turbine model, dynamic linearization of the process with adaptive gain calculus, two 1st order low pass filters for bump-less gain update and the GUI Fig 5.15, Fig 5.16.

The backbone of the HIL simulation is built on a flat sequence with two frames. The flat sequence has the role of executing sequentially the frames. Each frame contains a "G" language code.

The 1st frame, as in Chapter 4.3.1., is only for initialization of the start functioning point and the integrators of the state-space model inside frame two. The 1st frame is executed only once.

The 2nd frame contains 2 simulation loops and a while loop.

- The 1st simulation loop contains a math script with the process model, a calculus for anti wind-up gain and error formation. Dynamic linearization of the model is computed in "Model Linearization" subsystem and contains two first-order filters, and Kp and Ti array calculus. Gain calculus is done in a sub VI which is called and executed by the subsystem, each simulation step.
- The 2nd loop is a while loop and deals with the graphical user interface (GUI) and runs much slower than the first two loops.

The described HIL Simulation system makes use of an internal synchronization clock of the main simulation loop at 1kHz in order to achieve some real-time performance - SRT. Though the simulation in PC1 is synchronized to 1 kHz clock at a period of h=100 ms, the data flow and execution of the loop is not deterministic. The explanation is that Labview runs under a general purpose operating system (GPOS), e.g., Windows, which uses round robin and preemptive scheduling stacks for handling interrupts. In other words, a GPOS cannot prioritize the thread that runs the simulation code, the effect being the discard of missing periods, thus - SRT.

5.2.2.2. OPC server configuration

The first step in configuring an OPC Server is to create a communication channel with the PLC, specifying the device driver (communication protocol) and the adapter used. With this configuration, the device (PLC) is defined with specific characteristics: IP, type of CPU, rack and slot. In this stage variables can be configured by introducing their address from the PLC e.g., for Simatic controller "db1.dbd10". The OPC Server is configured for data update rate of 100 ms.

In order to validate the configuration an OPC Client is launched to test data connectivity and communication between the server and the PLC. The OPC Server project and the client are illustrated in Fig 5.17 and Fig 5.18.

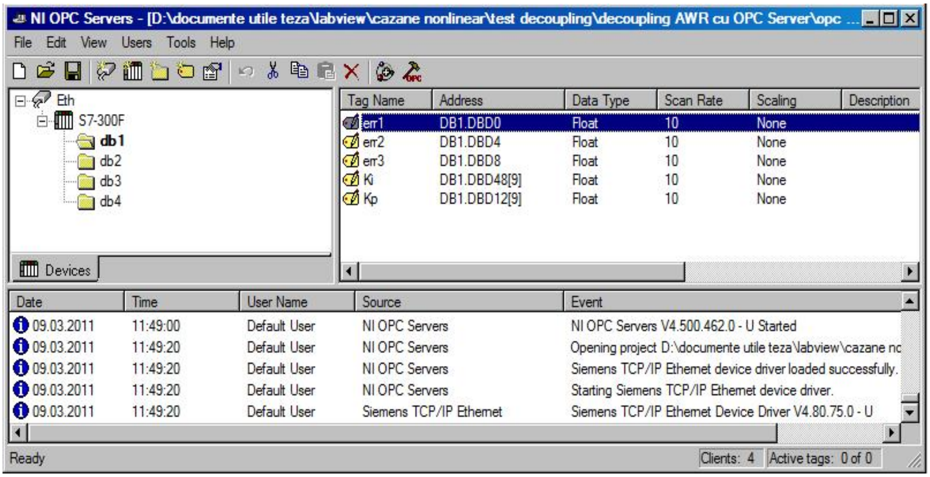

Fig 5.17. OPC Server project

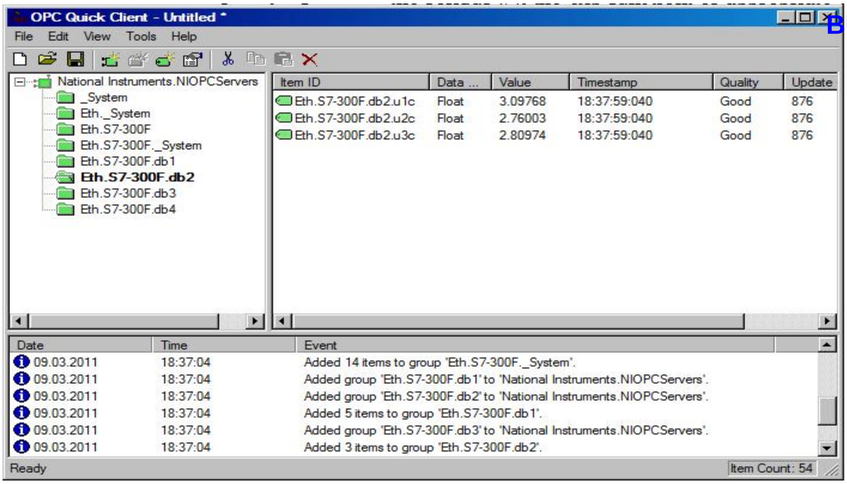

Fig 5.18. OPC Client communication test

5.2.2.3. Control algorithm implementation

The system under test (SUT) is physically represented by a real-time S7 315F 2PN/DP programmable logic controller.

From the software point of view, the PLC contains the gain-scheduled decoupled control. To proceed with control implementation the hardware configuration in Step7 needs to be done for the S7 300 PLC in "HWConfig" tool Fig 5.19. The method was described in Chapter 4.1.

Control is implemented using source code list editor (SCL) under the function block (FB) concept. The source code contains the algorithm for one discrete PI controller with anti wind-up. The PI controllers described in this section have the discrete form (5.1), related to Fig.3.8 in Chapter 3, following trapezoidal rule of integration, which is the right form for PLC implementation [5.22].

$$\begin{aligned} x_i(k) &= x_i(k-1) + \frac{Kp}{Ti}\frac{h}{2}[e_i(k)+e_i(k-1)] - \frac{K_{awr_i}}{Ti}\frac{h}{2}[awr_i(k)+awr_i(k-1)] \\ u_i(k) &= K_p e_i(k) + x_i(k) \end{aligned} \qquad (5.1)$$

The FB is then called nine times in a cyclic interrupt organization block (OB35) every t=100 ms, in order to achieve synchronization with the OPC Server. This is important, due to PLC variable scan cycle. The links and logic between the nine controllers Fig 5.14, for command implementation are carried out in organization block OB35 using ladder diagram (LAD) language. FBs work with PLC retain-memory through instance DBs (data blocks). This is the correct way of control implementation in PLCs, otherwise controller commands are not retained through the PLC scan cycle. The FBs work as object oriented classes, meaning that it is possible to instance the FB as many times as it is needed, but with a different instance DB (retain memory area).

PLC variables are defined as addresses in order to pin point correctly for OPC and send the errors, gain arrays, etc. The OPC mapping is shown in Fig 5.18. The variable addresses are also stored in DBs, but this time shared DBs, which all functions can access (Kp[1..9], Ti[1..9], error signals etc.). The DBs are also part of the PLC retain memory. The software architecture is illustrated in Fig 5.20. BUPT

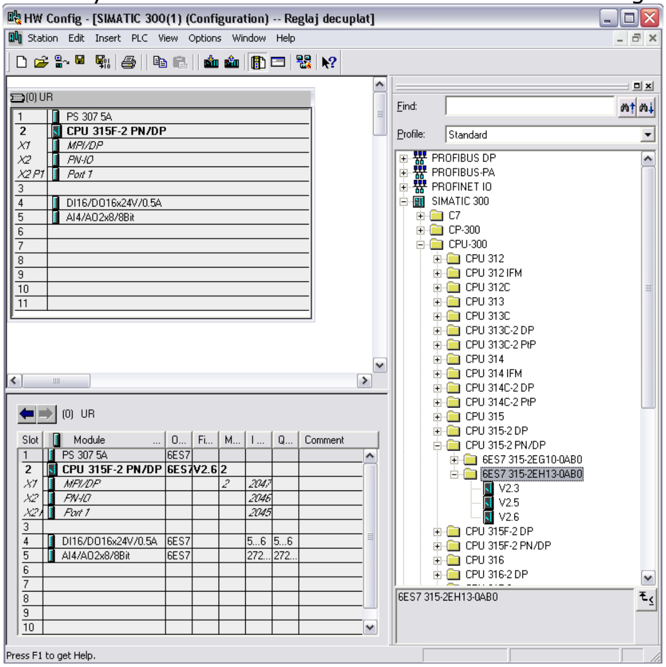

Fig 5.19. Hardware configuration of S7 300 PLC for control system

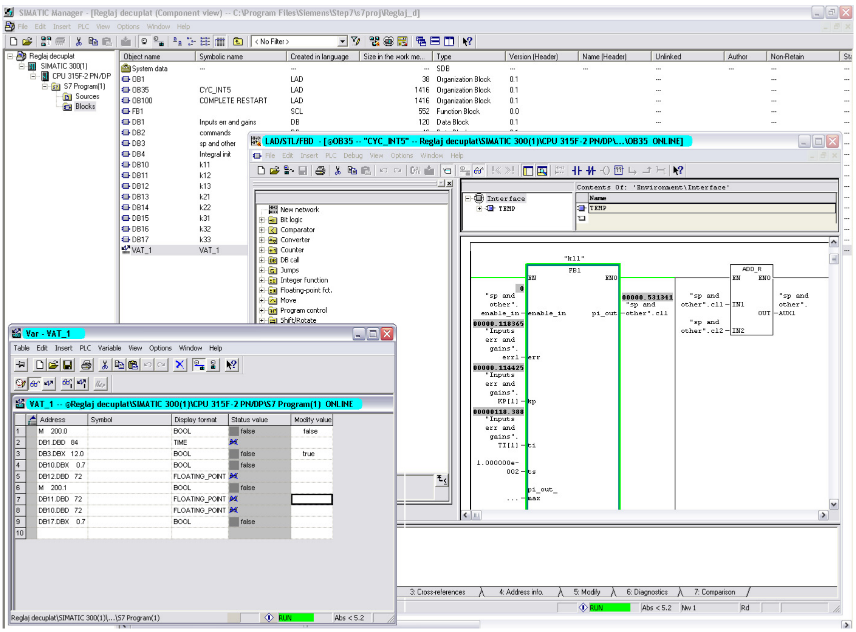

Fig 5.20. PLC software architecture for control system

5.2.2.4. Synchronization test

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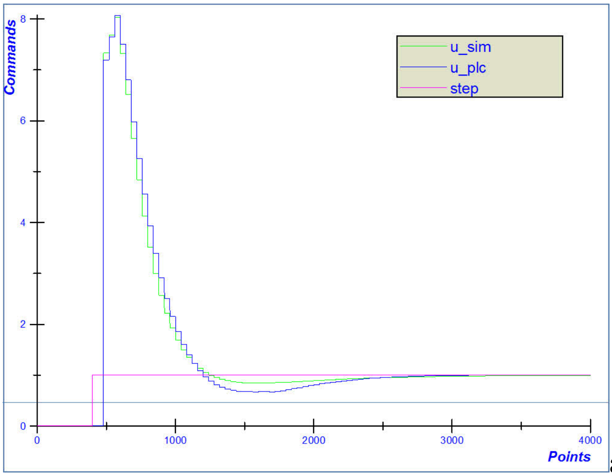
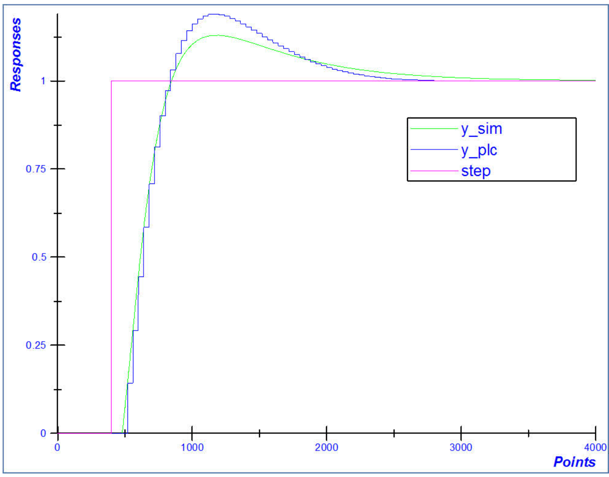
For test purpose a simple PI controller was implemented in the PLC at the SUT level and a 1st order system with time constant T=0.5s on the PC at the HIL simulation level. This configuration is compared to a classic simulation technique where the PI controller is implemented in the same device (PC with Labview) as the simulator under the same simulation loop.

The synchronization level reached in Fig 5.21 is good, slight differences being noticed between control commands and process outputs when the control runs in the PLC and in the simulator (Labview simulation loop). This was achieved by synchronizing the loop to an internal processor clock at 1 khz. The same configuration was applied to the HIL-SRT system as presented in Fig 5.16 with zero-order-holders blocks configured for 100ms, delays and ODE Solver chosen as Runge-Kutta 4 with fixed time step of 100 ms.



a)



b)

Fig 5.21. Comparison between a)commands and b)responses from the PLC - blue (u_plc,y_plc) and from the simulation – green (u_sim, y_sim) for a 1st order test process

5.2.3. Hardware-in-the-loop (HIL) PLC-PXI system with hard real-time constraints (HRT) – Test Platform 3

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The HIL-HRT system is based on an NI PXI-8106 RT dual core controller mounted on NI PXI-1042 rack. The PXI system communicates with the S7-300 PLC through industrial Ethernet, governed by the S7 TCP/IP protocol. To communicate with PLC, some special virtual instruments (VIs) were developed for encoding and decoding data under S7 protocol from and to PLC.

The PLC contains the control algorithm, while the PXI handles the boiler-turbine model, full duplex data transmission, and network variable updated for GUI.

The general system description is presented in Fig 5.22.

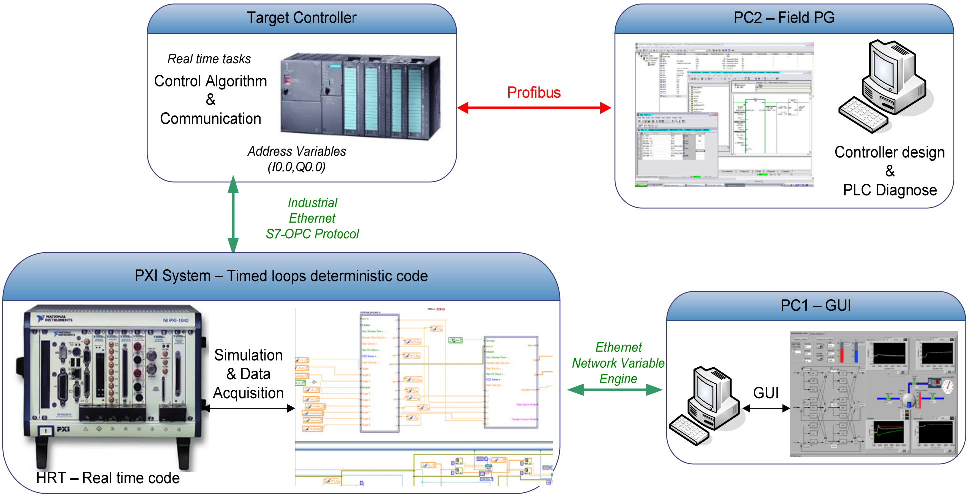

Fig 5.22. General implementation schematic of HIL-HRT (PLC-PXI)

PC1 or host computer reads the shared network variables, shows the GUI, and serves as a platform for VIs developing using LabView and download them to a RT target (e.g., PXI).

