NTC and PTC thermistors

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Contents

1 Introduction

This document aims to give a complete introduction to the world of thermistors. A thermistor, also called *thermally sensitive resistor*, is a device whose electrical resistivity is strictly bonded with the temperature. More precisely, there are two types of thermistors. The first one is called negative-temperature-coefficient (or **NTC**), meaning that its resistance changes in the opposite way of temperature: when the temperature rises, the resistance decreases, and vice-versa. The second type is the positive-temperature-coefficient thermistor (also known as **PTC**) which means that its resistivity increases if the environment gets hotter and is reduced when the temperature decreases.

The first part of the document covers some basic information that's important to know about thermistors, such as the materials and the history of these devices. The second part of the document analyzes the characteristic curves of the PTC and NTC thermistors, exploring the distinct behaviors displayed in different temperature conditions. Furthermore, the document explores practical applications, highlighting the various ways in which these thermistors are applied across different fields.

2 Background

This chapter focuses on a brief explanation of the physics behind thermistors by introducing and discussing the structure of the atom and the most crucial information that is needed for a better understanding of the topic. Then the attention will be shifted to discussing a specific type of material, known as semiconductors, that are largely utilized for the creation of electric components as far as thermistors. In the end, the document explores the historical progression and development of thermistors, with a particular focus on the NTC type which was the first to be discovered in the first half of the 19th century.

2.1 Outermost orbit and valence electrons

As is common knowledge, everything is made out of atoms, every living creature and every unanimated object. An atom is made out of three subatomic particles. The protons (which have a positive electric charge) and the neutrons constitute the nuclei of the atom. The electrons, carrying a negative charge, orbit around the nucleus in distinct orbits.

By observing the figure 1, it is possible to distinguish two important types of electrons: the inner electrons, which orbit around the inner shells, and the valence electrons that orbit in the **valence shell** (also called the outermost orbit). These electrons are crucial for determining the properties of the material [7]. Particularly depending on how much energy these electrons have, a material is going to be a good conductor rather than a good insulator.

When the outermost orbit is incomplete, valence electrons are separable from the atom. In some cases, at room temperature, there is enough energy to remove these electrons from the orbit. This is the case for most conductive elements like metals (copper, silver and gold) which can easily propagate both electricity and heat. On the

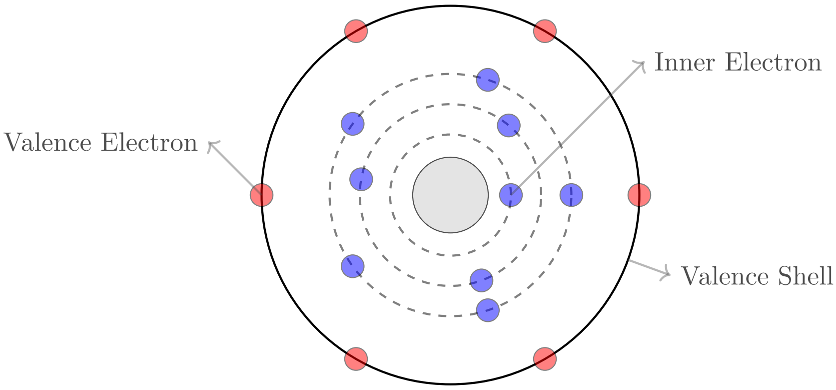

Figure 1: The orbits and electrons of an atom.

other hand, when a great amount of energy is needed to remove one valence electron from the valence orbit, the material is an insulator (also known as dielectric) like wood, glass or rubber [7].

2.2 Semiconductor materials

Other than conductors and dielectric elements there are other types of materials like semiconductors. This particular type of material is rather important to discuss because it is the key element in creating a thermistor. The peculiarity of a semiconductor element is that its conductivity stands between the inductors and the dielectric materials. The most common semiconductor materials are silicon and germanium but it is also used zinc, cadmium, boron and more [7]. These types of materials are highly popular because of their properties:

- They are light weight-wise and small dimension-wise;
- They are highly energy-efficient because they work with low voltage;
- Long-term degradation effects are insignificant.

