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POWER DEVICES AND SYSTEMS LABORATORY

Exercise 2U

AC voltage controller

Thyristors
Parameters of power electronic converters

Caution! Dangerous voltages are present in the measurement set-up.
Danger of shock if safety guidelines given are not followed!

Exercise and manual elaborated by
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Exercise Introduction

1. Exercise Aim and Plan

The aim of this exercise is to investigate operation and characteristics of a typical AC/AC converter: an AC voltage controller using the phase angle control method. In the specific case under analysis, it will perform the task of a halogen lamp dimmer.

In this circuit, the bidirectional thyristor, or the triac, will be used as the semiconductor switch. This exercise will thus create an opportunity to get acquainted with this group of devices as well as with a related one, the diac.

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 high interest in this exercise.

2. Thyristors

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	2.1	[12] Thyristor and Triac Ratings; Thyristor and Triac Characteristics	
B	Ben	7.2	2.2		
C	Ben	7.3, 7.3.1, 7.3.2, 7.3.3, 7.4.1, 7.4.2	2.3		
D	Ben	8.4	2.4	[11] 1.2, 1.3.1 [12] High Commutation Triacs	
E	Moo	1.8.1	2.5.c		

3. AC/AC Converter

3.1. Recommended reading

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

3.2. Lamp control 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

$$p_{\mathrm{sw}} = i_{\mathrm{sw}} u_{\mathrm{sw}} = 0 \tag{3.1}$$

so by definition

$$P_{\mathrm{c}} = P_{\mathrm{sw}} = (p_{\mathrm{sw}})_{\mathrm{av}} = 0 \tag{3.2}$$

Under this assumption from (3.31) we obtain

$$\eta = \frac{P_{\mathrm{o}}}{P_{\mathrm{o}} + P_{\mathrm{c}}} = \frac{P_{\mathrm{o}}}{P_{\mathrm{o}}} = 1 \tag{3.3}$$

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

$$p_{\mathrm{sw(off)}} \approx \frac{u_{\mathrm{s}}^2}{R_{\mathrm{off}}} \tag{3.4}$$

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

$$p_{\mathrm{sw(on)}} = i^2 R_{\mathrm{on}} \approx \left(\frac{u_{\mathrm{s}}}{R_{\mathrm{Lp}}} \right)^2 R_{\mathrm{on}} \tag{3.5}$$

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

$$\begin{aligned} P_{\mathrm{c}} &= \frac{1}{2\pi} \cdot \left[\int_{\Omega_0}^{\Omega_1} p_{\mathrm{sw(off)}} \,\mathrm{d}\Omega + \int_{\Omega_1}^{\Omega_3} p_{\mathrm{sw(on)}} \,\mathrm{d}\Omega + \int_{\Omega_3}^{\Omega_4} p_{\mathrm{sw(off)}} \,\mathrm{d}\Omega + \int_{\Omega_4}^{\Omega_5} p_{\mathrm{sw(on)}} \,\mathrm{d}\Omega \right] = \\ &= \frac{1}{2\pi} \cdot 2 \cdot \left[\int_{\Omega_0}^{\Omega_1} \frac{u_{\mathrm{s}}^2}{R_{\mathrm{off}}} \,\mathrm{d}\Omega + \int_{\Omega_1}^{\Omega_3} \left(\frac{u_{\mathrm{s}}}{R_{\mathrm{Lp}}} \right)^2 R_{\mathrm{on}} \,\mathrm{d}\Omega \right] = \\ &= \frac{1}{\pi} \left(\frac{1}{R_{\mathrm{off}}} \int_{\Omega_0}^{\Omega_1} u_{\mathrm{s}}^2 \,\mathrm{d}\Omega + \frac{R_{\mathrm{on}}}{R_{\mathrm{Lp}}^2} \int_{\Omega_1}^{\Omega_3} u_{\mathrm{s}}^2 \,\mathrm{d}\Omega \right) \end{aligned} \tag{3.6}$$

where Ω 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.

