Reconfigurable Unit for Precise RMS Measurements

Umberto Pogliano, Bruno Trinchera, and Fulvio Francone

***Abstract*—A system for the precise measurement of electrical quantities by means of the root-mean-square (RMS) value of ac voltages or currents is described. The system is based on a planar multijunction thermal converter (PMJTC) and low-cost electronic components. The miniboard circuitry can also be used in several experiments where flexibility is required. As a first application, the system can carry out ac voltage comparisons and ac or dc voltage measurements. The system is designed to operate with a single PMJTC sensor in the range where its sensibility is greater. This paper shows the possibility of employing the PMJTC sensors outside the laboratory environment. The performance of the unit has been characterized, and measurements of ac signal RMS values in the audio band (below 1.5 V) show stability better than 3 μV/V.**

***Index Terms*—Digital circuits, electrical variable measurement, programming, signal sampling, transducers.**

I. Introduction

THE MEASUREMENT of ac voltages and currents may involve several methods. Planar multijunction thermal converters (PMJTCs) are used to obtain uncertainties less than 1 part in 10^6 up to 100 kHz [1], [2]. Other measurement methods and systems have been employed [3]–[5], which are generally specialized to operate in the laboratory environment. In fact, in this environment, low and regular thermal drift, high-sensibility detection of the output electromotive force (EMF), and generation of a high-accuracy dc voltage or current to be compared with the unknown quantity are more easily attainable.

The proposed system is intended as a precision specific-purpose subsystem instead of other commercial instruments [6], which have a wider range of applications but are more expensive. One or more of these units, with the addition of suitable voltage dividers or transimpedance amplifier, can be employed for the measurements of ac voltage, ac current, and other electrical quantities.

The electronic circuits operating in the unit are a high-resolution, single-channel, analog-to-digital converter (ADC) acquiring the output of the PMJTC and a precision digital-to-analog converter (DAC) to generate the positive and negative dc voltages while a microprocessor controls measurement data acquisition and processing.

In comparison with [7], a characterization of the unit in terms of its stability and drift is given, graphically representing long-time measurements. Preliminary performances of the single blocks of the unit are also given.

Manuscript received June 6, 2008; revised September 12, 2008. First published November 18, 2008; current version published March 10, 2009. The Associate Editor coordinating the review process for this paper was Dr. Yi-hua Tang.

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Digital Object Identifier 10.1109/TIM.2008.2007054

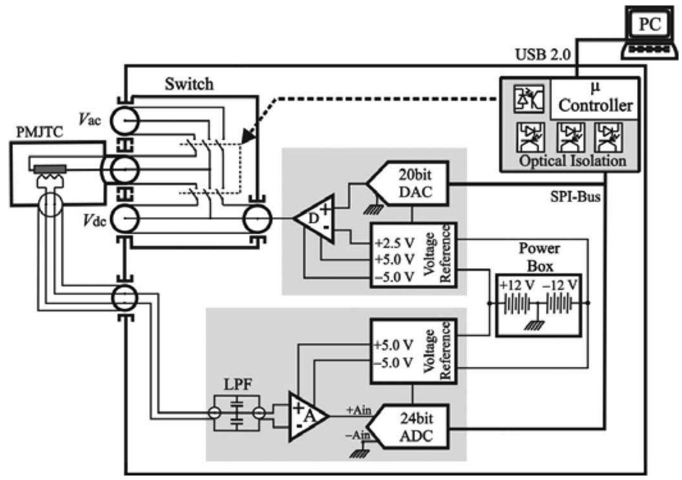

Fig. 1. Simplified schematic of the measurement unit.

II. System for Voltage Measurement

For a wider range of applications, the instrument has two inputs, where the ac and dc voltages can both be applied. The precision reference is derived from an internal programmable dc source. The input connectors are electrically isolated from the instrument front panel by polytetrafluoroethylene washers.

The inputs are selected by means of a coaxial switch constructed from mercury-wetted relays with contact resistances of less than 100 mΩ. The switching time during the application of the reversed dc voltage is 100 ns, whereas the switching time of the relays is about 3 ms. A partial compensation of the voltage across the switching unit is computed when the programmable internal DAC is used.