Additionally, generally, the semiconductor materials are *negative temperature coefficient* meaning that their conductivity increases with the temperature, and so the resistivity of the element decreases non-linearly. But this also means that when the temperatures are extremely low (near zero Kelvin) their conductivity properties are comparable to a dielectric material (so their resistance is extremely high).

It is important to note that the semiconductors do not follow Ohm's law. More precisely the current increases much more than the voltage; this peculiarity is used for the BJT transistors. Furthermore, specifically because of the resistivity/temperature curve they are widely used in thermistors, rectifiers, Zener diodes, varistors and photovoltaic cells [7].

Other types of materials

It is worth mentioning that the three types of material aforementioned are not the only ones. The *superconductors* are materials whose electrical resistivity reaches almost zero when the temperature is greatly below zero Celsius. These materials are usually metals or ceramics [7].

Moreover, there are *magnetic materials* that can differ in several types depending on their capability of being magnetized by magnetic fields. The diamagnetic and paramagnetic materials have a very low magnetic susceptibility (between 10^{-6} and 10^{-3}) meaning that they are not likely to propagate a magnetic field. Then there are the ferromagnetic and ferrimagnetic materials whose magnetic susceptibility depends on the magnetic field strength. Eventually, there are also antiferromagnetic materials whose susceptibility increases as the temperature increases but when the element reaches a critical temperature, the susceptibility starts decreasing again [7][8].

Furthermore, it is also important to mention the *ferroelectrics* which are a type of material whose natural electric polarization can be changed by the presence of an electric field [7][17].

2.3 History of thermistors

On February 21, 1833, Michael Faraday documented the initial observation of the negative temperature coefficient of resistance phenomenon but the in-depth study of this peculiar behavior started almost 100 years later, in the 1930s era.

In 1935 the company Koninklijke Philips Electronics introduced a "novel" NTC material, called *Starto*, which was a mixture of silicon and clay that aimed to improve room temperature resistance, temperature coefficient of electrical resistance in silicon-based components, and provide easy moldability with superior mechanical properties. The practical outcome of Starto components was not as expected because the resistance was greatly sensitive to the mixing oscillations and the silicon was not evenly distributed in the material causing self-heating and short circuit situations. In the same year, Walter Schottky tried to fabricate a *thermonegative resistor* made out of ceramic (based on copper oxidize or uranium dioxide) but the results were similar to the Starto components.

By the end of the 1940s, these types of thermistors became extremely popular thanks to Philips Research Laboratories which focused the studies on the pinel-structure ceramics - specifically based on iron oxidize. The laboratories proposed that electrons transition between different positions in the material representing a key development in comprehending the behavior of these materials. The studied materials were analyzed with temperatures up to 300°C, but in 1948, Torok discovered NTC materials that could have been utilized in temperatures up to 1200°C such as chromic oxide.

Starting in the 1950s, thermistors found application in advanced and sophisticated fields, including aerospace and cryogenic devices. Moreover, in the 1970s additional research about high-temperature NTC ceramics was conducted by Ford, Matsushita Electric, and Siemens. In the early 1990s, university-based research groups played a significant role in advancing NTC ceramics, investigating the aging of electrical properties and exploring innovative processing methods [6][2].

3 PTC thermistors

As aforementioned, a positive temperature coefficient thermistor (also called **posistor**) is a thermally sensitive resistor that varies its resistivity as the temperature of the environment changes. Particularly because it is a positive coefficient, as the temperature increases, the resistivity of the semiconductor device increases as well.

The posistor's structure is rather simple: a PTC material - such as ceramic and polymer materials - is put between two metal foil electrodes. The overall resistance of the PTC thermistor is given by the PTC material (also called *bulk*), the electrode resistance (which can be omitted) and the interface resistance [16].

