Siemens Matsushita Components

# The PTC Thermistor

## A user's guide

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Intensive development, combined with new technologies and advances in materials have resulted in ceramic PTC thermistors for a wide range of applications. These developments allow the PTC thermistor to be used as a temperature sensor, as a circuit protection device or as a self-regulating heating element.

### Structure and Function

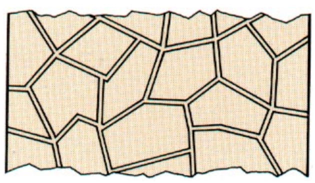
PTC thermistors are made of doped polycrystallite ceramic on a barium-titanate base. They have a typical resistance/temperature characteristic (*R/T*) over a specified temperature range which features a very positive temperature coefficient (PTC) and a resistance rise of several powers of ten. Reasons for such a resistance characteristic are the semiconducting and ferro-electrical properties of the titanate ceramic. Generally, ceramic is known as a good insulating material of high resistance.

Semiconduction and thus a low resistance are achieved by doping the ceramic with materials of a valency foreign to the lattice.

A proportion of the barium and titanium ions in the crystal lattice is replaced with ions of higher valencies to obtain a specified number of free electrons which determine the ceramic's conductivity.

The material structure is composed of many individual crystallites which are responsible for the PTC thermistor effect of an abrupt resistance rise (**Fig. 1**). At the edges of these monocrystallites, the so-called grain boundaries, potential barriers are formed. They prevent free electrons from diffusing into adjacent areas. Thus a high resistance results.

This effect is neutralized with low temperatures.



$$R_{PTC} = R_{grain} + R_{grain\ boundary}$$

$$R_{grain\ boundary} = f\,(T)$$

**Fig. 1 General principle of polycrystalline structure of a PTC thermistor. The PTC resistance $R_{PTC}$ is composed of individual crystal and grain boundary resistances. The latter is strongly temperature-dependent**

High dielectric constants and sudden polarization at the grain boundaries avoid the formation of potential barriers with low temperatures to enable a smooth transition of free electrons.

Above the Curie temperature, dielectric constant and polarization decline so far that there is a strong growth of the potential barriers and hence of resistance.

Beyond the range of the positive TC the number of free charge carriers is increased by thermal activation with the resistance decreasing and exhibiting a negative temperature characteristic (NTC).

### Characteristic data

In describing or selecting PTC thermistors the characteristic data $R = f\,(T)$ and/or $I = f\,(V)$ play an important role.

#### *R = f (T)* characteristic

The curve in **Fig. 2** refers to a PTC thermistor supplied with a low voltage which excludes any self-heating. In this case the PTC thermistor resistance is determined by the temperature over the entire characteristic. The characteristic of the positive TC is restricted to a relatively narrow temperature range between $T_{min}$ and $T_{max}$. The main feature to consider when selecting a PTC thermistor is the onset point of the steep resistance rise. Significant here is the reference temperature $T_{ref}$ at which the resistance $R_{ref}$ is twice the minimum value $R_{min}$, i.e. almost the ferro-electrical Curie temperature. The resistance at room temperature, in this case 25 °C ($R_{25}$), is also of interest to the user. The end of the steeply rising part is determined by the resistance $R_{PTC}$ at temperature $T_{PTC}$. Due to the limited resistance rise, the PTC thermistor becomes conductible again after exceeding the temperature $T_{max}$.

#### *I = f (V)* characteristic

A typical current/voltage characteristic as shown in **Fig. 3** can be derived from the *R/T* curve in **Fig. 2**. This is resistive in the initial phase until the power consumed in the thermistor heats it up to a value at which the resistance rises abruptly. In other words, there is a current maximum (switching current $I_K$) when the thermistor reaches the reference temperature $T_{ref}$. The curve declines with rising temperature. It mainly refers to steady-state operating conditions with the PTC thermistor in thermal equilibrium at any point of the curve. The current value characterized as the switching current $I_K$ is an essential criterion when selecting PTC thermistors for current control and limiting tasks.

The residual current $I_C$ flowing with operating voltage $V_O$ supplied at thermal equilibrium is required to maintain the PTC thermistor's temperature. To provide protective functions a particularly high $I_K$ to $I_r$ ratio is most important.