PC2 is the same industrial field PG used for HIL-SRT with the same functions.

From the software development point of view, the G code running in PXI is divided into three priority based concept VIs presented in [5.23]:

- Time-Critical VI - Runs on RT target and contains the time-critical tasks and Real-Time FIFO VIs to transfer front panel data deterministically to the normal priority VI.
- Normal Priority VI - Runs on RT target and contains all non-deterministic network communication tasks to update the host VI with front panel data received from the time-critical VI.
- Host VI - Runs on the host computer and displays the front panel controls and indicators of the time-critical VI.

Following the rules presented in [5.23], the "G" code running in PXI is structured into three timed loops. Each loop deals with a number of tasks as follows:

- The 1st timed loop handles two simulation subsystems containing the nonlinear boiler-turbine model and the dynamic linearization. The loop is synchronized to 1 kHz clock, with a manual processor assignment - CPU0. The loop has an offset of a period in order to BUPT wait for the 2nd loop to start the communication with PLC. This is a time-critical loop.

- The 2nd timed loop handles the S7 TCP/IP protocol for data exchange with PLC. The VI that deals with sending/receiving data from the PLC, is called with a reentrant execution, with a pre-allocated clone for each instance in order to maintain the state for each instance and to save computing time. This loop is also time-critical executing under CPU1;
- The 3rd loop is a normal priority loop and makes the bidirectional transfer between RT variables and the network published variables used for the host loop. This loop executes whenever the CPUs are free. Loops 1-3 run in the PXI system.

The implementation principle is presented in Fig 5.23.

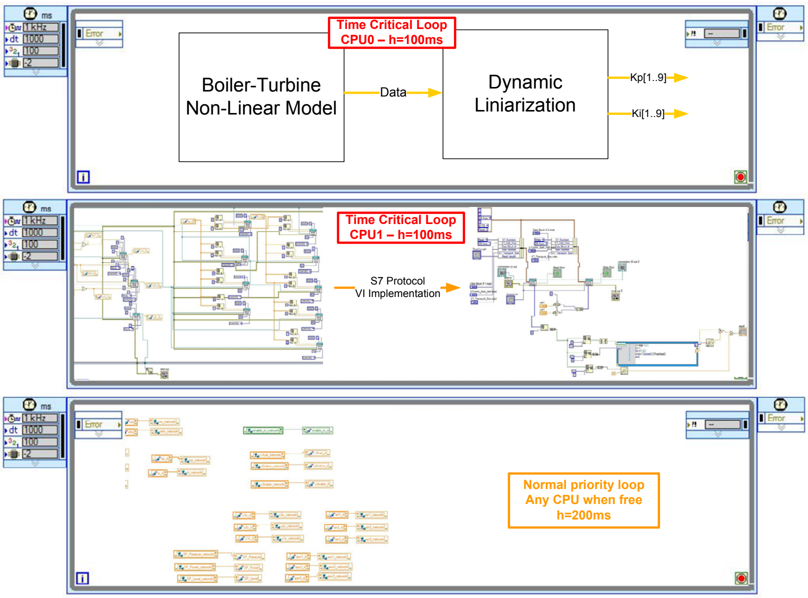

Fig 5.23. HIL-HRT software architecture

In conclusion the PLC code or SUT code is the same for the HIL-SRT and HIL-HRT. The HIL Simulation however differs between the 2 systems, but keeps the main building blocks for the 1st time critical loop (model and dynamic linearization).

The full "G" code of the three timed loops in Fig 5.23, are presented in Appendix 7. The VI which deals with S7 protocol decoding and data transport, in the 2nd timed loop is presented in Appendix 8, Fig.8A, while the host loop which deals with the GUI is illustrated in Fig.8B.

5.2.4. Comparative results of the three implemented test systems

In the present chapter, process signals and commands are analyzed in terms of system differences and performance; accuracy and cost; in order to determine which platform would be the best candidate for a power plant simulator. The systems competing are HIL-SRT and HIL-HRT because they offer realism, give operators time to respond and execute maneuvers during transients and provide tangible knowledge for complex control integration (in PLCs). The fully simulated scenario is also presented, jus for comparison purpose.

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The tests are carried out following two common power plant maneuvers.

- The 1st scenario is to build up pressure, and after that open the turbine valve for steam to rush to the turbine, to obtain more generated power.
- The 2nd scenario employs a simultaneous set-point on pressure and power load demand with the same effect.

5.2.4.1. Scenario 1 – Sequential Setpoints (Pressure & Power)

The test in figures Fig 5.24 - Fig 5.26 represent system responses to pressure demand P=15.22-17.22 bar at t=100s, sequentially followed by a power load demand E=3.31-6.31 MW at t=400s.

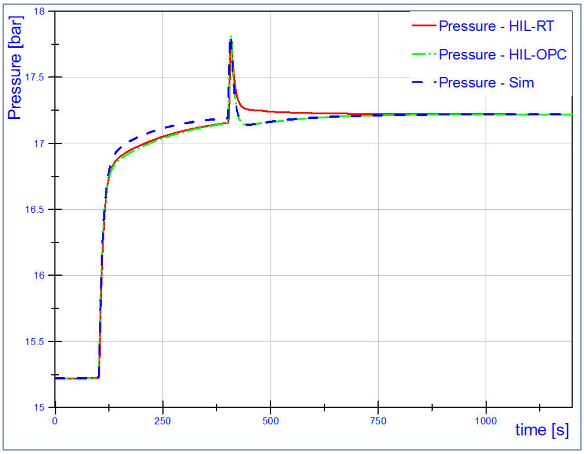

Fig 5.24. Sequential setpoints: pressure demand P=15.22-17.22 bar at t=100s followed by a power load demand E=3.31-6.31 MW at t=400s. Transient responses for **PRESSURE:** HIL-HRT – red (solid); HIL-SRT – green (dash-dot); Simulated – blue (dash)

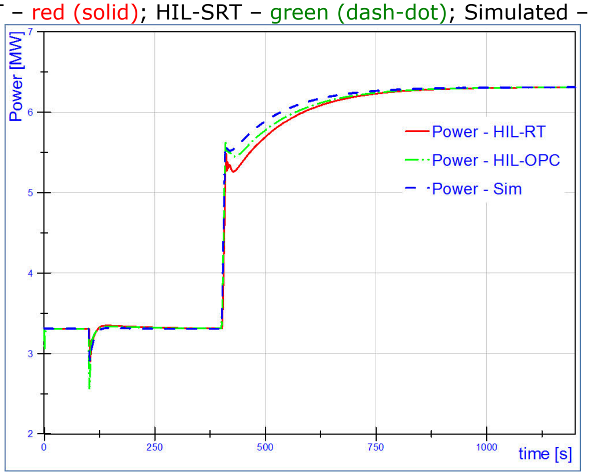

Fig 5.25. Sequential setpoints: pressure demand P=15.22-17.22 bar at t=100s followed by a power load demand E=3.31-6.31 MW at t=400s. Transient responses for **POWER**: HIL-HRT – red (solid); HIL-SRT – green (dash-dot); Simulated – blue (dash)

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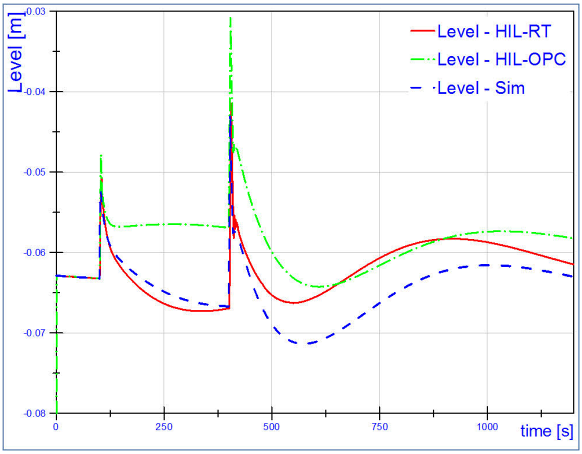

Fig 5.26. Sequential setpoints: pressure demand *P*=15.22-17.22 bar at *t*=100s followed by a power load demand *E*=3.31-6.31 MW at *t*=400s. Transient responses for **WATER LEVEL**: HIL-HRT – red (solid); HIL-SRT – green (dash-dot); Simulated – blue (dash)

The adaptive decoupled control works satisfactory being able to successfully compensate a major part of the dynamics of the other two loops.

Furthermore, by using HIL-RT, the water level has lower deviation from the setpoint Fig 5.26, which is a key feature in drum-type boiler unit control. However the deviation differences are not that great (<1.5%) and the cost for a PXI system is rather high. ***For this test the HIL-SRT solution is best suited for a simulator***, though some missed periods exist***.***

Figures Fig 5.27 - Fig 5.29 illustrate the combined controller commands for pressure, power and water level. In the HIL-HRT case, a more aggressive reaction of the controller is detected for pressure and power and a smoother one for water level, resulting in slightly better system responses in this particular case.

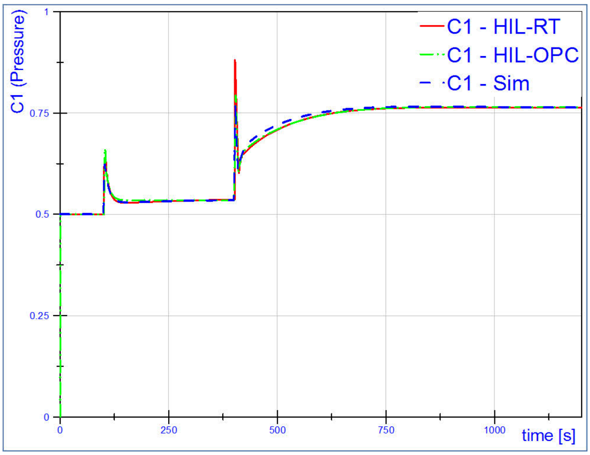

Fig 5.27. Sequential setpoints: pressure demand *P*=15.22-17.22 bar at *t*=100s followed by a power load demand *E*=3.31-6.31 MW at *t*=400s. Controller command on **FUEL VALVE**: HIL-HRT – red (solid); HIL-SRT – green (dash-dot); Simulated – blue (dash)

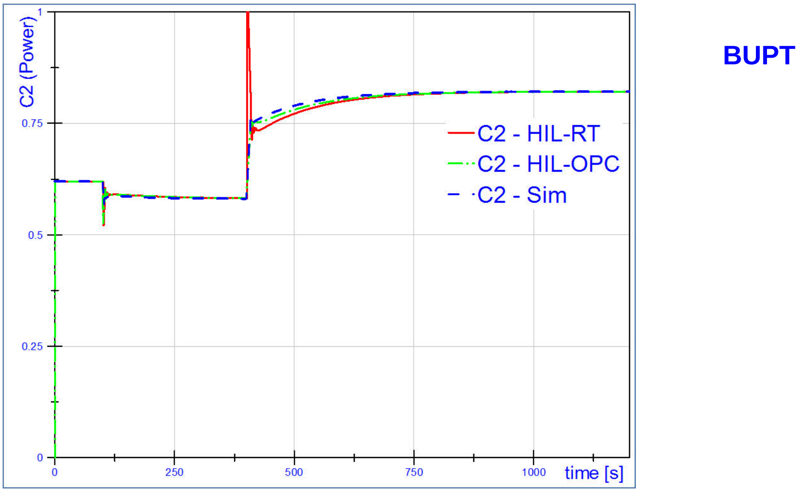

Fig 5.28. Sequential setpoints: pressure demand *P*=15.22-17.22 bar at *t*=100s followed by a power load demand *E*=3.31-6.31 MW at *t*=400s. Controller command on **STEAM VALVE**: HIL-HRT – red (solid); HIL-SRT – green (dash-dot); Simulated – blue (dash)

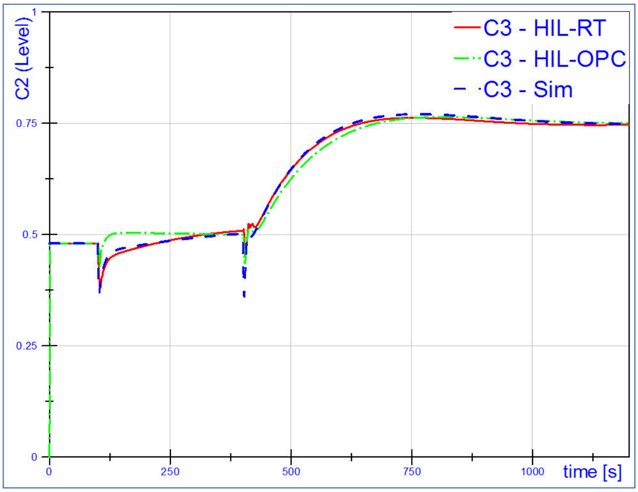

Fig 5.29. Sequential setpoints: pressure demand *P*=15.22-17.22 bar at *t*=100s followed by a power load demand *E*=3.31-6.31 MW at *t*=400s. Controller command on **WATER VALVE**: HIL-HRT – red (solid); HIL-SRT – green (dash-dot); Simulated – blue (dash)

5.2.4.2. Scenario 2 Simultaneous Setpoints (Pressure & Power)

The following test represent a simultaneous setpoint for pressure *P*=15.22-17.22 bar and power *E*=3.31-6.31 MW at *t*=100s.

For this particular test, the differences between the three systems are not significant Fig 5.30a),b),c) and Fig 5.31a),b),c), though a slight smoother response and a lower water level deviation can be observed in Fig 5.30c).