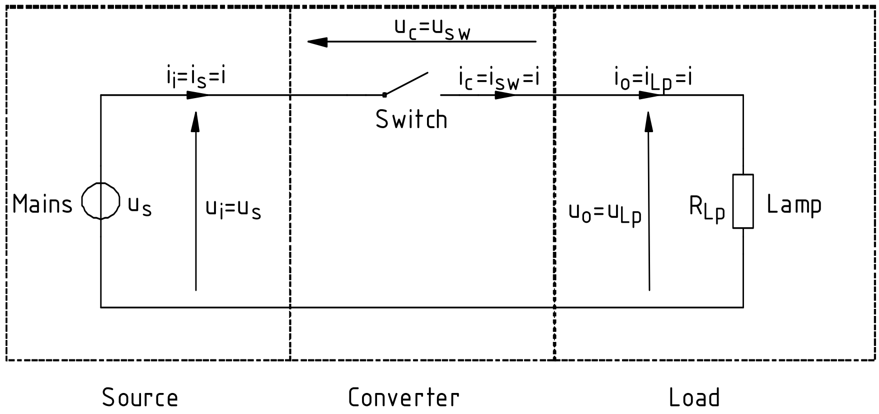

Fig. 1. Light bulb dimmer circuit based on a semi-conductor switch

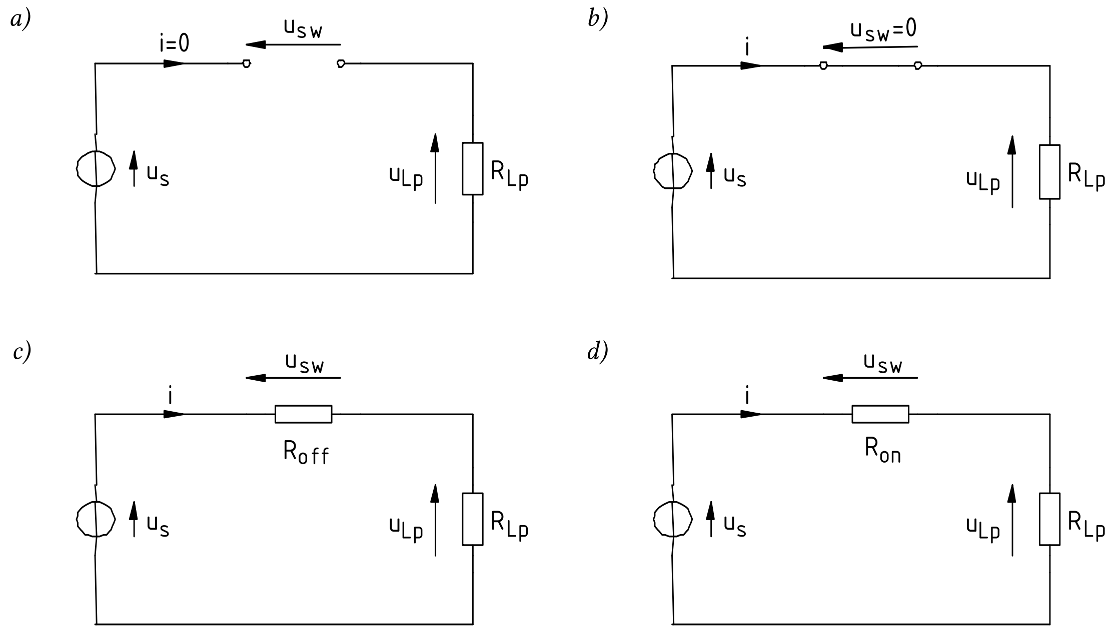

Fig. 2. Simplified equivalent schematic of the dimmer in two intervals of its operation: a), b) under the ideal switch assumption; c), d) with static power loss taken into account

3.2.b. Practical concept of a complete AC voltage phase-controlled converter

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_dC_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