The power-handling capability of a PTC thermistor is determined by the breakdown voltage $V_B$. This is because the thermistor would have to consume more electric power after reaching the resistance peak than it could dissipate. This unstable state leads to a thermal overload and, finally, may destroy the PTC thermistor.

Nowadays, advanced production techniques allow the difference between $V_B$ and the maximum operating voltage $V_{max}$ to be kept sufficiently large to guarantee excellent operational safety even under extreme conditions. Effects on the PTC thermistor performance, in particular on the *R*/*T* and *I*/*V* characteristics due to application parameters, are of importance to the user. A few essential relationships are described below in more detail.

### Voltage dependence of resistance

As mentioned above, the *R*/*T* curve shows the relation between resistance and temperature at zero load, i.e. with low operating voltage. The resistance is made up of the grain resistance and the grain-boundary "transition" resistance. The latter is decisive for the PTC thermistor resistance because of strong potential barriers built up in the hot state.

Consequently, higher voltages occur mainly at the grain boundaries so that the high field strengths there reduce the potential barriers and hence the resistance.

The greater the potential barrier, the more strongly this "varistor" effect influences the resistance.

Below the reference temperature, with only weak junctions, the major portion of the applied voltage is taken over by the grain resistance.

Hence field strength at the grain boundaries and the "varistor" effect are greatly reduced.

A typical resistance dependence on the field strength is shown in **Fig. 4**. It can be seen that the greatest resistance fall appears in the region of $T_{max}$ and thus of maximum resistance represented by decreased steepness of the curves.

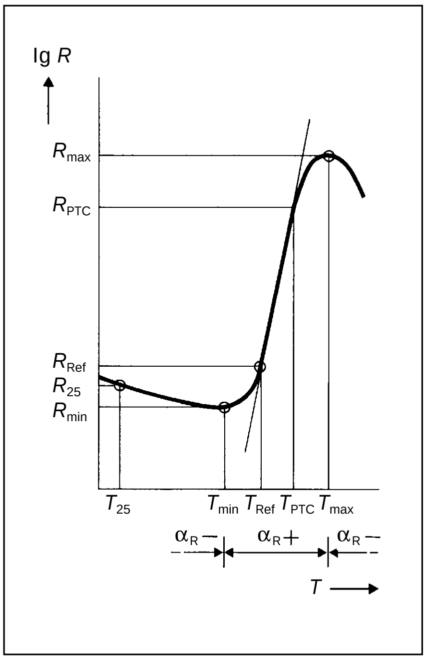



**Fig. 2 Resistance/temperature curve of a PTC thermistor. The temperature coefficient is positive between $T_{min}$ and $T_{max}$ and becomes negative beyond this range**

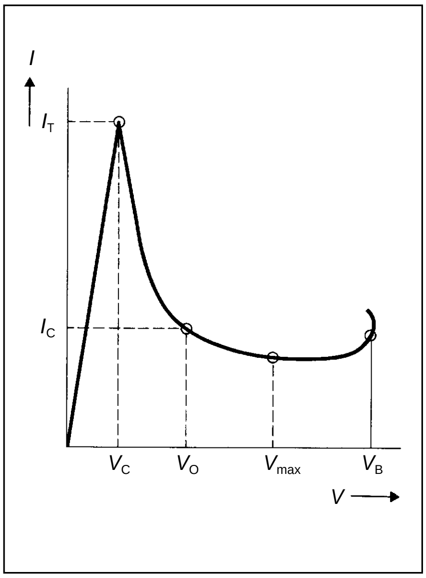



**Fig. 3 *I/V* characteristic of a PTC thermistor**

Due to the dependence of the positive temperature coefficient on the field strength, operation at high supply voltages is only possible by means of particular technological (grain size) and design (type diameter) measures.

### Frequency dependence of resistance

Its material structure makes the PTC thermistor not only a purely resistive but also a capacitive resistor with AC voltage due to the grain boundary junctions. An equivalent circuit diagram is shown in **Fig. 5**. The impedance measured at AC voltage declines with increasing frequency. **Fig. 6** shows the dependence of the thermistor resistance on the temperature at various frequencies. It implies that the PTC thermistor is not suitable for use in the LF and RF range but is restricted to DC and line frequency applications.

