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Adaptive DMC controller based on cloud computing

Abstract. *The adaptive DMC controller implemented in cloud adjust its parameters depending on the measured operating conditions. The control value determined by the controller is sent to the PLC. The regulation quality of the adaptive DMC controller is going to be verified on a fragment of the heat distribution system available in the laboratory located in the Department of Automation and Robotics.*

Streszczenie*. Adaptacyjny regulator DMC zaimplementowany w chmurze każdorazowo dopasowuje wartości nastaw w zależności od mierzonych warunków pracy. Wartość sterowania wyznaczona przez regulator jest przesyłana do sterownika PLC. Jakość regulacji adaptacyjnego regulatora DMC będzie sprawdzana przy pomocy fragmentu instalacji dystrybucji ciepłą dostępnej w laboratorium Katedry Automatyki i Robotyki. (****Adaptacyjny regulator DMC wykorzystujący rozwiązania chmurowe****).*

Keywords: adaptive DMC controller, cloud computing, PLC, control.
Słowa kluczowe: adaptacyjny regulator DMC, chmury obliczeniowe, PLC, regulacja

Introduction

Since the invention of Internet in the late 80s of the 20th century there were many attempts to integrate “Things” with network. Such case was presented for the first time in 1990, where John Romkey has adapted a toaster to work with the Internet [1]. Then in 1997 Paul Saffo presented the first description of sensors and how they could be used when connected to the Internet. Due to the increasing use of the sensors and other information-providing devices via the Internet in 1999, the term Internet of Things was used for the first time by Kevin Ashton [2]. The development of the field progressed over the following years, introducing more and more advanced technologies.

The development of the Internet of Things (IoT) had a huge impact on the industrial sector, creating a separate branch called the Industrial Internet of Things (IIoT). Initially, most of the technologies commonly used in industry were based on ad hoc solutions. Thanks to the Internet of Things, it was possible to implement more cost-effective solutions with greater adaptability. This made it possible to easily combine the fields of operational and information technology, reducing operational costs and increasing the importance of communication between machines.

The Internet of Things is closely related to Industry 4.0, being one of its pillars [3][4]. The same situation applies to cloud computing. The use of cloud computing provides fast systems for processing, analysing and storing large sets of data generated by the Industrial Internet of Things. Additionally, cloud technologies offer large computing, network and mass storage resources.

Cloud computing can be a good solution for small, medium-sized enterprises providing a lot of benefits in technological, organizational and environmental aspects [5]. The benefits are also creating more and more promising startups [6]. There are available articles describing the use of cloud computing on a small scale, such as smart homes [7][8] or optimization problems [9]. This does not mean that there are no attempts to implement cloud computing in larger-scale projects. In [10] the authors used cloud computing when creating Smart Power Utilization Service System to collect, store, analyse and process huge amounts of information about energy consumption. Cloud technologies are also used in the Oil & Gas industry sector for demanding tasks such as seismic processing and modelling of fossil deposits for exploration purposes [11].

The rapid development of technology poses new challenges related to meeting energy needs. The use of coal, oil and natural gas in electricity can easily satisfy the consumption demands. However, the negative effect of using fossil fuels is the increase in Greenhouse gas (GHG) emissions. This term is used to describe gases that retain in the atmosphere e.g. carbon dioxide methane. To reduce the amount of gases emitted, countries are trying to increase the use of renewable energy sources (RES) [12]. Adapting these types of energy sources provides benefits, opportunities and challenges in many sectors, such as agriculture [13]. A significant challenge is the high variability in the amount of energy supplied. In order to maintain the stability of the supply parameters, this variability must be compensated for by the power system.

In this paper, the authors presented the use of cloud computing in the business concept based on a Software as Service (SaS) model. The business model would be based on a paid subscription, under which the client would receive a resource in the form of a computing cloud controlling the plants in factory. The service provider would be responsible for all the aspects related to the proper control of the plant such as: stability, quality of control etc. In the future, it may also influence the stability of the electricity system's parameters by controlling the current power consumption if the proposed solution is applied on a wider scale.