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

and a phase angle

$$\varphi_d = \mathrm{arctg} \frac{-1}{\omega R_d C_d} \tag{3.8}$$

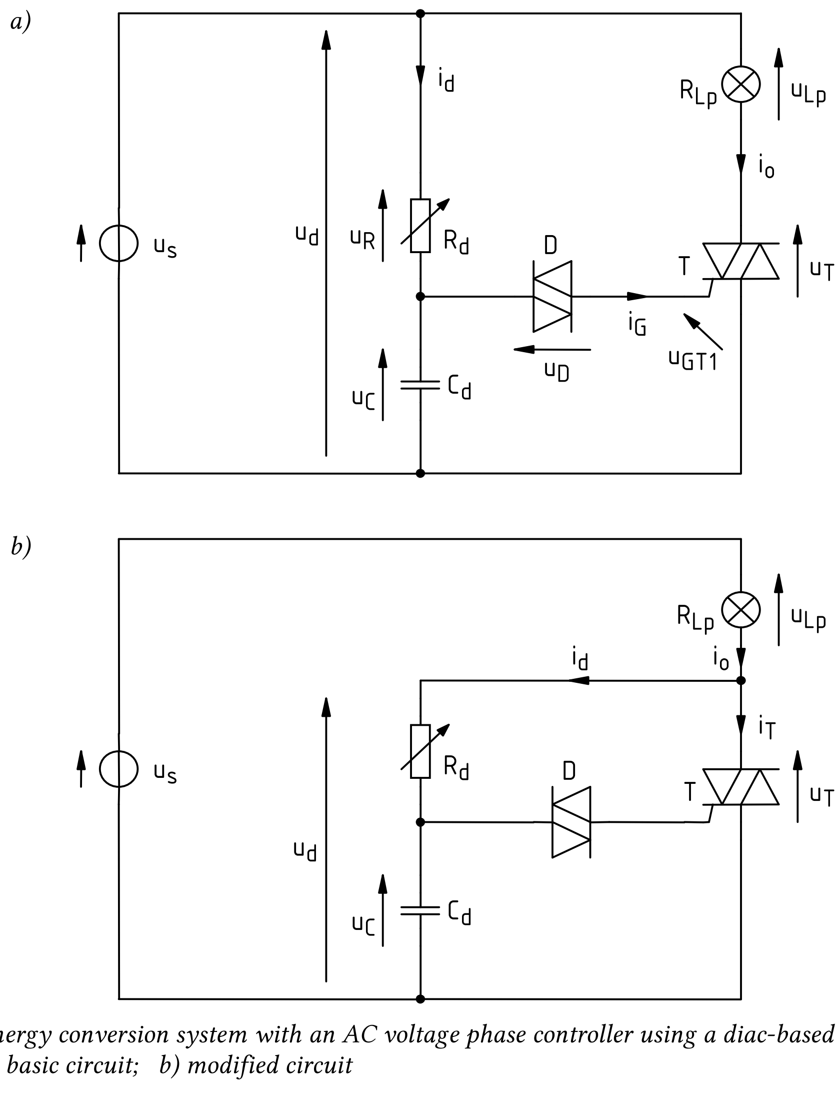

Fig. 3. Complete energy conversion system with an AC voltage phase controller using a diac-based triac control circuit: a) basic circuit; b) modified circuit

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

$$I_d = \frac{U_s}{Z_d} \tag{3.9}$$

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

$$u_d = u_R + u_C \tag{3.10}$$

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 is 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

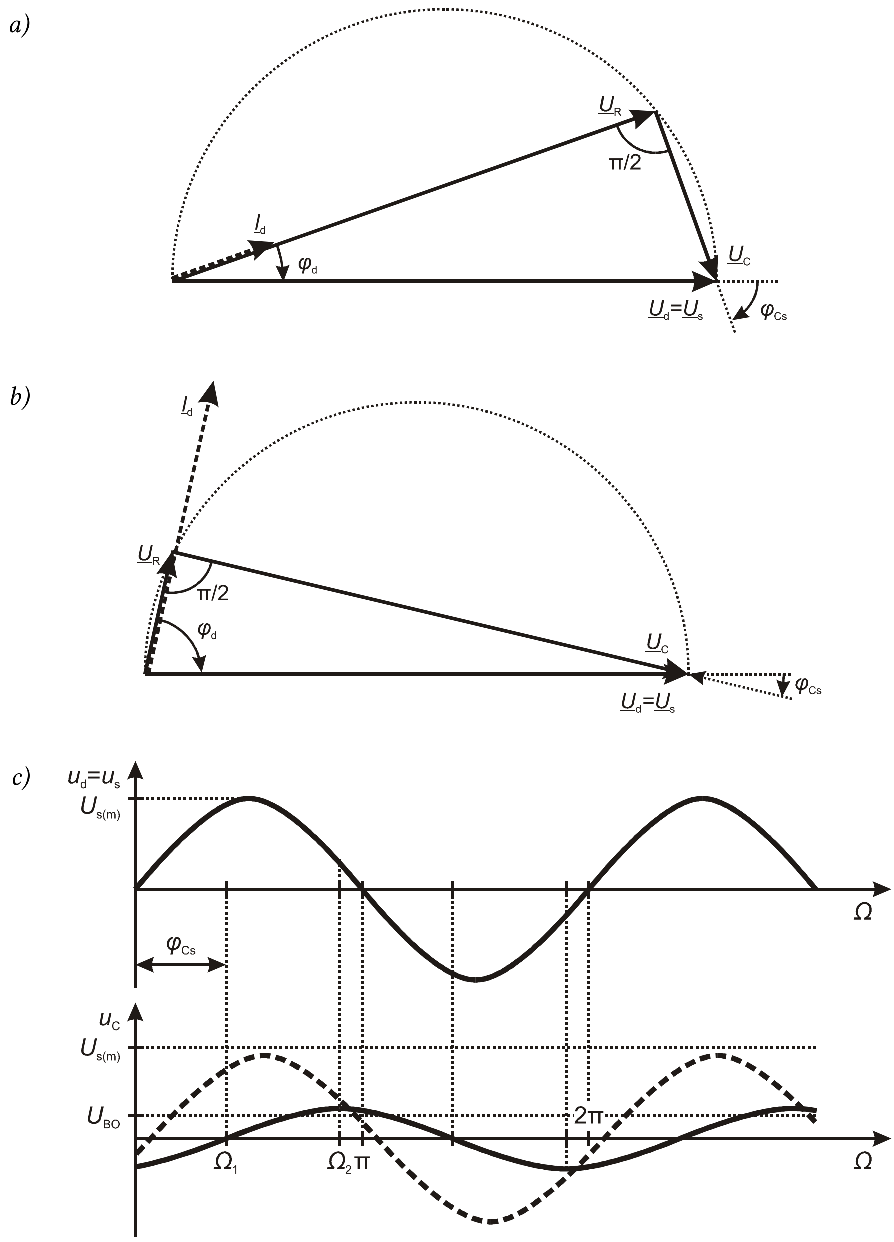

Fig. 4. Operation of R_dC_d divider without taking into account the presence of the diac: a) phasor diagram for a large resistance ($R_d > 1/\omega C_d$); b) phasor diagram for a small resistance ($R_d < 1/\omega C_d$); c) voltage waveforms (for a large resistance—solid line and for a small resistance—dashed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

$$\varphi_{Cs} = -\frac{\pi}{2} - \varphi_d \tag{3.11}$$

Here $\varphi_d < 0$ and as φ_{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 Ω_1 and maximum u_C is attained at the angle of

$$\Omega_2 = \Omega_1 + \frac{\pi}{2} = |\varphi_{Cs}| + \frac{\pi}{2} \tag{3.12}$$

