



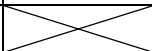
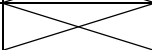
POWER DEVICES AND SYSTEMS LABORATORY

# Exercise 2

## Thyristors

### Electronic converter parameters AC voltage phase controller

Indicatory work plan

| Part | 15'   | 30'      | 45' | 1 <sup>h</sup> | 1 <sup>h</sup> 15' | 1 <sup>h</sup> 30' | After Class |
|------|---|----------|-----|----------------|--------------------|--------------------|-------------|
| A    |  | 4.1/1-12 |     | 4.1/13-17      |                    | 4.1/18-30          | 5           |
| B    |  | 4.2/1-11 |     | 4.2/12-15      |                    | 4.2/16-25          |             |

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Łódź 2015



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## Exercise Introduction

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### 1. Exercise Aim and Plan

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The aim of this exercise is to get acquainted with the thyristor (SCR and triac) and—based on the example of a triac-based AC/AC converter—to introduce the idea of semiconductor switch as well as of electronic converters working in switched mode. The investigated circuit will also give an opportunity to introduce the diac—an electron device closely related to the thyristor. References given provide an extensive description of these devices for the sake of completeness and equivalency between the English and the Polish manuals. However, this is excessive for this course as details of thyristor operation are not of interest in this exercise.

The main axis of the exercise is the assembly (from ready-made functional blocks), investigation and comparison of two circuits accomplishing the task of dimming an incandescent lamp: an electromechanical one based on a variable resistor, and an electronic one based on a TRIAC. Results will give an answer to the question whether it is expedient to develop power electronics, thus introducing to this branch of electronic science.

This manual also gives the possibility to supplement in-circuit measurements with simulation-based investigation. The simulations make it possible to observe waveforms that are not accessible in the measurement set-up, which will enable analysis of the electronic dimmer's operating principle.

The exercise also enables getting acquainted with a great part of measurement equipment and simulation software that will be used in the laboratory along the semester.



## 2. Thyristors

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### 2.1. Recommended reading

| Ref. | Textbook | Excerpt                                | Equivalent in the Polish Manual | Complementary Reading   | Complements in this Manual |
|------|----------|--|---------------------------------|---|----------------------------|
| A    | Ben      | 7, 7.1.1, 7.1.2, 7.1.4                 | #2 2.1                          | [12] Thyristor and Triac Ratings; Thyristor and Triac Characteristics |                            |
| B    | Ben      | 7.2                                    | #2 2.2                          |   |                            |
| C    | Ben      | 7.3, 7.3.1, 7.3.2, 7.3.3, 7.4.1, 7.4.2 | #2 2.3                          |   |                            |
| D    | Ben      | 8.4                                    | #2 2.4                          | [11] 1.2, 1.3.1<br>[12] High Commutation Triacs                       |                            |
| E    | Moo      | 1.8.1                                  | #2 2.5.c                        |   |                            |





### 3. AC/AC Converter

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#### 3.1. Recommended reading

| Ref. | Textbook | Excerpt | Equivalent in the Polish Manual | Complementary Reading | Complements in this Manual |
|------|----------|---------|---------------------------------|-----------------------|----------------------------|
| F    | Moo      | 4.2.4   | #2 3.2.a                        |                       |                            |
| G    | Moo      | 4.3.1   | #2 3.2.b–c,e                    |                       |                            |
|      |          |         | #2 3.2.d                        |                       | 3.2.a                      |
|      |          |         | #2 3.3                          |                       | 3.2.b–e                    |
|      |          |         | #2 3.1                          |                       | 3.3                        |

## 3.2. Controlling the incandescent lamp using an electronic power converter

### 3.2.a. Efficiency

If we assume that the semiconductor switch (triac) is ideal, then there is no power loss in it, because when the switch is on, its current  $i_{sw} = 0$ , and when it is off, the voltage across it  $u_{sw} = 0$ , which means that at any moment

$$p_{sw} = i_{sw} u_{sw} = 0 \quad (3.1)$$

so by definition

$$P_c = P_{sw} = (p_{sw})_{av} = 0 \quad (3.2)$$

Under this assumption from (3.31) we obtain

$$\eta = \frac{P_o}{P_o + P_c} = \frac{P_o}{P_o} = 1 \quad (3.3)$$

Real semi-conductor switches are not ideal, though. As shown in Fig. 2c–d, they have a finite resistance  $R_{off}$  in the off-state and a non-zero resistance  $R_{on}$  in the on-state. This results in energy being lost—dissipated as heat. The instantaneous power of this loss may be estimated as follows:

- (1) in the off-state (1<sup>st</sup> interval)—under the assumption that  $R_{off} \gg R_{Lp}$  (so the entire source voltage  $u_s$  will be present across the switch based on the voltage divider principle):

$$p_{sw(off)} \approx \frac{u_s^2}{R_{off}} \quad (3.4)$$

- (2) in the on-state (2<sup>nd</sup> interval)—under the assumption that  $R_{on} \ll R_{Lp}$  (the value of the current resulting only from the value of  $R_{Lp}$ ):

$$p_{sw(on)} = i^2 R_{on} \approx \left( \frac{u_s}{R_{Lp}} \right)^2 R_{on} \quad (3.5)$$

In such a case, average power loss in the converter—considering the symmetry of half-periods of the supply voltage sinusoid—equals

$$\begin{aligned} P_c &= \frac{1}{2\pi} \cdot \left[ \int_{\Omega_0}^{\Omega_1} p_{sw(off)} d\Omega + \int_{\Omega_1}^{\Omega_3} p_{sw(on)} d\Omega + \int_{\Omega_3}^{\Omega_4} p_{sw(off)} d\Omega + \int_{\Omega_4}^{\Omega_5} p_{sw(on)} d\Omega \right] = \\ &= \frac{1}{2\pi} \cdot 2 \cdot \left[ \int_{\Omega_0}^{\Omega_1} \frac{u_s^2}{R_{off}} d\Omega + \int_{\Omega_1}^{\Omega_3} \left( \frac{u_s}{R_{Lp}} \right)^2 R_{on} d\Omega \right] = \\ &= \frac{1}{\pi} \left( \frac{1}{R_{off}} \int_{\Omega_0}^{\Omega_1} u_s^2 d\Omega + \frac{R_{on}}{R_{Lp}^2} \int_{\Omega_1}^{\Omega_3} u_s^2 d\Omega \right) \end{aligned} \quad (3.6)$$

where  $\Omega$  is the phase angle corresponding to time. According to (3.31), this average power results in a decrease of converter's efficiency. As can be seen from equation (3.6), power loss is greater when the off-state resistance  $R_{off}$  of the switch is smaller, and when the on-state resistance  $R_{on}$  is greater

and this—which is important—with respect to the load resistance. The supply voltage influences both components in the same way.

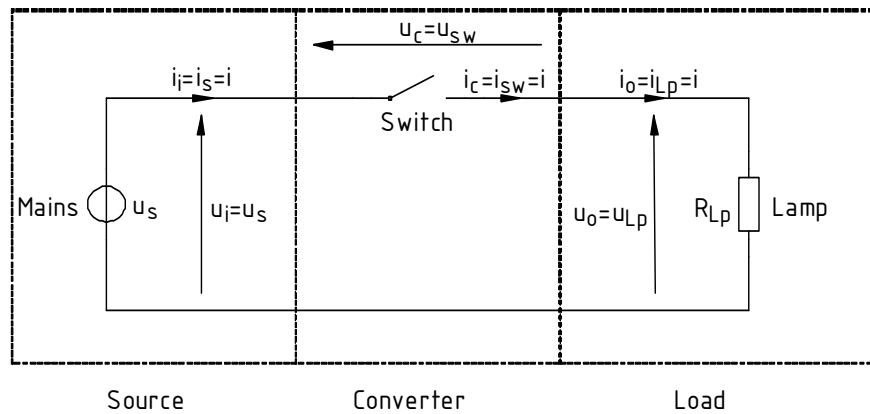


Fig. 1. Light bulb dimmer circuit based on a semi-conductor switch

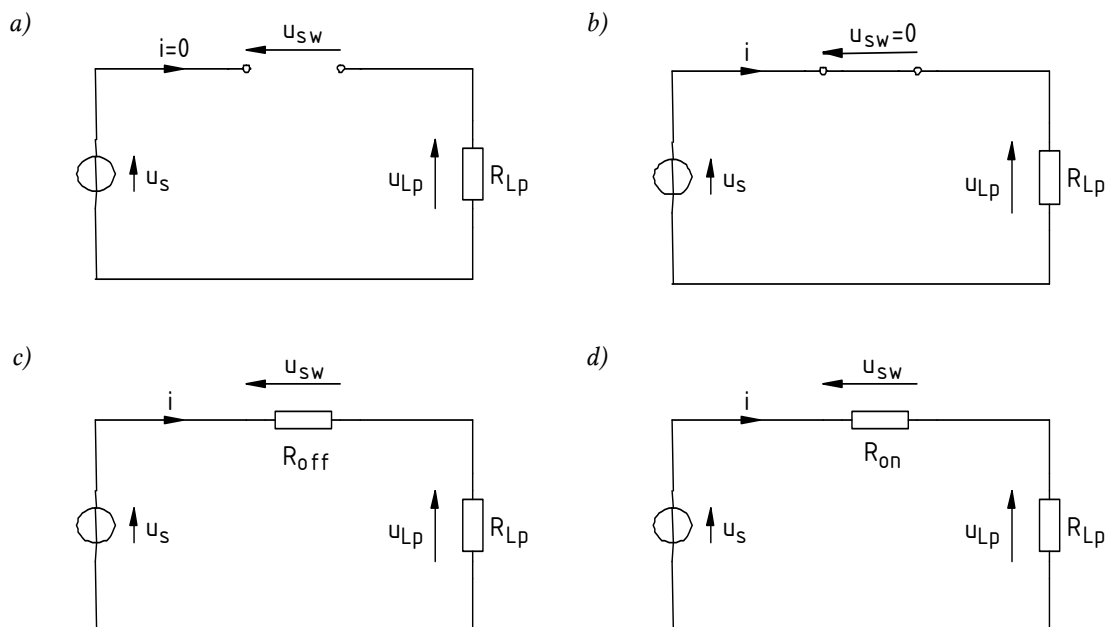


Fig. 2. Simplified equivalent schematic of the dimmer in two intervals of its operation: a), b) under the ideal switch assumption; c), d) with static power loss taken into account

### 3.2.b. Practical concept of a complete AC voltage phase controller

In the textbook, only the principal (power) circuit has been considered. We did not think about how to cause the triac to turn on at a desired—and variable—moment. This function must be performed by a separate circuit—the control one. Its task will be to generate pulses of gate current  $I_G$  that will trigger the triac's gate and turn it on.