Concept

The preliminary research of the cloud control concept was presented in [14]. In the previous work the server was responsible only for parametrization of the DMC controller and storage the tunned parameters. Storing this type of data reduced the number of performed parametrizations, which was beneficial to the controlled process. There is no need to disturb the system in any way, only to switch to the parameters of another operating point without any impact. The control law was implemented directly on the PLC controller which used the tuning parameters received from the server.

In the new concept (fig.1), the list of server tasks has been changed. The server was still performing the DMC controller parameterization process and an adaptation mechanism was implemented enabling better control of non-linear plants. Additionally the control law has been transferred from the PLC to the sever and now only the value of control signal is transmitted from the server. It was decided that the server would only support analogue signals of actuators due to the sampling time value. All binary signals were handled directly by the PLC, which ensured an appropriate level of security. This approach has significantly reduced the workload of the PLC controller.

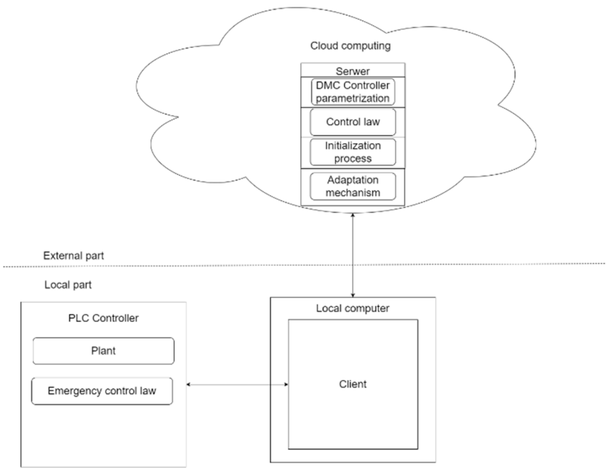

Fig.1 The modified concept described in this paper.

In this paper, the authors showed only an approach to control a single PLC, but it's possible to control more PLC controllers using one cloud. In this situation, all control laws can be implemented directly in the cloud. This makes it possible to use simpler and cheaper types of PLC controllers, which reduces the implementation cost. The idea of controlling more than one PLC is presented on figure 2.

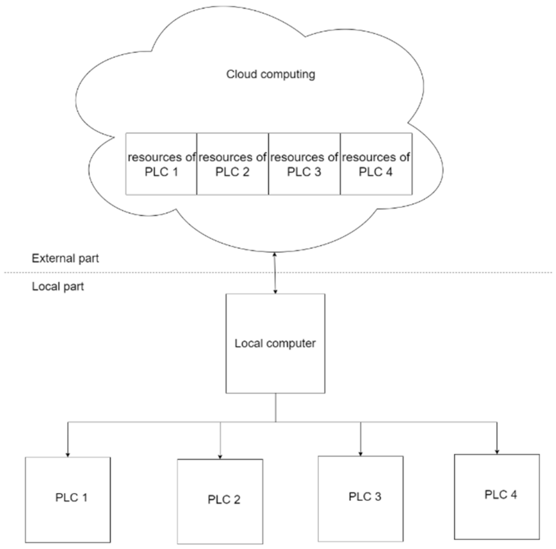

Fig. 2 An example of an approach to controlling more than one PLC

The concept of controlling multiple PLC controllers can be archived by changing the source code of the local computer. Each PLC will have an identification number that will be helpful in its operation. In the cloud, each PLC controller will have separate resources.

It should be taken into account that when using external resources, the user is at greater risk of cyber-attacks. In presented concept (Fig. 2) loss of control over the local computer will be dangerous, because it will affect all PLC controllers. To prevent such a situation, advanced firewall technologies should be applied. This should increase the security level of the control system.

