AC/DC CONVERSION AND POWER SUPPLY FUNDAMENTALS

International Faculty of Engineering – BASIC ELECTRICITY – Exercise 22 *

1 Aim of the exercise

The aim of this laboratory exercise is to introduce the basic principles of AC-to-DC power conversion. The operation of a transformer, half-wave and full-wave rectifier circuits, and capacitive voltage filtering is investigated experimentally. Voltage waveforms at different stages of the circuit are observed and compared using an oscilloscope, the influence of the smoothing capacitor and load is analyzed, and the concept of RMS voltage together with its relation to peak and DC voltages is introduced.

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:

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

where:

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

The ideal waveform of such kind is presented in Fig. 1; in practice, it can be slightly distorted.

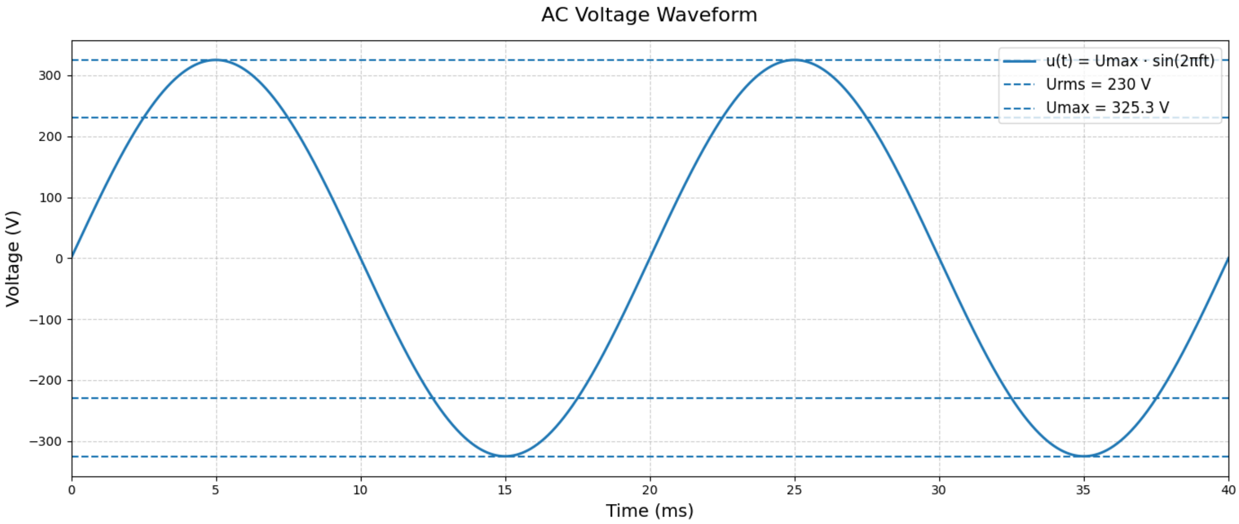

Figure 1: Ideal sinusoidal AC voltage waveform (230 V RMS, 50 Hz)

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

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For a time-dependent voltage $u(t)$, the RMS value is defined as:

$$U_{RMS} = \sqrt{\frac{1}{T}\int_0^T u^2(t)\,dt}$$

where:

- T - signal period,
- $u(t)$ - instantaneous voltage.

The formula follows directly from the expression for the average power dissipated in a resistor:

$$P = \frac{u^2(t)}{R}.$$

Consider energy transferred over one signal period T. As the voltage $u(t)$ varies with time, the power also changes with time. Therefore, the energy transferred over one period T cannot be obtained simply by multiplying the power by the signal period T as is done in DC circuits where the voltage U is constant. For a varying voltage $u(t)$, this relation is only valid over an infinitesimally short time dt. Consequently, a small portion of energy dE transferred during the time interval from t to $t + dt$ is equal to:

$$dE = \frac{u^2(t)}{R}dt.$$

The total energy over one period T can be obtained by integration.

