Adaptive Identification and PSD Controller Implementation into 8-bit Microcontroller

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***Abstract*—** An application and an implementation of an adaptive identification and of Takahashi PSD controller are described in this article. The application is based on 8-bit HCS08 microcontroller (DZ family) from Freescale semiconductor. This family is intended for automotive application, and also for general purposes. Except the microcontroller, a power part and analog part of circuit was used for measure and converting a thermocouple temperature; it is directly measured inside the heater. This system is designed for fast temperature control of soldering precise tips.

The controlled system is identified during heating process by the recursive least square method at the beginning of control process and on demand of user (when the tip is replaced by other type).

The hardware was designed to save space and to minimize power loses on switching transistor. It leads to have the transistor without heatsink. The transistor was selected from PowerTrench family with an extremely low $r_{DS(ON)}$ resistance.

***Keywords* —** ADC conversion**,** discrete controller, implementation, microcontroller, modifications, recursive identification, thermocouple.

I. Introduction

DIGITAL PID controllers are known in a whole industry domain and they are frequently used, especially due to their easy setting and theirs favourable price. However, these controllers can be efficiently replaced by their own modifications or by the controllers based on algebraic methods, as a result of a powerful 32-bit microcontrollers boom.

The PID controllers are effective for a fast-response control [1], [2], whereas they do not provide additional functions and do not keep a control quality together. The controllers are modified for purposes of a control-quality improvement [3], [4] and several methods and procedures for their calculations and modifications have been introduced [2], [3], [5]. Modifications usually include limitations of control signal, reductions of wind-up effect, input signal filtration, restrictions of derivative part, automatic settings of controller parameters and theirs various combinations. These modifications may increase the control quality [5], prevent the oscillations of the controlled system or reduce peaks of controlled value if a step-regulation is desired. An example of the PID controller with modifications can be a fast temperature control of soldering irons with requirements of no overshoots, fast response and of depressed level of oscillations. This case of control is commonly necessitated if the high-power soldering irons are used in assembling of electronic parts onto printed circuits boards or theirs repairs. Especially, if the multi-layered boards or soldering areas with a high thermal capacity are soldered, the fast controller response is completely necessary because the high-power tips are commonly used and they can be easily overheated in the case of they are not actively used or if other type of electronic component is soldered.

The main purpose of this paper is firstly to construct an appropriate hardware for fast temperature control, and secondly to design, simulate and verify the PID controller with modifications for this process. In addition, this hardware including the controller is designed for equivalent devices, for example the device with two soldering tips. In the paper, some minor changes in settings are described for these devices.

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II. Controlled System

The controlled system is a solder tip in our case, but there could be used any heater up to 144W (limited by a transformer 18V/8A and by a heat sink mounted to rectifier diodes). The temperature measure is provided by a thermocouple which is internally connected direct to a heater element [6]. The heater has the 3Ω resistivity and maximum allowed power peak 192W at 24V. If 24V are applied continuously, the heater gets overheated, it begins radiate at red color and next it damages itself (melts, interrupts electric circuit, damages handle). At this condition the temperature probably exceeds 1000°C.

Due to the measurement by thermocouple and the producer does not give information about type of thermocouple, identification had been proceeded by applying 5% power in tip and by solder wrapping. The solder was selected from usually available solders which are listed in Table 1.

Tab. 1 Soft solders and melting point [7]

No.	Alloy	Melting point [°C]
1	Sn60Pb40	183 – 190
2	Sn63Pb37	183
3	Sn60Pb38Cu2	183 – 190
4	Sn99Ag0.3Cu0.7	217 – 228
5	Sn95.5Ag3.8Cu0.7	217 – 218
6	Sn96.5Ag3Cu0.5	217- 220

As can be seen at Fig. 3 and Fig. 4, the alloys No. 1 and No.5 were used for thermocouple identification.

