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Principles of Smart Grids on the generation electrical and thermal energy and control of heat consumption within the District Heating Networks

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Abstract: One part of the process of development and application of methods and principles of Smart Grids in electricity and heat production is numerical modeling and simulation of Power and Heating Plants, Power Systems, and also District Heating Networks. Due to the venue of the IFAC Congress this paper deals with the comparison between Czech and South Africa. Similarity is given by the fact, that basic fuel is coal. In the Czech Republic, it is produced 64% of its electricity from coal, mostly lignite (brown), in the heat generation the coal has an even larger share of 90%. In South Africa, it is produced 85% of its electricity from coal (heat is insignificant due to climatic conditions). From this perspective, the Czech Republic and South Africa dealt with similar problems, e.g. using of coal mills, combustion chambers and equipment, whole powdered steam boilers and their optimal intelligent Smart Control. The power and heat source is controlled according to the Daily Consumption Diagrams, which are corrected by the current and predicted weather conditions (air temperature, solar irradiation, wind, rain and frost). For predicting consumption are used methods of classical and artificial intelligence control. Control of electricity and heat is carried out using advanced methods of optimal control, including the different configurations of machine room equipments and the Main Heat Exchangers Station - MHS The developed Information and Control System serves as an on-line support system for the operators and dispatchers and is part of the operating procedures in the implementation of Smart Grid.

Keywords: Smart Grids, Smart Control, District Heating Networks, Engineering Simulators, Operators Support System.

1. INTRODUCTION

Almost half of all energy generated in Europe is used for heating and cooling, and the benefits of optimizing these systems are overwhelmingly large. In a district heating system there is no operational information link between the energy company and customers (Balate, et.al., 2006). The whole system is purely demand driven in the sense that the production units can only react to the aggregated demand of the customers. However, the control systems in each consumer substation operates solely on very local parameters which typically leads to volatile demand profiles with peak loads during morning and evenings which is not desirable from either a technical, financial or an environmental point of view (Project InCoSysE, 2011).
Smart Heat Grid technology turns all this around by providing a platform for operational interaction between the energy company and their consumers. In a typical district heating system an energy company can only react to the heat demand without doing anything about it. On the other hand, in a Smart Heat Grid the energy company takes control of the heat demand. The reason that Smart Heat Grid technology works from a business perspective is that the energy company is generally interested in optimizing the operational behaviour in relation to the heat load (MW), while the building owners want to save energy (MWh). A Smart Heat Grid combines these two goals into an operational unity, and provils all actors with added benefits in relation to financial and environmental impact (Neuman, 2012b).

Effects designed and verified method of intelligent control in the Smart Grid Heating are following:

a. A combined heat and power (CHP) plant produces electrical power as well as heat for the DHS (Neuman, 2012a). In a CHP plant water is boiler to steam which is in turn overheated to about 500-600 °C. The steam is then used to run a turbine, which in turn is connected to a generator which converts the mechanical energy to electrical energy. When the steam has passed through the turbine its pressure and temperature is decreased in a condenser unit which absorbs the heat from the steam and transfers it to the water medium in the district heating system. The condensed water (previously steam) is then led back to the original boiler in which the process is repeated. In a normal power plant the heat is normally emitted as waste heat in the turbine/generator process.

b. By instead utilizing this heat a CHP plant is capable of achieving higher levels of energy efficiency in relation to the primary fuel (80-90%) than traditional power plants (30-50%), see (Project InCoSysE, 2011). CHP plants are common in many DHS and when building new production plants CHP is many times the preferred choice of production, since its efficient use of primary energy makes the system financially and environmentally sound.