3.1 Charateristics

One of the most important properties of the PTC thermistor is the characteristic curve between the **resistance** R and the **temperature** T, which has to be converted from Celsius (or Fahrenheit) to Kelvin. Its curve is a positive exponential graph that respects the following equation [15][11]:

$$R = R_0 \, e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

Where R is the calculated resistance at the temperature T and R_0 is the resistance measured at temperature T_0. The coefficient β is the thermistor constant and it depends on the materials used to build it and on the thermistor dimensions. It is possible to obtain this value by measuring its resistance value at two different temperatures and computing the following equation [15].

$$\beta = \frac{\ln \frac{R_2}{R_1}}{\frac{1}{T_2} - \frac{1}{T_1}}$$

Using the previous equations, the curve can be plotted by writing down the equations using MATLAB, or other programming languages. Figure 2 shows how much the resistance increases as the temperature increases. In this case, the coefficient β has been calculated by assuming that when $T_1 = 358.15K = 85°C$, $R_1 = 40k\Omega$ and when $T_2 = 253.15K = -20°C$, $R_2 = 30\Omega$.

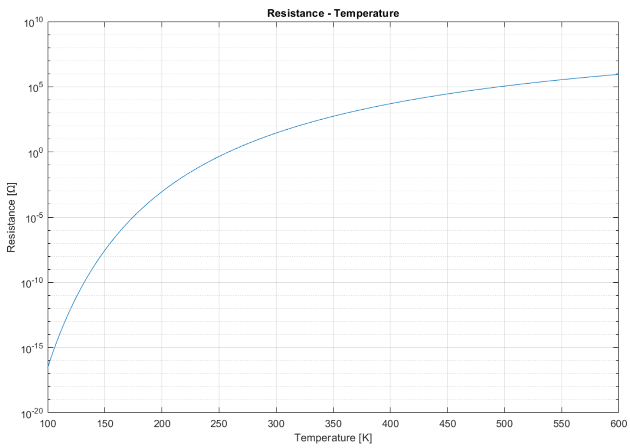

Figure 2: PTC resistance-temperature logarithmic curve, from -173˚C to 326˚C.

By restricting the plot between -13°C and 126°C it is more noticeable the exponential behavior of the posistor: the image 3 shows the limited exponential curve of the PTC thermistor.

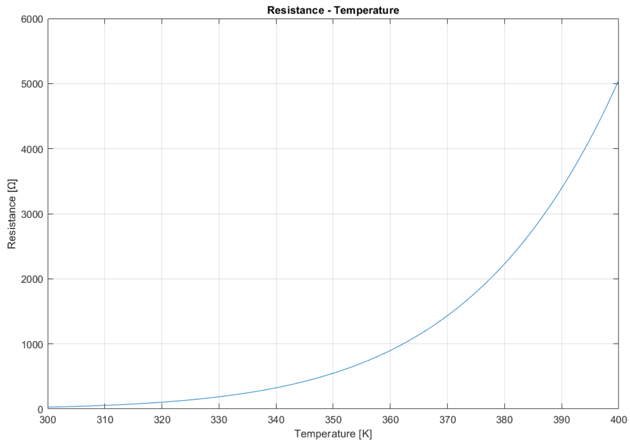

Figure 3: PTC resistance-temperature curve, limited between -13°C and 126°C.

In both of the plots the resistance value or the change ratio drastically increases as the environment gets hotter. Generally, the equation describes the behavior of the PTC thermistor in an interval of temperature: in the PTC materials there is a temperature, called **Curie point** where the resistance starts to rise exponentially in comparison with the temperature (as shown in figure 2 and 3); before the Curie temperature, the PTC thermistor does not increase drastically their resistance when the temperature raises. Generally, the Curie point in the PTC materials is between 50°C and 400°C [4].