An exemplary complete (i.e. including the principal as well as the control circuit) energy conversion system that contains an AC voltage controller is presented in Fig. 3a. The principal circuit is composed of a source (the mains)  $u_s$ , a receiver (the light bulb)  $R_{Lp}$  and a switch (the triac) T. On the other hand, the control circuit is composed of an RC network  $R_d C_d$  and a diac D. As can be seen, in this case the control circuit is directly supplied from the mains, too.

The control circuit considered here, of which the diac is an important element, is one of the simplest possible. In more exigent applications it happens to be necessary to use mains zero detection circuits, generate pulse trains (instead of single pulses), protect the triac from too high a voltage or current rise rate etc. Triac control is frequently realised using digital circuits.

### 3.2.c. The role of the RC divider

Apart from the diac, the RC network also plays an important role in the dimmer. In this case it constitutes an impedance voltage divider. Fig. 4a shows the phasor diagram for this circuit where the presence of the diac has been neglected for the moment.

The  $R_d C_d$  circuit may be described by means of an impedance magnitude

$$Z_d = \sqrt{R_d^2 + \left(\frac{-1}{\omega C_d}\right)^2} \quad (3.7)$$

and a phase angle

$$\varphi_d = \arctg \frac{-1}{\omega R_d C_d} \quad (3.8)$$

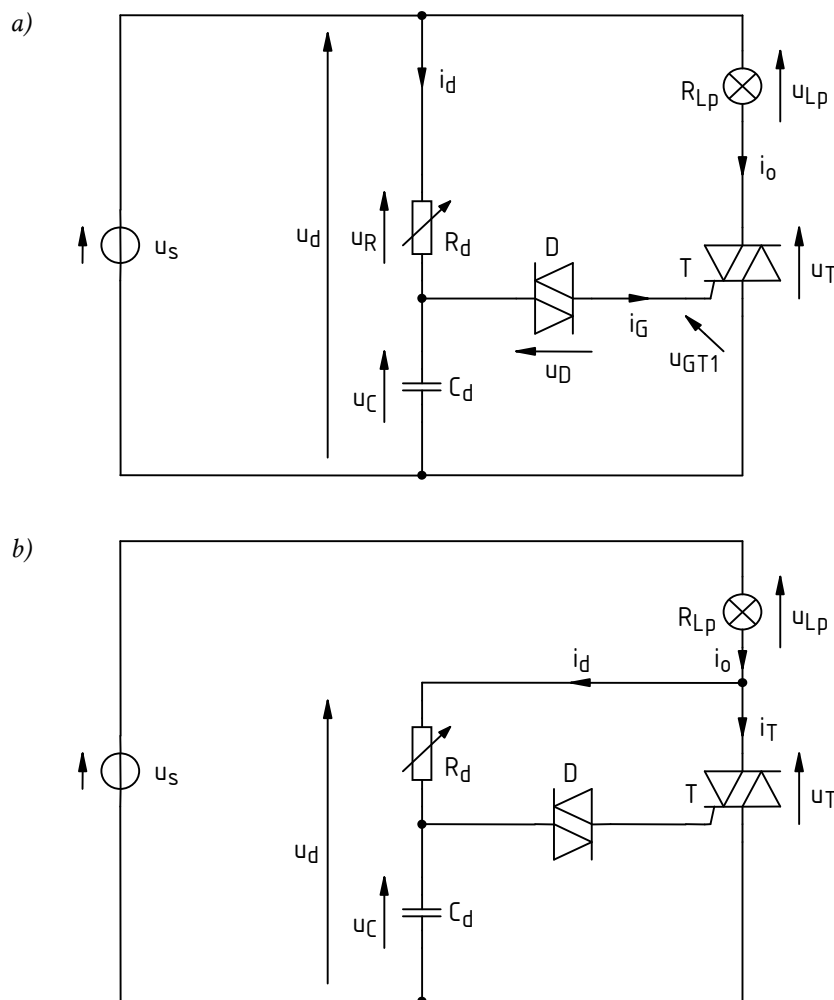


Fig. 3. Complete energy conversion system with an AC voltage phase controller using a diac-based triac control circuit: a) basic circuit; b) modified circuit

When a voltage  $u_d$ , equal to the mains voltage  $u_s$ , is applied to the RC network, a current  $i_d$  flows with an rms value of

$$I_d = \frac{U_s}{Z_d} \quad (3.9)$$

shifted with respect to the voltage by a phase angle of  $-\varphi_d$ . As for a capacitive network  $\varphi_d < 0$ , the phase of the current is in result greater than the phase of the voltage. Thus, the current precedes the voltage.

It is obvious that

$$u_d = u_R + u_C \quad (3.10)$$

so  $u_R$  and  $u_C$  phasors add up to give the  $u_d$  phasor. It is also known that the voltage across  $R_d$  resistor must be in phase with  $i_d$  current, and the voltage across  $C_d$  capacitor must be delayed by an angle of  $\pi/2$  with respect to this current. This leads to a phasor diagram shown in Fig. 4a. The system of  $\underline{U}_R$ ,  $\underline{U}_C$  and  $\underline{U}_d$  phasors must form a right triangle and it follows from geometry theorems that this triangle is inscribed in a circle with a diameter of  $U_d$ .

Based on the resulting diagram we can state that the voltage across the capacitor is shifted with respect to the mains voltage by the angle of

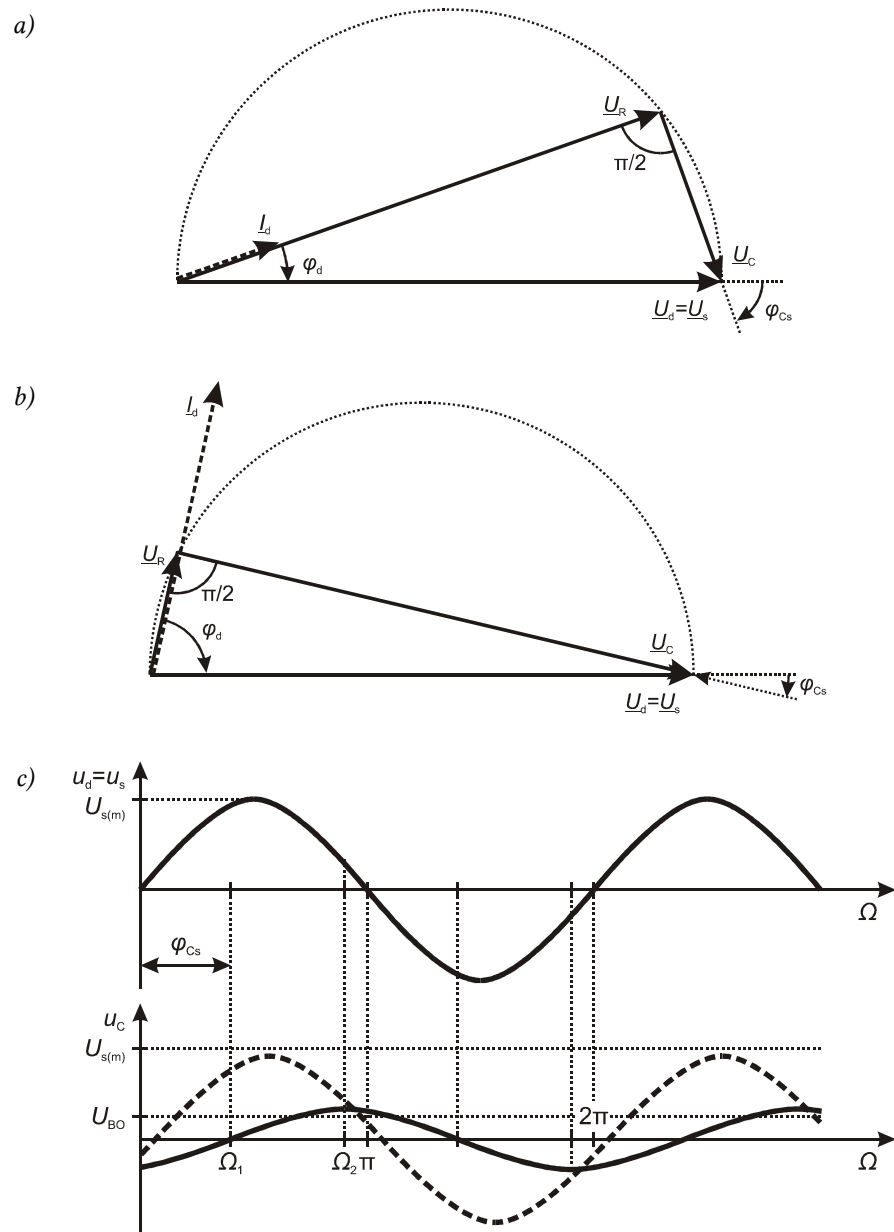


Fig. 4. Operation of  $R_d C_d$  divider without taking into account the presence of the diac: a) phasor diagram for a large resistance ( $R_d > 1/\omega C_d$ ); b) phasor diagram for a small resistance ( $R_d < 1/\omega C_d$ ); c) voltage waveforms (for a large resistance—solid line and for a small resistance—dashed line)

$$\varphi_{Cs} = -\frac{\pi}{2} - \varphi_d \quad (3.11)$$

Here  $\varphi_d < 0$  and as  $\varphi_{Cs}$  is also negative, we conclude that  $u_C$  is delayed with respect to  $u_s$ .