Firstly, this paper will show a model of the coal mill, which was developed for realization of a simulation model for Operator Training Simulator (Neuman, et. al., 2004). The models of steam boiler and turbine are depicted in (Neuman, et. al., 2009). District heating units connection model was also developed, i.e., steam boiler - steam common pipeline - condensing turbines, turbines with controlled extraction steam pressure, and back pressure turbines, i.e., whole machine room – also see in (Neuman, et. al., 2009). In the case of heat generation it is technology equipment of machine room and the Main Heat Exchangers Station (MHS), related to the heat distribution system - District Heating Networks. Complex system serves as an on-line support system for the operator and (thermal) dispatcher (Neuman, 2011b).
Secondly, this paper will describe in detail the model and simulation experiments with on-line support system for control of central power and heating plant in company United Energy - Komorany for region District Heating Networks MO-CHO-LI (connecting towns: Most - Chomutov - Litvinov) in Northern Bohemia (Project InCoSysE, 2011).

2. CONTROL OF DISTRICT HEATING NETWORKS

The object of complex project is Hierarchical Intelligent Control System of Municipal District Heating Networks (Project InCoSysE, 2011). The district heating supply system (DHSS) is mostly very large and complex system and its behavior and characteristic depends on many various and parameters. Many of them are unfortunately very strong stochastic, some are known with little or bigger uncertainty and all this brings many problems to control for such system. Mostly we should use some non-classic control methods, which can be included in class of intelligent control methods. Their main characteristics are:

- The ability adapt control algorithm to the state of controlled system and its relevant environment
- The ability change control goals depend on conditions for controlled system operation
- The ability use and handle uncertain and/or uncompleted input data
- The ability to predict some important data and parameters (Balate, et. al., 2006).

Main idea is prepare model of whole district heating supply system (all its parts) as a simulation model. With use this simulation model is then possible simulate different control strategies used in given and predicated state of controlled system. The simulation and its analysis it is possible to make continual and faster as are the control interventions – it is with today computers (they have enough performance) and in process of heat transfer (it is mostly not so fast – there is a big "inertia" against changes) realistic. From the analysis results is possible derive corresponded control operations (or, at least, recommend they to the control personal).

The control strategy is based on predictiction of the outside temperature and consumer' heat energy (Balate, et. al., 2009).

As consumers' demands are predicted, the open loop control could be directly applied to the district heating network. The difficulty is enhanced by the fact that time delays can´t be neglected in the distribution network. In this paper a model of district heating network is defined for optimization and control purposes. This model is versatile and could be used to model many kinds of heating network. The new control strategy could be applied to various kinds of district heating network (multi supply points, cogeneration or heat-only networks, multi logoped network). This is a general idea of "Smart Grids application to Municipal District Heating Networks".

3. SMART GRID OF COMPLEX DISTRICT HEATING SUPPLY SYSTEM

In the beginning it is necessary to explain the process of project implementation Heat Smart Grid that this post was not entirely clear and debatably. The goal of project was the development intelligent control of district heating systems (DH).

A common District Heating System can be divided into several blocks (Vasek, et. al, 2014):

a. Production
b. The primary circuit (Transmission),
c. The secondary circuit (Distribution)

The basic elements of the district heating is production block, i.e. central cogeneration heat and electricity. This is a classic supply-burning brown coal, including coal bunkers, **coal mills**, combustion chamber, heat exchangers flue gas / steam, steam common bus, condensing steam turbines - condensing steam turbines with controlled extraction steam - a back-pressure turbines - see diagram in Figures 10 and 11.

Other parts of "Production block" are gradually machine room with regeneration, the main heat exchange station (MHS) containing basic heaters (ZO) and top heaters (SO). Next blocks of District Heating System is „Transmission part" (the primary circuit) and "Distributin part" (the secondary circuit), which is connected with a heat consumption part (individual consumers, houses, industry) via heat exchange stations (HS).

Every part has own basic control system, which perform basic functions of appropriate part of whole system. Over these is proposed Smart Grid, which co-ordinate control of whole system and try find the optimal control with use of information about state of controlled system and its relevant environment. The configuration of our Intelligent / Smart Grid Control of DHSS is in Fig.1. (Neuman, et. al., 2012b).