### Influence of thermal conductivity on PTC thermistor temperature

**Fig. 7** shows the electric power $P_{el}$ generated in a thermistor as a function of its temperature.

With a fixed operating voltage, an operating point is determined in accordance with the ambient temperature and the thermal conductivity of the device to the environment.

The thermistor heats up to an operating temperature above the reference temperature (operating point $A_1$ in Fig. 7).

With rising temperature or reduction of thermal dissipation to the surroundings, the heat generated in the thermistor cannot be eliminated and the PTC thermistor temperature rises.

Subsequently, the operating point on the curve falls, i.e. $A_2$ in Fig. 7, thus considerably decreasing the current.

This limiting effect is maintained until $T_{max}$ is exceeded. A further temperature rise at given operating voltage would destroy the thermistor.

### Ambient temperature effects on *I/V* characteristic

Two *I/V* characteristics of the same thermistor at two different ambient temperatures $T_1$, and $T_2$ (with $T_1$, < $T_2$) are shown in **Fig. 8**.

An increase in ambient temperature with all other conditions maintained results in a higher resistance in the thermistor and thus reduces the current. The curve of $T_2$ lies below that of $T_1$.

The ambient temperature also effects the breakdown voltage.

With rising temperature the device reaches the critical switching temperature while the power or operating voltage is still low. Hence $V_{B1}$ is below $V_{B2}$.

## Applications

As shown in **Fig. 9**, there are two main functional groups of PTC thermistors. Technological advances have led to high-quality PTC thermistors for numerous applications. In this context, power semiconductors have been of particular interest in recent years. The table presents the various fields of application which will be briefly described.

### PTC thermistor as a switch

A PTC thermistor is used when a series-connected load requires a delayed switch-off many times per hour. Examples of such delayed switching are in degaussing circuits for color TV, control of starting-split-phase AC motors and relay delays. **Fig. 10** shows a typical circuit of a PTC thermistor connected in series with a special load and the delayed falling edge of the load current. The switching function of the PTC thermistor is defined by controlling the current flowing through the load at fixed high operating voltages and limiting subsequent heating of the PTC device with current differences generally being around a factor of 1000.

The switching time *t*, achieved is determined approximately by the equation.