Waveforms of  $u_s$  and  $u_C$  in the considered case are presented in Fig. 4c (in the bottom plot see the solid line). Zero crossing of the voltage  $u_C$  only occurs at the angle of  $\Omega_1$  and maximum  $u_C$  is attained at the angle of

$$\Omega_2 = \Omega_1 + \frac{\pi}{2} = |\varphi_{Cs}| + \frac{\pi}{2} \quad (3.12)$$

If we make  $R_d$  smaller, the  $\varphi_d$  angle (its absolute value) increases and a greater  $I_d$  current flows in the circuit as a result of impedance  $Z_d$  decreasing. A smaller voltage  $\underline{U}_R$  appears across a smaller resistance but instead, a greater current causes a greater voltage drop  $\underline{U}_C$  across the capacitor. When added, phasors  $\underline{U}_R$  and  $\underline{U}_C$  must still yield the invariable supply voltage  $\underline{U}_s$ . Also, the angles between these phasors and the phasor  $\underline{I}_d$  cannot change. This leads to the phasor diagram shown in Fig. 4b.

Both equation (3.11) and the phasor diagram demonstrate that the phase shift  $\varphi_{Cs}$  (its absolute value) decreases. Waveforms of voltages  $u_s$  and  $u_C$  in this case are shown in Fig. 4c (in the bottom plot see the dashed line).

Let us consider two extreme cases:

- (1) For  $R_d \rightarrow \infty$  the network  $R_d C_d$  would gain a purely resistive character so phasors  $\underline{I}_d$  and  $\underline{U}_R$  would be in phase with phasor  $\underline{U}_s$  (triangle's vertice moves towards the right end of phasor  $\underline{U}_s$ ) and  $\varphi_{Cs}$  angle would equal  $-\pi/2$ . The amplitude of  $u_C$  would approach zero and  $\Omega_2$  (the angle of maximum  $u_C$  value) would approach  $\pi$ ;
- (2) For  $R_d \rightarrow 0$  the network would gain a purely capacitive character so  $\underline{U}_C = \underline{U}_s$  (triangle's vertice moves towards the left end of phasor  $\underline{U}_s$ ) and  $\varphi_{Cs} = 0$ . The amplitude of  $u_C$  would approach the amplitude of  $u_s$  and  $\Omega_2$  would approach 0.

### 3.2.d. The role of the diac

A diac begins to conduct current after voltage across it exceeds its breakover voltage  $U_{BO}$  which is of the order of 30 V. In the considered circuit the diac is connected between the upper terminal of the capacitor  $C_d$  and the triac's gate. Thus, the voltage across the diac is expressed by

$$u_D = u_C - u_{GT1} \quad (3.13)$$

As no current flows in the gate circuit (excepting the neglectable diac's leakage current), we may assume that the entire voltage  $u_C$  is applied to the diac.

When the voltage  $u_C$  exceeds  $u_{BO}$  of the diac, the latter device turns on (breaks over) which means that the loop  $C_d$ -D-G-MT1 is closed. As a result, a current  $i_G$  starts to flow in this loop supplied from the capacitor  $C_d$ . After some time the capacitor discharges and the current flow is stopped. If both the amplitude and the duration of current  $i_G$  pulse are sufficiently large, the triac will be turned on (triggered) and a current—equal to the lamp current  $i_o$ —will flow between its main terminals MT2 and MT1. Thus, energy will be delivered to the lamp.

After diac turns on, the voltage across the capacitor remains constant as it equals the sum of diac's on-state voltage  $U_{on}$  and triac's gate circuit voltage  $u_{GT1}$ .

The phase angle at which the capacitor voltage  $u_C$  attains the level of diac's break-over voltage depends on two factors:

- (1) the delay angle  $\varphi_{Cs}$  of the voltage  $u_C$  with respect to the voltage  $u_s$ ,
- (2) the rise rate of the voltage  $u_C$ , which results from this voltage's amplitude.

As we concluded in our analysis of the divider  $R_d C_d$ , both those factors are influenced by the current value of  $R_d$ . A decrease in  $R_d$  causes the delay angle to decrease and the voltage amplitude to

increase, so  $U_{BO}$  value is reached sooner (see Fig. 4c). An increase in  $R_d$  causes the delay angle to increase and the voltage amplitude to decrease, so  $U_{BO}$  is reached later. Thus, by changing the setting of resistor  $R_d$  we can obtain different triac turn-on angles  $\alpha$ . This way we can change the average power supplied to the lamp.

In order to obtain reliable triac turn-on, the amplitude of  $u_C$  should never be lower than the diac's break-over voltage  $U_{BO}$ . This should be assured by the circuit designer with appropriate  $R_d$  and  $C_d$  values. These values should also provide an adequately large impedance  $Z_d$  (3.7) so as the divider does not draw too large a current from the mains since it reduces efficiency and power factor of the converter.

The value of  $R_d$  must never be zero. In such a case, the entire mains voltage  $u_s$  would be applied between the gate and main terminal 1 of the triac. As this voltage surely exceeds the triac's absolute maximum gate voltage  $U_{GM}$ , the triac would be destroyed. In practice this is avoided by introducing an auxiliary constant resistor in series with the potentiometer. Unfortunately this reduces the range of the turn-on angle  $\alpha$  that can be achieved.

### 3.2.e. Modified circuit

In this exercise, a slightly modified system will be investigated. Its schematic is shown in Fig. 3b. It differs from the basic one by the way of connecting the  $R_dC_d$  network (the impedance voltage divider).

In the beginning, the operation of the circuit is just as described above. As there is no current flowing in the principal circuit ( $i_T = 0$ ), the lamp current is equal to a small—with respect to the nominal lamp current— $R_dC_d$  divider current  $i_d$ . Thus, the lamp is not lit. As the impedance of the voltage divider  $Z_d$  (3.7) is much greater than the load impedance, virtually the whole mains voltage is applied across the divider and so the assumption of  $u_d = u_s$  can still be hold. The triac is then turned on in the same way as it was in the basic circuit.

After the triac is turned on, the voltage across its principal circuit  $u_T$  falls to a small value. The assumption of  $u_d = u_s$  is no longer valid; instead,  $u_{Tp} \approx u_s$ . At the same time,  $u_d = u_T$ , which means that the divider is shorted by the low on-state resistance between the triac's main terminals. This forces the discharge of the capacitor and so, deactivation of the divider. This is favourable because it makes it more difficult for the triac to be turned on during commutation at current's zero-crossing. As we noticed, in the basic circuit the divider was constantly supplied from the mains, which caused a constant flow of some current through the gate of the triac.

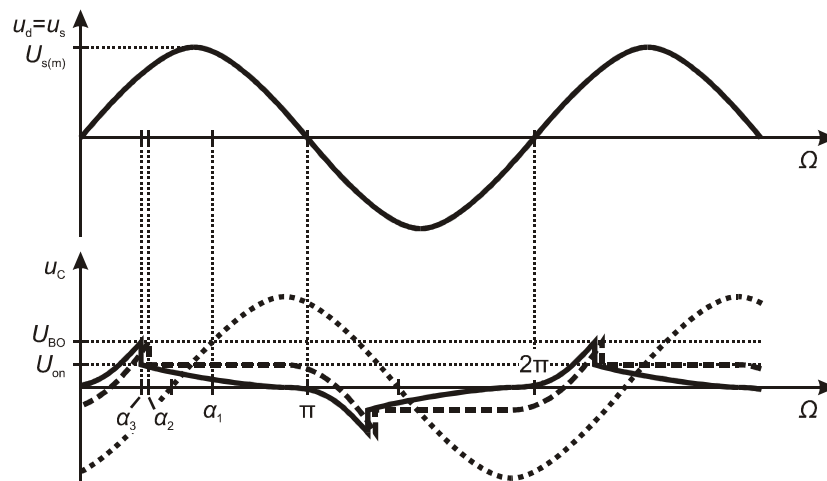


Fig. 5. Waveforms in the control circuit considering the diac turn-on (different scales for  $u_C$  and  $u_s$ ): without considering the presence of the diac (dotted line), basic circuit (dashed line), modified circuit (solid line)

Additionally, the triac's switching into conduction state is sharp which initiates a transient state. For safety reasons, an insulation transformer will be used during the experiment. Its secondary winding inductance would form an RLC network together with the  $R_dC_d$  divider. The transient would evoke oscillations there that could result in an incorrect triac triggering. The deactivation of

the divider after triac turn-on prevents the oscillations from occurring and causes the voltage across the capacitor to slowly go down to zero.

It should be added that the transient state due to the diac turn-on also results in a change in the capacitor voltage waveform. After diac turn-on, the voltage  $u_D$  across it is equal to some constant value,  $U_{on}$ . Under the assumption that  $u_{GT1} \ll U_{on}$ , this is also equal to the voltage across the capacitor  $u_C$  (Fig. 5, dashed line) unless—in the modified circuit—it has time to discharge thanks to being shorted through the triac,  $u_C$  becoming equal  $u_T \approx 0$  then (Fig. 5, solid line).