The use of an external service to control the plant should take into account situations related to failures that may have occurred, e.g. loss of connection. In this case the plant would be left without any control. To prevent such a situation, the emergency control law should been implemented in the PLC. This ensures safe control of the plant until the cause is removed. The emergency control law should be always on standby. It should track the actual control value to ensure bumpless switching. The same applies to the control law implemented on the cloud. Later in this paper, the authors determined the optimal waiting time for reconnection, which does not significantly affect the quality of control.

Model

The structure of the plant used in this project is the same as in [14], but the method of controlling the plant was changed (fig. 3). Instead of changing the value of the heater power, now the flow rate is changed. The flow rate varies based on the degree of valve opening, and the power of the heater is considered as an input that can change and introduce disturbances. This is one source of non-stationarity and non-linearity in the system. The proposed control method will become increasingly popular due to the use of renewable energy sources. The power produced by these types of source can vary depending on many circumstances. A great example are solar panels, where the power produced is closely related to sensitivity of sunlight. Under conditions of variation in delivered power, it is more important to maintain a constant temperature of the medium than its flow rate.

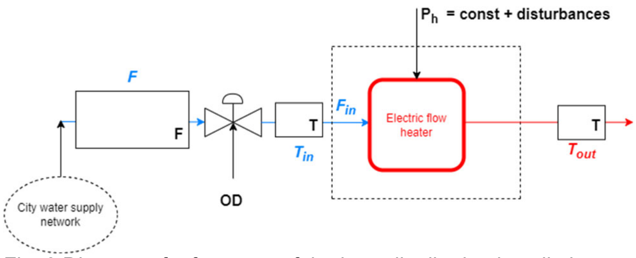

Fig. 3 Diagram of a fragment of the heat distribution installation

The water with inlet temperature T_{in} [°C] is heated inside the electric flow heater of constant volume V = 1,6 [L] to the temperature T_{out} [°C]. The flow rate F_{in} [l/min] is changed by means of the control valve according to the value of signal OD [%]. The flow rate that can be obtained is in the range <0; F>, but from a practical point of view the range has been narrowed to <F_{min}, F>. The value of F_{min} was set at 2,5 [l/min], as operations at lower flow rates was not recommended. The mean power P_h [%] of the heater is changed by the PWM (puls width modulation) signal and kept constant. The value P_h was set to 70 [%] of the nominal power of the heater P_{nom} = 12 [kW].

The plant model needed for the simulation and tests was taken from the article [15] and was modified in accordance with the presented control method. The first part of the model was a non-linear first order dynamic equation (1).

$$\frac{dT^*_{out}}{dt} = \frac{OD \cdot F}{100 \cdot 60 \cdot V}\left(T_{in} - T^*_{out}\right) + \frac{P_h \cdot P_{nom}}{100 \cdot c_s \cdot \rho_s \cdot V} \tag{1}$$

where: c_s – specific heat of water 4200 [J/kg°C], ρ_s – water density 1 [kg/L], T^*_{out} – not measured temperature [°C]

To obtain the measurable temperature at the outlet of the electric flow heater the dynamics of the sensors, the heater itself and other omitted phenomena must be taken into account. For this reason (2) should be applied.

$$K(s) = \frac{T_{out}(s)}{T^*_{out}(s)} = \frac{k(P_h)}{(1+s\cdot\tau_1(F))\cdot(1+s\cdot\tau_2(F))} \cdot e^{-s\cdot\tau_0(F)} \tag{2}$$

where (3), (4), (5)

$$K(P_h) = -0{,}002347 \cdot P_h + 1{,}012 \tag{3}$$

$$\tau_1(F) = \tau_2(F) = 19{,}08 \cdot F^{-0{,}4293} - 4{,}042 \tag{4}$$

$$\tau_0(F) = 11{,}93 \cdot F^{-0{,}78} + 2{,}37 \tag{5}$$

where: T_{out} – measurable temperature at the outlet of the electrical flow heater [°C], $k(P_h)$ – gain depending on the power of heater, $\tau_1(F)$, $\tau_2(F)$ – time constants depending on the flow rate [s], $\tau_0(F)$ – dead time depending on the flow rate [s]

