Resistors and compensators

Part 2

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In the second part of this two-part article we will discuss the construction and functioning of a so-called compensator. A compensator is a measuring device especially designed for measuring of voltages lower than 1 V. This article builds on the understanding of precision resistors as may be obtained from the first part of this article which appeared in Maxwell issue 20.4 (July 2017).

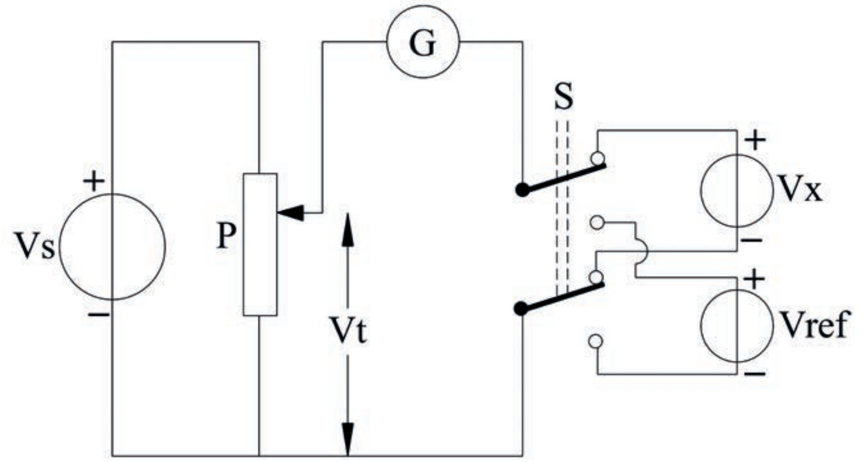

Figure 1. Basic schematic of a compensator.

History of the compensator

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

Further information may be obtained from the article by Luther [2]. Compensators have been built from about 1900 to 1960. Of course, no electronic devices such as digital voltmeters were available in those years.

Thermocouples

The interest in compensators arose because investigators were interested in measuring physical properties such as temperatures using thermocouples or Pt100 resistors and measurements of voltages produced by biological phenomena such as nerves and muscles.

The working of a thermocouple is based on the thermo-electrical effect in which a junction of two different metals produces a voltage which is a function of the temperature [3]. Usually a thermocouple measuring circuit consists of two junctions (e.g. copper to constantan and constantan to copper). One junction is kept at 0 °C (the cold junction) and the other junction is inserted in a flame or furnace to measure the temperature. Over a 0 to 1000 °C temperature range, a thermocouple generates a typical voltage of about 40 mV. To measure a temperature with 0.1% accuracy the compensator should have a resolution of at least 0.04 mV. For a correct determination of the temperature, it is important to measure the output voltage of a thermocouple without imposing any electrical load on the device.

> *“To measure a temperature with 0.1% accuracy the compensator should have a resolution of at least 0.04 mV”*

Measurement principle of a compensator

Figure 1 gives the basic schematic of a compensator. Firstly, using the switch S, a reference voltage V_{ref} is connected to the compensator. This reference voltage is often produced by a Weston cell having an output voltage of 1.018656 V [4].

The tap on the potentiometer *P* is adjusted until the current through the galvanometer equals zero. The current through the V_{ref} then also equals zero. One could say that the voltage V_{ref} is compensated by the voltage V_t on the tap of the potentiometer, hence the name compensator for this measurement device. After compensation has been achieved, the value of the resistor below the tap is denoted (R_1).

The reference cell is then replaced by the unknown voltage V_x.

After compensation has been has been detected, again the value of the resistor below the tap is written down (R_2). It then holds that $V_x = (R_2 / R_1) \cdot V_{ref}$. It should be remarked that the battery voltage V_s drops out

Figure 2. Wolff compensator KDE84.

◄ *Figure 4.* Detail of the back side of the switch in the Bleeker compensator.

Figure 3. Switch in a Bleeker compensator.

of the equation. To prevent thermal heating of the resistors, the battery is only connected to the compensator for a short period of time. Effectively, the source of the unknown V_x delivers no current as is required for thermocouples.

