AGH University of Science and Technology in Krakow

Department of Power Electronics and Energy Control Systems

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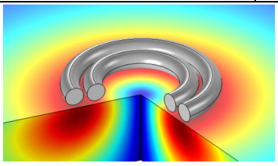

Electoheat - laboratory

Title of exercise:

Temperature control

Date:	Date of assessment:	Rate:

I. Introduction

1. Temperature measurements

Temperature measurements are made in a indirect way only - by measuring a quantity which depends upon temperature in a known way. There are many such quantities, e.g. liquid volume used in popular thermometers.

Devices used to temperature measurements can be divided into groups taking into account the kind of the quantity used or the way of the measurement.

a) The former criterion - the kind of the quantity used:

- non-electric devices – using e.g. liquid, dilatation or bimetal sensors,
- electric devices – using e.g. resistive or thermocouple sensors.

In case of resistive sensors the temperature magnitude is determined based on the sensor resistivity measurement, which depends upon temperature. The material most often used for building such sensors is platinum.

Another example are thermocouple sensors, which produce a temperature-dependent voltage as a result of the thermoelectric effect. A thermocouple consists of two different conductors forming an electrical junction - Fig. 1.

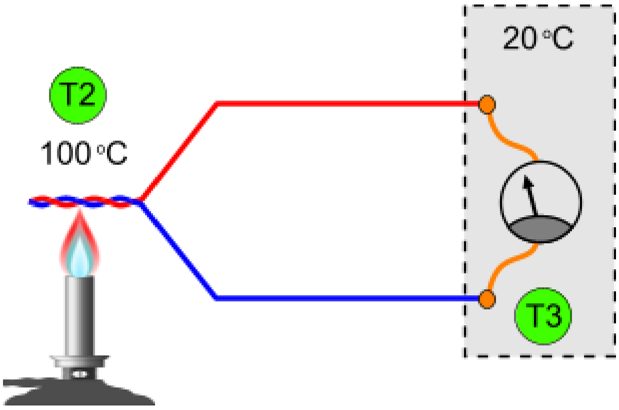

Fig. 1. Principle of temperature measurement using a thermocouple

b) The latter criterion - the way the measurement is carried out:

- devices, which require direct contact with the measurement point,
- contactless devices – pyrometers.

The devices from the first group perturb the temperature field and have to be properly selected to assure a required measurement accuracy. Pyrometers are remote-sensing thermometers. They determine, from a distance, the temperature of a surface from the spectrum of the thermal radiation it emits.

2. Temperature control

2.1. On/Off Control

An on-off controller is the simplest form of temperature control device. It is often used in electric heating (Fig. 2). The output from the device is either on or off, with no middle state. An on-off controller switches the output only when the temperature crosses the setpoint. For heating control, the output is on when the temperature is below the setpoint, and off – above setpoint. Since the temperature crosses the setpoint to change the output state, the process temperature will be cycling continually, going from below setpoint to above, and back below. In steady state conditions the turn-on time and the cycle duration time are practically the same in each cycle.

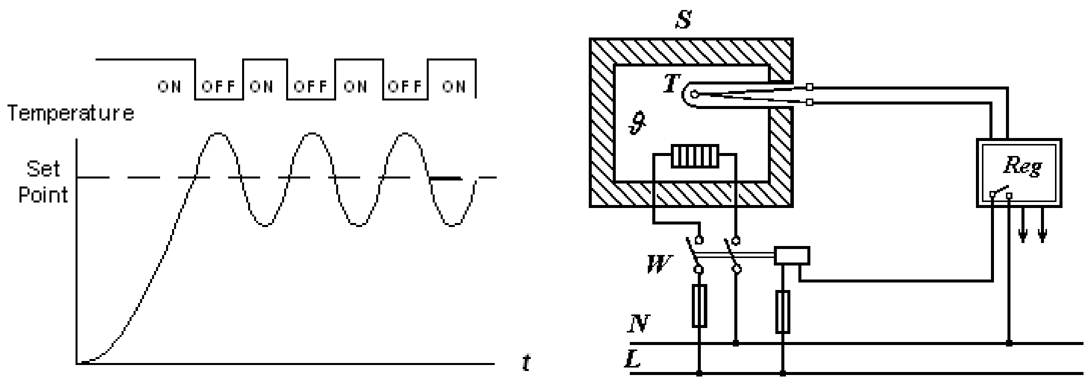

Fig.2. Principle of on-off control and diagram of a resistance furnace control system
S - resistance furnace or heater, *Reg* - on-off controller, *W* - contactor, *T* - temperature sensor, ϑ - temperature.

