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DESIGN OF A THERMAL WATTMETER IN THE AUDIO FREQUENCY RANGE

This paper describes the development of a system for the measurement of power in the audio frequency range. Flexible units operating with a strategy based on the evaluation of rms quantity by a thermal method have been constructed. For each unit of the set-up, measurements and a preliminary characterization have been performed. The main quantities to be measured are two voltages, difference and sum. The difference voltage has been evaluated by means a vectorial voltmeter, instead the sum voltage by means a rms voltmeter. The module of the voltage difference in the acoustic band seems to be lower than 10 μV. Further investigation and results will be extended when all components of the measuring system will be employed together.

1. INTRODUCTION

Methods and systems for the measurement of the electric power in the audio-frequency range and above are described by several authors in various papers. The demand for power traceability coming from both the scientific and industrial areas aims at the development of measurement set-ups and instruments with adequate precision.

The different strategies applicable for precise power measurements are based, for example, on digital sampling, current comparators power bridge and time division approach, [1]-[4]. The level of uncertainty obtained is lower when bridge comparators are used, however, above 1 kHz the level rises to more than 30·parts in 10^6.

Further techniques for power measurements at higher frequencies include the use of thermal converters [5] for precise measurements of the rms value of electric quantities such as voltage and current, with both sinusoidal and non sinusoidal waveforms.

In the method proposed here, the operating principle requires a preliminary manipulation of the signals in both the current and the voltage channels. Before being processed the voltage is attenuated by a resistive divider and the current is converted into a proportional voltage through a precise shunt resistor built for operating in the wide frequency range.

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Then, the ac-dc transfer comparison of the resulting voltages will be performed by a unit implemented by means a planar multijunction thermal converter (PMJTC) in a single chip configuration. The input and the output of the thermal convert is controlled electronically by a flexible unit built by low cost precision components, such as the ADC, DAC, transimpedance amplifier, switches and reference dc controlled voltages, which are chosen with low noise performances. The main features of the unit are the low power consumption and the isolation via fast speed optical link. A microcontroller provides to transfer data from the flexible unit to the PC according to the USB 2.0 specifications. It contains three inputs connected with a fast coaxial switch, which connects the voltage signals at the output of the analog processing device to the input of the thermal converter.

2. THE THERMAL WATTMETER

The thermal wattmeter operation is described by the following equation:

$$(v(t) + R \cdot i(t))^2 - (v(t) - R \cdot i(t))^2 = 4 \cdot R \cdot v(t)i(t), \tag{1}$$

where v(t) is the input voltage and $R \cdot i$(t) another voltage proportional to the input current.

Then, considering the mean power in one period:

$$P = \frac{1}{T}\int_0^T v(t) \cdot i(t)dt = \frac{1}{4T \cdot R}\int_0^T \left((v(t) + R \cdot i(t))^2 - (v(t) - R \cdot i(t))^2\right)dt = \frac{1}{4 \cdot R}(V_s^2 - V_d^2), \tag{2}$$

where Vs(t) and Vd(t) are the sum and the difference between two quantities v(t) and $R \cdot i$(t).

Mathematical operations were processed in parallel by a precise analog unit constructed with two similar double stage transformers. Thermal methods offer a precise way for the measurement of both terms in the Eq. 2. There can be evaluated either by a simultaneously or a non simultaneously sampling method. At present a technique based on the second approach is adopted, so it implies that the power to be measured is almost constant.

A simplified schematic design of the thermal wattmeter for power measurement in the audio frequency range is shown in Fig. 1.

The wattmeter is assembled by one or two units for the measurement of the rms (in Fig. 1 it is represented the version with one unit that will be completed and tested as a first version). In the wattmeter there are two analogic processing devices for computing the sum and the difference of two signals obtained respectively by a compensated resistive voltage divider and shunt having a wide frequency band.

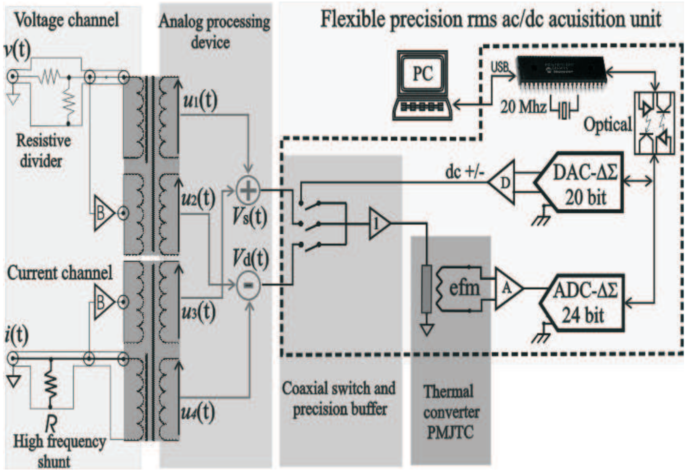

Fig. 1. Simplified design block diagram of the measuring system.