For this test, the HIL-SRT solution is also best suited for a simulator, **in terms of system responses accuracy, and controller commands.** BUPT

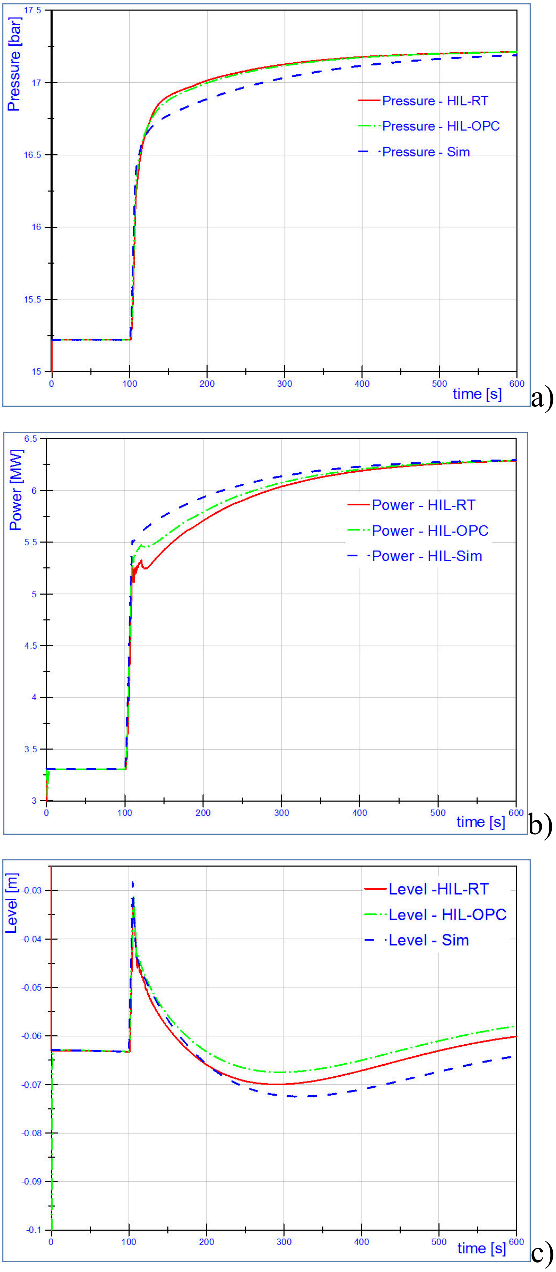

Fig 5.30. Simultaneous setpoints: pressure demand P=15.22-17.22 bar and power demand E=3.31-6.31 MW at t=100s. Transient responses for outputs: Pressure (a), Power (b) & Water level (c) for HIL-HRT – red (solid); HIL-SRT – green (dash-dot); Simulated – blue (dash)

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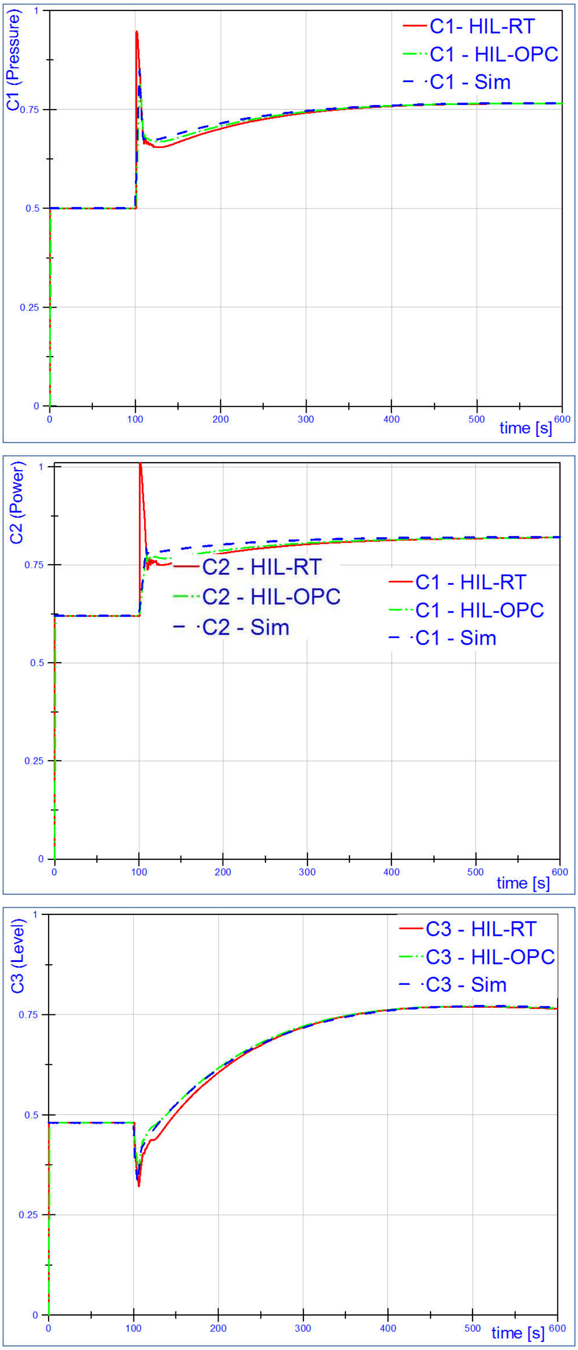

Fig 5.31. Simultaneous setpoints: pressure demand *P*=15.22-17.22 bar and power load demand *E*=3.31-6.31 MW at *t*=100s. Transient responses for valve Commands: fuel (a), steam (b) & water (c) for HIL-HRT – red (solid); HIL-SRT – green (dash-dot); Simulated – blue (dash)

Both tests are realized at 50% boiler load. The pressure and power setpoints are successfully followed with a minimum value in water level deviation (6%). BUPT

Regarding pressure and power, the HIL-SRT and HIL-HRT system signals are similar which allows the author to validate the cheaper HIL-SRT system for this particular process.

A GUI is developed in Fig 5.32 to facilitate the human-machine interaction. The operators start the simulation in one of the four operating points. They have the possibility to make manual or automatic maneuvers by switching the "enable_in" button. By modifying the set points, they can observe transient and stationary process responses.

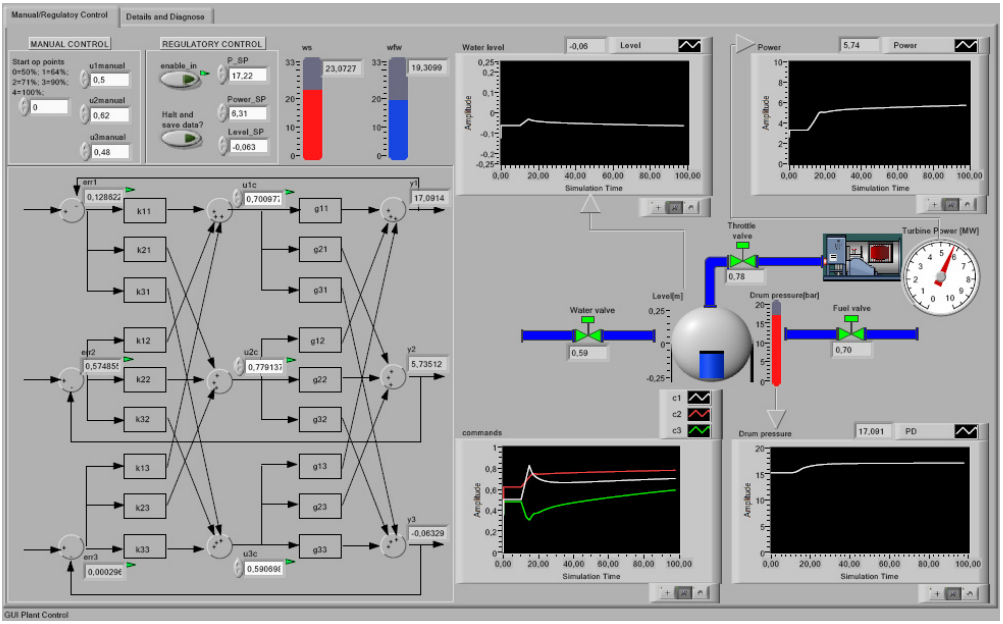

Fig 5.32. Graphical user interface boiler turbine model and decoupled control.

5.2.5. Conclusions for section 5.2

The main purpose of this chapter is to develop a real-time implementation of a hardware-in-the-loop (HIL) system for testing control strategies in thermal power plants.

Three implementation systems are developed and compared by testing, i.e., 1) fully simulated system, 2) soft real-time constrained HIL system with OPC server, and 3) hard real-time constrained HIL deterministic system.

The main conclusion drawn is that the HIL-SRT system behaves closely in terms of controller commands and system responses to the HIL-HRT system, though some missed or discarded periods exist. This fact validates the cheaper and easier to implement HIL-SRT system as a real-time power plant simulator.

The main contributions consist in:

- Implementing and validating a hardware-in-the-loop test system with hard real time constraints (HIL-HRT) using a PXI-PLC hardware and a hardware-in-the-loop test system with soft real time constraints (HIL-SRT), for control strategies testing for thermal power plants.

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- Comparing and analyzing the differences in control and process signals using HIL-HRT system versus HIL-SRT, and fully simulated system in order to choose the most suited cost-effective solution.
- Providing a fully functional real-time test platform for a wide range of power plant maneuvers in either manual or automatic mode.

5.3. Some security issues regarding wireless control systems in SCALANCE industrial networks

Some security weaknesses of Scalance wireless access points and clients are discussed in the present chapter with focus on control systems. These devices, developed by Siemens, are commonly used for wireless communication in control systems based on PLCs (Programmable Logic Controller). After the 2010 identification of the Stuxnet worm, which presumably targeted PLCs from uranium enrichment facilities in Iran, these devices become of more interest to the security community. Here we analyze some vulnerabilities both in a static environment, at the configuration level, as well as in a dynamic environment where this devices are used for a remote control scenario. We show some vulnerabilities in both situations, in particular flaws in the authentication protocol from their web-based configuration and an attack which halts the communication by using deauthentication packets. As proof-of-concept the author simulates the evolution of a process which is controlled over the wireless network and could be seriously affected by an adversary unless a local controller is present for redundancy in case of communication failures.

Scalance access points [5.25] and clients [5.24] are used in Siemens industrial control environments to construct complex network infrastructures. For example they can be configured to form stand-alone networks, mixed networks with or without multi-channel configuration, wireless distribution systems or redundant wireless LANs. Thus the security of these devices is vital for the security of the entire network infrastructure. They are equipped with the usual security suite for wireless access points which includes no security and WEP up to WPA with AES. It is debatable whether security devices that can be part of a critical infrastructure should have, even as optional, weak security options such as WEP which is commonly known to be trivial to break. Here we analyze a Scalance access point and a client both in a dynamic environment in the context of a remote control scenario.

In particular in the remote control scenario these devices are vulnerable to a deauthentication attack, in which communication between access points and client is lost and this could drastically affect the control scenario. While control algorithms that are resilient to network delays and uncertainties were proposed [5.26], still such solutions are not always implemented.

The ***relevance to the thesis*** of the present chapter lies in two scenarios where the valve/pump actuators, controlling fuel, steam and water of the boiler turbine system are a) physically inaccessible or b) the feedback signals from sensors or analog controller commands are affected by disturbances. Scenario b) is actually a fact at the Thermal Power Plant South of Timisoara, many signals being affected by electromagnetic fields from power cables due to old architecture.

Either way, a wireless control scenario can be considered, but before that, a risk and reliability assessment needs to be done.

An example of wireless control architecture is presented below.

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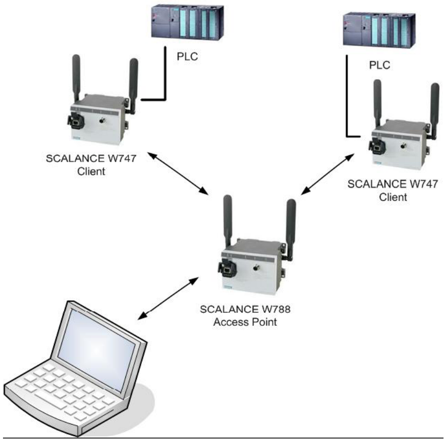

Fig 5.33. Generic example of Scalance based network

5.3.1. Attack over a remote control scenario: application setting

The case study is conducted using hardware-in-the-loop (HIL) simulation concept as illustrated in Fig 5.34. For simulation the G language from Labview was used. The target controller, which contains the control algorithm, is a Simatic S7-315F PLC [5.27] which is programmed using Step7 software. Communication is carried out using and Ole for Process Control (OPC Server) for tag-address conversion and wireless medium employing Siemens specific Scalance family routers.

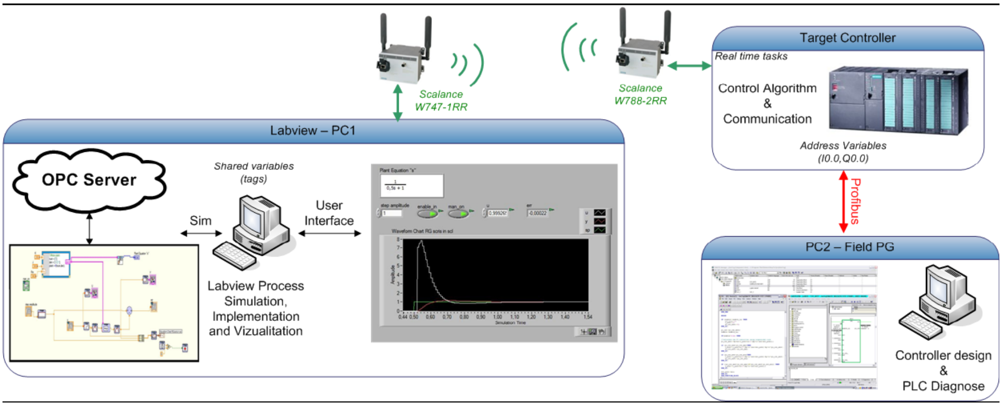

Fig 5.34. Application setting for remote control scenario

The simulation consists of a 1st order system, with a time constant of 0.5s, which is frequently used for modeling pumps, valves and other execution elements. The corresponding transfer function is given in the next equation:

$$H(s) = \frac{1}{0.5s + 1} \tag{4.2}$$

The control consists of a simple feedback loop around the process output using a PI controller. It is essential to underline that the PI described is purely discrete, following trapezoidal rule of integration, given in the next relation:

$$H_{PI}(k) = K_p e(k) + \left\{ u_i(k-1) + \frac{K_p}{T_i}\left[\frac{e(k)+e(k-1)}{2}\right]h \right\} \quad (5.3)$$

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The PLC and the OPC Server are synchronized at t=10ms, while the Labview simulation loop is synchronized using HIL-SRT principle, discussed in Section 5.2.2 of the present chapter.

5.3.2. Attack over a remote control scenario: attack scenario

The attack scenario is carried out on the system given by transfer function (4.2). The control gains are fixed to K_P=7 and T_I=2s, with output command limits set to -50 and +50, as for a frequency inverter for controlling a variable speed execution element.

The step size of the controller is set to h=10ms. At t=0.5s a step is applied to system set-point with an amplitude of A=4. The error is computed and fed to the control algorithm in the PLC. The PLC command initiates and stabilizes the system around the set-point. In case of an attack, in this simulated scenario, communication is completely lost with the process. The OPC Server and simulator exchange data through a shared variable engine. If communication is lost to the PLC, the OPC Server changes the quality of these variables to “bad” which denotes PLC communication failure with the OPC. The result consists in sending and maintaining by the simulator the last command value given by the controller. Visual signaling is done by turning red the time stamp of the shared variable.

A comparison between how the command and response should react in a normal automation situation and an attack scenario are given in Fig 5.35 and Fig 5.36. When the attack is initiated the control command is maintained at the last value given by the controller, resulting, in this particular case, in an increasing process output evolution shown in Fig 5.35.