In order to prevent damage to contactors and valves, a hysteresis is added to the controller operations. This means that the temperature has to exceed the setpoint by a certain amount before the output will turn off or on again. The hysteresis prevents the output from “chattering” (that is, engaging in fast, continual switching if the temperature’s cycling above and below the setpoint occurs rapidly).

On-off control is usually used where a precise control is not necessary, in systems which cannot handle the energy’s being turned on and off frequently, where the mass of the system is so big that temperatures change slowly enough.

Block diagram of an on-off temperature control system is shown in Fig.3. The control object *S* (electric furnace or heater) is usually approximated by a 1st order inertial element with delay time. Block *T* reflects the time constant of the temperature sensor, which is usually assumed to be a 1st order inertial element. However, to assure good performance of the control system, the temperature sensor *T* time constant should be much lower than the control object *S* time constant. It should be added, that this is often not difficult to obtain, because heating devices are usually characterized by big time constants. ϑ is the measured temperature of object *S*, ϑ^* is a signal from the temperature sensor converted into temperature magnitude and ϑ_w^* - preset temperature. The difference ε between the preset temperature ϑ_w^* and the measured temperature ϑ^* is applied to the controller *Reg* input. The controller *Reg* is a non-linear element containing an aforementioned hysteresis. The controller turns on an off, via contactor *W*, the heating element, determining its temperature waveform. The controller output signal *u* is called “duty cycle” and is a ratio of turn-on time t_z to the duration of the switching cycle.

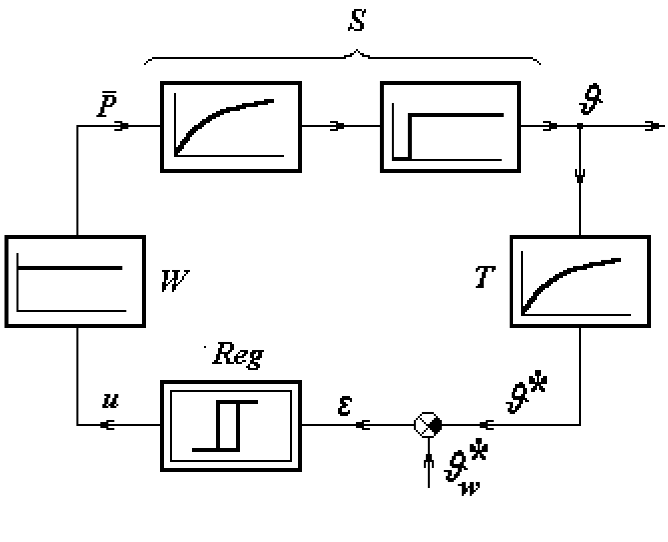

Fig.3. Block diagram of an on-off temperature control system

Figure 4 presents time waveforms of temperature and input power in steady-state conditions in more detail. They show the time delay of the temperature $\vartheta^*(t)$ of the sensor with regard to the actual temperature $\vartheta(t)$ of the object *S*. It can also be seen that after the input power has been turned off the temperatures $\vartheta^*(t)$ and $\vartheta(t)$ still rise for a while. The reason is that the heat is transferred from the heating element to the environment where the body to be heated is placed, and at the moment the power goes off, the heating element temperature is higher than the temperatures $\vartheta^*(t)$ and $\vartheta(t)$ and therefore they rise for some time. A reverse phenomenon occurs after the input power has been turned on - the temperatures $\vartheta^*(t)$ and $\vartheta(t)$ still fall for some time.

After the power has been turned on for the first time, (Fig. 4, t=0) temperature $\vartheta(t)$ rises in a way similar to the exponential function. If the power were turned on long enough, temperature $\vartheta(t)$ would reach its limit value ϑ_g, at which power losses would be equal to the input power. In many cases reaching limit temperature ϑ_g would destroy the heating device; therefore this has to be avoided.

ϑ_2^* is the temperature, at which the power is turned off and ϑ_1^* is the temperature, at which the power is turned on. The difference between the both temperatures is the aforementioned hysteresis *H*.

