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Trilateral South American project: a reference system for measuring electric power up to 100 kHz – progress report II

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Abstract: Three countries in South America are jointly developing a reference system for measuring electric power up to 100 kHz. The objective is the construction of three similar measuring systems, one for each institute. The measuring system, its design requirements, and the current status of its development are described. This project will contribute to provide calibration services in measuring ranges still not covered by the three institutes.

Keywords: power, electric power, wideband wattmeter, sampling methods, regional project.

1. INTRODUCTION

In the last decades, the increased use of nonlinear loads in power distribution networks has caused a significant increase in the waveform harmonics degrading the quality of the power delivered to the customer. The reliable measurement of waveform harmonics requires refined techniques.

The nonlinear loads include the new technologies of compact lighting and the use of switching converters. The latter are used both in transmission and distribution networks in power electronics applications. Such loads also include switched-mode power supplies (SMPS) used in many appliances. SMPS switch voltages (in the order of 400 V) in frequencies in the range of kilohertz producing harmonics beyond 1 MHz [1][2].

International comparisons on harmonic power are being planned at the level of the Consultative Committee on Electricity and Magnetism (CCEM) and of the Inter-American System of Metrology (SIM).

To address this concern, the Instituto Nacional de Metrologia, Qualidade e Tecnologia (Inmetro), in Brazil, the Instituto Nacional de Tecnología Industrial (INTI), in Argentina, and the Administración Nacional de Usinas e Transmisiones Eléctricas (UTE), in Uruguay, are jointly developing a reference system for measuring electric power up to 100 kHz. The objective is the construction of three similar measuring systems, one for each institute. The project is supported in part by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), in Brazil.

This project will contribute to provide calibration services in measurement ranges still not covered by the three institutes. The project will also contribute to improve the traceability not only of electric power but also of related quantities such as ac-dc transfer, voltage ratio, phase angle, ac voltage and ac current.

2. MEASURING SYSTEM

Calibration systems for harmonic power analyzers and power quality measuring instruments generally consist of a digital generator with two independent channels (one for voltage and one for current). Arbitrary voltage and current waveforms are programmed and applied to the instrument under calibration. The amplitude ratio and phase displacement of the two signals can be adjusted by changing the generator settings. Voltage dividers and current shunts with flat responses in all the frequency range of interest are used to convert with high accuracy the high voltages and currents to the relatively low voltages required by the digitizer inputs. The harmonic parameters of such waveforms and the electric power are estimated from the digitized data and the resulting estimates are compared with the readings of the device under calibration.

The reference measuring system comprises (see figure 1): an arbitrary waveform function generator with two synchronized channels, a power amplifier, a transconductance amplifier, a resistive voltage divider, a current shunt and a digitizer with two synchronized channels.

2.1. Arbitrary waveform function generator

Arbitrary waveform function generators based on direct digital synthesis (DDS) present many advantages in comparison with other techniques. The DDS technique consists in the digital processing to generate signals at different frequencies and phases selectable by software from a reference clock. It shows a higher frequency resolution and a lower harmonic distortion than those obtained through other techniques (for instance, phase-locked loop). The frequency stability in the DDS technique depends only on the external reference oscillator employed, thus allowing multiple devices to be synchronized.

The design requirements for such generator were presented in [3]. A two-channel version of the design described in [4]-[6] will be implemented. The circuit changes are not significant. The input buffer and analog-to-digital converter (ADC) are doubled and two power supplies for the ADC modules need to be used.

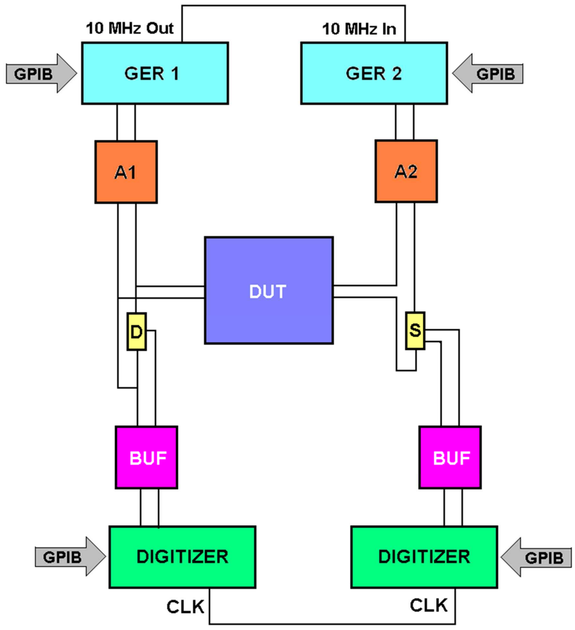

Figure 1. Simplified block diagram of the reference measuring system. (GER1 – channel 1 of the arbitrary waveform function generator, GER2 – channel 2 of the arbitrary waveform function generator, A1 – power amplifier, A2 – transconductance amplifier, D – resistive voltage divider, S – current shunt, BUF – buffer, DIGITIZER – two-channel digitizer, CLK – clock, and DUT – device under calibration)