Intelligent control of district heating system works based on the prediction of heat consumption, which depends on the behavior of individual consumers (called agents), the weather conditions (outdoor air temperature, sunshine, wind). The requirement for heat production consistent with the prediction heat consumption is sent to a central support system of thermal dispatcher, which on the base of variants simulations "advise" to the dispatcher what configuration of the steam turbines and heat exchangers will be requested amount of heat in the required time available for consumption (Vasek, et. al., 2014).

4. ENGINEERING SIMULATOR CONFIGURATION

Intelligent control of district heating system was developed using existing elements, such as a realistic model of the central energy source (coal steam boiler, machine room), which was developed previously for Operator Training Simulator.

Engineering Simulator is created from modules of own NEUREG library called "EnergySIM". This library could be used for modelling of all types of power plants (Conventional Power Plants, Combined Cycle Power Plants, etc.) based on following modules: Drum Boilers, Steam Turbines, Superheaters, Reheaters, Once-Through Boilers, Fluidized Bed Boilers, Gas Turbines. The "distributed control system" is also emulated in MATLAB-SIMULINK (Neuman et al 2002). The layout of it is in Fig.2.

5. MODELING OF SUBSYSTEMS

The base information for creating structure of an Engineering Simulator represents by Process Instrumentation Diagram (P&ID). It is demonstrated on an example of a Coal Feeders & Mills subsystem (Neuman, et. al., 2011a). This subsystem is depicted in Fig.6. Other subsystems modelled by the same way are following: Feeding Water, Air Supply Loop, Flue Gas Loop, Super Heaters, Common Steam Collector, Steam Turbines & Generators.

In the P&ID are depicted all the objects which are either manipulated by control or were some measurement is performed. This specific requirement invokes a need to have technology object-oriented models of all such elements, which are depicted in the P&ID (Neuman, et al., 2003).

5.1 Coal Feeders & Mills subsystem

In the coal mills and feeders technological scheme, which is depicted in Fig.5, such process elements are mentioned in the following description of its function.

V1 Total air control valve
V2 Primary air control valve
V3 Secondary air control valve
V4 Core air control valve
V5 Cold air control valve
PA Primary air
SA Secondary air
CA Core air

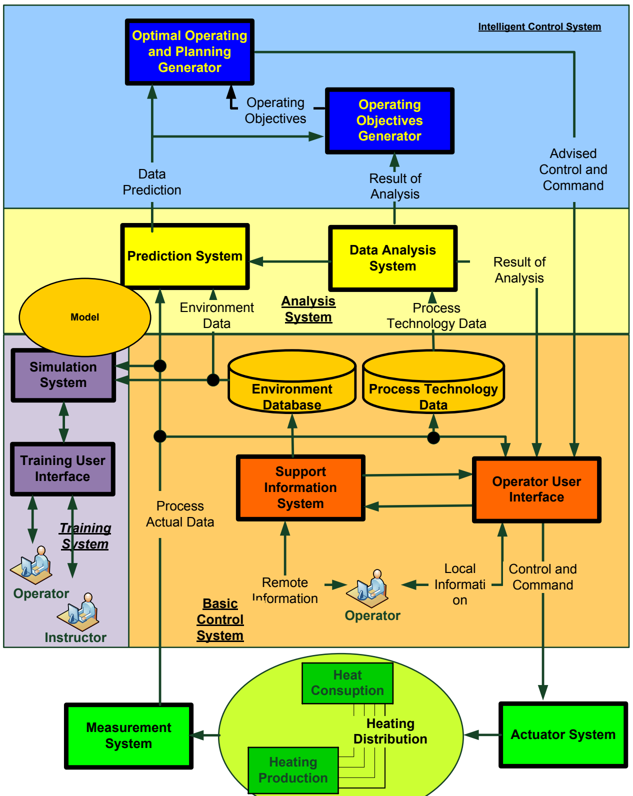

Fig.1. The scheme of Smart Grid of district heating supply system with its control and training systems

