Design of a Thermal Converter with Frequency Output

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***Abstract*—This paper describes the design for a thermal converter (TC) with frequency output under development at INMETRO. The TC uses commercially available discrete components, eliminating the need for large investments in special environments (clean rooms) for its construction. Today's available surface-mount resistors for high frequency applications display nearly pure resistive behavior up to the GHz region, enabling the operation of the TC in a wide frequency range. A thermistor is used as temperature sensor, connected to an oscillator in order to provide a frequency output proportional to the input power.**

***Index Terms*—ac voltage, ac-dc transfer, thermal converters, measurement standards, frequency measurements.**

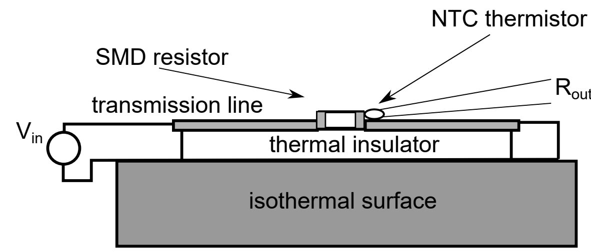

Fig. 1. Basic structure of the new TC design. V_{in} is the input voltage and R_{out} is the resistance output of the thermistor, that will feed an oscillator to generate a frequency proportional to the input power.

I. Introduction

Despite the recent developments in Josephson-based AC voltage calibration systems [1], the accurate characterization of the root-mean-square (rms) values of time-varying (ac) signals is still most widely done by the use of thermal converters (TCs). A basic TC consists of a heater structure and a temperature sensor, which allows the comparison of ac and dc quantities [2]. Currently, most of the TCs use thermocouples as temperature sensors, as they have many advantages over other temperature sensors, like the low sensitivity to ambient temperature due to its differential nature [3]. However, to make the ac-dc transfer at μV/V level, it is necessary to measure the output voltage of the thermocouples with a resolution better than 10^{-6}, which can be critical for TCs using a single thermocouple. On the other hand, modern frequency counters can achieve resolutions up to 10^{-12} per gate second, and are cheaper than the nanovoltmeters with the required resolution.

This paper sugests the design for a TC, combining the technological enhancements available on commercial SMD (surface-mount device) high frequency resistors with the versatility of a "digital" (frequency) output, consonant with the new systems that are being developed at INMETRO for AC Voltage [1], power [4] and impedance [5].

II. Thermal Converter Structure

The basic structure for the proposed TC is presented in Fig. 1. The temperature sensor is a micro-bead NTC (negative temperature coefficient) thermistor, with bead diameter smaller than 100 μm. The heater element is a SMD resistor. To improve the frequency response of the TC, we can use SMD resistors with nearly pure resistive behavior for frequencies up to 50 GHz [6]. A bigger dynamic voltage range can be obtained using CVD (Chemical Vapor Deposition) Diamond subtrate chip resistors [7], with nominal power ratings up to tens of watts. Using such resistors, the number of steps in a traditional step-up procedure to build up all the voltage scale can be reduced, which represents an economy in time and a reduction in uncertanties. The main idea here is to use the available technology developed by the industry of SMD resistors to build an improved TC.

The first prototypes built are using high density polystyrene foam cut with nearly 1 mm thickness as thermal insulator, and the transmission line is painted using silver conductive ink. To ensure the operation of the TC in microwave frequencies, care must be taken to design the transmission line with an appropriate substrate. The width of the transmission line is calculated using a microstrip transmission line model to match the transmission line impedance with the heater impedance.

III. Oscillator

The output of the thermistor should be connected to an oscillator to generate a frequency signal. In order to make ac-dc transfer measurements at μV/V level, the oscillator must have a short term stability better than 10^{-6}. Preliminary measurements using a very simple CMOS oscillator topology (Fig. 2) showed a frequency stability of nearly 40 ppm over 15 minutes, and 10 ppm over 1 minute, which is insufficient for the application.

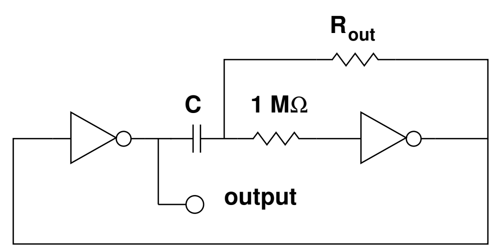

Fig. 2. Simple CMOS oscillator topology. The output frequency is $f = 1/(2.2R_{out}C)$, where R_{out} is the resistance of the thermistor.