The system is powered by an internal battery and the total power supplied is less than 5 W. Optical isolation is employed to insulate electrically the programmable control unit from the switch, the acquisition and the DAC units.

To increase the flexibility of the system, the PMJTC is placed outside the system, and a special geometry is adopted to decrease the interference of the system with the operation of the PMJTC.

The input/output resistance of the thermal converter directly influences the resistance isolation of the system.

Fig. 1 schematically describes the main blocks implemented inside the unit.

III. Construction Details

A. Programmable DC Source

The internal programmable dc source employs a sigma–delta 20-bit DAC. This DAC generates and adjusts the voltage under digital control. It can use either internal or external precision voltages as dc references.

The DAC has an internal control loop that refreshes the internal registers and allows several operations. The value of each dc voltage step is controlled by three registers. Twenty-four-bit values are stored in the offset and gain calibration registers.

The final value at the output of the DAC is a combination of the digital code and the lowest dc quantization step of about 4 μV, which is limited by the DAC resolution. Its output is buffered to increase the output current by a low-noise circuitry.

B. ADC Digitizer System

The acquisition system for measuring the EMF of the PMJTC sensor is based on a sigma–delta ADC with 24-bit resolution and a preamplifier with fixed gain G, high input impedance, and low input voltage noise. The offset produced by the bias current of the preamplifier is stable enough to produce the same contribution both in ac and dc. The ADC has a self-calibration procedure that is activated every time the reference voltage or internal programmable gain amplifier (PGA) is changed.

C. Control Unit

The microcontroller is a low-cost high-performance 1-Mb Flash nanowatt technology universal serial bus (USB) controller. The on-chip USB transceiver, V2.0-compliant serial interface engine works at a full speed of 12 Mb/s under the program control.

All digital bus operating with a serial peripheral interface (SPI) protocol has been isolated by means of an optical multichannel interface operating up to 10 Mb/s.

Future updates or special measurement procedures can be stored without extracting the microcontroller.

To increase the flexibility in view of other applications, an additional library of command routines has been written in CVI. Under remote control, the chip operates in several modes.

1) *Single ADC or DAC procedure:* This is the single read–write procedure at different speeds, from 10 to 80 samples/s for the ADC and 5 kilosamples/s for the DAC, to test the performance of both converters. In this case, the synchronous SPI bus is not used simultaneously. This mode is particularly employed when the single internal blocks of the unit have to be tested and compared for internal calibration.

   The ADC readings are calibrated against a known dc calibrator; instead, the voltage generated by the DAC is measured by means of a precision commercial voltmeter.

2) *Loop procedure:* This is the realization of the sequence loop during ac–dc transfer measurements, which consists of the control of the scanner and the dc voltage generation and acquisition.

To ensure the maximum speed of communication, complex processing, which requires multiple machine cycles, is implemented with a personal computer (PC).

D. Analog Reference System

The analog reference system consists of a group of high-accuracy voltage references. In particular, two sets of voltage references are used. The first set is used for the high-resolution ADC and DAC circuits having low noise (1.5 μVpp) and low temperature coefficient (0.5 ppm/$^\circ$C). The second set is a CMOS voltage regulator that is suitable for a battery-powered system. It supplies the operational amplifier. The CMOS voltage regulator has a maximum output current capability of 40 mA and is current limiting.

E. Filter and Precision Amplifiers

The low-pass filter (LFP) has been realized with two precision 2×4.7 μF capacitors having polymer conductive film dielectric. Its cutoff frequency is about $\upsilon \cong 1.7$ Hz and is calculated from the output resistance of the PMJTC, which is about $R_{\mathrm{PMJTC}} \cong 10$ kΩ. A low-noise amplifier A (see Fig. 1) with BiFet input having a gain of $G = 25$, output noise $e_n \leq$ 3 nV/$\sqrt{}$Hz, dc bias current about 250 pA, and maximum offset voltage less than 0.5 mV has been inserted between the LFP and the input of the precision ADC.

