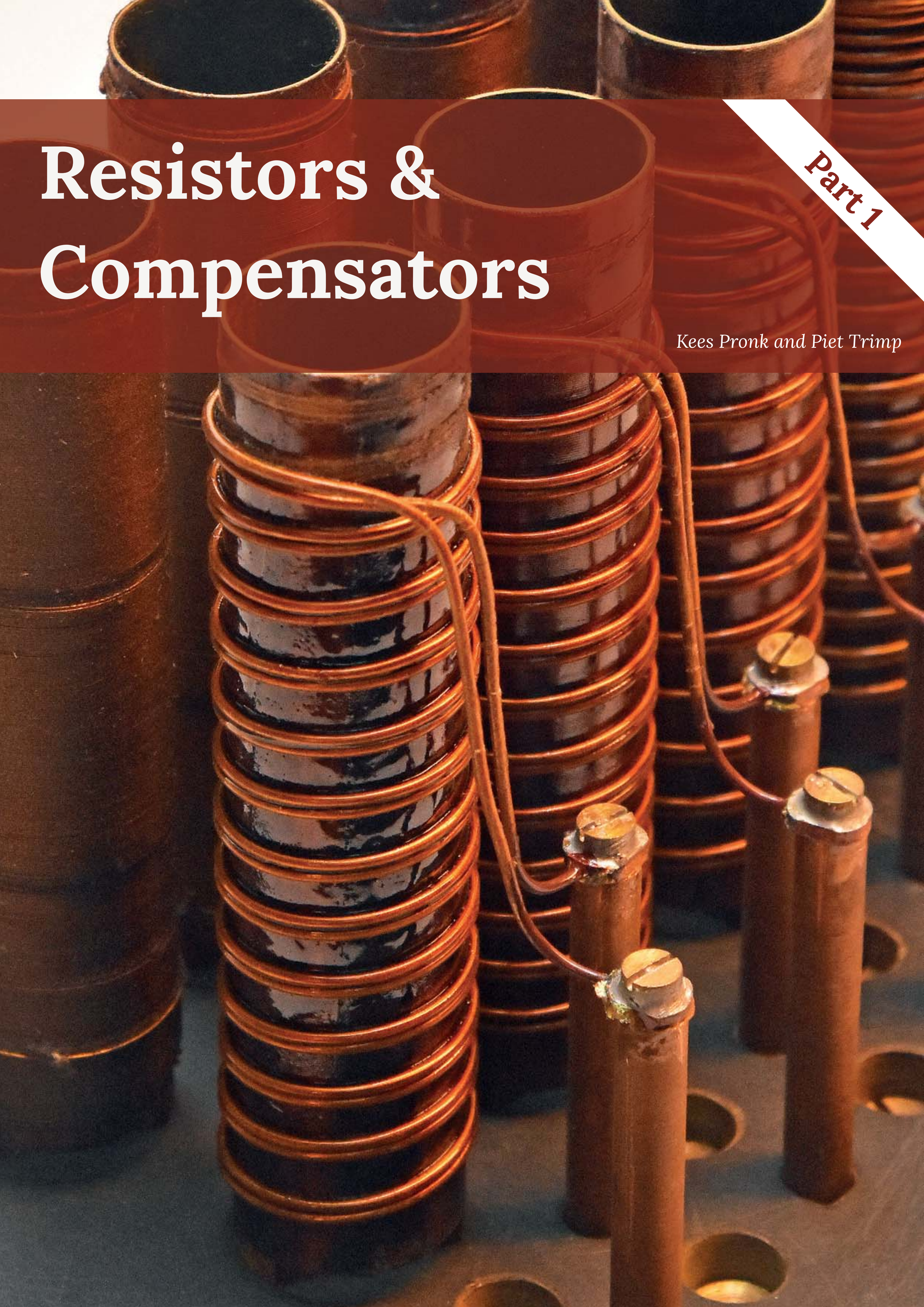

Resistors & Compensators

Kees Pronk and Piet Trimp

In this two-part article we will discuss a measurement technique for measuring very small voltage values using so-called compensators. Inside a compensator very accurate resistors are needed to function as voltage dividers. In the first part of this article, we discuss how to manufacture and measure such high-precision resistors. After having obtained knowledge about the construction of precision resistors we will explain the construction and use of compensators in part 2 of this article.

