RMS Voltage Measuring System for Precise Evaluation of Electric Quantities

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Abstract-This paper is about the design and the construction of a system for the measurement of the RMS voltage. One or more of these systems can be employed as building blocks for a wide range of applications in the field of electrical metrology. The first implementation demonstrated its functionality and the possibility to reach a stability of the AC voltage measurement in a wide frequency range with an accuracy within 10 parts in 10^6, limited only by the DC voltage accuracy of the DAC employed.

I. Introduction

Multijunction thermal converters [1] are the most precise devices available at the moment for the AC voltage traceability for frequencies up to 1 MHz. However, up to now, the use of these converters has been confined mainly within metrological laboratories, where they are employed to calibrate precise AC voltmeters or other AC measuring instruments. At Istituto Nazionale di Ricerca Metrologica (I.N.RI.M), Italy, like in other metrological laboratories, systems and methods have been developed for this purpose [2], [3].

As multijunction thermal converters are also available as components [4], the possibility of employing them for the construction of specific measurement systems is considered in this work. The target is to build an electronic assembly, easily connectable to a computer for setting-up precision measurement systems in AC, to be used both in metrological laboratory and for usual precise measurements.

Fields of application for one or more of these subsystems will be, more naturally, the measurement of AC voltage or AC current, but also AC voltage and AC current ratio, power and impedance.

II. The system

The construction of this system requires taking into account the specific characteristics of a thermal converter: its response in time, the drift of the electromotive force with a constant input voltage. In fact, the main profitable property of a multijunction thermal converter is not the stability of its input-output characteristics but the equal response to respectively the mean value of a positive and a negative DC voltage and an AC voltage having the same RMS value.

So, to be used at its best level of accuracy, a thermal converter needs a good thermal circuit to assure a drift in temperature sufficiently regular to approximate, during a period of some minutes, a linear drift.

Furthermore, in these conditions, for AC voltage or AC current measurements, some other requirements are also appropriate:

- The electromotive force at the output of the device, which is at the level of 100 mV at the nominal voltage, must be detected with high accuracy and separated from noise and drift.
- The DC voltage supplied during the sequence must be both stable and known at the level desired for the AC measurements.
- In order to avoid a long settling time the switching between AC and DC must be as quick as possible.

The basic scheme of the system is represented in Fig. 1.

A planar multijuction thermal converter (PMJTC) can be supplied either by the external unknown AC voltage source or by an internal DAC through a two-positions switch. An ADC is connected to the output of the thermal converter. The value of the electromotive force at the input of the ADC is read for fix time periods and the mean value is computed.

During the measurement sequence the AC voltage at the input of the system is connected to the thermal converter and the relevant electromotive force E_{AC} is measured. Then, from the parameters of the input-output characteristics of the thermal converter, previously stored in the computer, the sensitivity of the thermal converter $s = (\partial V/\partial E)_{VP}$ and the approximate DC voltage of the working point (*VP)* is evaluated.

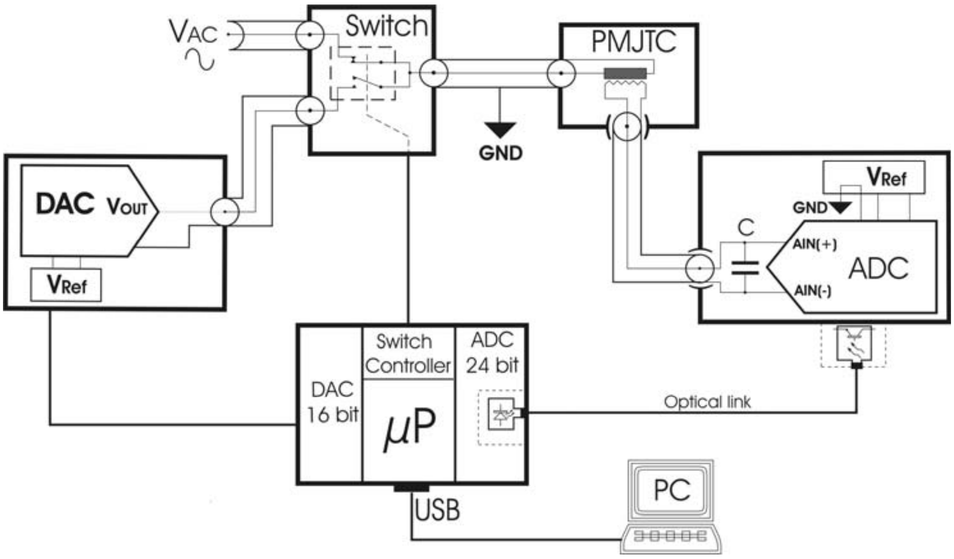

Fig. 1 Basic circuit of the system for the measurement of RMS voltage.