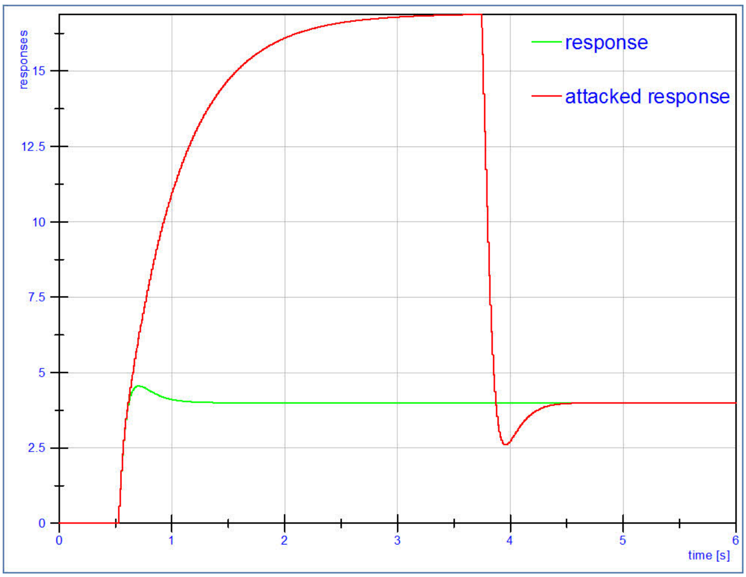

Fig 5.35. Process response with attack (red) and without attack (green)

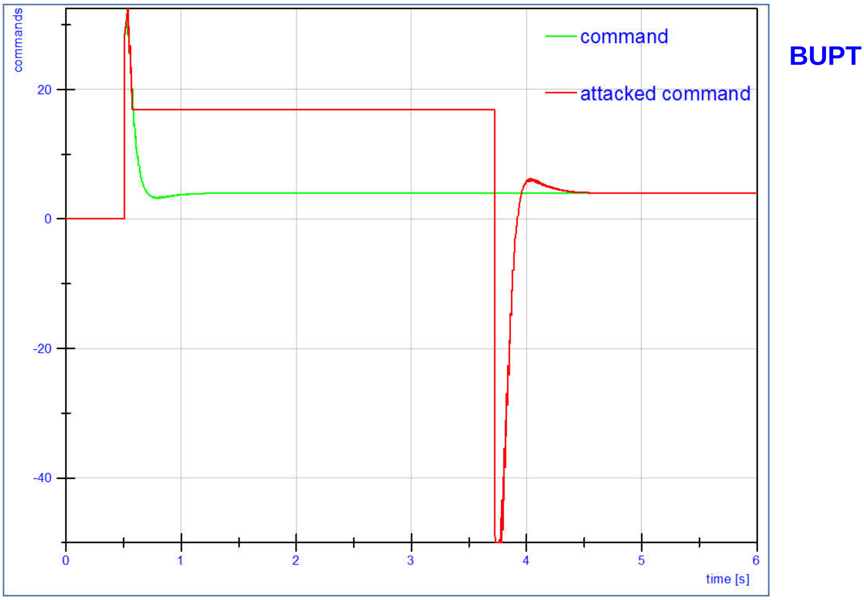

Fig 5.36. Controller command with attack (red) and without attack (green)

In a real life scenario, commands sent to the actuator inputs are zero or remain at the last known value, before the communication failed (depending on the settings in the frequency inverter), resulting in unexpected behavior and even critical situations. Moreover if the attacker knows how the process responds, it might be able to bring the process in a desired state, by activating/deactivating the attack. In this last case the process oscillates around the desired point. The behavior might be compared to a control with proportional (P with large gain) or bi-positional action. The main issue when interrupting communication to a controller in real-life and simulated scenario is that the controller (usually PI controllers most common) will detect a constant error and no matter how large is the command, this error cannot be compensated. Though the controller works perfectly, the command will grow larger and larger in amplitude (absolute value) during the attack. This leads to a huge command if there is no anti wind-up protection mechanism.

5.3.3. Conclusions for section 5.3

Security flaws are a serious threat for control systems in present days. While in the past these systems were isolated from the public, things changed and with the introduction of wireless networks they became exposed to malicious adversaries. This case study shows that even carefully designed products still have flaws such as the flaws on the authentication interface in Scalance modules. On the other hand flaws that are inherent to the communication protocol can become fatal for a remote control scenario. This is shown by the case study in which an active adversary can cut down communication and let the control process evolve at its will. Fixing these issues requires both security expertise and clever design from the control system engineer which should be aware of the adversary capability in general. In general wireless communication cannot guarantee a continuous communication, thus in the best case a local controller should be available for redundancy or the PLCs must have a fail-safe mode of operation in the case of communication losses. This however, significantly increases the costs of the control systems.

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While for standard applications from home to the business sector wireless communication is possibly the preferred alternative, in safety critical tasks, such as control systems, it is likely that wireless should be used only when cables are not a feasible alternative.

5.4. Conclusions

The present chapter starts by introducing key building blocks for designing an industrial automation system, based on world-widely used process equipment and software in Chapter 5.1. This comes from the need of: 1) integrating fully simulated control scenarios into industrial real-time targets and 2) program frequency inverters for control of asynchronous machines of the valve and pump actuators for steam, water, and heat flux.

The main contribution of Chapter 5 is to develop real-time implementations of hardware-in-the-loop (HIL) systems for testing control strategies in thermal power plants.

Three implementation systems are developed and compared by testing, i.e., 1) fully simulated system, 2) soft real-time constrained HIL system with OPC server, and 3) hard real-time constrained HIL deterministic system.

The main conclusion drawn is that the HIL-SRT system behaves closely in terms of controller commands and system responses to the HIL-HRT system, though some missed or discarded periods exist. This fact validates the cheaper and easy to implement HIL-SRT system as a real-time power plant simulator.

The main contributions consist in:

- Implementing and validating a hardware-in-the-loop test system with hard real time constraints (HIL-HRT) using a PXI-PLC hardware and a hardware-in-the-loop test system with soft real time constraints (HIL-SRT) for control strategies testing for thermal power plants.
- Comparing and analyzing the differences in control and process signals using HIL-HRT system versus HIL-SRT, and fully simulated system in order to choose the most suited cost-effective solution.
- Providing a fully functional real-time test platform for a wide range of power plant maneuvers in either manual or automatic mode.

The chapter ends with a tele-control application which simulates the risk of a wireless control scenario into an industrial environment. The main conclusion is that for standard applications, from home to the business sector, wireless communication is possibly the preferred alternative, on the other hand in safety critical tasks, such as process control systems, it is likely that wireless control scenarios should be used only when cables are not a feasible alternative.

[5.1] M. Iacob, G.-D. Andreescu, and N. Muntean, "SCADA system for a central heating and power plant," in Proc. 5th International Symposium on Applied Computational Intelligence and Informatics SACI 2009, Timisoara, Romania, pp. 159–164, May 2009.
[5.2] M. P. Groover, Automation, Production Systems, and Computer-Integrated Manufacturing, 3rd Ed., Pearson Education Inc., Prentice Hall, 2008.
[5.3] S. A. Boyer, SCADA: Supervisory Control and Data Acquisition, 2nd Ed., ISA, 2004.

BUPT

[5.4] F. Adamo, F. Attivissimo, G. Cavone, and N. Giaquinto, "SCADA/HMI systems in advanced educational courses," IEEE Transactions on Instrumentation and Measurement, vol. 56, no. 1, pp. 4–10, Feb. 2007.

[5.5] http://www.automation.siemens.com/sites-static/TIA/en/index.html

[5.6] Siemens Simatic Manager Help Manual, 2006.

[5.7] TIA Democase Anhang C-Komponenten des TIA-Demokoffers.doc, 2007.

[5.8] Siemens Simatic Manager Help on LAD, 2006.

[5.9] Siemens Simatic Manager Help on S7Graph, 2006.

[5.10] Siemens, SINAMICS G120 documentation CD, 06/2006.

[5.11] Siemens, G120 CU240S and CU240E Control Units, FW_3.2_enUs.pdf, 2009.

[5.12] Siemens, IQ Sense, LV20_02_IQSense.pdf, 2004.

[5.13] Siemens WinCC Flexible Help Manual, 2006.

[5.14] W. Winiecki and P. Bilski, "Time aspects of virtual instrument designing", in Proc. 20th IEEE Instrumentation and Measurement Technology Conference (IMTC'03), vol. 2, pp. 913–918, Vail, CO, USA, May 2003.

[5.15] S. Nabi, M. Balike, J. Allen, and K. Rzemien, "An overview of hardware-in-the-loop testing systems at Visteon," SAE technical paper series, SAE International, USA, March 2004.

[5.16] M. Schlager, W. Elmenreich, and I. Wenzel, "Interface design for hardware-in-the-loop simulation," in Proc. IEEE International Symposium on Industrial Informatics (ISIE 2006), vol. 2, pp. 1554–1559, Montreal, Canada, July 2006.

[5.17] W. Winiecki, "Methodology of virtual instruments time analysis," IEEE Transactions on Instrumentation and Measurement, vol. 55, no. 1, pp. 21–25, Feb. 2006.

[5.18] P. Bilski and W. Winiecki, "Time optimization of soft real-time virtual instrument design," IEEE Transactions on Instrumentation and Measurement, vol. 54, no. 4, pp. 1412–1416, Aug. 2005.

[5.19] W. Grega, "Hardware-in-the-loop simulation and its application in control education," in Proc. 29th ASEE/IEEE Frontiers in Education Conf. (FIE'99), San Juan, Puerto Rico, Nov. 1999, vol. 2, pp. 12B6/7–12.

[5.20] "OPC Specifications", OPC Foundation [Online]. Available: http://www.opcfoundation.org.

[5.21] F. Iwanitz and J. Lange, "OPC-Fundamentals, Implementation and Application", H. Fachverlag, Ed. Germany: Huthing, , ISBN 3-7785-2904-8, 2006.

[5.22] Ch. Salzmann, D. Gillet, and P. Huguenin, "Introduction to real-time control using LabView with an application to distance learning," Int. Journal of Engineering Education, vol. 16, no. 3, pp. 255–272, 2000.

[5.23] National Instruments, "LabVIEW Real-Time Module User Manual," April 2004 edition.

[5.24] Siemens AG. SIMATIC NET Operating Instructions, SCALANCE W747-1RR (Ethernet Client Module IPCF), 2005.

[5.25] Siemens AG. SIMATIC NET Operating Instructions, SCALANCE W788-1RR (Access Point iPCF), 2005.

[5.26] O. C. Imer, S. Yksel, and T. Basar, "Optimal control of lti systems over unreliable communication links", Automatica, 42(9):1429 – 1439, 2006.

[5.27] Siemens AG. S7-300 CPU 31xC and CPU 31x, Technical Data, 2006.

6. CONCLUSIONS AND CONTRIBUTIONS

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6.1. Objectives

The present work is dedicated to designing, testing and implementing several suitable control strategies for natural circulation boiler processes with associated turbine in thermal power plants. The implementation makes use of modern and fundamental features like Hardware-in-the-loop and Real-Time having as final result an industrial thermal power plant simulator for control strategy testing and also operator training. The system is designed in such a way that facilitates the simulator integration into the existing SCADA/DCS infrastructure developed in Chapter 2, by making use of the centralized S7-400 controller, OPC Server and Redundant Process Servers.

Important features concerning real thermal power plant control implementation are also described along the dissertation, with an accent placed on control of variable speed execution elements, complex control strategy integration and a simple safety scenario, all with Siemens technology. An insight into slow dynamics processes is also illustrated. Towards the end a risk assessment is done in a wireless control scenario on field execution equipment.

The ***main objectives*** of the thesis are:

i) To provide the *know-how* for successfully designing, *integrating and upgrading control strategies* in real thermal power plant systems.
ii) To provide a Hardware-in-the-Loop *real-time simulators* for rapid control strategy testing/validation/integration and also dispatcher training for improved thermal power plant process control.

These main objectives are achieved in terms of the following results:

- SCADA platform (hardware and software) for integrating automatic control: designed SCADA system for COLTERM thermal power plant south of Timisoara, SCADA system functionality and utilization – *Chapter 2*.
- Head-start for control and simulator implementation using SCADA platform, based on applications employing world-wide National Instruments and Siemens Automation technology - *Chapters 3 & 5*.
- Process based approach of thermal power plants having as core three developed models (low-order model, complex physical law based model, interpretation model-approximation model)– *Chapters 3 & 4*.
- Design, implementation and test two control strategies (PI cascade control, multivariable decoupled control) with integration capability in the centralized SCADA system – *Chapters 3 & 4*.
- Two test stand platforms for implementations of control paradigms testing using modern concepts like hardware-in-the-loop and real-time with industrial targets – *Chapter 5*.
- Risk analysis of a wireless control scenario on process actuators when cables and busses are not a feasible solution – *Chapter 5*.

6.2. Discussion and conclusion

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Based on the results presented in the dissertation:

A) **Two main control strategies** (cascade control & multivariable decoupled control) **and three fitted and extended models were developed**.

B) **Three implementations are discussed** for control strategy testing, from which 2 employing HIL and RT concepts.

A) Control strategies and models – discussions and conclusions

The **1st model: *low-order boiler-turbine model*** is easy to implement and understand but unfortunately has serious drawbacks when dealing with the following issues:

- No information whatsoever about water dynamics, hence no automatic control possibility on the loop.
- No information regarding distribution of steam and water in the riser and down-comer.
- No information linked to internal parameter variations: steam quality, steam volume ration and other.
- The shrink and swell dynamic, is not implemented in order to be compensated.
- In order to perfectly fit the model to a thermal power plant, tests need to be carried out at the real site with large setpoint differences, an issue which is not always possible.
- Accurate responses only for small deviations from nominal operating conditions.
- Lack of approach in physics laws, which results

As conclusions, the application presents an open loop dispatcher training simulator implemented in Labview for Colterm heating power plant in Timisoara, Romania. The system employs real-time capability, graphical user interface (GUI), uninterrupted operator interaction, having as background a low order boiler-turbine model for dynamic simulation. The operator can manually controls the fuel charge on each of the three boilers, the turbine valve position and the steam to consumers in order to anticipate parameter evolution on each of the boiler units and on the power generated by the turbine.

The ***2nd model with associated control: the complex 4th order Åström and Bell model with cascade gain scheduled control*** is extended to a 5th order model with actuators.

As conclusions, the performance of the gain-scheduled cascade control with a feed-forward loop is discussed versus a simple PI control law addressing the following issues:

- The cascade control improves the settling time of the water level, and reduces the swell effect, though it slightly has larger overshoot for both 50% and 90% load.
- Using 1 feedback control the command decreases, due to the swell effect and after a period of time increases. By using 3 feedback control, the feed-forward steam loop adds predictability to the control structure and deals better and faster with disturbances acting on the inner loop.

The **3rd *model with associated control: a 3rd order interpretation model developed by Åström and Bell with multivariable gain-scheduled decoupled control.***

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As conclusions, the 2nd control solution employing a centralized multivariable gain-scheduled decoupled control for a boiler-turbine system is presented. Unlike the cascade control solution presented in Chapter 3.3, the present multivariable control solution deals with process interaction reduction based on decoupled control. The multivariable decoupled centralized control method is chosen with good performances in transient responses for controlling a boiler-turbine unit. The control strategy is improved by gain-scheduling technique based on dynamic model linearization. Due to hard input constraints, adaptive PID control with anti-windup is designed. To eliminate undesired bumps in system responses, when adaptive controller gains are shifted, the updated PI controller gains are filtered.

B) HIL and RT test platforms for control strategies - discussions and conclusions

Three implementation systems are developed and compared by ***testing***, i.e., 1) fully simulated system, 2) soft real-time constrained HIL system with OPC server, and 3) hard real-time constrained HIL deterministic system. The best control test platform for thermal power plants is chosen in terms of cost, accuracy and reliability.

As conclusions, the HIL-SRT system behaves closely in terms of controller commands and system responses to the HIL-HRT system, though some missed or discarded periods exist. This fact validates the cheaper and easier to implement HIL-SRT system as a real-time power plant simulator.

6.3. Original contributions

The present thesis includes, from the author's point of view, the following original contributions:

- ❖ Design and develop a SCADA/DCS system for the thermal power plant south of Timisoara as implementation platform for thermal power plant control solutions (Chapter 2).
- ❖ Give a head-start for control and simulator implementation using SCADA platforms, based on applications employing world-wide state-of-the-art National Instruments and Siemens Automation technology (Chapters 3 & 5).
- ❖ Develop, extend and fit three models: low-order model, complex physical law based model, interpretation -approximation model in order to match, in terms of constructive and functioning parameters, the thermal power plant south of Timisoara (Chapters 3 & 4).
- ❖ Implement and test the three fitted boiler-turbine models of thermal power plant (Chapters 3 & 4).
- ❖ Carry out a critical analysis of the three boiler-turbine models by presenting the pros and cons of each of them (Chapters 3 & 4).
- ❖ Design, implement and test two control strategies (PI cascade control, multivariable decoupled control) with integration capability in the centralized SCADA system (Chapter 3 & 4).

