

# NONLINEAR RESISTORS, THERMISTORS, VARISTORS

1. **The purpose of the paper:** Highlighting the characteristics of thermistors and varistor

2. **Theoretical background:**

## 2.1. Thermistors

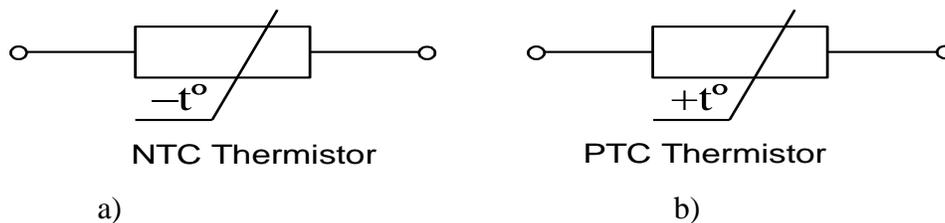
The thermistor is a resistor whose resistance strongly depends on temperature, showing a nonlinear V-I characteristic.

Specific to this temperature dependence, compared with that of fixed linear resistors, is the fact that for a temperature variation with one degree the value of the thermistors resistance changes by tens of percents. In other words, it is possible that within a narrow temperature range the thermistor would halve or double its resistance value.

Decrease or increase in resistance is closely correlated with the type of the thermistor, which can be:

- a) negative temperature coefficient, NTC
- b) positive temperature coefficient, PTC.

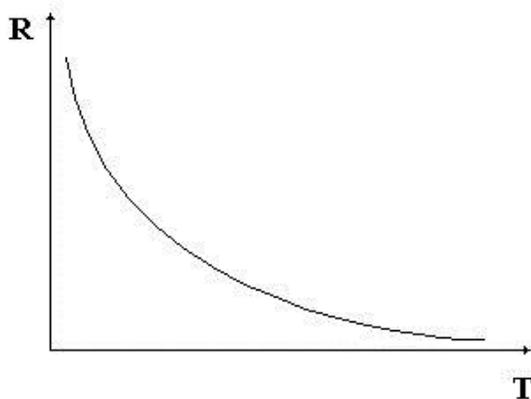
Thermistors' symbols are shown in Figure 1.



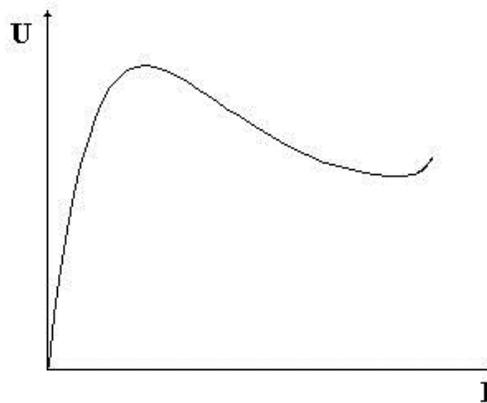
**Fig. 1** Symbols for the thermistors. a) NTC b) PTC.

### 2.1.a. NTC thermistors

A NTC thermistor has a thermal characteristic having the type as in fig. 2 and an electrical characteristic of the type in fig.3.



**Fig. 2** Thermal characteristic of the NTC thermistor.



**Fig. 3** Electrical characteristic of the NTC thermistor.

The thermal characteristic is given by:

$$R_T = A \cdot e^{\frac{B}{T}} \quad (1)$$

where:

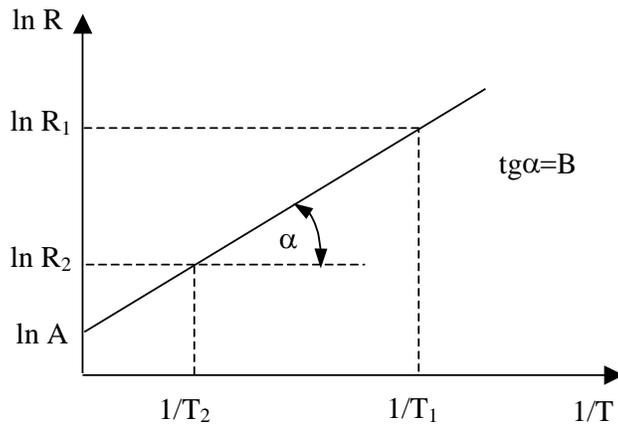
- $R_T$  is the thermistor resistance at temperature  $T$  (expressed in Kelvin [K]);
- $B$  is a material constant (measured in Kelvin) that characterizes the sensitivity of the thermistor; usually  $B = (2000-5000)$  K;
- $A$  (also known sometimes as  $R_\infty$ ) is a constant that depends on the type of the thermistor, measured in ohms and it represents the thermistor's resistance as the temperature tends (hypothetically) to infinity.