Another important coefficient to know about is the **dissipation constant** δ which describes the power needed to increase the thermistor temperature by 1° Celsius through self-heating. The dissipation constant varies on the construction materials of the thermistor and the environment [15]. The constant δ is useful to describe the power dissipation of the thermistor when its temperature is T (at thermal equilibrium) and the ambient temperature is T_0:

$$P = VI = \delta(T - T_0)$$

By knowing the power dissipation it is then possible to plot the **current-voltage** relationship when the PTC thermistor is in a state of thermal equilibrium. Sure enough, by knowing the constant δ and the room temperature T_0, the power dissipation P can be obtained and then it is possible to calculate the voltage and the current relationship:

$$V = \sqrt{P \cdot R} \qquad\qquad I = \sqrt{\frac{P}{R}}$$

By setting $\delta = 4.5mW/^{\circ}C$ and the room temperature $T_0 = 25^{\circ}C = 298.15^{\circ}K$, it is possible to plot some important relationship. Figure 4 describes the relationship between the current and the temperature in the PTC thermistor: as the temperature increases the current decreases; this is because when the temperature increases, also the resistance increases and, as such, the current flowing through will reasonably decrease.

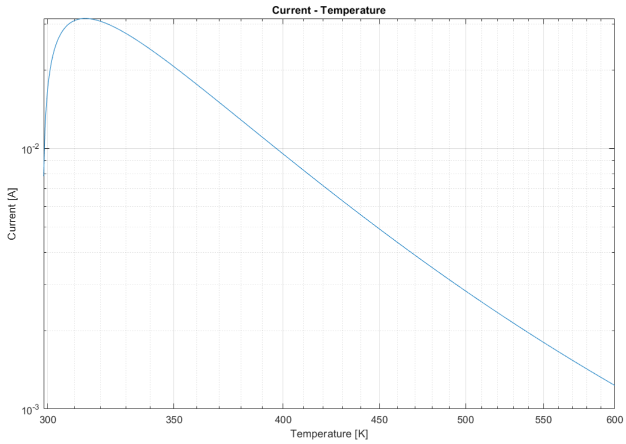

Figure 4: Corrent-temperature relationship of a PTC thermistor.

The relationship between the temperature and the voltage is shown in the image 5. Contrarily to the current-temperature relationship, here, as the temperature increases, the voltage of the thermistor rises as well because its resistivity intensifies.

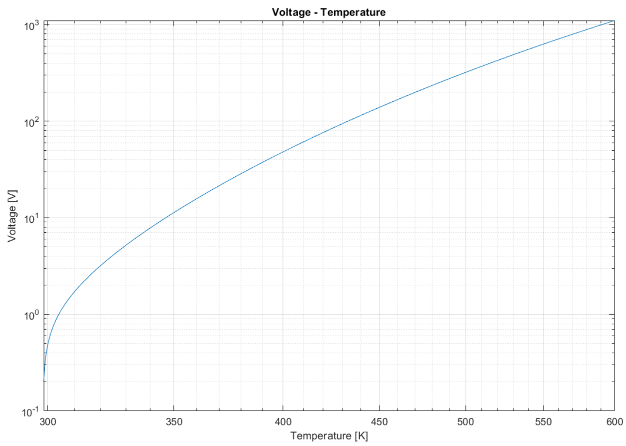

Figure 5: Voltage-temperature relationship of a PTC thermistor.

In the figure 6 there is the characteristic curve current-voltage of the PTC thermistor. The plot is an *insofar* curve: when the slope is positive there is a constant-resistance state meanwhile when the slope of the curve is negative there is a constant-power range [15].

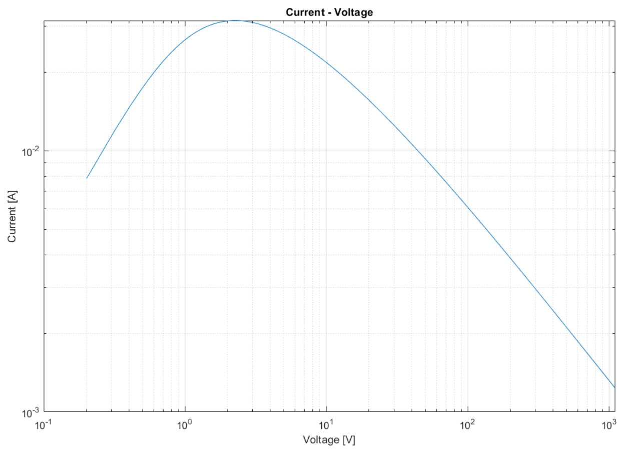

Figure 6: Current-voltage relationship of a PTC thermistor.

