WATER TEMPERATURE CONTROL USING AN ON-OFF CONTROLLER

International Faculty of Engineering – BASIC ELECTRICITY – Exercise 21 *

1 Aim of the exercise

The aim of this exercise is to become familiar with the basic elements of an AC electrical circuit controlled by a microcontroller and a solid-state relay (SSR). During the experiment, the circuit will be used to control the heating process and stabilize the temperature of water in an electric kettle using a simple on-off control method.

2 Theoretical introduction

The circuit used in this experiment is powered by alternating current (AC). Unlike direct current (DC), the voltage in an AC circuit changes continuously over time and periodically reverses its direction. In household electrical systems, the voltage waveform is approximately sinusoidal.

The instantaneous voltage can be described by the following equation:

$$u(t) = U_{max} \cdot \sin(2\pi f t) \tag{1}$$

where: $u(t)$ - instantaneous voltage, U_{max} - maximum voltage, f - frequency, t - time.

The ideal waveform is presented in Fig. 1. In practice, the most important parameter is the RMS (root mean square) voltage, also called the effective voltage. The RMS value represents the equivalent DC voltage that would produce the same heating effect in a resistor.

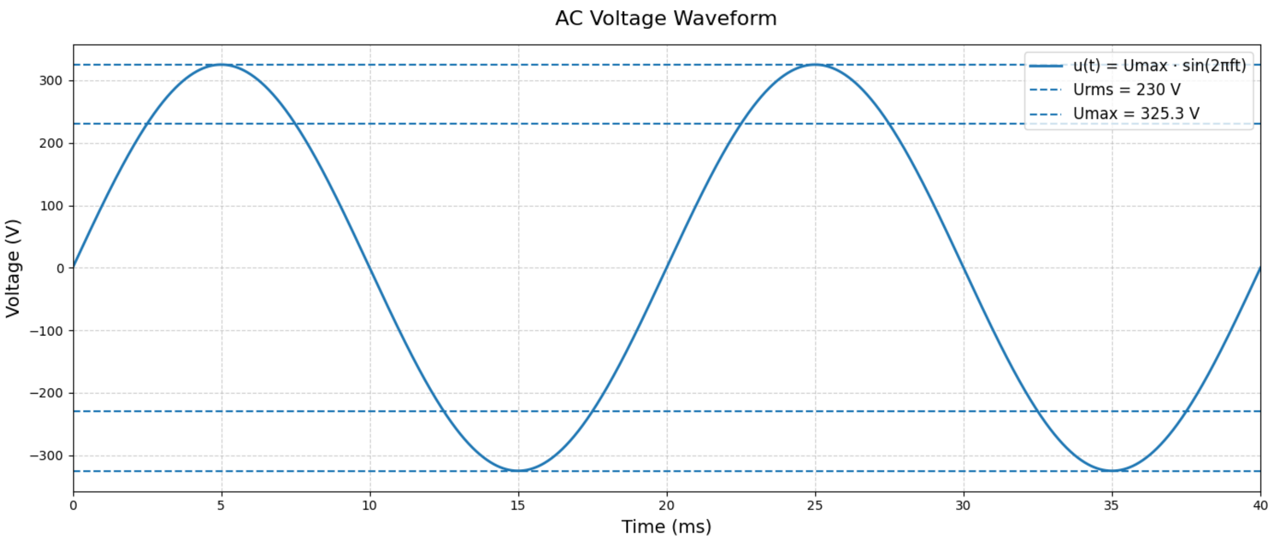

Figure 1: Ideal sinusoidal AC voltage waveform (230 V RMS, 50 Hz)

In the European Union, the standard RMS voltage is $U_{RMS} = 230$ V, and the frequency $f = 50$ Hz. The electric power P consumed can be calculated as:

$$P = U_{RMS} \cdot I_{RMS} \tag{2}$$

where I_{RMS} is the RMS current.

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2.1 Connections and their graphical representations

The electronic components used in this laboratory will be connected using a breadboard shown in Fig. 2. A breadboard allows you to quickly build and modify electrical circuits without soldering. At the top and bottom of the breadboard, you can find long power rails marked with red and blue lines. These rails are typically used to connect the voltage supply from the power source. Inside the main part of the breadboard, the connection points are internally linked in rows (in Fig. 2 the rows are vertical). For rows numbered from 1 to 64, all sockets in each group from A to E are electrically connected, and all sockets from F to J are also connected. This makes it possible to easily create circuits by inserting components and wires into the appropriate holes. Fig. 2 also presents a simple example of connecting a resistor and an LED diode to a battery power supply using the breadboard.