DMC algorithm

Dynamic Matric Control (DMC) was one of the first predictive algorithms invented, which was implemented in the late 1970s. The general idea of the DMC controller is based on a linear model of the plant. In case of DMC algorithm, the plant is approximated by a first order plus dead time (FOPDT) model. The model allows to predict the process variable over a prediction horizon H_P. Minimizing the performance index (6) allows determining an optimal increment of the control signal, which is the main purpose of the DMC algorithm. The horizons (H_P, H_C) used in formula (6) determine the size of the individual sums. They are related to how far the user wants to predict a given variable. Additionally, the parameter λ is a penalty imposed on future changes of the control variable. The user can influence the dynamics of the plant, by changing the value of the parameter.

(6) $$J(k) = \sum_{p=1}^{H_p}(y^{SP}(k+p|k) - y(k+p|k))^2 + \lambda \cdot \sum_{p=0}^{H_c-1}(\Delta u(k+p|k))^2$$

The procedure of tunning the DMC controller for a given operating point for a Single Input Single Output (SISO) plant was shown in figure 4.

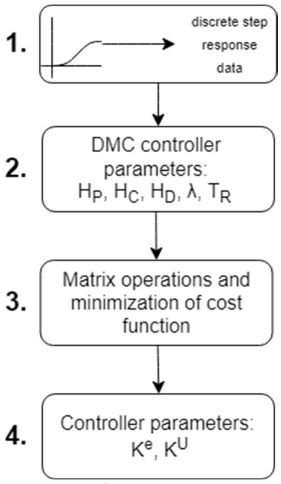

Fig. 4 Steps of tunning the DMC controller.

A more detailed process for tuning the DMC controller for a SISO plant is presented in [16]. The method of determining the DMC controller parameters was taken from [17]. After the DMC controller tuning process, the K^e and K^U matrices were used in (7) to calculate the change of control variable in the k moment. This value was then added to the previous value of control variable (8).

(7) $$\Delta u(k) = K^e \cdot [y^{SP}(k) - y(k)] - \sum_{j=1}^{H_D} K_j^U \cdot \Delta u(k-j)$$

(8) $$u(k) = u(k-1) + \Delta u(k)$$

Adaptive mechanism

Because the DMC algorithm uses a linear approximation of the plant, the controller is tuned for a specific operating point of the nonlinear system. In this case, the operating region of the controller can be significantly restricted for the assumption of linearity to hold true. In order to deal with the non-linearities and to ensure a satisfactory performance of the control system over a wider range of operating point, it is necessary to add an adaptive mechanism to the DMC controller.

In the proposed concept an adaptive mechanism similar to gain scheduling was implemented, in which the parameters of the DMC controller (K^U, K^e) are recalculated each time there was a demand. The change of the parameters was performed according to the chosen scheduling variables, which should be measurable and have the important impact on the dynamics of the process.

In presented work modified approach to gain scheduling is proposed, using two scheduling variables: setpoint temperature and heater power value. Then for several operating point the tuning process was performed to obtain matrices $K^U_{i,j}$ and $K^e_{i,j}$, where i = 1, 2, …, N_{RPT} j = 1, 2, …, N_{RPP} means the number of operating point for each scheduling variable. It should be kept in mind that the size of the $K^U_{i,j}$ depends on the dynamic horizon, which value can be different at each operating point. To ensure that the size of the matrix will be the same, it was assumed that it should be equal to H_{DMAX} = max {H_{D1}, H_{D2}, …, $H_{DNRPT+DNRPP}$}. The matrices with the missing values were filed with zeros until the condition was satisfied. The value of period T_R with which the controller is working also must be the same for all the operating point and equal T_{RMIN} = min {T_{R1}, T_{R2}, …, $T_{RNRPT+RNRPP}$}.