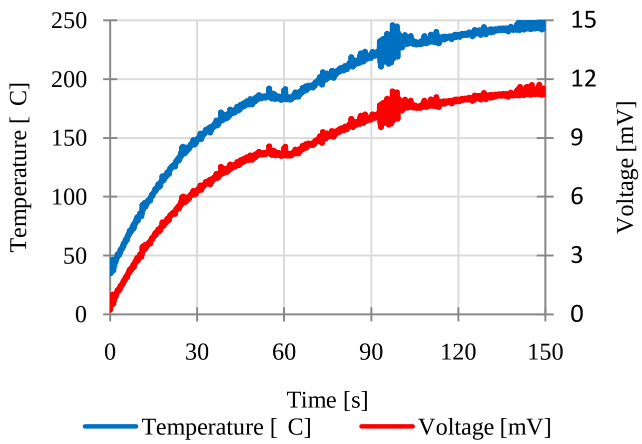

Fig. 1 thermocouple identification – alloy No. 1

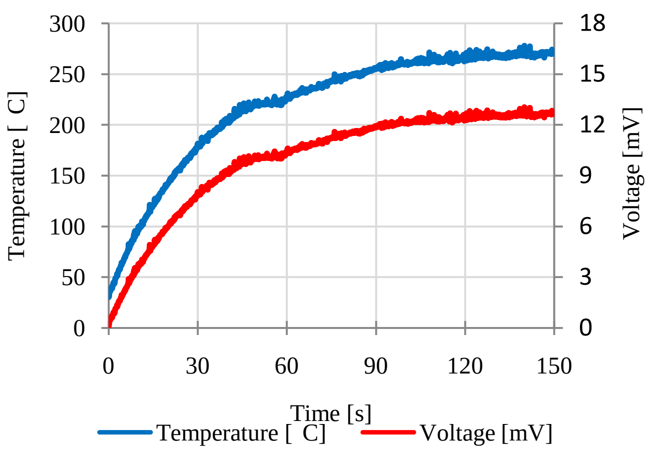

Fig. 2 thermocouple identification – alloy No. 5

Only voltages were measured during process and values at time approximately 60s when solders melted were used for comparison with table voltages of common thermocouples.

Tab. 2 Thermocouple voltages

Type	Materials	Constant at 200°C [μV/°C]
J	Fe-CuNi	55
K	NiCr-NiAl	40
S	PtRh10-Pt	8
B	PtRh30-PtRh6	2
N	NiCrSi-NiSi	33
E	NiCr-CuNi	74

Due to the nonlinearity of some type thermocouples, the table 2 is informative and exact voltage could be found in tables or calculated by appropriate equations.

The thermocouple was identified as type E, because the measured voltages were 8.15mV at 185°C and 10.08mV at 217°C.

III. Recursive Identification

The recursive identification – the least-square method [8], [11] - [14] is used to unsure high stability of controlled temperature during the changing of surround conditions. This method need no huge space memory in microcontroller and complicated calculations, because two steps of controller output value and temperature are sufficient to provide identification.

It can be deduced from soldering tip knowledge, thermocouple identification and the construction [6] (the thermocouple is direct joined with the heating spiral), that system can be described by the first-order discrete function:

$$G(z) = \frac{b_1 z^{-1}}{1 + a_1 z^{-1}} \qquad (1)$$

An implicit least-square identification method gets parameters by minimizing of summary squared errors. The equation (2) is considered

$$y(k) = \sum_{i=1}^{r} a_i f_i(k) + e(k), \qquad (1)$$

where $e(k)$ is an error, and a_i are unknown parameters. Next, for the error can be written

$$e(k) = y(k) - y_m(k) = y(k) - \sum_{i=1}^{r} a_i f_i(k), \qquad (2)$$

which is a difference of measured values $y(k)$ and modeled values $y_m(k)$ calculated by a regress calculation. The least square criterion can be written as (4)

$$J = \sum_{k=1}^{N} e^2(k) = \sum_{k=1}^{N} \left[y(k) - \sum_{i=1}^{r} a_i f_i(k) \right]^2. \qquad (3)$$

The criterion reaches a zero value if partial derivations by each parameter are equal to zero. A system of equations, which was got by a successive substitution of measured values into (2), has next form:

$$\begin{aligned} y(1) &= a_1 f_1 + a_2 f_2(1) + \cdots + a_r f_r(1) + e(1) \\ y(2) &= a_1 f_1 + a_2 f_2(2) + \cdots + a_r f_r(2) + e(2) \\ &\vdots \\ y(N) &= a_1 f_1 + a_2 f_2(N) + \cdots + a_r f_r(N) + e(N) \end{aligned} \qquad (4)$$

