Smith Predictor for Control of the Temperature Process with Long Dead Time

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Abstract: The analysis of a problem of development of control systems for objects with big time delay is carried out in this work. For such objects it is difficult to provide high-quality control, because the control is carried on the last status of object's output. The main setup methods of PID regulators have been examined. Based on this analysis the technique of complete synthesis of the regulator of higher level is given in order to regulate building's heating system. This work offers a new method of object's control with distributed delay. As the test bed for the offered structure of control the valve of hot water supply in a heat-node is used. Using the test bed the stability of the system with time delay have been studied, which is controlled by the PID regulator assisted by Smith Predictor used to compensate the dead time.

1 INTRODUCTION

Energy saving in the field of building's heating is important task, considering both the criteria of market capacity and the aspect of status of engineering systems. In the European Union, buildings are responsible for 40% of total energy consumption including approximately 20% absorbed in heating which can be effectively used in the demand side management (DSM) strategy as a shift able load.

Energy saving in heating systems from control point of view is characterized by the need of stable maintenance of air temperature for building's premises at adjusted comfort level in the presence of external perturbations affecting the building. Today, considering the development of automation equipment and large-scale implementation of individual thermal points, implementation of more effective heat controlling algorithms became possible (Altmann et al., 2005). Thermo-hydraulic processes in the building have big momentum; have non-linear or variable linear dynamic behaviour and distributed nature, subjected to vast number of the influencing factors, which direct measurements are extremely difficult in practice.

The management with prediction models in microclimate control algorithm allows increasing the effectiveness of HVAC system in buildings. There is a problem of the correct setup of the heating equipment as excessive increase in temperature on the heating element leads to overheating of rooms, which results in excessive consumption of thermal resource and decreased comfort level. At the same time it is necessary to consider that the greatest saving of thermal energy in heating systems of buildings is reached by using intellectual automation. It is explained by the fact that automatic control allows to save heat due to accounting of those factors, which can't be considered by calculation methods, such as:

- influence of solar radiation;
- accounting of fluctuations in outside air temperature;
- heat release from people and equipment;
- chaotic operating time of ventilation.

Thus, the development of intellectual management systems for heating systems is a relevant task. The adjustment method based on prediction is offered in this work.

Predictive control is not a single strategy, but a set of control methods with predictive model of the process expressed in specific order to obtain a

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control signal by minimizing objective’s function subjection to some constraints. In building’s control, one would aim to optimize delivered energy subjecting to constraints. One of advantage of this method is Smith Predictor time delay is effective taken outside the control loop in the transfer function relating the process output to setpoint. This method introduces extreme instability into the variable control system (Bogdanovs et al., 2018).

Smith Predictor control is a good decision to the problem of controlling the time delay systems. It approach improves the performance and reliability of the system in the real time applications. The Smith Predictor is a popular and effective long compensator for stable processes. One of advantage of this method is Smith Predictor time delay is effective taken outside the control loop in the transfer function relating the process output to setpoint. This method introduces extreme instability into the variable control system.

1.1 Related Works

The paper (Basnayake et al., 2015) in his work offers to replace PLC controllers of building’s automatics with new controllers designed based on artificial intelligence. These controllers use intellectual identification of users.

Work describes smart home systems that decrease energy consumption by studying human behavior pattern (Badlani and Bhanot, 2011).

Author proposed in paper simulation methods for the temperature control systems. Work results shown success usability of test model to use this regulation method in PLC controller for temperature control in buildings (Roengruen et al., 2009).

Book author describes regulation principles of process control and regulation methods in variable processes in building heating systems. This book discusses different approaches for regulation loops. It also shows the applying of Smith Predictor model in process control (King, 2010).

Author mentions the disadvantages of the applying the classical PID controller regulation and tuning. The paper shows examples how to improve system regulation with Smith Predictor. This control method allows avoids decreasing of regulator gain factor as result the system regulation performance increases (Srinivas et al., 2010).