Construction of a compensator

The main difficulty in constructing a compensator usable in the laboratory and in the field, is the construction of the potentiometer *P*. A proper linear behavior cannot be achieved using a slide wire or wire wound potentiometer. The potentiometer should therefore be constructed using a system of (rotary decade) switches and precision resistors such as used in the decade resistor box discussed in part 1 of this article.

> *"The main difficulty in constructing a compensator usable in the laboratory and in the field, is the construction of the potentiometer"*

To understand the design and construction of a compensator, Figure 2 shows the front of a Wolff compensator, one of the most elaborate and precise compensators available in the Study Collection of EWI in Delft [5].

This 6-decade Diesselhorst type compensator model KDE84 made by Otto Wolff in Berlin has been built in a wooden box of 73 by 43 by 22 cm and weighs about 30 kg. The knobs marked with Roman numerals I to VI are the switches controlling the six decades of the potentiometer *P*.

The box only contains the resistors forming the potentiometer *P*. The galvanometer and the voltage sources are external to the box. This compensator has probably been constructed around 1950. In those days, the cost was around fl 20 000 (Dutch guilders). Nowadays the cost would probably be around € 100 000.

Low contact resistance switch

Replacing the potentiometer *P* by a voltage divider constructed with rotary switches and wire wound precision resistors however, opens up a box of Pandora. Such a switch should be very reliable and wear proof and it needs to have a very low contact resistance. Therefore, it has to be constructed from various materials other than copper. Figure 3 gives a detail of such a switch inside one of our Bleeker compensators (Diesselhorst Compensator, serial number 30466).

The fixed contacts of such a switch need to be made from some wear resistant material with good electrical conductivity, so presumably, some copper alloy is used. The spring making contact with the fixed contacts is probably made out of phosphor bronze. The copper alloy to phosphor bronze junction, however, shows up as source of thermoelectricity disturbing the measurement. Equally, the junction between the copper alloy and the Manganin used for the precision resistor shows up as a source of thermoelectricity. The value of the thermal electricity of the spring contacts is about 0.04 V per degree Celsius and this voltage is thus directly introduced into the measurement. The resistance of the switching contacts is about 0.2 mΩ. This value means that any resistor used in the voltage divider should have a minimal value of 2 mΩ.

Thermal isolation of the switch

The situation becomes worse when the switch is operated. The mechanical movement of the switch introduces heat and, therefore changes the amount of thermoelectricity produced by the alloys. Even the presence of a human hand operating the switch will produce heat. Several constructive counter measures have to be taken. The knob operating the switch should be thermally isolated from the switch by means of a thermal isolation layer. Additionally, one should make sure that both ends of the resistor are kept at equal temperatures. Figure 4 shows a detail from the construction of back side (resistor part) of the decade switch. This figure also shows the bifilar winding of the resistor. One should notice that the poles for the connections to the resistors are mounted directly on the contact blocks of the switch.

There are also other requirements to the voltage divider chain. The galvanometer often used in those days was a Deprez & D'Arsonval type. These types of galvanometers are undamped second order systems. The damping is to be provided by the resistors in the voltage divider. Therefore, the value of these resistors should not be too high. Secondly, the voltage divider is loading the battery. The load should not be too dependent upon the positions of the switches. And finally, the load resistance should be high enough not to deplete the battery too fast. In short, a number of contradictory requirements do exist.

It may be glimpsed from the figure that all internal wiring in the compensator consists of thick massive copper wires.

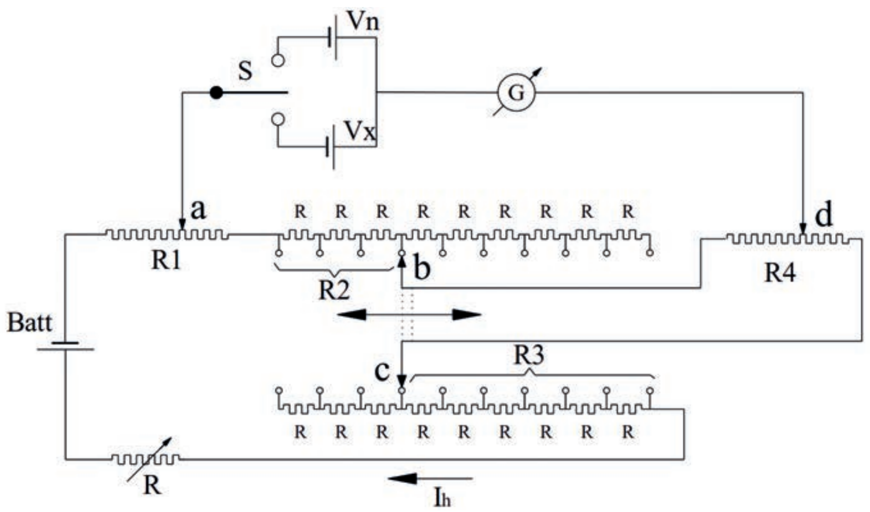

Figure 5. Feussner type decade switch.