Anyway, at the beginning of a next half-period, voltage  $u_C$  starts from a different level, closer to zero than what is shown in Fig. 4c and with the dotted line in Fig. 5. The diac's break-over voltage will then be reached sooner than it has been predicted without earlier analysis. Therefore, the triac turn-on angle  $\alpha$  will be smaller. For the basic circuit it will be  $\alpha_2$  instead of  $\alpha_1$  (the value for only the divider being taken into account). As in the modified circuit  $u_C$  will be even closer to zero—due to the capacitor discharge—the turn-on angle  $\alpha_3$  will be even smaller.



### 3.3. Controlling an incandescent lamp using electrical elements

#### 3.3.a. Controller requirements

In this exercise we consider the problem of controlling power of a receiver (load) supplied from the European low voltage supply network whose voltage  $U_s$  is 230 V (rms value) and frequency  $f_s$  is 50 Hz. The load is an incandescent lamp (a light bulb) whose nominal power  $P_{Lpn}$  is 150 W. The circuit is therefore a typical light dimmer.

When designing electronic equipment, the most important is to minimise costs and to facilitate assembly and operation. Therefore, control should be:

- (1) simple (i.e. involving little elements, low cost of the elements, small dimensions and weight, low physical power), and
- (2) efficient (i.e. making it possible to make maximal use of power drawn, so with high efficiency and power factor).

#### 3.3.b. Control with a variable resistor

For the considered system, the source is the low voltage supply network which is represented with an ideal voltage source (alternating and sinusoidal)  $u_s$ ; the load—the light bulb—is purely resistive so it may be represented with a resistor,  $R_{Lp}$  (Fig. 6). In the schematic, “i” and “o” subscripts refer to converter's input and output, “s” refers to the source (or the supply), “c” refers to the converter.

If we complement the system with a variable resistor connected in series, a voltage divider with a variable division ratio will be formed. We will describe it quantitatively now. In the circuit, a current  $i$ —as can be seen in the schematic, common to all the 3 elements—will flow. According to the Ohm's Law, its value will be

$$i = \frac{u_s}{R_p + R_{Lp}} \quad (3.14)$$

so its rms value will be

$$I = \frac{U_s}{R_p + R_{Lp}} \quad (3.15)$$

Also conforming to the Ohm's Law, rms value of the voltage across the lamp is expressed as

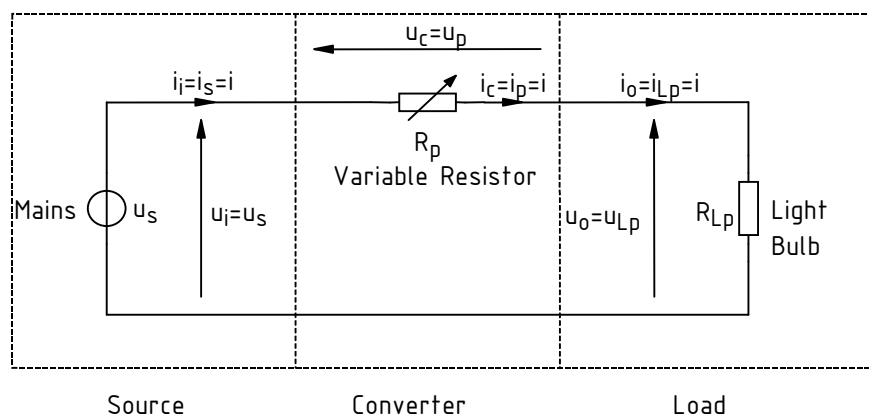


Fig. 6. Light dimmer circuit using a variable resistor

$$U_{Lp} = I_{Lp} R_{Lp} = IR_{Lp} = U_s \frac{R_{Lp}}{R_p + R_{Lp}} \quad (3.16)$$

Indeed we have obtained a resistive voltage divider, the division ratio depending on the current resistance  $R_p$  of the variable resistor.

We will now show that this way we can control the energy flow in the system. We are of course interested in the *net* energy flow, connected with conversion of energy into a useful form (in the considered case, light energy and—which is needless—thermal energy). This net energy flow in each period of circuit operation (in the considered case, in each mains voltage period) is characterised by the average (real) power. The light bulb being purely resistive, its average power is expressed as

$$P_o = P_{Lp} = I^2 R_{Lp} = U_s^2 \frac{R_{Lp}}{(R_p + R_{Lp})^2} \quad (3.17)$$

This relationship shows that by changing the resistance  $R_p$ , we influence the power flow from source to load. Thus, the variable resistor plays the role of a converter.

A maximum lamp average power is obtained for  $R_p = 0$  and equals

$$P_{o(\max)} = P_{Lp(\max)} = P_{Lp} \Big|_{R_p=0} = \frac{U_s^2}{R_{Lp}} \quad (3.18)$$

On the other hand, for increasing  $R_p$  we get

$$P_o \Big|_{R_p \rightarrow \infty} = P_{Lp} \Big|_{R_p \rightarrow \infty} \rightarrow 0 \quad (3.19)$$

The relative average output power  $P_{or}$ , defined with respect to its maximum value, is

$$P_{or} \stackrel{\Delta}{=} \frac{P_o}{P_{o(\max)}} \quad (3.20)$$

which in the case under consideration yields

$$P_{or} = U_s^2 \frac{R_{Lp}}{(R_p + R_{Lp})^2} \cdot \frac{R_{Lp}}{U_s^2} = \left( \frac{R_{Lp}}{R_p + R_{Lp}} \right)^2 = \left( \frac{1}{1 + R_p/R_{Lp}} \right)^2 \quad (3.21)$$

This quantity tells what portion of the maximum possible average power will be dissipated in the light bulb for a given  $R_p$  setting. It is obviously 1 (100%) for  $R_p = 0$  and 0 (0%) when  $R_p \rightarrow \infty$ .

The results obtained point out two severe disadvantages of the considered circuit:

- (1) it is not possible to get zero average output power, as in reality  $R_p \neq \infty$  always,
- (2) the control characteristic depends on both the variable resistor and the load—which can be seen from the  $P_{or} = f(R_p)$  relationship—so after the load is changed, this characteristic changes, too. Dimming of a 40-watt light bulb will proceed along a different curve than that for a 200-watt, i.e. for the same setting of  $R_p$  we will get a different percent of maximum average output power (as the light bulb resistance  $R_{Lp}$  will be different).

By analogy, the relative rms current value is defined as

$$I_r \stackrel{\Delta}{=} \frac{I}{I_{\max}} \quad (3.22)$$

which in the considered case leads to the relationship

$$I_r = \frac{U_s}{R_p + R_{Lp}} \cdot \frac{R_{Lp}}{U_s} = \frac{R_{Lp}}{R_p + R_{Lp}} = \frac{1}{1 + R_p/R_{Lp}} \quad (3.23)$$

### 3.3.c. Efficiency and power factor of the resistor-based circuit

The quality of energy conversion is primarily described by means of efficiency

$$\eta = \frac{P_o}{P_i} \quad (3.24)$$

It may be expected that it is not equal to 1, as the current flow through the resistor  $R_p$  produces a voltage drop across it and power dissipation in it. Thus, not all the input power gets to the load.

To calculate converter's efficiency, one must know the value of the average output power

$$P_o = P_{Lp} = \frac{U_s^2 R_{Lp}}{(R_p + R_{Lp})^2} \quad (3.25)$$

as well as that of the average input power which—taking into account that the load is purely resistive so there is no phase shift between current and voltage—is expressed with

$$P_i = P_s = U_s I = \frac{U_s^2}{R_p + R_{Lp}} \quad (3.26)$$

This way we obtain the formula for the converter's efficiency:

$$\eta = \frac{P_o}{P_i} = \frac{U_s^2 R_{Lp}}{(R_p + R_{Lp})^2} \frac{R_p + R_{Lp}}{U_s^2} = \frac{R_{Lp}}{R_p + R_{Lp}} \quad (3.27)$$

By analysis of (3.17) and (3.27) we can easily state that increasing the variable resistor's resistance leads to a decrease in the average power delivered to the lamp (so enables dimming) but at the same time it decreases efficiency. For extreme settings we obtain:

- for  $R_p = 0$ : the maximum lamp average power

$$P_{Lp} = P_{Lp(\max)} = \frac{U_s^2}{R_{Lp}} \quad (3.28)$$

which by definition equals the nominal power  $P_{Lpn}$  (assuming the lamp is supplied with a voltage  $U_s$  equal to its nominal one), and the efficiency  $\eta = 1$ ;

- for  $R_p \rightarrow \infty$ :  $P_{Lp} \rightarrow 0$  and  $\eta \rightarrow 0$ ;
- and the efficiency is halved for  $R_p = R_{Lp}$ , when the output power equals 1/4 of the maximal one.