F. Input Structure

The configurable unit presents an input structure that is symmetric with respect to the reference plane of the thermal converter and similar to a coaxial tee connector, as shown in Fig. 1. The nominal value of the input resistance of the configurable unit is equal to the input resistance of the thermal converter, i.e., $R_{\mathrm{IN}} \cong 180\ \Omega$. Additional elements in the input structure, such as the relays, are in series with the input resistance of the thermal converter. A calculation of the ratio between the nominal value of the contact resistance of a relay $\delta R_{\mathrm{Relay}}$ and the input resistance of the thermal converter R_{IN} gives a relative value of the systematic error of $\delta R_{\mathrm{Relay}}/R_{\mathrm{IN}} \cong 0.5$ mΩ/Ω.

The present structure does not seem entirely adequate to achieve an uncertainty level lower than 1 μV/V; other switches having a contact resistance less than 50 mΩ and an input circuitry based on operational amplifiers can be an alternative.

This requires the realization of a voltage follower having low noise and stability comparable with that of calibrators and a stable unity gain over a wide range of frequencies.

Fig. 2 presents a photo of the configurable unit, where the three main blocks show the digital control block, the ADC and DAC blocks, and the block of the input structure.

IV. Characterization of the Unit

A. Circuit for the Characterization

The new ac measurement unit has been inserted in a measurement setup, where there are both a precision ac voltmeter and an ac source. The ac voltmeter has been calibrated against the primary ac–dc standard at several frequencies. The simplified block diagram of the measurement setup is shown in Fig. 3. The two instruments are controlled by means of the general-purpose interface bus.

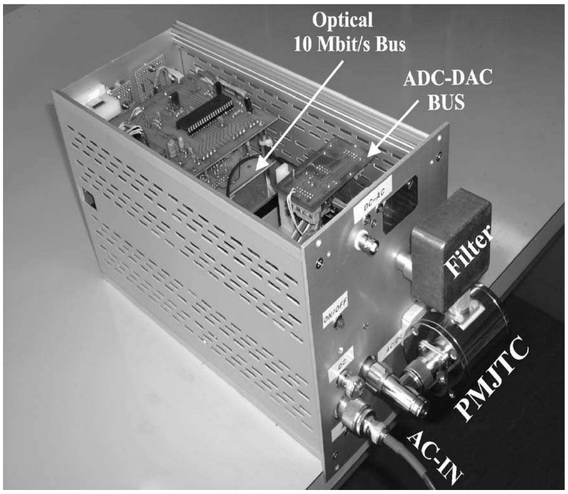

Fig. 2. Reconfigurable RMS measurement unit. The unit can be powered by a battery system, whereas the digital interfaces can directly be powered by the PC via a USB cable.

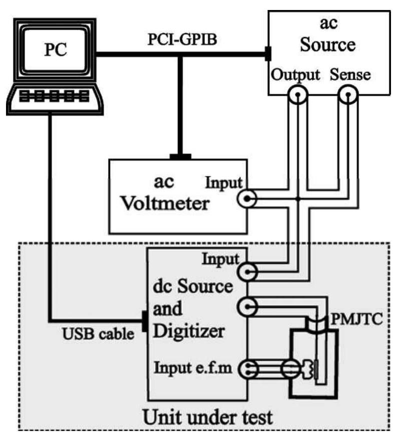

Fig. 3. Measurement setup for comparison of the constructed unit with the commercial instruments.

The precision ac source supplies the unit under test and the calibrated ac voltmeter. Some precautions are taken to reduce stray cable influences and to appropriately define the reference plane. For this application, the position closest to the input of the ac voltmeter seems to be the natural point where it is suitable to define and measure the ac voltage.

A short link ensures the transfer of the ac potential from the reference plane to the input of the unit under test. This way, the two units for the measurement of the ac voltage are in parallel with respect to the reference plane. Reciprocal influences of the two inputs are not taken into consideration, but preliminary measurements show that these interactions are present and not negligible. However, it is possible to continually and repeatedly monitor the ac voltage at the reference plane because there are certain time periods when the two ac instruments are connected in parallel and measure the same voltage in a synchronous mode.