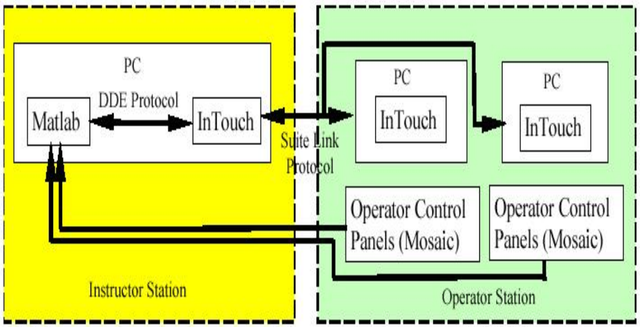

Fig.2. Layout of Engineering/Training Simulator

Mathematical description of the mill are following:
The basic coal accumulation equation in the mill is

$$\frac{dG}{dt} = M_E - M_A \qquad (1)$$

The pulverised coal delivery from the mill suits the formula

$$M_A = K_M\, Q_V^{1,2} \sqrt{G} \qquad (2)$$

The mill motor power demand one can characterize by

$$N_M = N_{MO} + b.G^2 \qquad (3)$$

The primary air flow rate equation used is

$$Q_V = \Delta P_C / R_C \qquad (4)$$

The total aerodynamic resistance in the primary air duct is

$$R_C = R_M + R_K \qquad (5)$$

where for the resistance of the mill is

$$R_M = R_{MO} + K_R.G \qquad (6)$$

and for the resistance of the primary air flow control valve is

$$R_K = 1/(K_V.\alpha) \qquad (7)$$

After linearization, for a given position α of the primary air flow control valve to which corresponds the resistance $R_K = 1/(\alpha.K_V)$ on obtain on the limit of stability the pulverized coal delivery from the mill

$$M_{A,MAX} = 0{,}442.K_M.\Delta P_C^{6/5}.(R_K + R_{MO})^{-0.7}.K_R^{-0.5} \qquad (8)$$

the primary air flow rate

$$Q_V^L = 0{,}583333.\Delta P_C / (R_K + R_{MO}) \qquad (9)$$

and the mass of coal accumulated in the mill

$$G^L = (R_K + R_{MO})/(1{,}4K_R) \qquad (10)$$

The curve H in the Q_V,G diagram on Fig.6 gives the boundary of the area of stabil working conditions of the mill.

The pulverised coal delivery from the mill suits the formula (Neuman, et. al, 2004). The following Figures 3. and 4., show the courses of the amount of primary air (PA) and motor current mill of the MO31, when the second mill shutdown MO33.
In both figures the axis are the same, x ... time <from 200 to 1600 [sec]>, change is made at the time of 600 sec.

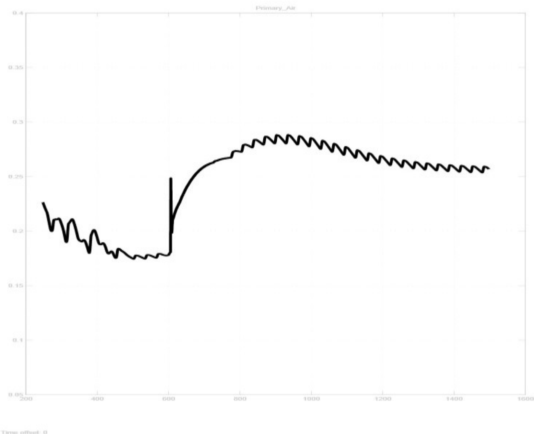

Fig.3. Primary Air (PA – Fig.5),
y axis is the amount of air <from 0.05 to 0.4 [m^2 /sec]>,
the measured value y < 0.17 to 0.3 [m^2 /sec]>