- Improve the centralized multivariable decoupled control by using gain-scheduled technique with dynamic linearization, controller order reduction and anti wind-up for process interaction compensation and better system responses (Chapter 4).
- Design and implement three simulators, based on the three presented boiler-turbine models with associated control, with graphical user interface (GUI) for operator / dispatcher training (Chapters 3 & 5).
- Develop two test stand platforms for control solutions testing and implementation in thermal power plants, making use of modern concepts employing real-time (RT) and hardware-in-the-loop (HIL) test systems (Chapter 5).
- Present a risk analysis of a wireless control scenario on process actuators (valve and pump control) when cables and busses are not a feasible solution (Chapter 5).

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Appendix 1 – Block diagram of the Labview control and communication "G" code for temperature control system

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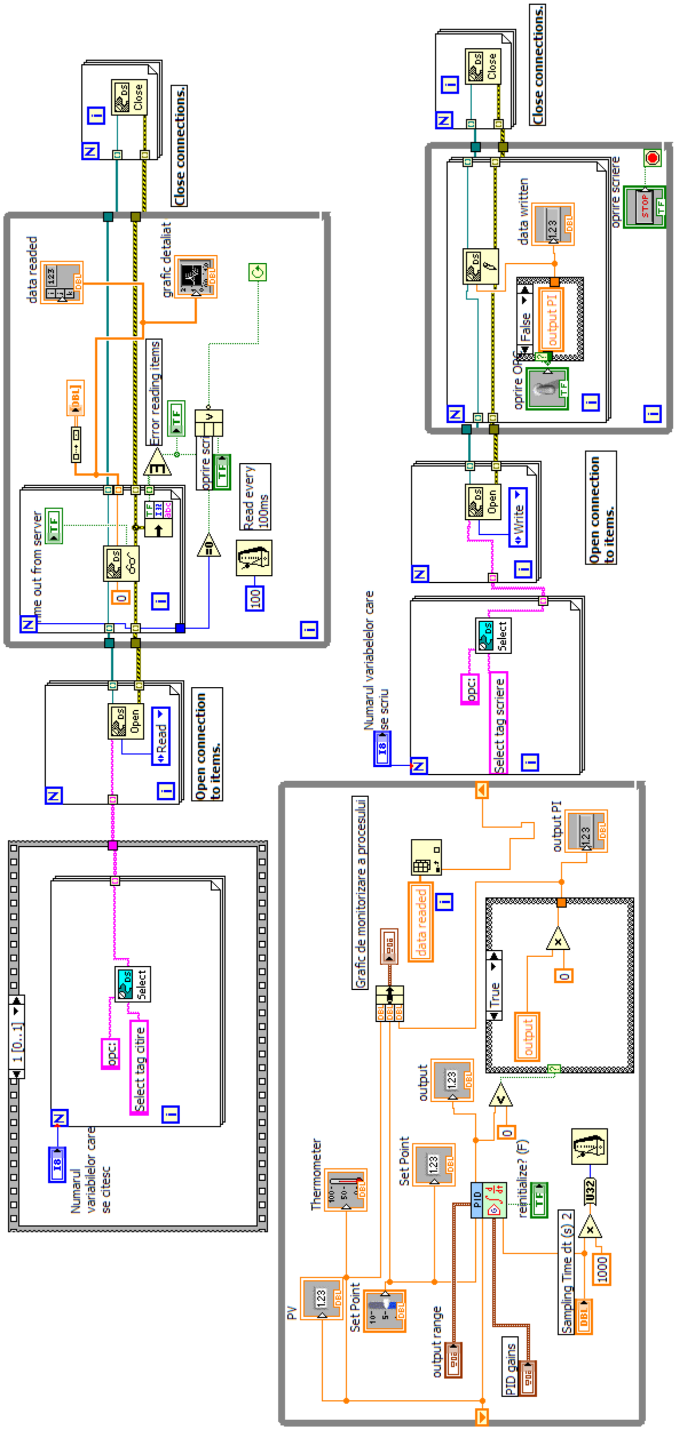

Appendix 2 – Boiler , turbine and overall simulator Labview "G" codes for low-order model

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The program was constructed in LabView and its structure consists of a sequence which in the first tab executes the initializations of the controls and indicators and in the second tab the logic of the simulator with associated graphical interface. Fig.2C. presents the simulation loop which runs under Runge-Kutta 4 ode solver with fixed time step of 0.1 seconds in non real time mode.

The loop contains three simulation subsystems which represent each of the boilers. The subsystems are constructed like in Fig.2A, with associated inputs and output.

The main simulation loop calls the subsystems in order to execute the boiler and turbine Fig.2B. algorithm and to pass data to the graph indicators which show drum pressure vs. throttle pressure and steam flow vs. generated steam. The steam flow from each of the boilers is then collected at the turbine inlet by means of a summation block, minus steam to consumers which is an input that the dispatcher can set. The GUI implementation is presented in Fig.2D.

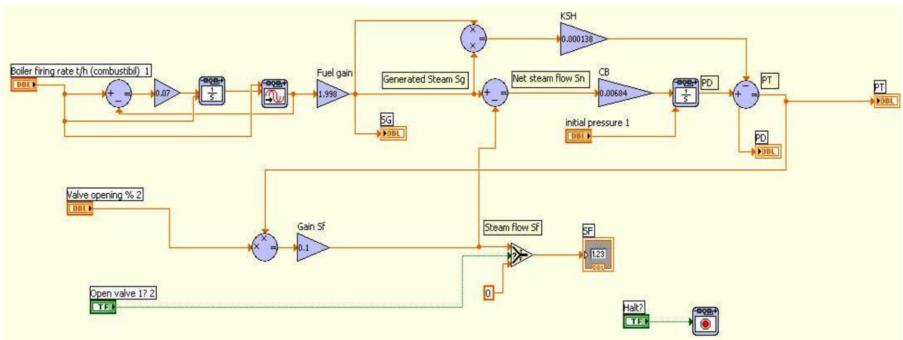

Fig.2A. – Boiler graphical code

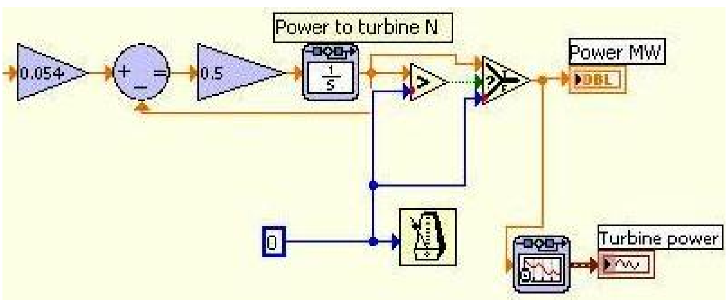

Fig.2B. – Turbine graphical code

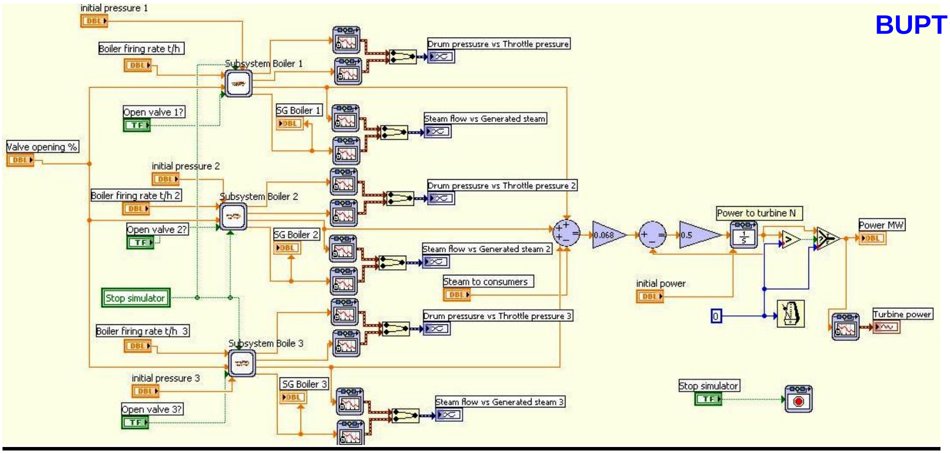

Fig.2C. - Overall simulator code (time critical loop)

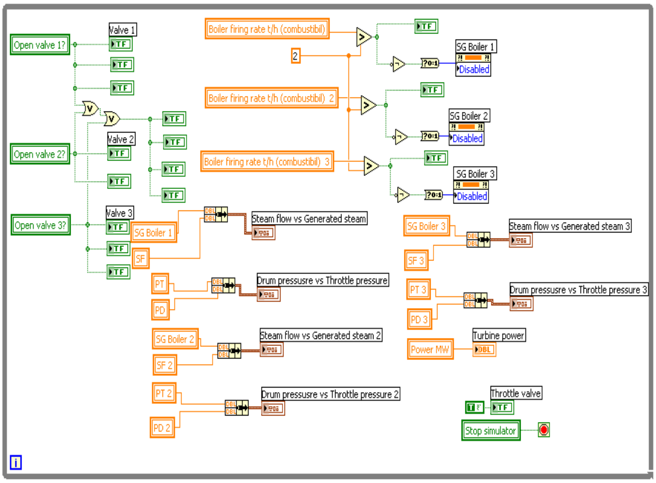

Fig.2D. – Graphical user interface code (host loop)

Appendix 3 – Coefficients and model code implementation for the Åström and Bell complex model

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1. Coefficients for quadratic approximations:

a_{01}=2.728e6, a_{11} = -1.792e4, a_{21} = - 924
a_{02} = 55.43, a_{12} = 7.136,a_{22} = 0.224
a_{03} = 1.408e6, a_{13} = 4.565e4, a_{23} = -1010.0
a_{04} = 691.35, a_{14} = -1.867, a_{24} = 0.081
a_{05} = 311.0, a_{15} = 7.822, a_{25} = - 0.32

2. Boiler formula node implementation code

```
//=======continuity equations and partial differentials==============
float32 a01=2.728e6, a11 = -1.792e4, a21 = - 924, a02 = 55.43, a12 =
7.136,a22 = 0.224, a03 = 1.408e6, a13 = 4.565e4, a23 = -1010.0,
a04 = 691.35, a14 = -1.867, a24 = 0.081, a05 = 311.0, a15 = 7.822, a25 = -
0.32, a06 = 5900,a16 = 250;
float32 hs,ros,hw,ts,row,Cp=650,hf,hc,tfw=104,dhs,dros,dhw,drow,dts;
hs = a01 +(a11 + a21*(p - 10))*( p - 10);
ros=a02 +(a12 + a22*(p - 10))*( p - 10);
hw = a03 +(a13 + a23*(p - 10))*(p - 10);
row =a04 +(a14 + a24*(p - 10))*(p - 10);
ts = a05 +(a15 + a25*(p - 10))*(p - 10);
hf = hw +(a06 + a16*(p- 10))*(tfw - ts);
hc = hs - hw;
dhs=2*a21*p+a11-20*a21;
dros=2*a22*p+a12-20*a22;
dhw=2*a23*p+a13-20*a23;
drow=2*a24*p+a14-20*a24;
dts=2*a25*p+a15-20*a25;
//==============e
coefficients============================
float32 Vt,Vst,alfav,niu,dalfavdp,dalfavdalfar,Vwd,qdc,qct,e11,e12,e21,e22,e32,
e33,e42,e43,  e44;
float32
Vd=31.4,mt=18000,mr=16000,md=2000,beta=0.3,K=25,Td=12,Vdc=11.41,
Vr=15,Ad=20,Adc=1.36;
Vt=Vdc+Vr+Vd; // calcul volum total
alfav=row/(row-ros)*(1-ros/((row-ros)*alfar)*ln(1+(row-ros)/ros*alfar));
niu=alfar*(row-ros)/ros;
Vwd=Vwt-Vdc-(1-alfav)*Vr;
Vst=Vt-Vwt;
dalfavdp=1/pow((row-ros),2)*(row*dros-ros*drow)*(1+row/(ros*(1+niu))-
(ros+row)/(ros*niu)*ln(1+niu));
dalfavdalfar=row/(ros*niu)*(1/niu*ln(1+niu)-1/(1+niu));
qdc=sqrt(2*row*Adc*(row-ros)*9.8*alfav*Vr/K);
```

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```
e11=row-ros;
e12=Vwt*drow+Vst*dros;
e21=row*hw-ros*hs;
e22=Vwt*(drow*hw+dhw*row)+Vst*(hs*dros+ros*dhs)-Vt+mt*Cp*dts;
e32=(row*dhw-alfar*hc*drow)*(1-alfav)*Vr+((1-
alfar)*hc*dros+ros*dhs)*alfav*Vr+(ros+(row-ros)*alfar)*hc*Vr*dalfavdp-
Vr+mr*Cp*dts;
e33=((1-alfar)*ros+alfar*row)*hc*Vr*dalfavdalfar;
e42=Vsd*dros+1/hc*(ros*Vsd*dhs+row*Vwd*dhw-Vsd-
Vwd+md*Cp*dts)+alfar*(1+beta)*Vr*(alfav*dros+(1-alfav)*drow+(ros-
row)*dalfavdp);
e43=alfar*(1+beta)*(ros-row)*Vr*dalfavdalfar;
e44=ros;
//==============state equations
==========================
float32 aux=e12*e21-e11*e22,K1=0.00057,Ks=17.13333333;