Plotting  $\ln R$  with respect to  $1/T$  the thermal characteristic becomes a straight line (fig.4), its parameters giving the constants  $A$  and  $B$ .

$$\ln R_T = \ln A + B \cdot \frac{1}{T} \quad (2)$$

$$B = \frac{\ln \frac{R_1}{R_2}}{\frac{1}{T_1} - \frac{1}{T_2}} \quad (3)$$

$$A = R_1 \cdot e^{-\frac{B}{T_1}} \quad (4)$$



**Fig. 4** Thermal characteristic of a NTC thermistor in the plane  $(\ln R, 1/T)$ .

The datasheets usually specify the following parameters:

- a) Rated resistance  $R_{25}$  - the value of thermistor's resistance at a temperature of  $25^{\circ}\text{C}$  and for zero dissipation conditions;
- b)  $B$  constant;
- c) The temperature coefficient (at the reference temperature, usually  $25^{\circ}\text{C}$ );

$$\alpha_{25} = \frac{1}{R_T} \cdot \frac{dR_T}{dT} \Big|_{T=298K} = -\frac{B}{T^2} \Big|_{T=298K} \quad (5)$$

Remark: This parameter can be inferred by knowing the value of the constant  $B$ .

d) Dissipation factor D [W / K] (sometimes denoted  $\delta$ ) is numerically equal to the thermistor's power dissipation (P) to a variation of 1°C (1K) between the thermistor's body temperature T and the ambient temperature T<sub>0</sub>;

$$D = \frac{P}{T - T_0} \quad (6)$$

e) The thermal time constant denoted by  $\tau$  indicates the time after which the thermistor's body temperature reaches 63.2% of the difference between the final temperature T<sub>f</sub> and the initial temperature T<sub>i</sub> when applying a temperature jump equal to  $\Delta T = T_f - T_i$ .

In Table 1 are shown some of the characteristics from the datasheet for the negative temperature coefficient thermistors produced by IPEE Curtea de Arges.

Table 1 Parameters of NTC thermistors produced IPEE Curtea de Arges.

Electrical Parameters	M.U.	TG 1101	TG1102	TG 1105	TG 1106	TG115 0	TG 121-680
Rated resistance R <sub>25</sub>	Ω	10	12	51	62	510	680
Temperature coeff. $\alpha_{25}$	% / °C	-3,3	-3,3	-3,7	-3,7	-4,1	-4,1
B	K	2900	2900	3300	3300	3650	3650
P <sub>max</sub>	W	0,6	0,6	0,6	0,6	0,6	0,5
Dissipation factor D	mW/°C	11	11	11	9,5	9,5	9,5
Time constant $\tau$	s	50	50	60	60	70	60

With regards to electrical characteristics V(I), it can be expressed by parametric equations by matching the power dissipated by the thermistor P<sub>d</sub> with the power evacuated it:

$$P_{ev} = D(T_c - T_a) = D \cdot \Delta T \quad (7)$$

where T is the body temperature of the thermistor and  $\Delta T$  overtemperature of the body of the component with respect to the environment (T<sub>a</sub>)

$$P_d = \frac{U^2}{R_T} = R_T \cdot I^2 \quad (8)$$

where: U and I are the voltage applied to the thermistor, respectively the current passing through it.