The decrease of efficiency results from an increase of power loss in the converter, i.e. increase of power dissipated in the variable resistor. This power equals

$$P_p = I^2 R_p = U_s^2 \frac{R_p}{(R_p + R_{Lp})^2} \quad (3.29)$$

so it is a decreasing function of  $R_p$ . However, it is not the absolute value which is important here, but rather the relative one, calculated with respect to the power delivered to the lamp. A comparison of (3.29) and (3.17) lets us see that in both cases the nominator increases in the same way, however the numerator stays constant for the lamp but increases for the variable resistor. Thus, in the variable resistor (the converter) more and more power is lost—with respect to the amount delivered to the lamp (the load):

$$\frac{P_c}{P_o} = \frac{P_p}{P_{Lp}} = \frac{U_s^2 R_p}{(R_p + R_{Lp})^2} \frac{(R_p + R_{Lp})^2}{U_s^2 R_{Lp}} = \frac{R_p}{R_z} \quad (3.30)$$

This in turn results in a decrease in efficiency according to the formula

$$\eta = \frac{P_o}{P_o + P_c} = \frac{1}{1 + \frac{P_c}{P_o}} \quad (3.31)$$

which is derived from (3.24) taking into account that all the input power  $P_i$  is either delivered to the load (in a part that amounts  $P_o$ ) or lost in the converter (in another part, which amounts  $P_c$ ):

$$P_i = P_o + P_c \quad (3.32)$$

A second parameter important for assessment of electric power conversion quality is the power factor

$$\lambda = \frac{P_i}{U_i I_i} \quad (3.33)$$

For the considered converter-receiver system this equals

$$\lambda = \frac{P_s}{U_s I} = \frac{U_s^2}{R_p + R_{Lp}} \cdot \left( U_s \frac{U_s}{R_p + R_{Lp}} \right)^{-1} = 1 \quad (3.34)$$

Thus, the considered system loads the supply network in an optimal way. All the electrical energy circulating in the circuit is converted to another form of energy (useful—as lamp light, or needless—as the heat dissipated both in the lamp and in the variable resistor). Putting it differently, converter's average (real) input power and apparent input power are equal and there is no reactive power flow.

## 4. Measurements and Simulations

### 4.1. Investigation of an electromechanical dimmer with a variable resistor

#### Measurement set-up

The moment when you should start connecting the set-up is clearly marked in the course of this manual. You should not begin these actions before you get acquainted with all the preceding information nor before completing previous tasks.

The circuit under investigation together with necessary meters is shown in Fig. 7 where:

- $L_p$  is an incandescent lamp,  $P_n = 150 \text{ W}$ ,  $U_n = 230 \text{ V}$ ,

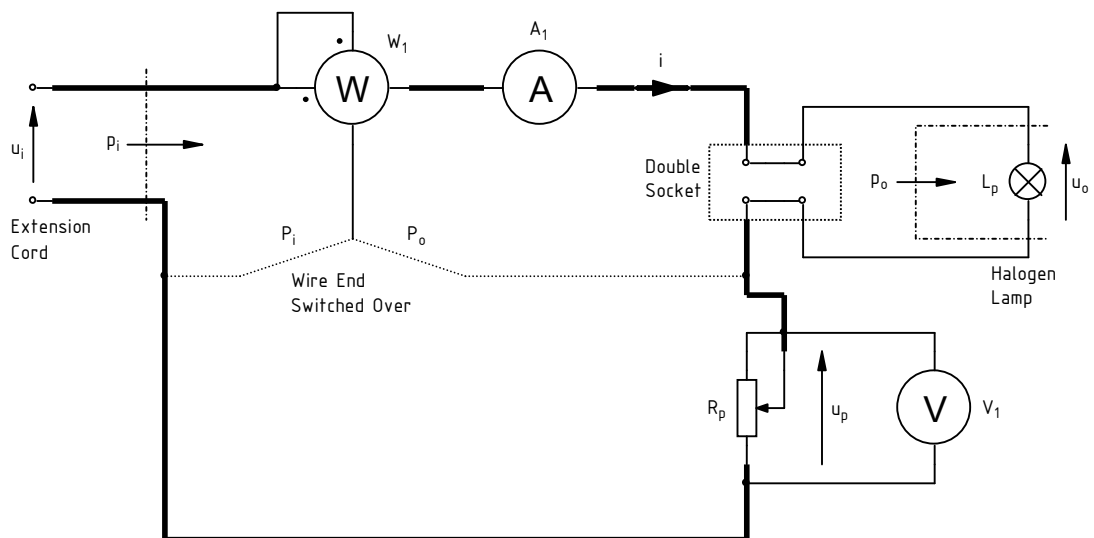


Fig. 7. Measurement set-up for the variable resistor-based dimmer

- $R_p$  is a slider-type high power variable resistor,  $R_{\max} = 1 \text{ k}\Omega$ ,  $P_n = 360 \text{ W}$ ,
- $W_1$  is a ferrodynamic analogue wattmeter,
- $A_1$  is an rms ammeter,
- $V_1$  is an rms voltmeter.

The circuit will be supplied with an AC voltage  $u_i$  directly from the 230 V, 50 Hz mains.

### Analogue wattmeter operation and usage

The structure of the wattmeter to be used is based on two coils: a fixed current one and a movable potential one, to which the meter's needle is attached. It is customary to draw the current coil (or its terminals in the wattmeter symbol) horizontally and the potential one, vertically. The operating principle of the device can be simplified as follows.

The current coil is wound on a gapped ferromagnetic core; the current flowing through this coil induces magnetic field. The potential coil is mounted on an axis. A large value resistor is connected in series with this coil, whose resistance is much greater than the coil's reactance; as a result, a small current flows through the coil. This current is practically proportional to the voltage that is applied to the potential sub-circuit (the coil with the resistor), as the phase shift is negligibly small because of the resistance to reactance ratio. It follows from magnetism laws that the magnetic field induced by the current coil acts on the potential coil, which constitutes a conductor leading a current. Magnetic field has its greatest strength in the gap of the core; for this reason, the potential coil is mounted in the gap so as to obtain a sufficiently strong action despite the small potential coil current. This way, magnetic field produces torque that makes the potential coil rotate by some angle and thus, a deflection of the needle is observed.

The torque is an increasing function of the product of both coil currents. Therefore, if the current coil is connected so that the current of a two-terminal device flows through it, and the potential coil (the series resistor included, but this is normally omitted in informal language), so that this device voltage appears across it, then the torque is a function of this device instantaneous power. However, the coil has some inertia and reacts to the average—and not instantaneous—torque. Thus, the needle's indication is a function of the average power of the device under consideration. A wattmeter can of course be also applied to four-terminal devices for which input or output power can be measured (one at a time, of course).

A ferromagnetic wattmeter has four binding posts. The ends of the current coil are connected to the binding post pair labelled as "A", whereas the ends of the potential one (strictly speaking, together with the large series resistor), to the pair labelled "V". One of the terminals is normally distinguished with an asterisk or a dot, both on the meter's casing and in schematics. This symbol marks the conventional coil beginnings and eases wattmeter connection in a way that its average power indication is positive. If we refer to the traditional way of voltage and current direction marking in power converter circuits, the beginning of the potential coil should be connected to the voltage arrow's *head*, whereas the beginning of the current coil, to the point which the current arrows points *from*. Other wattmeter connections are also possible, enabling average and passive power measurements in three-phase systems.

It should be pointed out that in the case of multiple-range wattmeters, separate measurement ranges apply to voltage and current. This yields multiple combinations that cannot be reflected on the scale. Therefore, the scale is labelled dimensionlessly with 100 divisions. The power value in watts is obtained from the formula

$$P[\text{W}] = \frac{P^*[\text{div}] \cdot k_w[\text{W}]}{100 \text{ div}} \quad (4.1)$$

where  $P^*$  is the wattmeter indication in divisions and  $k_w$  is the so-called wattmeter constant equal

$$k_w[\text{W}] = k_v[\text{V}] \cdot k_A[\text{A}] \quad (4.2)$$

and  $k_v$  and  $k_A$  are voltage and current ranges of the meter, respectively.

In the present exercise, the end of the potential coil can be connected in one of the two ways. The connection marked in Fig. 7 as  $P_i$  enables measurement of the converter's average input power  $P_i$ , as the input voltage is then applied to the potential coil. By analogy, another connection, marked as  $P_o$ , enables measurement of the converter's average output power  $P_o$ . The current coil is connected in the same way in both cases as for an AC voltage controller, input and output currents are the same.

### Setting up the circuit

1. Plug off the white extension cord from the mains and free all its sockets.
2. Assuming the light bulb is a purely resistive receiver, based on the formula for resistor's average power, calculate the rms value of the current that will flow in the circuit after supplying it from the 230 V mains at  $R_p = 0$ .
3. Configure the meters based on data given above and on your results from step 2:
  - (a) If a digital multimeter is used as the ammeter or as the voltmeter, use its knob to choose an appropriate function and range. Consider also choosing the rms value of AC waveform (typical markings are AC and ~; see also step 13).  
For an analogue meter, determine an appropriate range.
  - (b) Choose appropriate ranges for the wattmeter.
4. Make connections in the circuit according to the schematic and to the following guidelines (without plugging the extension cord to the mains):

**If a plug jams in a socket, don't draw it by force but rather spin around and gently pull up at the same time. Otherwise the plug will be damaged.**

- (a) First connect the current circuit—along the principal current  $i$  path (marked in bold in Fig. 7). Only afterwards connect the wattmeter's potential coil and the voltmeter.
  - (b) Connect the halogen lamp through a double mains-type socket.
  - (c) Use spade-to-banana adaptors for older meters' binding posts without any socket.
  - (d) Terminal arrangement of the variable resistor is given with a symbol on its upper surface. All the 3 terminals of this component should be appropriately connected to avoid unoccupied live terminals that can be accidentally touched.
  - (e) Use meter sockets appropriate for the function (when a multimeter is involved) used and for the ranges determined in step 3.
  - (f) Note the beginnings of wattmeter's coils.
  - (g) One wire should be fixed to the end of wattmeter's potential coil. Further connections should be realised in a way that enables future switching over (after de-energising the circuit) this wire's other end so as to toggle between  $P_i$  and  $P_o$  connections (see Fig. 7). The average input power measurement connection  $P_i$  should be realised initially.
5. Turn off digital meters for the moment.
  6. Set the wiper of the variable resistor approximately in the middle.
  7. Using the yellow-green wire, connect the case of the variable resistor to the protective earth pin in the main extension cord, in a way that makes it difficult for the wire to disconnect in the course of the exercise.
  8. Ask the teacher to check your connections. In the meantime, continue with steps 9–12.
  9. Turn on the computer.
  10. After logon completes, turn on the oscilloscope and configure the connection to the computer, strictly following the procedure described in a manual available at the laboratory stand.
  11. Using the communication application, upload initial settings to the oscilloscope:
 

[HM1507]

    - choose *Data* ▷ *Load* from the menu;

- choose *Settings (\*.set)* as file type;
- read the file *ustawienia\_2\_hm1507.set*;
- click the *Set* button.