If the next vectors are defined as

$$\begin{aligned}\mathbf{y}^T &= [y(1) \quad y(2) \quad \cdots \quad y(N)] \\ \mathbf{\Theta}^T &= [a_1 \quad a_2 \quad \cdots \quad a_r] \\ \mathbf{e}^T &= [e(1) \quad e(2) \quad \cdots \quad e(N)]\end{aligned} \tag{5}$$

and matrix

$$\mathbf{F} = \begin{bmatrix} f_1(1) & f_2(1) & \dots & f_r(1) \\ f_1(2) & f_2(2) & \dots & f_r(2) \\ \vdots & \vdots & \vdots & \vdots \\ f_1(N) & f_2(N) & \dots & f_r(N) \end{bmatrix} \tag{6}$$

with dimension (N, r), the equation system can be written by equation

$$\mathbf{y} = \mathbf{F\Theta} + \mathbf{e}. \tag{7}$$

Due to the (8), the error can be written as

$$\mathbf{e} = \mathbf{y} - \mathbf{F\Theta}. \tag{8}$$

It can be seen that the square criterion is a scalar, which can be expressed by equation

$$\mathbf{J} = \mathbf{e}^T\mathbf{e} = (\mathbf{y} - \mathbf{F\Theta})^T(\mathbf{y} - \mathbf{F\Theta}) \to \min. \tag{9}$$

The criterion minimum can be achieved by derivation

$$\left.\frac{\partial J}{\partial \mathbf{\Theta}}\right|_{\mathbf{\Theta}=\hat{\mathbf{\Theta}}} = 0. \tag{10}$$

Next equations are achieved after derivation:

$$\begin{aligned}\frac{\partial J}{\partial \hat{\mathbf{\Theta}}} &= \frac{\partial\left(y - \mathbf{F}\hat{\mathbf{\Theta}}\right)^T}{\partial \hat{\mathbf{\Theta}}}\left(y - \mathbf{F}\hat{\mathbf{\Theta}}\right) + \frac{\partial\left(y - \mathbf{F}\hat{\mathbf{\Theta}}\right)^T}{\partial \hat{\mathbf{\Theta}}}\left(y - \mathbf{F}\hat{\mathbf{\Theta}}\right) = \\ &= -\mathbf{F}^T\left(y - \mathbf{F}\hat{\mathbf{\Theta}}\right) - \mathbf{F}^T\left(y - \mathbf{F}\hat{\mathbf{\Theta}}\right) \\ &= -2\mathbf{F}^T\left(y - \mathbf{F}\hat{\mathbf{\Theta}}\right) = 0\end{aligned}. \tag{11}$$

If equation (12) is solved, we get

$$\mathbf{F}^T\left(y - \mathbf{F}\hat{\mathbf{\Theta}}\right) = 0 \tag{12}$$

and we can modify (13) to

$$\hat{\mathbf{\Theta}} = \left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T\mathbf{y}. \tag{13}$$

It can be simplified to

$$\hat{\mathbf{\Theta}} = \mathbf{F}^{-1}\mathbf{y}, \tag{14}$$

but it can be applied only for square matrix **F,** therefore $r = N$. Mean value $\hat{\mathbf{\Theta}}$ can be calculated by

$$\begin{aligned}\hat{\mathbf{\Theta}} &= \left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T\mathbf{y} = \left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T\left(\mathbf{F\Theta} + \mathbf{e}\right) = \\ &= \left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T\mathbf{F\Theta} + \left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{Fe} = \Theta + \left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T\mathbf{e}\end{aligned} \tag{15}$$

Next equation is applied for mean value of parameters estimation

$$E\left[\hat{\mathbf{\Theta}}\right] = \hat{\mathbf{\Theta}} + E\left[\left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T\mathbf{e}\right] \tag{16}$$

Estimation is impartial if $E\left[\hat{\mathbf{\Theta}}\right] = 0$. Therefore, it must be applied in equation (17) for second part

$$E\left[\left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T\mathbf{e}\right] = 0. \tag{17}$$