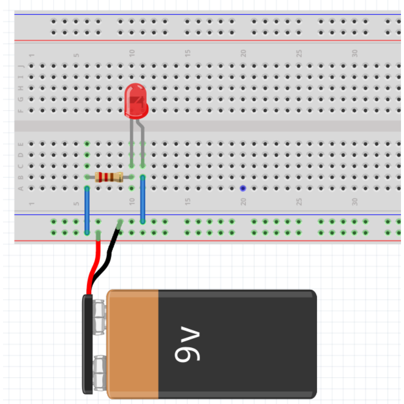


Figure 2: An example of connecting a resistor and an LED diode to a battery power supply using the breadboard

You can notice that the whole bottom row of the breadboard (marked with a red line) is connected to the positive (+) terminal of the battery, while the row above it (marked with a blue line) is connected to the negative (−) terminal. It is common to use red color to mark the positive terminal and black (or blue) color to mark the negative terminal. In Fig. 2, the left terminal of the resistor is connected to the positive terminal of the battery, the right terminal of the resistor is connected to the left terminal of the LED diode, and the right terminal of the LED diode is connected to the negative terminal of the battery.

Electrical circuits are usually represented using schematics - diagrams that show symbols of electronic components together with their electrical connections. The schematic corresponding to the circuit shown in Fig. 2 is presented in Fig. 3. You can notice the symbols of the battery, resistor, and LED diode. Note that resistors are sometimes represented using rectangular symbols instead of the zigzag line shown here.

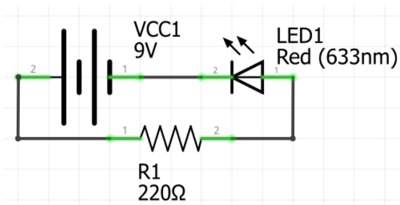


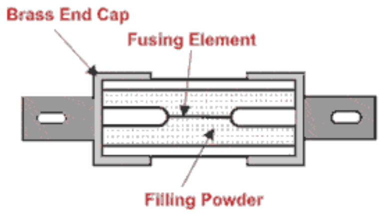
Figure 3: The schematic corresponding to the circuit shown in Fig. 2

2.2 Fuses and Circuit Breakers in AC Installations

Electrical installations must be protected against excessive current that could damage devices, overheat wires, or cause fire hazards. For this purpose, protective devices such as fuses and circuit breakers are used.

Older electrical installations often used fuse links (also called melting fuses or cartridge fuses). Inside the fuse there is a thin metal wire that melts when the current becomes too high, interrupting the circuit. After the fuse is damaged, it must be replaced with a new one. A simplified diagram of a traditional fuse link is shown in Figure 4(a)[1], while real examples of such fuses are presented in Figure 4(b)[2]. **Typical advantages are – simple construction, low price, reliable operation. Typical disadvantages – single-use operation, manual replacement required after activation.**

[1] https://manojbpl.blogspot.com/2015/04/what-are-hrc-fuses-and-how-they-are.html
[2] https://jeanmueller.pl/wkladki-topikowe-zwloczne