This work describes in the article compares the use of the Smith predictor control model with the PID regulator and the Model predictive control. The proposed comparison allows a better understanding of the use of models for the application of control characteristics in industrial equipment. (Vidyamol and Nasar, 2015).

Despite the large number of valuable research work describing different types of management, there is no management system, which could increase the effectiveness in existing buildings by using predictions. Control algorithms are developed for such research, described below, based on Smith's predictor, which are designed and used in building management system.

2 FORMULATION OF THE PROBLEM

In automation of heating, ventilation and air conditioning (HVAC) systems the PID regulators are used everywhere. They allow regulating motorized air dampers and hydraulic valves, frequency converters of pumps, fans and compressors are regulated. The problem of controlling inlet air temperature by direct-flow air handling unit (AHU) with water heater is considered in this publication. In cases when such AHU is equipped with simple ON/OFF ventilator without frequency converter or EC-regulator fan, the maintenance of stable set inlet air temperature is carried out by motorized valve through PID regulator (Prabhakara Rao and Voleti, 2011). Described AHU are found on outdated HVAC systems and also in specialized systems of production, professional kitchens, etc.

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In the commonly, used shunt group scheme circulation pump is operating constantly, ensuring freeze protection and a steady water temperature regulation with control valve, see in Figure 1.

Where:

1 – Shut off valve; 2 – Strainer; 3 – Three-way valve with actuator; 4 – Circulation Pump; 5,6 - Check valves; 7 – Thermometer; 8 – Manometer; 9 - Water/Air Heat exchanger; 10,13 – Balancing valves.

By launching such system, in order not to over cool inlet air, the triple running valve is usually completely opened, providing the maximum flow of heat carrier g and respectively the heat power Q.

The problem is that inlet air temperature undergoes strong fluctuations while the PID regulator finds the necessary valve position for heating the air from outside temperature to the one that is set. It negatively reflects on thermal comfort of people indoors and also it can influence technological processes.

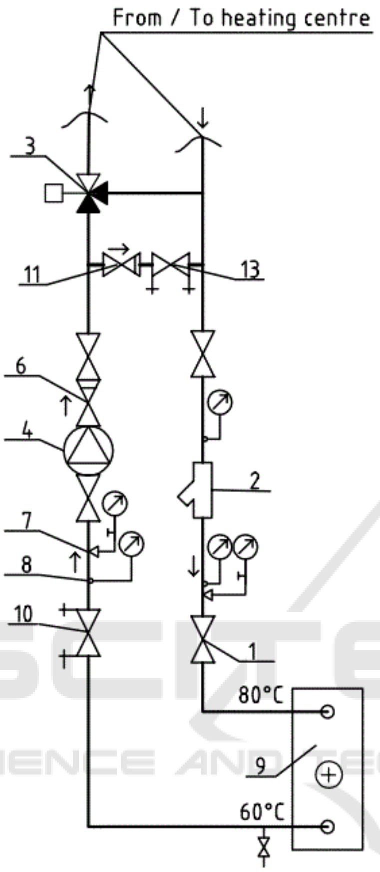

Figure 1: A typical AHU shunt group hydraulic scheme.

Heating energy transferred to the airflow by heating coil can be calculated using formula:

$$Q = g \times p \times c_{cw}(T_{in} - T_{out}) \quad (1)$$

Where:
Q - heating output, kW,
g - heating fluid flow, m3/s,
ρ - heating fluid density, kg/m3,
c_{cw} - heating fluid specifies heat, kJ/(kg*°C),
T_{in}, T_{out} - supply and return flow temperatures, °C.

In three-position regulators the actuator can hold three positions: completely open, normal (average) or completely closed [7.8].

The value of hysteresis H affects the accuracy temperature adjustment. Reduction the value of hysteresis zone not only increases the accuracy of adjustment, but also the frequency of opening the valve that leads to a fast wear of commutation elements.