Condition in (18) is fulfilled when parts of $\mathbf{F}$ and $\mathbf{e}$ are independent and $E(\mathbf{e}) = 0$. General relation (19) is applied for covariance matrix of random vector $\mathbf{z}^T = [z_1 \quad z_2 \quad \dots \quad z_n]$

$$\mathbf{C}[z] = E\left\{[\mathbf{z} - E(\mathbf{z})][\mathbf{z} - E(\mathbf{z})]^T\right\}. \tag{18}$$

If error $\mathbf{e}$ is uncorrelated signal $\left(E\left[\hat{\mathbf{\Theta}}\right] = 0\right)$, than covariance matrix of random part is

$$\mathbf{C}[z] = E\left\{[\mathbf{z} - E(\mathbf{z})][\mathbf{z} - E(\mathbf{z})]^T\right\} = E\left[\mathbf{ee}^T\right] = \sigma_e^2\mathbf{I}, \tag{19}$$

where σ_e^2 is error variance and $\mathbf{I}$ is unit matrix. If $E\left(\hat{\mathbf{\Theta}}\right) = \mathbf{\Theta}$, next equation can be written

$$\mathbf{C}\left(\hat{\mathbf{\Theta}}\right) = E\left[\left(\hat{\mathbf{\Theta}} - \mathbf{\Theta}\right)\left(\hat{\mathbf{\Theta}} - \mathbf{\Theta}\right)^T\right]. \tag{20}$$

If error $\mathbf{e}$ is uncorrelated, covariance matrix can calculated by

$$\mathbf{C}\left(\hat{\mathbf{\Theta}}\right) = \sigma_e^2 E\left(\mathbf{F}^T\mathbf{F}\right)^{-1}. \tag{21}$$

If matrix $\mathbf{F}$ doesn't include random parts, than $E\left[\left(\mathbf{F}^T\mathbf{F}\right)^{-1}\right] = \left(\mathbf{F}^T\mathbf{F}\right)^{-1}$ and (22) is modified to

$$\mathbf{C}\left(\hat{\mathbf{\Theta}}\right) = \sigma_e^2\left(\mathbf{F}^T\mathbf{F}\right)^{-1}. \tag{22}$$

Variations of $\mathbf{e}$ are determined by calculated parameters $\hat{\mathbf{\Theta}}$. Residues are calculated from equation (8)

$$\hat{\mathbf{e}} = \mathbf{y} - \mathbf{F\Theta} = \mathbf{y} - \hat{\mathbf{y}}, \tag{23}$$

where $\hat{\mathbf{y}} = \mathbf{F\Theta}$ is estimation of output value – predicted output value. Residual error function

$$J_R = \hat{\mathbf{e}}^T\hat{\mathbf{e}} \tag{24}$$

can be written. If $E\left(\hat{\mathbf{\Theta}}\right) = 0$, it can be applied for estimation of error variation

$$\hat{\sigma}_e^2 = \frac{J_R}{N} = \frac{1}{N}\sum_{i=1}^{N} e_i^2 \ . \tag{25}$$

For continual identification the equation (14) be rewritten for $k-1$ measurements to

$$\hat{\mathbf{\Theta}}(k-1) = \left(\mathbf{F}_{k-1}{}^T \mathbf{F}_{k-1}\right)^{-1} \mathbf{F}_{k-1}{}^T \mathbf{y}(k-1), \tag{26}$$

where

$$\mathbf{y}^T(k-1) = \begin{bmatrix} y(1) & y(2) & \dots & y(k-1) \end{bmatrix} \tag{27}$$

is a vector of output variables in the interval $(1, k-1)$, and

$$\hat{\mathbf{\Theta}}(k-1) = \begin{bmatrix} \hat{\theta}_1(k-1) & \hat{\theta}_2(k-1) & \dots & \hat{\theta}_r(k-1) \end{bmatrix} \tag{28}$$

is vector of optimal estimates of parameter values of transfer function. A matrix

$$\mathbf{F}_{k-1} = \begin{bmatrix} f_1(1) & f_2(1) & \dots & f_r(1) \\ f_1(2) & f_2(2) & \dots & f_r(2) \\ \vdots & \vdots & \vdots & \vdots \\ f_1(k-1) & f_2(k-1) & \dots & f_r(k-1) \end{bmatrix} \tag{29}$$