The adaptive mechanism presented in the form above switches its parameters between operating points. As mentioned earlier, the proposed concept uses two scheduling variables to adjust the controller parameters. If one of them (set point or heater power) changes, there is no problem in the operation of the algorithm. The problem occurs when both variables change at the same time and move to a point of operation for which the parameters have not yet been identified. To solve this, the algorithm will first adjust the controller parameters according to the heater's power (has priority) and then to the change of set point. The mechanism of the adaptive mechanism is presented on figure 5.

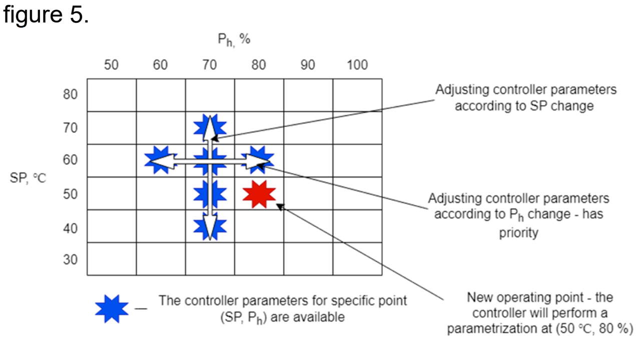

Fig. 5 An example of how two-dimensional interpolation works

The proposed concept does not require to have values for all the operating point (set point, heater's power). If a new operating point is used, the controller will perform a parametrization process and add to new values in the right place of table.

Test results

In order to test the proposed concept two experiments were carried out. In the first one, the heater power was constant P_h = 70 % and the operating point changed from T_{zad} = 50 °C to T_{zad} = 45 °C. In the second test , the operating point was set to T_{zad} = 45 °C and the heater power value was changed in accordance with the proposed scenario. This should be in line with possible variations typical for use of renewable energy sources. For evaluation the quality control of the proposed concept were used indicators in the time domain such as:

- settling time t_u - the time value after the response will be in close neighbourhood of the set point value, the boundaries of the close neighbourhood are determined by the deviation from the set point value $\Delta = \pm 2\%\ T_{zad}$
- maximum overshoot A_{max} – maximum value of the overshot (If the overshoot occur)

and integral indicators: IAE (9), ITAE (10) and IAU (11). The results were compared with an adaptive mechanism using only setpoint temperature as an scheduling variable.

(9) $$I_{IAE} = \int_0^T |e(t)| dt$$

(10) $$I_{ITAE} = \int_0^T t \cdot |e(t)| dt$$

(11) $$I_{IAU} = \int_0^T |\Delta u(t)| dt$$

The result of the first test were presented on figure 6.

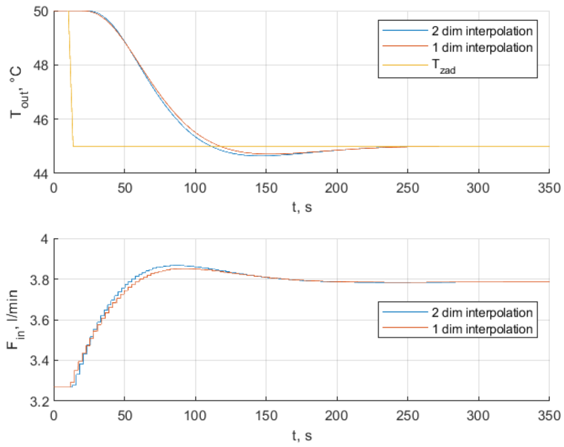

Fig. 6 The results of the first test

Table 1. The value of used indicators for the first test

Indicator	Type of adaptive mechanism	
	1 dimension	2 dimension
$A_{max,}$ [°C]	0,29	0,31
T_u, [s]	101,4	97,3
IAE	305,2	303,4
ITAE	16449	13585
IAU	0,0684	0,0652

As shown in the figure 6 the results for the two algorithms used are similar. The value of the maximum overshoot was higher for the two-dimensional concept than for the classical approach. However, the difference was not significant. The settling time was shorter for the new approach and the situation was similar in case of the values of integral indicators (Tab. 1). The value of IAU indicator describing the cost of control was similar for each concept.