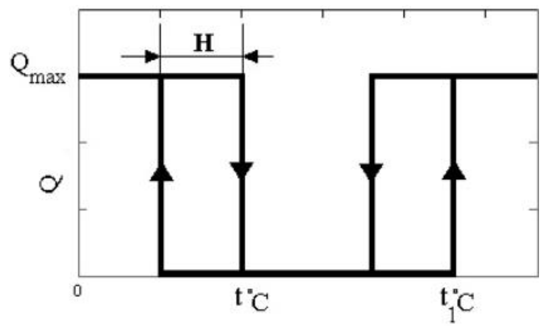

Figure 2: Characteristics of three-position regulator.

3 ENHANCED SMITH PREDICTOR FOR HEATING CONTROL

Buildings' modern heat-nodes regulating heat consuming by the use of valves and pumps which regulate heat supply to the building in compliance with a desirable temperature for locations. According to the temperature diagram and weather conditions further regulation of the consumed thermal energy takes place, thus, providing comfortable conditions taking into account the temperature of outside air. Microprocessor controller serves as a central device, which controls operation of valves and pumps. It allows regulating heat carrier's temperature according to temperature of outside air; to automatically reduce temperature and to control circulation pumps (Tala and Daxini, 2015). Heat carrier's temperature control is carried out by means of the PID regulator. Using PID control for Building Management System (BMS) is not effective method to control the heating system. Thus, a considerable change in set point occurs. Integral terms cause an overshooting error during the rise.

Since heat-node's temperature regulation is carried out by means of PID regulator according to temperature of outside air (especially in case of sharp temperature drop), systems form the delay of automatic control. As each link of the heat-node has its own response time bringing the negative phase displacement, it is capable to result in loss of stability in regulatory system (García and Albertos, 2013; Shi et al., 2008). It is necessary to apply the ratio between delay value and the object's time constant, described by the following ratio:

$$\frac{\tau}{\tau + T} > (0,2...0,5) \qquad (2)$$

T - object's time constant.

Where τ - heating valve delays, depend on weather and thermo hydraulic processes in the building.

Time of transport delay is calculated by formula:

$$\tau = \varepsilon\left(\frac{L}{\upsilon}\right) \qquad (3)$$

L - the distance from the sensor to the executing mechanism, m.

υ - movement speed of the substance m/s.

To determine dynamic characteristic ε of c the control object it is necessary to reveal the regularity in practice as it was done in this work, see Figure 3:

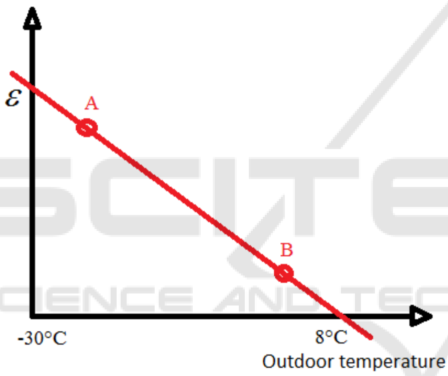

Figure 3: Dynamic characteristics of time delay of outside temperature.

The dynamic characteristic ε was determined experimentally. The best coefficient was defined at the temperature of 8 in point A and -23 in point B. A linear dependence was obtained after this. The linear dependence for each heating system is separate and it needs to be defined experimentally

The purpose of Smith's predictor – to foretell the signal strength at the object exit before it actually appears there. Due to this prediction the delay factor is excluded from the model, which allows predicting the behaviour of an object before the moment when signal appears at the exit.

Further, to make a prediction, it is necessary to use the model of object's control that consists of fractional rational part M_0 and delay $e^{-s\tau}$. Here, the R – common PID regulator, $P_0 e^{-s\tau}$ – additional characteristic of the control objects (see Figure 4).