is modified matrix $\mathbf{F}$ for $(k-1)$ measurements. If k-measurement is done and

$$\mathbf{y}(k) = \begin{bmatrix} y(k-1) \\ y(k) \end{bmatrix} \tag{30}$$

is described, the $\mathbf{F}_k$ matrix is

$$\mathbf{F}_k = \begin{bmatrix} \mathbf{F}_{k-1} \\ \mathbf{\Phi}^T(k) \end{bmatrix} \tag{31}$$

can be written, where

$$\mathbf{\Phi}^T(k) = \begin{bmatrix} f_1(k) & f_2(k) & \dots & f_r(k) \end{bmatrix} \tag{32}$$

The output vector can be written for k-measured variable

$$y(k) = \mathbf{\Theta}^T \mathbf{\Phi}(k) + e(k), \tag{33}$$

where $\mathbf{\Theta}^T$ is defined as

$$\mathbf{\Theta}^T = \begin{bmatrix} \theta_1 & \theta_2 & \dots & \theta_r \end{bmatrix} \tag{34}$$

A covariance matrix $\mathbf{C}(k)$ can be defined as

$$\mathbf{C}(k) = \left[\mathbf{F}_{k-1}^T \mathbf{F}_{k-1} + \mathbf{\Phi}(k)\mathbf{\Phi}^T(k)\right]^{-1}, \tag{35}$$

and it can be written as

$$\mathbf{C}(k) = \left[\mathbf{C}^{-1}(k-1) + \mathbf{\Phi}(k)\mathbf{\Phi}^T(k)\right]^{-1} \tag{36}$$

A general recursive algorithm can be written as

$$\hat{\mathbf{\Theta}}(k) = \hat{\mathbf{\Theta}}(k-1) + \mathbf{K}(k)\left[y(k) - \hat{\mathbf{\Theta}}^T(k-1)\mathbf{\Phi}(k)\right] \tag{37}$$

where $\mathbf{K}(k)$ is a time changing vector of gain and can be written as

$$\mathbf{K}(k) = \frac{\mathbf{C}(k-1)\mathbf{\Phi}(k)}{1 + \mathbf{\Phi}^T(k)\mathbf{C}(k-1)\mathbf{\Phi}(k)} \tag{38}$$

The recursive equation for the covariance matrix is

$$\mathbf{C}(k) = \mathbf{C}(k-1) - \mathbf{C}(k-1)\frac{\mathbf{\Phi}(k)\mathbf{\Phi}^T(k)\mathbf{C}(k-1)}{1 + \mathbf{\Phi}^T(k)\mathbf{C}(k-1)\mathbf{\Phi}(k)} \tag{39}$$

The vector of parameters $\mathbf{\Theta}^T(k)$ and vector of measurement data $\mathbf{\Phi}^T(k)$ can be written for second order transfer function as:

$$\mathbf{\Theta}^T(k) = \begin{bmatrix} a_1 & b_1 \end{bmatrix} \tag{41}$$

$$\mathbf{\Phi}^T(k) = \begin{bmatrix} -y(k-1) & u(k-1) \end{bmatrix} \tag{42}$$

IV. Discrete Controller

The modified PSD controller known as Takahashi PID controller [8] was selected due to the requirements of fast response and no overshoots of regulated value. The response is not direct affected by the controller, but the simple calculation of its parameters provides the fast response in a used 8-bit microcontroller.

The controller with modified derivative part is described by equation

$$u(k) = K_P\left\{e(k) - e(k-1) + \frac{T_0}{T_I}e(k) + \frac{T_D}{T_0}\cdot \right.$$
$$\left. \cdot\left[2y(k-1) - y(k) - y(k-2)\right]\right\} + u(k-1) \tag{43}$$

where its modified part limits action outputs if the value of w(k) changes and also limits the shifts of the action output to nonlinear zone. Changes of action outputs are also limited if the w(k) is included only by integral part of the controller which can be described as

$$u(k) = K_P\left\{-y(k) + y(k-1) + \frac{T_0}{T_I}\left[w(k) - y(k)\right] + \frac{T_D}{T_0}\cdot \right.$$
$$\left. \cdot\left[2y(k-1) - y(k) - y(k-2)\right]\right\} + u(k-1) \tag{44}$$

The equation (44) is used for in microcontroller and its parameters are calculated by next equations

$$K_P = 0.6K_{PK}\left(1-\frac{T_0}{T_K}\right) \quad (45)$$

$$T_I = \frac{K_P T_K}{1.2K_{PK}} \quad (46)$$

$$T_D = \frac{3K_{PK}T_K}{40K_P} \quad (47)$$

where T_0 is sampling period, T_K is critical period and K_{PK} is critical gain of controlled system.