The mean value $\overline{P}$ of input power in each switching period *C* can be expressed by $\overline{P} = P_n \frac{t_z}{C}$, where: P_{n} – rated power, *C* – temperature oscillation period in steady state conditions, t_{z} – time interval in which power is on in one period *C*. Ratio $u = \frac{t_z}{C}$ is called “duty ratio”.

In steady state conditions temperature $\vartheta(t)$ oscillates between $\vartheta_{\min}$ and $\vartheta_{\max}$ with double amplitude *R*, and the mean value of this temperature is often determined as $\vartheta_r = \frac{\vartheta_{\min} + \vartheta_{\max}}{2}$. Temperature ϑ_r is usually different from the preset temperature ϑ_w^* and the resulting steady-state control error $E_w = \vartheta_w^* - \vartheta_r^*$ can be both positive and negative.

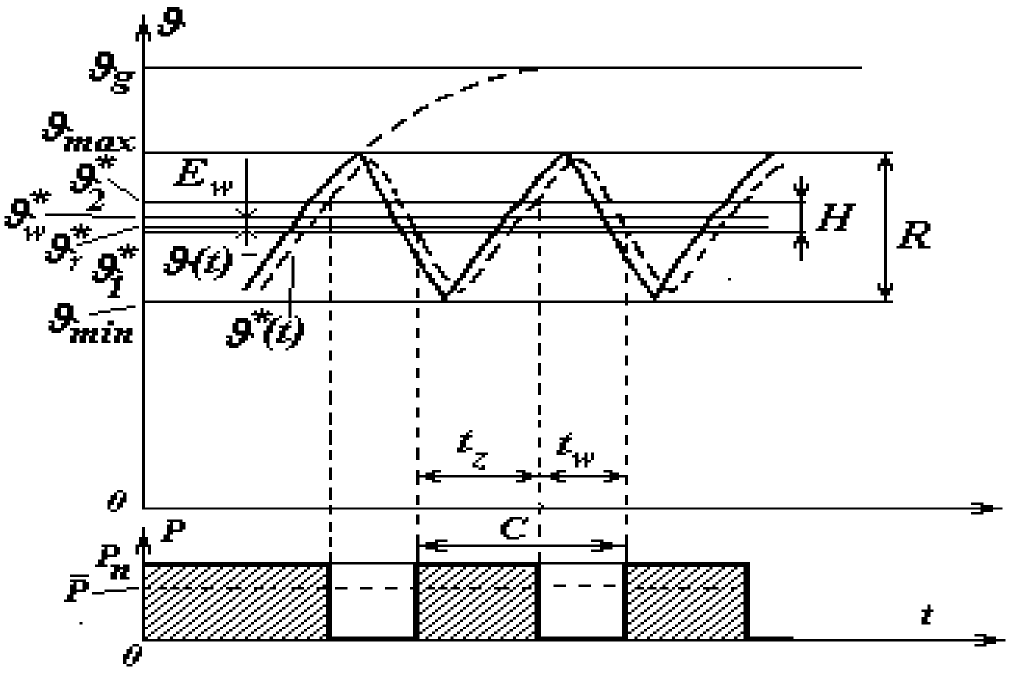

Fig. 4. Temperature waveforms in on-off control in steady-state condition.

2.2. PID control

PID control is usually used when high accuracy of temperature control is required – mainly in case of fast changing temperatures and objects with small thermal inertia. This is the case of many thermal processes used in modern laboratory investigations and industry. At the same time fast development in the fields of electronics, especially digital technology (microprocessors and microcontrollers), as well as the development of new calculation algorithms make it possible to build modern and not expensive PID controllers of high performance. Therefore the field of their applications is still widening.

Diagram of a temperature control system with a PID controller is shown in Fig. 5. The main difference compared to on-off control is that the power supplying the heating element can, in general, vary from 0 to rated power P_n (in on-off control only two values o power are possible: 0 or P_n). This implies using a controller with quite deferent properties than those used in on-off control. This also means that instead of a contactor used in on-off control a thyristor, a triac or another controlled power electronic device can be used. Supplying the heating element with small amounts of energy makes it possible to obtain a nearly constant temperature waveform in steady state conditions.