If we make R_d smaller, the φ_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 φ_{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 $R_d \to \infty$ the network R_dC_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 φ_{Cs} angle would equal $-\pi/2$. The amplitude of u_C would approach zero and Ω_2 (the angle of maximum u_C value) would approach π;

(2) For $R_d \to 0$ 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 Ω_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

$$u_D = u_C - u_{GT1} \tag{3.13}$$

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 φ_{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_dC_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 α. 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 ans 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 α 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, $u_{Lp} \approx u_s$. 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.

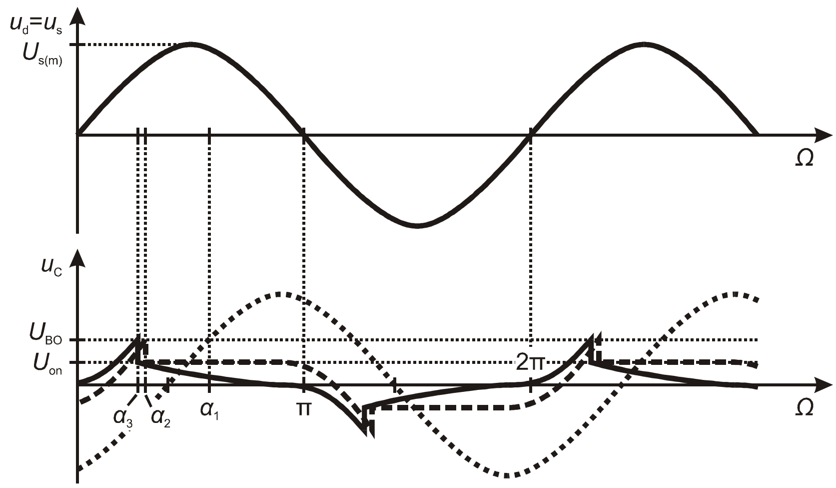

Fig. 5. Waveforms in the control circuit considering the diac turn-on (different scales for u_C and u_s): without considering the presence of the diac (dotted line), basic circuit (dashed line), modified circuit (solid line)

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 α will be smaller. For the basic circuit it will be α_2 instead of α_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 α_3 will be even smaller.

3.3. Lamp control 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 using 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) us; 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

$$i = \frac{u_s}{R_p + R_{Lp}} \tag{3.14}$$

so its rms value will be

$$I = \frac{U_s}{R_p + R_{Lp}} \tag{3.15}$$

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

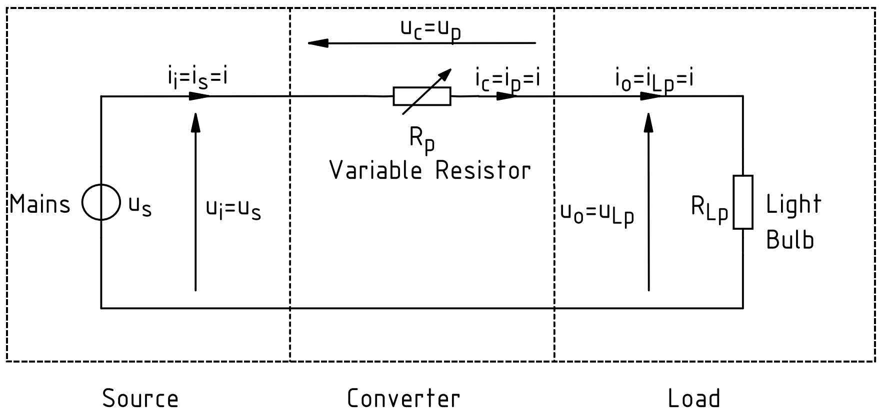

Fig. 6. Light dimmer circuit using a variable resistor

$$U_{\mathrm{Lp}} = I_{\mathrm{Lp}} R_{\mathrm{Lp}} = I R_{\mathrm{Lp}} = U_{\mathrm{s}} \frac{R_{\mathrm{Lp}}}{R_{\mathrm{p}} + R_{\mathrm{Lp}}} \tag{3.16}$$

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

$$P_{\mathrm{o}} = P_{\mathrm{Lp}} = I^2 R_{\mathrm{Lp}} = U_{\mathrm{s}}^2 \frac{R_{\mathrm{Lp}}}{(R_{\mathrm{p}} + R_{\mathrm{Lp}})^2} \tag{3.17}$$