The critical period and gain may be obtained by few methods like direct finding on real device with proportional controller (usable for high order systems) or by calculation from identified systems or its model.

The calculation of critical parameters of controlled system may use Ziegler-Nichols criterion and following equations for the first-order system:

$$K_{Pk}(T_0) = \frac{1-a_1}{b_1} \quad (48)$$

$$T_k(T_0) = 2T_0 \quad (49)$$

V. Controller Hardware

The Takahashi PID controller was implemented on special hardware developed especially for this case and for control the soldering tip. The hardware includes single double-sided board with microcontroller and digital circuits, analog part for amplification voltage from thermocouple with 16-bit, 250ksps SAR analog to digital converter and galvanically isolated power switch.

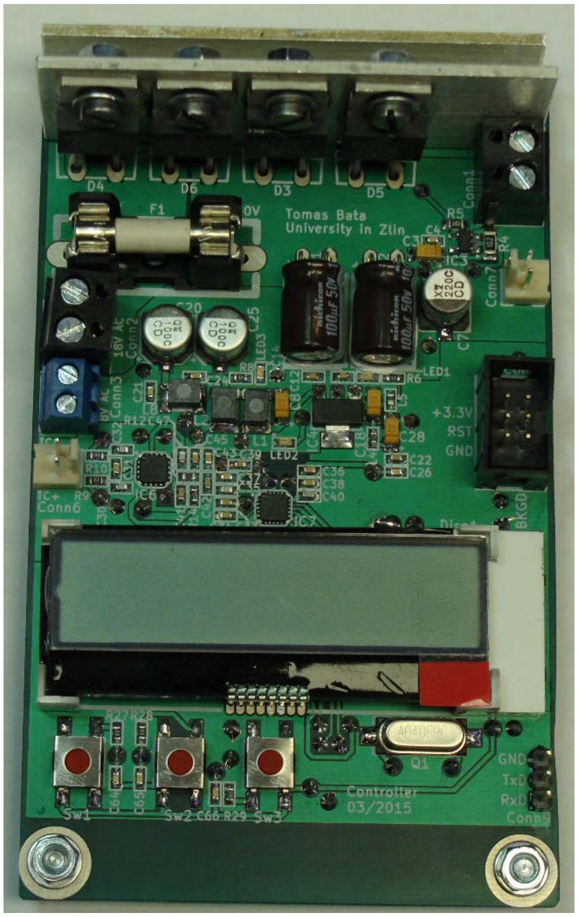

Fig. 3 the controller board, dimensions 66x110mm

MC9S08DZ60 8-bit microcontroller is intended for general purposes and automotive. The core can work at maximum frequency 40MHz and includes 4kB RAM memory for data, 60kB flash memory for program [15] and 2kB EEPROM memory which is used for save parameters of identification and of controller and user settings (temperature, times of hibernation and automatic power off).

The analog part measuring the temperature is based on instrumentation rail-to-rail amplifier AD8231 which has digitally settings of gain (1-2-4-8-16-32-64-128) [16]. The reference voltage was set to 1.0V in case of temperature measurement under 0°C. The 16-bit AD converter 7682 was selected. It has internally switchable reference (2.5V or 4.096V) and can operate in unipolar and bipolar mode [17]. In this case it was set to unipolar mode with 2.5V reference – resolution 38.17µV. The 250ksps sampling rate provides fast temperature measurement between two periods of controller and does not influence the output power, because the soldering tip uses common wires for heater and thermocouple. The heater must be switched of before temperature measurement; on the other hand the noise and inducted voltage is measured. Due to the demand on low power loses, the second version was designed. As it is plotted in Fig. 4, it designed for two systems or one system in tweezers. The MOSEFT transistors replace a bridge rectifier. The current flows through the opened transistor T1 and substrate diode inside the transistor T2 during the first half of sine period, in the second half it flows through the opened transistor T2 and substrate diode in T1. So, the power loses are eliminated to power loses on diode and $rds_{(ON)}$ at opened transistor. The switching loses are not significant and cannot be removed.