(a) A simplified diagram of a traditional fuse link

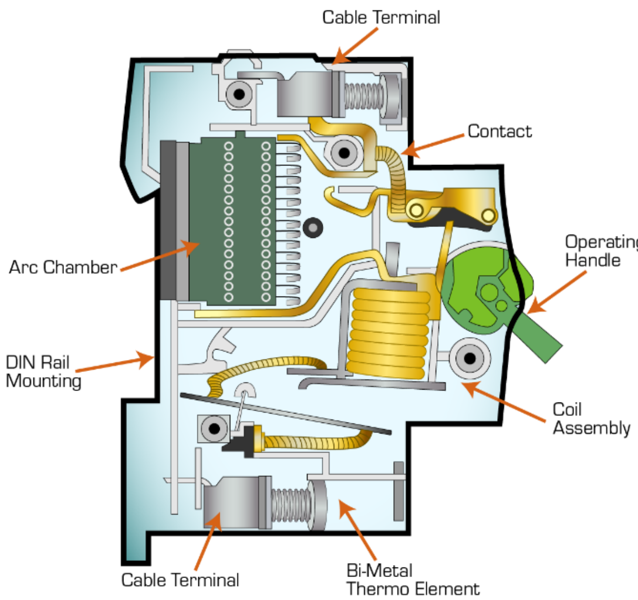
(b) Real examples of fuse links

Figure 4: Fuses – examples

Traditional fuse links are still used in some buildings and industrial systems. Modern electrical installations usually use miniature circuit breakers (MCBs). Unlike traditional fuse links, circuit breakers can be switched on again after activation. A circuit breaker disconnects the circuit automatically when the current exceeds a safe value. In many devices, this protection works using an electromagnetic mechanism. A very common marking found on household circuit breakers is, for example, B16. The letter at the beginning describes the tripping characteristic of the breaker, which determines how sensitive it is to short-term current surges. Common characteristics include:

- B — standard household devices,
- C — devices with higher startup currents (e.g. motors),
- D — devices with very high startup currents.

The number indicates the rated current of the breaker. For example, B16 means: type B characteristic, rated current equal to 16 A. This means that the breaker is designed for circuits whose normal operating current should not exceed 16 A. A simplified diagram of a circuit breaker is shown in Figure 5(a)[3], while real examples of circuit breakers are presented in Figure 5(b)[4].



(a) A simplified diagram of a circuit breaker

(b) Real examples of circuit breakers

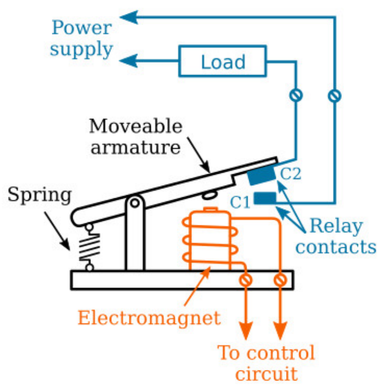
Figure 5: Circuit breakers – examples

2.3 Mechanical Contactors and Solid-State Relays

Electrical circuits often require elements that allow relatively large currents and voltages to be controlled by a low-power control signal. Two commonly used switching devices are mechanical relays (also called contactors in higher-power applications) and solid-state relays (SSRs).

[3] https://www.eeemadeeasy.com/how-to-open-a-circuit-breaker/
[4] https://onccy.com/the-difference-between-1p-2p-1pn-circuit-breakers/

A mechanical relay or contactor is an electromechanical switching device. Inside the device there is a coil that generates a magnetic field when electrical current flows through it. The magnetic field moves mechanical contacts, which either connect or disconnect the controlled circuit, Fig. 6(b) [5].



(a) Simplified diagram of a mechanical relay/contactor

(b) Example photograph of a mechanical relay/contactor

Figure 6: Mechanical relays/contactors – examples

The term relay is usually used for smaller devices, while contactor typically refers to devices designed for higher currents and industrial applications. Mechanical contactors are widely used in industrial systems, especially for controlling motors, heaters, pumps, and other high-power devices, Fig. 6(b) [6].
Typical advantages of mechanical relays and contactors:

- simple operating principle,
- relatively low price,
- ability to switch large currents,
- good electrical isolation between control and power circuits.

Typical disadvantages:

- moving mechanical parts wear out over time,
- audible clicking noise during operation,
- slower switching speed,
- possible sparking on contacts.

A solid-state relay (SSR) performs a similar function to a mechanical relay or contactor, but it contains no moving mechanical parts. Instead, semiconductor elements such as triacs or transistors are used to switch the electrical circuit. In this laboratory exercise, the SSR is controlled by a microcontroller, which allows automatic temperature regulation, Fig. 7 [7].

Figure 7: Example photograph of an SSR

[5] https://ecstudiosystems.com/discover/textbooks/basic-electronics/relays/electromechanical-relays/
[6] https://www.facebook.com/Elec.Eng.World/posts/a-contactor-and-a-relay-are-both-types-of-electrically-operated-switches-tha 1308460684659953/
[7] https://botland.store/blog/ssr-what-is-it-and-what-is-it-used-for/

Typical advantages of SSRs:

- silent operation,
- very fast switching,
- long operating lifetime,
- no mechanical wear,
- easy integration with microcontrollers.