An important source of information for these two articles is the thesis of J.C. Deiman who graduated in 1983 on the topic: *The History of the Compensator*. Parts of this article are taken directly from that thesis [1].

The history of the (standard) resistance

Around 1825 the technical-scientific researchers of that time were in search of the precise meaning of the term "resistance" and were experimenting with the construction of stable and predictable resistance values. After Georg Simon Ohm (1784 – 1864) formulated his well-known law in 1825, an urgent need for the construction of reliable and accurate resistors was felt [2]. For a standard resistor the following requirements have to be met: (i) The value of the resistance should be stable over many years, and (ii) the temperature coefficient should be as low as possible. In those years it also became important to express the unit of resistance in the then new rationalized system of units, S.I. (Système International). The base units in this "mKSA system" are the meter (m), the second (s), the kilogram (kg) and the ampere (A). The Ohm-unit can be expressed in the S.I system as $m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$.

In England, Wheatstone suggested around 1843 that a resistor should be defined by the resistance of a piece of copper wire having a length of a English foot, and having a weight of 100 grains. In France, telegraph engineers used around 1850 a kilometer-long steel wire with a thickness of 4 mm such as used for telegraph lines as a standard resistor. In Germany, the Physikalisch Technische Reichsanstalt (PTR) in Berlin adopted a mercury column of one meter in length and with a cross-section of 1 mm^2 as standard. In 1908 at an international conference in London the standard resistor was formally defined as the resistance of a column of mercury at the temperature of melting ice, with a weight of 14.4521 grams and a length of 106.300 centimeters. This "International Ohm" was maintained until 1948. In that year the standard was revised on the basis of more accurate measurements and a new "Absolute Ohm" was adopted such that 1 Int. Ohm equals 1.000495 Abs. Ohm. The reader should notice the high precision in these values; apparently, such measurement precision was already obtainable in those years.

It will be clear that handling these mercury standards is quite difficult. In the long run the stability of these mercury standards proved inadequate. Many investigations took place in developing the proper material for wire wound

Figure 1: *Precision Resistor by Otto Wolf, Berlin (Photo by: Kees Pronk)*

◀ ***Figure 4:*** *Bifilar winding of resistor (Photo by: Kees Pronk)*

Figure 2: *Precision resistor by C. Bleeker, Zeist (Photo by: Kees Pronk)*

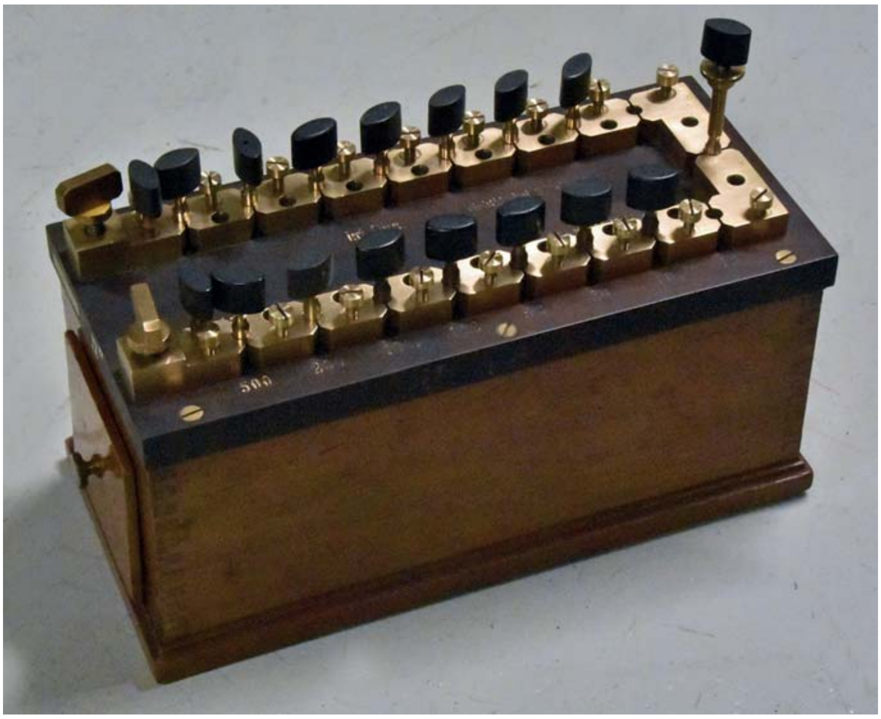

Figure 3: *Resistor box with taper brass contacts, by Otto Wolff, Berlin (Photo by: Kees Pronk)*

standard resistors. After much research the Manganin alloy (86% copper, 12% manganese and 2% of nickel) was found to be suitable for this application. The temperature coefficient of Manganine is 0.00001 K^{-1}, at 20 Celsius and the electrical resistance of Manganin is 43-48 μΩ.cm [3].