3.2 Applications

The applications of the posistors are remarkably important. One of the most popular uses of these devices is as *current limiters* to protect other devices. Sure enough, when there is an excess of current through a circuit it may result in a damaged component of the circuit, like the LED in figure 7; using a PTC thermistor prevents this from happening because when the current starts increasing through the thermistor, it will heat it making the resistance increase. When the resistance starts increasing the current flowing through it will decrease (as shown in figure 4) and the LED will be protected [15][14].

Other important applications are for the *temperature indicator*, when operating in parallel with a diode, or for *temperature control* purposes. In this case, the PTC posistor can control the power dissipated by another device that is connected in series [15][14]. The positive temperature coefficient thermistor may be also utilized to *measure the heating* consumption by a system. For example, it may be used to determine the fuel consumption in a vehicle or the heating consumption in a hot-water-based heating system [5]. Finally, the PTC thermister has found its way to space applications [9].

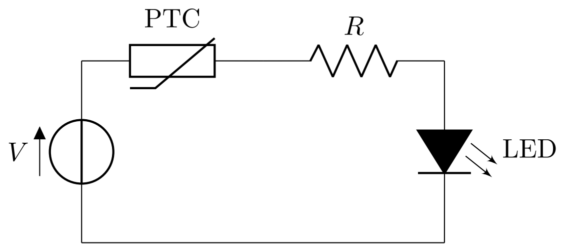

Figure 7: Current limiter PTC application

4 NTC thermistors

Unlike the PTC thermistor, the negative-temperature-coefficient (NTC) thermistor behaves inversely. This semiconductor device experiences a decrease in resistivity as the temperature increases. Its exceptional sensitivity to temperature variations contributes to its popular use across various applications.

4.1 Chrateristics

The NTC thermistor and the PTC thermistor, even though their functioning is opposite, have the same characteristic equation. As aforementioned, the equation that describes the behavior of the resistance R in relationship with the ambient temperature T is the following [3]:

$$R = R_0\, e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)}$$

Where R is the resistance at temperature T, which should be measured in Kelvin degrees, and R_0 is the resistance value measured at operating temperature T_0. The β coefficient describes the thermister constant which varies on temperature and materials used to build the device. It can be calculated using the same formula described in the PTC thermistors:

$$\beta = \frac{\ln \frac{R_2}{R_1}}{\frac{1}{T_2} - \frac{1}{T_1}}$$

By assuming that when $T_1 = 298.15K = 25°C$, $R_1 = 10k\Omega$ and when $T_2 = 358.15K = 85°C$. $R_2 = 1.4k\Omega$, it is possible to plot the resistance-temperature relationship of a negative temperature coefficient thermistor. As shown in figure 8, the curve shows that as the temperature rises, the resistance value decreases respecting the aforementioned equation.

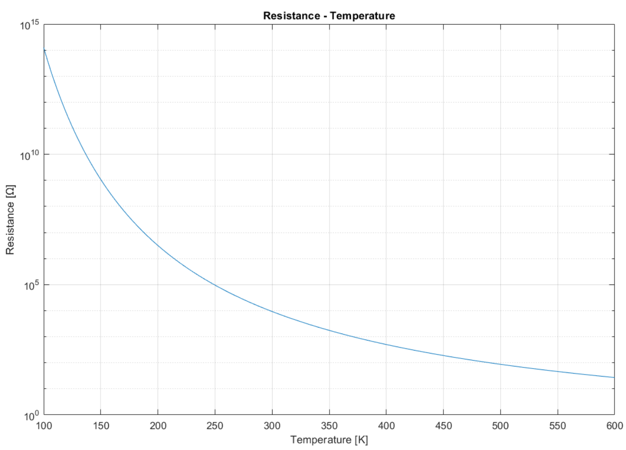

Figure 8: NTC resistance-temperature logarithmic curve, from -173°C to 326°C.

