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AC-DC TRANSFER AT BNM-LNE

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Abstract − This paper is an overview of the activities in the field of AC-DC transfer at BNM-LNE. Thermal converters, measurement principles and techniques are described. The different domains covered by AC-DC transfer at BNM-LNE are presented with indication of achievable uncertainties for each of them.

Keywords: AC-DC transfer, thermal converters

1. INTRODUCTION

Units used for measurements of voltages and currents are physically realised and maintained only for quantities which remain constant in time (DC quantity). Parameters, which characterise AC quantities, have then to be linked to the corresponding DC values. Thus the root mean square (RMS) value of AC signals can be linked to the corresponding DC quantity by comparing the energetic effects they produce to those produced by corresponding DC signals. Presently this comparison is performed with the best accuracy in the thermal domain by the means of thermal converters.

However, the response of thermal converters differs for AC and DC signals and greatly depends on frequency. One of the main tasks of National Metrology Institutes (NMI's) in the AC-DC transfer field is then to determine the frequency response of their standard thermal converters.

This paper describes the principle of AC-DC transfer measurements and the activity at BNM-LNE (formerly BNM-LCIE) in this domain. All the uncertainties are given as one standard deviation.

2. PRINCIPLE OF AC-DC TRANSFER MEASUREMENTS

The principle of AC-DC thermal transfer measurements is based on the comparison of the heating of a resistor produced by the successive application of AC and DC signals and measured by the means of a thermocouple fixed on the resistor. The procedure is the following : the AC signal to be measured is first applied to the heater resistor and the output voltage of the thermocouple is measured. Then the AC signal is replaced by a DC signal which is adjusted to produce the same output voltage of the thermocouple as previously. When this condition is fulfilled the DC signal is measured and it can be concluded that the RMS value of the AC signal is equal to the measured value of the DC signal.

Nevertheless as the response of a thermal converter is different for AC and DC signals, a correction called the AC-DC transfer difference has to be applied. The AC-DC transfer difference δ of a thermal converter is defined by :

$$\delta = \frac{E_{ac} - E_{dc}}{E_{dc}} \qquad (1)$$

where E_{ac} is the RMS value of the AC signal applied to the thermal converter and E_{dc} is the value of the DC signal which produces the same output voltage of the thermocouple.

In practice, DC signal is applied successively in both polarities to eliminate the reversal error arising from asymmetry in the construction of the thermal converter. E_c represents then the mean value of E_c+ and E_c-.

3. THERMAL CONVERTERS

3.1. Description of thermal converters

The oldest type of thermal converters, already used in the 50's [1], is single junction thermal converters (SJTC) which consists of a straight-wire heater element with a single thermocouple attached on its midpoint (See fig. 1). The heater/thermocouple combination is enclosed in a glass bulb which is generally evacuated. Such converters can be used for measurements of voltages of the order of 1 V and currents of the order of a few mA. For example, the specifications for one of the SJTC's commonly used at BNM-LNE are as follows : nominal input voltage : 0.5 V; nominal input current : 5 mA; input resistance : 90 Ω; output voltage of about 7 mV in response to a nominal value signal applied at the input ; output resistor : 8 Ω. The frequency domain covered by SJTC's is as wide as 10 Hz to more than 100 MHz.

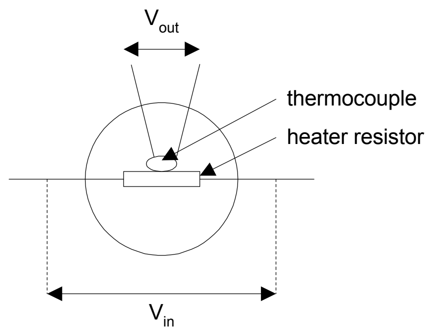

Fig. 1. Single junction thermal converter.

In the 60's some theoretical works [2] showed that thermal converters consisting of a great number of thermocouples connected in series and fixed on a heater resistance, so called multijunction thermal converters (MJTC's), should exhibit lower AC-DC difference than SJTC's up to some tens of kHz. This led to the development in some laboratories of such converters. PTB (Germany) developed in the middle of the 80's MJTC's with 56 thermocouples having a nominal input voltage of 3 V, an input resistance of 180 Ω, an output resistance of 900 Ω and an output voltage of about 100 mV in response to a nominal value input signal. AC-DC transfer difference of these converters is claimed to be less than or of the order of 1 part in 10^6 in the frequency range from 10 Hz to 100 kHz [3].