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 $R_{\mathrm{p}} = 0$ and equals

$$P_{\mathrm{o(max)}} = P_{\mathrm{Lp(max)}} = P_{\mathrm{Lp}}\Big|_{R_{\mathrm{p}}=0} = \frac{U_{\mathrm{s}}^2}{R_{\mathrm{Lp}}} \tag{3.18}$$

On the other hand, for increasing R_{p} we get

$$P_{\mathrm{o}}\Big|_{R_{\mathrm{p}}\to\infty} = P_{\mathrm{Lp}}\Big|_{R_{\mathrm{p}}\to\infty} \to 0 \tag{3.19}$$

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

$$P_{\mathrm{or}} \overset{\Delta}{=} \frac{P_{\mathrm{o}}}{P_{\mathrm{o(max)}}} \tag{3.20}$$

which in the case under consideration yields

$$P_{\mathrm{or}} = U_{\mathrm{s}}^2 \frac{R_{\mathrm{Lp}}}{(R_{\mathrm{p}} + R_{\mathrm{Lp}})^2} \cdot \frac{R_{\mathrm{Lp}}}{U_{\mathrm{s}}^2} = \left(\frac{R_{\mathrm{Lp}}}{R_{\mathrm{p}} + R_{\mathrm{Lp}}} \right)^2 = \left(\frac{1}{1 + R_{\mathrm{p}} / R_{\mathrm{Lp}}} \right)^2 \tag{3.21}$$

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 $R_{\mathrm{p}} = 0$ and 0 (0%) when $R_{\mathrm{p}} \to \infty$.

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 $R_{\mathrm{p}} \neq \infty$ always,

(2) the control characteristic depends on both the variable resistor and the load—which can be seen from the $P_{\mathrm{or}} = \mathrm{f}(R_{\mathrm{p}})$ 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

$$I_{\mathrm{r}} \overset{\Delta}{=} \frac{I}{I_{\mathrm{max}}} \tag{3.22}$$

which in the considered case leads to the relationship

$$I_{\mathrm{r}} = \frac{U_{\mathrm{s}}}{R_{\mathrm{p}} + R_{\mathrm{Lp}}} \cdot \frac{R_{\mathrm{Lp}}}{U_{\mathrm{s}}} = \frac{R_{\mathrm{Lp}}}{R_{\mathrm{p}} + R_{\mathrm{Lp}}} = \frac{1}{1 + R_{\mathrm{P}} / R_{\mathrm{Lp}}} \tag{3.23}$$

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

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

$$\eta = \frac{P_{\mathrm{o}}}{P_{\mathrm{i}}} \tag{3.24}$$

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

$$P_{\mathrm{o}} = P_{\mathrm{Lp}} = \frac{U_{\mathrm{s}}^2 R_{\mathrm{Lp}}}{(R_{\mathrm{p}} + R_{\mathrm{Lp}})^2} \tag{3.25}$$

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

$$P_{\mathrm{i}} = P_{\mathrm{s}} = U_{\mathrm{s}} I = \frac{U_{\mathrm{s}}^2}{R_{\mathrm{p}} + R_{\mathrm{Lp}}} \tag{3.26}$$

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

$$\eta = \frac{P_{\mathrm{o}}}{P_{\mathrm{i}}} = \frac{U_{\mathrm{s}}^2 R_{\mathrm{Lp}}}{(R_{\mathrm{p}} + R_{\mathrm{Lp}})^2} \frac{R_{\mathrm{p}} + R_{\mathrm{Lp}}}{U_{\mathrm{s}}^2} = \frac{R_{\mathrm{Lp}}}{R_{\mathrm{p}} + R_{\mathrm{Lp}}} \tag{3.27}$$

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 $R_{\mathrm{p}} = 0$: the maximum lamp average power

$$P_{\mathrm{Lp}} = P_{\mathrm{Lp(max)}} = \frac{U_{\mathrm{s}}^2}{R_{\mathrm{Lp}}} \tag{3.28}$$

  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 $R_{\mathrm{p}} \to \infty$: $P_{\mathrm{Lp}} \to 0$ and $\eta \to 0$;
- and the efficiency is halved for $R_{\mathrm{p}} = R_{\mathrm{Lp}}$, 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

$$P_{\mathrm{p}} = I^2 R_{\mathrm{p}} = U_{\mathrm{s}}^2 \frac{R_{\mathrm{p}}}{(R_{\mathrm{p}} + R_{\mathrm{Lp}})^2} \tag{3.29}$$

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):

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

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

$$\eta = \frac{P_o}{P_o + P_c} = \frac{1}{1 + \frac{P_c}{P_o}} \tag{3.31}$$

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):

$$P_i = P_o + P_c \tag{3.32}$$

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

$$\lambda = \frac{P_i}{U_i I_i} \tag{3.33}$$

For the considered converter-receiver system this equals

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

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.

C

Experiment

4. Measurements and Simulations

4.1. Measurement set-up

Set-up description

The moment when you should begin connecting the set-up is clearly marked later in this manual. Do not start before you get acquainted with all the preceding information or before completing preceding tasks.