The generator circuits have already been designed by INTI. The circuit components were purchased by Inmetro and they are waiting for authorization from Argentinian customs to be embarked to INTI. The printed circuit boards (PCB) are currently being manufactured in Brazil. Hopefully, the PCBs will be transported to INTI together with the circuit components so that the prototype integration and testing can be carried out by INTI by the time this article is published.

2.2. Power amplifier

The power amplifier is used to boost the output of a channel of the dual-channel generator to a nominal of 120 V RMS or 240 V RMS. In addition, the amplifier is designed to supply up to 100-mA RMS to accommodate the burden requirements without causing any significant error. A prime goal is to maintain the excellent short-term amplitude and phase stability inherent in the digital generator. In addition, there is a general need for a precision power amplifier that will provide an output swing of a few hundred volts at moderate power levels while maintaining good dc characteristics, stable gain, and wide bandwidth.

The design requirements for such amplifier were presented in [3]. The amplifier topology was selected by Inmetro. A total of 2 (two) amplifiers will be assembled: one using through-hole components based on [7] and another using SMD technology based on a one-stage version of [8]. The National Institute of Standards and Technology (NIST) is collaborating with the development of the second amplifier. The behavior of the two amplifiers will be compared. The circuit components were purchased and Inmetro will arrange the PCBs layout and manufacture to be finished by the time this article is published.

2.3. Transconductance amplifier

A transconductance amplifier ideally produces a current in a load proportional to an input voltage and maintains that current independent of the load terminal voltage. A total of 4 (four) transconductance amplifiers are being designed each covering the following ranges: 20 mA, 200 mA, 5 A, and 20 A. Budget restrictions prevented the construction of the 100 A module as had been planned in [3].

The design requirements for such amplifiers were presented in [3]. The amplifiers will contain only analog circuits to reduce electrical noise. Linear power supplies are utilized in all amplifiers except the 20 A module also to reduce electrical noise. Vishay Z-Foil resistors (VTA) with low TCR are employed in critical circuit locations to increase the output stability of the amplifier. For 20 A capability, the amplifier needs to have a 240 W capacity with adequate means to dissipate this power while also having a small physical geometry to maintain a low inductance in the output current circuit.

The amplifier circuits and product integration were designed by Inmetro based on [9]-[11]. Cooling tunnel assemblies to dissipate up to 240 W from the amplifier output transistors were already manufactured by Inmetro. The circuit components were purchased and Inmetro will arrange the PCBs layout and manufacture to be finished by the time this article is published.

2.4. Resistive voltage divider

There are 9 (nine) resistive voltage dividers to be used one at a time whose (binary) nominal value (from 4 V to 1024 V) depends on the test voltage selected [12][13]. Each divider comprises two cascaded, independently shielded sections: a range resistor and a shunt resistor. The dividers have input resistances ranging from 1 kΩ @ 4 V to 256 kΩ @ 1024 V. Thus the power amplifier output current is always 0.004 A. A 200-Ω shunt resistor is used so that the nominal output voltage of the dividers is always 0.8 V. The two sections can be calibrated together as a voltage divider or separately as resistors. This provides flexibility in testing.

To get high accuracy in all ranges of voltage and frequency, it is necessary that the divider behaves as a linear device. The most important nonlinear component in voltage dividers is dielectric losses. Vishay Z-Foil audio resistors (VAR) with low dissipation factor whose dissipated power in each resistor does not exceed 100 mW are therefore employed. It was confirmed by UTE that nonlinear effects are reduced considerably by soldering such resistors on PTFE boards (see [3] and references therein). Such boards have a very low dissipation factor. Once nonlinear effects have been minimized, stray capacitances are the most relevant linear parasitic effect. In this work a different shielding technique for nulling radial electric fields is explored [14].