Correlating (7) and (8), yields:

$$U = \sqrt{A \cdot D \cdot (T - T_0)} \cdot e^{\frac{B}{2T}} \quad (9)$$

$$I = \sqrt{\frac{D}{A} (T - T_0)} \cdot e^{-\frac{B}{2T}} \quad (10)$$

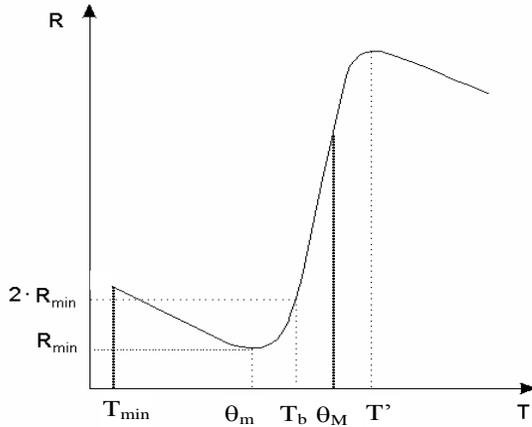
Plotting U = f (I) with respect to temperature it is observed that U has a maximum in the range of common temperatures, at the temperature T<sub>Um</sub>:

$$T_{Um} = \frac{B - \sqrt{B \cdot (B - 4T_0)}}{2} \quad (11)$$

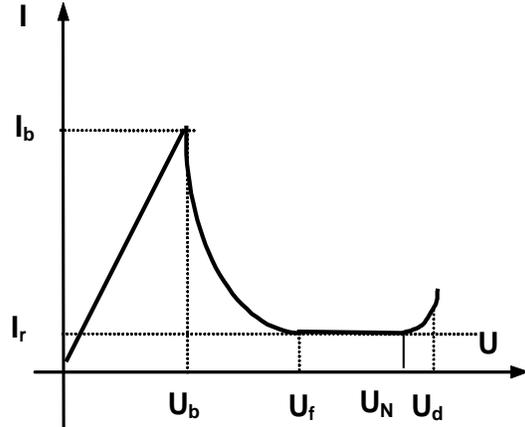
In order to obtain this maximum the condition B > 4T<sub>0</sub> must be fulfilled.

### 2.1.b. PTC thermistors

A PTC thermistor (with  $\alpha_T > 0$ ) has the thermal characteristic as in Figure 5 (characteristic of BaTiO<sub>3</sub>-based thermistors) and electrical characteristic given in figure 6.



**Fig. 5** Thermal characteristic of the PTC thermistor.



**Fig. 6** Electrical characteristic of the PTC thermistor.

Regarding Figure 5 it results that the PTC thermistor has a positive temperature coefficient only in a limited range of temperature ( $\theta_m - \theta_M$ ), this range being a specific characteristic of each type of thermistor.

With regards to the electrical characteristics (Figure 6) there are two important aspects: one given by the switching voltage and current (B), at the beginning of the downward portion of the characteristic, and the second (R) defined by the operating voltage at residual current ( $I_r$ ) (the constant level area on the characteristic). At voltages exceeding  $U_d$  the thermistor breaks down.

The thermal characteristic is given (approximately) by the formula:

$$R_T = A + C \cdot e^{BT} \tag{12}$$

The relationship is valid in the range  $\theta_m - \theta_M$  of Figure 5 with A, B and C constants depending on material and the device. Knowing the value of the thermistor's resistance at three temperatures T1, T2 and T3 one can determine the parameters A, B, C.

Currently, thermistors with positive temperature coefficient PTC, although having many applications, are used mainly as protective elements for the circuits (the consumers) by connecting them in series with the load to be protected. They behave as reversible fuses (that can be reset). Upon the emergence of an over-current in the circuit, the thermistor has a jump, its resistance increases significantly thereby reducing the current in the protected circuit to a safe value, which is not destructive to circuit elements. The resistance jump is due to the rapidly growing temperature of the PTC in accordance with the Joule – Lenz law. When lowering the current (possibly when there is a remedy for the defect that led to its growth) the PTC thermistor will switch to low resistance, the reversible safety becoming "good" again, hence still able to function.

Lately along with ceramic PTC thermistors, other have been developed based on conductive polymers which have a characteristic similar to that of classical PTC. The means to obtain the protection for circuit will be studied in section 3.4.

### 2.2. Varistors

Varistors are resistors whose resistance changes with voltage, so the current-voltage characteristic is nonlinear (Figure 7). In Figure 8 are some symbols for the varistors.