The EWI Study Collection [4] accommodates a large number of such standard resistors. An example standard resistor fabricated by Otto Wolff in Berlin is shown in Figure 1.

This resistance of this standard resistor is 10 Ohms and this Manganin resistor is calibrated in Int. Ohms. The accuracy is unknown because the calibration report is not available anymore. For optimal stability the unit should be submerged in a bath of isolating oil to be held at a 20 C. A hole is provided for entering a thermometer. The maximum load is 0.3A in air and 2A in oil.

In the Netherlands, the famous company C. Bleeker from Zeist designed and fabricated many standard resistors (see Figure 2 for an example). The value of the resistor shown here is 10 Int. Ohm at 20 Celsius and the accuracy is 0.01%. For some of these resistors a calibration report from the PTR is available. In his 1983 thesis J. C. Deiman compares measurements of a number of 1 Ohm standard resistors effectuated by Van Swaay in 1901 in Delft with measurements he had carried out in 1982 on the same resistors using the best electronic equipment available then. The results of these two sets of measurements turned out to be highly comparable.

Resistor boxes

To obtain easily selectable resistance values experimenters have been using resistor boxes with taper plugs. In such a resistor box precision resistors are mounted between brass contacts. By placing a taper plug between two contacts the resistor is short circuited. Because the taper plug and the contacts are both made from brass, inserting a plug does not introduce any thermal effect in the circuit. The accuracy of these resistor boxes is 0.01%. The EWI Study Collection features many such resistor boxes having different resistance values. Figure 3 shows an example of such a resistor box. This particular box was made by Otto Wolff from Berlin around the year 1900. The resistance values provided in this box are 0.1, 0.1, 0.1, 0.2, 0.5, 1, 1, 2, 5, 10, 10, 20, 50, 100, 100, 200, 500 Ohm. The reader should verify that using these values any discrete resistance value from 0.1 to 1000 Ohm may be constructed.

> *“As usual, students sometimes get reckless with laboratory equipment.”*

Figure 4 (SEE THE HEADER ON THE FIRST PAGE) shows the inside of this box. The resistors have a bifilar winding to make them usable also for higher frequencies.

Such resistor boxes with taper plugs were too expensive and too inflexible for engineering work. In response to that the industry therefore developed so-called decade resistor boxes using switches to select a particular resistance value. The EWI Study Collection owns many decade resistor boxes of various makes and accuracies. Figure 5 shows a professional five decade resistor box from the Bleeker company with the range of 0.1 Ohm to 11,111.1 Ohm. The accuracy is 0.01% and the maximum load is 0,5W per resistor. As will be shown in part 2 of this article, the use of switches will lead to unwanted thermo-electrical effects making precise measurements more difficult. For student labs the Technical University used cheaper (0.1% accuracy) decade switching boxes. As usual, students sometimes get reckless with laboratory equipment. During labs it happened quite often that the maximum current allowed by the manufacturer of the box was exceeded causing the box to break down. People responsible for the correct functioning of the lab equipment had provided a protection circuit inside the decade box. In the event the resistor box was overloaded, a lamp on the box would light-up.