[TDS1002B]

- open the *Get & Send Settings* tab;
- click *Open* and read the file *ustawienia\_2\_tds1002b.set*;
- click *Send Settings*;
- return to the *Screen Capture* tab.

[TDS224]

- choose *File > Open* from the menu and open the file *ustawienia\_2\_tds224.sht*; in a next dialog box click *Offline*;
- on the list shown in the left side panel unfold the installed oscilloscope, *Data, Settings*;
- in the window containing the settings file, select the entire contents and drag them with the mouse to the *Full Setup* item in the left side panel;
- wait while changes are being introduced on the oscilloscope, which is evidenced by changing screen elements (letters, numbers, curves).

12. Detach any voltage probes from the oscilloscope.

### Power conversion characteristics

#### Warning!

**From this point on, you can only continue after the instructor has explicitly accepted your wiring.**

#### While making measurements:

**Except for the safety-grounded case of the variable resistor, do not touch any parts of the measurement set-up when it is energised (connected to the mains)! Particularly do not touch internal parts of the variable resistor nor the point marked with yellow tape and dangerous voltage sign, nor the metal casing of the halogen lamp. Risk of shock!**

**Don't make any switch-overs in the circuit when it is energised! This also applies to changing analogue and digital meter ranges or functions! Risk of shock and meter destruction!**

**Always disconnect the circuit from the mains by plugging the extension cord's plug off the mains socket.**

**During all the experiment make sure that no wire touches the light bulb—risk of insulation damage due to high temperature!**

13. Turn on digital meters. For some of them it is necessary to select the AC component rms value measurement function (if it is not chosen with the main knob): [YF-...] blue button; [M-3660D] AC/DC button; [PC510, CD771] *Select* button.

**If a meter where the above function is selected with a button is turned off during measurements, it must be selected again after the meter is turned back on. Otherwise results obtained will be useless.**

**If the battery discharge indicator (a battery symbol) shows up on the meter's display, do not continue measurements but ask the teacher to replace the battery. Otherwise meter indications may become erroneous.**

14. Plug the extension cord into the mains socket (use the main extension cord at the laboratory stand).

15. Make a series of measurements for 10 to 15 points between the extreme settings of the variable resistor's wiper. For each measurement point measure and note down:



**For each measurement point, all the following sub-steps should be executed; only then you can proceed to a next measurement point!**

- (a) rms current  $I$  which is the indication of  $A_1$  (for an analogue meter make sure you read the value out of the proper scale);

If the ammeter used is an analogue one and has more than one measurement range, always use the lowest one that the currently measured value fits in. Only change the range after disconnecting the circuit from the mains. Make sure you read the indication out of the proper scale. Analogical remarks apply to the voltmeter.

- (b) rms voltage across the variable resistor  $U_p$  which is the indication of  $V_1$  (for an analogue meter make sure you read the value out of the proper scale);

**Warning!**

**Only change over the connection of wattmeter's voltage coil between  $P_i$  and  $P_o$  positions after plugging the extension cord off the mains.**

**Measurements of  $P_i$  and  $P_o$  may be done in either sequence, however, for any measurement point they must be done consecutively, i.e. without changing the variable resistor's setting!**

- (c) average input power  $P_i$  which is the indication of  $W_1$  when connected to  $P_i$  (note down the indication in divisions  $P_i^*$  together with the set voltage range  $k_V$  and current range  $k_A$ );
- (d) average output power  $P_o$  which is the indication of  $W_1$  when connected to  $P_o$  (note down the indication in divisions  $P_o^*$  together with the set voltage range  $k_V$  and current range  $k_A$ ).

**Ensure that data for a point corresponding to the maximum output power have been recorded upon completion of the above step.**

16. Measure the rms input voltage  $U_i$ :
- Plug the extension cord off the mains.
  - Switch over the voltmeter  $V_1$  so as to measure the input (mains) voltage  $U_i$ .
  - Re-energise the circuit.
  - Note down the indication of  $V_1$ .
17. Plug the extension cord off the mains.

**Time domain operation**

18. Prepare the current probe:
- attach the current probe to oscilloscope's channel 1 following the procedure described in a manual available at the laboratory stand;
  - set up the current probe following the procedure described in the manual;
  - if the current probe used has an adjustable current/voltage conversion ratio, set a conversion ratio appropriate for the current value determined in step 3;
  - set up the oscilloscope for using the current probe following the procedure described in the manual;
  - ask the instructor to demonstrate how to use the current probe;
  - close the probe around any wire leading the circuit's principal current  $i$  (i.e. the light bulb's one; current direction is not important in this case).
19. Switch over  $W_1$  voltage coil to the  $P_o$  position.
20. Plug the extension cord into the mains.
21. Set the variable resistor  $R_p$  to maximum output power.

22. Adjust oscilloscope settings ensuring that a current waveform conforming to the operating principle of the circuit under investigation (see Section 3.3.b) finally appears on the oscilloscope's screen:
- Set the time base, i.e., the horizontal scale (TIME/DIV or SEC/DIV knob depending on the model), so that 2–4 waveform periods can be observed on the screen.
  - Set channel 1 gain, i.e., the vertical scale (VOLTS/DIV), so that the waveform vertically fills in the screen to a maximum but does not extend beyond it.
23. Download the waveform image to the computer and save it to a file:
- [HM1507]
- click *Read* in the application;
  - choose *Data* ▸ *Save* from the menu;
  - save as a *Measurement* (\*.mes) file.
- [TDS1002B]
- in the *Screen Capture* tab, click *Get Screen*;
  - click *Save As* and save the image in a graphic format other than JPG.
- [TDS224]
- choose *File* ▸ *New Datasheet* from the menu, choose *Notes Sheet* and accept;
  - on the list shown in the left panel unfold the installed oscilloscope and *Display*;
  - drag the *Screen Copy* item and drop it in the newly created *Notes Sheet* window;
  - save the *Notes Sheet* document as an SHT file: menu *File* ▸ *Save Datasheet As*.
24. Note down the current/voltage conversion ratio of the current probe (see the probe's manual).
25. Without making any changes in the circuit, on the probe (or amplifier), nor on the oscilloscope, set the variable resistor  $R_p$  so that the average output power equals about 50% of its maximum value (i.e. the value indicated until now).
26. Repeat step 23.
27. Disconnect the current probe from the circuit and turn it (the probe) off using the *ON/OFF* switch (for the mobile probe) or turn off its amplifier (in other case).

### Concluding the investigation

28. Disconnect the circuit from the mains—plug the extension cord's plug off the mains socket.
29. Disconnect all the other wires.
30. Make and write down observations concerning dimensions and weight of circuit components of the dimmer investigated.

## 4.2. Investigation of a triac-based electronic dimmer

### Measurement set-up

The moment when you should start connecting the set-up is clearly marked in the course of this manual. You should not begin these actions before you get acquainted with all the preceding information nor before completing previous tasks.

The circuit under investigation together with necessary meters is shown in Fig. 8 where:

- $L_p$  is an incandescent lamp,  $P_n = 150 \text{ W}$ ,  $U_n = 230 \text{ V}$ ,
- $R_p$  is a potentiometer,  $470 \text{ k}\Omega$ ,  $P_n = 1/4 \text{ W}$ ,
- $R_{aux}$  is an auxiliary resistor  $10 \text{ k}\Omega$ ,  $P_n = 1/4 \text{ W}$ ,
- $C$  is a film capacitor,  $100 \text{ nF}$ ,  $U_n = 250 \text{ V (AC)}$  lub  $630 \text{ V (DC)}$ ,
- $D$  is a diac, DB3,
- $Th$  is a triac, BT136-600,
- $W_1$  is a digital wattmeter with wattmeter function (M-3860M),
- $V_2$  is an rms voltmeter, electromagnetic (a zigzag coil on core symbol) if analogue or true rms if digital.

The circuit will be supplied with an AC voltage  $u_i$  from the 230 V, 50 Hz supply network through an insulation transformer with a ratio of approx. 1:1.