Manufacturing such converters nevertheless remains complex and expensive. Modern photo lithographic process and thin film technology offer new low cost manufacturing possibilities. For the last ten years, number of studies have been performed in this domain over the world. In Europe they led to the development by the PTB in collaboration with IPHT (Institut fur Physikalishe Hochtechnologie) of planar thin-film multijunction thermal converters (TFMJTC's) [4]. Specifications and performances of these new devices are similar to those of previous MJTC's except for the output resistance which is now of the order of 10 kΩ. They are now commercially available.

3.2. Errors of thermal converters

One of the error sources of thermal converters is the influence of Peltier and Thomson effects. When a DC signal is applied at the input of the converter, Peltier effect arising at the interface between the heater and the cable and Thomson effect arising along all the heater due to the temperature gradient, affect the temperature distribution of the heater. When an AC signal is applied at a frequency above some tens of Hz, these effects do not appear more because of the thermal inertia of the converter. The temperature and consequently the output voltage of the thermocouple(s) are then different whether the converter is feeded by an AC or a DC signal, which is manifested by an AC-DC difference depending on the signal level but not depending on frequency.

Theoretical analysis of the influence of Peltier and Thomson effects was given many years ago [5]. More recently, the development of a "Fast Reversed DC Source" (FRDC source) offered an experimental method of evaluating their influence[6,7]. The FRDC source has three working modes, namely DC+, DC-, and FRDC modes (See fig. 2).

In the DC+ (resp. DC-) mode, switching of the signal delivered by the FRDC source is performed between the "+" (resp. "-") and "off" states. In the FRDC mode, switching is performed between "+", "-" and "off" states. In all cases, the "off" state is much longer (about 10 µs) than the transient time and at the same time much shorter than the thermal response of the thermal converter which is of the order of 1 or a few seconds. In all the modes the spectrum of the delivered signal is practically the same but when such signals are applied to a thermal converter thermoelectric effects appear only in DC+ and DC- modes. Influence of these effects can then be deduced from the difference of behaviour of the thermal converter in DC modes and in FRDC mode. Experiments performed with such a source at BNM-LNE and in number of other laboratories, allowed to measure the contribution of thermoelectric effects to the AC-DC transfer difference of various standard thermal converters. They particularly confirmed that these effects lead to very low AC-DC difference in the case of MJTC's.

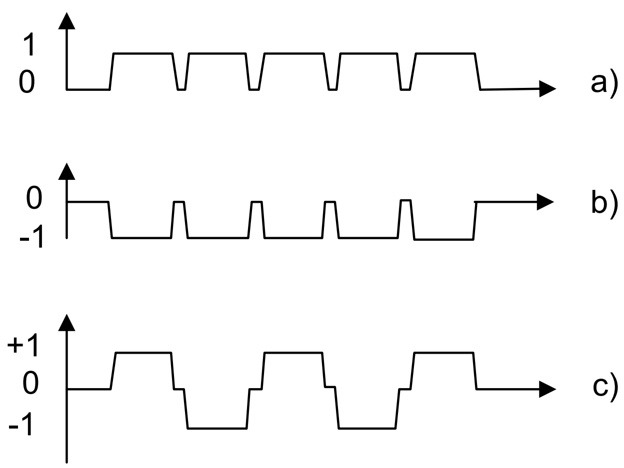

Fig. 2. Output signals of the FRDC source
a) DC+ mode b) DC- mode c) FRDC mode

At frequencies below some tens of Hz, the temperature of the heater varies at twice the frequency of the input signal because the thermal inertia is not infinite. Moreover amplitude of these variations increases when frequency decreases. As most of the physical phenomena which determine the temperature are not linear (temperature coefficient of the heater, radiation, convection if the heater is not in an evacuated enclosure), the mean value of the output voltage, which can be easily measured after filtering, does not depend only on the electrical power dissipated in the heater but also on other parameters as frequency. This is the origin of the "low frequency error".