$$E = \int_0^T \frac{u^2(t)}{R}dt$$

If the same energy was to be transferred due to the equivalent, constant voltage U_{RMS}, over the same period T, the energy would be expressed as:

$$E = \frac{U_{RMS}^2}{R}T.$$

Comparing this value with the previous formula yields:

$$\frac{U_{RMS}^2}{R}T = \int_0^T \frac{u^2(t)}{R}dt \rightarrow U_{RMS} = \sqrt{\frac{1}{T}\int_0^T u^2(t)\,dt}$$

where R cancels out from both sides of the equation. In other words, since the instantaneous power depends on the square of the voltage, the voltage must first be squared, then averaged over one period, and finally square-rooted to obtain a quantity expressed again in volts. This leads to the sequence:

- square the voltage,
- calculate the mean value,
- take the square root,

which explains the name Root Mean Square.
For a sinusoidal voltage:

$$u(t) = U_{\max}\sin(\omega t)$$

the RMS value is equal to:

$$U_{RMS} = \frac{U_{\max}}{\sqrt{2}} \approx 0.707U_{\max}$$

where $U_{\max}$ is the peak voltage. In the European Union, the standard RMS voltage in household electrical installations is equal to:

$$U_{RMS} = 230\text{ V},$$

the peak voltage:

$$U_{\max} \approx 325\text{ V},$$

and the frequency:

$$f = 50\text{ Hz}.$$

The electric power consumed by a device in the case of a purely resistive load can be calculated using the RMS voltage and RMS current:

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

where: P - electric power, U_{RMS} - RMS voltage, I_{RMS} - RMS current. For other types of loads, including inductive and capacitive loads, the power is expressed as:

$$P = U_{RMS} \cdot I_{RMS} \cdot \cos(\varphi)$$

where φ is the phase shift between the voltage and the current, which is not considered in this exercise.

2.1 Introduction to transformers

A transformer is an electrical device used to transfer energy between two circuits by means of electromagnetic induction. Transformers operate only with alternating current (AC), because their operation requires a time-varying magnetic flux. A constant direct current (DC) produces a constant magnetic field, which does not induce voltage in the secondary winding according to Faraday's law of electromagnetic induction. For this reason, a transformer connected to a pure DC source does not operate properly and may overheat due to the large current flowing through the primary winding.

A single-phase transformer consists of two wire coils, called the primary winding and the secondary winding, wound around a common ferromagnetic core. The alternating current flowing through the primary winding generates a time-varying magnetic flux in the core, which induces a voltage in the secondary winding, Fig. 2 [1].

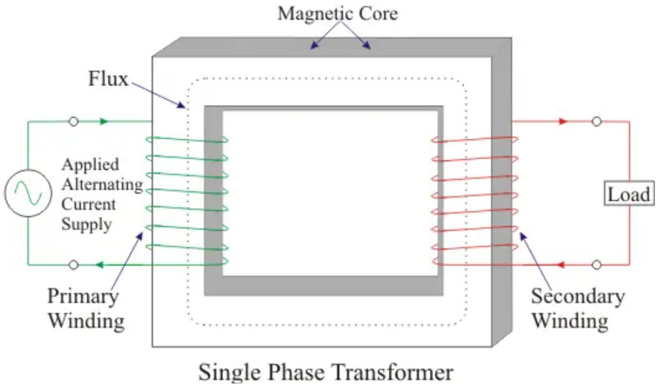

Figure 2: A simplified diagram of a single-phase transformer

The induced voltage is proportional to the number of turns in the winding. For an ideal transformer, the ratio of the voltages is equal to the ratio of the numbers of turns:

$$\frac{U_2}{U_1} = \frac{N_2}{N_1}$$

where: U_1 – primary voltage, U_2 – secondary voltage, N_1 – number of turns in the primary winding, N_2 – number of turns in the secondary winding.

If the secondary winding contains fewer turns than the primary winding, the transformer decreases the voltage (step-down transformer). Conversely, if the secondary winding contains more turns, the voltage is increased (step-up transformer).