$$t_s = \frac{K\,V\,(T_{Ref} - T_{amb})}{P}$$

$K$ = factor dependent on material properties

$V$ = thermistor volume

$T_{Ref}$ = thermistor reference temperature

$T_{amb}$ = ambient temperature

$P$ = switch-on power of the thermlstor

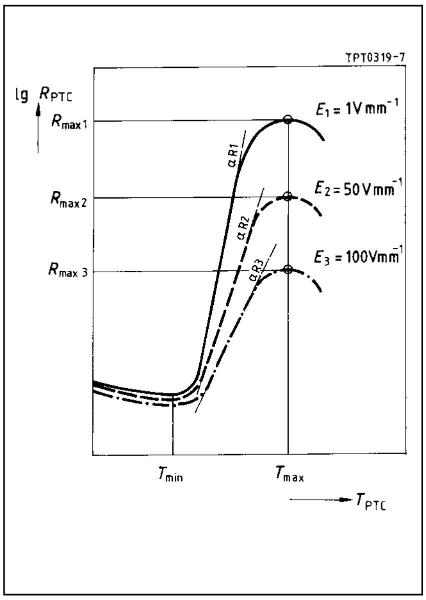



**Fig. 4 Influence of field strength *E* on the *R/T* characteristic (varistor effect)**

$\alpha_{R1} > \alpha_{R2} > \alpha_{R3}$

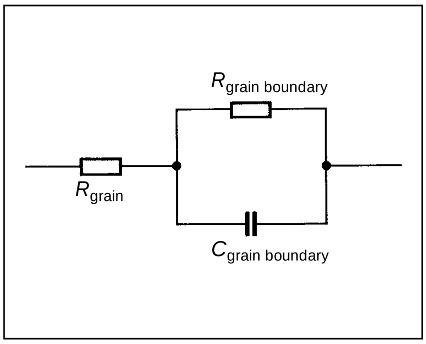



**Fig. 5 Equivalent circuit diagram for a PTC thermistor at AC voltage**

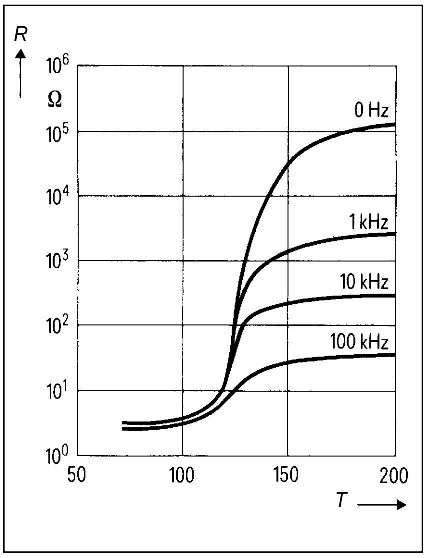



**Fig. 6 Frequency influence on the *R/T* curve**

It shows that the switching time depends mainly on the size and reference temperature of the PTC thermistor and on the power supplied. Through production techniques there are various ways of altering the switching time.

Switching times are prolonged by increasing the thermistor volume or the reference temperature. Short switching times are achieved by higher power. The curve in **Fig. 11** gives the switch-off power at different currents in the thermistor. The most frequently used ceramic material for these applications has a reference temperature of 120 °C.

### PTC thermistor used as a resettable fuse

Unlike the switches, the fuses are only actuated in the event of a consumer overload.

The thermistor resistance remains low at rated load operation and thus causes only small voltage drops at high operating currents.

They are likewise connected in series with the load and mostly have wire leads for easy mounting.

**Fig. 12** shows both operating states of a fuse PTC thermistor. The resistance is low during rated operation (operating point $A_1$). In the event of overload or short-circuit, the power consumption of the thermistor becomes so high that it heats up and limits the current through the load to a permissible low value (operating point $A_2$).

Most of the applied voltage then appears across the PTC thermistor. The residual current is sufficient to keep the PTC resistance high and gives a fuse action until the overload in the consumer equipment is eliminated. The switching current is one of the main parameters in the operation and selection of a PTC thermistor.

It is defined as the current at which the supplied electrical power is sufficient to heat up the device and thus limit the supply of current and initiate protectlve action.

The switching current depends mainly on

- PTC thermistor structure,
- PTC thermistor resistance,
- thermal dissipation conditions.