VI. Verification of the Controller

The Takahashi controller and recursive identification algorithm were verified on real devices at changing ambient conditions (laboratory temperatures from 17°C to 29°C, with and without cooling by pressured air flow). First, the step responses were measured and next the controller was verified

The verification was realized by connection through serial line interface and USB converter. The actually measuerd temperature, controller output and set value were sent each period T_0=100ms. The period of PWM output signal was chosen T_{PWM}=20ms (AC line period), because the output signal was generated by PowerTrench MOSFET transistor and the lowest value of the output signal was set to 10µs.

The first time system identification was measured with $u_{OUT} = 5\%$ and $u_{OUT} = 10\%$ in order to the soldering tip not to be overheated and damaged. Step responses of both measurements are shown on Fig. 5 and Fig. 6.

The continues step responses were calculated for these measurements and are written below (equation (50) corresponds to u=5%; equation (51) corresponds to u=10%).

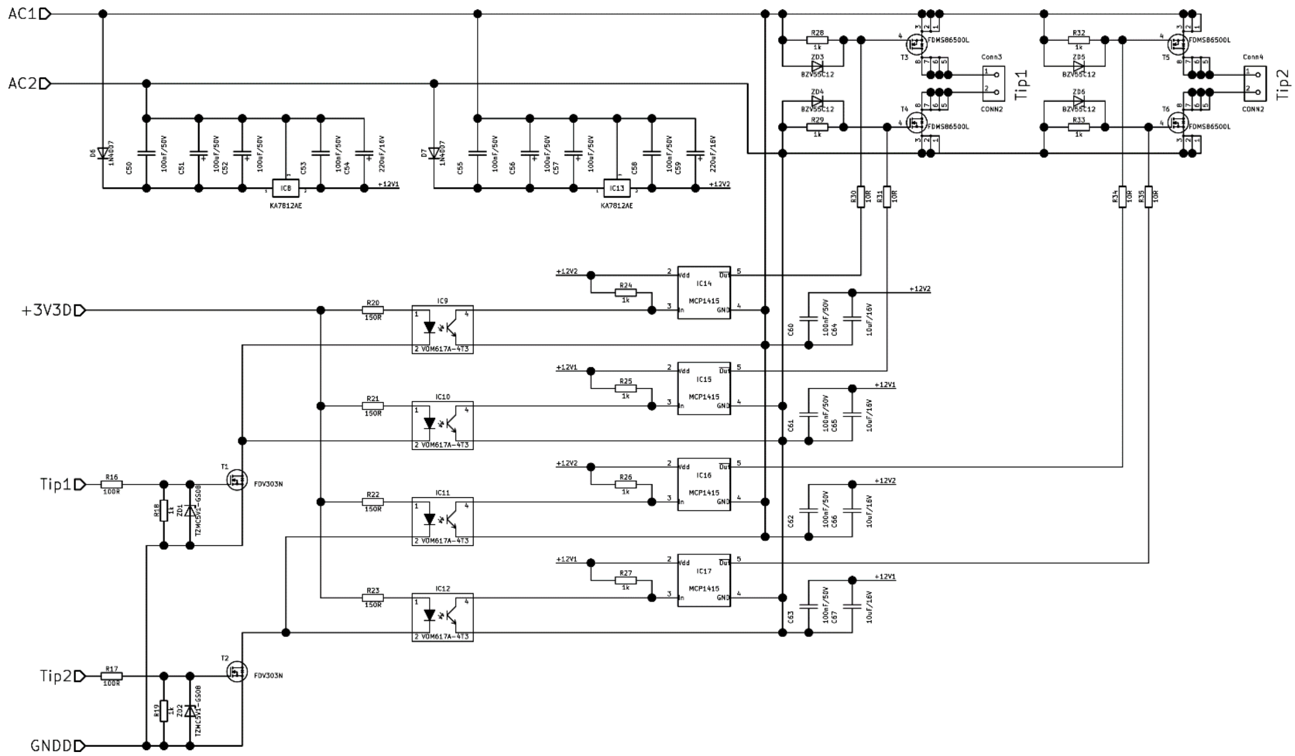

Fig. 4 power switches part for double system

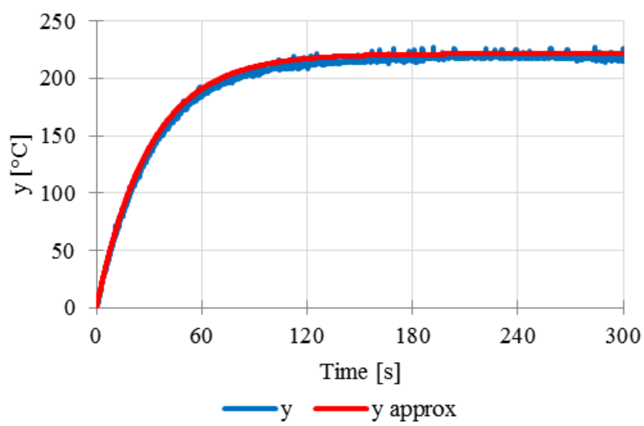

Fig. 5 system identification, u=5%

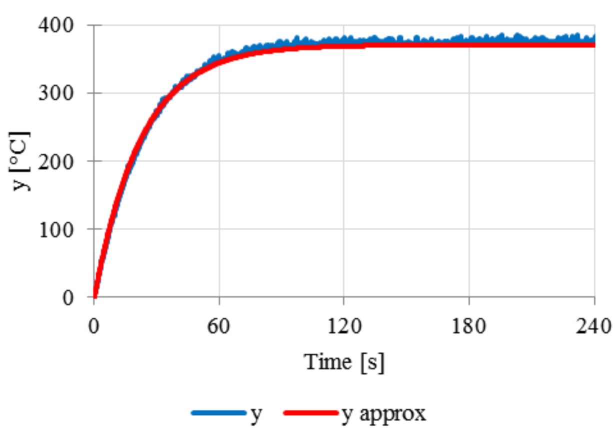