float32 PT;
PT=p-0.05*p;
qs=Kv*pow((p-PT)/K1,0.66);
dx2=u1*(hf*e12-e22)/aux+u2*e12/aux+qs*(e22-hs*e12)/aux;
dx1=-e21/e22*dx2+u2/e22+u1*hf/e22-qs*hs/e22;
qct=((hw-hf)/hc)*u1+(1/hc)*(ros*Vst*dhs+row*Vwt*dhw-
Vt+mt*Cp*dts)*dx1;
dx3=-e32/e33*dx1+u2/e33-alfar*hc*qdc/e33;
dx4=-e42/e44*dx1-e43/e44*dx3+ros/(Td*e44)*(Vsd0-Vsd)+u1*(hf-
hw)/(hc*e44);
//==============output equations
=========================
y1=p;
y2=(1/Ad)*(Vwt-Vdc-(1-alfav)*Vr+Vsd);
```

Appendix 4 – Main Labview cascade control simulator "G" code

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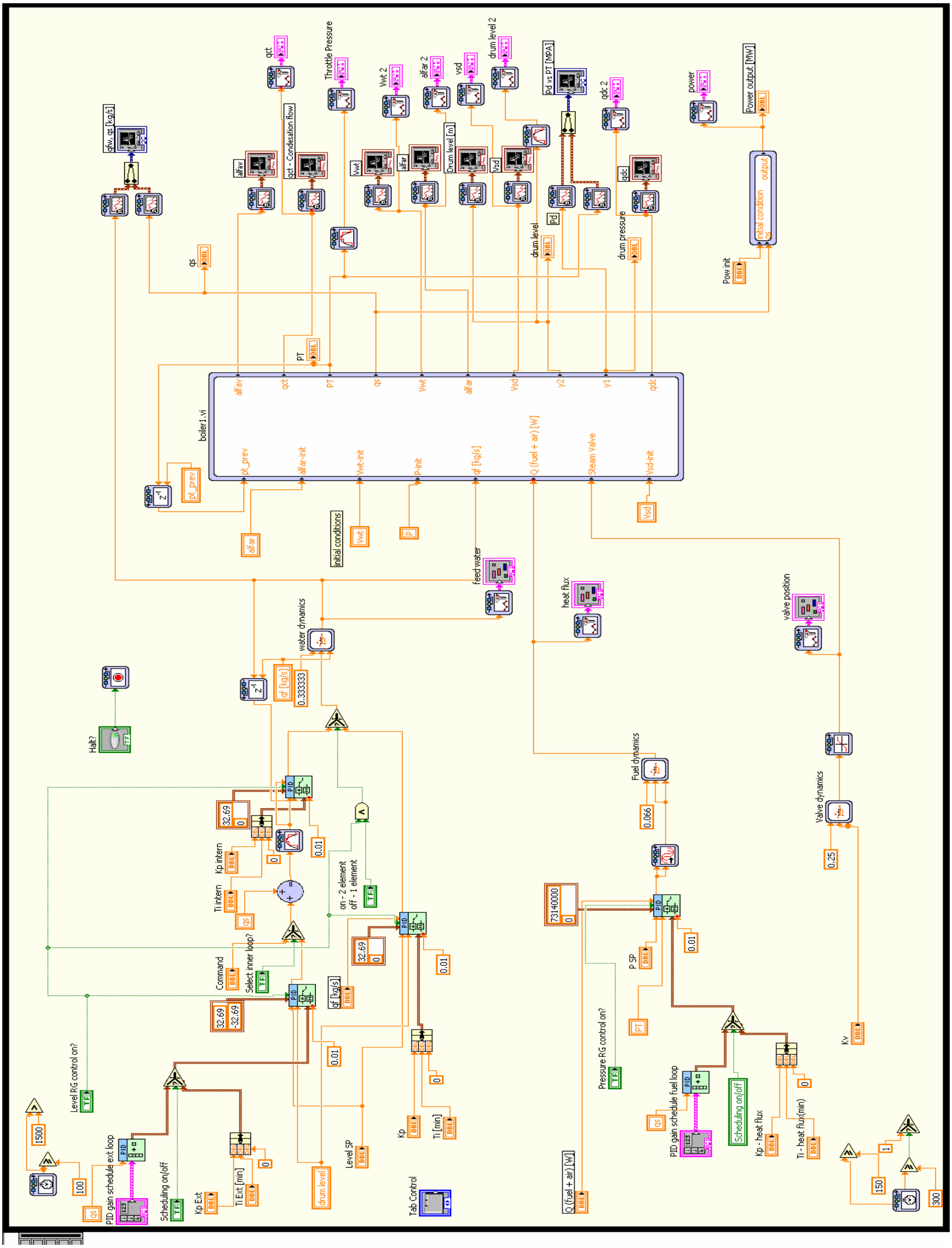

Appendix 5 – Controller gain relations for multivariable decoupled gain-scheduled control

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```
k1=0.055;k2=0.02;
ki=0.04;z3=0.01;
'coef det(G)'
beta0=a1*e2*i3+d1*h3*c1+g3*b1*f1-c1*e2*g3-f1*h3*a1-b1*d1*i3;

'coef K11'
alfa1k11=e2*i3-f1*h3+a2*i3*e1+a2*e2*i2-a2*h2*f1;
alfa0k11=a2*e2*(e2*i3-f1*h3);
Kp11=k1*alfa1k11/beta0; Ki11=k1*alfa0k11/beta0;

'coef K12'
alfa1k12=(10+a2)*(c1*h3-b1*i3)+10*a2*(c1*h2-b1*i2);
alfa0k12=10*a2*(h3*c1-b1*i3);
Kp12=k2*alfa1k12/beta0; Ki12=k2*alfa0k12/beta0;

'coef K13'
alfa1k13=(z3+a2)*(b1*f1-c1*e2)-a2*z3*c1*e1;
alfa0k13=a2*z3*(b1*f1-c1*e2);
Kp13=ki/beta0*alfa1k13; Ki13=ki*alfa0k13/beta0;

'coef K21'
alfa1k21=g3*f1-i3*d1+a2*(f1*g2-d1*i2);
alfa0k21=a2*(g3*f1-d1*i3);
Kp21=k1*alfa1k21/beta0; Ki21=k1*alfa0k21/beta0;

'coef K22'
alfa1k22=(a2+10)*(a1*i3-c1*g3)+10*a2*(a1*i2-c1*g2);
alfa0k22=10*a2*(a1*i3-g3*c1);
Kp22=k2*alfa1k22/beta0; Ki22=k2*alfa0k22/beta0;

'coef K23'
alfa1k23=(a2+z3)*(c1*d1-a1*f1);
alfa0k23=a2*z3*(-a1*f1+d1*c1);
Kp23=ki*alfa1k23/beta0; Ki23=ki*alfa0k23/beta0;

'coef K31'
alfa1k31=(d1*h3-g3*e2)+a2*d1*h2-a2*g3*e1-a2*e2*g2;
alfa0k31=a2*(d1*h3-g3*e2);
Kp31=k1*alfa1k31/beta0; Ki31=k1*alfa0k31/beta0;

'coef K32'
alfa1k32=(10+a2)*(b1*g3-a1*h3)+10*a2*(b1*g2-a1*h2);
alfa0k32=10*a2*(b1*g3-a1*h3);
Kp32=k2*alfa1k32/beta0; Ki32=k2*alfa0k32/beta0;
```

BUPT

```
'coef K33'
alfa1k33=(a2+z3)*(a1*e2-d1*b1)+a2*z3*a1*e1;
alfa0k33=a2*z3*(a1*e2-d1*b1);
Kp33=ki/beta0*alfa1k33; Ki33=ki*alfa0k33/beta0;

'vector packs'
Kp=[Kp11,Kp12,Kp13,Kp21,Kp22,0,Kp31,Kp32,Kp33];
Ki=[Ki11,Ki12,Ki13,Ki21,Ki22,0,Ki31,Ki32,Ki33];
```

Appendix 6 – Model and control simulation "G" code for boiler turbine Åström and Bell complex model with multivariable decoupled gain-scheduled control

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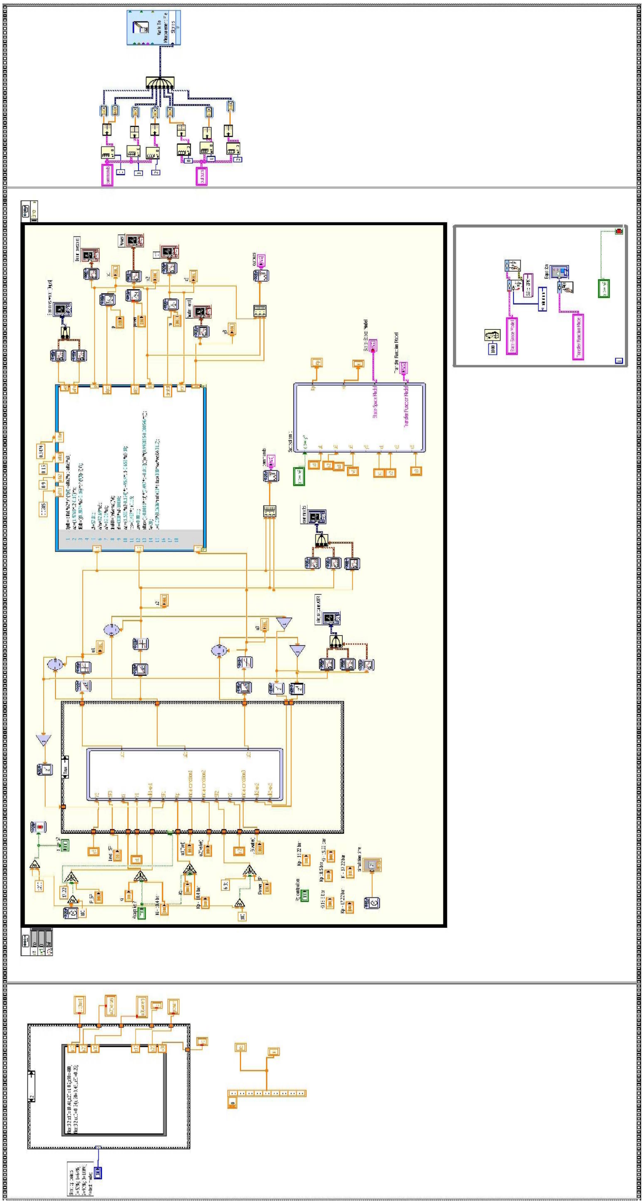

Fig.6A - Simulation code backbone – birds-eye view

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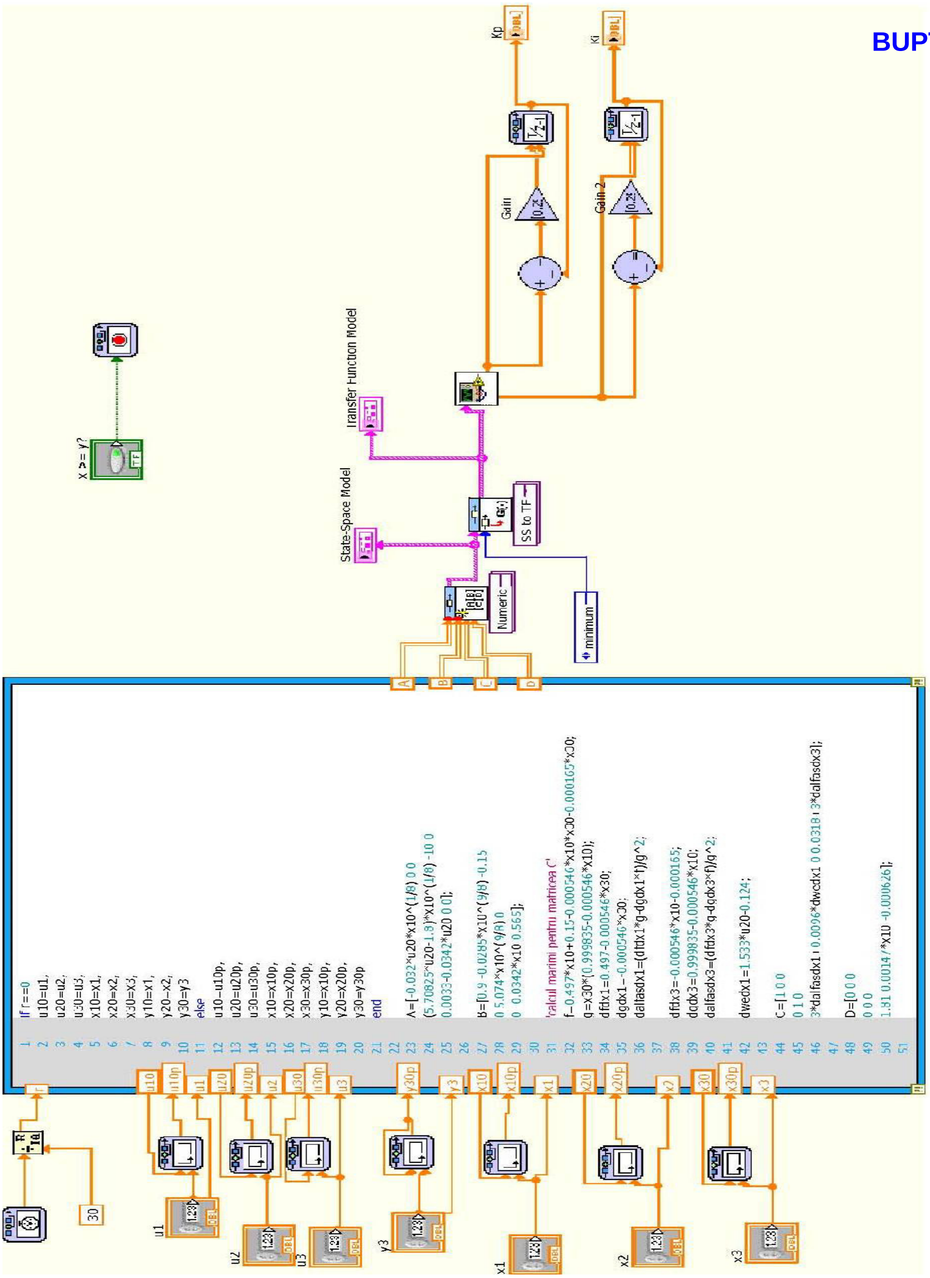