The "high frequency error" arises from the parasitic inductance of the heater and the stray capacitance between the heater and the ground and from the skin effect. This error increases generally with frequency and depends greatly on the design of the thermal converter. Coaxial structure of HF-type thermal converters, which are generally single junction converters, reduces the effects of stray capacitance and stray inductance.

4. LOW FREQUENCY AC-DC TRANSFER VOLTAGE STANDARDS

4.1. Primary standards

New primary standards used at BNM-LNE for low frequency AC-DC voltage transfer are a low frequency type TFMJTC with a 90 Ω input resistance for frequencies from 10 Hz to 1 kHz and a high frequency type TFMJTC with a 180 Ω input resistance for frequencies ranging from 1 kHz to 1 MHz. Voltage AC-DC transfer difference of these devices at the lowest uncertainty level (about 1 part in 10^6 up to 100 kHz and 20 parts in 10^6 at 1 MHz) are known at the input of the bare chip. In practice, the chip is mounted in an housing and the input signal is brought through a type-N connector and a short (about 2 cm) coaxial cable (See fig. 3). The error caused by the connector and the cable (arising from parasitic capacitances and inductances and from skin effect) and then the AC-DC transfer difference of the chip placed inside the housing and equipped with connection elements have been calculated at BNM-LNE in the reference plane of a coaxial type-N "T" connector linking this standard to the unit under test and the voltage source.

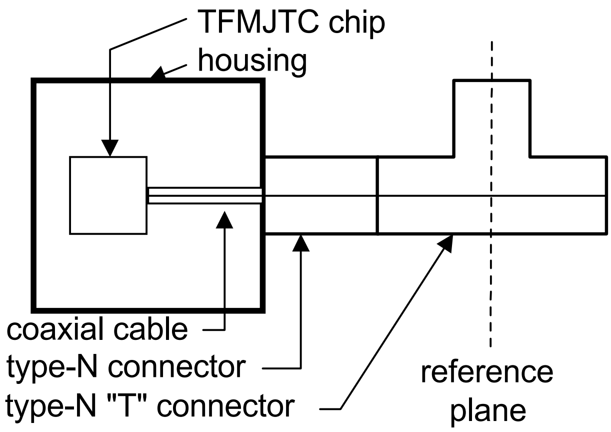

Fig. 3. Primary standard for voltage measurements.

4.2. Other standards

The nominal input voltage of TFMJTC is about 1 V. To use them at higher voltages a set of range resistors to be connected in series with the TFMJTC have been developed at BNM-LNE. These resistors are frequency compensated by the means of an internal screen connected at the high potential. The voltage domain covered by this set of converters is ranging from 0.5 V to 1000 V (See fig. 4).

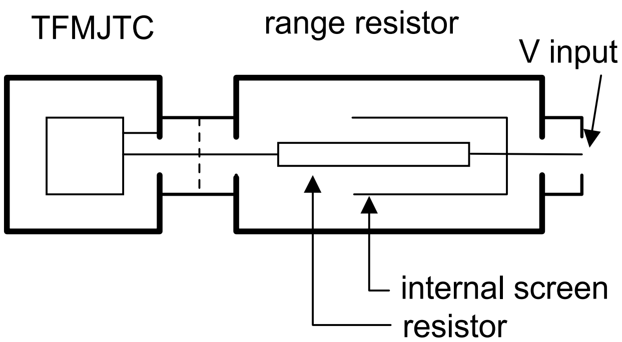

Fig. 4. Voltage thermal converter.

4.3. Calibration of low frequency AC-DC transfer voltage standards

A step-up procedure is used to calibrate the different converters which consists in calibrating the 2 V converter against the 1 V primary standard, then the 3 V converter against the 2 V converter and so on up to the 1000 V converter (See fig. 5). All these measurements are performed using a calibration set-up developed at BNM-LNE which is described in paragraph 8.

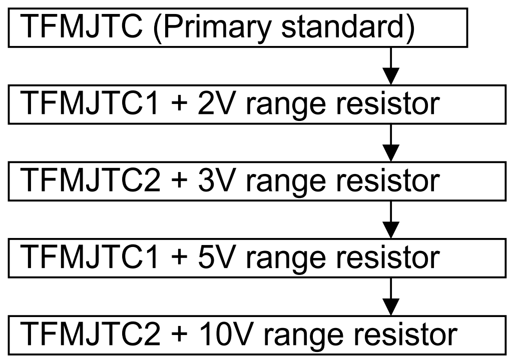

Fig. 5. First steps of the step-up procedure.