In some cases a PID controller can also control the power via a contactor – but it is turned on and off in quite a different way than at on-off control (a completely different control algorithm is used).

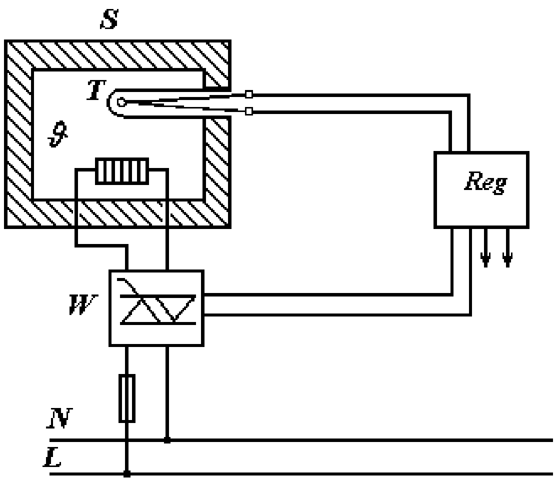

Fig. 5. Diagram of a resistance furnace control system with PID control

The output voltage of a PID controller is given by

$$u(t) = K_R \varepsilon(t) + \frac{1}{T_I}\int_0^t \varepsilon(\tau)\mathrm{d}\tau + T_D \frac{\mathrm{d}\varepsilon(t)}{\mathrm{d}t}$$

where

$\varepsilon(\tau)$ – control error,

K_R – gain coefficient,

T_I – integral action time,

T_D – derivative action time.

The controller integral part *I* assures a zero control error at constant input signal and thanks to derivative part *D* a fast reaction to input disturbances is achieved.

K_R, T_I and T_D are tuning parameters that have to be set by the user before the control process has begun. There are many methods to do this but it is not an easy task, as tuning parameters magnitudes depend upon the control object parameters.

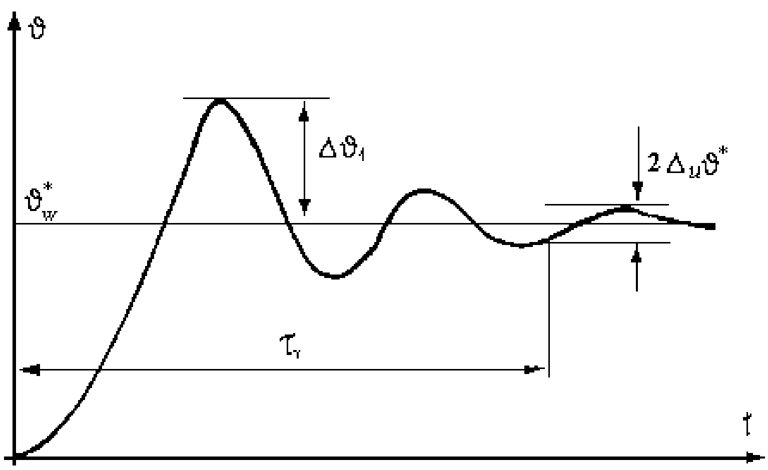

Fig. 6. Response of a closed loop PID control system to a step-change of the input

The control quality is usually assessed on the basis of transient temperature waveforms after a step-change of the input (Fig. 6). The quantities which determine the control quality are usually *first overshoot* $\Delta\vartheta_1$ and settling time τ_r, which is often determined for 5% tolerance $\Delta_u\vartheta^*$ of steady-state output.

2.3. Auto-tuning

A problem with PID controllers arises when the heating object parameters change – the control parameters of the system worsen and it is necessary to adjust the controller tuning parameters to the new conditions. This can be done by the user, which is very inconvenient. The problem can be solved by using so called *adaptive controllers*. One category of such controllers are controllers with *auto-tuning*. If necessary, the user starts a procedure of identifying the control object; afterwards the controller modifies its tuning parameters and returns to classical PID control automatically. Next, the procedure can be repeated at any time.

II. Program of the exercise

A diagram of the measurement system is shown in Fig. 7. Controller *RK1* is a universal controller MX-7. It can operate as an on-off controller, PID controller and has auto-tuning option. The temperature waveforms can be watched on-line on the monitor and they are written to a file.

The preset temperature for all measurements should be ϑ_w^* = 200°C.