Fig. 6 system identification, u=10%

There can be seen some diference caused by diferent measurement conditions.

$$G(s) = \frac{221.3}{30.3s+1} \tag{50}$$

$$G(s) = \frac{370.6}{22.6s+1} \tag{51}$$

The controll process is shown in Fig. 7 for two step changes of controlled temperature. As it is ploted in graph, the some noise can be seen in measured value. Due to this, the PID controller produces changing output. It can be probably removed by filtration of voltage from thermocouple. At this graph is low-pass 1.5kHz filter, but it seems that could be used filter with 50Hz or lower frequency.

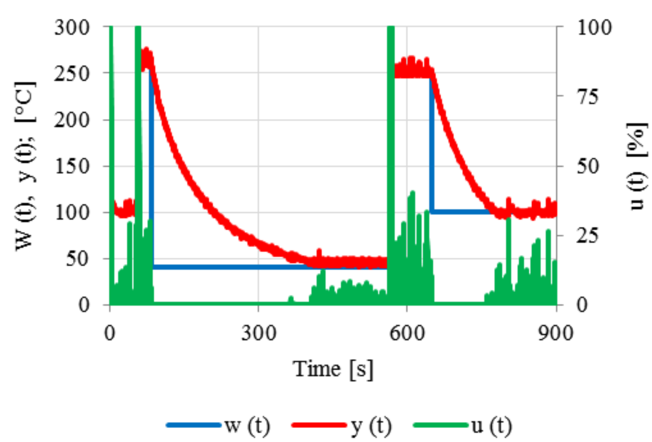

Fig. 7 the controll process

VII. CONCLUSION

The article deals with the application of Takahashi PID controller and recursive identification. The controller board with all circuits (digital, analog and galvanically isolated switch) was designed and manufactured and the controller implementation was verified on 8-bit microcontroller with sampling time 100ms and soldering iron.

The design of electronic circuits was universally devised for other types of heaters with thermocouples. The thermocouple type is independent, because the circuit does not includes specialized parts, but it is based on instrumentation amplifier and 16-bit, 250ksps AD converter.

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