In this procedure each converter is calibrated at a voltage less than its nominal voltage and serves then as the standard at its nominal voltage for the calibration of the next converter. The assumption that its AC-DC difference remains the same in both cases is verified up to about 100 V if the influence of thermoelectric effects in the heater resistor is small enough to be neglected. At voltages above 100 V the power dissipated in the range resistor (which can reach 5 W at 1000 V) induces a temperature rise and consequently a change in its electrical characteristics. As the range resistor does not dissipate the same power when the converter is used at its full range or at a lower voltage (a ratio of 2 for the voltage corresponds to a ratio of 4 for the power), its working temperature and then its electrical characteristics are different in both cases. This is finally manifested in a level voltage dependence of the AC-DC transfer difference. For these last five years strong efforts have been made by several NMI's in order to measure or evaluate this dependence. At BNM-LNE, a combination of a high value range resistor limiting the power dissipation to some hundred mW with a wide frequency band amplifier which should provide the needed current to a SJTC or a TFMJTC is under development (See fig. 6).

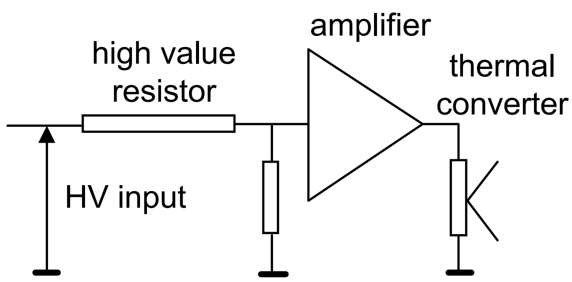

Fig. 6. System under development at BNM-LNE for measurement of voltage dependence of HV converters.

In such a system, the working temperature of the range resistor and consequently the resulting AC-DC difference should not be dependent on the applied voltage level. The only source of voltage dependence should arise from the amplifier behaviour and could easily measured at voltages of the order of one or a few volts.

Finally, with our new standard converters, the low frequency domain which was until now limited to 10 Hz – 100 kHz is being extended up to 1 MHz for voltages not exceeding some tens of volts. Overall uncertainties should be reduced and particularly an improvement from 35 parts in 10^6 to 15 – 20 parts in 10^6 at 1000 V / 100 kHz is expected.

5. HIGH FREQUENCY AC-DC TRANSFER VOLTAGE STANDARDS

New development activity in this field started four years ago. A set-up based on the same principle as that used for low frequency measurements has been developed (see paragraph 7) implying new standards.

5.1. Primary and other standards

Primary standards used at BNM-LNE for high frequency AC-DC voltage transfer are calculable thermal converters developed by VSL-NMi (The Nertherlands) [8]. They consist of a 90 Ω UHF type SJTC in series with a 700 Ω resistor leading to a nominal voltage of 4 V. Their AC-DC difference has been calculated in the frequency domain from 1 MHz up to 100 MHz. Devices serving as primary standards at BNM-LNE are periodically recalibrated at VSL and measured values are compared with calculated AC-DC differences.

The voltage domain from 0.5 V to 30 V is covered by a set of commercially available wide frequency band single range thermal converters.

5.2. Calibration of high frequency AC-DC transfer voltage standards

The procedure used to calibrate the high frequency standards is the same as the one used for low frequency standards. Nevertheless uncertainties which can be reached in this domain are much larger than for the low frequency domain. Firstly the model used to calculate the AC-DC difference of primary standards leads to uncertainties strongly increasing with frequency. Secondly HF sources are not as stable as low frequency sources leading thus to larger type A uncertainty. Thermal EMF's. developing in the HF switch can also bring an additional uncertainty component particularly at the lowest voltages. At the present time, the first step-up procedure in this domain at BNM-LNE is not completed and consequently final uncertainties have not yet been calculated. But as a comparison with the low frequency domain, uncertainties for high frequency primary standards lie between 1 part in 10^5 at 1 MHz and 1 part in 10^3 at 100 MHz.