2.1. Unit for rms voltage measuring

This unit, which is an evolution of that presented in [6], is based on a planar multijunction thermal converter and precision auxiliary units that equipages with an optical SPI – USB interface that provide to read-write digital code: The processing is made by means of a personal computer. The low power of the unit permits to supply the digital part by the USB and the analogic part by means of the internal battery. The main parts of the unit are:

- An analog to digital converter (ADC) with 24 bit resolution operating at low speed acquisition rate, 10-80 samples/s with low rms voltage noise, 420 nV. A precise transimpedance amplifier protects the ADC input and increases its flexibility for wideband application.
- A precision digital to analogic programmable (DAC) having 20 bit resolution. With the reference of 2.5 V the minimum dc digital quantized level is about 5 μV. The output of the DAC is buffered by a differential amplifier having noise lover than 10 nV/$\sqrt{\text{Hz}}$.
- A coaxial electro-mechanical switch with switching time better than 10 ms. The contact of the switches are wetted mercury and resistance about 100 mΩ. A precise voltage follower with compensated voltage error is under construction in order to remove the influence of the switch on the input resistance of the thermal converter. First measurements at fixed frequency shows a fluctuation lower than 15 parts in 10^6 when the switch is used.
- A digital board optically isolated and easy controllable via PC by mean a USB protocol. The board has been optimized for its use with multiple units as ADC and DAC. Further extension will provide an improved capability, implementing a dual

acquisition system based of the new precision ADC having 32 bit resolution with 4 ksamples/s with rms noise less than 4 nV/√Hz.

The measurement procedure is completely automatic and the samples can be collected with asynchronous digital technique. The integration time between the quantities is equal and the evaluation of the rms value of the ac electric quantities is compared with the reverse dc quantities generated by means of an internal programmable dc source. Due to the high accuracy possible for the rms voltage measurement made by a PMJTC, also the resulting measurement of power will be very accurate.

2.2. Analog processing device

The low level signals produced respectively in the voltage and current input channels are processed by means precise double stage transformers. The sum and difference are evaluated directly, without using additional electronic circuitry, by the transformers using their capability to decoupling the primary and the secondary coils, so that the signals can be added or subtracted simply connecting the secondary coils in series.

This offers both advantages: the isolation between the power source under test and the low signals measurement circuits, and the accuracy of the sum and the difference performed.

Two double stage 1:1 transformers have been built. Their preliminary characterization of the stray components has been made. From these parameters and by using a lumped model for the double stage transformer, a simulation of the error in magnitude and phase has been obtained, which show an error lower than 20 parts in 10^6 in magnitude and 10 parts in 10^6 in phase up to 20 kHz. This error seems to be adequate for measurements in the audio frequency range.

The limitation at higher frequencies is due mainly to the choice of the cores and the high number of turns necessary to operate at lower frequency. Another version of the processing device in the range from 1 kHz to 100 kHz is now under investigation.

2.3. The high frequency resistive divider

In order to reach a voltage level suitable for processing by the analogic processing device (about 1 V) the input is reduced using a resistive divider. In the prototype, as a preliminary resistive divider coaxial resistors in series with a 100 Ω SMD precision resistor have been used. The coaxial resistors are those employed for the ac-dc transfer standard of voltage operating for frequency up to 100 kHz. Their contribution to the ac-dc transfer difference up to 20 kHz is generally less than 10 parts in 10^6 in the range between 50 V and 150 V and less than 25 parts in 10^6 in up to 400 V.

The resistors at the low end of the divider are connected in parallel to a proper capacitor adjusted to compensate for the phase error. One of the coaxial resistive divider employed is shown in Fig. 2c.

2.4. High frequency current to voltage converter (shunt)

The precision wideband shunts have been studied, constructed and characterized for application in a wideband frequency range [7]. The design of the shunt provides unique features as the special geometry in order to extend the current and frequency. In order to have very low stray components, mainly the mutual inductance between the current input and the voltage output, it was a circular coaxial form designed for them. A shunt for the current of 10 A is shown in Fig. 2d.

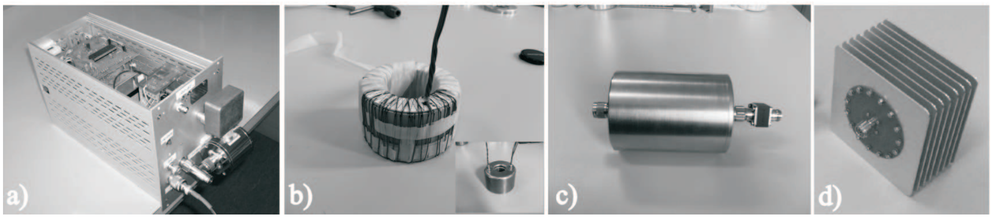

Fig. 2. Components of the audio frequency wattmeter prototype a) unit for ac-dc transfer measurement b) Inside transformer of the analogic processing device c) Coaxial resistive divider for voltage scaling d) coaxial shunt for current to voltage conversion.