Typical disadvantages:

- higher price,
- heat generation during operation,
- possible leakage current even when switched off,
- greater sensitivity to overheating.

2.4 Microcontrollers and Arduino

A microcontroller is a small programmable electronic device that can control other elements of an electrical circuit. A typical microcontroller contains:

- a processor,
- memory,
- input and output pins (I/O pins).

Microcontrollers are commonly used in automation, household devices, robotics, sensors, and industrial systems. In this laboratory exercise, the microcontroller is used to control the solid-state relay responsible for switching the kettle heater on and off.

Arduino is a popular educational and prototyping platform based on microcontrollers. It consists of:

- a programmable board,
- a simple programming environment,
- a large set of ready-to-use libraries.

Arduino is widely used in education because it allows electronic systems to be programmed in a relatively simple way, Fig. 11 [8].

Figure 8: Example photograph of an Arduino board

[8] https://botland.com.pl/

2.5 Basic structure of an Arduino program

A microcontroller is a small programmable device containing a processor, memory, and I/O pins. Arduino is a popular platform for prototyping. An Arduino program consists of two main functions:

```
void setup() {
        // initialization code
}
void loop() {
        // main program loop
}
```

The `setup()` function is executed only once after the microcontroller is powered on or reset. It is typically used for initialization. The `loop()` function is executed repeatedly in an infinite loop while the microcontroller is running.

2.6 Configuring a pin as an Output

Arduino pins can operate either as inputs or outputs.

- Input mode is used for reading signals from sensors or buttons.
- Output mode is used for controlling external devices.

To configure a pin as an output, the following instruction is used:

```
pinMode(pinNumber, OUTPUT);
```

For example:

```
pinMode(8, OUTPUT);
```

This instruction configures pin 8 as an output pin. An output pin can be set to one of two digital states:

- HIGH — high voltage level,
- LOW — low voltage level.

For most Arduino boards:

- HIGH corresponds approximately to 5 V,
- LOW corresponds approximately to 0 V.

To change the state of a pin, the following instruction is used:

```
digitalWrite(pinNumber, state);
```

For example:

```
digitalWrite(8, HIGH);
```

switches pin 8 to the HIGH state. Similarly:

```
digitalWrite(8, LOW);
```

switches pin 8 to the LOW state. In this experiment, these states will be used to control the SSR.

2.7 Conditional Statements

Microcontrollers often need to make decisions depending on sensor readings or program conditions. For this purpose, conditional statements are used. A simple conditional statement in Arduino has the following form:

```
if(condition)
{
        // instructions
}
```

For example:

```
if(temperature < 60)
{
        digitalWrite(8, HIGH);
}
```

More advanced programs may also use the `else` instruction:

```
if(condition)
{
        // instructions if condition is true
}
else
{
        // instructions if condition is false
}
```

3 Procedure of the experiment

3.1 Discussion of the circuit

Before starting the experiment, analyze the electrical circuit used in the laboratory setup. Name the main elements and identify the purposes of each of them. Discuss how these elements cooperate during the temperature control process.

3.2 Connecting the temperature sensor

Connect the DS18B20 temperature sensor according to the provided schematic diagram.