The voltage divider circuits, the special shielding and the product integration were all designed by UTE. The circuit components and PTFE boards were purchased by Inmetro and transported to UTE. The PCBs layout was carried out and a few prototypes have been assembled and tested by UTE. Inmetro is currently purchasing additional components requested by UTE and purchasing the adhesive labels containing the participant logos. UTE started assembling the voltage dividers. Hopefully, they will be fully assembled by the time this article is published. UTE is also developing a system based on [15] for measuring the phase displacement of the dividers (see [16]).

2.5. Current shunt

There are 12 current shunts to be used one at a time whose nominal value (20 mA, 50 mA, 100 mA, 200 mA, 0.5 A, 1 A, 2 A, 5 A, 10 A, 20 A, 50 A and 100 A) depends on the test current selected [17]. Their input resistances range from 40 Ω @ 20 mA to 0.008 ohm @ 100 A. Thus the nominal output voltage of the shunts is always 0.8 V. Vishay Z-Foil resistors (Z201) with low TCR whose power dissipated in each resistor does not exceed 0.33 W are employed to satisfy stability requirements (see [3] and references therein).

The current shunt circuits and PCBs layout were designed by INTI and Inmetro based on [18]. The circuit components were purchased by Inmetro and the PCBs manufactured in Brazil, all being transported to INTI. Inmetro is currently fabricating the shunts metallic panels containing the participant logos. INTI started assembling the current shunts [19]. Hopefully, the panels will be transported together with the items already available at Inmetro so that the current shunts can be fully assembled by INTI by the time this article is published.

Two additional units of each nominal value are being independently constructed by Inmetro for ac-dc transfer measurements and instrument calibration purposes. Inmetro assembled the 0.5 A, 1 A, 2 A, 5 A, 10 A and 20 A shunts and they have been already tested [20]. The remaining shunts will have been assembled and tested by the time this article is published. Inmetro elaborated software to model the current shunts behavior and estimate their ac-dc transfer and phase displacement [21]. An M. Sc. dissertation will be produced under Inmetro metrology postgraduate program to document the modeling and experimental results obtained.

2.6. Dual-channel digitizer

A high-resolution, digital sampling system based on a Sigma-Delta analog-to-digital converter (Σ–Δ ADC) has been developed and characterized [22]. The system has been modified to accommodate two synchronized channels.

The design requirements for such digitizer were presented in [3]. The “equivalent sampling rate (ESR)″ is the frequency with which the samples are outputted. As the Σ–Δ ADC works through oversampling, ESR = *f*s/OSR, where *f*s is the clock frequency and OSR is the oversampling ratio. The ADC allows a maximum clock frequency of 20 MHz and an OSR between 32 and 256, that is, 20 MHz / 32 = 625 kHz is the maximum ESR.

The digitizer circuits were designed by INTI. The circuit components were purchased by

Inmetro and transported to INTI. The PCBs layout was carried out by INTI and the PCBs manufactured in Brazil. Inmetro is waiting for authorization from Argentinian customs to embark the PCBs to INTI so that the prototype integration and testing can be carried out by INTI by the time this article is published.

3. PROJECT MANAGEMENT

The project is coordinated by Inmetro, who is responsible for the purchase and transportation of the components and parts needed to the construction of the modules, and for the transportation of the modules needed to the assembly of the measuring systems, in each participating country.

Inmetro is also responsible for the development of the wideband power and transconductance amplifiers. INTI is responsible for the development of the arbitrary waveform function generators, the dual-channel digitizers and the current shunts (and their calibration). UTE is responsible for the development of the resistive voltage dividers (and their calibration).

The project activities include the design, layout and documentation of the PCBs, the design and documentation of the electronic packaging of the modules, the calibration certificates of resistive voltage dividers and current shunts, the design and documentation of the software and firmware, and the measuring system integration, testing and documentation.

Electronic components and product enclosures, for assembling 3 (three) dual-channel digitizers, weighing 68.53 kg and amounting US$ 16,609.47 FOB (plus US$ 1,000 for transportation) embarked to INTI on May 18, 2016 after waiting at Inmetro since Sep 22, 2015 for Argentinian customs authorization. Vishay resistors, special connectors and PCBs for assembling 48 current shunts – 4 (four) units at each nominal value - weighing 37.95 kg and amounting US$ 51,312.92 FOB (plus US$ 816 for transportation) embarked to INTI on September 20, 2016 after waiting at Inmetro since Apr 12, 2016 (Vishay resistors and special connectors) and July 25, 2016 (PCBs) for Argentinian customs authorization. Electronic components and product enclosures, for assembling 3 (three) two-channel arbitrary waveform function generators, and PCBs for assembling the dual-channel digitizers, weighing 39.85 kg and amounting US$ 12,052.25 FOB are currently at Inmetro waiting since Feb 24, 2017 for Argentinian customs authorization to be embarked to INTI. Additional PCBs for the function generators are currently being manufactured for US$ 1,890.00.