3. ANALOG PROCESSING DEVICE CHARACTERIZATION

As described preliminary in section II.b the heart of the system is based on the analog processing unit that provides the main quantities V_s(t) and V_d(t). In Fig. 3 is described a coaxial setup measurement for the characterization of the analog processing unit and in Fig. 4 a photo of the system is given.

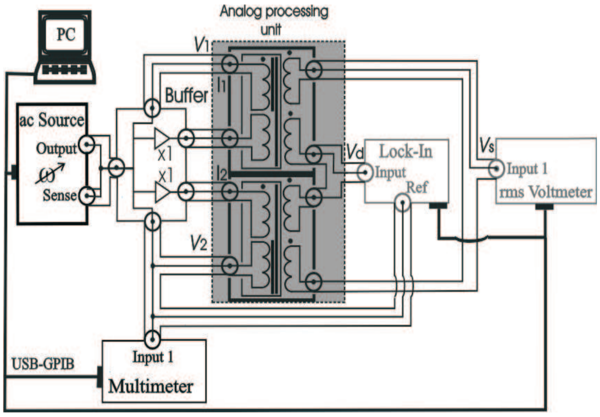

Fig. 3. Simplified coaxial schematic for the characterization of the analog processing unit.

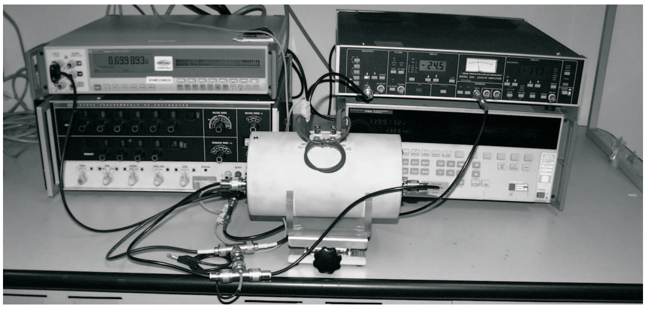

Fig. 4. A photo of the system for the characterization of the analog processing unit.

Four connectors are present in the analog processing unit, two inputs V_1 and V_2 and two outputs V_s and V_d. Both V_1(t) and V_2(t) input's signal are supplied by a programmable ac source. To ensure the suitable condition $V_1 \cong V_2$ two coaxial cables (from node N to the inputs I_1, I_2) having equal length are used. A lock-in amplifier is inserted to measuring the small difference signal V_s at several frequencies. The aim was at knowing this voltage at different frequencies. In general, if condition $V_1 \cong V_2$ is achieved and the two stages of the analog processing unit are symmetric with perfect ratio 1 : 1 the ideal response should be $\boldsymbol{V}_d = |V_d| \cdot e^{i\theta} \cong \mathbf{0}$. Instead, small deviations from the ideal ratio and the dissymmetry between the two stages together with stray capacitances at different frequencies create a small V_s potential detectable only by look-in amplifier.

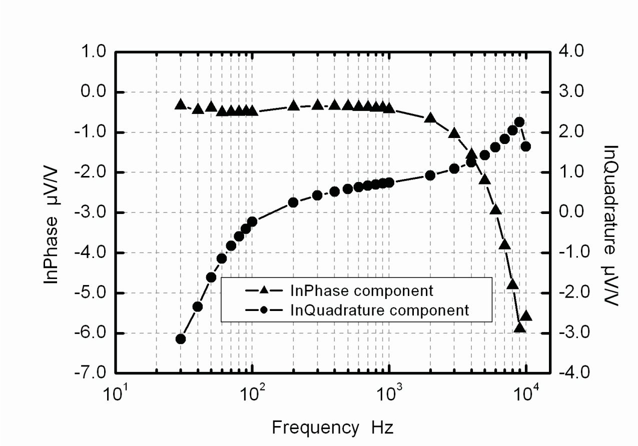

Fig. 5. Inphase and InQuadrature components of the difference signal (V_s) in the frequency range from 30 Hz to 10 kHz.

Fig. 5 shows the difference signal V_d in the acoustic band measured by means of a lock-in amplifier. An electronic circuit, buffer, with ideal gain G ≅ 1 has been inserted between the programmable ac source and the analog processing unit as shows Fig. 3. The main features of the buffer circuit is the high input resistance $R_{input} \cong 10$ MΩ using matched fet transistors capable to drive an output circuitry witch can delivers more than 100 mA in output and has an extended working band up to 1 MHz.

4. CONCLUSIONS

The constituent parts for a precision wattmeter operated in a wideband have been built.

At the moment, the single parts show an accuracy that, with some further adjustments, is better than 30 parts in 10^6 in the frequency range from 20 Hz to 20 kHz. This allows to anticipate that the precision of the wattmeter can be better than 50 parts in 10^6 in the whole audio frequency range. As the wattmeter is linked to a computer proper corrections could be applied from the current and voltage employed, so improving the accuracy of the measurements.

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