If the curve is restricted to more realistic temperature values (such as -13°C to 126°C), it's even more evident the inversely exponential curve which is described by the equation of the thermistor (figure 9).

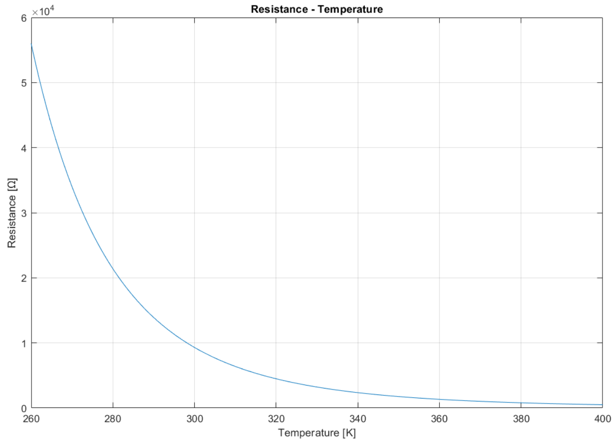

Figure 9: NTC resistance-temperature curve, limited between -13°C and 126°C.

By knowing the **dissipation constant** δ of the particular thermistor, it is possible to calculate the power consumption of the device, using the same equation mentioned on the PTC thermistor [10][12].

$$P = VI = \delta(T - T_0)$$

Where T_0 is the room temperature. Consequently, it is possible to calculate the equation for the voltage drop across the NTC thermistor and the current flowing through it [12].

$$V = (P \cdot R)^{\frac{1}{2}} \qquad I = \left(\frac{P}{R}\right)^{\frac{1}{2}}$$

By plotting the relationship between the current and the temperature, shown in figure 10, it is evident that when the temperature increases, the current rises as well. This is a direct consequence of the fact that when the temperature rises the resistance of the thermistor is reduced and more current flows through the semiconductor device.

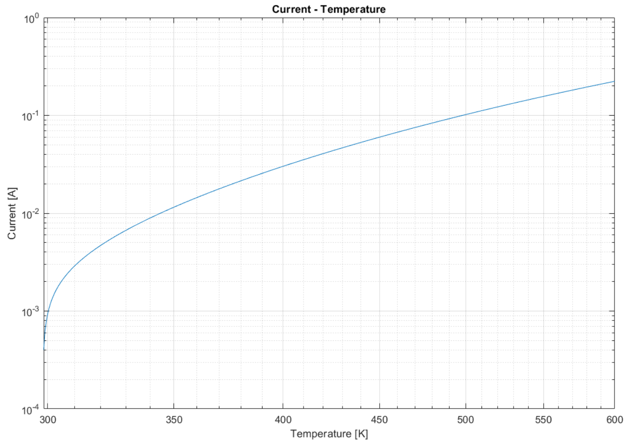

Figure 10: Corrent-temperature relationship of an NTC thermistor.

Observing the figure 11, it is evident that the voltage-temperature decreases as the temperature increases. This phenomenon is attributed to the inverse relationship between temperature and resistance, leading to a corresponding decrease in the potential difference across the thermistor.

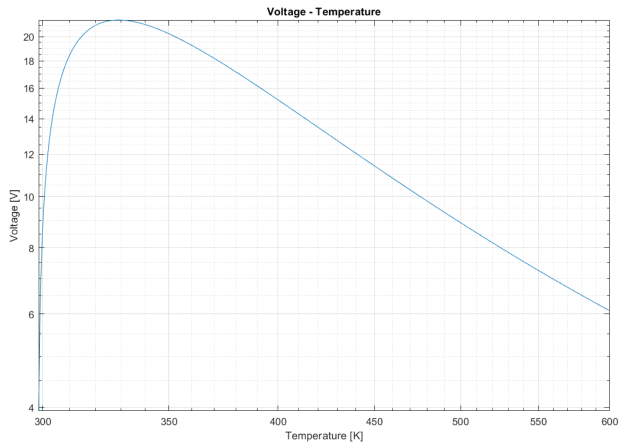

Figure 11: Voltage-temperature relationship of an NTC thermistor.