Vishay resistors, special connectors and PTFE boards, for assembling 27 resistive voltage dividers – 3 (three) units at each nominal value –, weighing 5.23 kg and amounting US$ 10.045.42 FOB (plus US$ 660 for transportation) embarked to UTE on Apr 08, 2016 after waiting at Inmetro since Feb 25, 2016 for Uruguayan customs authorization. Additional Vishay resistors and connectors weighing 2.80 kg and amounting US$ 2,602.60 FOB (plus US$ 460 for transportation) are currently waiting at Inmetro to be embarked to UTE. Further special connectors are currently being purchased for US$ 1,161.12 to finalize the assembly of the resistive voltage dividers.

Inmetro purchased (May 22, 2015) special connectors, (May 11, 2015) Vishay resistors, and (Apr 26, 2016) PCBs for assembling 24 current shunts – 2 (two) units at each nominal value – amounting US$ 24,759.40 FOB (plus US$ 4,015.46 for transportation). The special connectors arrived at Inmetro on Dec 11, 2015 and the Vishay resistors on Jan 15, 2016. The PCBs were ready in July, 2016.

Inmetro purchased on June 16, 2016, electronic components for assembling 12 transconductance amplifiers – 3 (three) units at each nominal range - weighing 15.55 kg and amounting US$ 9,936.77 FOB (plus US$ 227 for transportation). They arrived at Inmetro on Nov 14, 2016. Inmetro also purchased from May 11 to July 16, 2015, Vishay resistors for critical circuits of the abovementioned amplifiers amounting US$ 14,379.83 FOB. They arrived at Inmetro on Jan 15, 2016. Inmetro also purchased on July 29, 2015, 12 linear and 6 (six) switching-mode power supplies for assembling the abovementioned amplifiers weighing 51 kg and amounting US$ 7,659 FOB (plus US$ 953.35 for transportation). They arrived at Inmetro on Jan 20, 2016.

Inmetro developed a Brazilian supplier and purchased for US$ 174.86 24 units of 45-cm long flat flexible circuit material with 9-mm wide copper strips separated by a thin dielectric. Those cables have low impedance and will be used as the output conductors of the transconductance amplifiers. Inmetro also fabricated 11 cooling tunnel assemblies with 4 (four) black-anodized aluminum heat sinks each to be used in the abovementioned (and future) 5 A and 20 A transconductance amplifiers. Inmetro is currently manufacturing 24 units of 70x70-mm, 48 units of 130x130-mm and 24 units of 250x250-mm metallic panels for assembling all 72 current shunts – 6 (six) units at each nominal value. All aluminum panels will be anodized, matted (with small porous diameter for aesthetic purposes) and will contain the colored logos of the participants. Such service cost US$ 3,140. Two-thirds of these panels will be transported to INTI and the remaining will stay at Inmetro. Inmetro is currently purchased 18 units of 5-A amplifier PCBs, 12 units of buffer amplifier PCBs and 12 units of linear power supply PCBs for all the transconductance amplifier units. The PCBs cost US$ 1,300.

Inmetro purchased electronic components for assembling 3 (three) PTH power amplifiers weighing 2.80 kg and amounting US$ 1,744.91 FOB on September 03, 2016 and electronic components for assembling 4 (four) SMD power amplifiers weighing 8.55 kg and amounting US$ 4,321.78 FOB on March 21, 2017. They arrived at Inmetro only on June 27, 2017 as CNPq had problems with the renewal of her transportation security contract since January 2017. Inmetro also purchased on December 05, 2016, 12 units of 500-V and 6 units of +/-15-V linear power supplies for assembling the abovementioned amplifiers weighing 33 kg and amounting US$ 5,671.20 FOB (plus US$ 953.35 for transportation). They also arrived at Inmetro only on June 27, 2017.

Additional small scattered spending is not reported here. Nearly 90% of the funding allocated for this project has already been spent by July 2017.