Current-voltage electrical characteristics can be simplified through the relations (13).

$$I = k \cdot U^\alpha \quad \text{or} \quad U = C \cdot I^\beta \quad (13)$$

where k (or C) is a constant;

$\alpha$  (or  $\beta = 1/\alpha$ ) is the non-linearity coefficient which depends on the material used to make the varistors ( $\alpha \approx 5$  for SiC and  $\alpha \in [20, 40]$  for ZnO).

The main parameters of the zinc oxide varistors are:

- Rated voltage ( $U_n$ ) – the value of the continuous voltage at which the varistor is functioning when it's being traveled by the rated current, usually 1mA.
- Maximum Clamping Voltage,  $U_c$  - varistors are currently mostly used to limit the disturbing voltages. Therefore, any solicitation of the varistor at a higher current than 1mA is produced as a pulse. The maximum limiting voltage  $U_c$  is the peak voltage appearing at the terminals of the varistor when applying a 'standard' pulse of current of 8/20 $\mu$ s.
- Non-repetitive maximum overcurrent  $I_{nrp}$
- The maximum energy non-repetitively absorbed  $W_M(J)$ . For silicon carbide varistors the rated dissipated power  $P_n$  is also defined.
- Currents asymmetry - is a measure for the relative deviation of currents ( $I_1, I_2$ ) for the same voltage applied onto the varistor with both polarities.

$$asymetry = \frac{I_2 - I_1}{I_1} \cdot 100 \quad [\%] \quad (14)$$

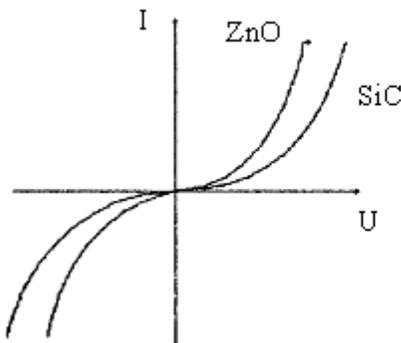


Fig. 7 Varistor's I(V) characteristic.

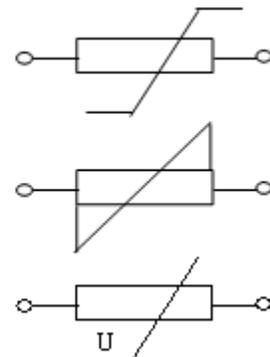


Fig. 8 Symbols for varistors.

### 3. Work procedure

#### 3.1. Determination of thermal characteristics of thermistors.

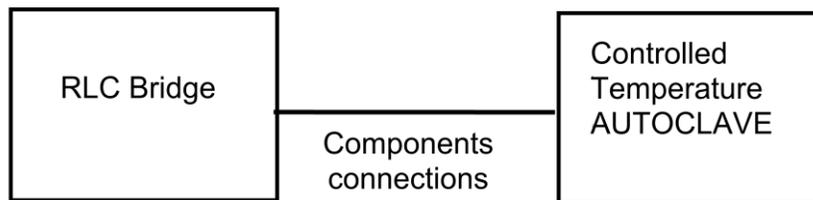


Fig. 9 Setup for obtaining the R(T) characteristic.

The thermistors to be measured will be placed in an autoclave. Their types are presented in Table 2.

Table 2 Characteristics for the thermistors (components) heated in the autoclave.

NTC1	EPCOS K164 470Ω
NTC2	EPCOS K164 1kΩ
PTC1	PTC265V 80 °150Ω (EPCOS C890)
PTC2	PTC30V13 (EPCOS C995)
R1	Carbon film resistor
R2	Metal film resistor

Some of the main parameters of the thermistors are filled in based on the input from the datasheet.

For NTC thermistors the following values will be written: R25, B, power at 25 degrees, dissipation factor, and thermal time constant. For PTC thermistors: the rated resistance, maximum voltage, reference temperature.

Then table 3 will be filled in for different values of the voltages  $U_a$  of the power supply. Resistance is measured with an RLC bridge. The first measurement will be at room temperature. The thermostatic oven will then be adjusted from 50°C with a step of 10 degrees. If there is an oscillation of the PTC thermistors, highlighted by the significant growth of the resistance, the measurement can be stopped before 150 °C.