Precursors to the Diesselhorst compensator

We will not mention all the designers having contributed to the development of the compensators described here. The interested reader is referred to the authors to obtain a copy of the Deiman thesis. Instead we will discuss shortly the Feussner decade, the parallel decade developed by White and then jump directly to the schematic of the compensator developed by H. Diesselhorst as described in [6]. The reader should verify that all the compensator developments described below contribute to resolving the requirements sketched earlier.

> *"The mechanical movement of the switch introduces heat and, therefore changes the amount of thermoelectricity produced by the alloys"*

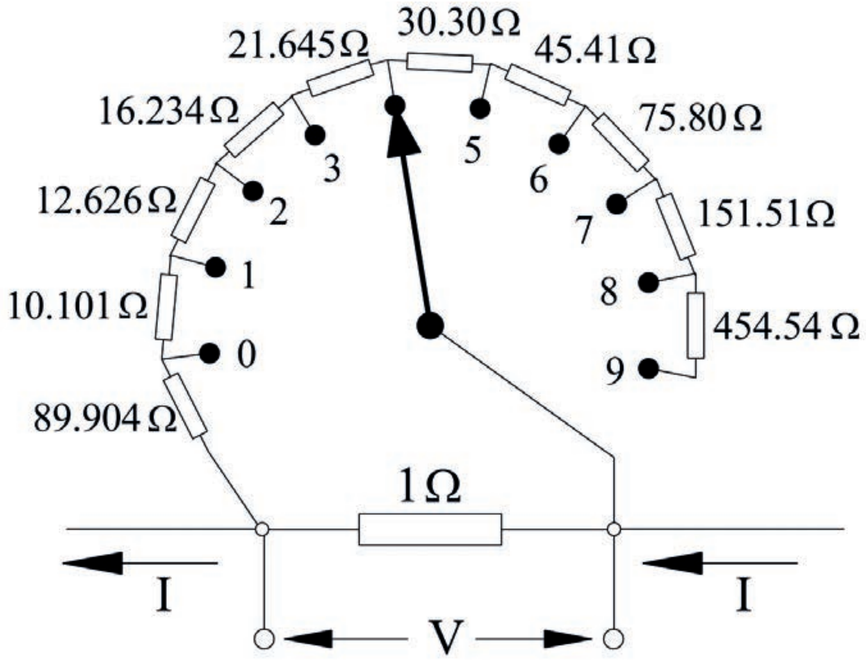

Figure 6 . Parallel decade by White.

In the Feussner system (Figure 5, one decade only), the switch replacing the potentiometer is implemented as a twin switch. This principle has been used by many constructors of comparators.

In this figure, Batt is the stable voltage source, R_1 *to* R_4 are precision resistors, where $R_2 + R_3$ is constant. Resistors *a* and *d* are slide wires. The contacts *b* and *c* are moving together, hence the name twin switch. E_n is the Weston reference cell and E_x is the unknown voltage. The current I_h is set to 1 mA using potentiometer *R*. In this set-up the thermo-electrical effects of the switches *b* and *c* are cancelling each other. Additionally, the resistance of the divider chain is made independent of the position of the switches.