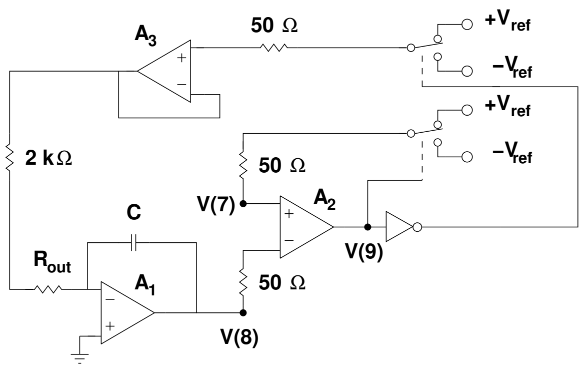

Fig. 3. Relaxation oscillator topology. The waveforms of $V(8)$ (the output voltage of the integrator), $V(7)$ (the reference threshold of the comparator) and $V(9)$ (the comparator output) are presented in Fig. 4.

A better stability can be obtained using a relaxation oscillator, as demonstrated in [8]. We are working with the topology of Fig. 3. In this circuit, the operational amplifier A_1 is an inverting integrator, and A_2 acts as a comparator. The comparator output is used to control two SPDT (single pole, double throw) switches, setting a new threshold for the comparator and a new input voltage for the integrator when the output of the integrator reaches the thresholds. The voltages $+V_{ref}$ and $-V_{ref}$ are stable reference voltages, used as thresholds for the comparator and as input to the integrator.

The operation of the circuit can be resumed by the waveforms presented in Fig 4. Those waveforms were obtained by SPICE software simulation, using the models provided by the manufacturers of the real components.

The fundamental frequency of the triangular wave $V(8)$ (the output of the oscillator) was measured for different R_{out} values using a FFT (fast Fourier transform) feature of SPICE software. The results are presented in Table I.

TABLE I
OSCILLATOR OUTPUT FREQUENCY FOR DIFFERENT R_{out} VALUES.

R_{out} [kΩ]	Output frequency [kHz]
10	170.00
8	180.00
6	195.70
5	207.77
4	220.00
2	260.00

We can see from Table I that the oscillator output frequency increases with the reduction of the thermistor resistance. As the TC uses a NTC thermistor, the output frequency will be directly proportional to the input signal power (or rms value).

One obvious drawback of this TC design is the need of powering up the oscillator, which makes the TC an *active* device, in opposition to the traditional approach, in which the TC is a *passive* device. Nevertheless, the frequency output has its advantages, as it permits the use of high resolution frequency counters as measuring devices, with the advantage of cost reduction in comparison to the nanovoltmeters.

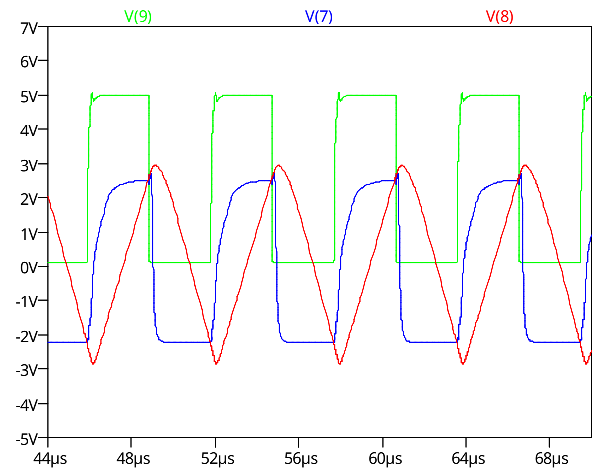

Fig. 4. Oscillator waveforms obtained by SPICE software simulation. The output of the oscillator can be taken from $V(9)$ (square wave) or $V(8)$ (triangular wave), but the latter is preferred because it has lower harmonics.

IV. CONCLUSION

This paper showed the design approach to build a TC aimed at ac-dc transfer measurements for LF and HF. The work is still at the beginning, and some experimental results will be obtained until the conference. We are building an oscillator with sufficient stability to make measurements at the μV/V level, based on the presented circuit and simulation results. The TC prototype needs some optimization, also, but the technology available in today's SMD resistors gives excellent possibilities on the operating ranges of this new TC. One critical issue is the contact between the thermistor and the heater, where we need to ensure good thermal contact and galvanic isolation. We should try some combinations of mixing epoxy glue with alumina in order to achieve this.

ACKNOWLEDGMENT

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