There are two measurements described here, namely, the stability and noise of the standard ac source directly measured by the ac voltmeter. These data can be used to correct the data measured with the configurable unit. Preliminary estimation of the ac source stability shows variations lower than 2 parts in 10^6.

The performance of the unit under test is expressed in terms of long-term stability using similar concepts and measurement procedures employed for the ac–dc transfer standard comparisons by means of the PMJTC sensor.

B. Measurement Procedure

The measurements made by the configurable unit are performed at fixed voltage.

The data are recorded by a PC, and an integration time of 1 s is used at both ac voltmeters.

Many internal operations of the unit under test, principally including switching between the inputs, generation of both positive and negative reference dc voltages, and measuring of the EMFs, follow the sequence normally used during ac–dc transfer comparisons, with a total time of

$$t_T = 4 \cdot (\Delta t_H + t_M). \tag{1}$$

The settling time of the thermal sensor has been evaluated using a unit step of 100 mV and $\Delta t_H = 10 \cdot \tau$, where $\tau \cong 1.4$ s. This time can be reduced when the differences between the voltages to be measured are lower. The time t_M is the time where the samples are collected by means of the digitizer system.

The times Δt_H and t_M are chosen to be 6 s; thus, the total time elapsed to carry out the sequence (ac–dc(+)–dc(−)–ac) is less than 1 min. The small differences between the voltages to be measured are principally associated with the offset of the dc voltage source. These temporal gaps seem to be in good agreement with the amplitude of the voltage differences and guarantee a stable thermal equilibrium during the comparison process.

The calculation of the ac RMS voltage is given as follows:

$$V_{\text{ac}} = V_{\text{DAC}} + \frac{1}{s} \cdot \Delta(\text{EFM}) \tag{2}$$

where V_{DAC} is the voltage generated by the internal programmable dc source, $s = \partial V / \partial \text{EFM}$ is the sensitivity of the thermal converter element calculated by direct measurements at the specific working point, and $\Delta(\text{EFM}) = \langle \text{EFM}_{\text{ac}} \rangle - \langle \text{EFM}_{\text{dc}} \rangle$ is the difference between the averages of the EMFs defined from the n samples EFM_i during times t_M as

$$\langle \text{EFM} \rangle = \frac{1}{n} \sum_{i=1}^{n} \text{EFM}_i. \tag{3}$$

V. Results

Some tests have been performed on the new unit, both as a system to compare the RMS values of two voltages and as a system to evaluate an ac voltage by comparison with the two voltages (i.e., normal and reverse) generated by the internal DAC.

The stability and drift of the EMF generated by the internal DAC reference and acquired by the digitizer unit are shown in Fig. 4.

These experimental data are obtained with the output of the DAC at 1.3 V. The EMF generated at the output of the PMJTC sensor is amplified by amplifier A (see Fig. 1).

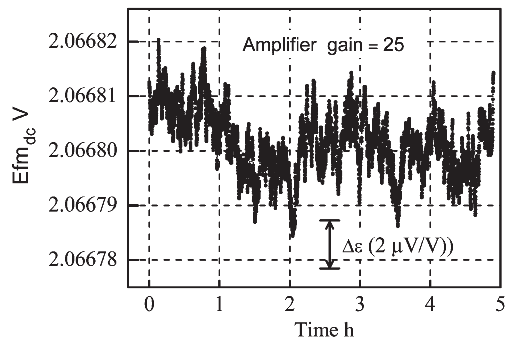

Fig. 4. Measurement by the ADC of the EMF generated by the PMJTC when supplied by the internal DAC.