6. LOW FREQUENCY AC-DC TRANSFER CURRENT STANDARDS

6.1. Primary standards

For current measurements at BNM-LNE, the primary standard is a PTB MJTC. Current (and voltage) AC-DC transfer difference from 10 Hz up to 100 kHz of such devices were published by PTB with an uncertainty of the order of 1 part in 10^6 [3]. This device is inserted into an housing and equipped with connection elements. Current AC-DC difference arising from connection elements was calculated at BNM-LNE and was shown to be only of a few parts in 10^7 at 100 kHz.

6.2. Other standards

New standards consisting of a HF type PLMJTC and a SJTC, each of them associated with a set of commercially available shunts covering the 5 mA to 20 A domain have been developed (See fig. 7).

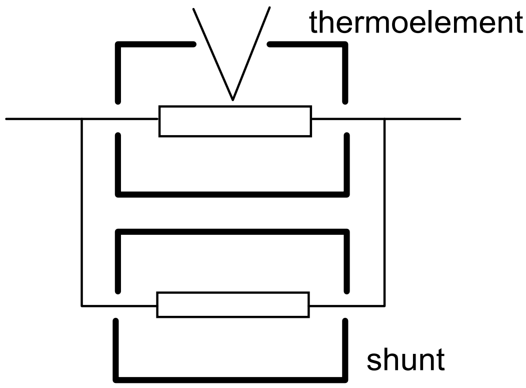

Fig. 7. Principle of a current thermal converter with a single juction thermoelement.

The reason for this choice is the very weak dependence of AC-DC difference of TFMJTC's on signal level, confirmed by measurements performed with the FRDC source. Nevertheless a high parasitic capacitance is observed between heater and thermocouples which is of the order of 9 pF (about 0.2 pF for SJTC's) [9]. As in current measurements, standard converter and converter under test are connected in series, only one of them is grounded. The influence of the parasitic capacitance being smaller when such a converter is grounded because the voltage developed between heater and thermocouples is lower in this configuration, the TFMJTC is always grounded in the step-up procedure and the no-grounded converter is always the SJTC. The first steps of the procedure are the following :

First step: TFMJTC/10mA calibrated against primary standard at 5 mA ;

Second step: SJTC/10mA calibrated against TFMJTC/10mA at 10 mA ;

Third step: TFMJTC/25mA calibrated against SJTC/10mA at 10 mA ;

Forth step: SJTC/25mA calibrated against TFMJTC/25mA at 25 mA and so on...

In the development of these standards, a particular attention was paid to thermal insulation between thermal elements and shunts which can dissipate up to 20 W. Coaxial structure of shunts and housings for thermal elements ensures protection against electromagnetic fields generated when highest currents are applied.

With these new standards, the frequency domain, previously limited to 20 kHz is being extended now up to 100 kHz or 50 kHz for the highest currents. Improvement of uncertainties which were previously of the order of 20 parts in 10^6 at 100 mA for example and between 50 and 60 parts in10^6 at 20 A is expected too.

7. CALIBRATION SET-UP

Automated calibration set-ups have been designed to measure the AC-DC difference of the converter under test by comparing it to a reference converter [10] (See fig. 8). Set-ups used for low frequency voltage, high frequency voltage and current measurements are based on the same principle. Only some specific details can vary. Voltage thermal converters are connected in parallel by the means of a type N tee so that the same voltage is applied on their inputs, and current thermal converters are connected in series by an home made adapter in order that the same current is flowing across them.