In an ideal transformer, the input and output powers are equal:

$$P_1 = P_2$$

which leads to the current relation:

$$\frac{I_2}{I_1} = \frac{N_1}{N_2}$$

where:

- I_1 – primary current,
- I_2 – secondary current.

Real transformers are not ideal and exhibit energy losses caused mainly by the resistance of the windings, eddy currents, and hysteresis in the magnetic core. Nevertheless, transformers are highly efficient devices and constitute a fundamental component of electrical power systems and power supplies.

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[1] `https://www.electrical4u.com/single-phase-transformer/`

2.2 Rectifier diode and half-wave rectifier

A rectifier diode is a semiconductor device that allows electric current to flow primarily in one direction. In an ideal diode, current flows without resistance when the diode is forward-biased, while no current flows when it is reverse-biased. In practice, a real diode exhibits a small forward voltage drop (typically approximately 0.7 V for a silicon diode) and a small leakage current in the reverse direction, see Fig. 3 (left) [2] and (right) [3].

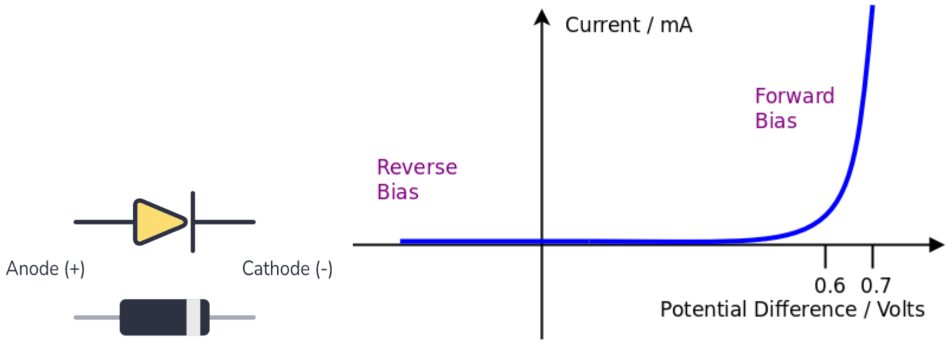

Figure 3: A rectifier diode with its symbol (left2) and example current-voltage characteristic (right)

The operation of a rectifier diode forms the basis of rectifier circuits, which are used to convert alternating current (AC) into direct current (DC).

The simplest rectifier circuit is the half-wave rectifier, consisting of a single diode connected in series with a load resistor. During the positive half-cycle of the input AC voltage, the diode is forward-biased and conducts current through the load. During the negative half-cycle, the diode becomes reverse-biased and blocks the current flow.

As a result, the output voltage contains only one half of the original sinusoidal waveform, Fig. 4 (left) [4]

$$u_{\text{out}}(t) = \begin{cases} u_i(t), & u_i(t) > 0 \\ 0, & u_i(t) < 0 \end{cases}$$

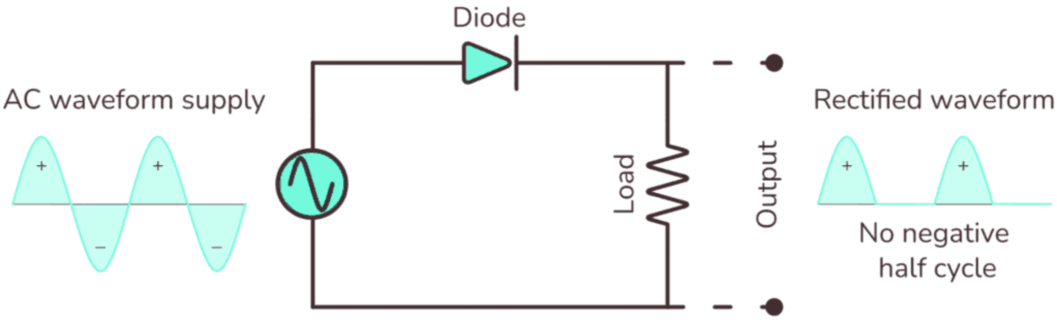

Figure 4: A schematic diagram of a half-wave rectifier and results of its operation

The output signal of a half-wave rectifier is a pulsating DC voltage with significant voltage variations. Although the polarity of the voltage remains unchanged, the voltage periodically drops to zero. Such a waveform can be observed directly using an oscilloscope.