Table 3

Crt. No.	Temperature [°C]	Resistance NTC1 [Ω]	Resistance NTC2 [Ω]	Resistance PTC1 [Ω]	Resistance PTC2 [Ω]	R1 [kΩ]	R2 [kΩ]
1	Ambient $\theta$						
2	50						
3	60						
...	...						
n	150						

Note: 1. After changing the temperature one must wait a certain period of time (approx. 10 min) to achieve the equilibrium temperature. An indication of this is the stabilization of NTC thermistor's resistance.

2. R1 is a carbon film resistor and R2 a metal film resistor. To measure the resistance values the RLC bridge can be used.

### 3.2 Plotting the V(I) characteristic for NTC thermistors.

The thermistors used are placed on the laboratory board with the layout from Figure 10.

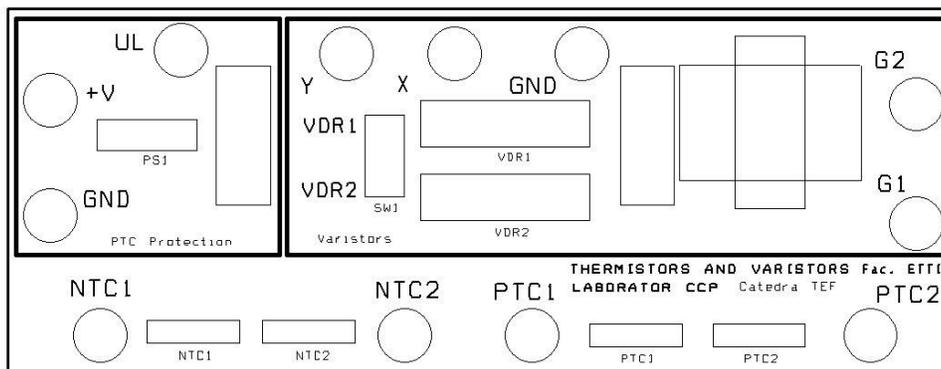
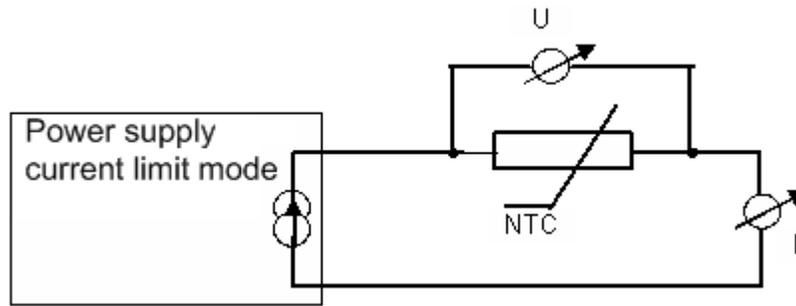


Fig. 10 Laboratory board

In order to determine the characteristic  $V(I)$  for the NTC thermistors the schematic used is the one from Figure 11.



**Fig. 11** Setup used for determining the  $V(I)$  characteristic for the NTC thermistors.

When determining the  $V(I)$  characteristic the voltage corresponding to the maximum of the characteristic must not exceed, otherwise the thermistor overheats and is destroyed. In order not to exceed the maximum voltage, the thermistor is supplied with constant current. This is possible when using the power supply with current limitation. Power supply voltage is fixed at  $U = 10V$ , which is the maximum voltage. The current is set at the current limit of the source. Tables 4a and 4b are populated. For the NTC1 thermistor having the resistance value of  $470\Omega$ , the current will be chosen between 0-80 mA with a step of 10 mA and for NTC2 with 1k value, the current will be between 0-40 mA with a step of 5 mA.