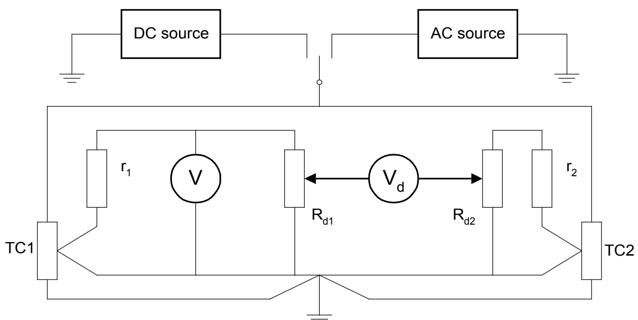

Fig. 8. Block diagram of the calibration set-up

Nanovoltmeter V directly measures the output voltage of the reference converter. Null-detector V_d measures the "differential" voltage between the outputs of two resistive dividers loading the outputs of the converters. When the output voltage of the converter under test is larger than the output voltage of the reference converter, the ratio of divider R_{d2} is adjusted to a value lower than 1 to keep V_d close to balance. The value k of the ratio of divider R_{d1} is determined and adjusted so that the condition $\partial V_d(E,k,...)/\partial E = 0$ (where E represents the value of the input signal applied to the converters) is verified. Slight variations of E (noise, short time instability,...) have then no significant influence on the voltage V_d. This way, as uncertainty on V_d is the main uncertainty component, type A uncertainty on the measurement of the AC-DC difference can be highly reduced in case of noisy or unstable input signals.

An AC-DC switching system allows to apply successively AC, DC+ and DC- signals to the input of the converters. Let V_a and V_{da} be the values measured by nanovoltmeters V and V_d when AC signal is applied and V_c and V_{dc} the mean values of the quantities measured by the same nanovoltmeters when DC signals are applied successively in one polarity and the other. Then, the difference between the AC-DC differences d_1 and d_2 of reference converter and converter under test is given by :

$$d_2 - d_1 = \frac{1}{n_1} \cdot \left(\frac{V_a}{V_c} - 1 \right) - \frac{1}{n_2} \cdot \left(\frac{k.V_a - V_{da}}{k.V_c - V_{dc}} - 1 \right) \quad (2)$$

where n_1 and n_2 are the exponent in the relation linking the output voltage V to the value E of the input signal of a converter which can be written as :

$$V = g.E^n \quad (3)$$

and are determined from changes of the output voltages of the converters produced by shifting the value of the input signal by a factor 10^{-2}.

In order to take into account an eventual drift of the system, the sequence AC, DC+, DC-, AC, DC+, DC- AC, DC+, DC-, AC is applied at the input of the converters at a regular time interval and each time values of V and V_d are read. Final values of V_a, V_{da}, V_c and V_{dc} are computed from this set of data using the least mean square method and modelling the drift by a polynom of 3[rd] degree.

AC and DC signals applied to the converters are generated by an AC and a DC voltage calibrators. For current measurements, a transconductance amplifier is inserted between the AC-DC switching system and the converters which transforms generated voltages in currents. For high frequency voltage measurements a RF synthesiser (125 kHz – 1040 MHz) associated with a RF amplifier (500 kHz – 1200 MHz) are used instead of the low frequency AC source and the low frequency switching system is replaced by a 50 Ω adapted system.

8. DEVELOPMENT OF AC VOLTAGE STANDARDS BASED ON JOSEPHSON EFFECT

It seems that uncertainties of a few parts in 10^7 is a limit for AC-DC transfer techniques. AC voltage sources based on the Josephson effect can theoretically lead to lower uncertainties.

When biased with an RF field with frequency f, a DC voltage V is developed across the Josephson junction which equal to :

$$V = \frac{n.f}{K_J} \quad (4)$$

where n is an integer, K_J the Josephson's constant. The voltage V_N across an array of N junctions is :

$$V_N = N.\frac{n.f}{K_J} \quad (5)$$

Two approaches are presently tested in some laboratories. In the first one, the Josephson array is divided into a binary sequence of array segments (binary array) [11]. The bias current of each segment is separately controlled to select the $n = 0$ or the $n = 1$ step. If the array contains M segments, then 2^M regularly spaced voltage levels can be developed across the array for a given RF frequency. This way, a stair case approximation of a sine wave (or of any arbitrary waveform) can be generated by selecting appropriate voltage levels in rapid succession. Such sources could generate AC voltages up to 1 V and more. Nevertheless in this method, the frequency band is limited because of the non infinitely short settling time of the array and uncertainty is degraded when frequency increases because of the transients generated by switching from one voltage level to an other.

In the second approach, a single array of Josephson junctions distributed along a wide bandwidth transmission line is used. When a pulse propagates along the line, a voltage pulse with a quantized time-integral area equal to n/K_J is induced across each junction it passes. If the array contains N junctions, a pulse train of frequency f generates an average voltage equal to $N.n.f/K_J$ across the array. Arbitrary waveforms are generated by gating the pulse train with a long digital code [12]. This method based on a so called pulse driven Josephson digital-analog converter can cover a wide frequency domain up to the MHz range but voltages which can be presently generated and in a near future are only of a few mV.