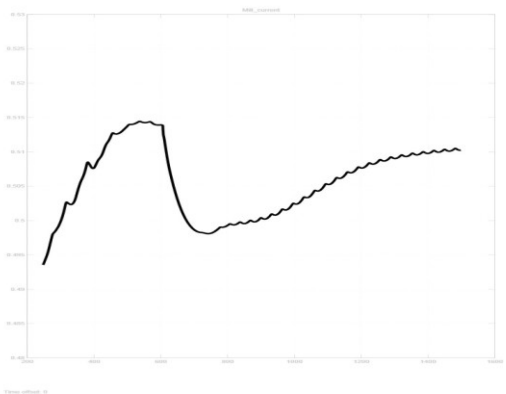

Fig.4. Current of the electric motor of the Mill,
y axis is the amount of air <from 0.48 to 0.53 [m^2 /sec]>,
the measured value y < 0.494 to 0.515 [m^2 /sec]>

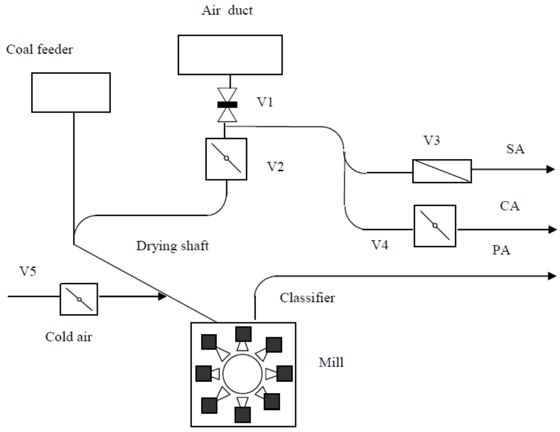

Fig.5. The coal mill and the adjacent equipment

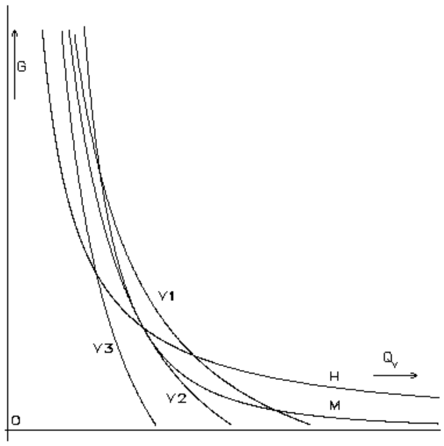

Fig.6. The characteristics of the coal mill

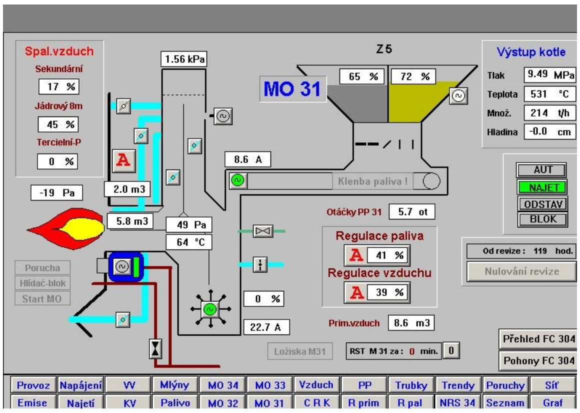

Fig.7. SCADA mimics of Coal Mills & Feeder

6. EMULATION OF BASIC LEVEL CONTROL

The project described in this paper did not include the optimization of the operation of mills and coal-fired steam boiler, and optimization of coal combustion. Therefore, the level of basic control system remained the same as the real operating system, including individual PID controllers and their parameter settings.

All the PID controlers are realized by Z-tranformation of the continuous PID controller. Equation for the continuous PID is following:

$$u(t) = r_0 e(t) + r_0 T_D \frac{de(t)}{dt} + \frac{r_0}{T_I} \int de(\tau) d\tau \quad (11)$$

is tranformed by trapezoidic method into discrete version of controller (with sampling period T):

$$u = q_2 z^{-2} + q_1 z^{-1} + q_0 \quad (12)$$

The Human Machine Interface (HMI) is realized in standard SCADA InTouch and the real descs and panels MOZAIC, which are connected through the PCI slots and I/O cards. The communication between MATLAB-SIMULINK and InTouch is based on standard DDE or OPC protocol.