One of the most useful properties of an NTC thermistor is its VI characteristic curve, shown in the figure 12. Noticeably, in the low-current region, there is low power dissipation and the thermistor does not heat up. In this state, the changes in the resistance will depend on the environment temperature rather than the heat produced by the device. When the current starts to rise it peaks at the maximum voltage level (V_{max}) and then the voltage starts to decrease due to the self-heating produced by the thermistor [10].

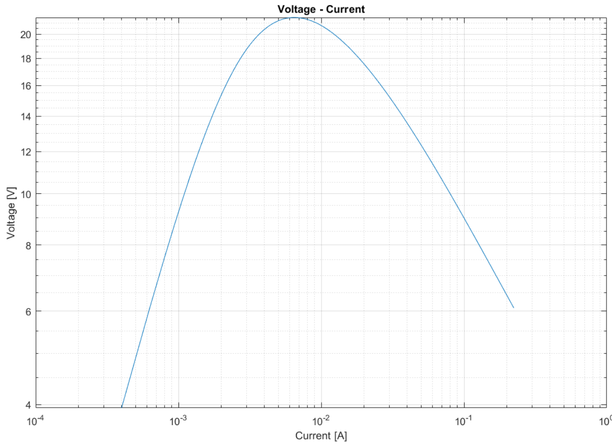

Figure 12: Voltage-current relationship of an NTC thermistor.

4.2 Applications

One of the most popular applications for the NTC thermistors is for *temperature measurement* [3][1]. This particular aspect of the negative temperature coefficient thermistor is vastly utilized in biomedical environments thanks to their high sensitivity to temperature oscillation [3][11]. These devices are largely used in *medical applications*, like the body-temperature measurement: this property can result in more advanced and sensitive thermometers or may be used for cancer reasearch and treatment [6].

A rather new application for the NTC thermistor takes into consideration its *self-heating* property. When the thermistor is in a self-heat state its sensitivity to any external temperature variation is significantly high. This property can find applications to measure pressure, flow and composition of gasses [10].

Negative temperature coefficient thermistors are also used in *home appliances* as far as washing machines, coffee makers, hair driers, fire alarms and home heating. Additionally, the NTC thermistors are used commonly in *automobiles* to measure the temperature of the water and oil, the temperature of the cylinder and the braking system and the air-conditioning system [6].

Other interesting applications of these devices are for measuring the *deep ocean* temperature [13] and for *space applications* (like the PTC thermistors), specifically in the launch of the ETS-VI satellite and the H-II satellite [9].

5 Conclusions

Noticeably, the three NTC plots are the exact inverse of the PTC plots due to their opposite functioning. The current-temperature PTC plot (figure 4) is very similar to the NTC voltage-temperature curve (figure 11) and, seemingly, the current-temperature NTC graph (figure 10) is nearly identical to the PTC voltage-temperature diagram (figure 5). The opposite functioning between the two devices can be observed between the voltage-current characteristic curve of the posistor (figure 6) and of the NTC thermistor (figure 12). The two plots are extremely similar with the only difference that the axes are inverted: in the graph 6 the y-axis describes the current meanwhile in the curve 12 the y-axis characterizes the voltage.

Nonetheless both PTC and NTC thermistors emerge as exceptionally versatile components with widespread applications. PTC thermistors find their niche in scenarios demanding self-regulation, where their inherent ability to modify resistance with temperature ensures stability and reliability. Conversely, the sensitivity of NTC thermistors becomes significantly important in applications requiring precise temperature measurements, aligning seamlessly with the demands of temperature-sensitive systems. The ability of these thermistors to perform dual functions makes them essential tools in many engineering areas, underlining their flexibility and importance in current electronic design.

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