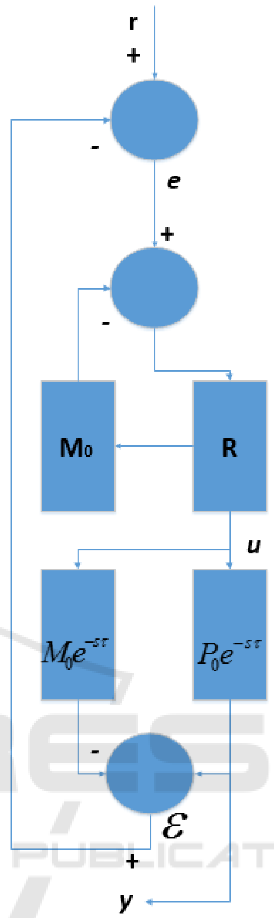

Figure 4: Control system with Smith's predictor.

We will assume that the model is absolutely exact. Then the difference between signals on model's outputs and the object will be equal to zero (ε = 0) (Hao et al., 2011). But in that case, directly from the diagram of Figure 4, it is possible to obtain:

$$y = P_0 e^{-s\tau}\left(\frac{R}{1+RM_0}\right) r = \left(\frac{P_0 R}{1+RP_0} e^{-s\tau}\right) \qquad (4)$$

In this expression the member $\left(\frac{P_0 R}{1+RP_0}\right)$ represents a transfer function of a system without delay. And it means that the link with the time delay is not included in the circuit of feedback and doesn't affect the stability and high-speed performance of the system, which means that there is adjustment in the circuit with the model without delay, and the transport delay is added to receive result (Kato et al., 2005). Due to this prediction the delay value is excluded from the model, which allows predicting of object's behaviour until the signal appears at the outlet.

Smith's predictor imitates a difference between the process model with no sensitivity zone and a real object. This adjusting signal is added to the measured output signal to foretell what signal would be at the exit if there were no delay (Dulău et al., 2010; Zhang, 2013).

The transfer function in (4) models the way a change in the voltage (0-10Volt) driving the water valve opening affects the heater temperature.

3.1 Practical Implementation of the Enhanced Smith Predictor for Heating Control

Simulations of the regulator in simulators based on Smith Predictor is labour-consuming, as the dynamic characteristics of ε is stochastic and separate for each building's heater and it is also hardly predictable. Simulation and laboratory conditions can differ highly, therefore, we have to try this adjustment method in practice and a real object was used for this, PLC (programmable logic controller) controller is shown in Figure 5.

The predicted value τ goes to Q(c), controller, which adjusts the controlling influence of AO (Analog Output).

This heater of the ventilation system is controlled with PLC controller in which software is written to control the valve of water heater.

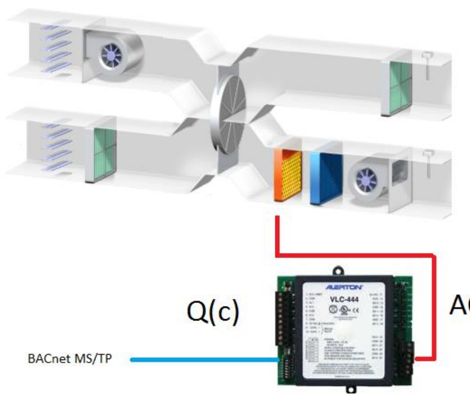

Figure 5: PLC Controller for AHU heater.

The controller by means of BACnet protocol is connected to the server where archiving of data and monitoring of the system is carried out. The water heater valve is a one analog output system.

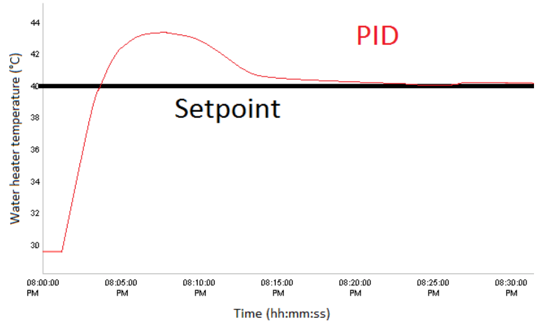

Figure 6: Experimental results for valve heating control with PID for outdoor temperature -5°C.