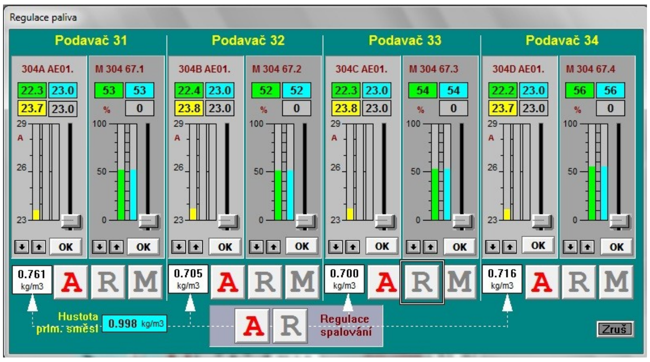

Fig.8. SCADA mimics of Air Control of the Coal Mills

7. CONTROL OF DISTRICT HEATING NETWORK

The interesting closed loop control is proposed in this chapter, concerning district heating network with one production power plant. The heat losses in pipes are considered (they increase with the supply temperature). The results show that the optima management for this kind of network is not necessary to keep the supply temperature as low as possible (Sandou, et. al, 2005), under the restriction that consumers' constraints are fulfilled.

A new control strategy is defined, which aims to be applicable for a large kind of networks and to be robust toward load prediction errors and model uncertainties. The control strategy is based on the algorithm of qualitative-quantitative method of output control of hot piping (Balate, et. al., 2006). The control strategy is based on predictiction of the outside temperature and consumer' heat energy. As consumers' demands are predicted, the open loop control could be directly applied to the district heating network. The difficulty is enhanced by the fact that time delays can not be neglected in the distribution network. In this paper a model of district heating network is defined for optimization and control purposes. This model is versatile and could be used to model many kinds of heating network. The new control strategy could be applied to various kinds of district heating network (multi supply points, cogeneration or heat-only networks, multi logoped network).

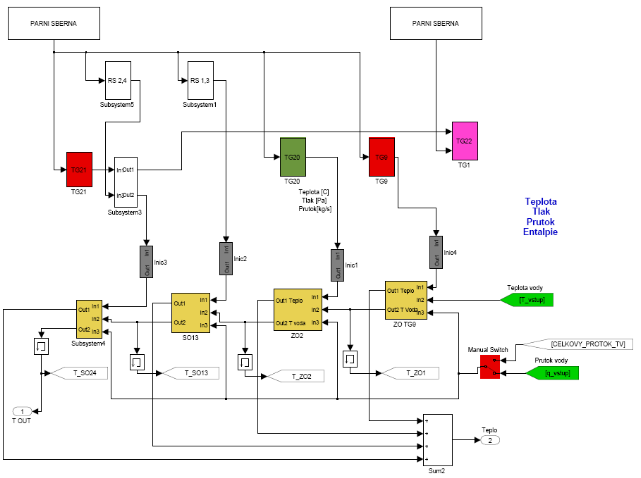

Fig.9. Scheme of MHS (ZO, SO)

Legend: green blocks from left to right - TG21, TG20, TG9; purple block - TG22;
yellow blocks: heaters SO24, SO13, ZO2, ZO1