Fig.6B. – Dynamic linearization subsystem content

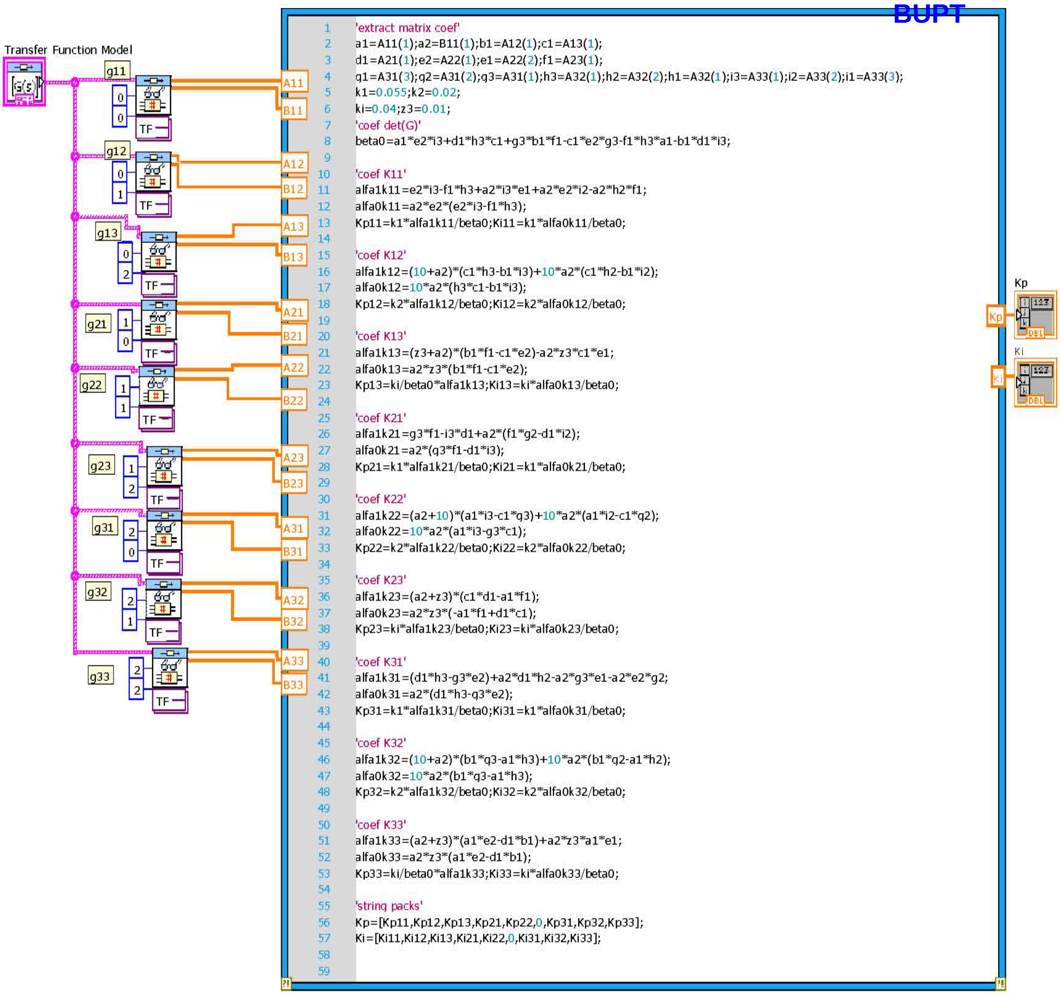

Fig.6C. – Controller gains sub-vi content

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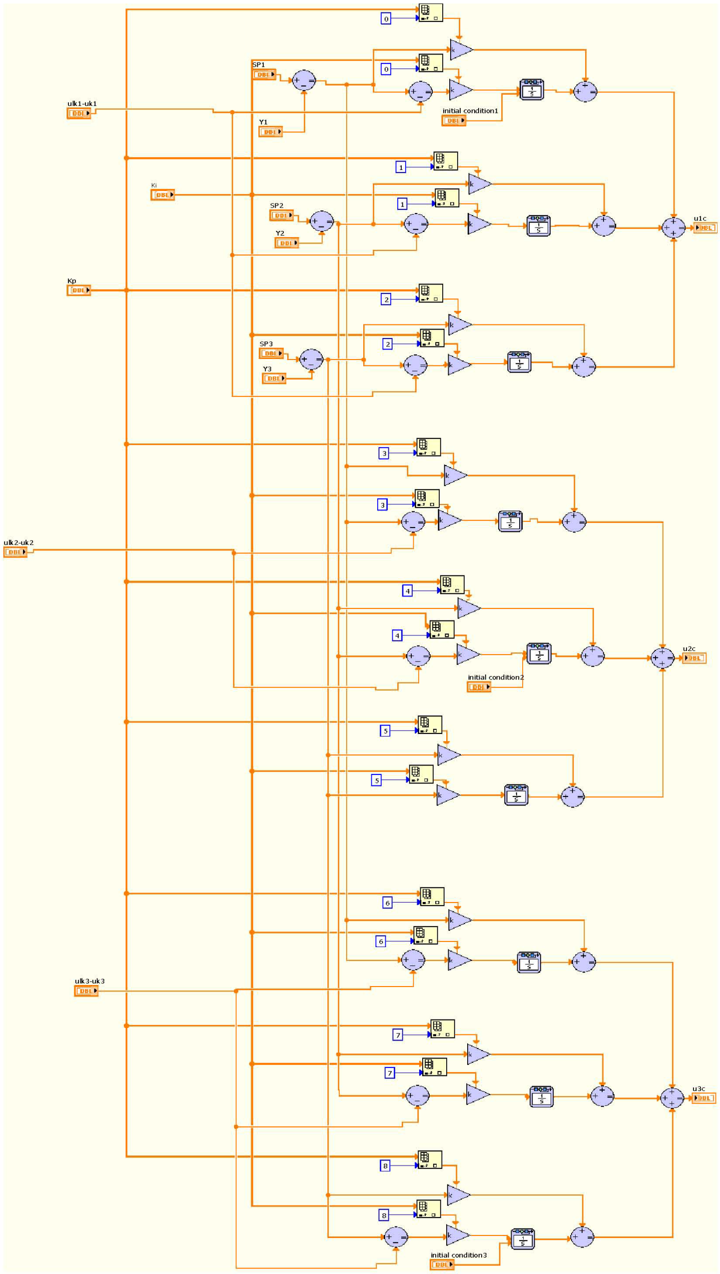

Fig.6D. – PI decupled control subsystem content

Appendix 7 – Real time "G" code implementation for boiler turbine Åström and Bell complex model running on PXI and multivariable decoupled gain- scheduled control running on PLC – Test Platform

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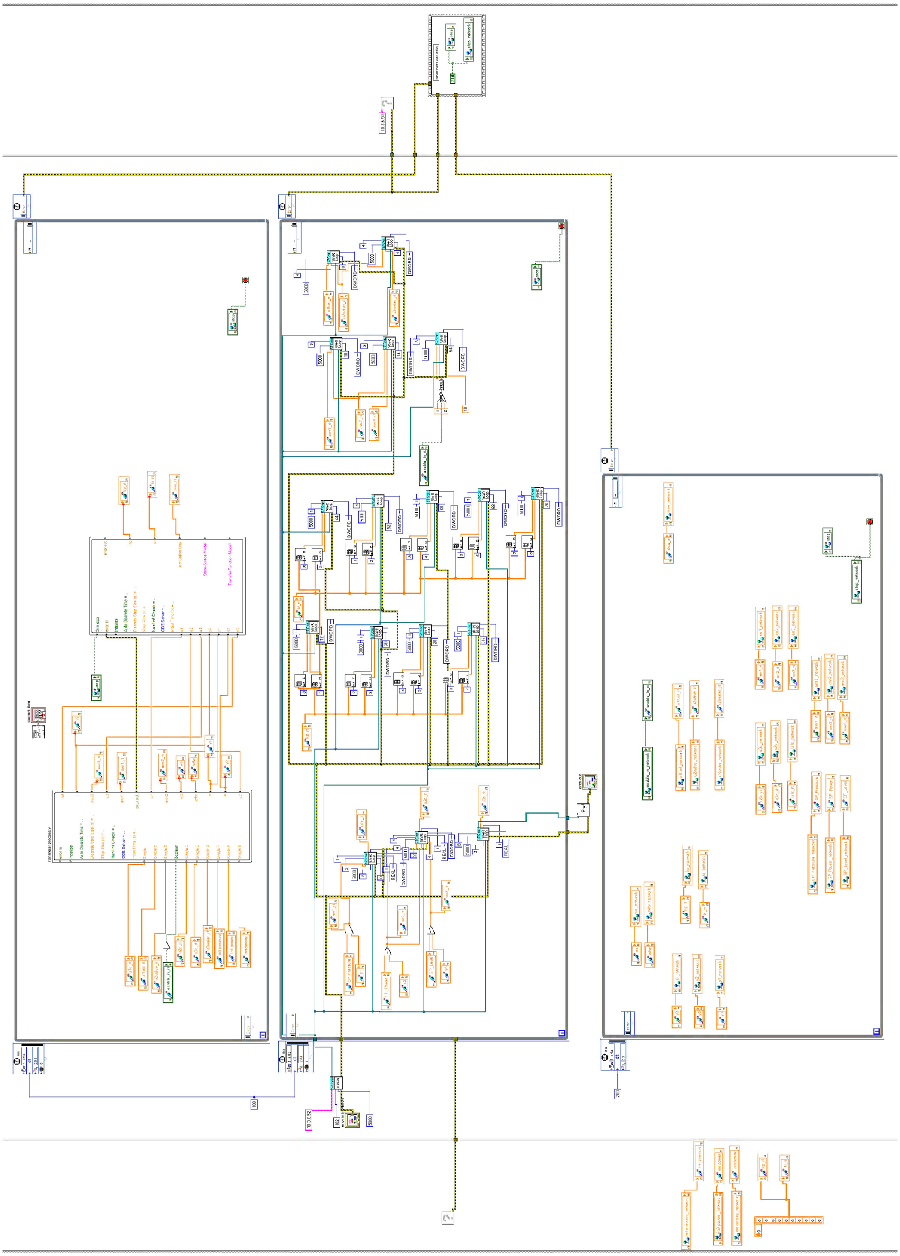

Appendix 8 – S7 TCP/IP transport protocol VI (8A) and Host loop VI "G" language code (8B) – Test Platform 3 BUPT

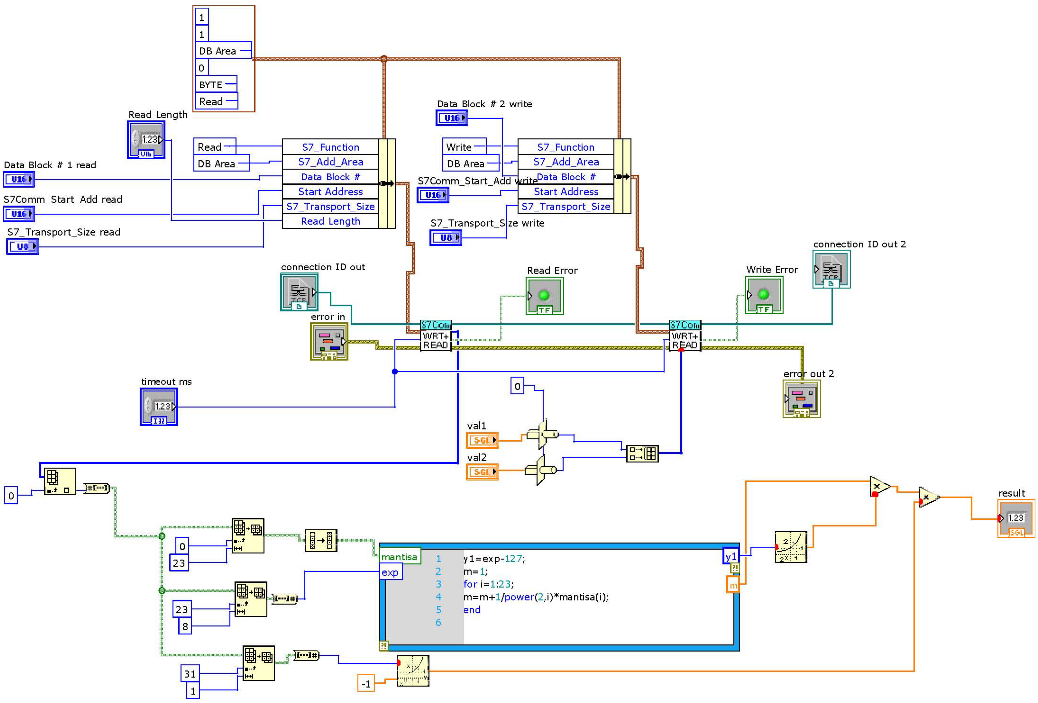

Fig.8A. – S7 TCP/IP data transport protocol VI

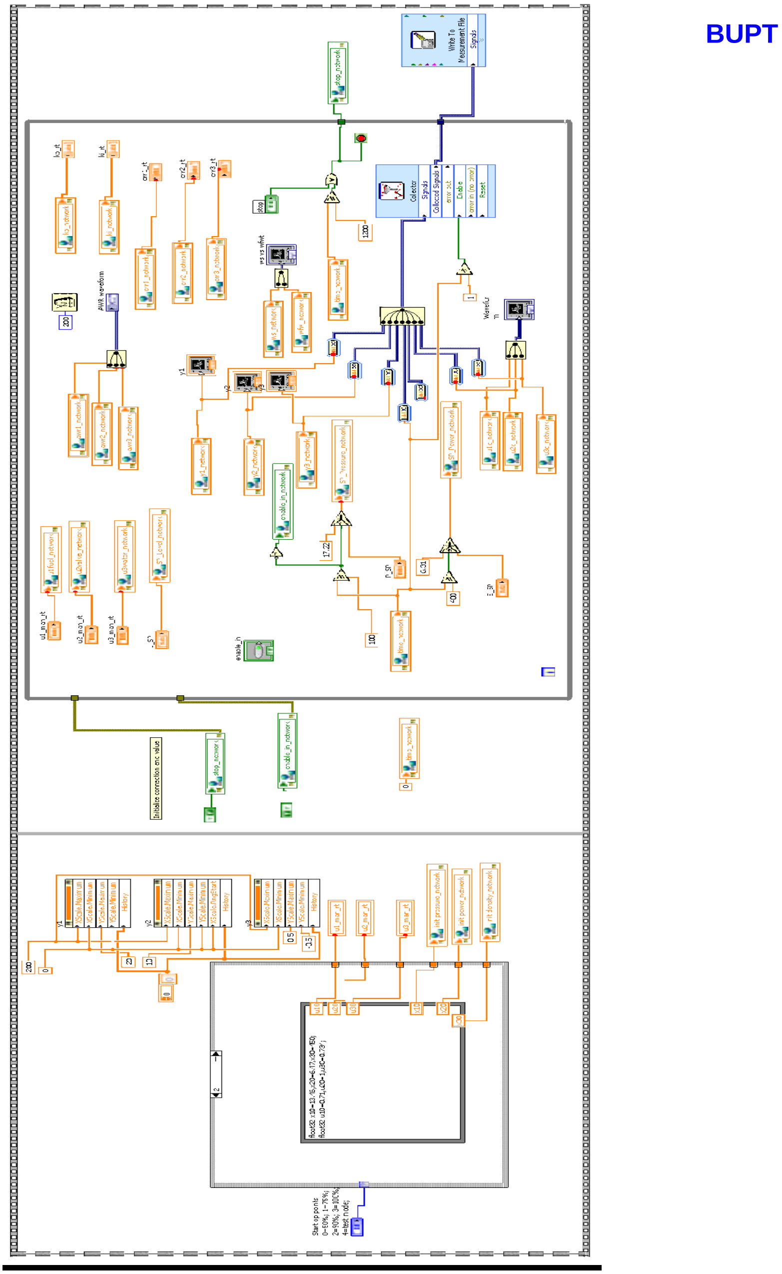

Fig.8B. – Host VI loop (normal priority - runs on PC1)

Author's papers related to the Ph. D. Thesis BUPT

1. ***Mihai Iacob***, Gheorghe-Daniel Andreescu, Nicolae Muntean, "SCADA system for a central heating and power plant" in Proc. *5th International Symposium on Applied Computational Intelligence and Informatics SACI 2009*, Timisoara, Romania, pp. 159–164, May 2009. (**ISI Proceedings, IEEE Explore, SCOPUS**).

2. ***M. Iacob***, G.-D. Andreescu, N. Muntean, SCADA system for a central heating and power plant, (in book chapter 8: Process Control and Automation Applications), in Instrument Engineers' Handbook Vol. 3: Process Software and Digital Networks, 4th Edition, Eds.: B.G. Liptak, H. Eren, CRC Press, USA, ISBN: 978-1439817766, pp. 930-939, Aug. 2011. (**CRC Press - Taylor & Francis Group** amazon.com

3. ***M. Iacob***, C.A. Bejan, G.-D. Andreescu, **Supervisory control and data acquisition laboratory**, *TELFOR Journal*, Belgrade, Serbia, ISSN: 1821-3251, vol. 2, no. 1, pp. 49-54, Nov. 2010.

4. C.A. Bejan, ***M. Iacob***, G.-D. Andreescu, SCADA automation system laboratory, elements and applications, Proc. 7th Int. Symposium on Intelligent Systems and Informatics, 2009, SISY '09, Subotica, Serbia, ISBN: 978-1-4244-5348-1, pp. 181-186, Sep. 2009 (**ISI Proceedings, IEEE Explore, SCOPUS)**.

5. ***M. Iacob***, G.-D. Andreescu, N. Muntean, Boiler-turbine simulator with real-time capability for dispatcher training using LabView, Proc. 2010 12th Int. Conf. on Optimization of Electrical and Electronic Equipment (OPTIM), Brasov, Romania, ISSN: 1842-0133, ISBN: 978-1-4244-7019-8, pp. 864-869, May 2010 (**ISI Proceedings, IEEE Explore, SCOPUS**).

6. Claudia Simona Bodnariu, ***Mihai Iacob***, Nicolae Muntean, "Temperature Monitoring and Control System using ADAM 6024 Module with Labview", *Timisoara's Technical Days* 2009.