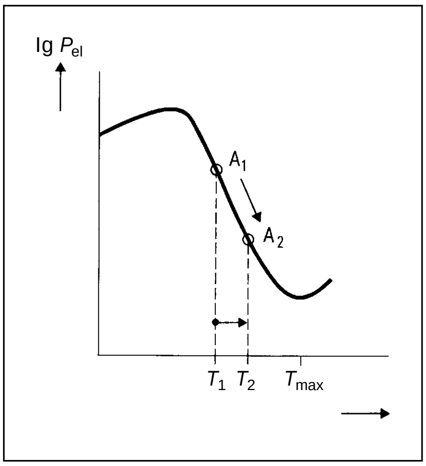



**Fig. 7 Electric power $P_{el}$ of a PTC thermistor as a function of temperature**

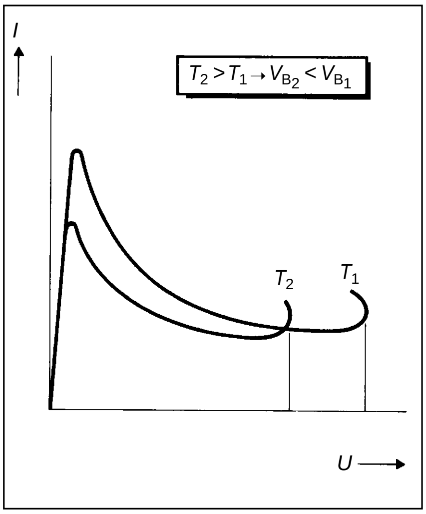



**Fig. 8 Influence of ambient temperature on the *I/V* curve**

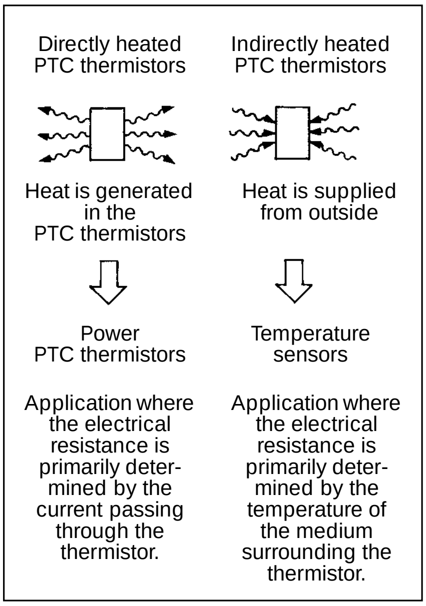



**Fig. 9 Main groups of PTC thermistors referred to their functions**

A minimum power (current) is required with a given structure for heating up the PTC thermistor to more than the reference temperature resulting in a particular current at a given thermistor resistance. In many cases, high currents are necessary. A rise is obtained with a given resistance by increasing the thermistor size (**Fig. 13**) or the reference temperature. Optimum conditions are achieved for high currents by utilizing the cooling effect of the environment.

To provide good thermal dissipation to the environment, PTC thermistor surfaces are made as large and thin as possible.

Additional use of heat sinks augments this effect so that switching performances exceeding 200 W per element can be achieved.

Another control mechanism is provided by the PTC resistance as shown in **Fig. 14**.

To keep the current loss at a minimum, PTC thermistors are produced with very small resistance tolerances of ± 25% and less so that functions are possible in applications with quite small current differences between rated and overload operation.

Most important for the current is the ambient temperature at which the PTC thermistor is operated. The relationship between current and ambient temperature is shown in **Fig. 15**.

A rise in ambient temperature results in a lower power consumption to switch the thermistor.

Lower ambient temperature has the opposite effect, i.e. higher power consumption and thus higher current.

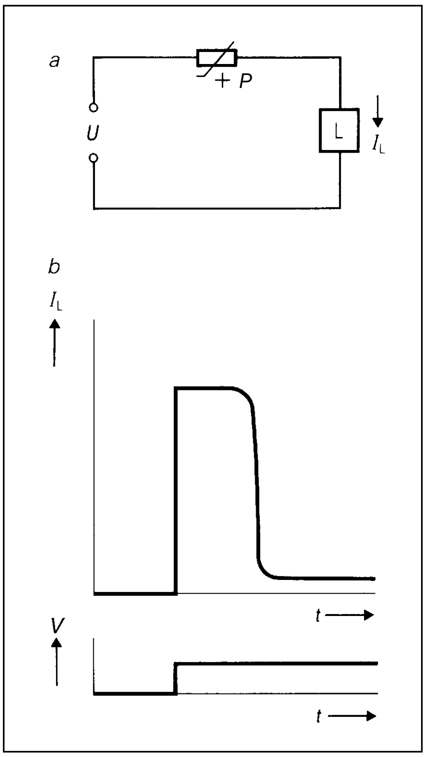



**Fig. 10 Typical circuitry of a switch PTC thermistor (a) and typical load current characteristic (b)**

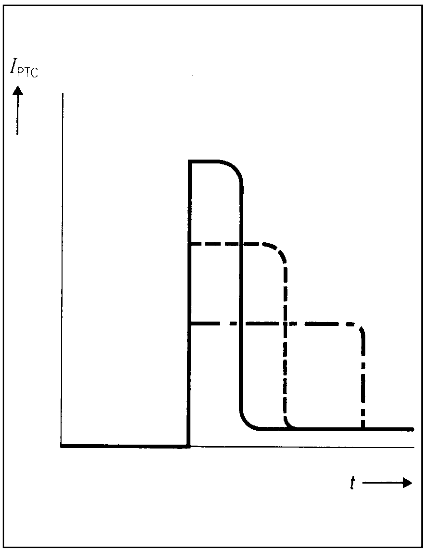



**Fig. 11 Typical switch-off behaviour of a PTC thermistor**

| **Power PTC thermistors** | | **Sensors** |
|---|---|---|
| Fuse | Short-circuit and overload protection | Temperature<br>Overtemperature protection<br>Measurement and control |
| Switch | Motor start<br>Degaussing<br>Time delay | Limit temperature<br>Motor protection<br>Overtemperature protection |
| Heater | Small heaters<br>Thermostats | |
| Level sensor | Limit indicator | |