In the following steps, beside to the AC voltage, voltages nearly equal to *VP* are applied by the DAC in both polarities and the corresponding electromotive forces are measured.
The AC voltage is then evaluated by:

$$V_{AC} = \overline{V}_{DC} + (\partial V/\partial E)_{VP} \cdot \left(\overline{E}_{AC} - \overline{E}_{DC}\right) \qquad (1)$$

where $\overline{V}_{DC}$ is the mean absolute value of the DC voltage applied by the DAC $\overline{E}_{AC}, \overline{E}_{DC}$ respectively the mean value of the electromotive force with the input connected to the AC voltage and the mean value of the electromotive force when the input is connected to the DC voltage.

III. First implementation

A first version of the system has been implemented for the experimental work.
The following components have been selected.

- The multijunction thermal converter, which is put in a thermally protected enclosure, has an input resistance of 180 Ω and a nominal voltage of 1.5 V. The output resistance is about 10 kΩ and, at the nominal voltage, the electromotive force is about 108 mV. The input of the thermal converter is directly connected to the switch without a buffer and the output is connected to a 10 μF capacitor for a preliminary filtering of the noise.
- The switch, for a fast transition between AC and DC, consists of two relays with mercury wetted contacts. The relays operate, in this first version, only the “high” connection is switched and the control of each of them operates separately with proper timing.
- The ADC for the measurement of the electromotive force is a sigma-delta component with 24 bit resolution, its input voltage range is selected is between –160 mV and 160 mV, with a capability of about 20 readings per second.
- The DAC is a resistance ladder, low noise device with 16 bit resolution. The maximum output current is 20 mA, so that it can supply directly the input resistance of the thermal converter at the nominal voltage.
- For both the DAC and the ADC the voltage references are high accuracy and ultra-low drift ones, with a maximum specified variation with temperature of 3 ppm/°C and noise less than $100\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$. They are set at 2.5 V by pin connection.

Other electronic circuits have been included in the system for the control of the battery and for detaching the input when the RMS value exceed of 10% the nominal voltage.

The ADC, the DAC and the switch are driven by a computer by means of a USB-SPI interface. The software that controls the system has been written in LabWindows and performs the following operations:

- Temporisation of the sequence.
- Determination of the sensitivity from the parameters stored.
- Setting of the DAC voltage to proper values.
- Measurement of the electromotive force for every voltage supplied to the multijuction thermal converter.
- Storage of all data and evaluation of the ac voltage.
- Display of the results.

IV. Preliminary results

In order to show the critical aspects of the operation, some preliminary results have been obtained with the multijunction thermal converter supplied by the internal DAC. The voltage at the input of the thermal converter was measured as a time function by a precision DC voltmeter and, at the same time, the electromotive force was acquired by the ADC.

The potential capability of the system can be summarised by the graph of Fig. 2. The graph V_{DC} line shows, after some time of acquisition, the variation in time of the voltage supplied by the DAC, while $s{\cdot}E_{DC}$ is the corresponding variation of the electromotive force multiplied by the sensitivity $\left(\partial V/\partial E\right)_{VP}$.

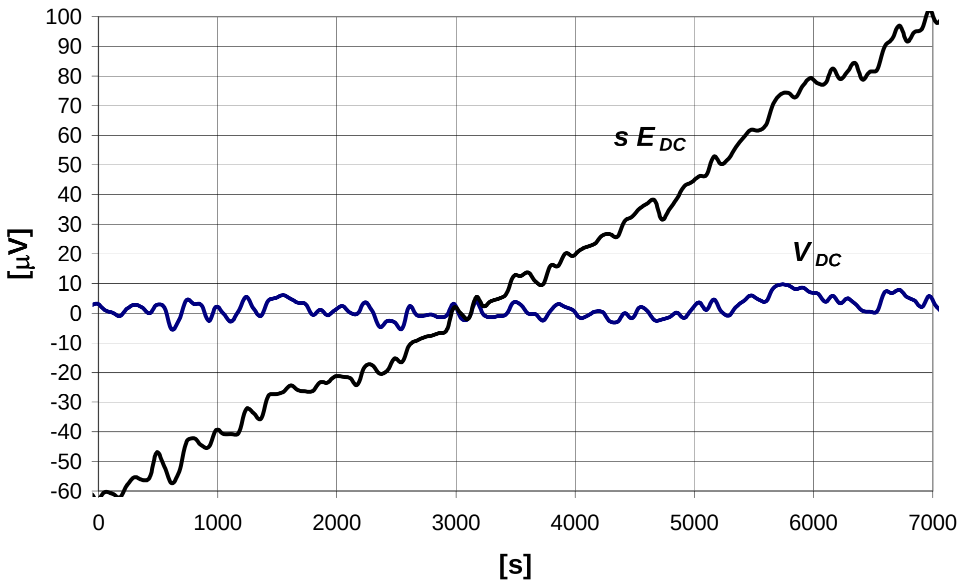

Fig. 2 Signals significant for the characterisation of the system. V_{DC} shows the stability of the DAC almost at the nominal value (1.4 V), $s\ E_{DC}$ is the contribution due to the variation of the electromotive force for the same voltage.