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

- Lp is an incandescent lamp, P_n = 150 W, U_n = 230 V,
- R_p is a potentiometer, 470 kΩ, P_n = 1/4 W,
- R_{aux} is an auxiliary resistor 10 kΩ, P_n = 1/4 W,
- C is a film capacitor, 100 nF, U_n = 250 V (AC) or 630 V (DC),
- D is a diac, DB3,
- Th is a triac, BT136-600,
- W_1 is a digital multimeter with wattmeter function (M-3860M),
- V_2 is a true rms digital voltmeter (M-3660D).

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 voltage ratio of approximately 1:1.

An oscilloscope will be used to measure the current i, with a current probe, and the input voltage u_i, using a voltage probe. The voltage probe will be attached using appropriate connectors to points marked in Fig. 7 and A and B.

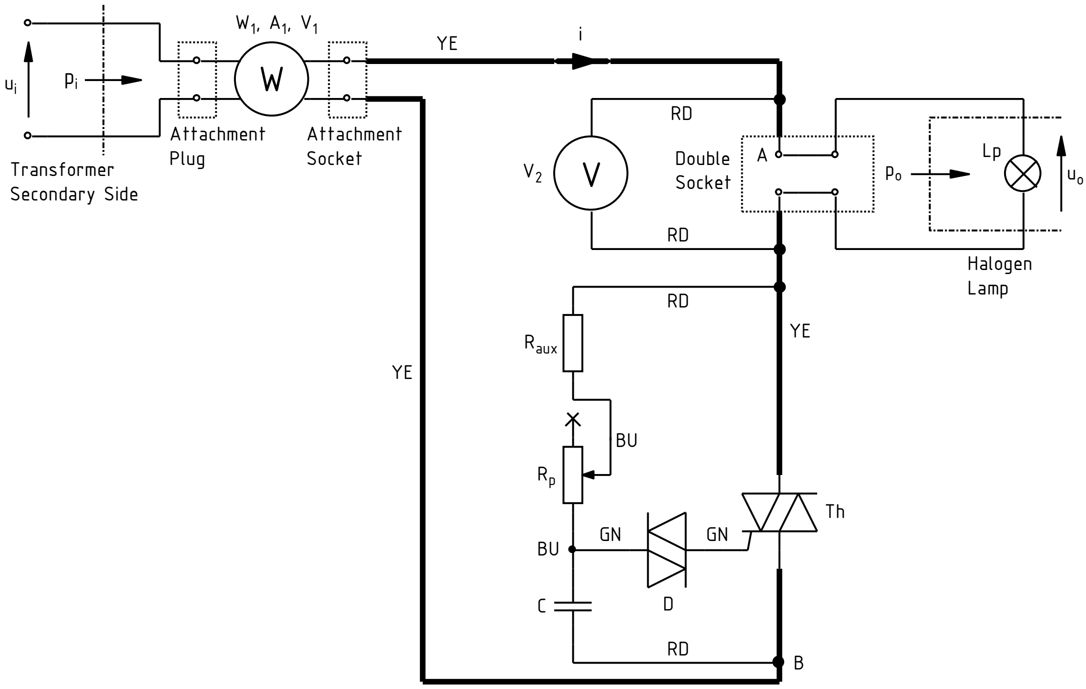

Fig. 7. Electrical schematic of the circuit under investigation

Operation of a multimeter with the wattmeter function

The operation of the wattmeter used is based on simultaneous recording of instantaneous current and voltage values at a given location within a circuit at consecutive moments of time. These data are processed including multiplication and averaging, resulting in the average power. The length of the averaging interval is of the order of hundreds of milliseconds, which results in an apparent delay between the measurement and the result being displayed; you should keep this in mind while setting output power.

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.

As recording of both voltage and current samples is necessary for power measurement, the multimeter can additionally calculate the rms value of the input current (which is symbolised by A_1 in Fig. 7) and the rms value of the input voltage (V_1). When the multimeter used operates in wattmeter mode, it displays all the three values (average power, rms current and rms voltage) simultaneously on its screen.