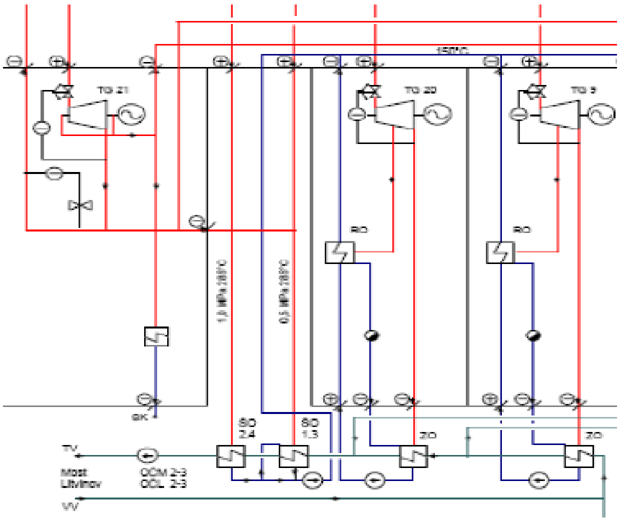

Fig.10. Relevant part of the technology scheme of central energy source

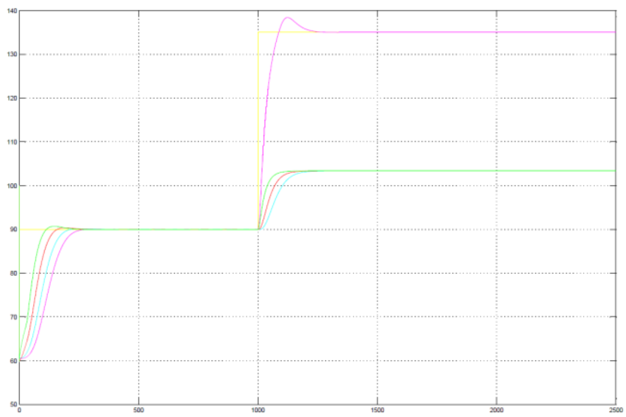

Fig.11. Trends of temperatures in the MHS

Legend: Green line - water temperature for ZO1, red line - the water temperature for ZO2, yellow line - output setpoint temperature, blue line - water temperature for SO1-3, Violet line - water temperature for SO2-4 - outlet temperature

Clarification of these simulated temperature changes are as follows:
- Only the first base heater ZO1 is used for heating of heat water from 60° C to 90° C. This means that the outlet temperature of ZO1 is 90° C. Due to its non-feed the outlet temperature of ZO2 is equal to the input temperature, but this is the output temperature of heater ZO1. So the output temperature of the heater ZO2 is also 90°C. At the outlet of SO1-3 is also 90°C, and at the outlet of SO2-4 is also 90°C.
- From economic reasons (the criterion of maximum efficiency) for heating the heat water to a temperature of 130°C is used two heaters, basic ZO1 and peaking SO2-4. At the output of ZO1 is about 104°C. This temperature passes without changing through the heater ZO2 and SO1-3. The heat water is heated to the required 130°C in heater SO2-4.

7.1 The principle of control method

The newly designed control "optimization", based on the heat that must be supplied for total water heating. So if we add as 100MW (done from the calculation of the difference between the reference and input value), then from the simulation tests we know that the best performance for the delivery of 100MW has a separate heater ZO1. The way of control lies in the fact that we control the heater ZO1 on the set point and the remaining heaters are not heated. As an example, heating 230MW is best to use a combination of ZO1 and SO2-4. It means that heater ZO1is heated to 100%, and the heater SO2-4 is controlled on the set point.

The principle of optimal control is based on the characteristics of individual heaters that have the highest efficiency at maximum power heating. The control thus seeks to ensure delivered such heat, which is needed at the maximum power heating.