4. REFERENCES

[1] Kyriazis G A 1997 Analysis of discrepancies between measured and predicted conducted emissions in switched-mode power supplies *In IEEE Internat. Symp. on Electromagnetic Compatibility (Austin)* 504

[2] Kyriazis G A 1995 Prediction of conducted emissions in switched-mode power supplies *EMC Test and Design* Aug. 1995 p. 10

[3] Kyriazis G A, Di Lillo L, Slomovitz D, Iuzzolino R, Yasuda E, Trigo L, Laiz H, Debatin R, Franco A M R, Afonso E 2016 Trilateral South American project: a reference system for measuring electric power up to 100 kHz – progress report", *Journal of Physics, Conference Series (Online)*, v. 733, p. 012068

[4] Adad W 2010 *Investigación sobre la generación de señales arbitrarias por el método de síntesis digital directa para su aplicación a la metrología eléctrica*, Tese de Ingeniería, Facultad de Ingeniería, Universidad de Buenos Aires

[5] Adad W and Iuzzolino R 2012 Arbitrary function generator using direct digital synthesis *CPEM Digest (Washington)* 622 ISBN 978-1-4673-0440-5

[6] Adad W and Iuzzolino R 2012 Low distortion signal generator based on direct digital synthesis for ADC characterization *ACTA IMEKO* **1** 59

[7] Laug O B 1987 A precision power amplifier for power/energy applications *IEEE Trans. Instrum. Meas.* **36** 994

[8] Waltrip B C, Laug O B and Nelson T L 2015 A 600 V voltage amplifier for power measurements *IEEE Trans. Instrum. Meas.* **64** 1373

[9] Laug O B 1985 A wide-band transconductance amplifier for current calibrations *IEEE Trans. Instrum. Meas.* **34** 639

[10] Laug O B 1996 A 100 A, 100 kHz transconductance amplifier *IEEE Trans. Instrum. Meas.* **45** 440

[11] Hess D T and Clarke K K 1998 Evaluation of 100 Ampere, 100 kHz transconductance amplifiers *CPEM Digest (Washington)* 611

[12] Slomovitz D, Trigo L, Aristoy G, Brehm M and Kyriazis G A 2016 Wideband resistive voltage divider for a standard wattmeter, *Journal of Physics, Conference Series (Online)*, v. 733, p. 012072

[13] Slomovitz D, Trigo L, Aristoy G and Brehm M 2016 Resistor dividers for power quality meters *CPEM Digest (Ottawa)* ISBN 978-1-4673-9134-4

[14] Slomovitz D, Trigo L, Aristoy G, Brehm M and Kyriazis G A Wideband resistive voltage divider for a standard wattmeter. Progress report. *XII SEMETRO*, Nov 26-29, 2017, Fortaleza, Brasil, *this issue*

[15] Pokatilov A, Kübarsepp T and Vabson V 2016 Effect of Keysight 3458A jitter on precision of phase difference measurement *IEEE Trans. Instrum. Meas.* **56** 2595

[16] Trigo L, Slomovitz D and Kyriazis G A Voltage-ratio calibration system up to 50 kHz *XII SEMETRO*, Nov 26-29, 2017, Fortaleza, Brasil, *this issue*

[17] Yasuda E, Di Lillo L and Kyriazis G A 2015 Design and construction of new shunts for a wideband sampling wattmeter *XI SEMETRO (Bento Gonçalves)* Nov 30 - Dec 02 ISBN 978-85-86768-10-1

[18] Rydler K -E and Tarasso V 2008 Extending ac-dc current transfer measurement to 100 A, 100 kHz *CPEM Digest (Boulder)* 28 ISBN 978-1-4244-2399-6

[19] Yasuda E, Di Lillo and Kyriazis G A Construction of new shunts for a wideband sampling wattmeter *XII SEMETRO*, Nov 26-29, 2017, Fortaleza, Brasil, *this issue*

[20] De Souza R M, Kyriazis G A and Landim R P AC-DC current shunts: assembling and characterization at Inmetro *XII SEMETRO*, Nov 26-29, 2017, Fortaleza, Brasil, *this issue*

[21] Kyriazis G A, De Souza R M, Yasuda E and Di Lillo L Modeling wideband cage-type shunts *XII SEMETRO*, Nov 26-29, 2017, Fortaleza, Brasil, *this issue*

[22] Iuzzolino R 2011 *Josephson waveforms characterization of a Sigma-Delta Analog-to-digital converter for data acquisition in metrology*, Dr.-Ing. Dissertation, Technische Universität Braunschweig TU-BS Diss. ISBN 978-3-86387-095-9

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