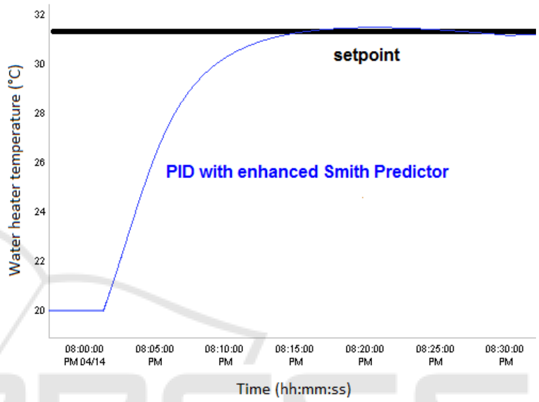

Figure 7: Experimental results for valve heating control with enhanced Smith Predictor for outdoor temperature -2°C.

The Figure 6 shows that by using standard PID regulator the precise adjustment of the heating valve is not reached and based on this a new method of adjustment system with great delay was studied. The Figure 7 shows the experimental (with outdoor temperature from 8°C to -25°C) result, received with Smith's predictor.

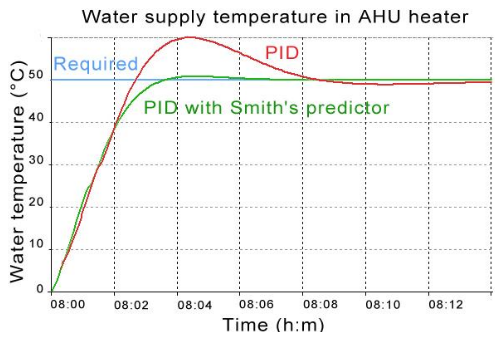

Figure 8: Results for valve heating control with outdoor temperature -8°C from PID regulator and PID with Smith's predictor.

The Figure 8 shows the experimental (with outdoor temperature -8°C) result, received with Smith's predictor. The structure of this predictor is also given in this Figure 4.

From Table 1 it can be said that PID with Smith Predictor gives better transient response characteristics than PID controller for process with constant time delay.

Table 1: Comparison of responses.

Model	Characteristics			
	Max. Peak (%)	Rise time(s)	Peak time(s)	Settling time(s)
PID	25	420	480	840
PID Smith's predictor	2	118	32	360

4 CONCLUSIONS

The article shows that for objects with a big value of transport delay it is suggested to use Smith Predictor. When compared to the usual PID, the Smith Predictor more improves the system's response to set-point changes.

Finally the experimental result of the heating control with both traditional PID regulator and PID with Smith predictor are built in PLC microcontroller. By comparison with traditional PID regulator, the experimental results demonstrate the effectiveness of the proposed methods towards the heating valve delays and system uncertainties integrated in the building heating control system (see Table 1). A consistency of Smith predictor control signals of all possible time delays can be generated in advance and the actual delays will be compensated. This control method is mathematically simple implemented in PLC microcontroller with reduce resources.

The temperature control system based on the Smith Predictor controller can precisely control the temperature inside the instrument. Therefore, it is able to provide the best temperature for enzymatic detection to ensure the accuracy of results. Should the system under control be an integral process, complementary outside temperature should also be incorporated into the control system.

In future work is planned to address all above-mentioned problems within the framework of research by providing following solutions:

Matlab machine learning toolbox could solve the problem of optimizing the Building Management System algorithm by analyzing weather forecast for the next day and sing Finite Difference Method in self-learning model. The automation of the home or the building has a great potential in reducing the cost and energy consumption using, machine learning for intelligent control.

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