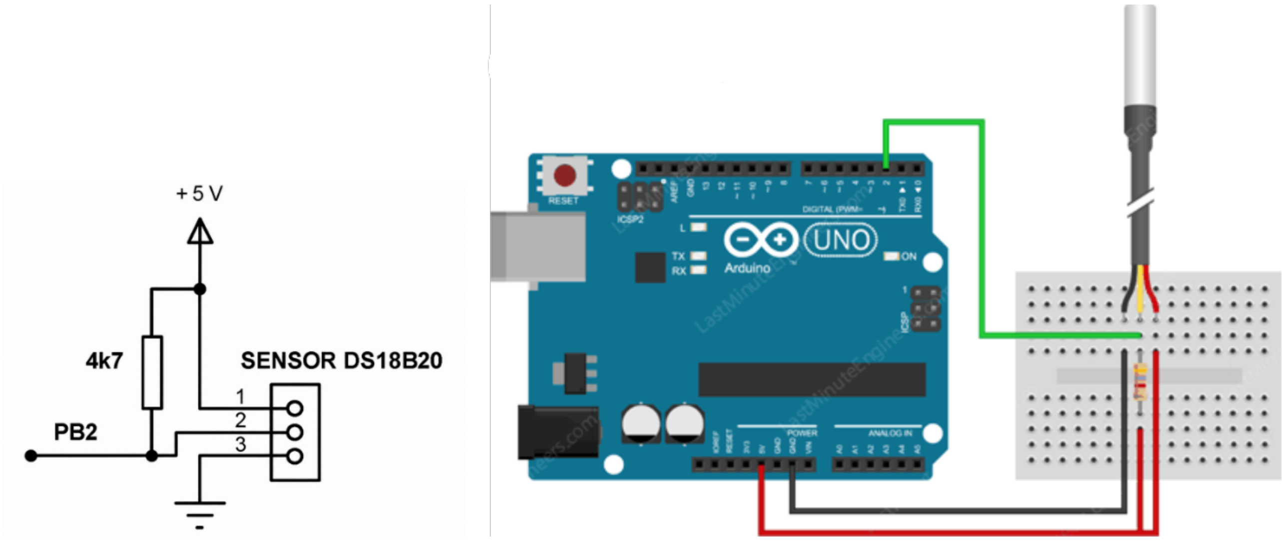


Figure 9: Schematic diagram for connection of the temperature sensor (left) and realization (right)

The sensor pins should be connected as follows:

- Output 1 to Arduino pin VCC (red),
- Output 2 to Arduino Digital pin 2 (PB2), and
- Output 3 to Arduino pin GND (black).
- Use a 4k7 pull-up resistor on the signal line.

The signal line should be connected through a pull-up resistor marked as: 4k7. This notation means: $4.7\,\text{k}\Omega = 4700\,\Omega$. The pull-up resistor ensures that the signal line remains in a stable HIGH state when no device is actively forcing the line to LOW. Without this resistor, the signal could become unstable and produce incorrect readings.

3.3 Testing the temperature measurement

Upload the example Arduino program provided by the instructor and verify whether the temperature is measured correctly. To test the sensor operation, gently warm the sensor using your hand and observe whether the measured temperature increases.

3.4 Testing the relay control

Connect the solid-state relay (SSR) to the microcontroller. Any digital pin from 3 to 13 may be used to control the "+" input of the SSR. Connect the "–" input of the SSR to ground (GND).

Modify the program so that:

- the relay turns ON when the measured temperature is below 30°C,
- the relay turns OFF when the temperature is greater than or equal to 30°C.

At this stage, do not connect the kettle yet. Observe the indicator LED on the relay module in order to verify whether the relay changes its state correctly.

3.5 Water Temperature Control

After verifying that the relay control works correctly:

- set the target temperature specified by the instructor,
- pour the amount of water specified by the instructor into the kettle,
- connect the kettle to the SSR circuit,
- run the program again.

Observe the temperature changes during the experiment. **Using the provided worksheet, draw a graph of temperature as a function of time**. Based on the obtained results, explain the general shape of the graph and the behavior of the control system.

3.6 Efficiency Calculation

The efficiency of water heating can be estimated by comparing:

- the electrical energy supplied to the system,
- the useful thermal energy gained by the water.

The input electrical energy may be calculated using:
Calculate efficiency η by comparing electrical input energy E_{input} to thermal energy E_{useful} as:

$$E_{input} = P \cdot t \tag{3}$$

and

$$E_{useful} = c \cdot m \cdot \Delta T \tag{4}$$

where $c \approx 4200$ J/(kg·K) for water. Using these equations, calculate the heating efficiency:

$$\eta = \frac{E_{useful}}{E_{input}} \cdot 100\% \,. \tag{5}$$

~

LABORATORY

OF

TECHNICAL MECHANICS

Exercise 21

WATER TEMPERATURE CONTROL USING AN ON-OFF CONTROLLER

Group: ____________________________
Team: ____________________________

date ____________________________ **Name**

and surname:

1. ____
2. ____
3. ____
4. ____
5. ____
6. ____

Rated power of the kettle:

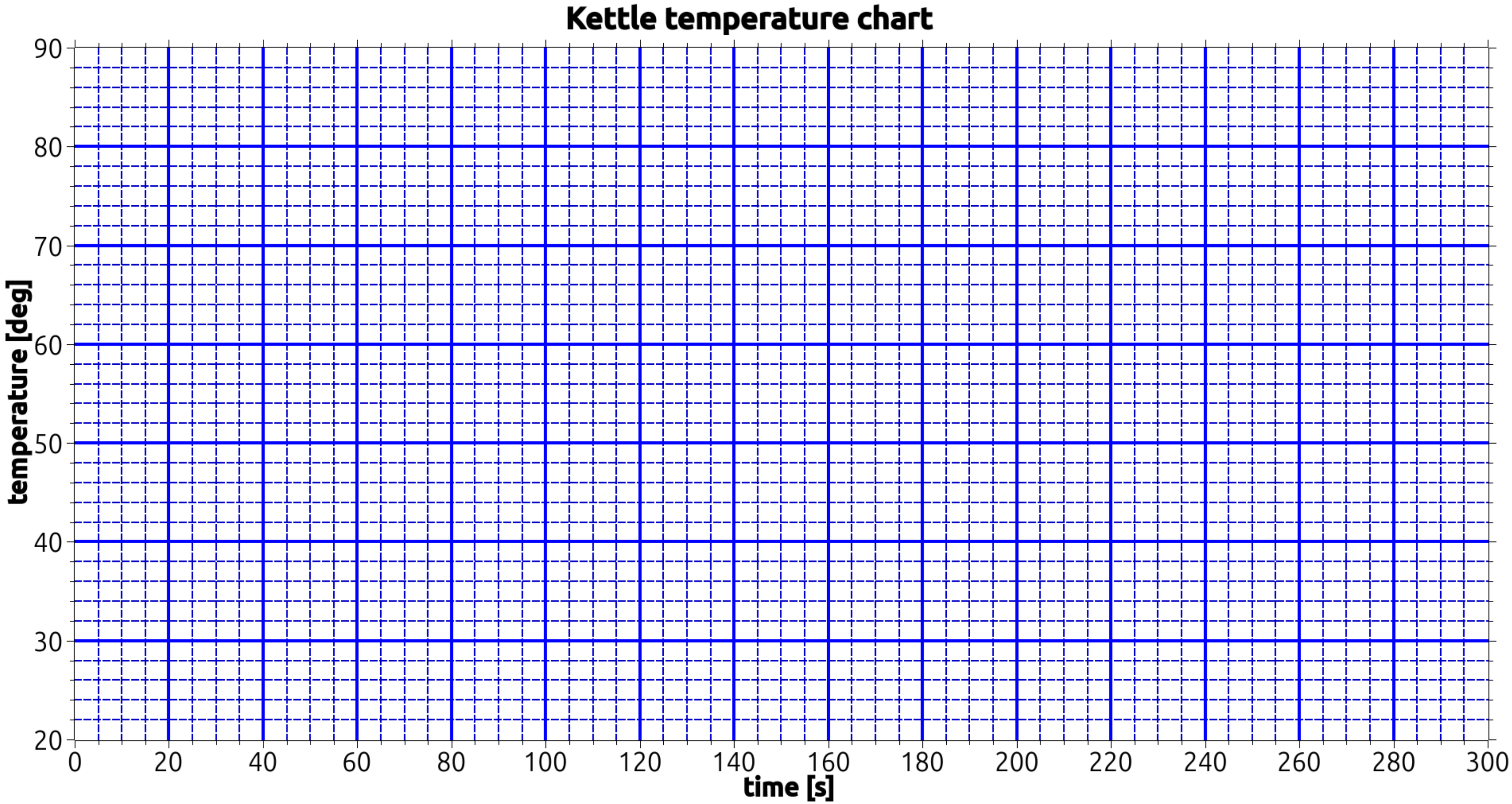
$P = \dots\dots\dots\dots\dots\dots$ W

Heating efficiency:

$E_{in} = \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots$ J

$E_{useful} = \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots$ J

$\eta = \frac{E_{useful}}{E_{in}} \cdot 100\% = \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\%$



Kettle temperature chart
temperature [deg]
time [s]
90
80
70
60
50
40
30
20
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300