7. ***M. Iacob***, G.-D. Andreescu, R. Antal, A.-M. Dan, Multivariable adaptive control with hardware-in-the-loop for a drum-type boiler-turbine system, Proc. 2011 19th Mediterranean Conf. on Control and Automation (MED), Corfu, Greece, ISBN: 978-1-4577-0124-5, pp. 898-902, June 2011 (**IEEE Xplore, SCOPUS**).

8. ***M. Iacob,*** G.-D. Andreescu, Implementation of hardware-in-the-loop system for drum-boiler-turbine decoupled multivariable control, Proc. 2011 6th IEEE Int. Symposium on Applied Computational Intelligence and Informatics (SACI), Timisoara, Romania, ISSN: 978-1-4244-9108-7, pp. 45-50, May 2011 (**IEEE Xplore, SCOPUS**).

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9. ***M. Iacob***, G.-D. Andreescu, Real-time hardware-in-the-loop test platform for thermal power plant control systems, Proc. 2011 IEEE 9th Int. Symposium on Intelligent Systems and Informatics (SISY), Subotica, Serbia, ISBN: 978-1-4577-1975-2/11, pp. 495-500, Sep. 2011 (**IEEE Xplore, SCOPUS**).

10. ***M. Iacob*** and G.-D. Andreescu, Drum-boiler control system employing shrink and swell effect remission in thermal power plants, Proc. 2011 3rd International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), Budapest, Hungary, ISSN: 2157-0221, ISBN: 978-1-4577-0682-0, pp. 1-8, Oct. 2011, (**IEEE Xplore, SCOPUS**).

11. Marius Cristea, Bogdan Groza and ***Mihai Iacob,*** **"**Some Security Issues In SCALANCE Wireless Industrial Networks", ARES 2011, 6th International Conference on Availability, Reliability and Security, Viena, Austria, ISBN 978-0-7695-4485-4, pp. 493-498, August, 2011, (**IEEE Xplore, SCOPUS**).

Citations of paper no. 1 by:

1. N.A. Othman, N.S. Damanhuri, I.R. Ibrahim, R. Radzali, M.N. Mohd, Automated monitoring system for small scale dual-tariff solar PV plant in UiTM Pulau Pinang, in Proc. World Congress on Eng. 2010, WCE 2010, London, UK, ISSN 2078-0958, ISBN 978-988-18210-7-2, vol. 2, pp. 945-947, Jul. 2010. (Univ. Teknologi MARA, Malaysia) (INSPEC, iaeng.org-pdf).
2. Adhikesh, S. Vijaya Chitra, Padma Prasad Munirathinam, SCADA based oil field monitoring system, in Proc. 8th International Conf. Computational Systems and Communication Technology, CSCT 2010, Cape Institute of Technology, Tamil Nadu, India, paper 34, 5p., May 2010. (Kongu Engineering College, Perundurai, India).

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IEEE CONFERENCES

Implementation of hardware-in-the-loop system for drum-boiler-turbine decoupled multivariable control

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Applied Computational Intelligence and Informatics (SACI), 2011 6th IEEE International Symposium on
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Publication Year: 2011 , Page(s): 45 - 50

IEEE CONFERENCES

Real-time hardware-in-the-loop test platform for thermal power plant control systems

Iacob, M.; Andreescu, G.-D.;
Intelligent Systems and Informatics (SISY), 2011 IEEE 9th International Symposium on
Digital Object Identifier: 10.1109/SISY.2011.6034378
Publication Year: 2011 , Page(s): 495 - 500

IEEE CONFERENCES

Drum-boiler control system employing shrink and swell effect remission in thermal power plants

Iacob, M.; Andreescu, G.;
Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), 2011 3rd International Congress on
Publication Year: 2011 , Page(s): 1 - 8

IEEE CONFERENCES

Multivariable adaptive control with hardware-in-the-loop for a drum-type boiler-turbine system

Iacob, M.; Andreescu, G.-D.; Antal, R.; Dan, A.-M.;
Control & Automation (MED), 2011 19th Mediterranean Conference on
Digital Object Identifier: 10.1109/MED.2011.5983118
Publication Year: 2011 , Page(s): 898 - 903
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IEEE CONFERENCES

Boiler-turbine simulator with real-time capability for dispatcher training using LabView

Iacob, M.; Andreescu, G.-D.; Muntean, N.;
Optimization of Electrical and Electronic Equipment (OPTIM), 2010 12th International Conference on
Digital Object Identifier: 10.1109/OPTIM.2010.5510509
Publication Year: 2010 , Page(s): 864 - 869

IEEE CONFERENCES

SCADA system for a central heating and power

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plant

Iacob, M.; Andreescu, G.-D.; Muntean, N.;
Applied Computational Intelligence and Informatics, 2009. SACI '09. 5th International Symposium on
Digital Object Identifier: 10.1109/SACI.2009.5136232
Publication Year: 2009 , Page(s): 159 - 164

IEEE CONFERENCES

SCADA automation system laboratory, elements and applications

Bejan, C.A.; Iacob, M.; Andreescu, G.-D.;
Intelligent Systems and Informatics, 2009. SISY '09. 7th International Symposium on
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Documents

Cristea, M., Groza, B., Iacob, M.
Some security issues in Scalance wireless industrial networks
(2011) *Proceedings of the 2011 6th International Conference on Availability, Reliability and Security, ARES 2011*, art. no. 6046006, pp. 493-498.

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Document Type: Conference Paper
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Iacob, M., Andreescu, G.-D.
Real-time hardware-in-the-loop test platform for thermal power plant control systems
(2011) *SISY 2011 - 9th International Symposium on Intelligent Systems and Informatics, Proceedings*, art. no. 6034378, pp. 495-500.

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Iacob, M., Andreescu, G.-D., Antal, R., Dan, A.-M.
Multivariable adaptive control with hardware-in-the-loop for a drum-type boiler-turbine system
(2011) *2011 19th Mediterranean Conference on Control and Automation, MED 2011*, art. no. 5983118, pp. 898-903. Cited 1 time.

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Iacob, M., Andreescu, G.-D.
Implementation of hardware-in-the-loop system for drum-boiler-turbine decoupled multivariable control
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Ordodi, V., Dumitrel, G.-A., Gruia, A., Iacob, M., Jinescu, G., Perju, D.
Electrochemical microinstallation for cytostatic wastes epuration
(2010) *Revista de Chimie*, 61 (9), pp. 857-861.

ISSN: 00347752
CODEN: RCBUA
Document Type: Article
Source: Scopus

Iacob, M., Andreescu, G.-D., Muntean, N.

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Boiler-turbine simulator with real-time capability for dispatcher training using LabView
(2010) *Proceedings of the International Conference on Optimisation of Electrical and Electronic Equipment, OPTIM*, art. no. 5510509, pp. 864-869.

ISSN: 18420133
ISBN: 9781424470198
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Bejan, C.A., Iacob, M., Andreescu, G.-D.
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(2009) *SISY 2009 - 7th International Symposium on Intelligent Systems and Informatics*, art. no. 5291169, pp. 181-186.

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Iacob, M., Andreescu, G.-D., Muntean, N.
SCADA system for a central heating and power plant
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Author(s): Iacob, Mihai; Andreescu, Gheorghe-Daniel; Muntean, Nicolae

Book Group Author(s): IEEE

Title: SCADA System for a Central Heating and Power Plant

Source: SACI: 2009 5TH INTERNATIONAL SYMPOSIUM ON APPLIED COMPUTATIONAL INTELLIGENCE AND INFORMATICS

Pages: 149-154

Published: 2009

Abstract: Modern process control systems are used in industrial automations for flexibility, modularity and reliability, employing state of the art technology based on three concepts: Distributed Control System (DCS), Programmable Logic Controller (PLC) and most importantly Supervisory Control and Data Acquisition (SCADA). This paper deals with design and implementation of a SCADA system for a central heating and power plant, which is planned to supervise and control field distributed electric devices using Siemens equipment and software "Process Control System 7" (PCS7). The system also allows web-based applications via OPC and web server by using the existing communication infrastructure. Redundancy is present at the server levels. The system is currently in use at COLTERM Central Heating and Power Plant South (CET South) of Timisoara.

Conference Title: 5th International Symposium on Applied Computational Intelligence and Informatics

Conference Date: MAY 28-29, 2009

Conference Location: Timisoara, ROMANIA

Times Cited in Web of Science: 0

Total Times Cited: 0

ISBN: 978-1-4244-4477-9

Book DOI:

Record 2 of 3

Author(s): Bejan, Cristina Anita; Iacob, Mihai; Andreescu, Gheorghe-Daniel

Book Group Author(s): IEEE

Title: SCADA Automation System Laboratory, Elements and Applications

Source: 2009 7TH INTERNATIONAL SYMPOSIUM ON INTELLIGENT SYSTEMS AND INFORMATICS

Pages: 161-166

Published: 2009

Abstract: This paper presents practical laboratories for teaching purpose in Supervisory Control and Data Acquisition (SCADA) systems. A SCADA system is described in terms of architecture, process interfaces, functionality, and application development facilities. These concepts are implemented on an integrated automation system, particularly for digital control of electric drives with distributed peripheral, i.e., Totally Integrated Automation with Democase from Siemens. Using this system, a wide range of applications can be designed, implemented and tested. A practical labs set are presented to introduce gradually the main SCADA elements, and finally to develop an application to control an induction motor in interlocked manual/automatic mode, with touch-screen Human Machine Interface (HMI). The system employs industrial busses like PROFIBus and industrial Ethernet. The SCADA system also shows trends, alarms, motor frequency and automatic sequence of motor speed profile.

Conference Title: 7th International Symposium on Intelligent Systems and Informatics

Conference Date: SEP 25-26, 2009

Conference Location: Subotica, SERBIA

Sponsor(s): IEEE

Times Cited in Web of Science: 0

Total Times Cited: 0

ISBN: 978-1-4244-5348-1

Book DOI:

Record 3 of 3

Author(s): Iacob, Mihai; Andreescu, Gheorghe-Daniel; Muntean, Nicolae

Book Group Author(s): Transilvania Univ Brasov, Fac Elect Engn & Comp Sci

Title: Boiler-Turbine Simulator with Real-Time Capability for Dispatcher Training Using LabView

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Source: OPTIM 2010: PROCEEDINGS OF THE 12TH INTERNATIONAL CONFERENCE ON OPTIMIZATION OF ELECTRICAL AND ELECTRONIC EQUIPMENT, PTS I-IV

Book Series Title: Proceedings of the International Conference on Optimization of Electrical and Electronic Equipment

Pages: 864-869

Published: 2010

Abstract: This paper presents an open loop dispatcher training simulator for boiler-turbine implemented in LabView for COLTERM heating power plant of Timisoara, Romania. The system employs real-time capability, graphical user interface (GUI), uninterrupted operator interaction, having as background a low order boiler-turbine model for dynamic simulation. The operator manually controls the fuel charge on each of the three boilers, the turbine valve position and the steam to consumers, to anticipate parameter evolution on each boiler and the electric power generated by turbine.

Conference Title: 12th International Conference on Optimization of Electrical and Electronic Equipment

Conference Date: MAY 20-21, 2010

Conference Location: Brasov, ROMANIA

Sponsor(s): IEEE, IAS; IEEE, PELS; IEEE, IES

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Process Management, Maintenance, Safety, and Reliability

Process Control and Automation Applications

Mihai Iacob
Horea, no. 116B, 330141 Deva (Romania)
+40755069787
mihai.iacob@aut.upt.ro; mikyblue00@yahoo.com

07.08.1984
Nationality: Romanian

LOOKING FOR A POST-DOCTORAL POSITION IN SYSTEM ENGINEERING AND AUTOMATIC CONTROL AND SIMULATION

RESEARCH INTEREST

- Simulations, modeling and control of industrial processes using Hardware-in-the-loop, Rapid control prototyping and Real-time principles
- Control and simulation of thermal power plants focused on boiler – turbine units
- PLC/SCADA/DCS systems using redundant/fail-safe controllers and communication
- Communication using OPC Servers for interaction of systems from different manufacturers
- Improving efficiency of industrial processes

WORK EXPERIENCE

Dates	01 September 2007 - 01 September 2008
Occupation or position held	PLC,DCS,SCADA Engineer
Main activities and responsibilities	Engineering and implementing SCADA/DCS/PLC systems Main activity was to implement a SCADA/DCS system for monitoring and command of a thermal power plant having as beneficiary Colterm C.E.T. South Timisoara
Name and address of employer	TECHNOCONCEPT SRL Blvd. Iuliu Maniu, no. 2B, Timisoara (Romania)
Type of business or sector	SCADA engineering/implementation
Dates	01 January 2011 – Present – Part time
Occupation or position held	PLC,DCS,SCADA Engineer
Main activities and responsibilities	Engineering and implementing a SCADA automation system. Main activity is to implement a SCADA system for monitoring and control of a drinking water treatment station for Aquaserv, in Targu Mures, Romania. Specific activity - integrating the

	Chlorination, Ozonation and Active Carbon Filters into the existing SCADA infrastructure under a redundant operating server concept with distant monitoring with a Web Server. Also reducing the response times of the existing HMI systems. Siemens software and hardware are used.
Name and address of employer	TECHNOCONCEPT SRL Blvd. Iuliu Maniu, no. 2B, Timisoara (Romania)
Type of business or sector	SCADA engineering / automation engineer

BUPT

EDUCATION

Dates	01 October 2008 - Present
Principal subjects / occupational skills covered	Ph.D Student in System Engineering
Name and type of organisation providing education and training	POLITEHNICA "University" of Timisoara (University) Blvd. Vasile Parvan, No. 2, 300223 Timisoara (Romania)
Dates	September 2003 - September 2008
Title of qualification awarded	Bachelor degree in automation and applied informatics
Principal subjects / occupational skills covered	System theory and automatic control, Automatic systems for process control, Modelling and Simulation, Programmable Logic Controllers; Programming languages: PLC specific languages, C, Java, Pascal.
Name and type of organisation providing education and training	POLITEHNICA "University" of Timisoara (University) Blvd. Vasile Parvan, No. 2, 300223 Timisoara (Romania)
Dates	December 2007
Title of qualification awarded	Cambridge Certificate of Advanced English - CAE
Principal subjects / occupational skills	English in use, Speaking, Writing, Reading, Listening
Name and type of organisation providing education and training	British Council Timisoara (Romania)

PROFESSIONAL SKILLS

BUPT

- Software packages for GUI development (SCADA) and PLC programming languages (scl, stl, lad, fbd, sfc, cfc) from different manufacturers (Siemens, Omron, Abb)
- SCADA/DCS/PLC systems on Siemens software (MicroWin, WinCC, Step7, PCS7 etc) and equipment (s7400,s7300,s7200)
- National Instruments equipment (PXIs & PCI systems) and software (Labview) for simulation, automatic control, data acquisition and programming under real-time, hardware-in-the-loop and rapid control prototyping concepts.
- OPC servers for communicating between automation equipment from different manufacturers
- Familiar with LabJack, Adam acquisition boards

WORKSHOPS AND TRAININGS

- 2007 – Present - Several trainings on Siemens : ''Totally Integrated Automation'', ''Microautomation'', ''Industrial Communication'', ''Process Control Systems'' etc ;
- Trainings on National Instruments : '' Labview Data Acquisition and Signal Conditioning 2009'', ''Machine Condition Monitoring - Seminar on Machine Vibration 2010''
- 2009 – 2010 Several National Instruments Webminars on Labview programming and toolkits (Control design and simulation, Realtime, Signal express etc)
- 24,25 September 2009 - Training in ''Scientific playwright''