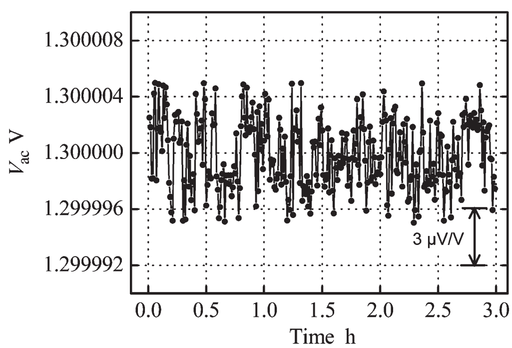

Fig. 5. Stability of an ac RMS voltage measured with the configurable unit following the ac–dc procedure by means a PMJTC.

The measurements made over some hours without changing the DAC polarity or the switch position demonstrate the following:

1) that the EMF generated by the internal DAC has stability in terms of the equivalent input voltage better than 3 μV/V within 1 h;
2) that the equivalent input noise after removing the drift is less than 2 μV/V with an observation time less than 30 min.

Fig. 5 shows the stability of the ac voltage measurement made by the configurable unit.

Moreover, in this case, the input voltage is 1.3 V, which is the most stable voltage supplied by the ac calibrator (range 1 V).

The stability of the measurement of an external voltage and the comparison between two external voltages resulted in a peak-to-peak spread of less than 10 parts in 10^6, with no significant drift of the mean and standard deviation lower than 3 parts in 10^6.

If, however, the switch is kept connected to the internal DAC, which is regularly switched from the positive to the negative value, the difference between the positive and negative values appears to be within a band less than 5 parts in 10^6, which indicates the possibility for further improvements.

VI. Conclusion and Possible Improvements

The functionality test and the experimental results of the configurable unit for an RMS measurement setup have shown good repeatability of the determination of the ac voltage and of the comparison between two voltages. Since this unit employs a PMJTC, it is inherently calibrated for the ac–dc transfer in a wide frequency range and can be used for many applications in the field of precision electrical measurements.

In this version, a more precise voltage reference, an improved DAC with high resolution, and a precise low-noise amplifier at the output of the multijunction thermal converter have been employed. Now, the predominant source of the measurement instability is apparently dependent on variations of the relay resistances. Thus, on the basis of the desired frequency range, the accuracy of the results can be improved by either introducing buffers at the input of the PMJTC or replacing the relays with units having lower and more stable contact resistances.

Acknowledgment

The authors would like to thank V. D'Elia for the construction of the external box power that supplies the flexible unit and G. C. Bosco for some measurements for the characterization of the flexible unit.

References

[1] M. Klonz and R. Bergeest, “Accurate thin film multijunction thermal converter on a silicon chip,” *IEEE Trans. Instrum. Meas.*, vol. 38, no. 2, pp. 335–337, Apr. 1989.
[2] L. Scarioni, M. Klonz, and E. Keßler, “Explanation for the AC–DC voltage transfer differences in thin-film multijunction thermal converters on silicon chips at high frequencies,” *IEEE Trans. Instrum. Meas.*, vol. 56, no. 2, pp. 567–570, Apr. 2007.
[3] U. Pogliano, G. C. Bosco, G. La Paglia, and G. Zago, “Flexible system for precision and automatic comparison of AC measuring device,” *IEEE Trans. Instrum. Meas.*, vol. 42, no. 2, pp. 295–300, Apr. 1993.
[4] M. Klonz, T. Weimann, F. Völklein, H. Dinter, and A. Lerm, “AC–DC-mV-transfer with highly sensitive thin-film multijunction thermal converters,” *IEEE Trans. Instrum. Meas.*, vol. 42, no. 2, pp. 612–614, Apr. 1993.
[5] B. Stojanović, M. Klonz, H. Lainz, and S. Kraicanic, “AC–DC voltage transfer module with thin-film multijunction thermal converter,” *IEEE Trans. Instrum. Meas.*, vol. 52, no. 2, pp. 355–358, Apr. 2003.
[6] Operators Manual, *5790A AC Measurement Standard*, Jan. 1992. PN 893284. [Online]. Available: http://assets.fluke.com/manuals/5790A___omeng0400.pdf
[7] U. Pogliano, B. Trinchera, and F. Francone, “Configurable unit for precise RMS measurements,” in *Proc. CPEM*, Broomfield, CO, Jun. 2008, pp. 236–237.

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