BNM-LNE is involved in the European project JAWS (Josephson Arbitrary Wave Synthesizer) which target is the development of such a source. Our main contribution will be the development of a transportable cryosystem with a shortened probe and precise comparison of Josephson AC voltage with AC-DC transfer at the end of the project. During the next two years, standards for low voltage AC-DC measurements will be developed and calibrated at BNM-LNE.

9. CONCLUSION

AC-DC transfer activities at BNM-LNE cover low frequency voltage measurements, high frequency voltage measurements and current measurements. In each domain, the present work tends to the improvement of uncertainties or/and the extension of the domain. For AC measurement, application of Josephson effect to generate standard AC voltages is explored as an independent method from AC-DC transfer.

REFERENCES

[1] F. L Hermach, "Thermal converters as AC-DC transfer standards for current and voltage measurements at audio frequencies", *J. Res. Nat. Bur. Stand.,* vol. 48 n°2, pp. 121-138, February 1952.

[2] F. J. Wilkins, T. A. Deacon and R. S. Becker, "Multijonction thermal convertor", *Proc. Inst. Elect. Eng.,* vol. 112, n°4, pp. 794-805, April 1965.

[3] M. Klonz, "AC-DC transfer difference of the PTB multijonction thermal converter in the frequency range from 10 Hz to 100 kHz", *IEEE Trans. Instr. Meas.,* vol. IM-36, n°2, June 1987.

[4] M. Klonz and T. Weimann, "Accurate thin film multijonction thermal converter on a silicon chip", *IEEE Trans. Instr. Meas.,* vol. 38, n°2, April 1989.

[5] F. C. Widdis, "The theory of Peltier and Thomson effect errors in thermal AC-DC transfer devices", *IEE,* Monograph n°497 M, January 1962.

[6] M. Klonz, R. Zirpel and B. Stojanovic "Improving speed and AC accuracy of AC-DC transfer using a fast reversed DC", *CPEM'90 Conf. Digest,* pp. 68-69, 1990.

[7] M. Klonz, T. Spiegel, R. Zirpel, B. D. Inglis, G. Hammnod, H. Sasaki, K. Takahashi and B. Stojanovic, "Measuring thermoelectric effects in thermal converters with a fast reversed DC", *IEEE Trans. Instr. Meas.,* vol. 44, n°2, pp. 379-382, April 1995.

[8] C. J. van Mullem, W. J. G. D. Janssen, and J. P. M. de Vreede, "Evaluation of the calculable high frequency AC-DC standards", *IEEE Trans. Instr. Meas.,* vol. 46, n°2, April 1997.

[9] P. S. Filipski, M. Boecker, "Experience with high-output-resistance MJTC AC-DC transfer standards", *IMTC'02 Conf. Digest,* pp. 85-89, Anchorage (USA), May 21-23, 2002.

[10] A. Poletaeff, "Automated comparator for accurate AC-DC difference measurements at the BNM-LCIE", *IEEE Trans. Instr. Meas.,* vol. 48, n°2, pp. 412-414, April 1999.

[11] C. A. Hamilton, C. J. Burroughs and R. L. Kautz, "Josephson D/A converter with fundamental accuracy", *IEEE Trans. Instr. Meas.,* vol. 44, n°2, pp. 223-225, April 1995..

[12] S. P. Benz, C. A. Hamilton, C. J. Burroughs, T. E. Harvey, L. A. Christian and J. X. Przybysz, "Pulse driven Josephson digital/analog converter", *IEEE Trans. Appl. Supercond.,* vol. 8, n°2, pp. 42-47, June 1998.

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The BNM (Bureau National de Métrologie) was funded in 1969 to animate and co-ordinate actions undertaken in the field of metrology in France. Since May 2001, five members, who are the French State, represented by the Department of Industry and the Department of Research and Technology, and four organisations each accommodating a National Metrology Institute form the BNM. The LNE (Laboratoire National d'Essais) is one of these organisations and accommodate the BNM-LNE. Among other metrological activities, BNM-LNE is in charge of the definition, maintening and improvements of national standards in the field of electricity for which 25 people are involved.