Table 4a

I [mA]	0	10	20	30	....	....	80
U [V]	0						

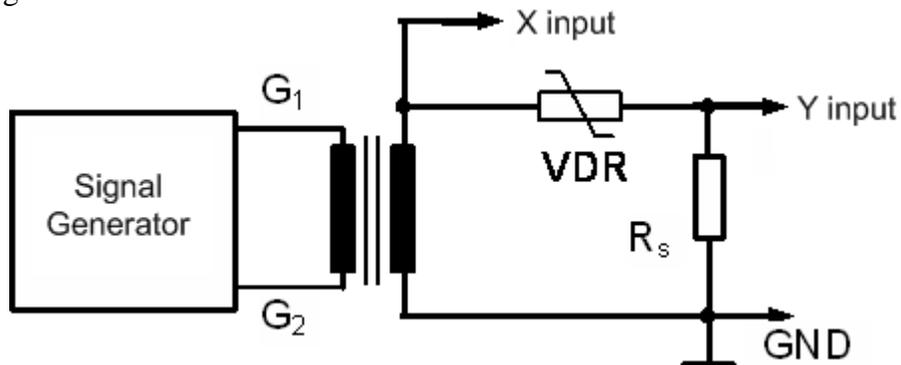
Table 4b

I [mA]	0	5	10	15	....	....	40
U [V]	0						

Note: After changing the current value, a certain amount of time has to pass ( $\sim 3$  time constants) necessary for reaching the thermal stationary regime.

### 3.3 Determining the $I(V)$ characteristic of varistors

In order to visualize the characteristic for varistors the right hand side of the laboratory board is used. The two VDR1 type JVR 11 and SIOV07K25 from EPCOS are identified. The electrical setup is provided in figure 12.



**Fig.12** Setup for observing the I(V) characteristic of varistors.

In order to view on the screen of the oscilloscope the I(V) characteristic of a varistor it is necessary to apply on the X input of the oscilloscope a voltage proportional to the voltage applied to the varistor and on the Y input, simultaneously, a voltage proportional to the current passing through the varistor. The voltage proportional to the current is produced by placing a resistor  $R_s$  in series with the varistor ( $R_s=100\Omega$ ).

The generator permits using voltages up to 20Vpp. To increase the voltage a transformer is used. The frequency will be chosen around 50 Hz.

On the screen of the oscilloscope divisions will be read. The switch SW1 (Figure 12) allows switching between VDR1 and VDR2. 2 varistors will be measured, both with ZnO, populating for each varistor the fields in Table 5.

Oscilloscope will have the following settings:

- X-axis, amplification: 2V/div; the oscilloscope probe: 10:1
- Y-axis amplifier: 200 mV / div, the oscilloscope probe: 1:1

With these data resulting scale factors  $K_x = 20 \text{ V / div}$ ,  $K_y = 2\text{mA/div}$ .

Table 5

	VDR1									
Iv [mA]										
Uv [V]										
	VDR2									
Iv [mA]										
Uv [V]										

A sufficiently high number of points have to be chosen (10-16) in order to allow plotting a clear graph.  $I_v$  and  $U_v$  values are computed using the scale factors  $K_x$  and  $K_y$ :  $I_v \text{ [mA]} = K_y \cdot I_v \text{ [div]}$  și  $U_v \text{ [V]} = K_x \cdot U_v \text{ [div]}$ .

### 3.4. Study of the protection with PTC polymer thermistors

The left side of the board in figure 10 is used. The type of the thermistor is Polyswitch RXE030 and the load resistance has a value of  $33\Omega$ . Table 6 is populated with the data for the PTC thermistor using the datasheets.

Table 6 Data for the polymer-based thermistor

Crt. No.	Hold current	Trip current	Maximum jump time at	Pd (W)	Initial resistance		Post-trip resistance R1 max. ( )
	$I_H$ (A)	$I_T$ (A)	$5xI_H$ (s)		R min.	R max.	
RXE030							

Details regarding polymer thermistors can be found in datasheets and in the papers [2] and [4].

The measurement diagram is provided in Figure 13.

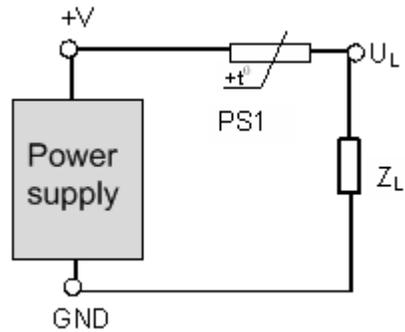


Fig. 13 Electrical setup for protection circuit using a PTC thermistor as a reverse safety switch

Table 7 is populated for the cases:

- A voltage of 10 V is applied between the terminals + V and GND that leads to establishing a smaller current through the circuit PS1-Z<sub>L</sub> than the hold current I<sub>H</sub>. As a result, almost all of the source voltage is applied to the load R<sub>L</sub> = 33Ω which is in the normal operating mode. The power dissipated by the load is below the rated power (5W).
- Simulate the accidental occurrence of a dangerous voltage by increasing the voltage of the power supply to 20V, which would exceed the rated load, which in actual situations may damage it. Thanks to the PTC thermistor the current through the circuit will be limited to a non-dangerous value.
- The power supply is stopper, thus resetting the protection. The 10V voltage is set again and step a) is redone.