2.3 Full-Wave Bridge Rectifier and Capacitive Filtering

A major disadvantage of the half-wave rectifier is that only one half of the AC waveform is utilized, resulting in low efficiency and large voltage fluctuations. A more efficient solution is the full-wave bridge rectifier, commonly called the diode bridge or Graetz bridge.

A bridge rectifier consists of four diodes arranged in such a way that the current flowing through the load always has the same direction, regardless of the polarity of the input AC voltage. During the positive half-cycle of the input voltage, two diodes conduct current, while during the negative half-cycle the other two diodes conduct, see Fig. 5. [5]

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[2] `https://www.build-electronic-circuits.com/rectifier-diode/`

[3] `https://pfnicholls.com/Electronics/diodes.html`

[4] `https://www.build-electronic-circuits.com/rectifier-diode/`

[5] `https://www.build-electronic-circuits.com/rectifier-diode/`

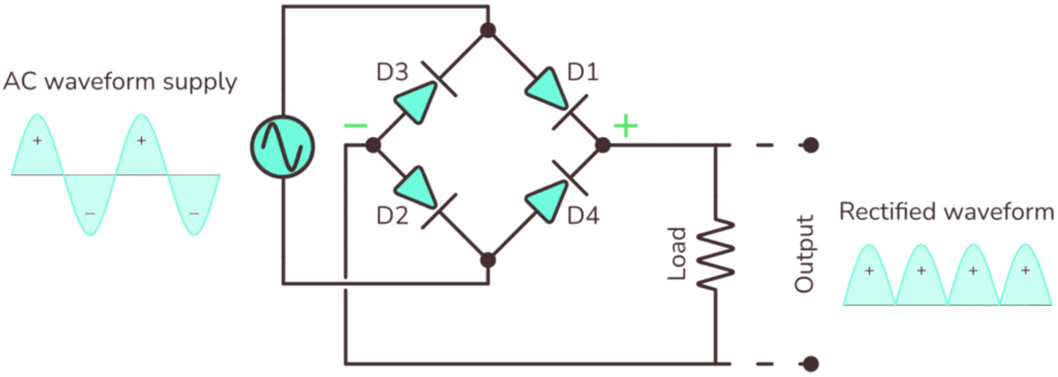

Figure 5: A schematic diagram of a full-wave rectifier and results of its operation

As a result, both halves of the sinusoidal waveform contribute to the output voltage. The output signal therefore consists of positive voltage pulses occurring at twice the frequency of the input AC signal. Compared to the half-wave rectifier, the output voltage drops to zero for a much shorter time, which makes the signal easier to smooth using a capacitor.

Although the bridge rectifier produces a unidirectional voltage, the output still contains significant fluctuations called ripple voltage. In power supplies, these fluctuations are commonly reduced using a smoothing capacitor connected in parallel with the load, see Fig.6. [6]