In the parallel decade by White (Figure 6), various resistors are switched parallel to a base resistor. The values of the resistors have been chosen such that the total resistance increases in equal steps. The reader is invited to check this out by calculating the resistance for each of the positions of the switch. The switch is only present in the parallel track and

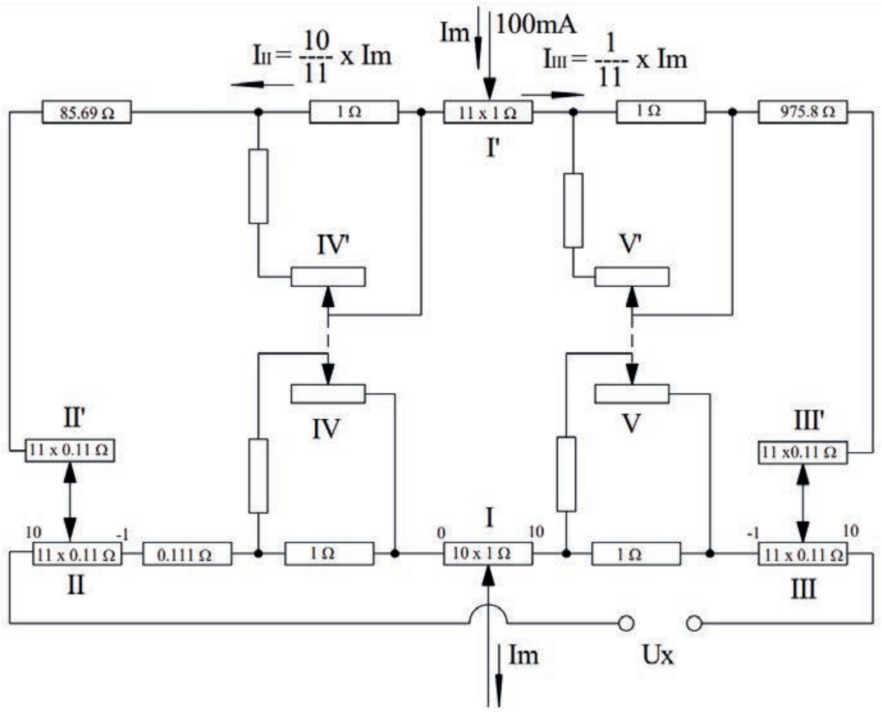

Figure 7. Diesselhorst compensator schematic.

the switch contacts do not contribute much to the total resistance. Additionally, the thermo-electric effects of the switch are weakened by the values of the resistors in the circuit.

Schematics of the Diesselhorst compensator

The 5 digit Diesselhorst compensator [6] as shown in Figure 7 is a very cleverly engineered combination of the above schematics: the Feussner twin switch and the parallel White decade. The reader is invited to study the schematic thoroughly and understand how the effects of thermoelectricity are minimized. The current *I* from the battery is split into two parts: $I_{11} = (10/11) \cdot I$ and $I_{111} = (1/11) \cdot I$. The accuracy of this split is very much dependent upon the values of the fixed precision resistors in the circuit.

The switches marked with Roman numerals I to V (as in Figure 2) are indicated in the schematics by the same numerals. The switches marked I and I' (and further to V and V') are the twin switches from the Feussner approach. The total resistance of the compensator is about 14 Ω.

Conclusion

The compensation technique has been used for many decades in the 20th century. In those days, this technique was the only reliable method to reliably and precisely measure low voltages such as those from thermocouples. The EWI Study Collection [5] in Delft guards several compensators from various famous manufacturers (Bleeker, Wolff, Dauphinee). Compensators according to Raps (not discussed here) and Feussner can be seen at the Academic Heritage Collection TU Delft in the library (upon appointment). All these compensators internally use the schematics by Feussner, White and Diesselhorst.

When you are interested to know more about compensators, you are always welcome to visit us on Mondays in the basement of the low building of EWI.

[1] J.C. Deiman: The History of the Compensator (1983), Thesis report (in Dutch), TH Delft.
[2] Präzisions-Gleichspannungskompensatoren, Konstruktionsmerkmale und gegenwärtiger Stand, Teil II; Helmuth Luther, Archive für technisches Messen, Blatt J931 – 11 January 1970.
[3] https://en.wikipedia.org/wiki/Thermocouple
[4] https://en.wikipedia.org/wiki/Weston_cell
[5] Study Collection EWI, TU Delft. http://www.ewi.tudelft.nl/en/the-faculty/studieverzameling/
[6] Thermokraft freier Kompensationsapparat mit fünf dekaden und konstantem kleiner Widerstand, H. Diesselhorst, Zeitschrift für Instrumentkunde, January 1908.