Apart from the quasi-linear drift, which can be removed by a proper sequence of AC and DC measurements, it is evident from the graphs a degree of correlation between the two variations which partially compensates the instability of the voltage generated by the DAC. In fact, as shown in (1) the two terms plotted in the graph take part in the determination of the AC voltage with opposite sign.

So, if the DAC is calibrated at a sufficient level, measurements of AC voltage better than 10 parts in 10^6 can be made for frequency up to 100 kHz where the AC-DC transfer difference of the multijunction thermal converter is lower than this level.

V. New version of the system

A second version of the system has been designed and is now being implemented and its schematic circuit is shown in Fig. 3. The main differences with respect to the previous one are:

- The ADC for the measurement of the electromotive force is a sigma-delta component with 24 bit resolution and its input voltage range is selected is between 0 and 2.5 V. The data rate of the ADC is set by the speed pin. With data rate used of 10 samples per second the ADC has lowest noise and excellent rejection of both 50 Hz and 60 Hz line-cycle interference. To drive the ADC only two pins are needed and the offset error is removed by an auto-calibration procedure that can be initiated at any time. The gain of the internal programmable amplifier (PGA) of the ADC is set to one and it has a drift about 0.2 ppm/°C. In the operative conditions, the spread of repetitive measurements (1-σ) is about 420 nV RMS.

- Between the output of the thermal converter and the input of the ADC there is a low noise amplifier interposed. It consists of a couple of operational amplifiers configured as an instrumentation input/output driver with a total harmonic distortion (THD) better than -115 dB in the frequency range from 100 Hz to 30 kHz.
- The DAC has 20 bit resolution and a sigma-delta architecture. Compared to the previous version the maximum output current is 0.5 mA. The low noise buffer B (Fig. 3) guarantees the current required the resistance input of the PMJTC sensor. For precision measurement the DAC architecture provides the self-calibration system in terms of offset calibration and gain calibration. Both codes are stored in separate register called offset calibration register and full-scale calibration register.
- The system is isolated from the PC by means of optical links.

The ADC, the DAC and the switch are connected to a computer by means of a USB-SPI interface. The software that controls the system is charged on the flash memory of the board. It has been written in LabWindows and a suitable new library of commands in this language has been constructed.

In the software program the following upgrades have been introduced:

- The full code was developed inside the micro-controller (quasi real time system) to drive ADC and DAC.
- The final code is sent to the PC according to the new full-speed specification of USB 2.0.
- The PC only needs a minimum code to work and the transfer speed is limited only by the operative system installed.

This new version has not been tested as an entire system yet. But, from the preliminary tests on the subsystems, the following features are expected:

- The increased DAC accuracy and resolution results in a most precise reference voltage in dc, at a level less than 3 parts in 10^6.
- The noise introduced in the measurement of electromotive force of the thermal converter by the amplifier and the ADC is lower than 100 nV.

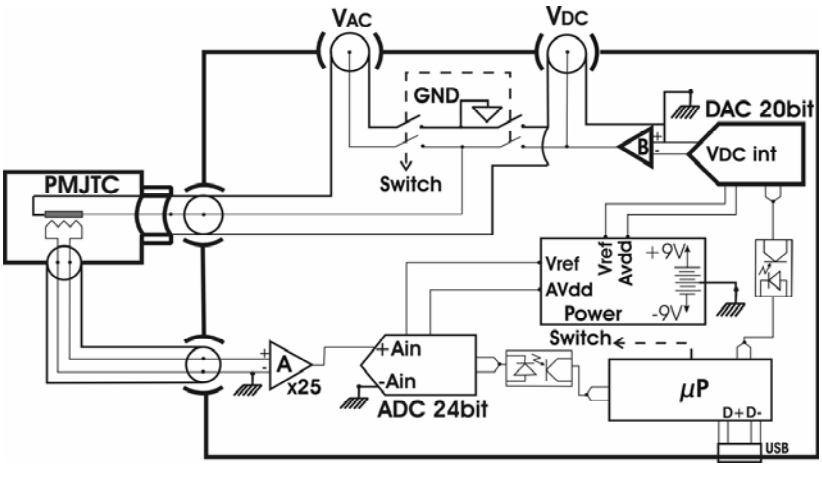

Fig 3. Schematic circuit of the new system.

VI. Conclusions

The functionality test and the experimental results on the first experimental system show the feasibility of a system for the precise measurement of the RMS AC voltage in a wide frequency range by means of a simple electronic circuit, which can be used for many applications in the field of the electrical metrology.

The first experimental system was not optimised. In the new version with a more precise DC voltage reference a different DAC with higher resolution and a precise low noise amplifier at the output of the multijunction thermal converter have been introduced. In this way, we expect that the system will operate at a level of accuracy adequate for high precision measurement instruments.

References

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