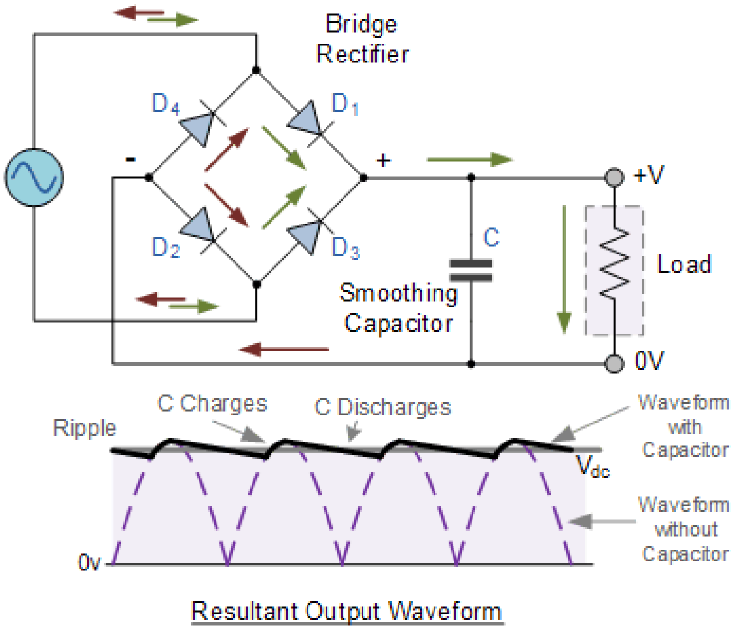

Figure 6: Bridge rectifier with smoothing capacitor and example output waveform

The capacitor charges when the rectified voltage increases and discharges through the load when the voltage decreases. As a result, the voltage across the load becomes much more constant.

For sufficiently large capacitance and moderate load current, the output voltage approaches the peak value of the rectified waveform:

$$U_{\text{out}} \approx U_{\max}.$$

In a real bridge rectifier, the output voltage is slightly lower because the current passes through two conducting diodes simultaneously. For silicon diodes, the total voltage drop is typically approximately:

$$U_{\text{drop}} \approx 2 \times 0.7 \text{ V} = 1.4 \text{ V}.$$

The remaining small periodic variations of the output voltage are called ripple. Their magnitude depends mainly on the capacitance, the load current, and the input signal frequency. Increasing the capacitance generally reduces the ripple amplitude and improves voltage smoothing.

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[6] `https://electronics.stackexchange.com/questions/363454/smoothing-a-full-wave-rectifier-voltage`

3 Procedure of the experiment

1. Familiarize yourself with the laboratory setup, including the transformer, rectifier diodes, smoothing capacitor, oscilloscope, and load (light bulb). Discuss the role and function of each circuit element.
2. Connect the oscilloscope to the transformer secondary winding and observe the AC voltage waveform. Measure the peak voltage and determine the approximate RMS voltage. Draw the observed waveform in the laboratory report.
3. Assemble the half-wave rectifier circuit on the breadboard using a single rectifier diode.
4. Observe the output voltage of the half-wave rectifier using the oscilloscope:
   - without the load connected,
   - with the light bulb connected as the load.
5. Compare the observed waveforms and draw them in the laboratory report.
6. Connect the smoothing capacitor in parallel with the load. Observe the change in the output voltage waveform and the reduction of ripple voltage. Sketch the resulting waveform and indicate the ripple in the laboratory report.
7. Assemble the full-wave bridge rectifier circuit using four rectifier diodes.
8. Observe the output voltage of the full-wave rectifier using the oscilloscope:
   - without the load connected,
   - with the light bulb connected as the load.
9. Compare the obtained waveforms with those of the half-wave rectifier and draw them in the laboratory report.
10. Connect the smoothing capacitor to the full-wave rectifier circuit. Observe the output waveform and compare the ripple amplitude with that of the half-wave rectifier. Sketch the waveform in the laboratory report.
11. Compare all measured waveforms and discuss the influence of the rectifier type and smoothing capacitor on the output voltage.

LABORATORY
OF
TECHNICAL MECHANICS

Exercise 22

AC/DC CONVERSION AND POWER SUPPLY FUNDAMENTALS

Group: ____________________
Team: ____________________

date ____________________ **Name**

and surname:

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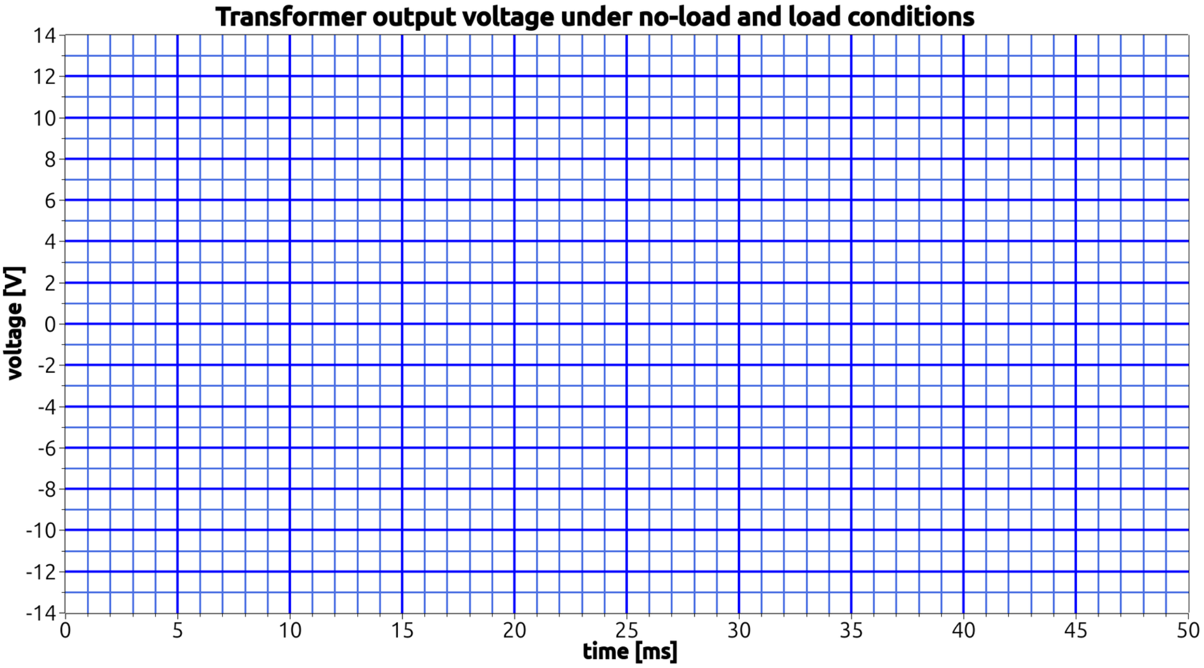
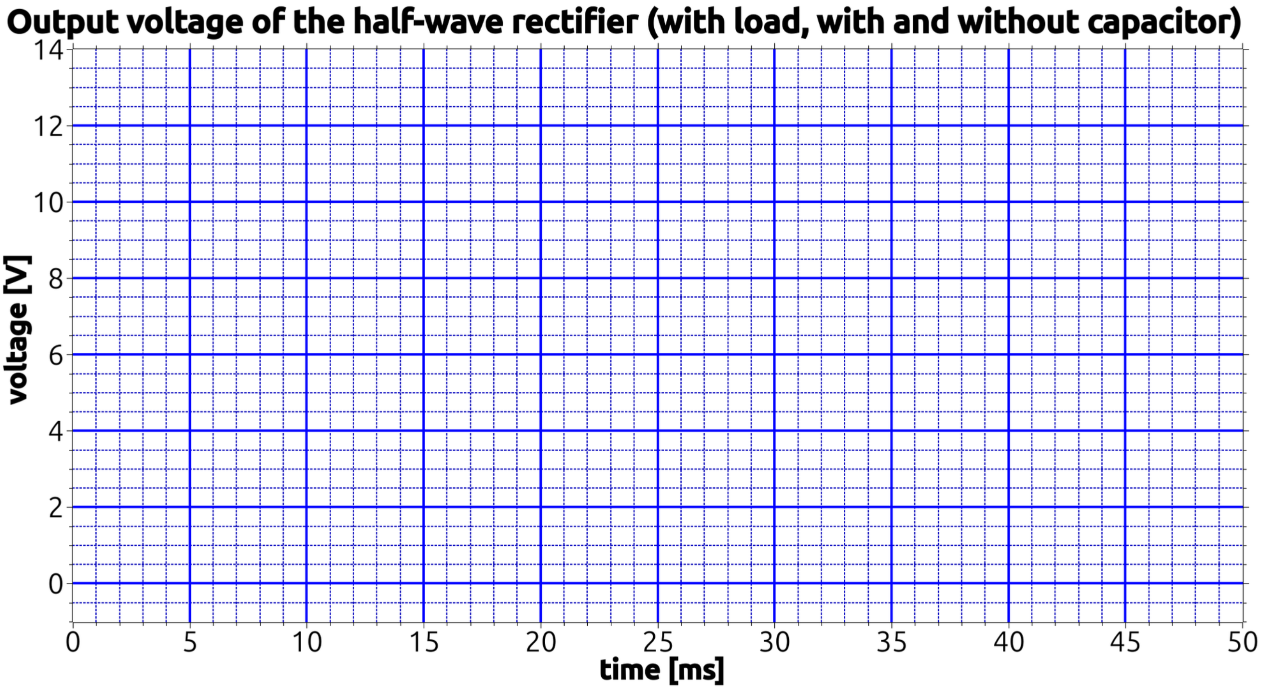