## PTC thermistor as a heater

The use of PTC thermistors is not confined to switching and current sensing but also includes heating applications because of very good resistance/temperature characteristics. The positive characteristic of the temperature coefficient avoids the need for the additional control and excess temperature devices required for conventional heating systems. The operating voltage is applied directly to the thermistor.

The low-resistance part of the *R/T* characteristic (Fig. 2) is of particular design as here very high heating performances are achieved. To utilize this effect, it is essential to avoid device temperatures in the high-resistance range. This is achieved by incremented heat transmission to the surface of extremely thin thermistors.

Excellent heat flow from the thermistor to the heating system is obtained by placing the device between and close to two solid heat emitting bodies. Symmetrical thermal decoupling is most effective in this case.

Special care has to be taken when mounting the thermistor by means of potting. Due to an increased thermal resistance of the sealing compound, the heat transmission is seriously affected. The thermistor is heated up excessively and thus reaches the critical temperature. A detailed description of the PTC thermistor as heating element is given in [1].

For line-commutated PTC devices one should avoid soldering because of the steep temperature rises during heating up and sometimes very high operating temperatures .

The devices are offered by manufacturers with clamps which guarantee suitable thermal decoupling.

Heating thermistors are at present available in various sizes for all applications within a temperature range of 40 to 290 °C.

## PTC thermistor as a temperature sensor

Only the steep section of the thermistor's *R/T* characteristic is used. Its resistance has to be considered as a function of the ambient temperature $R_{PTC} = f\,(T_{amb})$.

To obtain this relation between resistance and temperature without self-heating and/or varistor effects, these temperature sensing devices have to be operated with the lowest possible field strengths.

To allow a rapid response, the thermistors have very small dimensions. Materials with very steep *R/T* waveforms are preferable to maintain a high regulation accuracy.

There are types available with temperature coefficients above 30%/K in the operating range.

PTC temperature sensors are mainly employed in electric motors to monitor the winding temperature.

Sensors with switching temperatures from –30 to +180 °C (SMD 90 – 130 °C) are available for a great diversity of temperature sensing tasks.