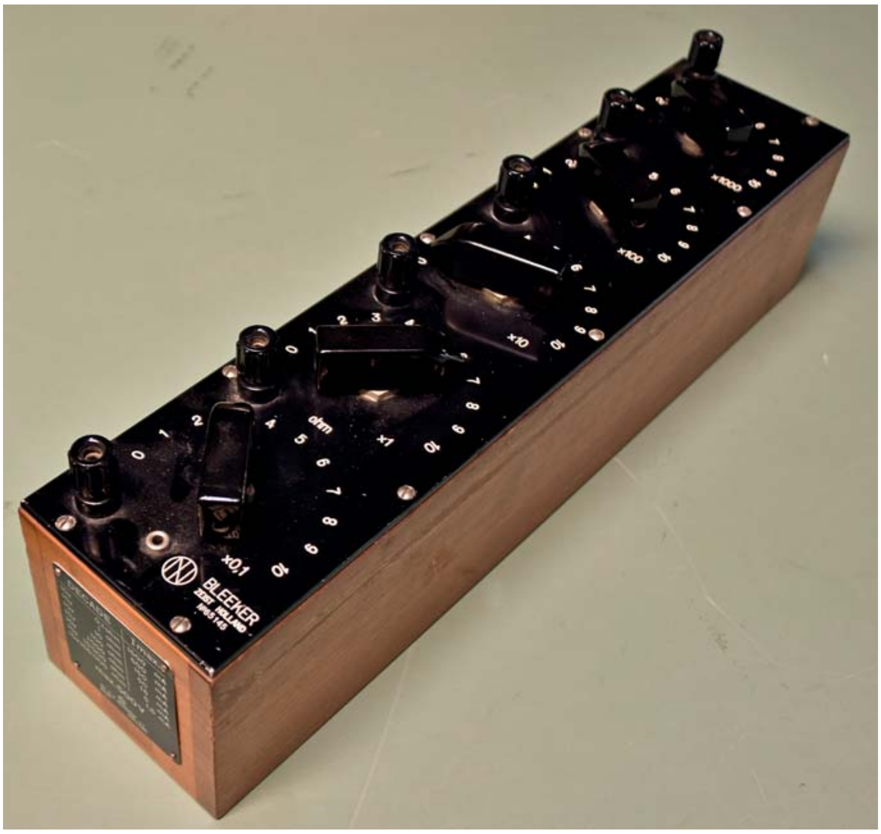

Figure 5: *Switchable resistor box by Bleeker, Zeist (Photo by: Kees Pronk)*

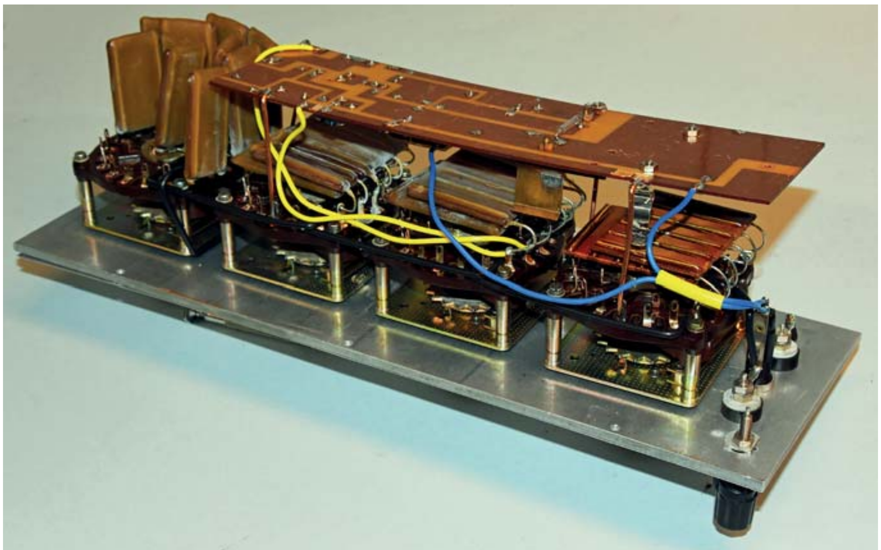

Figure 6: *Resistor box with built-in overload protection circuit (Photo by: Kees Pronk)*