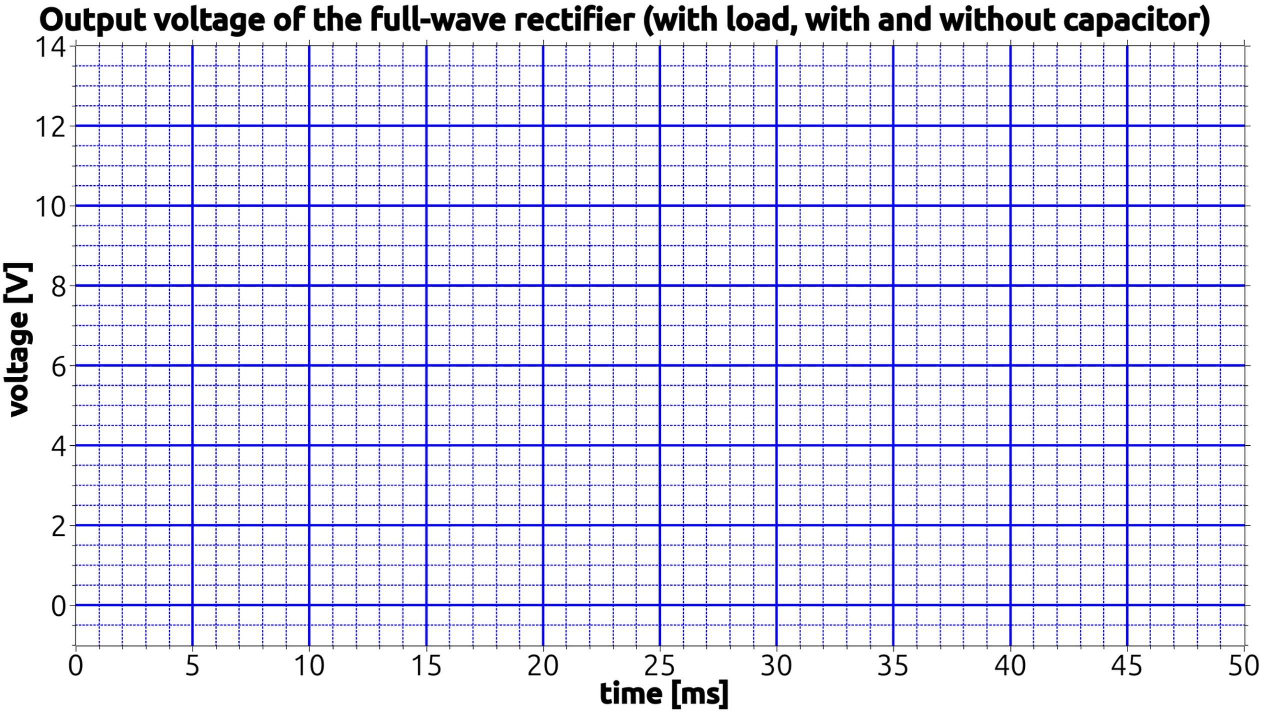




Calculation of the RMS value (without capacitor):



Calculation of the RMS value (without capacitor):