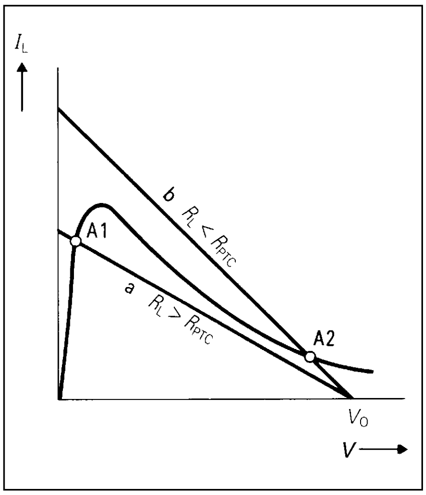



**Fig. 12 Operating states of an overload protection PTC thermistor**
**a rated operation**
**b overload operation**

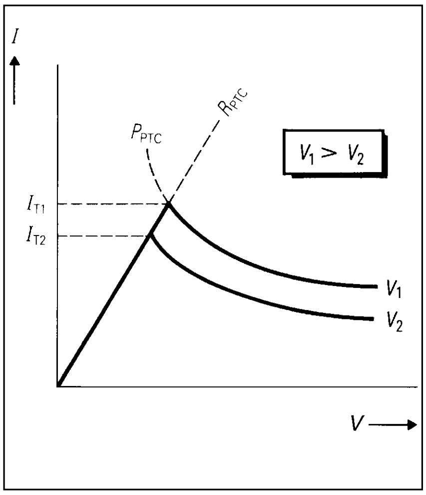



**Fig. 13 Switching current dependence on thermistor volume at given resistance $R_{PTC}$**

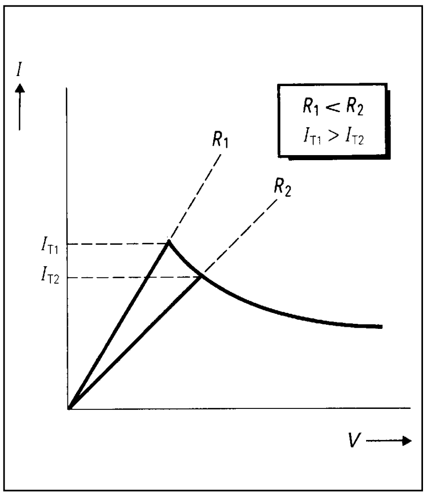



**Fig. 14 Influence of the PTC resistance on the switching current**

## PTC thermistor as a level sensor

These sensors are operated at voltages that will cause the reference temperature to be sightly exceeded. A thermal equilibrium of power consumption and dissipated quantity of heat is reached.

Indication is achieved by altering the conditions of thermal conductivity.

This results in a change of the PTC thermistor power and hence of the power supplied.

With constant voltage the thermistor current is a measure of the prevailing cooling conditions.

As shown in **Fig. 16**, the current rises when the thermistor is dipped into a liquid because the additional cooling reduces the thermistor's resistance as a result of the positive temperature coefficient. The device responds to every change of thermal conditions.

The principle is used to indicate levels on the basis of presence or absence of liquid at particular heights.

As a large difference between the indication signals of both states is advantageous, thermistors with very high reference temperatures are used, thus eliminating the undesired influence of high ambient temperatures.

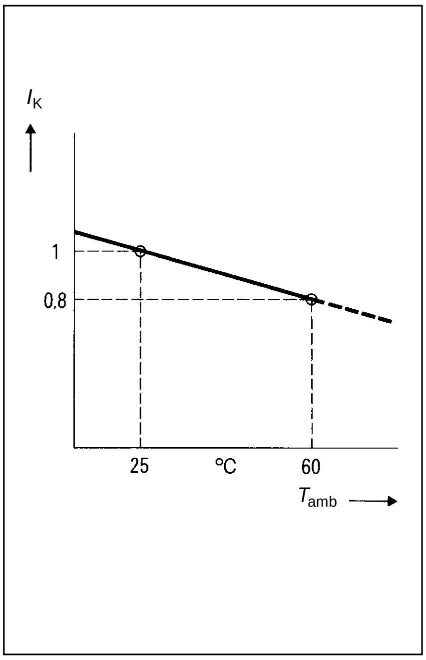



**Fig. 15 Switching current as a function of ambient temperature**

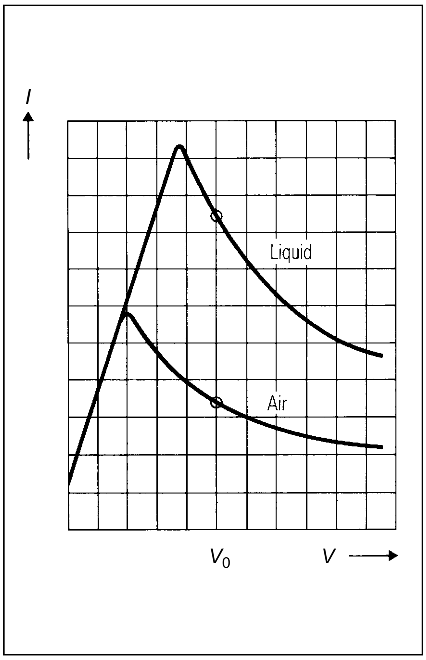



**Fig. 13 Current/voltage curves of a PTC thermistor exposed to air and to liquid**

To prevent the monitored liquids from affecting the ceramic, level sensors are housed in hermetically sealed packages .

This allows the use of PTC thermistors to monitor levels of engine oil, cooling water, brake fluid, petrol and fuel oil. The same principle is applied when monitoring air flows by utilizing the cooling effect of air in movement.