Table 7

Case	U <sub>A</sub> [V]	U <sub>L</sub> [V]	I <sub>L</sub> = U <sub>A</sub> /R <sub>L</sub> [mA]	U <sub>PTC</sub> =U <sub>A</sub> -U <sub>L</sub> [V]	P <sub>L</sub> =U <sub>A</sub> ×I [W]	P <sub>PTC</sub> [W]
A	10V					
B	20V					
C	10V					

U<sub>A</sub> - voltage of the power supply, U<sub>L</sub> - voltage drop on the load and I<sub>L</sub> - the current through the circuit, U<sub>PTC</sub> - the voltage at the terminals of the PTC, P<sub>L</sub> power dissipated by the load, P<sub>PTC</sub> - the power dissipated by the PTC.

Determine the time in which the activation of protection takes place using the graph in the datasheet ("time to trip").

#### 4. Processing experimental data

4.1 Using the data from Table 3 plot the variation of the resistance versus temperature for the 4 thermistors.

4.2 For the NTC thermistors compute by (3) and (4) the parameters A and B with  $\theta_1 \approx \theta_a$  and  $\theta_2 \approx 100^\circ\text{C}$ .

4.3 For PTC thermistors the switching temperature T<sub>b</sub> is identified as in Figure 5. Compute the constants A, B and C. For B and C choose two temperatures for which the resistance is large, neglecting A. Parameter A is computed by choosing a temperature for which the resistance is low, using B and C previously determined.

4.4 Temperature variations of the R1 and R2 resistors are compared between each other and with those of the thermistors.

4.5 Using the data from Table 4a and 4b plot  $V(I)$  for NTC thermistors. Specify the value for the maximum voltage  $U_m$ . Calculate the maximum voltage and compare it with measured values.

4.6 Based on the data in Table 5 plot  $I_v(U_v)$ . Using the data from the table coefficients  $\alpha$  and  $k$  are computed. For a certain voltage  $U_v$  chosen in the area with increasing values for the current check the symmetry of the  $I(V)$  characteristic. If possible compute the asymmetry of the currents by means of formula (14)

4.7 Populate table 7 with the data.

4.8 Observations, conclusions on thermistors and varistors characteristics, the results, method of measurement, etc. (taking into account the above aspects)

## 5. Questions and conclusions

5.1 What is the effect of the increase of the ambient temperature onto the characteristic  $V(I)$  of the NTC thermistor? Indicate the effects based on the relations 9-10.

5.2 The dissipation factor of the thermistor changes if the thermistor is immersed in oil rather than air?

5.3 What would be the effect of raising the  $V(I)$  characteristic using a NTC thermistor placed in the heated autoclave?

5.4 Why does the NTC thermistor have a linear characteristic for low levels of current and voltage?

5.5 How would the  $V(I)$  characteristic of an NTC thermistor look like if, theoretically speaking, the measurements were made very quickly, in a time  $t \ll \tau$ ?

5.6 Deduce formula (11).

5.7 If you change the temperature values in the calculation process of the parameter  $B$  in section 4.2 what could be noticed? Provide comments based on the bibliography.

5.8 Compute the parameters  $k$  and  $\alpha$  for the equivalent varistor obtained by connecting in series two identical varistors.

5.9 How do you explain the shape of the  $R(T)$  characteristic for the PTC thermistor? Study the literature.

5.10 What factors influence the time in which the thermal stationary regime is reached in 3.1?

5.11 Can changes in ambient temperature during the experiment affect the precision of the measurements?

## 6. Content of the paper

6.1. Experimental data, data processing, conclusions, interpretations, determinations.

6.2. Answers to questions

## References

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