In the second part of the test, the heater power was initially P_h = 80 %, then the value changed to P_h = 55 % (at time 40 s). Finally, there was an increase to around P_h = 75 % (at time 520 s). This reflected the change in power when using renewable energy sources (Fig. 7).

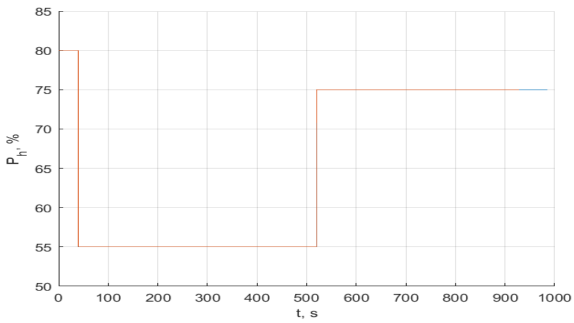

Fig. 7 Change of heater's power over time

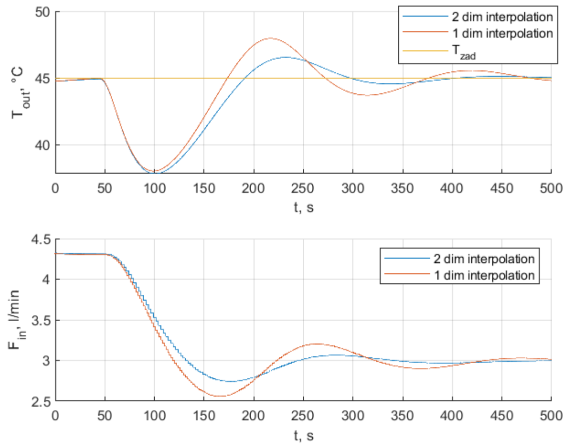

Fig. 8 The results of the first change in heater power

Table 2. The value of used indicators for the first change of power

Indicator	Type of adaptive mechanism	
	1 dimension	2 dimension
$A_{max,}$ [°C]	6,8	7,1
T_u, [s]	440,1	279,9
IAE	846,8	748,9
ITAE	142160	105250
IAU	0,2862	0,2027

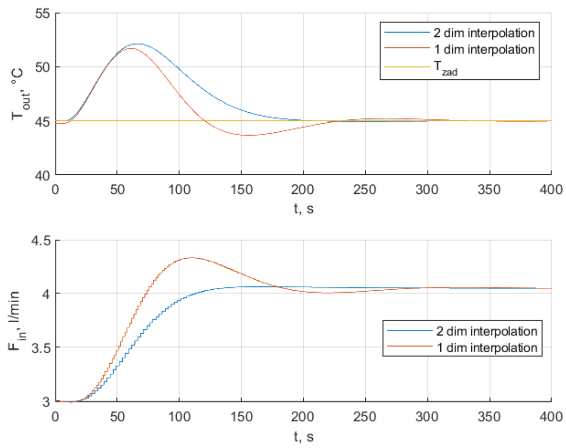

Fig. 9 The results of the second change in heater power

Table 3. The value of used indicators for the second change of power

Indicator	Type of adaptive mechanism	
	1 dimension	2 dimension
$A_{max,}$ [°C]	6,9	7,1
T_u, [s]	205,9	166,6
IAE	595,4	508,6
ITAE	48226	44600
IAU	0,1734	0,1084

The results for the first change in power were shown in figure 8 and for the second one in figure 9. The values presented in table 2 and 3 describe a similar situation. In which the value of the maximum overshoot was higher for the two-dimensional compared to the one-dimensional. However, the difference value had no significant impact on the quality of the control. This conclusion was confirmed by the values of the other indicators in the tables. The values of settling time, IAE and ITAE were always lower for the proposed concept than the classical approach. The cost of control (IAU) in each scenario was also lower for the two-dimensional approach compared to the classical. This means that the 2-dimensional mechanism allows for more conservative control due to the cost of control and, at the same time, more efficient control time.