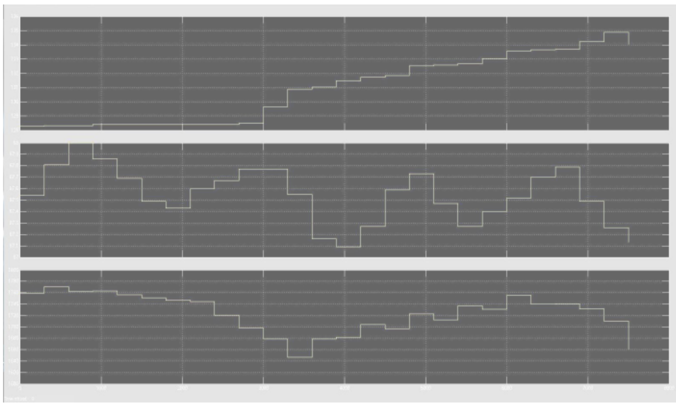

Fig.12. Overview of input values read from ORACLE

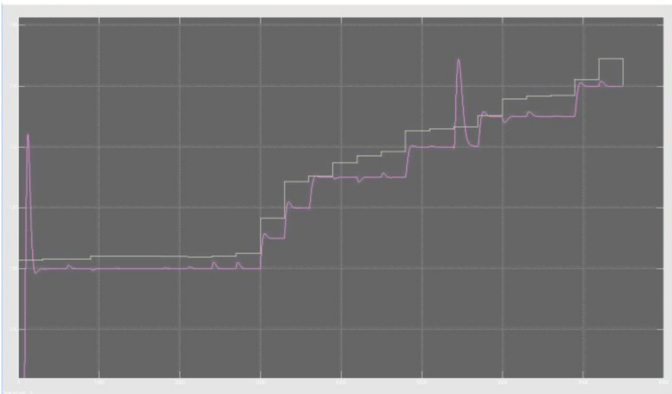

Fig.13. Comparison of the calculated and desired values of output circulating water temperature T_V

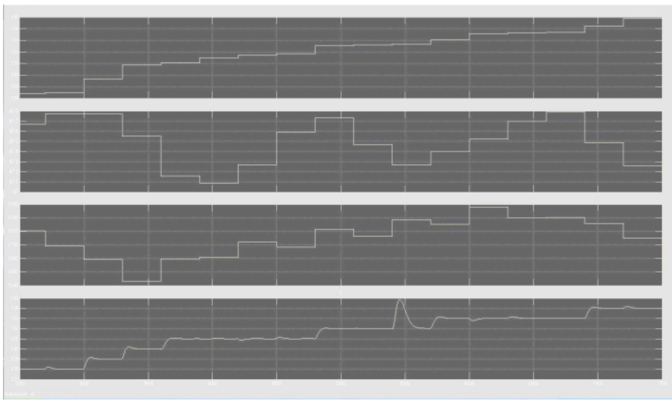

Fig.14. Overview of input values read from ORACLE and output values: order from the top: desired temperature T_Z, return temperature T_{VV}, circulating water flow rate M, the output water temperature T_V

By simulations were detected maximum heat supplied from individual heaters (SO1-3 = about 45MW, ZO2 = about 60MW, ZO1 = about 110MW, SO2-4 = about 145 MW) at the outlet, so after taking into account their efficiency. Knowing the temperature difference between the inlet water and set point of it and also the flow rate, so we know how amount of heat we could deliver. Furthermore, we know that the higher efficiency of the delivery of the same heat one heater as opposed to two heaters (Project InCoSysE, 2011).

So 100MW of heat we supply to the heater ZO1 and not to SO2-4 (which have lower efficiency for the same heat) or to ZO2 and SO1-3 (a combination of the two heaters is also less efficient). Detailed deviations from the set point is solved by PID controller, which controls the selected heater directly to the output value. It is therefore possible to use only one PID controller, but since each heater has a different characteristics, it is preferable for optimizing the settings of controllers to use one PID controller for each heater.

8. CONCLUSIONS

This paper presents a framework for implementing basic Smart Heat Grids technology in a District Heating Network (Neuman, et. al., 2009). The DH system is evaluated through simulation experimentation based on operational constraints from an industrial installation. The parametrization and verification of model´s features were performed only with participating of the most experienced operators, therefore the fidelity is very high.

Smart Heat Grids are becoming an important element of modern ways in district heating systems, but at the same time, there are numbers of existing heating plants with combined production which are able to produce huge amounts of heat or with higher energy efficiency. This paper wanted to point out the suitability of the combination of modern trends with existing ones and show that the interconnection can be beneficial for both systems.

Simulation results show that the deployment of intelligent control system can be achieved by optimizing operating parameters (as in version "on-line" support system, as well as "in-line" direct real-time control). Achieving an optimal level of control is a far better meet the requirements for the production and consumption of heat, while achieving better energy efficiency and reduce fuel consumption.

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