4.2. 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 soft start device 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 average power of a resistive two-terminal device, 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 turned on, supposing it is an ideal switch (zero voltage between its main terminals).
3. Leave the meters switched off for the moment.
4. Make connections in the circuit according to the figure and the following guidelines (still without plugging the extension cord to the mains or the wattmeter's attachment to the transformer's secondary side 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 colours as shown in Fig. 7:
      - 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 path of the principal current i (marked in bold in Fig. 7). Only afterwards wire the control sub-circuit and connect the voltmeter.
   (d) Use meter sockets appropriate for functions used and for circuit data given above and determined in step 2.
5. Set the wiper of the variable resistor approximately in the middle of its range.
6. Attach a voltage probe to the circuit:
   (a) attach a voltage probe with an attenuation of 100:1 to the channel 2 of the oscilloscope;
   (b) at points marked in Fig. 7 as A and B (not at any other points of the circuit, even if they have the same voltage potential), insert single connectors enabling a voltage probe to be connected;
   (c) connect the probe to the connectors in a way to measure the input voltage u_i in accordance with its direction as shown in Fig. 7.
7. Ask the instructor to check your connections. In the meantime, continue with steps 8 to 10;
8. Turn on the computer. After logon completes, turn on the oscilloscope and, if necessary, configure its connection to the computer following the manual available at the laboratory stand.
9. Using the oscilloscope communication application, upload initial settings to the oscilloscope:
   - go to the *Get & Send Settings* tab,
   - click *Open* and read the file *ustawienia_2u_tbs1052.set*,
   - click *Send Settings* (not *Send to multiple*),
   - return to the *Screen Capture* tab,
   - make sure that in the lower part of the screen, measurements are active for the maximum and RMS values of the channel 1 waveform as well as for the frequency of the channel 2 waveform; re-send settings otherwise.

10. Prepare the current probe for use:
    (a) attach the current probe to the oscilloscope's channel 1 following the procedure described in a manual available at the laboratory stand;
    (b) set up the current probe following the procedure described in the manual;
    (c) clamp the probe around any wire leading the principal (lamp) current *i*, in accordance with its direction as shown in Fig. 7.

4.3. Carrying out measurements

Power conversion characteristics

1. Turn on the meters and configure them:
   (a) using the knob, select an appropriate function for the multimeter W_1;
   (b) using the knob, select appropriate (according to the circuit data given above) function and range for the multimeter V_2;
   (c) using the *AC/DC* button, activate the AC measurement function on the multimeter V_2 (activation is indicated as "AC" on the display).

   If the abovementioned meter turns off during measurements, <u>the abovementioned function must be re-activated</u> after the meter is turned back on. Otherwise results obtained will be useless.

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

   While performing measurements:

   Do not touch any parts of the measurement set-up when it is energised. Particularly do not touch the terminals of the voltage probe, the connectors which it is attached to, elements placed between the top and bottom plates of component blocks nor the metal casing of the halogen lamp. Risk of shock!

   Don't make <u>any</u> switch-overs in the circuit when it is energised! This also applies to the voltage probes and to the connectors which it is attached to!

   Always disconnect the circuit from the mains by plugging the wattmeter's attachment off the transformer's secondary side socket. The transformer may stay connected to the mains <u>provided</u> safety measures are applied, including not touching itself or screw terminals to which wires are connected.

   Warning!

   Before proceeding any further, it is obligatory to obtain an explicit acceptance of your wiring from the instructor.

2. Plug the white extension cord into the main power strip at the laboratory stand. Next, plug the wattmeter's attachment into the transformer's secondary side socket.
3. Ensure that voltage and current waveforms conforming to the operating principle of the circuit under investigation have appeared on the oscilloscope's screen. It may be necessary to check a different dimmer potentiometer setting as well as to adjust oscilloscope settings:
   (a) set the time base, i.e. the horizontal scale (*Horizontal Scale* knob), so that approximately one waveform period can be observed on the screen;
   (b) set channel 1 and 2 gains, i.e. vertical scales (*Vertical Scale* knobs), so that waveforms fill the screen vertically to the maximum extent but without extending beyond it.
4. Set the potentiometer in the position resulting in the maximum output power (and thus, to the maximum illuminance).
5. For 10 to 15 points roughly evenly distributed between the extreme settings of the potentiometer's wiper (these extreme positions included), measure and write down:

   For <u>each measurement point</u>, <u>all the sub-steps below</u> must be executed before proceeding to a following measurement point!

   (a) average input power P_{i}, which is the indication of the meter W_1;

As mentioned in Sub-chapter 4.1, while the multimeter W_1 operates in its wattmeter mode, it simultaneously displays average power, rms current and rms voltage on its screen. Thus, in order to read out rms current or voltage, the multimeter's operating mode should not be changed with the knob to ammeter or voltmeter.

According to the operating principle of the digital wattmeter described in Sub-chapter 4.1, its indication is refreshed in relatively long time steps. After power in the circuit changes, the appropriate new indication is only obtained after it stabilises, which may take up to a few seconds.

(b) rms current I, which is the indication of the meter A_1;

(c) rms input voltage U_i, which is the indication of the meter V_1;

(d) rms output (lamp) voltage U_o, which is the indication of the meter V_2;

(e) the time interval Δt_α corresponding to the triac turn-on delay phase angle α, using the oscilloscope as described below:

- push the *Cursor* button;
- if needed, use the first top button next to the screen and the *Multipurpose* knob to select *Type*: *Time*;
- if needed, use the second button next to the screen and the *Multipurpose* knob to select *Source*: *Ch1*;
- with an appropriate button next to the screen choose *Cursor1* and move cursor 1 with the *Multipurpose* knob, then acting by analogy with cursor 2, so as the cursors enclose the interval where current does not flow;
- the *Δ … s* indication on the right-hand side of the screen is the Δt_α interval length requested.