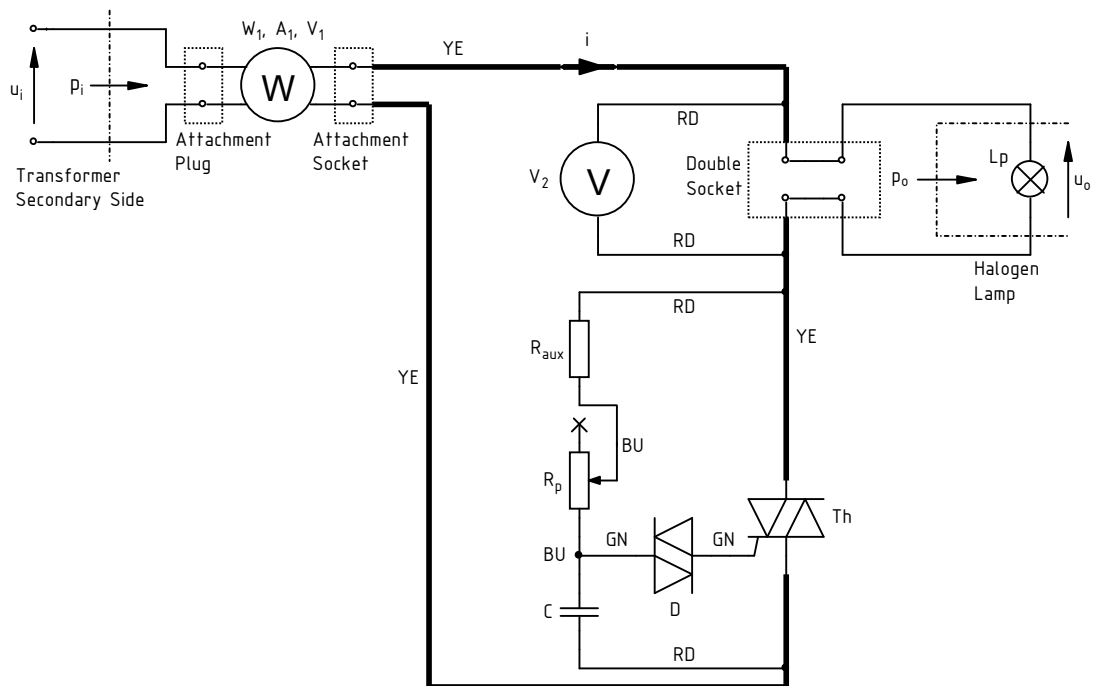


Fig. 8. Measurement set-up for the triac-based dimmer

### Operation and usage of the multimeter with wattmeter function

The operation of the wattmeter used is based on simultaneously recording instantaneous current and voltage values in a given location within a circuit in consecutive moments of time. These data are processed including multiplication and averaging and the average power is obtained. The length of the averaged sample is of the order of one second, which results in display being considerably delayed; this should be kept in mind during output power setting.

It follows from the above that both the ammeter and the voltmeter internal circuits must be used to measure power. Their proper connection has been made easier with an attachment in the plug-and-socket form with a side connection to the multimeter. The plug of the attachment is connected to the power source whereas the further part of the circuit (i.e., the part on the receiver's side) is plugged in its socket. The multimeter connector is a three-terminal plug which should be inserted into the meter's sockets so that labels on the connector and on the meter's casing are consistent with each other.

Thanks to the recording of both voltage and current samples being necessary for power measurement, the multimeter can easily calculate rms input current (which is symbolised by  $A_1$  in Fig. 8) and rms voltage ( $V_1$ ). Therefore, when the multimeter is used in wattmeter mode, it displays all the three values (average power, rms current and rms voltage) simultaneously on one screen.

### Setting up the circuit

1. Plug off the white extension cord from the mains and free all its sockets. Plug the transformer's primary side plug (through a black soft start device if available) into one of the extension cord's sockets. Leave the transformer's secondary side socket unoccupied.
2. Assuming the light bulb is a purely resistive receiver, based on the formula for resistor's average power, calculate the rms value of the current that will flow in the circuit after supplying it from the 230 V mains when the triac is ideally turned on (zero voltage between its main terminals).
3. Configure the meters based on data given above and on your results from step 2:
  - (a) Using the knob, choose an appropriate function on the multimeter  $W_1$ .
  - (b) If a digital multimeter is used as the voltmeter  $V_2$ , use its knob to choose an appropriate function and range. Pay attention to choosing the AC waveform rms value measurement (typical markings are AC and  $\sim$ ; see also step 12).

For an analogue meter, determine an appropriate range.

4. Make connections in the circuit according to the figure and the following guidelines (without plugging the extension cord to the mains nor the wattmeter's attachment to the transformer's socket):

**If a plug jams in a socket, don't draw it by force but rather spin around and gently pull up at the same time. Otherwise the plug will be damaged.**

- (a) Use wires with insulated (with the exception of wires connecting to standard grid sockets) plugs that contain an extra vertical socket enabling to make multiple connections at one point.
  - (b) Apply colour coding as shown in Fig. 8:
    - yellow (YE) and red (RD) for the high-voltage part,
    - green (GN) for the triac gate circuit,
    - blue (BU) for the rest of the control circuit.
  - (c) First connect the current circuit—along the principal current  $i$  path (marked in bold in Fig. 8). Only afterwards wire the control sub-circuit and connect the voltmeter.
  - (d) Use meter sockets appropriate for the function (of the meter) used and for the ranges determined in step 3.
  - (e) Use spade / banana adaptors for older meters' binding posts without any socket.
5. Turn off digital meters for the moment.
6. Set the wiper of the variable resistor approximately in the middle.
7. Ask the instructor to check your connections. In the meantime, continue with steps 8–11;
8. Turn on the computer.
9. After logon is finished, turn on the oscilloscope and configure the connection to the computer, strictly following the procedure described in a manual available at the laboratory stand.
10. Using the communication application, upload initial settings to the oscilloscope:

[HM1507]

- choose *Data* ▸ *Load* from the menu;
- choose *Settings* (\*.set) as file type;
- read the file *ustawienia\_2\_hm1507.set*;
- click the *Set* button.

[TDS1002B]

- open the *Get & Send Settings* tab;
- click *Open* and read the file *ustawienia\_2\_tds1002b.set*;
- click *Send Settings*;
- return to the *Screen Capture* tab.

[TDS224]

- choose *File* ▸ *Open* from the menu and open the file *ustawienia\_2\_tds224.sht*; in a next dialog box click *Offline*;
- on the list shown in the left side panel unfold the installed oscilloscope, *Data*, *Settings*;
- in the window containing the settings file, select the entire contents and drag them with the mouse to the *Full Setup* item in the left side panel;
- wait while changes are being introduced on the oscilloscope, which is evidenced by changing screen elements (letters, numbers, curves).

11. Prepare the current probe:

- (a) detach any voltage probes from the oscilloscope;
- (b) attach the current probe to oscilloscope's channel 1 following the procedure described in a manual available at the laboratory stand;
- (c) set up the current probe following the procedure described in the manual;
- (d) if the current probe used has an adjustable current/voltage conversion ratio, set a conversion ratio appropriate for the current value determined in step 3;
- (e) set up the oscilloscope for using the current probe following the procedure described in the manual;
- (f) ask the instructor to demonstrate how to use the current probe;
- (g) close the probe around any wire leading the circuit's principal current  $i$  (i.e. the light bulb's one; current direction is not important in this case).

### Power conversion characteristics

#### Warning!

**From this point on, you can only continue after the instructor has explicitly accepted your wiring.**

#### While making measurements:

**Do not touch any parts of the measurement set-up when it is energised (connected to the mains)! Particularly do not touch internal parts placed between the top and bottom surfaces of the functional blocks nor the metal casing of the halogen lamp. Risk of shock!**

**Don't make any switch-overs in the circuit when it is energised! This also applies to changing analogue and digital meter ranges or functions! Risk of shock and meter destruction!**

**Always disconnect the circuit from the mains by plugging the extension cord's plug off the mains socket.**

**During all the experiment make sure that no wire touches the light bulb—risk of insulation damage due to high temperature!**

12. Turn on digital meters. For some of them it is necessary to turn on rms measurement (if it is not chosen with the main knob): [YF-...] blue button; [M-3660D] *AC/DC* button; [PC510, CD771] *Select* button.

**If a meter where the above function is selected with a button is turned off during measurements, it must be selected again after the meter is turned back on. Otherwise results obtained will be useless.**

**If the battery discharge indicator (a battery symbol) shows up on the meter's display, do not continue measurements but ask the teacher to replace the battery. Otherwise meter indications may become erroneous.**

13. Plug the white extension cord into the principal power strip at the laboratory stand. Plug the wattmeter's attachment into the transformer's secondary side socket.
14. Ensure that one period of a current waveform conforming to the operating principle of the circuit under investigation has appeared on the oscilloscope's screen. It may be necessary to check with other dimmer potentiometer setting as well as to adjust oscilloscope settings:
- Set the time base, i.e., the horizontal scale (TIME/DIV or SEC/DIV knob depending on the model), so that one waveform period can be observed on the screen.
  - Set channel 1 gain, i.e., the vertical scale (VOLTS/DIV), so that the waveform vertically fills in the screen to a maximum but does not extend beyond it.
15. Make a series of measurements for 10 to 15 points between the extreme settings of the variable resistor's wiper. For each measurement point measure and note down:

**For each measurement point, all the following sub-steps should be executed; only then you can proceed to a next measurement point!**

- average input power  $P_i$  which is the indication of  $W_1$ ;

**According to the multimeter operating principle described above, while in the wattmeter mode, this device simultaneously displays on the same screen average power, rms current and rms voltage. As a result, in order to read out rms current or voltage, the multimeter's operating mode should not be switched with the knob! Risk of damage to the multimeter!**

- rms current  $I$  which is the indication of  $A_1$ ;
- rms input voltage  $U_i$  which is the indication of  $V_1$ ;
- rms output (incandescent lamp) voltage  $U_o$  which is the indication of  $V_2$  (for an analogue meter);

If the voltmeter used is an analogue one and has more than one measurement range, always use the lowest one that the currently measured value fits in. Only change the range after disconnecting the circuit from the mains. Make sure you read the indication out of the proper scale.