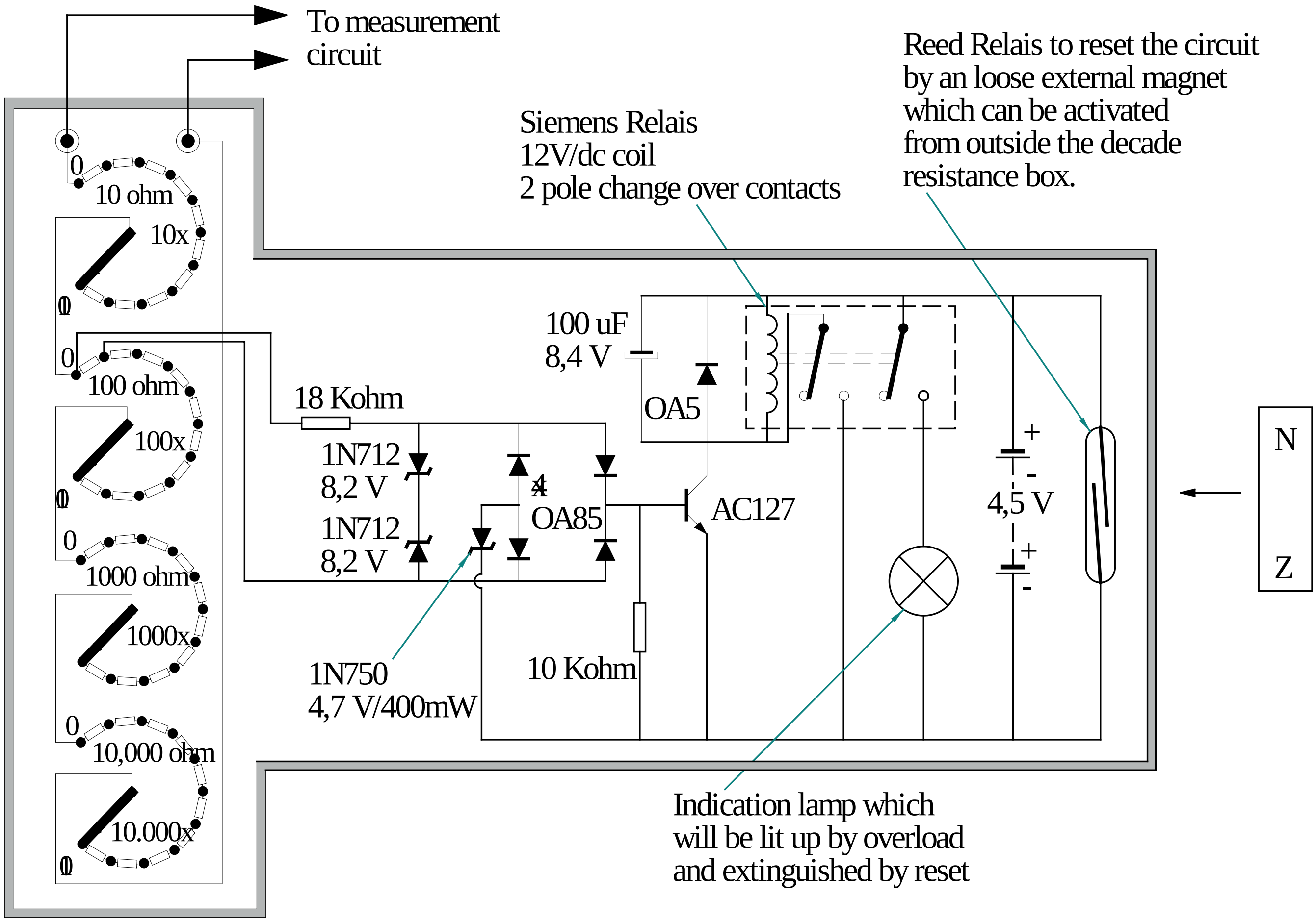

Figure 7: Schematic of the overload detection circuit

The lab assistant could usually intervene in time to prevent damage to the box. The circuit was reset by magically holding a magnet against the bottom of the box where a hidden reed switch was mounted. A picture of such a box opened for inspection is given in Figure 6. The schematic of the protection circuit can be found in Figure 7. The reader is invited to study the functioning of this circuit. One should note that a battery has been built into the resistor box. The current drawn from this battery should be minimal when no overload is detected or when the box is stored.

Conclusion

In preparation for the second part of this article we have discussed the development and construction of very precise resistors. This development started around 1850 and continued until one hundred years later. Many objects of that period are guarded in the Study Collection of EWI at the TU Delft. In the second part of this article we will discuss the design and use of a so-called Compensator, a device optimized for precise measurements of voltages.

References:

[1] J.C. Deiman: The History of the Compensator (1983), Thesis report, TH Delft.

[2] G.S. Ohm, Vorläufige Anzeige des Gesetzes, nach welche Metalle die Elektrizität leiten, In: C. Piel, Das Grundgesetz des elektrischen Stromes (1983), Leipzig.

[4] *https://en.wikipedia.org/wiki/Manganin*

[4] Study Collection EWI, TU Delft. *http://www.ewi.tudelft.nl/en/the-faculty/studieverzameling/*