The third experiment conducted in this project was to determine the waiting time for restoring the connection. The value of waiting time shouldn't heavily affect the quality control of the plant. A scenario was created in which the connection to the server was disconnected after 20 seconds at the operating point equal to T_{zad} = 40 °C. At the same time, an emergency situation occurred and one of the heater coils burned out. This resulted in a power reduction of 1/3. Then after a certain amount of time t_p the connection was restored.

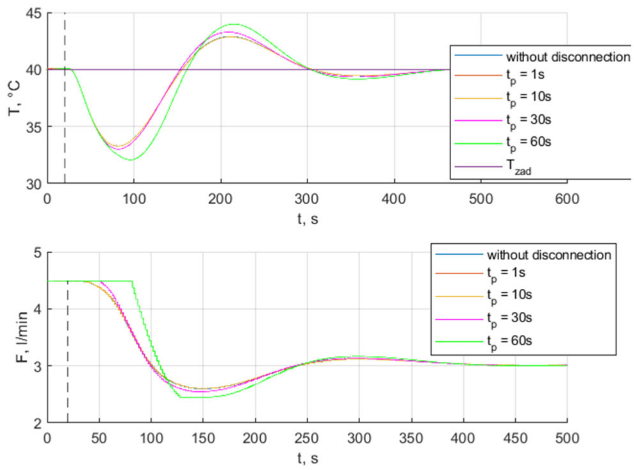

Fig. 10 The results of the second conducted experiment

As shown in the figure 10 the maximum reconnect wait time that didn't significantly impact the quality control was 30 seconds. However, this didn't mean that after that time, the control over the plant was no longer possible. Even after 60 seconds it was possible, but the quality was much worse compare to previous times.

Conclusion

As shown in this paper, using cloud computing is a great opportunity to start a business based on paid subscription. This can reduce the cost and time of implementing new plants in the factory. Transferring more advanced control algorithms from controllers to cloud computing results in the use of simpler PLC controllers.

The use of renewable energy sources is changing the way some plants are controlled. This article presents a great example in which an electric flow heater had to be controlled by the flow. The change in the control method also resulted in a change in its dynamics (non-linear). The occurrence of non-linear plant dynamics was the reason for implementing the adaptation mechanism. In the case of the plant used in this paper, one dimensional (dependent on one scheduling variable) gain scheduling was sufficient to obtain satisfying results when heat power was the control variable. Using flow as the control variable makes the system more nonlinear and the adaptive mechanism should be improved. Modifying the adaptive mechanism by adding another scheduling variable influenced the quality control. The results of each test performed for change of setpoint were similar, which was expected. There was a slight increase in the maximum overshoot value, but the difference was negligible. Importantly there was a significant decrease in the settling time compared to the one-dimensional solution. The largest difference in settling time value occurred when the power dropped from 80% to 55% (Tab. 2). Moreover, all values of integral indices were lower in the case of the two-dimensional concept. In authors opinion, the benefits of implementing a more complex gain scheduling algorithm were worthwhile.

When using external services, the user is exposed to many unexpected things that may occur. One of such situation is loss of connection, which is extremely dangerous when the plant is controlled by a cloud service. In this situation, it's important to determine the value of reconnection wait time. The value is different for each controlled plant. For the plant used in this paper, the optimal value of reconnection wait time was equal to 30 seconds.

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