Upon completion of the above step, ensure that data for a measurement point corresponding to the maximum output power have been recorded.

Time-domain operation

6. Set the potentiometer R_p in a position resulting in the maximum input power. Write down the value of this power $P_{i(max)}$. Write down the indications of A_1 (the rms value of the current I) and V_2. Using these values, calculate and write down the present (thus, the maximum) average output power $P_{o(max)}$.
7. Adjust the time base of the oscilloscope (*Horizontal Scale*) so as 4 to 5 waveform periods can be observed on the screen.
8. Download the waveform image to the computer and save it to a file:
   - in the OpenChoice Desktop application, go to the *Screen Capture* tab,
   - click *Get Screen*;
   - click *Save As*,
   - in the *Save as format* field, select PNG,
   - choose a location for the file and give it a name,
   - accept with the mouse (not with the *Enter* key, as this would cause another activation of the *Save As* button).
9. Without making any changes in the circuit, on the current probe or on the oscilloscope, set the potentiometer R_p so that the average input power equals about 50% of its maximum value $P_{i(max)}$ written down in step 6. Write down the indications of A_1 (the rms value of the current I) and V_2. Using these values, calculate and write down the present (thus, the maximum) average output power P_o.
10. Repeat step 8.
11. Unclamp the current probe from the conductor. If the probe is battery-powered, turn it off with the *ON/OFF* switch.

Concluding measurements

12. 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 extension cord off the main power strip;
    (c) plug the transformer's plug, together with the soft start device, off the extension cord.
13. Remove remaining connections.
14. On the oscilloscope, turn off the averaging mode: push *Acquire* and select *Sample* with an appropriate screen button.

D

Results

5. Processing Results

5.1. Electrical characteristics

Control characteristics

1. For each measurement point, calculate:
   (a) triac turn-on delay phase angle α, using the Δt_α interval length measured and the mains frequency, which should be read out of any one of the recorded oscilloscope images (the *Frequency* indication), based on the proportion

$$\frac{\alpha}{\Delta t_\alpha} = \frac{2\pi}{T_s} \tag{5.1}$$

   where T_s is the mains period; after obtaining the result in radians, convert it to degrees and use the latter unit later on;
   (b) apparent input power S_i, from its definition (see Manual 0, Ref. D), using the measured values of current I and voltage U_i;
   (c) average output power P_o, using U_o and I values measured and considering that an incandescent lamp is a purely resistive receiver ($\varphi = 0$; see Manual 0, Ref. D);
   (d) relative rms current I_r, from its definition (3.22), assuming that the maximum value is identical with the maximum measured one;
   (e) relative average output power P_{or}, from its definition (3.20), assuming that the maximum value is identical with the maximum measured one;
   (f) lamp resistance R_{lp}, using U_o and I values measured.
2. Fill in Part 1 of the report (leave η and λ columns in the result table unfilled for now).

Receiver character

3. Fill in Part 2 of the report.

Effect of receiver's nonlinearity on converter characteristics

4. * Fill in Part 3 of the report.

Output power control principle

5. Fill in Part 4 of the report.

Power conversion quality

6. For each measurement point, calculate:
   (a) converter efficiency η, from its definition (see Manual 0, Ref. B);
   (b) converter-load system power factor λ, from its definition (see Manual 0, Ref. D).
7. Add results obtained to the table in Part 1 of the report. Add formulae used in the space provided for this purpose.
8. Fill in Part 5 of the report.

5.2. Triac application

1. Fill in Part 6 of the report.

E

Information

6. Required Knowledge

6.1. Prerequisites

- Schematic and general principle of operation of the AC voltage controller using phase control (from the principal circuit point of view only, disregarding the control circuit).
  (Ref. F and Section 3.2.b)

6.2. Test scope

1. Instantaneous electrical power. Average power definition and its relationship to instantaneous power. Root-mean-square value definition. Average power of a resistive receiver.
   (Manual 0, Ref. C)
2. Apparent power, reactive power and power factor. Interpretation and importance of the different power quantities. Generic formulae and values for a linear inductive load (phase angle-based formulae). Efficiency and motivations for increasing it.
   (Manual 0, Refs. B and D)
3. Schematic and general principle of operation of AC voltage controller using phase control (from the principal circuit point of view only, disregarding the control circuit). Characteristics of: average output power, power factor and efficiency (graphical form, without formulae). Advantages and drawbacks for the final consumer and for the owner of the power distribution network.
   (Refs. F and G, Sections 3.2 and 3.3.a; report)
4. Thyristors. Symbol, main terminals, control (drive) terminal. Static characteristics of the principal circuit including operating states for an SCR and for a triac. Characteristics of the particular states (how they manifest externally, without considering physical phenomena inside a structure).
   (Ref. A and Manual 0, Ref. H)
5. Thyristor turn-on and turn-off mechanisms (from the point of view of voltages and currents observed at device terminals, without describing physical phenomena inside a structure). Mechanisms observed in the converter investigated.
   (Refs. B, C and D; report)

7. References

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[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.