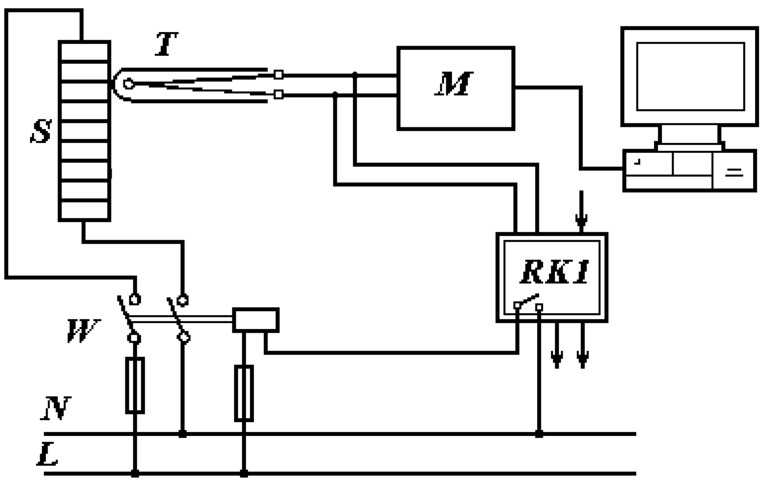

Fig. 7. Diagram of the measurement system

S – heating object, *T* – temperature sensor (a thermocouple), *RK1* – temperature controller, *M* – measuring unit transmitting data to a computer.

II.1. On-off control

The aim is to demonstrate the influence of the heating object parameters, of the temperature sensor parameters, of the supply voltage magnitude and of heat transfer conditions on the temperature waveform in steady-state.

Activate on-off control.

a) **Measurement 1 –** heating element from an oil heater, temperature sensor with **higher** thermal inertia.

In steady-state condition determine the following, using the controller display and a stopwatch:

- temperature ϑ_2^*, at which the power is turned off,
- temperature ϑ_1^*, at which the power is turned on,
- minimum temperature $\vartheta_{\min}$,
- maksimum temperature $\vartheta_{\max}$,
- period C of temperature oscillations,
- time interval t_z when power P_n is on in one period C.

Based on the results obtained calculate the following (Fig. 4):

- the difference R between $\vartheta_{\max}$ and $\vartheta_{\min}$,
- hysteresis H,
- ratio $u = \dfrac{t_z}{C}$,
- temperature ϑ_r,
- error E_w.

b) **Measurement 2** – heating element from an oil heater, temperature sensor with **lower** thermal inertia.

c) **Measurement 3** – heating coil of resistance wire, temperature sensor as in Measurement 2, thermal inertia of this heating coil is lower than thermal inertia of the heating element from Measurement nr 1 and nr 2.

d) **Measurement 4** – lower supply voltage than in Measurement 3. The rest – as in Measurement 3.

During measurements 2 – 4 measure and calculate the same quantities as in measurement 1. Compare the results obtained. Draw conclusions.

e) **demonstration -** turned on a fan to change the conditions of heat exchange between the heating coil and the surroundings**.** The rest – as in Measurement 4.

What has changed compared to Measurement 4? Why?

II.2. PID control with use of auto-tuning

The aim is to demonstrate auto-tuning and steady-state temperature waveforms in PID control.

Measurement 5 – A heating plate is used, its thermal inertia is the highest of all the heating elements used.

Activate PID control.

Note a time delay in the temperature increase after the power has been turned on.

Set any controller tuning parameters and note them.

Activate auto-tuning function. Watch the temperature waveforms – initially they will be similar to those in on-off control. During that time the controller identifies the control object (the heating plate).

Next, the oscillations amplitude starts decreasing. This means that the controller has replaced its initial tuning parameters with optimum parameters calculated based on the identification and has switched to PID control.

Check the new tuning parameters of the controller and note them. Compare them with the initial ones. Make sure they have been changed automatically by the controller itself.

Watch the temperature waveform in steady state. Compare it with the waveforms obtained in on-off control.

III. Laboratory report

On the basis of the executed exercises prepare the report containing:

- control system block diagram used during the laboratory,
- temperature time waveforms (registered during the exercise) obtained from the files,
- measured and calculated values,
- influence of various factors on the temperature waveforms,
- comparison of properties of on-off control and PID control,
- conclusions.

IV. Bibliography

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