- the time interval  $\Delta t_\alpha$  corresponding to the triac turn-on delay phase angle  $\alpha$ , using the oscilloscope as described below:

[HM1507]

- push long the *ON/OFF* button under the screen—after a beep, cursors should be displayed or hidden;
- if needed, use the  $\Delta V/\Delta t$  button (push long) to change the cursors' type from horizontal to vertical;
- using the *I/II* (not *CHI/CHII*) button, choose one of the cursors and use the *CURSOR* knob so that the cursors enclose the period of current non-conduction;
- the value of  $\Delta t$  indicated in the right bottom screen corner is the  $\Delta t_\alpha$  we are looking for.

[TDS224]

- push the *CURSOR* button;
- if needed, use the first button right to the screen to choose *Type = Time*;
- if needed, use the second button to choose *Source = CH1*;
- move the cursors using knobs *CURSOR 1* and *CURSOR 2* (grey markings under small knobs in the *VERTICAL* section) so that they enclose the period of current non-conduction;
- the value of *Delta* indicated on the right-hand side of the screen is the  $\Delta t_\alpha$  we are looking for.

[TDS1002B]

- push the *CURSOR* button;
- if needed, use the first button right to the screen to choose *Type = Time*;
- if needed, use the second button to choose *Source = CH1*;
- with an appropriate button right to the screen choose *Cursor1* and move cursor 1 with the large knob in the top-left corner of the oscilloscope's panel and then, act by analogy with cursor 2 so as the cursors enclose the period of current non-conduction;
- the  $\Delta t$  indication on the right-hand side of the screen is the  $\Delta t_\alpha$  we are looking for.

**Ensure that data for a point corresponding to the maximum output power have been recorded upon completion of the above step.**

### Time domain operation

16. Set the potentiometer  $R_p$  so that maximum power is delivered to the lamp. Note down the indications of  $A_1$  and  $V_2$ . Based on them, calculate the present (thus the maximum) average output power  $P_{o(max)}$ .
17. Adjust the time base of the oscilloscope (TIME/DIV or SEC/DIV) so as 2–4 waveform periods can be observed on the screen.
18. Download the waveform image to the computer and save it to a file:
 

[HM1507]

  - click *Read* in the application;
  - choose *Data* ▷ *Save* from the menu;
  - save as a *Measurement (\*.mes)* file.

[TDS1002B]

  - in the *Screen Capture* tab, click *Get Screen*;
  - click *Save As* and save the image in a graphic format other than JPG.

[TDS224]

  - choose *File* ▷ *New Datasheet* from the menu, choose *Notes Sheet* and accept;
  - on the list shown in the left panel unfold the installed oscilloscope, *Data* and *Display*;
  - drag the *Screen Copy* item and drop it in the newly created *Notes Sheet* window;
  - save the *Notes Sheet* document as an SHT file: menu *File* ▷ *Save Datasheet As*.
19. Note down the current/voltage conversion ratio of the current probe (see the probe's manual).
20. Without making any changes in the circuit, on the probe (or amplifier), nor on the oscilloscope, set the potentiometer  $R_p$  so that the average output power equals about 50% of its maximum value calculated in step 16. (Calculate the current average output power as before based on indications of  $A_1$  and  $V_2$ . As an estimate, you may first use the value of  $P_1$  indicated by  $W_1$ .)
21. Repeat step 18.
22. Disconnect the current probe from the circuit and turn it (the probe) off using the *ON/OFF* switch (for the mobile probe) or turn off its amplifier (in other case).

**Concluding the investigation**

23. Disconnect the circuit from the mains in the following order:
  - (a) plug the wattmeter's attachment off the transformer's secondary side socket;
  - (b) plug the transformer off the extension cord and the extension cord off the mains socket.
24. Disconnect all the other wires.
25. Make and write down observations concerning dimensions and weight of circuit components of the dimmer investigated.



## 5. Result Processing

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### 5.1. Electrical characteristics

#### Control characteristics

1. For the resistor-based circuit, calculate at each measurement point:
  - (a) average input power  $P_i$  and average output power  $P_o$  based on Eq. (4.1), wattmeter indications  $P^*$  (in divisions) as well as voltage ( $k_V$ ) and current ( $k_A$ ) ranges of this meter;
  - (b) input apparent power  $S_i$  based on definition (see Manual 0, Ref. D) and the measured values of current  $I$  and voltage  $U_i$  (a single value for  $U_i$ —assume that the supply network was ideal, i.e. its voltage was constant irrespective of the power drawn);
  - (c) relative rms current  $I_r$  based on the definition (3.22) and using the maximum measured value;
  - (d) relative average output power  $P_{or}$  based on the definition (3.20) and using the maximum measured value;
  - (e) resistor setting  $R_p$  based on Ohm's Law, using the measured values of voltage across this resistor  $U_p$  and its current  $I$ ;
  - (f) incandescent lamp resistance  $R_{Lp}$  based on the relationship for a resistor's average power (see Manual 0, Ref. C), using the measured values of lamp average power  $P_o$  and its current  $I$ ;
  - (g) relative resistor setting with respect to lamp resistance:

$$R_{pr} = \frac{R_p}{R_{Lp}} \quad (5.1)$$

2. For the triac-based circuit, calculate at each measurement point:
  - (a) apparent input power  $S_i$  (based on definition as above);
  - (b) average output power  $P_o$  based on  $U_o$  and  $I$  values measured assuming that the incandescent lamp is a purely resistive receiver ( $\varphi = 0$ ; see Manual 0, Ref. D);

- (c) relative rms current  $I_r$  (based on the definition as above);
- (d) relative average output power  $P_{or}$  (based on the definition as above);
- (e) triac turn-on delay phase angle  $\alpha$  based on  $\Delta t_\alpha$  interval length measured and mains frequency that is known, based on the proportion

$$\frac{\alpha}{\Delta t_\alpha} = \frac{2\pi}{T_s} \quad (5.2)$$

where  $T_s$  is the supply network period (convert the result from radians to degrees).

3. Fill in Part 1 of the report (leave  $\eta$  and  $\lambda$  columns in the tables unfilled for now).

### Principle of output power control

4. Fill in Part 2 of the report.

### Power conversion quality

5. For either circuit, calculate at each measurement point:
  - (a) converter efficiency  $\eta$  based on definition (see Manual 0, Ref. B);
  - (b) converter/load system power factor  $\lambda$  based on definition (see Manual 0, Ref. D).
6. Add results obtained to the tables in Part 1 of the report. Add formulae used in the appropriate space.
7. Fill in Part 3 of the report.

## 5.2. Circuit realisations of the dimmer

### Overall assessment of dimmer solutions

1. Use the Internet (save screen shots of web pages) to calculate the approximate total cost of each of the investigated dimmer solutions (only dimmer components should therefore be taken into account, not the receiver nor measurement equipment):

(a) the variable resistor-based circuit:

- it is suggested to search for “(power) variable resistor” or “(power) rheostat” (or “opornik suwakowy”, “opornik nastawny”);
- adding a currency symbol such as „zł” may speed up the search;
- pay attention to the nominal power or current that should be consistent with values appearing in the circuit under investigation, considering at minimum their orders of magnitude (see Sections 3.3.a and 4.1);

The variable resistor used in the experiment was overrated with respect to power. The real needed power rating may be roughly estimated based on the relationship for resistor's average power using the mains voltage of 230 V and the resistor's resistance of 1 k $\Omega$ .

(b) the triac-based circuit (see data and designations given in Section 4.2):

- you may try to search for the triac using its symbol's first characters (letters and first digits);
- all the diacs available on the market have similar parameters, so a specific diac type is not important;
- note the capacitor's rated voltage;
- “film capacitor” may refer to polyester, polypropylene and similar materials, and MKT is an acronym for a popular series of such devices.

2. Fill in Part 4 of the report.

### Triac in the electronic converter

3. Fill in Part 5 of the report.



## 6. Required Knowledge

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### 6.1. Prerequisites

- Schematic and general principle of operation of the variable resistor-based and the triac-based dimmer circuit. (From the principal circuit point of view—disregard the control circuit.)  
(see Ref. F and Section 3.2.b)

### 6.2. Test scope

#### Problems within the scope of this manual

1. Schematic and general principle of operation of the variable resistor-based and the triac-based dimmer circuit. (From the principal circuit point of view—disregard the control circuit.) Characteristics of: average output power, power factor and efficiency. (Graphical form, not the formulae.) Advantages and drawbacks.  
(see Refs. F and G, Sections 3.2 and 3.3.a, report)
2. Thyristors. Symbol, main terminals, control (drive) terminal. Static characteristics of the principal circuit including operating states for the SCR and for the triac. What are the main features of each state? (how do they manifest externally without considering physical phenomena inside the structure). (see Ref. A and Manual 0, Ref. H)

#### Problems within the scope of Manual 0

1. Power converter function and ports. Input power, output power, power loss and efficiency. Motivations for increasing the efficiency.  
(see Manual 0, Ref. B)
2. Instantaneous electrical power. Average power definition and its relationship to instantaneous power. Root-mean-square value definition. Average power of a resistive receiver.  
(see Manual 0, Ref. C)
3. Apparent power, reactive power and power factor. Interpretation and importance of the different power quantities. Values for a linear inductive load (phase angle-based formulae).  
(see Manual 0, Ref. D)

## 7. References

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- [1] Benda V., Gowar J., Grant D. A.: *Power Semiconductor Devices: Theory and Applications*. Wiley, 1999. ISBN 0-471-97644-X.
- [2] Moorthi V. R.: *Power Electronics: Devices, Circuits, and Industrial Applications*. Oxford, 2005. ISBN 0-19-567092-2.
- [11] *Snubberless™ and logic level TRIAC behavior at turn-off*. Rev. 3. STMicroelectronics, March 2008. Application Note AN439.
- [12] *Thyristors and triacs: Introduction*. Philips Semiconductors, February 1996.